TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
DEPARTMENT OF MATERIALS AND ENVIRONMENTAL TECHNOLOGY

INJECTION MOLDING AND PROPERTIES OF COMPOSITES FILLED WITH SYNTHETIC AND NATURAL FIBERS

SÜNTEETILISTE JA LOODUSLIKE KIUDUDEGA TÄIDETUD KOMPOSIITIDE VORMIMINE JA OMADUSED

MASTER THESIS

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Tallinn 2021

(*On the reverse side of title page*)

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Hereby I declare, that I have written this thesis independently.
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May 24, 2021

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Department of Materials and Environmental Technology

THESIS TASK

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Thesis topic:

"Injection molding and properties of composites filled with synthetic and natural fibers"

"Sünteetiliste ja looduslike kiududega täidetud komposiitide vormimine ja omadused"

Thesis main objectives:

1. To prepare and study the Low-Density polyethylene, Recycled polyethylene and Polypropylene composites filled with cotton, polyester and 50/50 mixture of polyester+cotton fibers for injection molding applications.
2. To investigate the influence of fiber type and content on mechanical properties and morphology of composites.
3. To investigate the influence of UV aging on to the mechanical properties.
4. To investigate the effect of compatibilizer on to the mechanical properties and morphology of LDPE composites.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Fiber milling, premixing, compounding and injection molding of LDPE, RePE and PP composites with cotton, PET and 50/50 mixture of PET+cotton fibers.	June 2020
2.	Mechanical & morphology testing of LDPE and RePE composites.	Sept 2020
3.	UV aging and mechanical testing of UV aged composites.	Dec 2020
4.	Fiber milling, premixing, compounding and injection molding of LDPE composites with cotton fibers, PET fibers and MAPE compatibilizer.	Mar 2021
5.	Mechanical & morphology testing of LDPE composites with compatibilizer.	April 2021

Language: English **Deadline for submission of thesis:** 24 May 2021

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PREFACE

First and foremost, I would like to thank my supervisors, research scientist Dr. Illia Krasnou for his valuable guidance, continuous inspiration, motivation and ever cooperating attitude during the course of this work and senior lecturer Dr. Elvira Tarasova for providing all kind of possible help and advice during this thesis and project work.

I am greatly thankful to all the staff members of the Technology of plastics department and would like to acknowledge my friends & well-wishers for their support and unlimited encouragement throughout this research work.

The fundamental concept of this research work is to discover the possibility to utilize cotton and polyester fibers recovered from textile waste as a filler or reinforcement for thermoplastic composites. The use of recycled textile fibers as filler/reinforcement can provide cost saving and environmentally friendly as well. During this research work, composite compounds of LDPE (low density polyethylene, RePE (recycle polyethylene) and PP (polypropylene) filled with different percentages of PET, cotton and 50/50 mixture of PET+Cotton fibers were produced by using twin screw compounder. Later these compounds were processed by injection molding technology to manufacture dumbbell shape specimens. The effect of various fiber content i.e., 10-40 wt. % on mechanical properties, morphology and UV aging was studied. Furthermore, effect of maleic anhydride grafted polyethylene coupling agent with 30 wt. % of PET and cotton fibers on mechanical properties and morphology was investigated. By studying results, it was discovered that flexural strength was improved, impact strength reduced in LDPE and RePE composites but increased in PP composites. Tensile strength was slightly reduced by the incorporation of PET and cotton fibers in thermoplastic composites. Incorporation of MAPE improved the mechanical properties and bonding of cotton and matrix LDPE polymer.

All the research work was performed beneath the supervision of the research scientist Dr. Illia Krasnou and senior lecturer Dr. Elvira Tarasova in the materials and environmental technology department at Tallinn university of technology, Estonia.

Keywords: Cotton and polyester fibers, thermoplastic polymer composites, injection molding, mechanical properties, textile waste

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List of abbreviations and symbols

CO^2 – Carbon dioxide

CTN – Cotton

EOC – Ethylene octene copolymer

FTIR – Fourier-transform infrared spectroscopy

GPa – GigaPascal

LDPE – Low density polyethylene

MAPE – Maleic anhydride grafted polyethylene

MFI – Melt flow index

MPa – MegaPascal

PA – Polyamide

PE – Polyethylene

PEA – Polyester amide

PEEK – Polyether ether ketone

PET – Polyethylene terephthalate

PP – Polypropylene

PS – Polystyrene

RePE – Recycled polyethylene

SEM – Scanning electron microscopy

UV – Ultraviolet light

1. INTRODUCTION

Over the past few decades, polymers and polymeric composite materials have emerged as dominant replacement for traditional materials like ceramics, wood and metals. The demand and applications of composite materials are growing gradually, conquering new markets day by day. Modern fibrous composite materials are being used in wide range of applications ranging from everyday domestic products to sophisticated industrial applications. The motives why composites are carefully chosen for such applications are primarily their lightweight, high strength to weight ratio, non-corrosive property, high tensile strength, high stiffness properties as well as their ease of production and design flexibility. (A. Ticoalu, 2010). Composites reinforced with synthetic fibers like glass, aramid and carbons fibers are broadly used in numerous applications ranging from construction industry, automotive industry, sports goods and aerospace industry. (G. M. Matoke, 2012). Though these synthetic fiber reinforced polymer composites provide high-class mechanical properties, they also possess serious downsides such as high density, health risks, poor recyclability, highly cost, environmental concerns and non-biodegradable properties. (Begum K., 2013). Hence, the research in fiber reinforced polymer composites has been shifted towards use of environment friendly, sustainable, cheap, lightweight, low density and renewable materials and these fibers are getting more attention in recent years as a substitute to synthetic fibers. (D. Nabi Saheb, 1999).

These days, the scope of studying polymeric composites with textile waste as reinforcement has increased in research activities. The use of polymeric materials-based composites with fibers from industrial by-products or waste as reinforcement is appealing the consideration of researchers. The key purpose to use textile wastes are that the textile waste is cheaper, can be profitable and recent textile products are made from natural as well as synthetic materials, so recycling of this waste materials to produce new composites can also be environment friendly.

Textile and apparel products consumption has seen a swift increase due to the rapidly rising world population, consumers' buying power, day by day changing in fashion designs and patterns. (Rachael E. Marshall, 2013) Fast fashion textile sector is accountable for higher production and consumption of textiles and apparel. Currently on average, an individual purchases 60% more clothing products and uses half of the time as compared to 15 years ago. This change in consumption behaviors is producing an enormous amount of textile waste. (RICK Leblanc, 2020) The textile industry is an integral part of Estonian industrial sector and financial resources. It provides jobs to 13% of total industrial labor force. The clothing industry had approx. 5% stake of sales in total sale of commercial output and overall exports of apparel sector during 2015

were valued around €400 million which is five percent of total overseas sell by Republic of Estonia. (ECTA, 2021).

Contribution of textiles in waste stream is considerable as significant quantity of valuable fibrous products are discarded after usage. Millions of tons of waste is produced annually in the manufacturing and disposal of clothing and textile products. Fast increase in generation of textile waste is causing serious problems on the human health and environment as well. A huge percentage of the textile waste is obtained from both natural and synthetic materials and their blends as well. Natural material is cotton and synthetic materials are polyesters. Both of these natural and synthetic fibers are responsible for these harmful results. Disposal or dumping of such bulky amount of wastes is a critical problem for the textile manufacturing. Until now there is not enough capability in Baltic states to reprocess the used clothes, which means that large quantities of garments end up in landfill, which is the wastage of potential economic opportunities. (Helen Saarniit, 2019).

Landfilling the textile waste has major impact on the environment. Once landfilled, natural fibres may take up to hundreds of years to decompose. Decomposed textile waste generates greenhouse gases that contributes to global warming. (Caiyou Zhao, 2014). Furthermore, synthetic textiles are designed not to decompose due to their non-biodegradable nature and toxic characteristics, their harmful effects on environment due to landfilling are incalculable. In the landfill, they can release toxic substances into groundwater and surrounding soil. (Rick Leblanc, 2020) Hence, just by disposing the textile waste we are harming the environment in several manners and wasting valuable resources at the same time. Textile recycling is a challenge which needs to be addressed as we struggle to move nearer to a zero landfill society. One of the solutions is to reuse the textile wastes with polymer materials and produce composites for lower weight applications.

This research work is focused on development of thermoplastic composites with textile waste as filler for injection moulding applications. Cotton and polyester waste were used as fillers for LDPE, RePE and PP matrix polymers. In the initial phase, compounds were prepared with fiber loads of 10%, 20%, 30% and 40% by compounding at twin-screw extruder. In next phase, these compounds were processed on injection molding machine in order to produce the bone shape specimen for testing. Lastly, the mechanical properties and morphology of fiber-filled polymer composites were examined in comparison with pure polymer.

2. LITERATURE SURVEY

A comprehensive literature survey to have an overview regarding the cotton and polyester fiber-filled polymer composites, production processes and mechanical testing is presented as a part of thesis work in this chapter. In the last part of this chapter the possible applications of cotton and polyester fibers reinforced composites are discussed as well.

2.1 Composite materials

Composite materials are recently one of the hotspot study topics in the advanced technology. In this modern era, their auspicious characteristics make them eligible for vast industrial applications like automotive, construction, aerospace, sports, biomedical, marine, electrical and numerous other countless industries. The main reason behind this swift evolution and popularity in the area of material sciences and engineering is because composites offer extremely attractive combination of toughness, stiffness, low weight and environmental stability. (Dipen Kumar Rajak, 2019). Composites have risen as a new vital class of advanced and engineering materials as they offer numerous features which cannot be achieved with other materials.

A composite material is defined as the composition or formation of two or more immiscible materials with remarkable different chemical or physical properties. Combining those together fabricates a material which owns unique properties which are different and superior from individual components. (T. W. CLYNE, 2019). In composite materials, one of the components is known as "binder or matrix" that gives the shape and bonds to the material and the other component is called reinforcement, that gives good mechanical properties. Reinforcement offers the strength and stiffness and helps to support the operational loads. The purpose of matrix is to uphold the position and orientation of the reinforcement and transfer load to reinforcement material when applied. (Saira Taj et al., 2007). Composites can be categorized into four categories based on the nature of matrix material. These categories are ceramic matrix composites (CMCs), metal matrix composites (MMCs), polymeric matrix composites (PMCs), and carbon/carbon composites (CCMs). (S. T. Peters, 1998). Amongst these types, polymer matrix composites are the most common advanced composites. Polymer composites comprises of a thermoplastic or thermoset usually reinforced by fibers but fillers or ground mineral particles are also used. These materials can be shaped into a wide range of designs and sizes. Moreover, they offer great strength and stiffness with corrosion resistance as well. The reasons for the admiration and vast usage of polymer composites

are their low cost, high strength and simple manufacturing techniques. (Saira Taj et al., 2007). The most common matrix materials used in PMCs are epoxy, phenolics, vinyl esters, polyethylene (PE), polypropylene (PP), polyamide (PA), polyester (PET), polyether ether ketone (PEEK) and polystyrene (PS).

2.1.1 Polymer composites with cotton fibers

Natural fibers are being used for around past 3,000 years to reinforce materials. Altogether, any fibers which are not synthetic or man-made fibers are known as natural fibers. They can be sourced from plants or animals. The increase in environmental awareness and community interest and the new environmental regulations led to thinking of the use of environmentally friendly materials. Many natural fibers have been studied for use in polymer composites such as jute, sisal, bamboo, wood, coir, hemp, cotton, wool, flax, rice husk, wheat, oats, barley, grass, kenaf, reeds, ramie, kapok, banana fiber, pineapple leaf fiber, papyrus and many others. (A. K. Bledzki, 1999) Nevertheless, cellulose fibers have some drawbacks because of their inherent characteristics, like incompatibility when used with hydrophobic polymer matrix, tendency to procedure aggregates while processing and poor moisture resistance. (A .L. Martínez-Hernández, 2007).

Composited reinforced with natural fibers can provide mass specific mechanical stiffness values as same as offered by composites reinforced with glass fibers. Furthermore, natural fibers are around half lighter than glass and mostly cheaper as well. (Paul Wambua, 2003). Cotton fibers are one of the natural fibers which are high-quality cellulosic fibers and can be used as reinforcement is polymeric composites because of cheaper prices and high availability. One of the key advantages of cotton fibers is fiber fineness as compared to flax fibers. Flax fibers have a thickness of around 40–620 μm whereas cotton fibers have thickness of around 12–38 μm. (Jörg Müssig, 2010). Specifically, in case of thermoplastic plastic composites reinforced with short length fibers, the thickness of fiber is significantly important.

According to (Sam-Jung Kim et al., 2008), as the fiber content increased the tensile strength of PP composites filled with wood fibers decreased, while PP composites filled with cotton fibers showed the opposite behavior. With the incorporation of 10% of cotton fibers, the tensile strength decreased, while when the cotton fiber content was increased to 20% and 30%, the tensile strength increased accordingly, this happened due to the entanglement of cotton fibers. A study was conducted by Y. Mwaikambo and Bisanda for the performance of cotton-kapok fabric-polyester composites, it reported that tensile strength of polyester matrix composite filled with cotton fabric decreased as the content

of cotton fabric increased. The reason is perhaps increase in voids as the cotton fabric volume element increased. (Leonard Y. Mwaikambo, 1998). Their study also reported that the flexural strength of PP composites filled with cotton fiber increased by increasing the wt. % of cotton fibers.

Bio-degradable composites with PEA reinforced with cotton and flax fibers (30% fiber content) were investigated by (L. Jiang, 1999). A considerable increase of 163%, 255% and 350% was observed in mechanical properties like flexural strength, flexural modulus, tensile strength and Young's modulus as well. Cotton fibers have been successfully used to reinforce polyolefins in many studies, in some studies raw cotton fibers have been used as a reinforcement while a vast majority of researchers chosen to use recycled cotton fibers from textile industry waste. (Albert Serra et al., 2019). Recycled cotton fibers recovered from the textile waste have some advantages like low cost and easily excessive availability, but they have some drawbacks as well such as these fibers comprise textile dyes. A prior research unveiled that the existence of dyes in cotton fibers reduced its hydrophilicity which permitted to attain better interphases without usage of coupling agents at all. Furthermore, these dyes improved the distribution of fibers without any treatment. Nevertheless, the composite materials which were reinforced with dyed cotton fibers showed lower tensile strength than those which were produced with other natural fibers and comparable to PP composites reinforced with low content of glass fibers. (Quim Tarrés et al., 2018).

A study for the successful preparation of PP composites reinforced by using cotton fibers, these cotton fibers were attained from textile waste according to (Rafael S. Araújo et al., 2017). The cotton fibers were firstly bleached and then chemically surface modified by silanization or acetylation procedures. The effectiveness of both treatments was confirmed by FTIR and X-ray spectroscopy. The effect of fiber percentage and chemical modifications were examined by thermomechanical and mechanical testing. The results presented that the incorporation of recycled cotton fibers increased the tensile strength, storage modulus and Young's modulus i.e., stiffness.

One more remarkable study was conducted by (Yi Zou et at., 2011) described a unique method of reusing the textile waste of fabrics with blend of PET and cotton to prepare composite materials without any extra polymer matrix material and reinforcement medium. PET works as a matrix material and cotton acts as a reinforcing agent. The results of this research show the 36% higher Young's modulus, around 150% higher modulus of elasticity, comparable impact strength but 44% less tensile strength and 17% lower flexural strength when compared to PET material.

2.1.2 Polymer composites with polyester fibers

Synthetic fiber composites usage in manufacturing industries is unpreventable as their properties are superior than natural fibers. The most popular and commonly used synthetic fibers used in polymer composites are glass, aramid and carbon fibers. Synthetic fibers are employed to produce high-performance polymer composites items such as FRP tanks, aerospace components, automotive parts and construction panels. (Mohammad Jawaid, 2019). Synthetic fibers generally have persistent diameter, uniform size, smooth surfaces, significant rigidity and perform in more predictable fashion. The most frequently and significantly used synthetic fibers for engineering applications are glass, metallic and naturally derived man-made fibers etc. Implanting these fibers in polymer matrix empowers them to act as more strong, stiff and tough materials. (Sabu Thomas, 2014).

Perhaps polyester fibers are the utmost common type of synthetic fibers and most commonly polyester fibers are manufactured from PET. Textile industry is the biggest application field of PET fibers. PET fibers can be produced with elastic modulus of up to ~ 10 GPa, tensile strength of ~ 1 GPa and toughness of 200 MJ/m³. One more advantage of PET fibers is that they can be produced cheaply in large scale by melt spinning process. (P. M. Visakh, 2015). Over the past few years, composites filled with PET fibers have been effectively investigated by researchers.

According to (Mohammad Asgari et al., 2012), thermal properties and impact strength of PP matrix composite filled with PET fibers showed good performance. Powdered PP with MFI of 5 g/10 was compounded with a commercially available PET fibers of textile polyester. Composites with fibre content of 5, 10, 15, 20, and 30% were thoroughly combined at 180 °C in a mixer for approximately 10 minutes. Afterwards, compounded mixture was molded by using hot press at 180 °C temperature & pressure of 100 bar. Produced PP/PET fiber composite materials showed increase in impact strength by almost 20% and up to 65% increase in tensile strength and elastic modulus.

The research results of (M.A López-Manchado et at., 2001) showed that incorporation of PET fibers in PP/EOC (Polyolefin Elastomer) blends made the material stiffer and more enhanced the mechanical properties as well. PET fibers showed the more noticeable reinforcing effect at high concentrations i.e., above 50%, which resulted in increase of Young's modulus of around 90%. Moreover, in morphology analysis SEM images confirmed the good adhesion of PET fibers with the PP/elastomer matrix. Another study was conducted by (C. Saujanya et al., 2001) to examine the structure development and mechanical properties PP matrix composite reinforced by means of PET fibers with and without compatibilizer viz. maleic anhydride (MA). The results exhibited that the

mechanical properties of these composites such as tensile modulus and impact strength enhanced as compared to neat PP. Moreover, in structural studies in the absence of compatibilizer, the PET fibers proved to be strong nucleating agent for PP spherulites thus showed transcrystalline morphology. Whereas, in existence of maleic anhydride, no transcrystalline growing was detected. SEM analysis of fractured surfaces revealed the adhesion of PET fibers to PP matrix was better in presence of compatibilizer than without it.

Studies were successfully able to produce composites with LDPE and PP homopolymers and their blends as well reinforced by short length polyester fibers according to (M Arroyo and J.P. Vigo, 1995). Their study suggests that the strength of composites depends on the configuration of matrix as compared to fiber percentages and only in case of LDPE/PP ratios of above 1, flexural strength showed a very noticeable increase with increase in fiber content. Furthermore, tensile and flexural modulus increase as PP and PET fibers contents increase. Scanning electron micrographs suggests a better degree of bonding between composite of LDPE and PET fibers as compared to composites of PP and LDPE/PP blend at 50/50 ratio.

2.2 Injection molding of thermoplastic composites

Injection molding is one of the most important and widely used fabrication method for plastic and composite products manufacturing. Injection molding is a technique which produce molded products by injecting plastic materials molten by heat into a mold, then cooling which solidify them and after cooling the part is ejected by the help of ejector pins. (Pramendra K. Bajpai et al., 2020). This technique is suitable for the mass production of articles with complicated shapes with low fabrication cost. Irrespective the design of the machine, all injection molding machines use power source, injection unit, mold assembly and clamping unit to accomplish the 4 phases of process cycle.

Fiber reinforced thermoplastics can be processed by means of injection molding as well. Short fiber reinforced thermoplastics are injection moldable materials comprising of thermoplastics matrices with discontinuous fibers, generally in the length span of 10 mm down to < 0.1 mm. The very short fibers and lower fiber contents are obligatory to allow the compounds to be effortlessly injection molded and for achievement of a good surface finishing. (MYER KUTZ, 2002).

The use of injection molding technology is increasing for fiber filled thermoplastic composites. The process for injection molding of thermoplastic composites is similar to injection molding of thermoplastic materials without reinforcements. Reciprocating

screw machine is preferred for the processing of reinforced materials as it provides better homogeneous mixing, metering and melt temperature control. The use of fiber in the material enhances the mechanical strength and offers better dimensional stability to the product. (Sanjay K. Mazumdar, 2002). A limitation with injection molding process for reinforced plastics is that the only short fibers can be used. The final molded parts comprise fibers which range between 0.2 to 6 mm in length because fibers breakdown as they pass through machine's screw, barrel, nozzle, or further portions of the equipment and mold.

