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DEVELOPMENT OF COMMERCIAL APPLICATIONS FOR  
RECYCLED PLASTICS USING FINITE ELEMENT  
ANALYSIS

by

Nanjunda NarasimhaMurthy

A thesis submitted to the faculty of

Brigham Young University

in partial fulfillment of the requirements for the degree of

Master of Science

School of Technology

Brigham Young University

December 2005



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BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

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This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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**BRIGHAM YOUNG UNIVERSITY**

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## ABSTRACT

# DEVELOPMENT OF COMMERCIAL APPLICATIONS FOR RECYCLED PLASTICS USING FINITE ELEMENT ANALYSIS

Nanjunda NarasimhaMurthy

School of Technology

Master of Science

This thesis investigates the suitability of thermo-kinetically recycled plastics for use in commercial product applications using finite element analysis and statistics. Different recycled material blends were tested and evaluated for their use in commercial product applications.

There are six different blends of thermo-kinetically recycled plastics used for testing and CATIA is used for finite element analysis. The different types of thermo-kinetically recycled plastics blends are: pop bottles made of PolyethyleneTeraphthalate (PET), milk jugs made of High-Density Polyethylene (HDPE), Vinyl seats made of Poly Vinyl Chloride (PVC) and small amount of Polypropylene (PP) and Urethane, electronic scrap made of engineering resins like Acrylo-Nitrile-Butadiene Styrene (ABS), Polystyrene (PS) and Polycarbonate (PC), agriculture waste consisting of Low



Density Polyethylene (LDPE), industrial waste consisting of Nylon (PA66) and PolyethyleneTerephthalate (PET), household waste consisting of Polystyrene (PS).

The methods employed during the study include three phases for each of six blends available:

1. Density, tensile and impact testing of each blend
2. Correlation of mechanical properties to blend
3. Finite element analysis of the service performance of a product made from each thermo-kinetically recycled plastic blend

This thesis shows that some of the recycled plastics materials that were tested are qualified to be used in the pallet. Those materials that qualified were Industrial waste consisting of Nylon and PolyethyleneTerephthalate, household waste consisting of Polystyrene.

## **ACKNOWLEDGEMENT**

When I was at Central Institute of Plastics Engineering & Technology, India, pursuing Plastics Engineering Diploma, I wanted to combine my knowledge of Mechanical Engineering and Plastics in useful research. I learnt that not much work was done in Finite element analysis of plastics. My dream of 5 years has finally come true. Here I am grateful to goddess Amba Bhavani for her blessings she has given me and for this wonderful opportunity to be at BYU studying with wonderful professors, and students. I thank all those who have been good examples to me and who have helped me.

I owe a great deal of gratitude to my beloved parents Smt.B.S.Nagarathna and Sri.N.NarasimhaMurthy, who supported me and have been willing to sacrifice their comfort to attain my educational goals. This achievement is a good example for my family. I appreciate the support of my two older brothers Mr.N.Gireesh, Mr.N.Harish, cousin Mr.D.N.Guruprasad, Dr.Elaine Hoffman, Department chair, Bemidji State University, and Dr.William Brauer, Professor, Bemidji State University, without whom this endeavour would have remained as a dream.

I am very grateful for my committee chair, Dr. Michael P. Miles, who helped me throughout this project. He is a good teacher, great mentor, and his great knowledge has been very resourceful. I am very impressed with his magnanimity. I would like to thank

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## **CHAPTER 1**

### **INTRODUCTION AND PROBLEM STATEMENT**

#### **INTRODUCTION**

“The existing pattern of resource will lead to a collapse of the world system within the next century. These were the words that hit the headlines when the world was shaken by the first oil crisis in 1973. This view point, advocated in ‘The Limits of Growth’ (Meadows, et al, 1972) dominated the thinking throughout the 1970s and much of the 1980s and led to a wide acceptance of the depletion of resources as a central environmental, economic and political issue. It was based on the premise that natural resources, particularly oil, were about to run out. This pessimistic prediction has, however, proved to be false and the collapse of oil prices in 1986 marked the end of the ‘the era of resource scarcity’. New concerns over the future of the global environment then started to emerge.

One of these was a keen sense of human vulnerability to environmental changes. It soon became apparent that a unifying approach to concerns over the environment, economic development and the quality of life was necessary if human (and other) life was to be sustained for an indefinite period in the future and is referred to as Sustainable Development. The Brundtland report (UN Commission, 1983) gave the most commonly

used working definition of sustainable development, as that which ‘meets the needs of the present without compromising the ability of future generations to meet their own needs.

The Brundtland report prompted numerous actions at international levels and instigated the Earth Summit held in Rio de Janeiro in June 1992. In response many countries started developing their own plans of action and setting out strategies for sustainable development. One of the main causes of environmental degradation, however, is unsustainable development by the rich. The ‘big seven’ i.e., USA, Japan, Germany, Canada, France, Italy and UK, make up less than 12% of the world’s population, but consume 43% of the world’s fossil fuel (the resource from which most of synthetic polymers and plastics are derived) (Azapagic, Adisa. Emsley, and Hamerton, 2003, pp 2-9). If the rest of the world continued to consume the fossil fuel as the UK does today, we would need eight and a half planets to sustain current global consumption in 2050. Also, various environmental and government groups focus much attention on plastics materials and products as these consume fossil fuels and are discarded after use, usually as landfill.

However, consumption of material and energy resources is not the only issue surrounding polymeric materials and products. Because of their wide spread use and our ‘linear’ consumption patterns (in which materials and products are used only once and then discarded), plastics also contribute to an ever-increasing amount of solid waste.

The fact that only 4% of the world’s oil reserves are used in manufacture of plastics is sometimes used as an argument that they don’t contribute much to the degradation of the environment, but 4% still represents a valuable resource. Furthermore, there are other issues to consider, such as the generation of (long-lived) solid waste and pollution associated with polymeric materials and products.

Consider the example of percentage the post-consumer waste recycled in Europe during 1999. Out of 19 million tons only about 6 million tons (or 30%) were recycled in Western Europe in 1999 (APME, 1999). Hence addressing the problem of polymers in the environment remains an important goal.

The use of resources management of waste in a more sustainable fashion cannot be achieved in any single way. However efficiently we use resources, the laws of thermodynamics teach us that some waste will always be generated. This, coupled with increasing consumption and the fact that it is difficult to persuade people to change their lifestyle, requires an integrated resources and waste management strategy. The waste management hierarchy involves following the options of reduction, re-use, recycling, incineration and landfill. The options reduction, re-use and recycling (aimed at turning waste back into resources through re-use and recycling of materials) will lead to conservation of natural resources and reduction of other environmental damage.

With a population of at least 250 million people and a highly developed consumer economy, the need to implement a robust solid waste management scheme in the USA is crucial. With the production of polymers in excess of 30 million tons per annum (1995 data), the country is the world's largest polymer producer. The amount of plastics consumed annually in the USA has grown steadily from 1960, when it constituted 0.5% of the municipal solid waste (MSW) to 1996, when the Figure had risen to 12.3 % (Edgecombe, F.H.C, 1998, pp 29-39). The five most prevalent polymers in MSW are (in decreasing order) LDPE, HDPE, PP, PS and PET. Fortunately, post-consumer recycling has also grown appreciably in recent years; e.g. 617000 tons of rigid plastics containers were recycled in 1997, representing a growth around 4.1% over the previous year.



At the end of their first life cycle, or perhaps after being re-used several times, polymers can be recycled to yield new polymeric materials or products. The following are options that exist for recycling plastics:

- Mechanical recycling : Recycles plastics back into usable materials
- Chemical recycling: Recycles plastics back into fuels
- Energy recovery: Recovers energy from plastics ”(Azapagic, Emsley & Hamerton, 2003, pp 2-9 )

Recycled plastics lose some amount of their properties during the mechanical recycling process. However, advancements in mechanical recycling technologies have helped recycled plastics to retain much of their properties. Integrigo Composites LLC has developed one such patented recycling method for retaining properties of recycled plastics and converting them into a usable, compression-molded material.

While recycled plastics have properties which are good enough for many applications, there has not been an effort to carefully characterize the specific mechanical properties of recycled plastics (including those that are recycled using the thermo-kinetic method). An attempt has been made in ‘Recycling Technologies of Plastics for an End-Use- of –Life Washing Machine (Gotoh, T, Sumida. Y, Fukushima. Y et.al: Shapu Giho / Sharp Technical Journal) to estimate mechanical properties of recycled plastics. The results revealed that the tensile and fatigue strength characteristics of recycled material sustain approximately 90% of those of a virgin material.

However, a thorough investigation, including finding commercial applications for recycled plastics, has not been done.

## **1.1 PROBLEM STATEMENT**

We know that plastic is light, easy to store and transport, comes in an endless variety of textures and shapes and can hold almost anything. Also, mechanical properties of these plastics can be modified to suit the needs of critical applications by compounding these plastics with other chemicals. Those properties make it attractive to designers, manufacturers and packagers, who use it for anything from plastic bearings to ketchup bottles. However, modifications of properties pose challenges of frequent testing of material properties, standardization of material properties and frequent product testing.