Injection molding process variables are categorized into five most important types that contains pressure, temperature, time, speed and stroke. These associations cannot be willingly separated. (P D Kale et al., 2021). The mechanical properties, quality of the injection molded parts and achievement of optimum production rate depends on various process parameters, any changes may lead to faulty parts. These key parameters include injection pressure, injection speed, injection time, screw back-pressure, melt temperature, barrel and mold temperature, cooling time, ejection pressure, mold geometry shape, shot size and heat transfer action of material flow field. (Y. K. Shen et al., 2002). Careful selection of earlier stated process variables can avoid complications associated to excess flash on product's parting lines, weld lines, short molding, flow lines, sink marks, burn marks, bubbles, poof surface finish, part warpage and shrinkage etc. Shrinkage and warpage generally result in molded items with out of required dimensions and tolerance limits. (Sanjay K. Mazumdar, 2002). Too high barrel temperature can degrade the polymer material. Low mold temperature results in poor surface finish of part. A higher screw backpressure delivers more thorough mixing, but it breaks the fibers into shorter lengths. This reduces the mechanical properties but improve the part surface quality. Fast injection rates and speed helps in better filling of mold due to pseudoplastic behavior of polymer melts. (Michael G. Bader, 2002).

The injection speed is usually set at the minimum value which is needed to fill the component completely without any processing defects. If the injection speed is too low, it could result in surface defects like weld lines, flow lines and incomplete cavity fill or short molding. Whereas too high injection speed will result in the formation of flashes. Basically, the injection speed regulates the degree of molecular orientation, therefore affects the bonding, orientation and shrinkage. (Hans-Peter Heim, 2015). Processing parameters such as processing temperature, screw and injection speed have a huge impact on mechanical properties of the composites. The material backflowing is reduced by the processing parameter of holding pressure. Holding pressure also helps to stop the part shrinkage which occurs during the cooling period, so the best possible production result is accomplished. Very high holding pressure will cause extra flash in

the part. While, if the holding pressure is too low, it will cause the dimensional instability and excessive shrinkage in the part. (Jackie, 2018).

A study by (Lee et al., 1997) compared orientation of fibers for fast slow molding filling situations. The results revealed that in case of slow filling more fibers are oriented in flow direction because of shear flow instead of fast filling case. According to (E. S. Zainudin et al., 2006), Bright & Darlington described that a accomplish an improved surface finish, fast injection speed is typically applied. In reinforced thermoplastics an un-glossy surface finishing is a usual issue, so it is recommended to use a higher injection pressure, speed, mold and melt temperature while processing.

2.3 Mechanical properties testing

2.3.1 Tensile test

The tensile strength test is of key importance to explain the mechanical properties of polymeric systems. Ultimate tensile strength (or tensile strength) is defined as the stress which the test material could withstand before breaking under stretching. Tensile strength can be calculated as maximum load at breaking point divided by cross sectional area of specimen. Tensile test generates stress-strain diagram which is utilized to find out tensile strength at yield, tensile strength at break, modulus of elasticity, tensile strain, elongation, elongation at break, energy at break etc. (Mohammad Jawaid, 2019).

$$\sigma = F/A \tag{2.1}$$

Where,

σ = Tensile stress, F = Force, A = Area

$$E = \sigma/\varepsilon \tag{2.2}$$

Where,

E = Young's modulus, σ = Tensile stress, ε = Tensile strain

The tensile strength of fiber reinforced plastic composites relies on numerous factors such as the basic properties of matrix material and fibers, fibers aspect ratio, manufacturing process of composites, processing parameters and last but not the least the interfacial bonding between the fibers and matrix material. (Pramendra K. Bajpai et al., 2020). In tensile testing, the produced test specimen is placed between two grips

of universal testing machine and both are pulled in opposite direction at a pre-set test speed and force which is required to pull the specimen is calculated in order to determine the extent to which sample stretches before it breaks. (Mariam AlMaadeed et al., 2020).

Plastics and composites are polymer materials with added ingredients with aim to improve performance or cost reduction. Plastics and composites are also tensile tested to evaluate the quality of product. The result of tensile test facilitates to identify materials, design products to encounter forces and essential quality inspections for materials. (PRESTO TESTING INSTRUMENTS, 2017).

2.3.2 Flexural/bending test

The stress-strain performance of materials at bending is of great significance to a product designer and polymer manufacturer as well. Flexural strength is the capability of the material to resist the bending forces which are functional perpendicular to its lengthwise direction. Flexural properties are described and calculated in terms of the maximum stress and strain which take place at the outer surface of the test specimen. Flexural strength test has numerous advantages over tensile test. If a material is utilized in the shape of a beam and service failure happens in bending, then for design purpose bending test is more appropriate than a tensile test, as it may provide a strength value quite different from the computed strength of the outer fiber in the bent beam. (MYER KUTZ, 2002).

Flexural strength test is performed for plastics and polymer composites on universal testing machine in three-point bending or four-point bending methods. In three-point bending test the test specimen is placed like a supported beam on a two support pins set at a distance away from each other and a load applied on the center point of test specimen by means of a loading nose generating thee points bending at a specified rate. In three-point bending test flexural strength is calculated by using the following equation: (Wolfgang Grellmann, 2013)

$$\sigma \mathrm{f} = \frac{3FL}{2bd^2} \tag{2.3}$$

Where:

σf = flexural strength, F = maximum load, L = support distance, b = width of the test specimen, d = thickness of the test specimen

Usually, the result data of flexural test is used in selection of materials for components that can support loads without bending. Bending testing can help to obtain a semi qualitative idea of the fiber-matrix interfacial strength of a composite. (Akhil Mehndiratta et al., 2017). Bending test provides flexural response, flexural strength, fracture toughness and flexural modulus, which are very critical and valuable in engineering design and application. Flexural modulus indicates about the stiffness of a material once flexed. Flexural modulus is determined in the initial time of testing by division of variation in stress by the related variation in strain.

2.3.3 Impact test

The impact test symbolizes an energetic scenario, where sample accommodate distortion and rapture processes in relatively quicker time period. Impact strength is amongst most important mechanical properties of polymeric materials. The standard Izod and Charpy tests are the most widely used procedures to find out the impact strength of polymer and composite materials. The sample is subjected to fracture by hammer pendulum impact and the energy absorbed by a material is determined. The major difference between Izod and Charpy tests is the position of the notched test specimen. In Izod test the test specimen is clamped vertically as a cantilever beam whereas in Charpy test the specimen is placed horizontally as a simple beam on the support blocks of testing machine. Moreover, the notch faces the pendulum in the Izod impact test, but the position is opposite in the Charpy impact test. The specimen to be tested for Charpy impact test must be notched. The objective to notch the test specimen is to create a stress concentration region which encourages a brittle failure rather than ductile. (Steven M. Kurtz, 2015). The impact strength of polymers and plastics reveals about the toughness of these materials. Toughness is the capability of polymeric materials to absorb the energy which is applied. If the impact strength of a material is high, its toughness is high. (MYER KUTZ, 2002).

Before starting the impact test, the pendulum is lifted in upward position. The test specimen is placed on the support blocks of the testing machine. Samples must be placed in such a way that the striking edge of pendulum hit the center of the notched specimen. Cautiously adjust the notched sample so that the center of the notch is located in the axis of impact. The pendulum hammed is released and swing through. The impact energy absorbed by the test sample is recorded. This energy will be put in the following equation to calculate the impact strength values of testing material.

$$acN = \frac{W}{h \times bN} \times 10^3 \qquad (2.4)$$

Where:

a_{cN} = Impact strength (KJ/m²)

W = Energy absorbed by the test specimen (J)

b_N = Width at the notch base of the test specimen (mm) – 8 mm

h = Thickness of the test specimen (mm) – 4 mm

2.4 The objectives of the study

The aim of research work is focused on the problem of reuse of cotton and polyester textile waste and preparation of thermoplastic composites with LDPE, PP and recycled LDPE by injection molding. Also, to investigate the influence of fibrous filler type (cotton, polyester and mixed), and fiber content on to mechanical properties and morphology of polymer-fiber composites.

The objectives of this study are:

- Preparation of polyester and cotton fibers by milling in cutting mill.
- Vacuum drying of cotton fibers to get rid of moisture.
- Weighing, premixing and compounding of polyester, cotton fibers and their mixture (50-50%) with LDPE, PP and RePE at 10%, 20%, 30% and 40% of fiber content.
- Pelletizing of the compounds.
- Processing of the compounds by injection molding to produce the standard dumbbell shape test specimens for testing purposes.
- To take note of the influence of different fiber types and contents on the processing conditions and parameters on injection molding.
- To test the produced composites properties:
  - The melt flow rate of cotton fibers filled LDPE compounds and effect of fiber content on melt flow behavior.
  - The mechanical properties by tensile strength test, flexural strength test and Charpy impact strength test.
  - The effect of UV aging on to the mechanical properties.
  - The effect of coupling agent on to the mechanical properties and morphology.
  - To compare the tensile strength of composites produced by using recycled T-shirt polyester and cotton fibers with raw fibers.
  - Morphology of composites by Scanning electron microscopy (SEM).
  - To compare the results of all produced composites with each other and with neat polymer matrix samples.

3. MATERIALS AND METHODS

3.1 Materials

3.1.1 Polymer matrix materials

Following three different polymer matrix materials were used for composite preparation:

1. Low-density polyethylene (LDPE) powder, supplied by Egyeuroptene with MFI = 5 g/10 min @ 2.16 kg, temperature 195 °C.
2. Polypropylene (PP) powder, supplied by Egyeuroptene with MFI = 14 g/10 min @ 2.16 kg, temperature 210 °C.
3. Recycled low-density polyethylene (RePE) powder, supplied by PlastFrog OÜ with MFI = 4.8 g/10 min @ 2.16 kg, temperature 195 °C.

3.1.2 Reinforcement fibers

Polyester fibers supplied by Advansa GmbH (Hamm, Germany) with density 6.7 dtex, average 30 μm fiber diameter and 12 mm fiber length.

Cotton fibers supplied by Lemoine Estonia OÜ (Tallinn, Estonia) with average 15 μm fiber diameter and 16 mm fiber length.

50/50 mixture of cotton and polyester.

Sampling plan is represented in Table 1.

Additionally, recycled cotton and polyester fibers recovered from T-shirts waste were also used for composites preparation in order to compare the performance with composites produced by using raw cotton and polyester fibers. These recycled fibers were used at 30 wt. % with LDPE and PP matrix materials. Table 2 represents the sampling plan for recycled fibers which was followed during this thesis work.

3.1.3 Coupling agent

To improve the adhesion between LDPE thermoplastic matrix and reinforcement fibers, a coupling agent of FUSABOND E226 – maleic anhydride modified polyethylene supplied by DUPONT was employed. Coupling agent ratio was 5% and 7% of total weight of reinforcement fibers. Coupling agent was used only in composites with 30 wt. % of

cotton and polyester fibers. Table 3 below represents the sampling plan for coupling agent which was followed during this thesis work.

Table 1. Sampling plan for compounding and injection molding

S No.	Sample	Fiber Content %				
1	Pure LDPE	0	-	-	-	-
2	LDPE + PET fibers		10	20	30	40
3	LDPE + Cotton fibers		10	20	30	40
4	LDPE + PET/cotton fibers (50/50)		10	20	30	40
5	Pure PP	0	-	-	-	-
6	PP + PET fibers		10	20	30	40
7	PP + Cotton fibers		10	20	30	40
8	PP + PET/cotton fibers (50/50)		10	20	30	40
9	Pure RePE	0	-	-	-	-
10	RePE + PET fibers		10	20	30	40
11	RePE + Cotton fibers		10	20	30	40
12	RePE + PET/cotton fibers (50/50)		10	20	30	40

Table 2. Sampling plan for compounding and injection molding with recycled T-shirt fibers

S No.	Sample	Fiber Content %
1	LDPE + PET fibers	30 %
2	LDPE + Cotton fibers	30 %
3	LDPE + PET/cotton fibers (50/50)	30 %
4	PP + PET fibers	30 %
5	PP + Cotton fibers	30 %
6	PP + PET/cotton fibers (50/50)	30 %

Table 3. Sampling plan for compounding and injection molding for coupling agent

S No.	Sample	Fiber Content %	Coupling Agent %
1	LDPE + PET fibers	30 %	5 %
2	LDPE + Cotton fibers	30 %	7 %

Overall road map of composite preparation is represented in Figure 1.

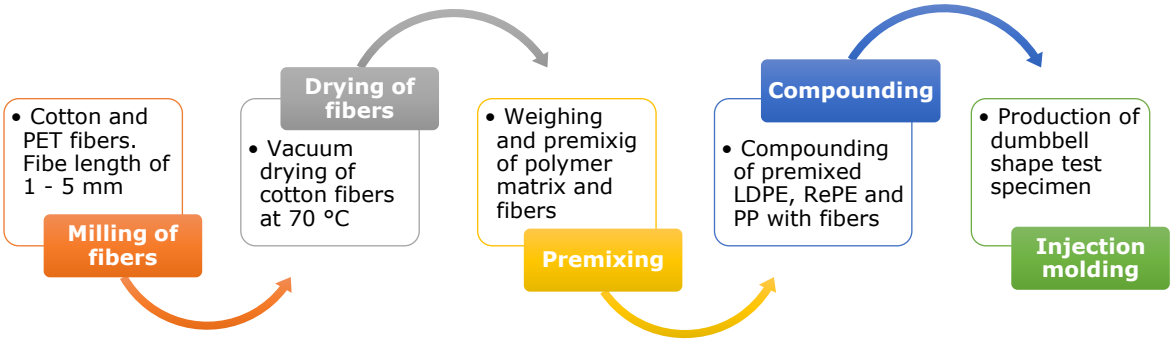

Figure 1. Workflow of composites specimen preparation for the research work

3.2 Milling of fibers

To start the project work, cotton and PET fibers were milled to reduce the fiber lengths to the range of 1 to 5 mm (short fibers). The fibers were milled in RETSCH cutting mill as shown below in Figure 1 below. 2 mm sieve was used to mill PET fibers and 12 mm sieve was used for milling of cotton fibers.

Figure 2. Un-milled (left) and milled (right) cotton fibers

Figure 3. Un-milled (left) and milled (right) polyester fibers

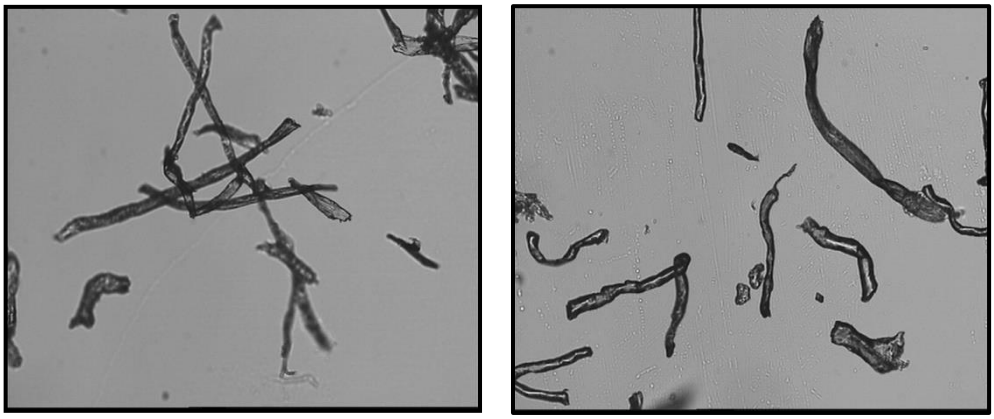

Figure 4. Optical microscopy images of milled fibers: cotton (left), polyester (right)

3.3 Fibers drying

After milling, the cotton fibers were dried in a vacuum drying oven at 70 °C and at a vacuum pressure of 50 bars overnight to remove the moisture from the fibers. Dry fibers are necessary in the compounding and processing with most of polymer materials to avoid bubbling. Vacuum drying ovens are used for quick and effective drying of heat and oxidation sensitive substances.

3.4 Premixing

Premixing is a process in which plastic pellets or granules are mixed additives before production process to get a homogenous mixture. The homogenous mixing is the key to dimensional stability, process stability, uniform texture and good mechanical properties. After milling of fibers, the physical mixing of LDPE/PP/RePE matrix polymer materials and reinforcement fibers (cotton and PET fibers) were carried out. All mixtures were mixed in batch mixer for 15 minutes to achieve proper and homogeneous mixing of matrix and reinforcement fibers. Needed weights of polymer matrixes and fibers for premixing are given in appendix.

3.5 Compounding

After the premixing, composites were produced by compounding using a lab scale twin-screw Brabender under the name of "Brabender Plasti Corder – PLE 651". The key reason for compounding in this project was to provide uniform material in pellet form to use in injection molding process. It found be quite difficult to feed lightweight fibers

together with polymer materials. Compounds were prepared for all composite recipes given in Table 1-3.

Compounder was switched ON before usage to obtain the required temperatures needed for the polymer matrix materials. Extruder standard temperatures set for LDPE are RePE were 160 °C for Zone 1 (feeding zone), 180 °C for Zone 2 (melting zone), 190 °C for Zone 3 (metering zone) and 185 °C for Zone 4 (die). Extruder standard temperatures set for PP were 180 °C for Zone 1, 185 °C for Zone 2, 185 °C for Zone 3 and 190 °C for Zone 4. Before starting the processing, the desired temperatures were achieved. First, the extruder screw and barrel were cleaned/purged by using PE/PP/RePE materials so that there should not be any other residual material in the extruder which may affect compounded material. Extruder screw speed was around 45-50 rmp and torque was kept under 100 Nm. After screw cleaning, premixed PE/PP/RePE and fibers mixture was fed manually in the compounder hopper in small portions. The extrudate filaments or strands continuously produced from the die were accumulated on conveyor belt with cooling air fans to cool down the strands in short period of time and these strands were cut into small granules of around 4 mm by using a pelletizer which was connected after the conveyer belt. These granules were used as a feedstock for injection molding process.

Figure 5. Brabender Plasti Corder – PLE 651 twin screw compounder and produced composite pellets

3.5.1 Observations during compounding

Following are the issues and observations while preparing composite compounds.

- Due to light weight and large volume, fibers specially cotton fibers were very difficult to feed into the compounder hopper towards the screw area. Fibers were pressed with the help of a wooden stick all the time to facilitate feeding. Moreover, very small quantity of mixture material was fed into to hopper and pressed with the help of wooden stick, by doing this feeding problem was successfully solved.
- At cotton fibers contents of 30 % and 40% with LDPE, RePE and PP as well, the fibers stuck and burnt inside the extruder and it required to clean it with cleaning compound. It did not solve the problem completely, so the extruder head was removed to clean the screen. After cleaning, smooth compounding operation was achieved.
- Some fiber burning was observed in compounding of PET and cotton fibers of waste T-shirts.

3.6 Injection molding

Injection molding machine was used for the production of dumbbell shape test specimen. The dimensions of the dumbbell shape test specimens are as illustrated in the standard ISO 572 – 2 i.e., 150 × 10 × 4 mm and cross-section area is 40 mm².

Injection molding machine was switched ON before production to achieve the required temperatures for Injection molding process. Injection molding machine was cleaned with pure LDPE/PP/RePE materials to remove the previous material residues. Firstly, pure LDPE, PP and RePE specimens were produced as a reference samples to compare with fiber reinforced composite samples. Soon after, compounded granules were fed into the hopper of the injection molding machine and about 30–35 composite test specimens were produced for each material. The sample production processes for pure matrix materials and composites filled with 10% and 20% fibers were very fast, effortless and achieved with minimal processing parameters. Nevertheless, as the fiber content increased, short molding issue was noticed as melt with high amount of fibers was poorly flowing. To overcome this issue, injection molding processing parameters were adjusted accordingly to improve the melt flow and to fill the complete mold cavity. The process parameters which were changed includes injection pressure, injection speed, holding pressure, holding pressure time, dosing speed and barrel temperature. The list of compounds and their respective processing parameters are given in Appendix.

The following injection molding machine was used for specimen production:

Machine: Battenfeld BA230E Clamping force: 230 KN

Figure 6. Battenfeld Injection molding machinery in TalTech processing lab

The short molding or issues in mold filling was observed, to overcome these issues injection pressure and speed were increased up to 34% and 114% respectively during processing of compounds with higher fiber content as due to low MFI or high viscosity of the melt which caused issue of mold filling. Increasing the value of injection pressure and speed helped to fill mold cavity completely and eliminated the short shots issue. So, injection pressure and speed were set at optimum values according to the conditions of specimens while processing.

Figure 7. Short molding issue during the injection molding of RePE with cotton fiber content of 30%

NOTE: It is important to note here that injection molding of PP compounds with cotton fiber content of 40% & PET+Cotton 40% and RePE compounds with 30% and 40% cotton fibers were unable to achieve and no samples were produced as the material did not show sufficient flow to fill complete mold cavity. All processing parameters were

adjusted and set to maximum values in order to make the compound flow in the injection molding machine and to fill the mold cavity but unfortunately samples were unable produce due to NO FLOW of the materials.

3.7 Testing of organofibers filled composites

3.7.1 Melt characterization

Melt flow index (MFI) was tested according to the standard ASTM D1238 to analyse the melt flow rate of LDPE composites loaded with cotton fibers and the effect of cotton fiber content on melt flow behavior was found out. The equipment used for MFI testing was CEAST melt flow junior. The most common method of characterizing how a polymer will flow is the melt flow index (MFI) test. The melt flow index provides an indication of a material's flow characteristics at a single, low shear rate and at a single melt temperature. The MFI test was performed at the testing temperature for 195 °C which is suitable temperature for LDPE. Weights used for testing were 2.16 kgs and 5 kgs. Preheating time was 5 minutes which is standard time for LDPE. Ten specimens of each sample were tested in ten minutes to calculate the average melt flow rate of composite materials.

Figure 1. Melt flow index test of PE compound with cotton fibers

3.7.2 Mechanical properties testing

Bending or flexural strength testing was performed on universal testing machine – Instron 5866. Three-point bending testing was carried out according to the ISO 178 and ISO 14125 standards. The basic purpose of the bending testing was to measure the

flexural strength and flexural modulus of composite materials with different cotton and polyester fiber concentrations. To conduct this test, 5 specimens of pure matrix materials and fiber reinforced composites with 10%, 20%, 30% and 40% fiber content were tested at a test speed of 2 mm/min and load cell of 10 KN was used for testing. The test result values and curves for each specimen were generated automatically by using the Bluehill software in computer system which was connected to the universal testing machine.

Tensile strength testing was carried out on universal testing machine – Instron 5866 as per the international standards ISO 527-2 and ISO 527-4. Tensile test takes the measurements of the load or force which is needed to fracture and elongation of the test specimen under stretching. 5 dumbbell shape samples were tested at a test speed of 2 mm/minute and with a load cell of 10 KN. The distance between the grips of tensile machine was set at 11 cm. The dimensions of the dumbbell shape test specimens were 150 × 10 × 4 mm and cross-section area was 40 mm^2. The test results and tensile stress strain curves were automatically generated by the help of Bluehill computer software.

Charpy impact strength testing was accomplished by means of Zwick 5102 pendulum impact tester and in conformity with standard ISO 179. Before performing the test, the test specimens were V-notched. Notch depth was 2 mm and top of the notch has round shape. The notched samples were carefully positioned horizontally on the support blocks of the machine in such a way that striking edge of the pendulum hit the center of the notched specimen. 5 samples were tested and impact energy absorbed by the specimen were recorded from the screen of impact tester.

Figure 2. V-notched composite samples for Charpy impact test

3.7.3 UV aging of composites

UV aging of bone shaped samples was conducted in UV chamber equipped with UVA-351 type fluorescent lamps according to the standard EN ISO 4892-3. These UV lamp

have wavelength of about 365 nm and intensity of 0.89 W/m²/nm. It is very significant to observe the mechanical properties of polymeric composites before and after UV radiation as photo-oxidative degradation caused by UV radiations degrades the material unpredictability, destroys or activates bonds. Hence it is vital to find out the degradation rate to determine the expected life span of material. Pure polymer and composites samples were placed in UV chamber to study and analyze the change in mechanical properties which are influenced by UV radiations. The samples were placed for 2000 hours in the UV chamber and later on mechanical testing was carried out.

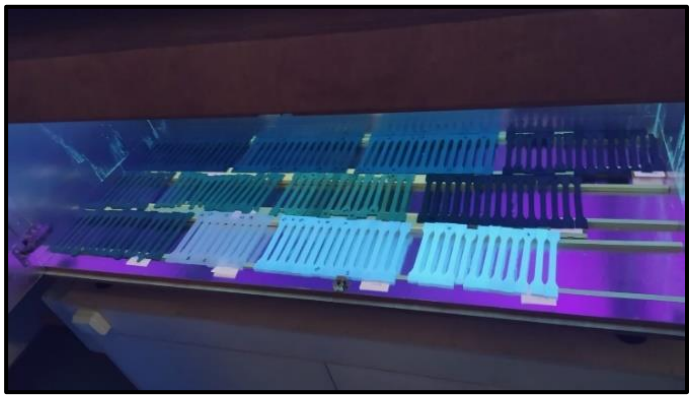

Figure 3. Composite specimens in UV aging chamber

3.7.4 Morphology of composites

Scanning electron microscopy (SEM) was performed to study the morphology of composites and to examine the structure of composites, how well fibers are distributed, mixed or dispersed in the composites: how polymer matrix and fibers reacted in the composite and their porosity etc. SEM is a useful technique for determining fiber diameters and identifying morphological characteristics on fiber surfaces. SEM analysis was carried out with HITACHI TM-1000 table microscope. Samples to be tested were cut into a small size from cross sectional area and then glued on sample mount plate by the help of special double-sided carbon conductive tape. Several magnifications were used to study the morphology, structural and surface features of composites. The result optical view was displayed on the computer and was analyzed as per the requirements.

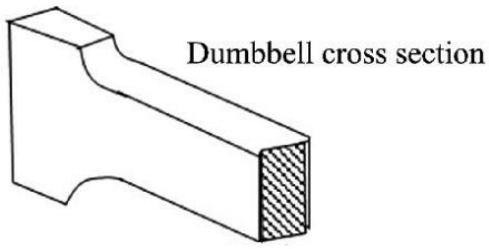

Figure 4. Sample preparation scheme for SEM analysis

4. RESULTS AND DISCUSSIONS

4.1 Melt flow index (MFI)

As it can be clearly understood from the MFI test results that there is a significant change in the melt flow behavior of composite compounds with the incorporation of cotton fibers and polyester. As the fiber content in composite is increasing, the melt flow is decreasing. For example, the MFI of pure LDPE material is 5.0 g/10 min. By incorporation of 10% cotton fibers in LDPE, the MFI decreased to 0.98 g/10 min. Furthermore, the MFI of LDPE composite filled with 20% of cotton fiber decreased to 0.31 g/min and by increasing the cotton fiber content to 40% further decreased the MFI to 0.18 g/10 min. Addition of 10% polyester fibers in LDPE, decreased the MFI to 3.4 g/10 min and by increasing polyester fiber content to 30% further reduced the MFI to 1.3 g/10 min. These results indicate that cotton and polyester fibers constrained the flow and significantly increase the viscosity of molten composite material. In comparison, composites with polyester fibers showed better flow as compared to cotton fibers.

In injection molding, a very runny plastic material is preferred as it allows faster processing (quick injection of material into the mould) and production cycle time is lower, equipment energy consumption is lower and hence the processing cost is lower. For a material with low MFI values, a significant alteration in processing parameters may be required as it takes more time and pressure to fill the mould cavity. Table 4 shows the MFI values of cotton fiber filled LDPE composites and Figure 12 displays the changes in MFI due to increase in cotton fiber content.

Table 4. Melt flow index test results for cotton fiber filler LDPE composites

Test Samples	MFI Result
Pure LDPE	5.0 g/10 min @ 2.16 kgs
90% LDPE + 10% Cotton fibers	0.98 g/10 min @ 2.16 kgs
80% LDPE + 20% Cotton fibers	0.31 g/10 min @ 2.16 kgs
70% LDPE + 30% Cotton fibers	0.32 g/10 min @ 5 kgs
60% LDPE + 40% Cotton fibers	0.18 g/10 min @ 5 kgs
90% LDPE + 10% Polyester fibers	3.4 g/10 min @ 2.16 kgs
80% LDPE + 20% Polyester fibers	1.7 g/10 min @ 2.16 kgs
70% LDPE + 30% Polyester fibers	1.3 g/10 min @ 5 kgs
60% LDPE + 40% Polyester fibers	0.4 g/10 min @ 5 kgs

The standard testing load was increased from 2.16 kgs to 5 kgs for 30% and 40% cotton and polyester fiber-filled compounds as 2.16 kgs standard load was unable to push the material through the channel of MFI tester.

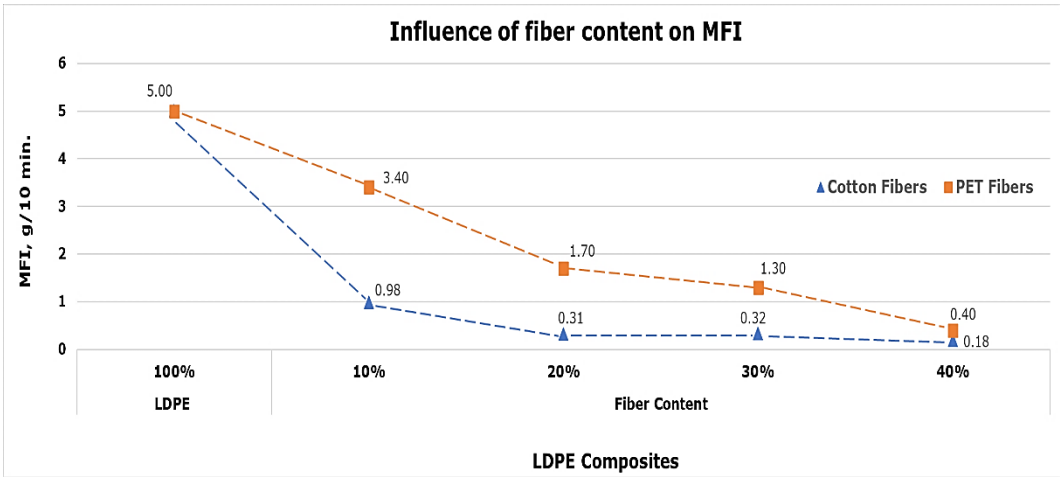

Figure 5. Effect of Cotton and Polyester fiber content on Melt flow index

4.2 Mechanical properties

4.2.1 Flexural or bending test

The results of flexural strength of fibers filled LDPE and RePE composites are very similar to each other. From figure 13 and 15 it is evident that the flexural strength of composites are higher than those of matrix materials. It is also observed that the flexural strength increases with an increase in fiber load in the composites. It is clearly seen that flexural strength has a continuously increasing trends for all types of fibers: cotton, PET and 50/50 mixture of PET/cotton. For instance, LDPE filled with 40 wt. % of PET fiber showed a 93% increase in flexural strength and 40 wt. % of cotton fiber showed an 81% increase in flexural strength. Whereas RePE filled with 40 wt. % of mixture of PET/cotton fiber showed a 90% increase in flexural strength. Increase in fiber content revealed a huge elevation in the flexural modulus simultaneously. Flexural modulus is also found to be increasing continuously with increase in fiber content in case of cotton, PET and mixture of PET+cotton fibers as well. LDPE filled with 40 wt. % of PET fiber showed a 90% increase in flexural modulus and LDPE filled with 40 wt. % of cotton fiber showed a 260% increase in flexural modulus. In case of RePE, the addition of PET fibers up to 20 wt. % and 40 wt. % showed an improvement in the flexural modulus by 56% and 142% respectively. It can be concluded that the fibers significantly improved the strength and modulus of PE and RePE composites. The results of flexural modulus for LDPE and RePE composites are given in Figure 14 and 16.

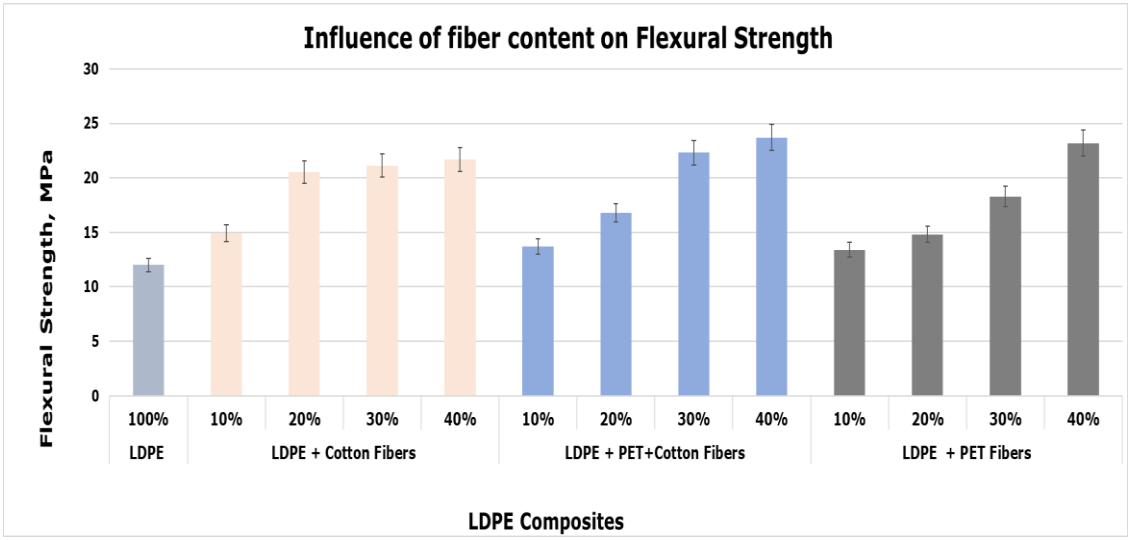

Figure 6. Flexural Strength (MPa) of PE samples with different Fiber Contents

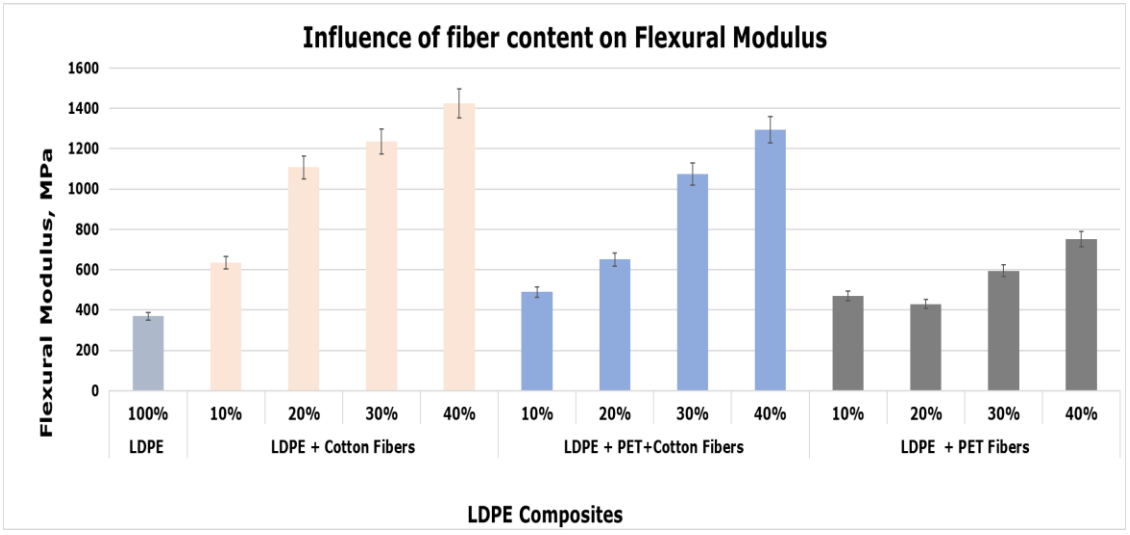

Figure 7. Flexural Modulus (MPa) of PE samples with different Fiber Contents

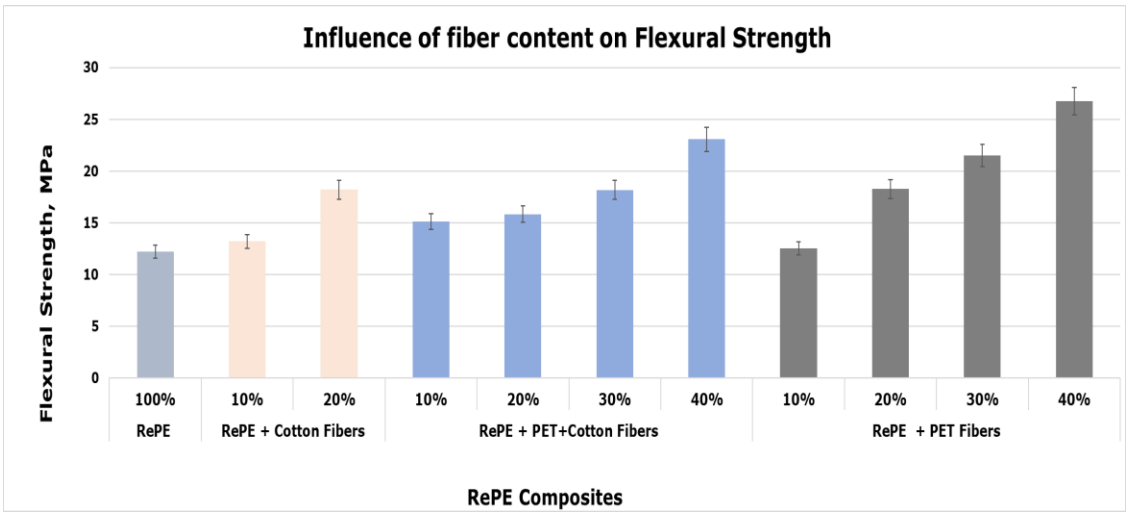

Figure 8. Flexural Strength (MPa) of RePE samples with different Fiber Contents

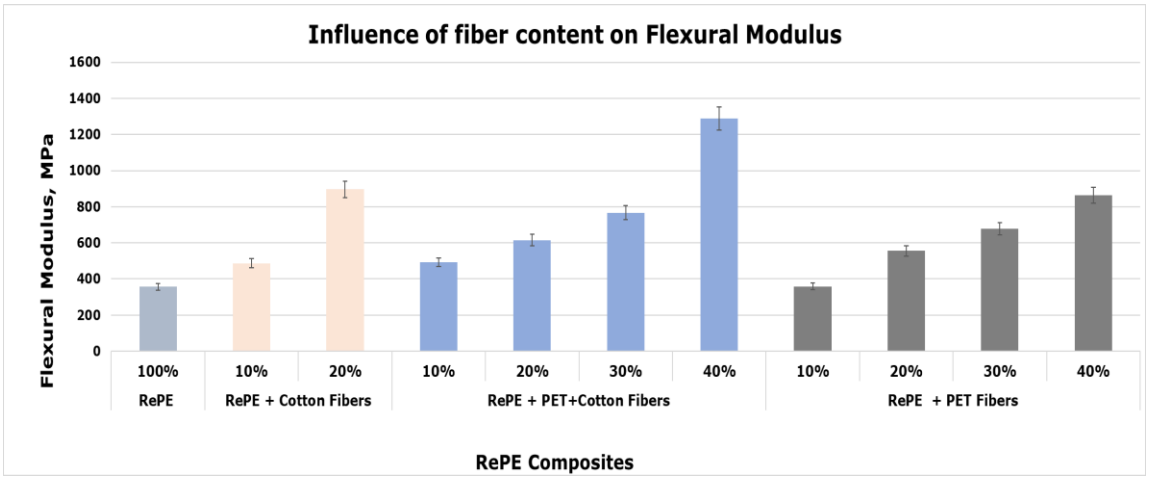

Figure 9. Flexural Modulus (MPa) of RePE samples with different Fiber Contents

The flexural test results of PP composites in Figure 17 clearly suggests that there is no considerable change in flexural strength by the addition of fibers loading up to 10 wt. % when compared to pure PP specimens. However, the results showed that in cotton and mixture of PET/cotton fibers filled composites the flexural strength is found to be deceasing with an increase in fiber content. For instance, PP filled with 30% fiber content of cotton and mixture of PET/cotton fibers showed a 22% and 21% decrease in flexural strength respectively. Conversely the result was different in PET fibers filled PP composites. The flexural strength was observed to be continuously increasing with increase in PET fiber content. For example, PP composites filled with 40 wt. % of PET fiber showed an 10% improvement in flexural strength. Furthermore, increase in fiber loading showed an improvement in the flexural modulus. For instance, the addition of PET, cotton and mixture of PET/cotton fibers up to 20 wt. % showed an increase in the flexural modulus by 5%, 31% and 51% respectively. It can be concluded that fiber load reduces the flexural strength but improves the stiffness of PP composites.