As recycling of plastics becomes inevitable for sustainable development, the challenges associated with virgin plastics as mentioned above, are also the challenges with recycled plastics. In fact, the challenges become more relevant in recycled plastics as their properties are usually not as good as their virgin counter parts. It is known that plastics will lose some amount of properties, but it is difficult to know what amount of properties will be lost.

Recycling of plastics using the thermo-kinetic process is under review to better understand what happens to the material properties of plastics as they are processed into products. Several methods for testing and characterizing have been developed to do this. Testing to understand materials and products is essential in learning structure, behavior, suitability in commercial product applications and behavior in structural product applications. These features determine the strength or weakness of the product.

The following are important challenges related to thermo-kinetically recycled materials apart from processing which makes recycling difficult and expensive:

- Inadequate material properties information for various recycled plastics and blends
- Insufficient information regarding structure-property relationship of different blends
- Need for standardized mechanical properties to use in engineering analysis
- Lack of guidelines for using recycled plastics and their blends in commercial products
- Expensive product testing

What is needed is a faster, cheaper, more reliable way to test new theories regarding thermo-kinetically recycled materials and products made from them. Finite element modeling and statistical techniques are the methods that will help determine which properties should undergo further real-world testing for validation and analysis.

A review of the literature showed that very little work has been done in modeling the performance of parts made from recycled plastics. Therefore, a model will be developed and tested as a part of this thesis work.

In addition to the above, not many guidelines exist that will tell us about the suitability of using recycled plastics blends in commercial applications. A statistical approach can help by establishing necessary guide lines. This also makes it imperative that statistical guidelines include the range of possible tensile properties and corresponding deflections of recycled plastics under loading conditions.

## 1.2 OBJECTIVE OF RESEARCH

Every time thermo-kinetically recycled plastics blends are tested, properties such as elastic modulus differ. This makes the process of evaluating suitability of a material for commercial applications difficult. In order to address this problem, we must apply statistics to establish an acceptable range of properties, falling within the range lets the recycled plastics blend to be considered for products.

Finite element analysis (FEA) can be used to simulate closely the conditions of actual product testing. The fidelity of the FEA model depends on the how well the CAD model resembles the actual product, the type of meshing, and the ability of the pre-processor and post-processor of the finite element software.

The properties of recycled plastic blends vary significantly and the objective of this research is to account for this statistical nature. Since FEA software considers only elastic modulus and Poisson's ratio for finding deflection and stress, the statistical nature of recycled blends can only be taken into account by considering two values for elastic modulus. The mean value and a lower limit value for modulus are the two values considered since most of the values of elastic modulus of recycled plastic blends fall between these two values. The mean value of elastic modulus can be obtained by assuming that the elastic modulus values obtained by tensile testing of ten specimens of each recycled plastic blend are normally distributed (same for lower limit of modulus too). Then lower limit (mean -  $3\sigma$ ) of the elastic modulus for each of recycled blend can be calculated. The  $\sigma$  value in the calculation of lower limit of modulus for each recycled plastic blend can be calculated by sample standard deviation of elastic moduli and using

central limit theorem of statistics ( $\sigma = \text{sample standard deviation}/\sqrt{\text{sample size}}=10$ ). Then, FEA will be carried out to find respective deflections and stress distribution.

### 1.3 METHODOLOGY

For this research there are six different blends of recycled plastics available. The different blends are listed as follows:

- Pop bottles made of PolyethyleneTeraphthalate (PET), milk jugs made of High-Density Polyethylene (HDPE)
- Vinyl seats made of Poly Vinyl Chloride (PVC) and small amount of Polypropylene (PP) and Urethane (TPU)
- Electronic scrap made of engineering resins like Acrylo-Nitrile-Butadiene Styrene (ABS), Polystyrene (PS) and Polycarbonate (PC)
- Agriculture waste consisting of Low Density Polyethylene (LDPE)
- Industrial waste consisting of Nylon (PA66) and PolyethyleneTeraphthalate (PET)
- House hold waste consisting of Polystyrene

The work plan has three phases for each of the six blends:

1. Density, Tensile and Impact testing of each blend
  - Careful Density, Tensile and Impact testing to assure repeatable results
2. Comparison of mechanical properties of recycled plastic blends to corresponding virgin plastic blend
  - Density, Yield stress, and elastic modulus as percentage of corresponding properties of virgin plastic blend
  - Normal distribution approach to statistical nature of recycled plastic blend

3. Finite element analysis of the service performance of a product made from each thermo-kinetically recycled plastic blend
  - Develop a product design of a pallet using CAD, then determine service loading conditions
  - Analyze the response in terms of deflection and ratio of yield stress to maximum von Mises stress of the product to service loading
  - To determine suitability of each recycled plastic blend in commercial applications

## **1.4 DELIMITATIONS**

This research will focus only on finding suitability of the six different blends of thermo-kinetically recycled plastics for a molded pallet supplied by Integrigo composites LLC. For characterizing material properties of Integrigo composites LLC supplied materials, only density, tensile and impact tests will be done. Design of the pallet will be done in Solid Works and then imported into CATIA for FEA. Finite element analysis will be done using CATIA.