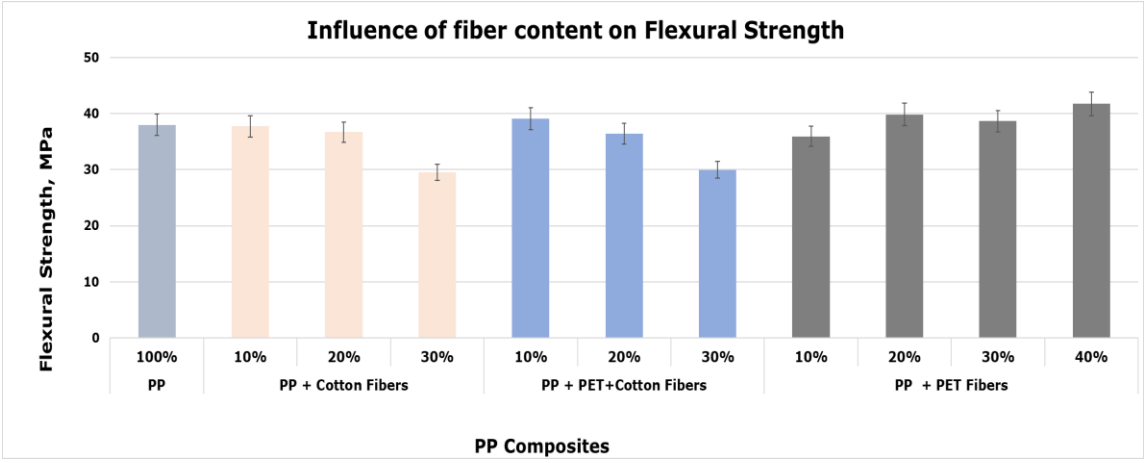

Figure 10. Flexural Strength (MPa) of PP samples with different Fiber Contents

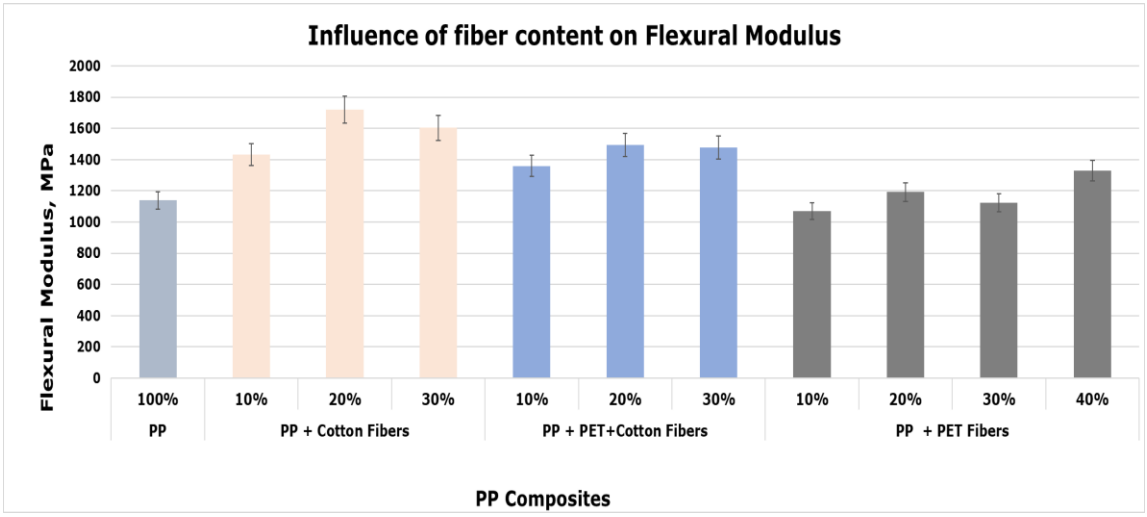

Figure 11. Flexural Modulus (MPa) of PP samples with different Fiber Contents

To conclude, the results of flexural properties, it can be stated that the fibers improved the flexural strength of LDPE and RePE composites whereas it decreases the flexural strength of PP composited. Incorporation of fibers improves the stiffness of LDPE, RePE and PP composites.

4.2.2 Impact test

The is clearly evident from the outcomes of impact strength test that the fiber loading is straightly correlated to the impact properties of LDPE and RePE composites, the impact strength considerably decreases with the increase of cotton, PET and mixture of PET+cotton fiber content. For example, the addition of 10 wt. % of PET, cotton and mixture of PET+cotton fibers in LDPE composites showed a very similar decrease (63%, 59% and 61% correspondingly) in impact strength. Moreover, load up to 40% content of PET, cotton and PET+cotton fibers showed 86%, 77% and 86% decrease in the impact strength of LDPE composites respectively (Figure 19). RePE composites also displayed the impact strength outcomes trends similar to LDPE composites. In RePE composites, the impact strength decreases constantly as the PET, cotton and mixture of PET+cotton fiber content increases. In particular, RePE composites filled with 20 wt. % of PET, cotton and mixture of PET+cotton fibers indicated a 67%, 51% and 65% drop in impact strength in that order.

There are few unfavorable properties which fibers add. The addition of fibers lowers the elongation at break of the polymer therefore decrease the toughness or impact strength. In composites with ductile matrix materials like LDPE, addition of fibers caused brittleness that is why the facture toughness reduced. According to (Bohuslav Kokta et

al., 2008), fibers can decrease the impact strength of the composites by two means: fibers have a tendency to hinder deformation and ductile movement of polymer molecules, which actually lower the capability of composites to absorb energy at the time of crack propagation. Also, fibers also generate high stress concentration areas which need less energy to initiate a crack appearance. For a good impact property, it is necessary to have an optimum level of adhesion between fibers and matrix.

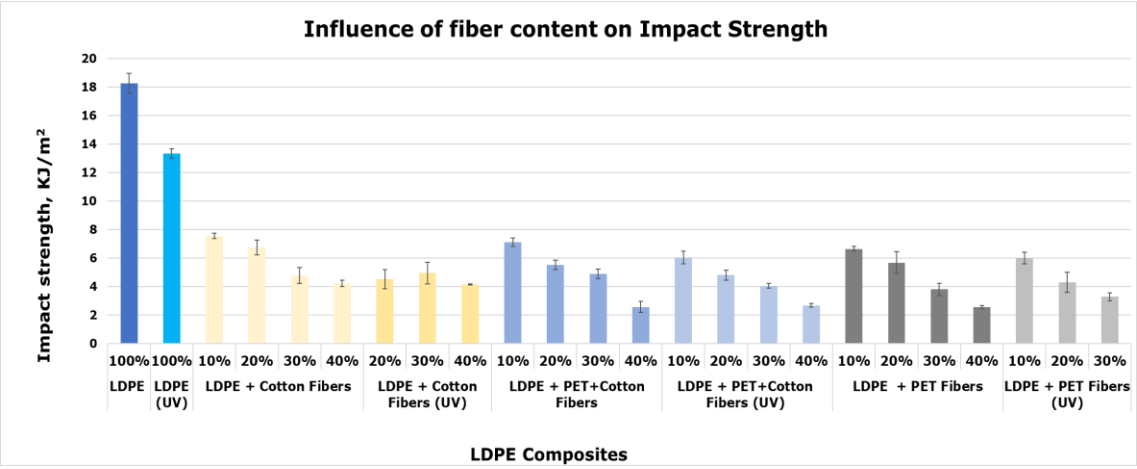

Figure 12. Influence of fiber loading on impact strength of LDPE composites before and after UV aging

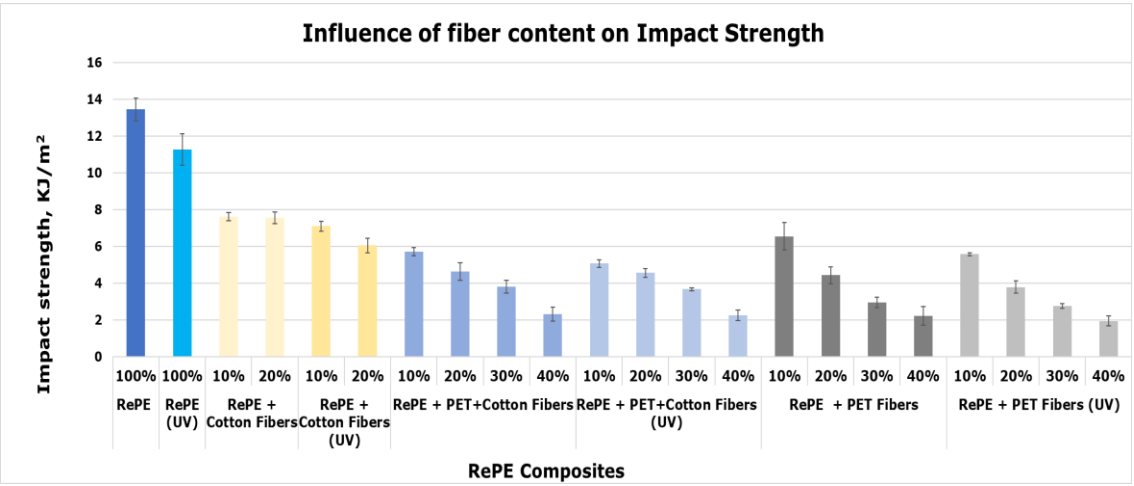

Figure 13. Influence of fiber loading on impact strength of RePE composites before and after UV aging

On the other hand, in PP composites the addition of 10 wt.% PET fibers showed a 224% improvement in impact strength whereas PP filled with 20% and 30% PET fiber content remained stable and did not cause noticeable change in impact strength. But by the addition of 40 wt. % of PET fibers with PP, the impact strength decreased by 36%. On the contrary, the incorporation of cotton and mixture of PET+cotton fibers significantly

improved the impact strength of PP composites. For example, the PP composites of cotton fibers showed an increase of 732% in the impact strength with fiber content of 20 wt. %. Moreover, inclusion of 30 wt. % of mixture of PET+cotton fibers indicated an almost 450% improvement in the impact strength. Impact strength results fiber-filled PP composites show that the impact strength or fracture toughness depends mainly on the toughness of matrix polymer; different polymer matrix materials with the similar fibers and similar fiber content may have different impact strength results.

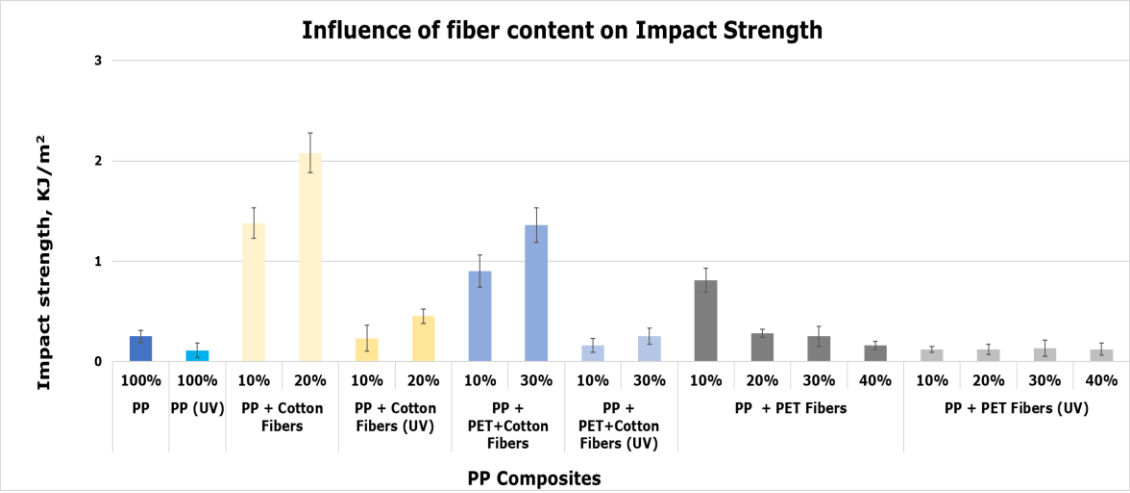

Figure 14. Influence of fiber loading on impact strength of PP composites before and after UV aging

4.2.3 Tensile test

The results of tensile strength test for LDPE composites obviously suggests that there is slight decrease in tensile strength of composites with incorporation of 10 wt. % of fiber loading when compared to neat LDPE. For example, LDPE filled with 10 wt. % of PET, cotton and mixture of PET+Cotton fibers showed a 21%, 20% and 24% decline in tensile strength respectively. However, it can be clearly seen from the test results that as the fiber content increased in LDPE composites the tensile strength values are increased continuously as well and with 40 wt. % of PET, cotton and mixture of PET+Cotton fibers the tensile strength of composites is similar to neat LDPE. Moreover, the fiber loading is directly proportional to the composites' stiffness, as by increasing fiber loading the Young's modulus increases significantly. For instance, the composites of 40 wt. % of PET, cotton and mixture of PET+Cotton with LDPE showed a 94%, 277% and 211% sequentially. Though, it is obvious from the test results that the energy at break or toughness of the composites reduced by increase of fiber content and it showed a continuous declining trend. For example, the addition of 30 wt. % of PET, cotton and PET+Cotton fibers in LDPE indicated a 96%, 99% and 99% drop in energy at break

consecutively. The result of tensile strength indicates that all type of fibers improves the tensile strength and Young's modulus of LDPE composites whereas the toughness reduces by the addition of all type of fibers.

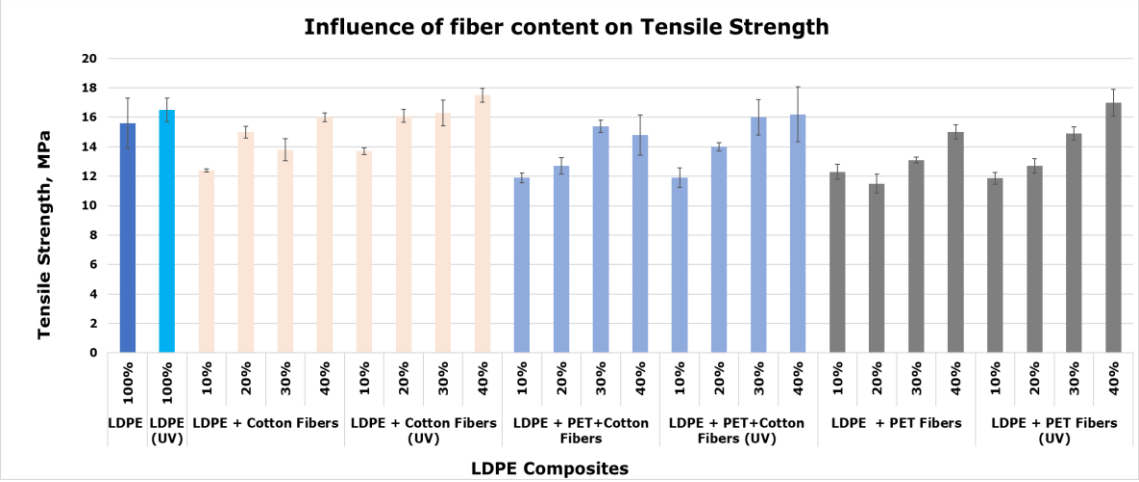

Figure 15. Influence of fiber content on tensile strength of LDPE composites before and after UV aging

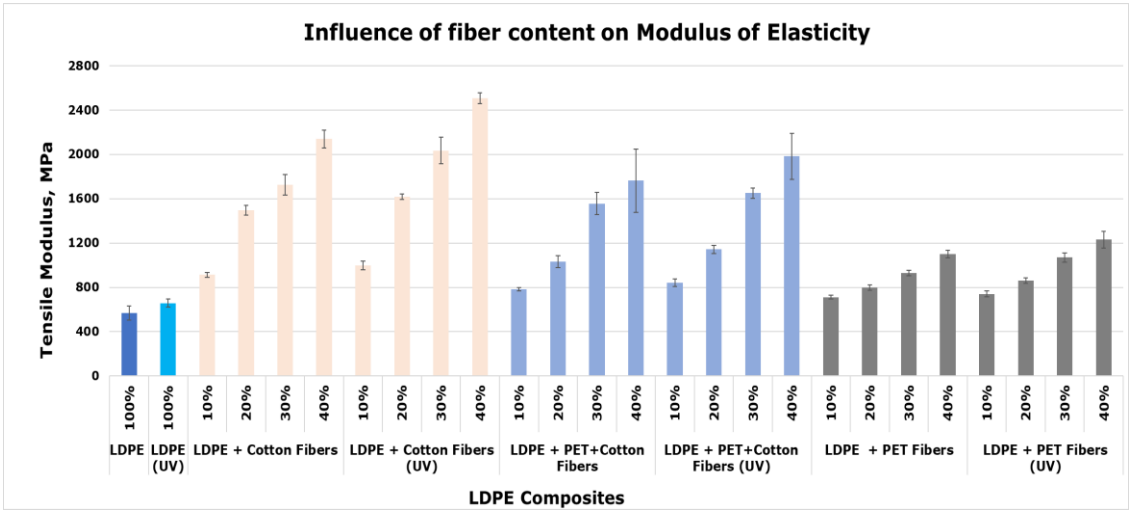

Figure 23. Influence of fiber content on Modulus of elasticity of LDPE composites before and after UV aging

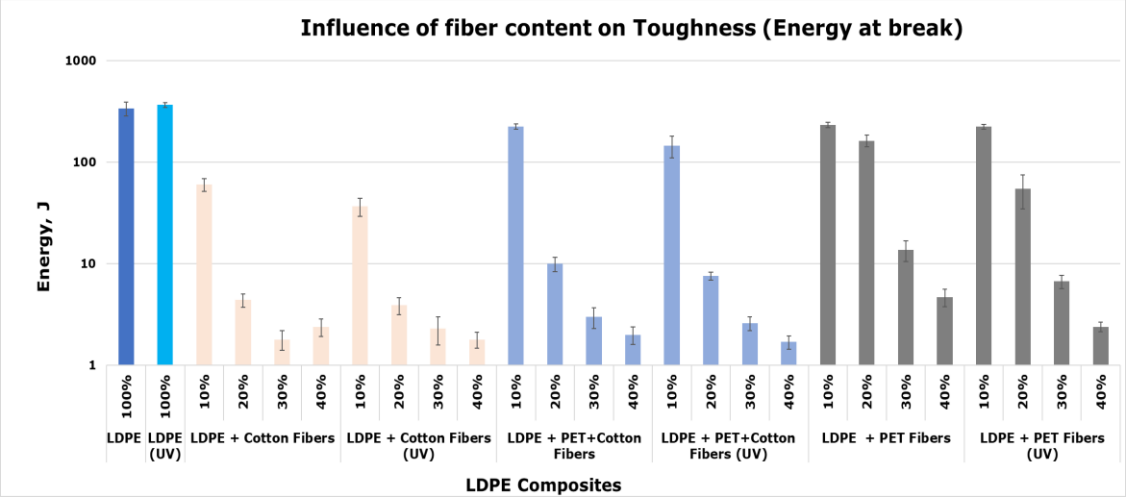

Figure 24. Influence of fiber content on toughness of LDPE composites before and after UV aging

For recycled PE composites, it is apparent from test results that pure recycled PE material has the highest tensile strength. By adding 10% PET, Cotton and mixture of PET+Cotton fibers in RePE material the tensile stress sustained by the composite material was decreased. For instance, RePE filled with 10 wt. % of PET, cotton and mixture of PET+Cotton fibers showed an almost 37% decline in tensile strength. As the fiber content (Cotton and PET) is increased in RePE composite the tensile strength values are increased respectively but even with 40% fiber content the tensile strength values are less than the pure RePE tensile strength values. Whereas in case of incorporation of mixture of PET+Cotton fibers the tensile strength values are almost same for 10% to 40% fiber content which shows that increasing the fiber content did not increase or decrease the tensile strength of the RePE composites and it remained almost same. Furthermore, similar to the results of LDPE composites, in RePE composites the fiber loading is also directly proportional to the stiffness, by increasing fiber loading the modulus of elasticity increases substantially. For instance, the composites of 20 wt. % of PET, cotton and mixture of PET+Cotton with RePE showed a 37%, 97% and 50% sequentially. However, it is evident from the test results that the energy at break or toughness of the composites reduced by increase of fiber content and it showed a continuous decreasing trend. For example, the addition of 10 wt. % of PET, cotton and PET+Cotton fibers in RePE indicated a 58%, 75% and 56% decline in energy at break or toughness consecutively.

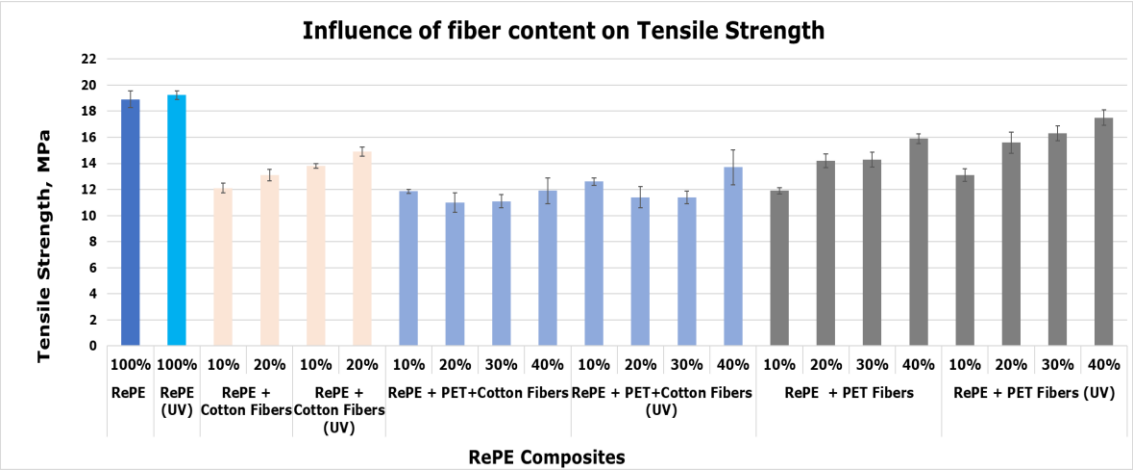

Figure 25. Influence of fiber content on tensile strength of RePE composites before and after UV aging

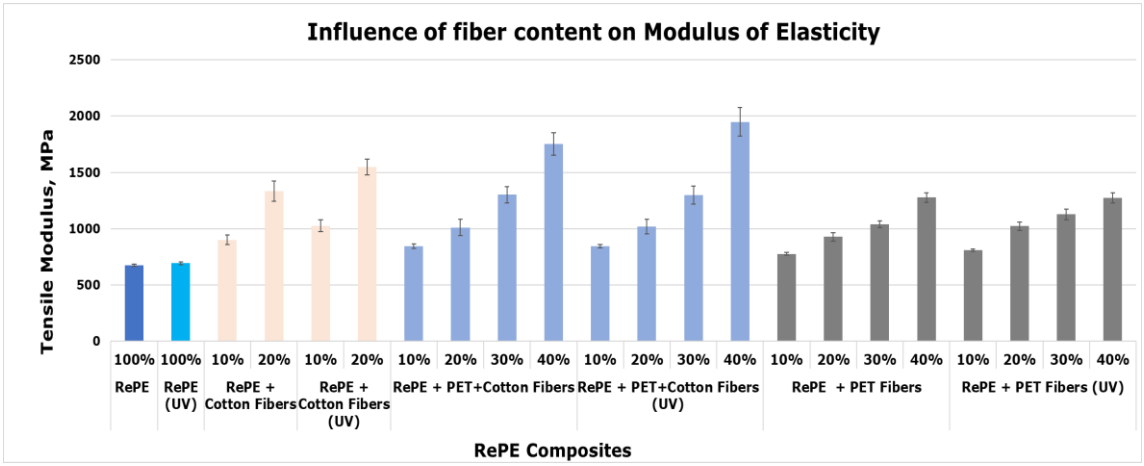

Figure 16. Influence of fiber content on Modulus of elasticity of RePE composites before and after UV aging

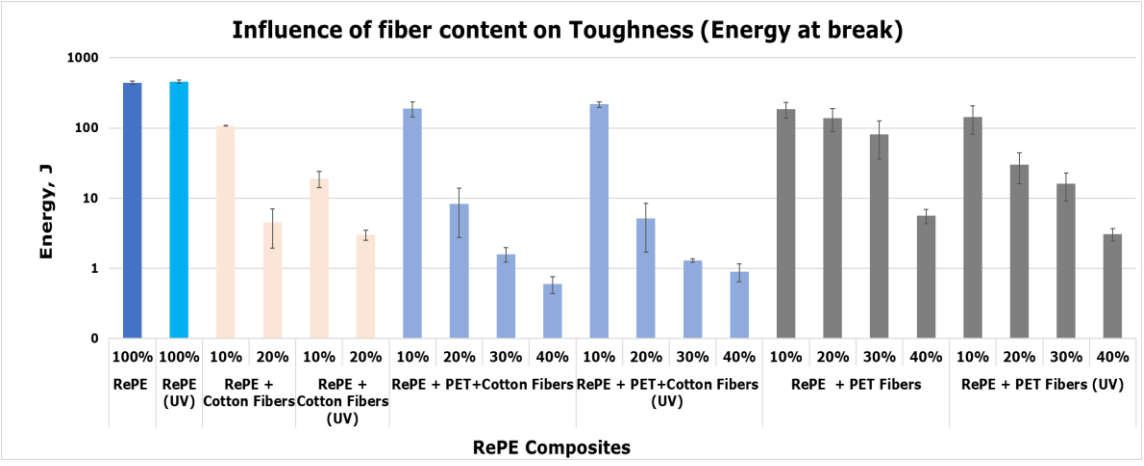

Figure 27. Influence of fiber content on toughness of RePE composites before and after UV aging

For polypropylene composites, it can be clearly seen from results showed in Figure 24 that tensile strength reduced by the incorporation of the fibers and as the cotton and mixture of PET+cotton fiber content is increased the tensile strength further decreased. For instance, the PP composites with 20 wt. % of cotton and mixture of PET+Cotton indicated a 17% and 30% decrease. Whereas incorporation of PET fibers in PP composites showed a similar tensile strength up to 30% wt. % as compared to neat PP. However, by adding 40 wt. % of PET fibers with PP indicated a 15% drop in tensile strength. Furthermore, it was also observed that modulus of elasticity increased by the inclusion of PET, cotton and mixture of PET+cotton fibers. For example, the composites of 30 wt. % of PET, cotton and mixture of PET+Cotton with PP showed a 19%, 40% and 16% successively. Although, results also indicates that the energy at break or toughness of the composites lowered by increase of fiber content and it showed a continuous declining trend similar to LDPE and RePE composites.

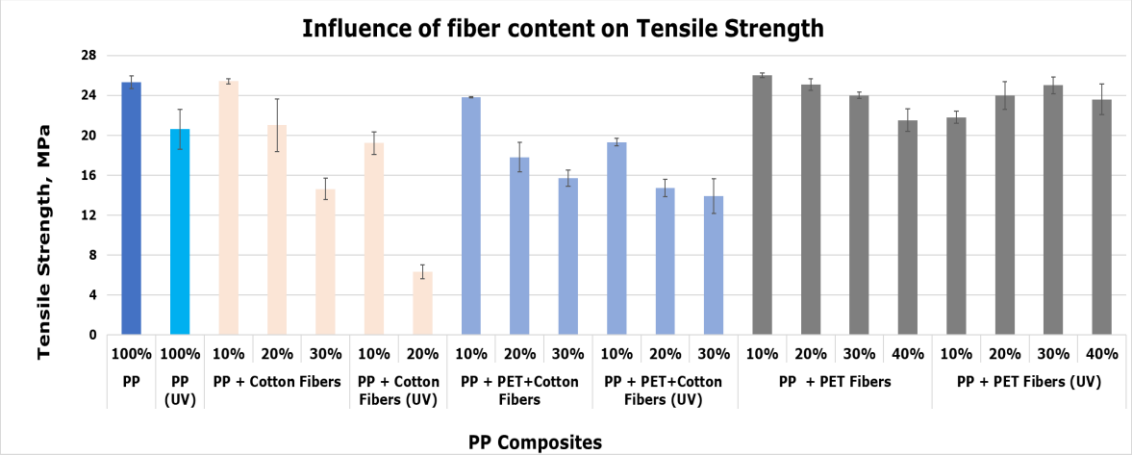

Figure 28. Influence of fiber content on tensile strength of PP composites before and after UV aging

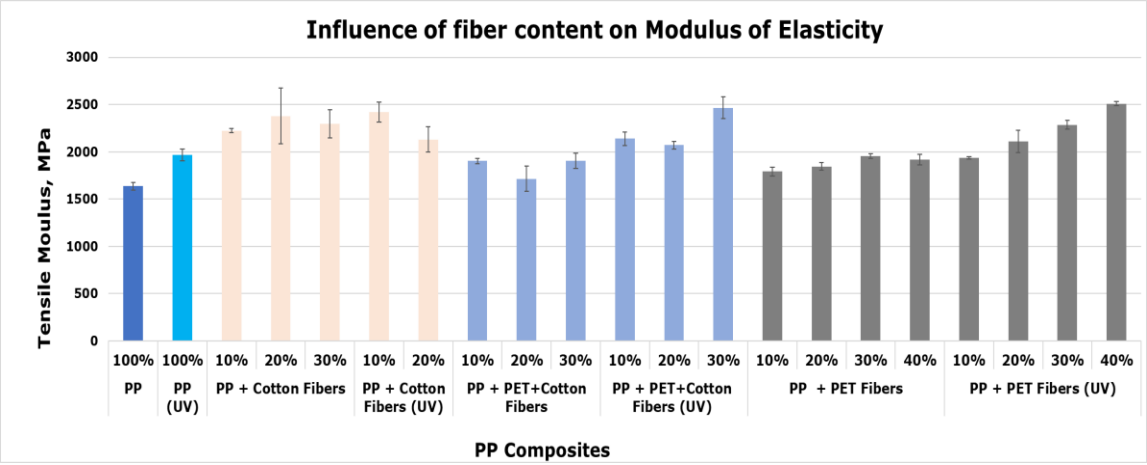

Figure 29. Influence of fiber content on Modulus of elasticity of PP composites before and after UV aging

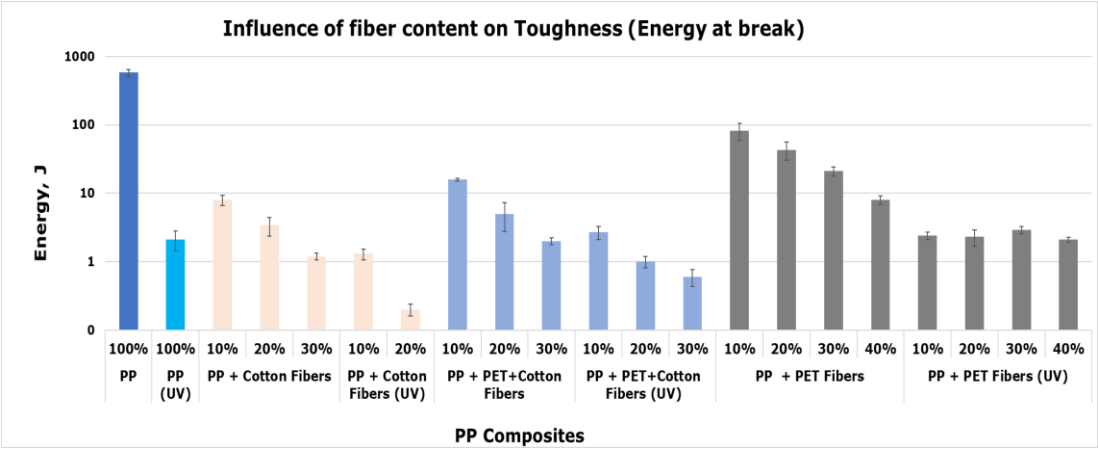

Figure 17. Influence of fiber content on toughness of PP composites before and after UV aging

If we compare the tensile test results of composites with all three matrix materials (LDPE, RePE and PP), it can be seen that they all showed similar trends in stiffness and toughness. Modulus of elasticity increased by incorporation of fibers and as the fiber content increased the stiffness also increased. Toughness was reduced significantly by the addition of fibers and as the fiber loading increased the toughness decreased substantially. In case of tensile strength, LDPE and RePE composites showed similar trends i.e., tensile strength reduced by the inclusion of fibers but tensile strength continuously increased with the increase of fiber content. However, PP composites showed a comparable tensile strength by addition of 10 wt. % of fibers when compared to pure PP but as fiber content increased the tensile strength decreased continuously. The tensile strength, modulus of elasticity and energy at break test results for PE, RePE and PP before and after UV aging are represented in Figure 22 to 30.

4.3 UV aging

4.3.1 Impact test after UV aging

By analyzing the results of impact strength of neat matrix polymers and composite samples after UV aging, it is evident that the impact strength of LDPE, RePE, PP and their composites decreased significantly after the UV aging. For example, the impact strength of pure LDPE showed a 27% decrease after UV aging. Moreover, the results of neat PP indicated a 56% reduction in impact strength after UV aging. Similarly, LDPE composites filled with 20 wt. % of PET, cotton and mixture of PET+cotton fibers, showed a decrease in impact strength up to 24%, 33% and 13%. Whereas RePE composites filled with 20 wt. % of PET, cotton and mixture of PET+cotton fibers, indicated a drop

in impact strength up to 14%, 8% and 2%. While PP composites filled with 20 wt. % of PET and cotton fibers, indicated a decline in impact strength up to 57% and 78%.

Results of LDPE, RePE and PP composites with PET, cotton and mixture of PET+cotton fibers after UV aging indicates that different matrix polymers with the same fibers have different degree of decrease in impact strength. This decrease in impact strength of neat matrix polymers and their composites can be because of embrittlement after 2000 hours of UV aging. Due to the UV photodegradation, the polymeric matrix materials became fragile and brittle which caused the significant reduction in impact strength. UV radiations causes chain scissoring and breaking at micro level that itself are not visible by naked eye. But it can be seen in forms of discoloration and rough surface, this phenomenon is described as cracking and crazing. Impact strength test results of composite materials after UV aging are characterized in Figure 19-21.

4.3.2 Tensile test after UV aging

It is apparent from the test outcomes that aged-LDPE and aged-RePE composites showed similar tensile strength trends. Tensile strength increased after UV aging as compared to same specimens before UV aging. The increase in fiber content increased the tensile strength continuously for both aged and non-aged PE-based materials. For instance, composites of PET, cotton and mixture of PET+Cotton with LDPE showed an almost 10%, 7% and 10% increase in tensile strength successively with fiber content of 20 wt. %. Whereas composites of PET, cotton and mixture of PET+Cotton with RePE indicated a nearly 10%, 14% and 4% increase in tensile strength consecutively with fiber loading of 20 wt. %. However, the aged-PP composites showed a comparatively different tensile strength and tensile strength decreased after UV aging when compared to same specimens before UV aging and as the fiber content increased the tensile strength decreased constantly. For example, composites of PET, cotton and mixture of PET+Cotton with PP suggested a 4%, 70% and 17% reduction in tensile strength sequentially with fiber content of 20 wt. %.

Furthermore, while comparing the modulus of elasticity (stiffness) and energy at break (toughness) of aged-LDPE, aged-RePE and aged-PP composites, it is clear and evident that the stiffness increased whereas the toughness decreased after the UV. It can be said that the UV aging affects the polymer matrix but did not the fibers as all type of fibers behave similarly. To conclude the results, it can be said that UV aging has improved the tensile strength and by increase in modulus of elasticity values the stiffness is increased after UV aging. This increase of the tensile strength and modulus of elasticity could be described by crosslinking processes in LDPE and RePE polymer

matrix materials which can strengthen the structure of the composites and recrystallization processes of PE material. In aged-PP composites the degradation initiates breaking of bond in structure and chain scission decreases the tensile strength under UV exposure.

4.4 Tensile testing of T-shirt fibers composites

The tensile test results of LDPE and PP composites filled with 30 wt. % of recycled T-shirt fibers are given in Figure 31 to 34. As it can be seen composites of recycled T-shirt-PET, T-shirt-cotton and their mixture (T-shirt-PET+Cotton) with LDPE with 30 wt. % of fiber loading showed no significant change in tensile strength when compared to pure LDPE material. For example, LDPE loaded with 30% of T-shirt-cotton fibers indicated a 13% decline in tensile strength in comparison with neat LDPE and showed almost similar tensile strength when compared to LDPE composites filled with 30 wt. % of raw cotton fibers. Whereas LDPE composites filled with 30 wt. % of recycled T-shirt-PET fibers indicated almost similar tensile strength in comparison with neat LDPE and showed a 14% increase in tensile strength when compared to LDPE composites filled with 30 wt. % of raw PET fibers. At the same time, the modulus of elasticity of composites filled with 30 wt. % of T-shirt fibers showed significant increase when compared to neat LDPE and also indicated an improvement in comparison with composites filled with raw fibers with the exclusion of LDPE filled with 30 wt. % of mixture of T-shirt-PET+Cotton fibers which showed 21% decline in modulus of elasticity when compared to composites with 30 wt. % of mixture of PET+Cotton raw fibers.

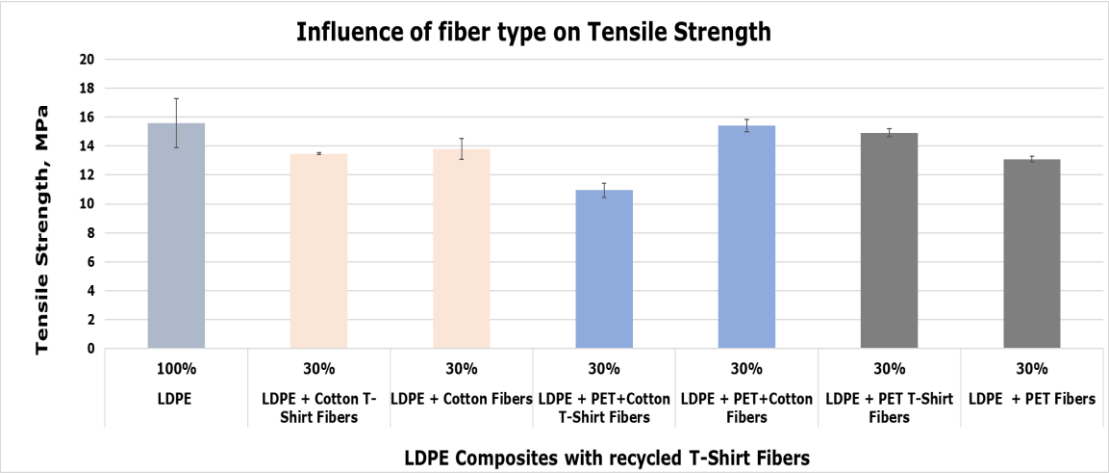

Figure 18. Tensile strength (MPa) of LDPE composites with recycled T-shirt fibers

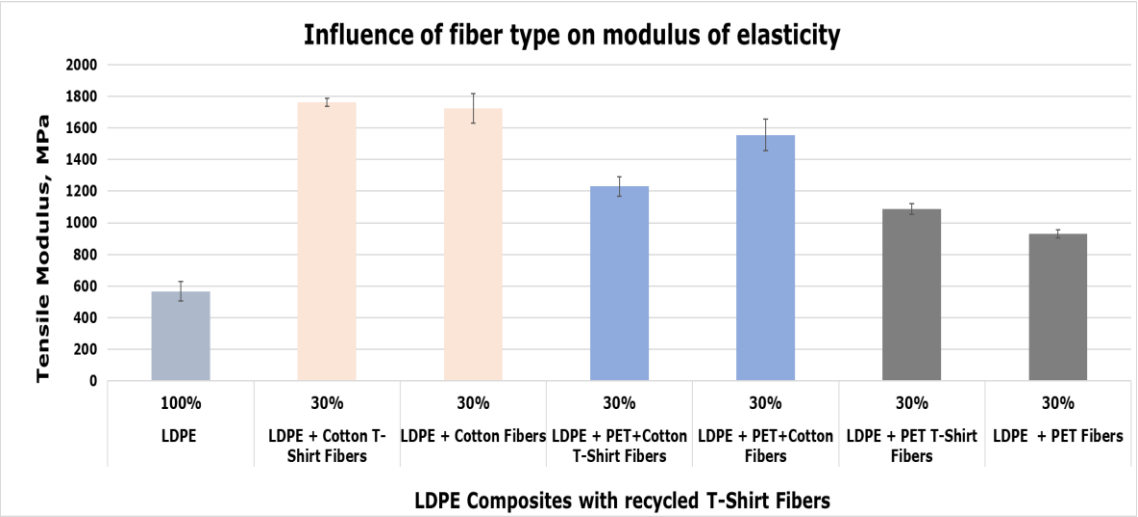

Figure 32. Young's Modulus (MPa) of LDPE composites with recycled T-shirt fibers

Comparably, the test results of PP composites filled with 30 wt. % of recycled T-shirt-PET, cotton and mixture of T-shirt-PET+Cotton fibers showed almost similar tensile strength when compared to neat PP and further improved the tensile strength in comparison with composites filled with 30 wt. % of raw PET, cotton and mixture of PET+Cotton fibers. For example, PP filled with 30 wt. % of T-shirt-cotton fibers showed a similar tensile strength in comparison with pure PP and indicated a 75% increase in tensile strength when compared to PP composites filled with 30 wt. % of raw cotton fibers. Furthermore, the Young's modulus of composites filled with 30 wt. % of T-shirt fibers showed considerable improvement when compared to neat PP and additionally indicated an increase in comparison with composites filled with raw fibers. For example, Young's modulus of composites filled with 30 wt. % of recycled T-shirt-cotton fibers showed a 104% increase when compared to neat PP and 45% improvement in comparison with PP composites filled with 30 wt. % of raw cotton fibers.