The use of a normal distribution for establishing an acceptance limit for recycled plastics materials assumes that the values of elastic modulus for a material, obtained by testing are normal random variables and satisfy all the conditions that are necessary for the same.

This study will take only default values of meshing supplied by CATIA and compression load as loading condition for finite element analysis. The qualification of

thermo-kinetically recycled material for commercial application will be done based on deflection and ratio of yield stress to maximum von Mises stress obtained from FEA.

## **CHAPTER 2**

### **BACKGROUND AND REVIEW OF LITERATURE**

#### **2.1 INTRODUCTION**

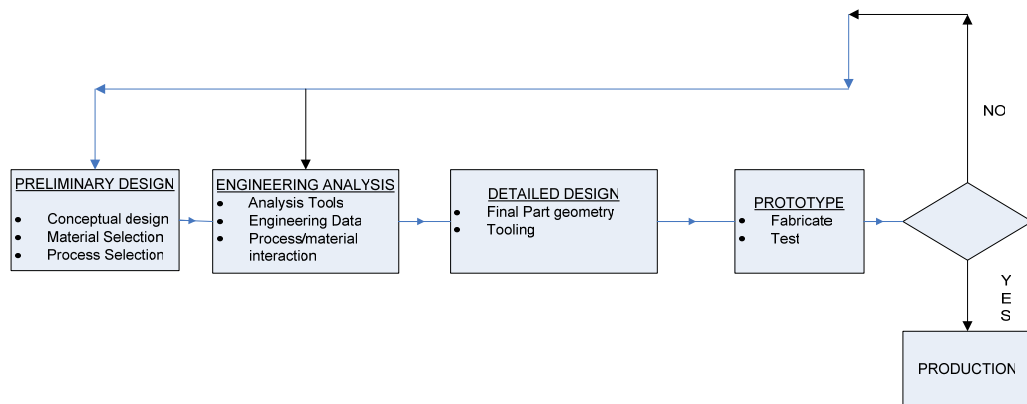
“Increasingly, [recycled] plastics materials are considered for use in load bearing components, and the ability to apply mechanical analysis effectively to design for performance continues to grow in importance. In order to foster this technology growth, issues specifically relevant to the mechanical behavior and analysis of [recycled] plastic parts must be identified, approaches for handling these issues defined and experience in their effectiveness documented.

Whenever a new class of materials enters engineering use, there is a necessary period of technology development and adjustment before a well-structured and logical process of design with such materials reaches maturity. Before such a logical process can evolve, several more fundamental developments must occur. For example the elemental structure of the material must be well understood in order to facilitate material invention and fundamental evolution. Furthermore the processes used for forming the material into useful shapes must become routine and well controlled, and an understanding of the relationship between the material’s morphology and its mechanical properties must also be developed. As these technologies mature, it becomes possible to recognize that the



material's properties and manufacturing processes offer specific advantages for achieving the functional requirements of a part. Out of these technologies arises a framework for conceiving potential approaches for application of the material and manufacturing processes to achieve functional goal.

If after sufficient development of these fundamental technologies, materials evolve with mechanical properties sufficient to consider their use in load-bearing application, then engineering design will be required to determine the necessary size and shape of the part to achieve the required level of performance. That process is greatly facilitated if the material properties necessary to define engineering performance of a component are well defined and there are accurate analytical procedures available for application of the properties to define geometry. Once these quantitative methodologies are in place, the ability to understand mechanical behavior and to identify the most effective use of the material is significantly enhanced. Without their presence, the only alternative is a time-consuming and costly approach of trial and error” (Trantina and Nimmer, 1994, pp 1-2).



*Figure 2.1* Design engineering process  
(Trantina, Gerry, and Nimmer, Ron, 1994, pp-14).