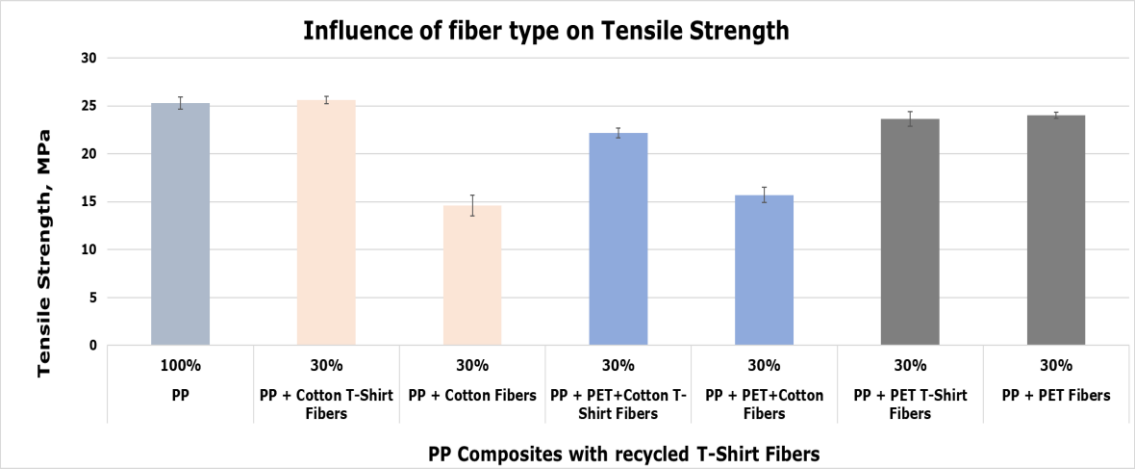

Figure 33. Tensile strength (MPa) of PP composites with recycled T-shirt fibers

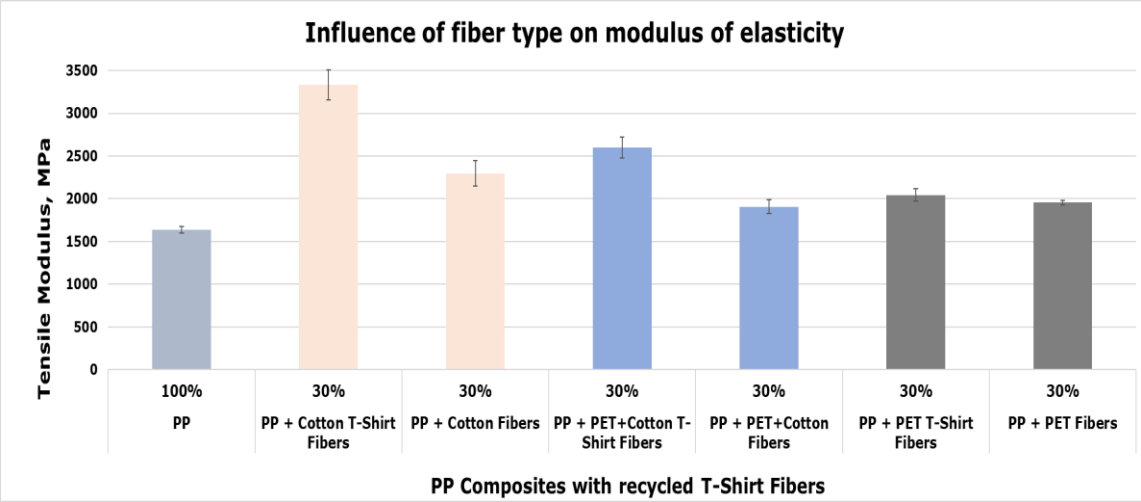

Figure 19. Young's Modulus (MPa) of PP composites with recycled T-shirt fibers

By studying the results of recycled T-shirt PET and cotton fibers it can be stated that it is possible to utilize the recycled textile fibers for LDPE and PP polymeric composites production by compounding and injection molding techniques. Furthermore, these composites show almost similar tensile strength at fiber loading of 30% when compared to neat LDPE and PP. Moreover, also indicates improvement in tensile strength when compared T-shirt fibers filled composites with raw PET and cotton fiber-filled composites. Additionally, at the same time the stiffness is significantly improved. The improvement of recycled T-shirt fibers could be explained by better compatibility of those fibers to polymer matrix due to pigments and additives to T-shirt fibers, similar results were reported in literature. (Albert Serra et al., 2019).

4.5 Morphology analysis

Scanning electron micrographs of un-milled, milled cotton & PET fibers and fractured surfaces of PE and PP composites filled with different percentages of PET, Cotton and PET+Cotton fibers are shown in Figure 35 to 41 which helps to understand how fibers are distributed and dispersed into the polymer matrix materials.

Figure 35 shows the SEM images of samples cotton and polyester fibers. It is evident that the cotton fibers (natural fibers) have more irregular shapes and variable diameters as compared to the polyester fibers (synthetic fibers). Polyester fibers are absolutely round shaped whereas the cellulosic fibers are almost flat and curved. Polyester fibers have higher thickness as compared to the cotton fibers (Table 4). Furthermore, due to milling in knife cutter the edges of fibers are not cut off smoothly this could be due to the hammering effect of knife as far as knife cutter milling machine used is not specially designed for fiber cutting. It is also noticed that some fibers are also damaged from the edges.

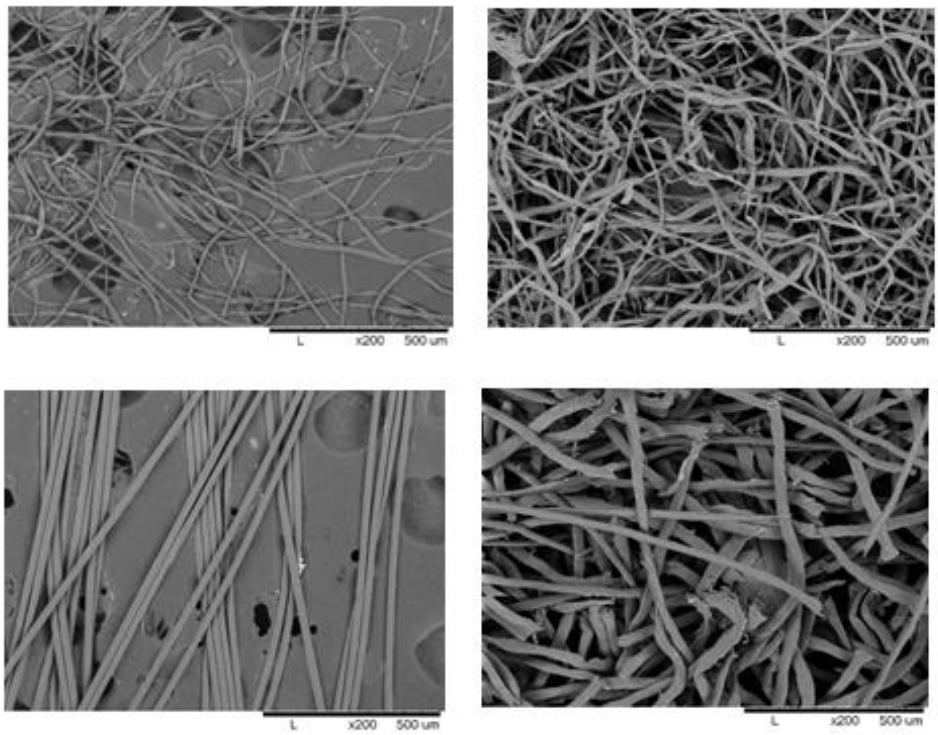

Figure 20. SEM images of cotton (top left), milled cotton (top right), PET (bottom left) and milled PET (bottom right)

4.5.1 Composites with PET fibers

As it can be clearly seen from the SEM images that there are three sizes of polyester and cotton fibers inside the moulding i.e., very large, medium and very small or fiber dust. Small size fibers are mainly seen at the edges of the cross-section of moulding, especially in case of PET fibers, whereas the big and medium size fibers are mostly found in the center (see Table 4) and small fibers and particles are concentrated near edges. In polyester fiber composites with high fiber content, the large fibers with more matrix material can be seen in center area. The molten material probably segregated into two phases during injection of the melt into the mold. Big fibers increase the viscosity of melt and concentrate in the core of mold, but melt with smaller fibers and dust particles have lower viscosity and moves towards the edges or border of the mold. Another reason for phenomena of PET fibers segregation from core to walls could be due to the smoother surface of big PET fibers, this causes the melt density variation: smooth fibers stay in the center of the mould, but shorter fibers and particles with rough surface pushed out to the walls of the mould. For future study, it is suggested to avoid the generation of fiber dust during milling of fibers and to collect and remove the fiber dust before mixing and compounding.

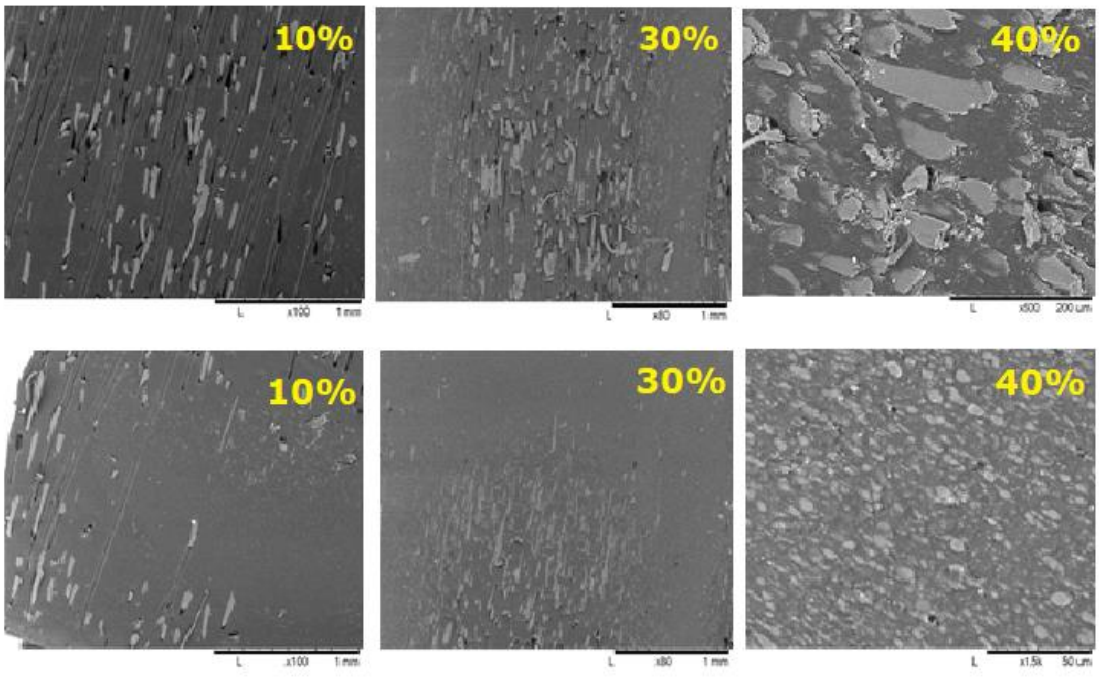

Figure 21. SEM images taken from the core of PE+PET composites (top), SEM images taken from the edge of PE+PET composites (bottom)

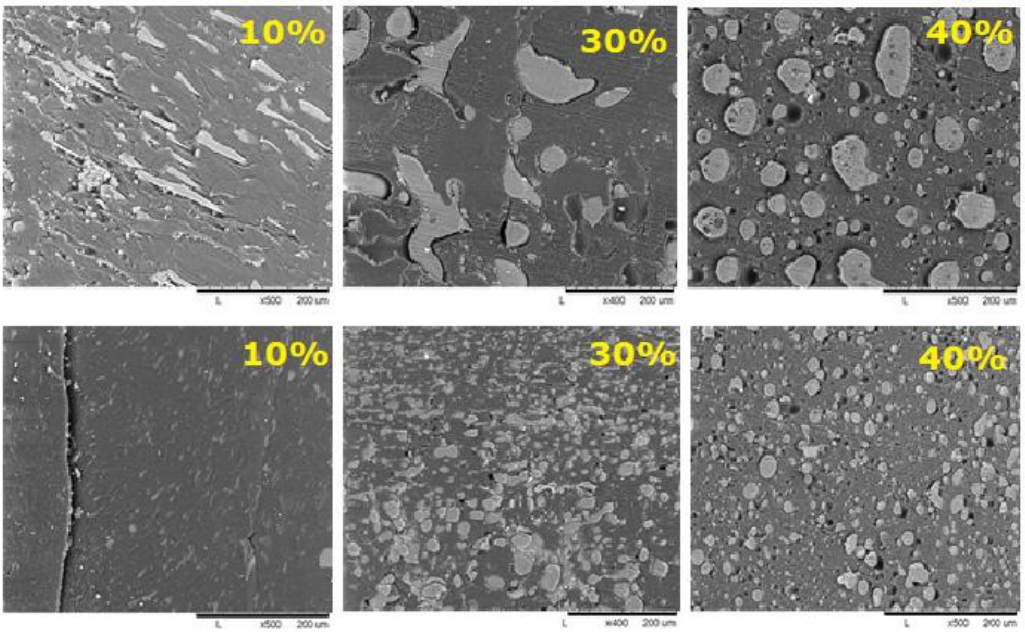

Figure 37. SEM images taken from the core of PP+PET composites (top), SEM images taken from the edge of PP+PET composites (bottom)

4.5.2 Composites with Cotton fibers

Moreover, it can be seen in figure 36 to 41 that as the fiber content is increasing, voids or pores are observed in composites especially with fiber contents of 30% and 40%. More voids are noticed in composites where cotton fibers are involved. Voids are mostly located in center because of the poor flow of cotton in molten plastic jet as during flow it pushed the polymer material towards the edges, so it created voids.

The formation of fibers agglomeration can be seen with an increase in fiber content as bundles of fibers are compactly packed in the center and the sizes of fibers are bigger than milled fibers which provided the strength and stiffness to the composite materials. In cotton fiber composites, cotton fibers show uniform dispersion in the PE and PP matrix materials.

There is no good adhesion between the fibers and the polymer matrix. If we discuss about fiber orientation or alignment, it can be seen from SEM images that fibers are well aligned in one direction. This alignment improved the mechanical properties as the flexural strength and stiffness (flexural modulus and modulus of elasticity) of the composite samples were much higher than the neat polymer matrix samples. Moreover, tensile strength of PE composites with 40% fiber content is almost same to pure polymer sample. In case of PP, by addition of 10% fibers improved the tensile strength but as the fiber content is increased the tensile strength is decreased, this may happen because of large voids and pores which can be clearly seen in SEM images.

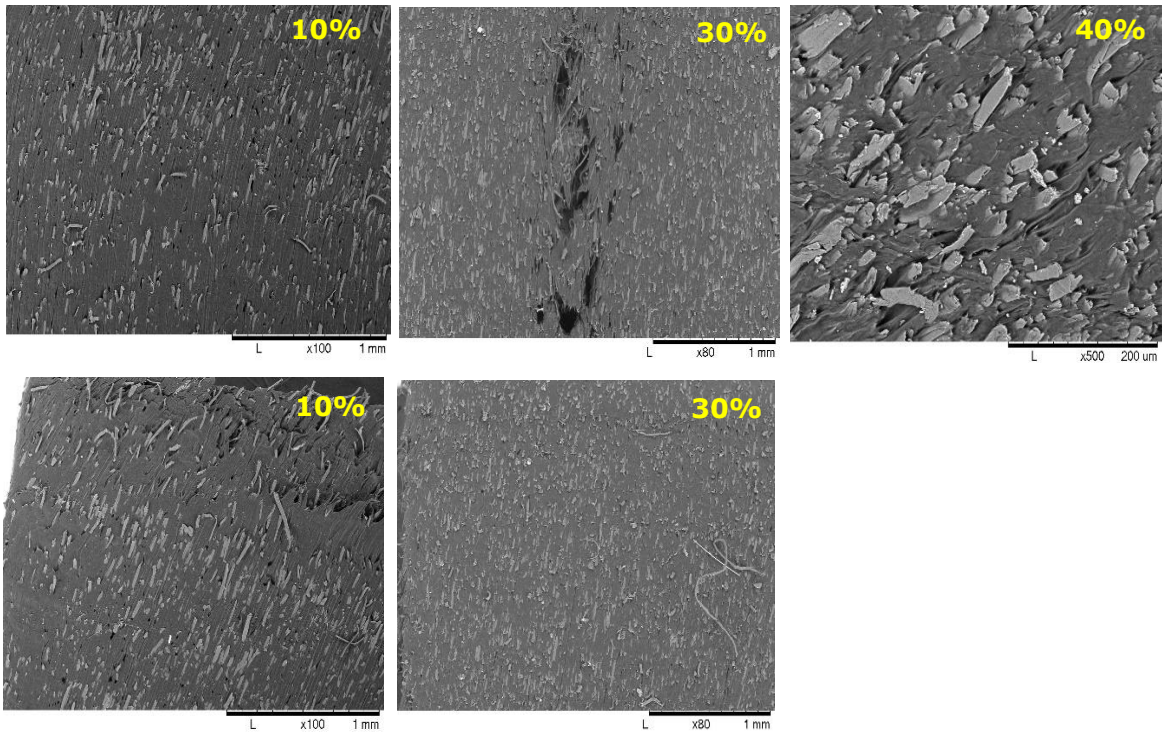

Figure 38. SEM images taken from the core of PE+Cotton composites (top), SEM images taken from the edge of PE+Cotton composites (bottom)

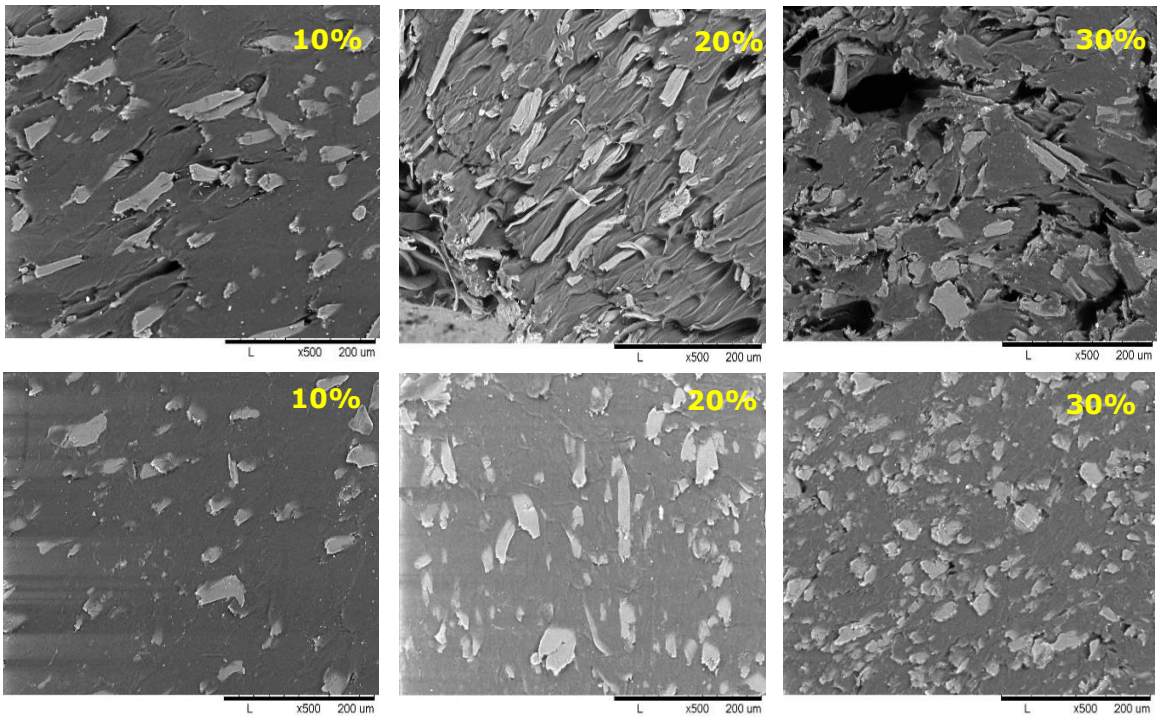

Figure 39. SEM images taken from the core of PP+Cotton composites (top), SEM images taken from the edge of PP+Cotton composites (bottom)