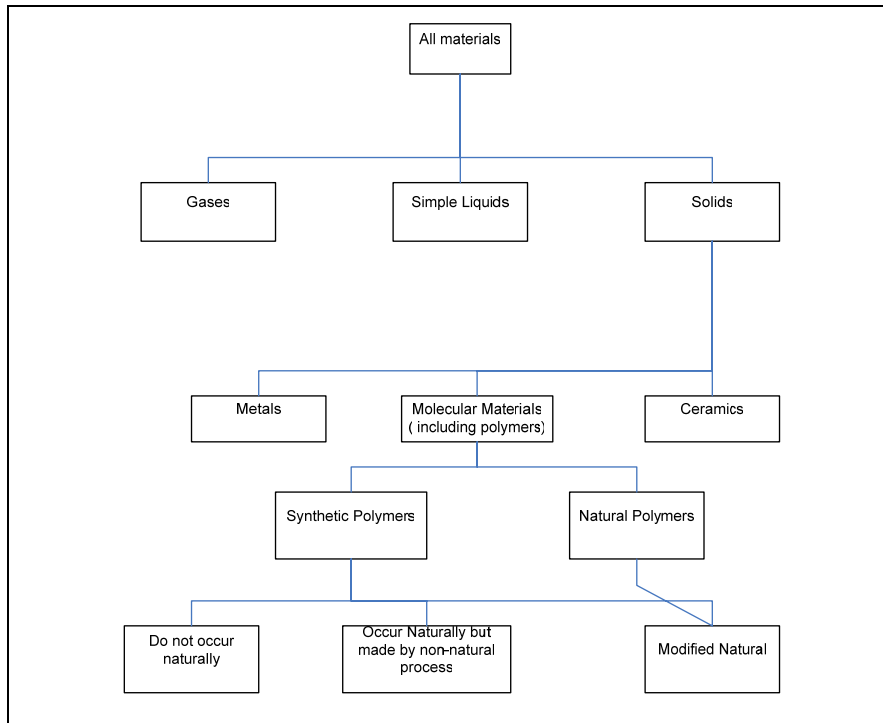
Thus, the primary purpose of this literature review is to summarize various researches done in the field of recycled plastics materials, material morphology, and structure property relationship, manufacturing processes, design and finite element analysis.

A background review of literature pertaining to this study includes a search of holdings in the Harold B. Lee Library at Brigham Young University in Provo, Utah, the Compendex Engineering Database, Society of Plastics Engineers Database, and the Academic Search Elite (EBSCO) database. In addition to the literature search done at the library, information for this study was gathered from Internet searches and several articles were also obtained through interlibrary loan.

Even though the majority of existing research on recycled plastics does not directly relate to this research, many articles with peripheral information will aid the reader in understanding this research and are reviewed for this study.

## **2.2 DEFINITION, CLASSIFICATION AND SOURCE**

“All plastics are polymers but all polymers are not plastics” (Central Institute of plastics engineering and Technology, 1999). “Plastics are materials composed principally of large molecules (polymers) that are synthetically made or, if naturally occurring, are highly modified” (Strong, 2006, p1). This definition of plastics can be illustrated in a systematic classification diagram as shown in Figure 2.2 (Strong, 2006, pp1).



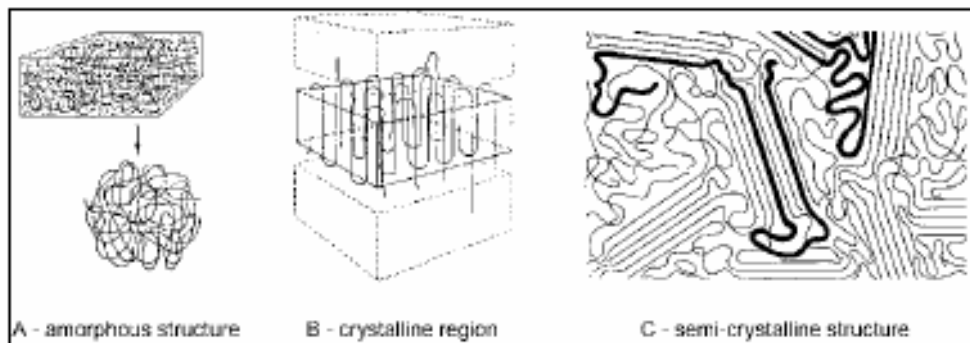
*Figure 2.2* Classification of plastics  
(Strong, A. Brent, 2006, p1)

Plastics are further divided into two categories depending on how they behave when they are subjected to heat. They are:

- Thermoplastics: plastics that can generally be safely processed several times by melting and shaping the melt and the final product are obtained by cooling (Azapagic, Adisa & Hamerton, 2003, p19).
- Thermosetting plastics: plastics that can be processed only once and will cure on heating (which is an irreversible reaction) to form cross-links (resulting in a three dimensional network) (Azapagic, Adisa & Hamerton, 2003, p19).

Thermoplastics can be divided into two categories depending on their structure:

- Crystalline plastics: “[contain] polymer chains that exhibit an ordered molecular structure. The term crystalline is actually a misnomer since crystalline plastics are actually only semi-crystalline in nature. They have regions of ordered molecular structure and also have regions of no order or form (amorphous). Crystalline plastics have more temperature-dependent mechanical properties than amorphous plastics.
- Amorphous plastics: In contrast to semi crystalline plastics, amorphous plastics are composed of randomly oriented polymer chains and do not exhibit any ordered molecular structure. Amorphous polymers rely on increased polymer chain lengths (higher molecular weight) and physical entanglement of those chains for structural integrity” (Trantina and Nimmer, 1994, p 15-16).



*Figure 2.3* Amorphous and crystalline structure of thermoplastics.  
(Spoomaker)

Thermo plastics can also be categorized into three groups. They are:

- Commodity plastics: are used in house hold applications and have lower mechanical properties such as Young's modulus
- Engineering plastics: are used in engineering applications such as structural components and have better mechanical properties compared to commodity plastics. These are the materials that play major role in replacing metals and are important for this thesis.
- Specialty plastics: These are used in specialized applications demanding higher mechanical properties than engineering plastics, such as aerospace and high temperature applications.

The definition and classification of recycled plastics (thermoplastics) is similar to aforementioned virgin plastics (thermoplastics) classification.

“Post-consumer plastic wastes can be divided into two different groups depending on their source:

- Mixed plastics from household waste and
- Plastics from the industrial sectors

The first category involves medium or short life articles that are used in such products as food, pharmaceutical, and detergent packaging. The majority of these articles are composed of thin protective films: a variety of bottles for soft drinks, food and cosmetics, sheeting for blisters (packaging), strapping and thermoformed trays.

There are five different plastics that contribute to the total amount of domestic plastic waste, namely, polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET) and polystyrene (PS). The blend of this mixed plastic

waste (MPW) can change depending on the regional habits and seasons of a year, and also on the mode of waste collection. A typical blend may be PE 39%, PVC 22%, PET 19%, PS 8% and PP 12% (by weight).

Polyethylene, polypropylene, blends of polypropylene with elastomers and polyethylene terephthalate (PET) are the most frequently recycled polymers obtained from industrial plastics wastes” (Chanda and Roy, 1998, 950-956).

Recycled plastics can also be divided into two categories as homogeneous fraction and mixed plastics waste, depending on number of plastics present.

### **2.3 ESSENTIAL FACTORS FOR MECHANICAL PROPERTIES OF RECYCLED PLASTICS**

Four essential factors that can be used to improve the mechanical properties of recycled plastics are:

- Crystallization (crystallinity) (ordered molecular structure)
- cross-linking
- increasing inherent stiffness of polymer molecules
- increasing melt flow index (molecular weight)

Combination of any two or all of the four essential factors have proved effective in achieving various properties with virgin plastics. For recycled plastics composed of inherent flexible chains, crystallization and cross-linking are the only available means to enhance properties (Chanda and Roy.1998, p46-48).

Crystallites (crystallinity) promote rigidity, hardness, and heat resistance [on the other hand amorphous regions give rise to flexibility of polymer chains] (Chanda and Roy, 1998, p25). In recycled plastics the amount of crystallinity is usually less than that of virgin plastics.

“The structure of polymer chains present in the cross-linked polymer is similar to the wire structure in a bed spring, and chain mobility, which permits one chain to slip by another, is prevented. For example cross-linking by sulfur at about 5% of the possible sites gives rubber enough mechanical stability to be used in automobile tires still enables it to retain flexibility. Introducing more sulfur introduces more cross-links and makes rubber inflexible and hard” (Chanda and Roy, 1998, p 46-48) (which will have greater tensile strength but elongation at break will be less). This is true for virgin and recycled plastics as well i.e., cross-linking to some degree will give good mechanical properties and flexibility, increased cross-linking will make plastics inflexible and hard, except that cross-linking can be brought about by different means other than sulfur.

Increasing the inherent stiffness of polymer molecules is advantageous because absence of crystallinity makes the material completely transparent, and the absence of cross-linking makes it readily moldable.