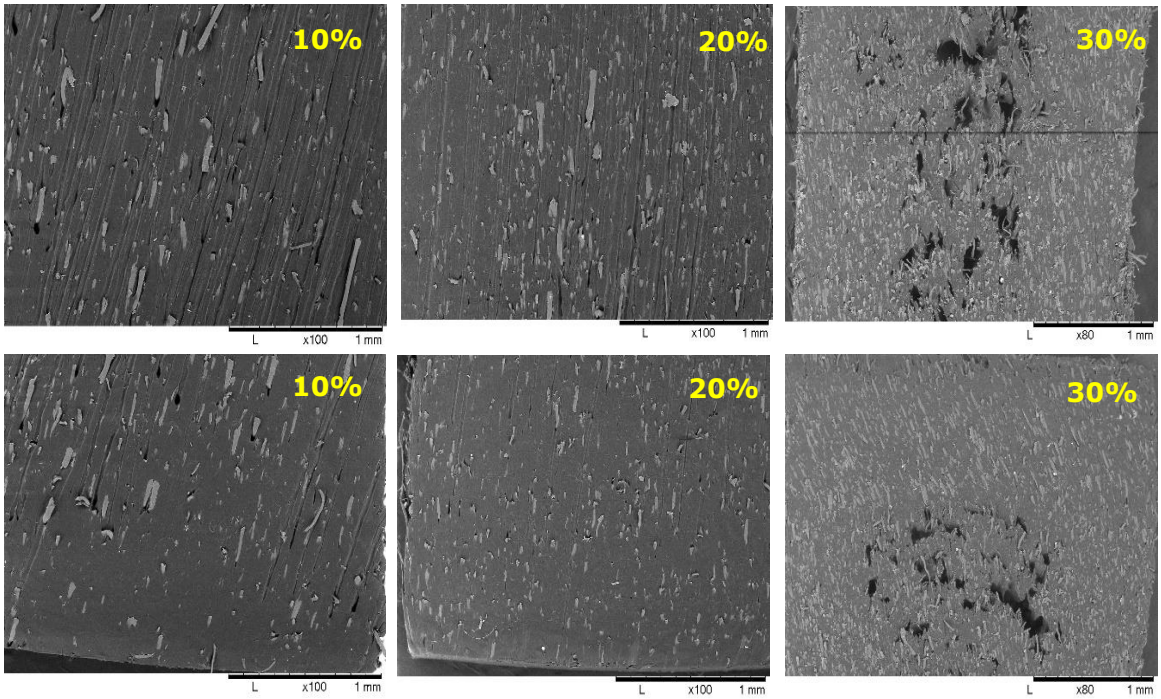

Figure 40. SEM images taken from the core of PE+PET+Cotton composites (top), SEM images taken from the edge of PE+PET+Cotton composites (bottom)

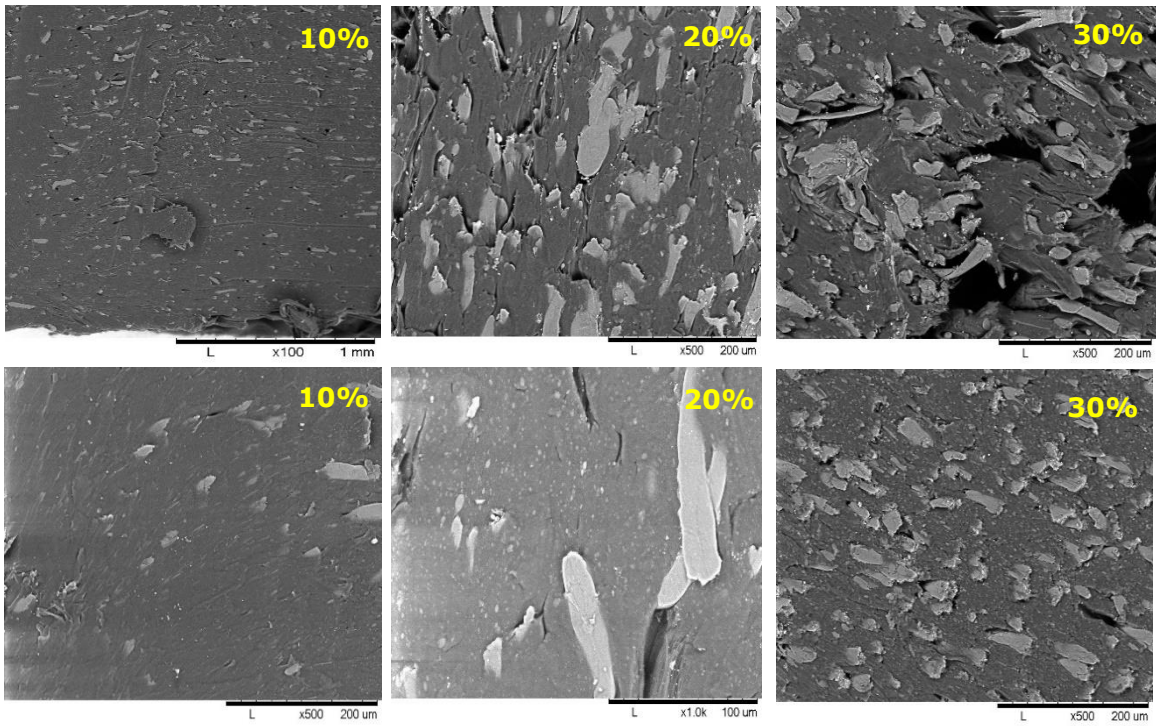

Figure 41. SEM images taken from the core of PP+PET+Cotton composites (top), SEM images taken from the edge of PP+PET+Cotton composites (bottom)

The results of SEM analysis suggest to improve the compatibilization of filler to matrix (for example by addition of coupling agent), this will improve the morphology and mechanical properties of the composites.

Table 4. Average fiber thickness in various PP and PE composites

Composite Samples	Average fiber thickness in center	Average fiber thickness at edges
PP+10% PET	7.4 µm	5.3 µm
PP+20% PET	25.1 µm	7.0 µm
PP+30% PET	38.8 µm	14.0 µm
PP+40% PET	25.3 µm	15.3 µm
PP+10% Cotton	15.0 µm	17.5 µm
PP+20% Cotton	14.8 µm	19.9 µm
PP+30% Cotton	19.1 µm	23.2 µm
PE+40% PET	29.9 µm	3.1 µm
PE+40% Cotton	22.3 µm	
Fibers	**Milled (Average fiber thickness)**	**Milled (Average fiber length)**
PET Fibers	28.9 µm	0.71 mm
Cotton Fibers	12.7 µm	

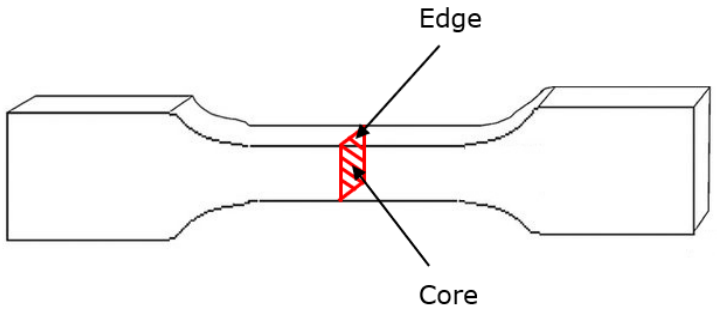

Figure 42. Edge and core areas of composite samples for SEM analysis

4.6 The effect of coupling agent on PE-based composite

4.6.1 Effects on morphology

The study the effect of coupling agent extra samples were prepared: PE + 30% Cotton + 7% MAPE and PE + 30% PET + 5% MAPE. Here % of MAPE is calculated to the weight of fibers.

Scanning electron micrographs of fractured surfaces from cross sectional area of PE composites filled with PET and cotton fibers are presented in Figure 43 and 44 which help out to look at how well fibers are adhere and distributed into the polymer matrix after addition of maleic anhydride grafted polyethylene coupling agent (compatibilizer).

Figure 45 shows that the compatibilizer did not provide any improvement in PET fibers distribution in PE composites. Still the larger size fibers are found in the center of composite specimen. Whereas the small size fibers or fiber dust is settled at the ages of the specimen. However, incorporation of MAPE in PET fibers filled composites caused delamination at the edges of the composite which could be due to the failure in adhesion between layers or debonding at the polymer-fiber interface caused by MAPE coupling agent.

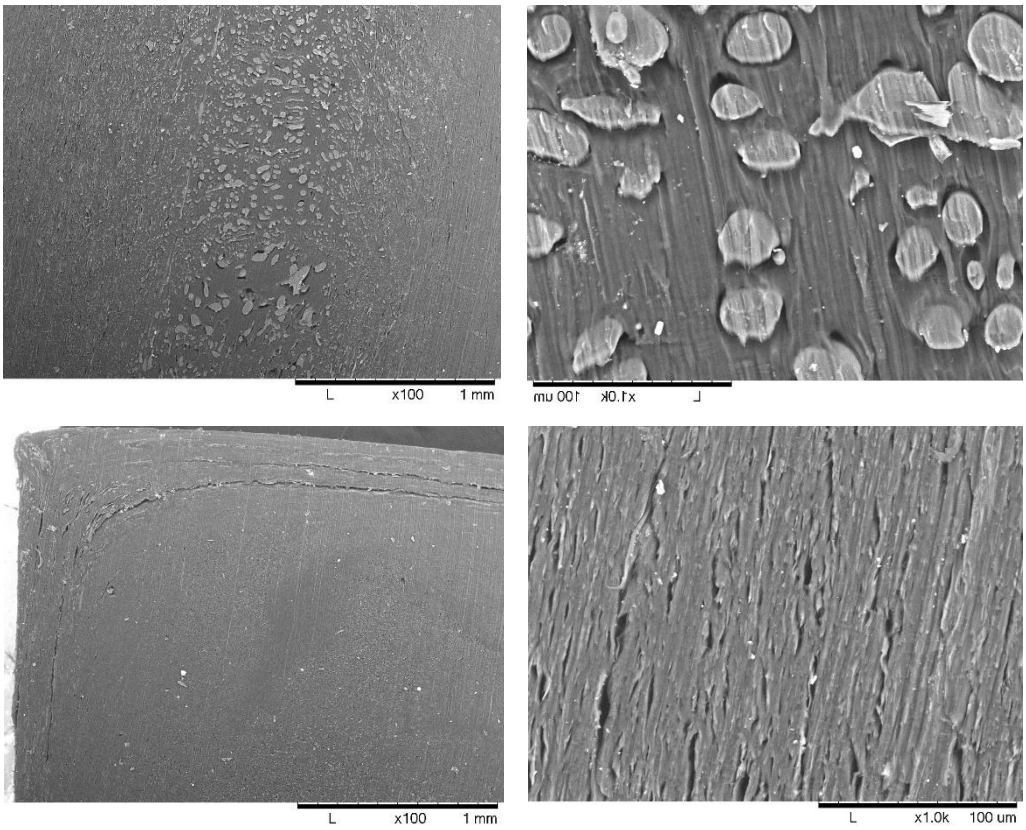

Figure 43. SEM images taken from the core of the samples of PE + 30% PET + 5% MAPE (top left and right), SEM images taken from the edge of samples of PE + 30% PET + 5% MAPE (bottom left and right)

On the other hand, the presence of MAPE compatibilizer in cotton fiber filled composite helped to reduce or eliminate the voids and cracks formation which indicates significant improvement in bonding between cotton fibers and PE matrix material. Furthermore, MAPE further improved the distribution of cotton fibers in PE matrix material. This improvement in adhesion and dispersion is confirmed by the elevation of mechanical properties of cotton fiber filled PE composites.

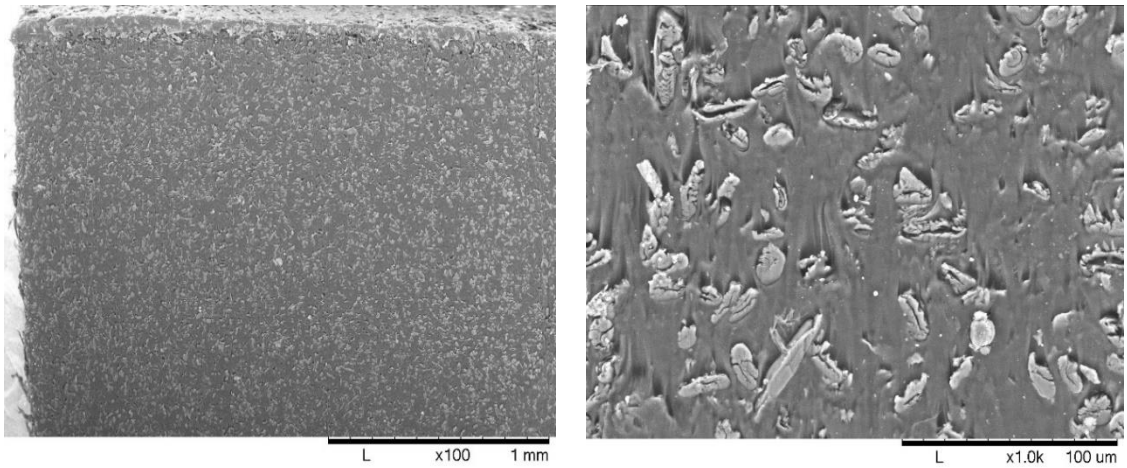

Figure 44. SEM image of PE + 30% Cotton + 7% MAPE (left), SEM image taken from the core of sample of PE + 30% Cotton + 7% MAPE (right)

4.6.2 Effects on mechanical properties

Tensile test The result of tensile test clearly showed that there is a significant change in tensile strength and modulus of elasticity after the incorporation of MAPE in composites filled with 30 wt. % of cotton fibers. For example, tensile strength increased by 80% when compared to composites filled with 30 wt. % of cotton fibers without any coupling agent. Furthermore, there is improvement in modulus of elasticity of 11% in comparison with composites filled with 30 wt. % of cotton fibers without coupling agent.

On the other hand, inclusion of MAPE in composites filled with 30 wt. % of PET fibers showed a 15% increase in tensile strength when compared to material without compatibilizer. Moreover, Young's modulus also increased by 9% compared to composite without coupling agent.

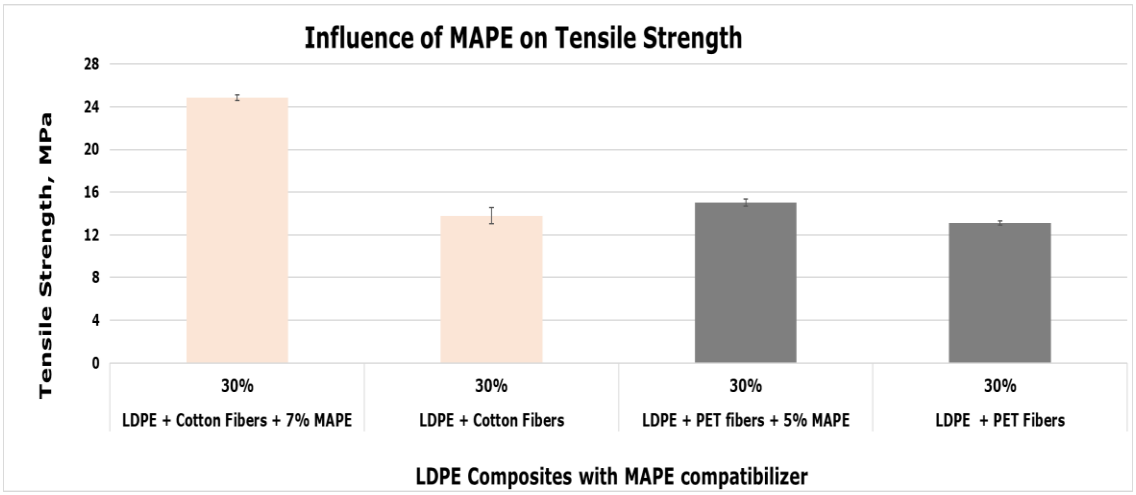

Figure 45. Tensile strength (MPa) of LDPE composites with MAPE compatibilizer

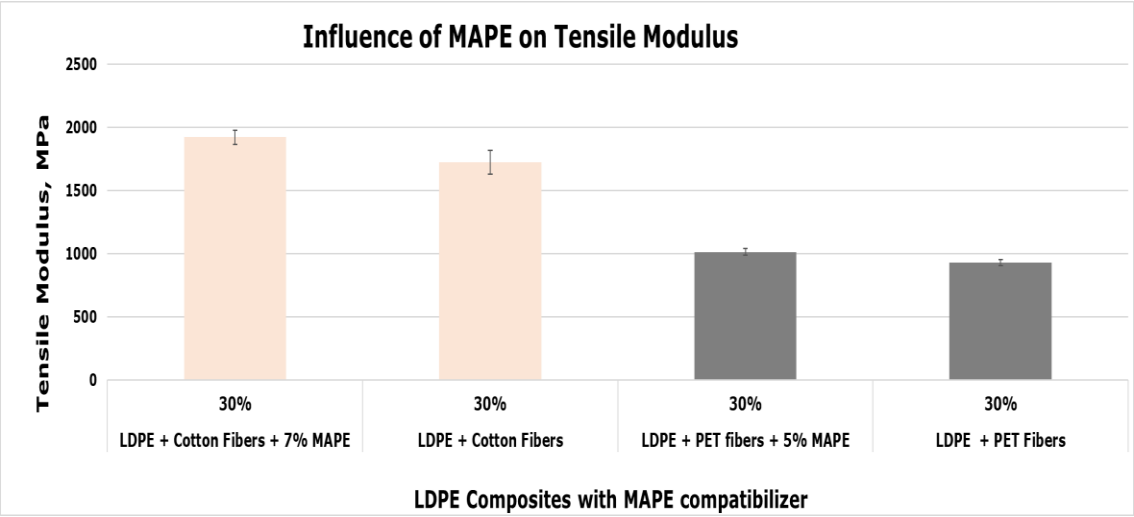

Figure 46. Tensile Modulus (MPa) of LDPE composites with MAPE compatibilizer

Flexural Test The flexural test results suggests substantial improvement in flexural strength after the addition of MAPE in LDPE composites filled with 30 wt. % of cotton and PET fibers when compared to composites without coupling agent. For instance, LDPE filled with 30 wt. % of cotton fibers and 7% MAPE showed a 29% improvement in flexural strength when compared to composite without compatibilizer. On the other hand, there is no considerable change in flexural modulus between composites with and without coupling agent.

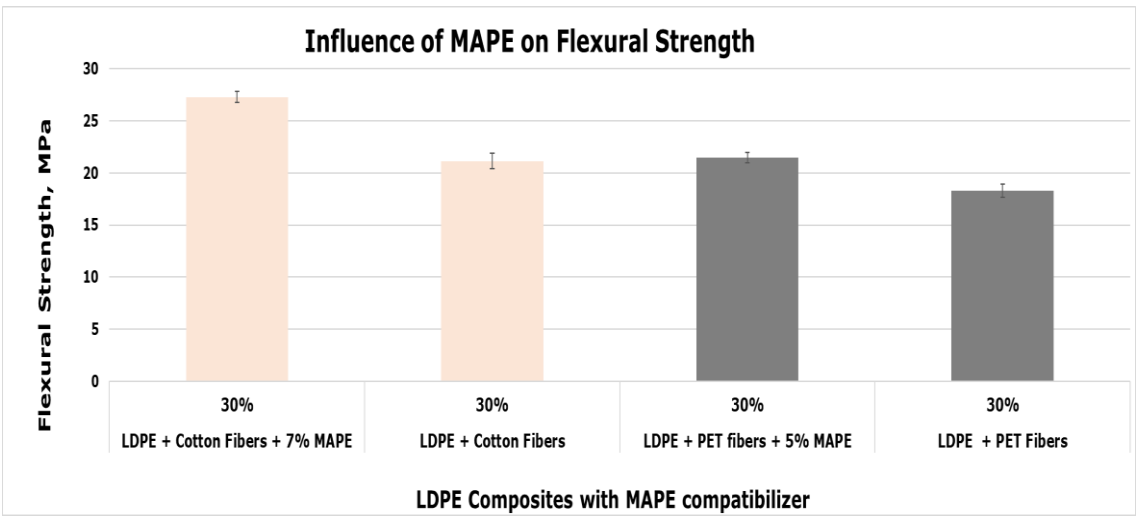

Figure 47. Flexural strength (MPa) of LDPE composites with MAPE compatibilizer

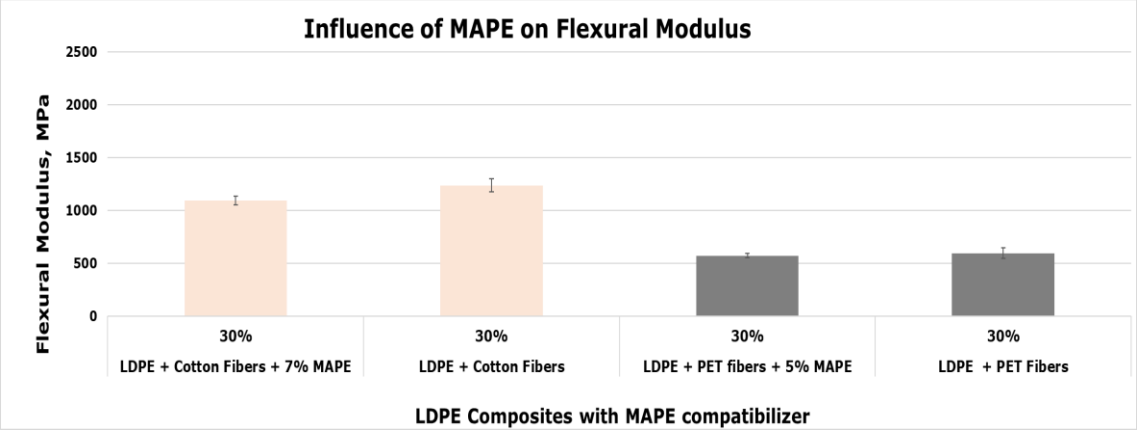

Figure 48. Flexural Modulus (MPa) of LDPE composites with MAPE compatibilizer

Impact Test The Charpy impact strength test results show considerable improvement in impact strength after the incorporation of MAPE in LDPE composites filled with 30 wt. % of cotton and PET fibers in comparison with composites without coupling agent. For example, LDPE composites filled with 30 wt. % of cotton fibers + 7% MAPE and 30 wt. % of PET fibers + 5% MAPE indicated about 56% increase in impact strength when compared to LDPE composites without compatibilizer. One should notice that MAPE has stronger coupling effect on cotton fibers rather than PET what is relevant to both PE and PP matrixes.

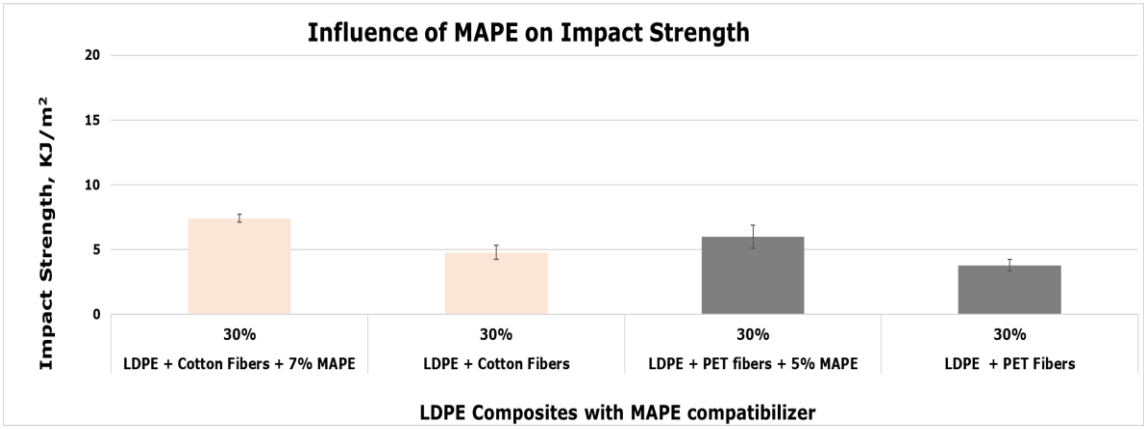

Figure 49. Impact strength (KJ/m^2) of LDPE composites with MAPE compatibilizer

CONCLUSIONS

The results of this work could be summarized in following conclusions:

1. Polyolefin composites with fiber content up to 40 wt. % can be compounded and injection molded with slight changes in processing parameters as compared to neat polyolefins. Addition of fibers significantly decreases the MFI of composites.

2. Incorporation of PET, cotton and mixture of PET+Cotton fibers slightly reduces the tensile strength of composites. Whereas Young's modulus is improved by the addition of fibers which makes the composites stiffer.

3. Flexural strength and flexural modulus of composites is increased by the incorporation of PET, cotton and their mixture as well.

4. Fiber content reduces the impact strength of composites, which makes them more brittle and less tough.

5. Presence of MAPE coupling agent improved the tensile, impact and flexural properties in cotton and polyester fibers filled LDPE composites. Furthermore, MAPE compatibilizer improves the bonding between and fibers and LDPE matrix.

6. The adhesion is poor between fibers and matrix materials especially in PET fibers. Composites with cotton fibers shows good distribution whereas composites with PET fibers indicates the poor distribution of fibers in core and edges of moldings.

7. Cotton and polyester fibers recovered from textile waste has the potential to be prospective filler for the fabrication of injection molded domestic or household plastic products.

SUMMARY

The results of this work show that short fiber-filled PE and PP could be efficiently processed by injection moulding. It has significant importance as injection moulding is the most efficient method for large scale production of single-type items.

The incorporation of fibers into plastic matrix allows to achieve mechanical properties and performance similar to more expensive plastic types with higher molecular weight. For example, fiber-loaded LDPE could be used to replace HDPE or fiber-loaded PP could be used to replace PVC and cross-linked PE in some applications.

For injection moulding applications natural, synthetic and mixed fibers could be loaded into a plastic matrix up to 30-40 wt.% that is a theoretical optimum for polymer-fiber composites. Thus, the combination of optimal material properties and cost-effective processing method could give large economic and environmental benefits. The usage of fibers recovered from textile waste as filler for polymer-fiber composites is definitely nature-friendly approach for plastic industry.

Nevertheless, the incorporation of synthetic and natural fibers into polymers for the injection moulding application demands further development: to improve the compatibility of fibers to matrix and improve the flowability of composite, also the appearance of composite materials.

KOKKUVÕTE

Käesoleva töö tulemused näitavad, et lühikeste tekstiilkiududega täidetud polüetüleeni (PE) ja polüpropüleeni (PP) saab tõhusalt töödelda survevalu teel. Sellel on märkimisväärne tähtsus, kuna survevalu on kõige tõhusam meetod ühetüübiliste esemete suuremahuliseks tootmiseks.

Kiudude lisamine plastmaatriksisse võimaldab saavutada mehaanilisi omadusi mis sarnanevad kallimatele plasttüüpidele, millel on suurem molekulmass. Näiteks võib kiududega armeeritud madaltihedat PE kasutada kõrgtiheda PE asendamiseks. Armeeritud PP võib mõnes rakenduses kasutada polüvinüülkloriidi või ristseotud PE asendamiseks.

Uuringus kasutatud sünteetiliste ja loodulike kiudude või nende segude optimaalne sisaldus komposiidis on survevalu puhul kuni 30-40 massiprotsenti. Optimaalse kiusisalduse ja kulutõhusa tootmismeetodi kombineerimine võib anda suuri majanduslikke ja keskkonna alaseid eeliseid. Tekstiilijäätmetest ringlusse võetud kiudude kasutamine polümeerkomposiitide täiteainena on kindlasti loodussõbralik lähenemine plastitööstusele.

Sellegipoolest nõuab survevalu rakenduste jaoks sünteetiliste ja looduslike kiudude lisamine polümeeridesse komposiitmaterjali edasist arengut: parandada tuleb kiudude kokkusobivust maatriksiga ja kohandada komposiitmaterjalide voolavust ning välimust.

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APPENDIX

APPENDIX 1

Impact strength of LDPE, RePE and PP composites before and after UV aging

S No.	Matrix polymer (wt. %)	Fiber (wt. %)	Impact strength (kg/m²)	Impact strength after UV aging (kg/m²)
1	Pure LDPE 100%	-	18.26	13.34
2	LDPE 90%	10% PET fibers	6.64	5.99
3	LDPE 80%	20% PET fibers	5.67	4.28
4	LDPE 70%	30% PET fibers	3.79	3.28
5	LDPE 60%	40% PET fibers	2.55	N/A
6	LDPE 90%	10% CTN fibers	7.54	N/A
7	LDPE 80%	20% CTN fibers	6.73	4.50
8	LDPE 70%	30% CTN fibers	4.77	4.94
9	LDPE 60%	40% CTN fibers	4.21	4.13
10	LDPE 90%	10% PET+CTN fibers	7.10	6.03
11	LDPE 80%	20% PET+CTN fibers	5.51	4.79
12	LDPE 70%	30% PET+CTN fibers	4.88	4.04
13	LDPE 60%	40% PET+CTN fibers	2.56	2.66
14	Pure RePE 100%	-	13.45	11.27
15	RePE 90%	10% PET fibers	6.55	5.59
16	RePE 80%	20% PET fibers	4.44	3.80
17	RePE 70%	30% PET fibers	2.97	2.78
18	RePE 60%	40% PET fibers	2.24	1.95
19	RePE 90%	10% CTN fibers	7.62	7.11
20	RePE 80%	20% CTN fibers	6.57	6.06
21	RePE 90%	10% PET+CTN fibers	5.71	5.07
22	RePE 80%	20% PET+CTN fibers	4.65	4.57
23	RePE 70%	30% PET+CTN fibers	3.83	3.68
24	RePE 60%	40% PET+CTN fibers	2.32	2.26

25	Pure PP 100%	-	0.25	0.11
26	PP 90%	10% PET fibers	0.81	0.12
27	PP 80%	20% PET fibers	0.28	0.12
28	PP 70%	30% PET fibers	0.25	0.13
29	PP 60%	40% PET fibers	0.16	0.12
30	PP 90%	10% CTN fibers	1.38	0.23
31	PP 80%	20% CTN fibers	2.08	0.45
32	PP 90%	10% PET+CTN fibers	0.90	0.16
33	PP 70%	30% PET+CTN fibers	1.36	0.25

APPENDIX 2

Flexural properties of LDPE, RePE and PP composites

S No.	Matrix polymer (wt. %)	Fiber (wt. %)	Flexural strength (MPa)	Flexural modulus (MPa)
1	Pure LDPE 100%	-	12.0	369.10
2	LDPE 90%	10% PET fibers	13.40	469.30
3	LDPE 80%	20% PET fibers	14.80	430.20
4	LDPE 70%	30% PET fibers	18.30	594.60
5	LDPE 60%	40% PET fibers	23.20	752.0
6	LDPE 90%	10% CTN fibers	14.93	635.21
7	LDPE 80%	20% CTN fibers	20.51	1106.93
8	LDPE 70%	30% CTN fibers	21.13	1236.43
9	LDPE 60%	40% CTN fibers	21.71	1424.03
10	LDPE 90%	10% PET+CTN fibers	13.70	488.80
11	LDPE 80%	20% PET+CTN fibers	16.80	651.0
12	LDPE 70%	30% PET+CTN fibers	22.30	1073.80
13	LDPE 60%	40% PET+CTN fibers	23.70	1293.80
14	Pure RePE 100%	-	12.20	356.30
15	RePE 90%	10% PET fibers	12.54	359.15
16	RePE 80%	20% PET fibers	18.27	555.16

17	RePE 70%	30% PET fibers	21.51	679.06
18	RePE 60%	40% PET fibers	26.76	863.81
19	RePE 90%	10% CTN fibers	13.20	486.80
20	RePE 80%	20% CTN fibers	18.20	895.60
21	RePE 90%	10% PET+CTN fibers	15.10	491.84
22	RePE 80%	20% PET+CTN fibers	15.82	615.22
23	RePE 70%	30% PET+CTN fibers	18.16	766.23
24	RePE 60%	40% PET+CTN fibers	23.06	1287.25
25	Pure PP 100%	-	38.0	1138.10
26	PP 90%	10% PET fibers	35.91	1069.54
27	PP 80%	20% PET fibers	39.85	1192.76
28	PP 70%	30% PET fibers	38.64	1123.82
29	PP 60%	40% PET fibers	41.72	1329.82
30	PP 90%	10% CTN fibers	37.72	1431.86
31	PP 80%	20% CTN fibers	36.68	1720.81
32	PP 70%	30% CTN fibers	29.53	1604.42
33	PP 90%	10% PET+CTN fibers	39.07	1359.60
34	PP 80%	20% PET+CTN fibers	36.43	1493.05
35	PP 70%	30% PET+CTN fibers	29.97	1477.83

APPENDIX 3

Tensile properties of LDPE, RePE and PP composites

S No.	Matrix polymer (wt. %)	Fiber (wt. %)	Tensile strength (MPa)	Tensile modulus (MPa)	Energy at break (J)
1	Pure LDPE 100%	-	15.6	567.0	337.5
2	LDPE 90%	10% PET fibers	12.3	711.5	232.5
3	LDPE 80%	20% PET fibers	11.5	796.5	162.3
4	LDPE 70%	30% PET fibers	13.1	930.2	13.7
5	LDPE 60%	40% PET fibers	15.0	1098.7	4.7

6	LDPE 90%	10% CTN fibers	12.4	912.3	60.0
7	LDPE 80%	20% CTN fibers	15.0	1495.0	4.4
8	LDPE 70%	30% CTN fibers	13.8	1725.0	1.8
9	LDPE 60%	40% CTN fibers	16.0	2138.5	2.4
10	LDPE 90%	10% PET+CTN fibers	11.9	785.0	224.0
11	LDPE 80%	20% PET+CTN fibers	12.7	1033.0	10.0
12	LDPE 70%	30% PET+CTN fibers	15.4	1556.0	3.0
13	LDPE 60%	40% PET+CTN fibers	14.8	1763.0	2.0
14	Pure RePE 100%	-	18.9	676.0	437.0
15	RePE 90%	10% PET fibers	11.9	776.0	185.0
16	RePE 80%	20% PET fibers	14.2	929.0	139.0
17	RePE 70%	30% PET fibers	14.3	1039.0	81.0
18	RePE 60%	40% PET fibers	15.9	1277.0	5.6
19	RePE 90%	10% CTN fibers	12.1	901.0	107.1
20	RePE 80%	20% CTN fibers	13.1	1333.0	4.5
21	RePE 90%	10% PET+CTN fibers	11.9	844.0	190.0
22	RePE 80%	20% PET+CTN fibers	11.0	1011.0	8.3
23	RePE 70%	30% PET+CTN fibers	11.1	1302.0	1.6
24	RePE 60%	40% PET+CTN fibers	11.9	1753.0	0.6
25	Pure PP 100%	-	25.3	1637.0	579.5
26	PP 90%	10% PET fibers	26.0	1790.0	82.0
27	PP 80%	20% PET fibers	25.1	1844.0	43.0
28	PP 70%	30% PET fibers	24.0	1955.0	21.0
29	PP 60%	40% PET fibers	21.5	1918.0	8.0
30	PP 90%	10% CTN fibers	25.4	2223.0	8.0
31	PP 80%	20% CTN fibers	21.0	2377.0	3.4
32	PP 70%	30% CTN fibers	14.6	2297.0	1.2
33	PP 90%	10% PET+CTN fibers	23.8	1903.0	15.8
34	PP 80%	20% PET+CTN fibers	17.8	1714.0	5.0
35	PP 70%	30% PET+CTN fibers	15.7	1906.0	2.0

APPENDIX 4

Tensile properties of LDPE and PP composites with recycled T-shirt fibers

S No.	Matrix polymer (wt. %)	Fiber (wt. %)	Tensile strength (MPa)	Tensile modulus (MPa)
1	LDPE 70%	30% PET fibers	14.92	1087.0
2	LDPE 70%	30% CTN fibers	13.47	1763.0
3	LDPE 70%	30% PET+CTN fibers	10.95	1230.0
4	PP 70%	30% PET fibers	23.64	2045.0
5	PP 70%	30% CTN fibers	25.63	3335.0
6	PP 70%	30% PET+CTN fibers	22.15	2600.0

Mechanical properties of LDPE + cotton and PET fibers + MAPE composites

S No.	Composite Samples	Tensile strength (MPa)	Tensile modulus (MPa)	Energy at break (J)	Flexural strength (MPa)	Flexural modulus (MPa)	Impact strength (kg/m²)
1	LDPE + 30 % cotton fibers + 7% MAPE	24.90	1922.0	11.9	27.30	1049.1	7.42
2	LDPE + 30 % PET fibers + 5% MAPE	15.0	1014.0	20.0	21.50	570.2	5.98

APPENDIX 5

Weight of matrix and fibers for premixing and compounding

S No.	Sample	Fiber Content %	Weight of matrix	Weight of fibers	Total weight
1	Pure LDPE/PP/RePE	-	-	-	-
2	LDPE/PP/RePE + Cotton fibers	10 %	450 gms	50 gms	500 gms
3	LDPE/PP/RePE + Cotton fibers	20 %	400 gms	100 gms	500 gms
4	LDPE/PP/RePE + Cotton fibers	30 %	350 gms	150 gms	500 gms
5	LDPE/PP/RePE + Cotton fibers	40 %	300 gms	200 gms	500 gms
6	LDPE/PP/RePE + PET fibers	10 %	450 gms	50 gms	500 gms
7	LDPE/PP/RePE + PET fibers	20 %	400 gms	100 gms	500 gms

8	LDPE/PP/RePE + PET fibers	30 %	350 gms	150 gms	500 gms
9	LDPE/PP/RePE + PET fibers	40 %	300 gms	200 gms	500 gms
10	LDPE/PP/RePE + PET/Cotton fibers (50/50)	10 %	450 gms	50 gms	500 gms
11	LDPE/PP/RePE + PET/Cotton fibers (50/50)	20 %	400 gms	100 gms	500 gms
12	LDPE/PP/RePE + PET/Cotton fibers (50/50)	30 %	350 gms	150 gms	500 gms
13	LDPE/PP/RePE + PET/Cotton fibers (50/50)	40 %	300 gms	200 gms	500 gms

Weight of matrix and waste T-shirt fibers for premixing and compounding

S No.	Sample	Fiber Content %	Weight of matrix	Weight of fibers	Total weight
1	LDPE/PP + Cotton fibers	30 %	350 gms	150 gms	500 gms
2	LDPE/PP + PET fibers	30 %	350 gms	150 gms	500 gms
3	LDPE/PP + PET/Cotton fibers	30 %	350 gms	150 gms	500 gms

Weight of matrix, fibers and coupling agent for premixing and compounding

S No.	Sample	Fiber wt. %	CA %	Wt. of matrix	Wt. of fibers	Wt. of CA	Total wt.
1	LDPE + Cotton fibers	30 %	7 %	350 gms	150 gms	11 gms	511 gms
2	LDPE + PET fibers	30 %	5 %	350 gms	150 gms	9 gms	509 gms

APPENDIX 6

Injection molding processing parameters PE, RePE and PP compounds

S No.	Sample	Dosing Speed (rpm)	Injection Pressure (bar)	Injection Speed (rpm)	Cycle Time (sec.)
1	Pure LDPE 100%	5	73	7	18.3
2	LDPE 90% + 10% PET fibers	5	73	13	22
3	LDPE 80% + 20% PET fibers	7	90	13	25
4	LDPE 70% + 30% PET fibers	9	99	13	29

5	LDPE 60% + 40% PET fibers	9	99	14	33
6	LDPE 90% + 10% CTN fibers	5	73	13	22
7	LDPE 80% + 20% CTN fibers	5	82	13	25
8	LDPE 70% + 30% CTN fibers	5	97	13	29
9	LDPE 60% + 40% CTN fibers	5	98	13	31
10	LDPE 90% + 10% PET+CTN fibers	5	73	13	22
11	LDPE 80% + 20% PET+CTN fibers	5	90	14	25
12	LDPE 70% + 30% PET+CTN fibers	5	99	15	28
13	LDPE 60% + 40% PET+CTN fibers	5	99	15	31
14	Pure RePE 100%	5	75	8	18.5
15	RePE 90% + 10% PET fibers	5	95	13	22
16	RePE 80% + 20% PET fibers	7	95	13	26
17	RePE 70% + 30% PET fibers	9	99	13	30
18	RePE 60% + 40% PET fibers	9	99	13	33
19	RePE 90% + 10% CTN fibers	5	99	15	26
20	RePE 80% + 20% CTN fibers	5	99	15	29
21	RePE 90% + 10% PET+CTN fibers	6	95	13	23
22	RePE 80% + 20% PET+CTN fibers	7	99	15	28
23	RePE 70% + 30% PET+CTN fibers	7	99	15	31
24	RePE 60% + 40% PET+CTN fibers	8	99	15	35
25	Pure PP 100%	5	73	5	18.3
26	PP 90% + 10% PET fibers	5	90	11	22
27	PP 80% + 20% PET fibers	5	95	12	32
28	PP 70% + 30% PET fibers	5	99	14	33
29	PP 60% + 40% PET fibers	5	99	15	34
30	PP 90% + 10% CTN fibers	5	73	9	22
31	PP 80% + 20% CTN fibers	5	99	14	32
32	PP 90% + 10% PET+CTN fibers	5	78	8	22
33	PP 80% + 20% PET+CTN fibers	5	99	15	34
34	PP 70% + 30% PET+CTN fibers	5	99	15	36

APPENDIX 7

Injection molding processing parameters of compounds with recycled T-shirt fibers

S No.	Sample	Dosing Speed (rpm)	Injection Pressure (bar)	Injection Speed (rpm)	Cycle Time (sec.)
1	LDPE 70% + 30% PET fibers	9	95	12	29
2	LDPE 70% + 30% CTN fibers	5	95	13	29
3	LDPE 70% + 30% PET+CTN fibers	5	95	13	29
4	PP 70% + 30% PET fibers	5	90	9	31
5	PP 70% + 30% CTN fibers	5	95	13	32
6	PP 70% + 30% PET+CTN fibers	5	90	11	32

Injection molding processing parameters of compounds with coupling agent

S No.	Sample	Dosing Speed (rpm)	Injection Pressure (bar)	Injection Speed (rpm)	Cycle Time (sec.)
1	LDPE 70% + 30% PET fibers	8	99	13	29
2	LDPE 70% + 30% CTN fibers	6	99	15	30

APPENDIX 8

LDPE, PP and RePE composite samples with different fibers and fiber contents

LDPE + recycled T-shirt fiber composites

PP + recycled T-shirt fiber composites