The melt flow index (MFI) is a measure of molecular weight and molecular weight distribution characteristics of plastics in industry. If the melt index for a particular blend is a larger number, which means the material flows easily that plastic will have shorter chains and therefore low molecular weight (Strong, Brent, 2006). The opposite is also true. A low melt index means longer chains and high molecular weight. MFI values in combination with crystallinity (small value of MFI and high % of crystallinity in

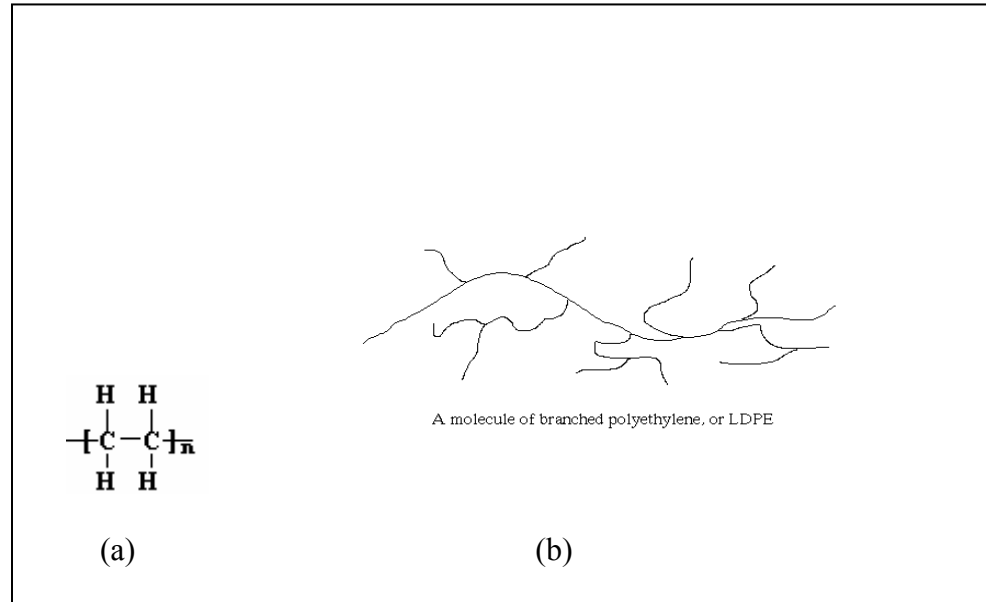
recycled plastics means, polymer chains are closely packed with long polymeric chains) would help in deriving meaningful conclusions about the structure of recycled plastics materials.

“[One of] the possible routes to recycling of mixed plastic waste (MPW) to obtain secondary materials with acceptable mechanical properties could be to blend them with virgin polymers, or at least with recycled homopolymers (polymers having same similar type of monomers repeating in polymeric chain). For example, experimental results (La Mantia, 1992, 37: 145) of processing and properties of blends of virgin LDPE and MPW have shown that all mechanical properties, with the exception of elongation at break, are very similar to those of the virgin material if the MPW content doesn't exceed 50%” (Chanda and Roy, 1998 , p 951).



## 2.4 RECYCLED PLASTICS

### 2.4.1. Low Density Polyethylene (LDPE)



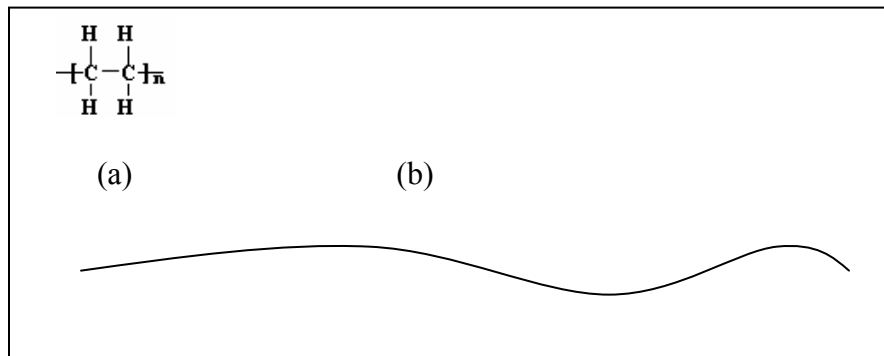
*Figure 2.4* (a) General formula of PE (b) a molecule of branched PE or LDPE  
(Source: Macrogalleria)

In its virgin form, LDPE also known as ‘linear’ or ‘flexible’ PE contains a high level of side branching with long side branches (Azapagic, and Hamerton, 2003, pp52-53, 57-58). As the name suggests LDPE has low density (0.92 g/cc) which is caused by low degree of crystallinity and this is related to the high level of side branching with both short and long chain branches. LDPE has crystallinity typically below 40% and its structure is predominantly amorphous (Strong, 2006, p229). It is tough, but has moderate tensile strength (Brydson, 1995, p212) [10MPa (Azapagic, and Hamerton, 2003, pp52-53, 57-58)] among polyethylenes and low tensile strength compared to other commercial

thermoplastics [170 MPa (Azapagic, and Hamerton, 2003, pp52-53, 57-58)]. The low tensile strength of LDPE is due to side branching which results in fewer intermolecular attractions exist in the open structure, and therefore, the energy that allows the molecules to move independently is lower (Strong,2006,p228-229). Thermo-kinetically recycled LDPE retains about 93% (0.856 g/cc) of density and 84% - 100 % ( 8.4 – 13 MPa) of the tensile strength compared to virgin material (Brough, 2001, p51-55). The exact reason for the loss is not known as further research needs to be done to determine the structure of thermo-kinetically recycled LDPE plastics.

However, the loss of density and tensile strength can be attributed to molecular rearrangement during thermo-kinetic recycling process along with branching (Fann, Chang, Hsieh, Huang and Yih Lee Jiunn, 1996, 61, 1375-1385). In addition to the above, the loss in density and tensile strength can also be attributed to chain scission of the polymer upon recycling (smaller chains mean more branching and less intermolecular forces and hence low density and tensile strength).

## 2.4.2. High Density Polyethylene (HDPE)



*Figure 2.5* (a) General formula of PE (b) a molecule of linear PE or HDPE  
(Source: Macrogalleria)

A polyethylene (PE) polymerized under low temperature and pressure will result in more linear structure with only a few, short branches. This type of PE is called high-density polyethylene (HDPE) (Strong, 2006, pp 229-230).

As the name implies polymer chains in HDPE can easily pack tightly and form crystalline structures, thus increasing density (0.96 g/cc)". In a general sense, crystallinity and density increase with molecular weight due to increase in chain length (Strong, 2005, p 234).

An increase in molecular weight increases mechanical properties such as tensile strength and impact strength (Chanda and Roy, 1998, pp 3-4). In general HDPE is stiffer, and stronger (28MPa) than LDPE (10MPa) [(Azapagic, and Hamerton, 2003, pp52-53, 57-58)]. The degree of crystallinity of post consumer recycled (PCR) HDPE increases initially as material is recycled, but decreases significantly after four extrusion cycles

(Doyon, Carreau and Vergnes, 1994, pp 2876). The loss in crystallinity of PCR HDPE (copolymer) can be as much as 10 % (Zahavich, Takacs, and Viachopoulos, 1995, p2052) per cycle. The reasons for this phenomenon can be attributed to chain scission and cross-linking degrading mechanisms.

In addition to the above, the processing steps used in recycling of HDPE (milk bottles) can individually alter the degree of crystallinity in the material; however, the net effect on the crystallinity of the final product is less or negligible. If both chain-scission and cross-linking occur during the processing and recycling of HDPE, the final molecular structure may be very different from the parent material. Even though the degree of crystallinity will remain the same, the crystals and the link between crystals may be stiffer due to cross-linking in recycled HDPE (Herzberg, and Hornberger, 1998).

The Differential Scanning Calorimetry (DSC) results of HDPE show decrease in percentage crystallinity and there is an increase melt flow index (Baquero, Moreno, Ichazo, and Sabino, 2002) (please refer to the following tables 2.1-2.2-2.3-2.4). These results show that there is a change in the structure of recycled HDPE. To be specific, recycled HDPE contains polymer chains that are smaller (lower molecular weight) obtained by chain-scission during the recycling process (there may be cross-linking too). However, an increase in elastic modulus compared to the virgin material can be attributed to cross-linking of polymer chains.

Table 2.1 shows density, glass transition temperature and crystallinity values of recycled plastics (PP, HDPE, PVC, PET and PS). Table 2.2 shows melt flow indices of post consumer (p-c), post industrial (p-ind) and virgin plastics obtained from material testing.

Table 2.1

*Density, Glass transition temperature, crystallinity values of recycled plastics*  
(Braton.1980, Green and Petty.1998)

Resin	Density (g/cm <sup>3</sup> )	Glass Transition Temp. (C)	Fracture at Cryogenic Temp.	Brittle Temp. (C)	Crystallinity	Polarity
PP	~0.90-0.91	-20	Fractures	< 20	High	Low
HDPE	~0.94-0.97	-122	Difficult to Fracture	~-150	High	Low
PVC	~1.32-1.40	75	Easy to Fracture	~-20	Low	Polar
PET	~1.33-1.42	79	Difficult to Fracture	—	Intermediate	Polar
PS	~1.04-1.07	100	Fractures	~ 90	Low	Nonpolar

Table 2.2

*MFI values obtained from material testing*  
(Baquero, Moreno, Ichazo, and Sabino, 2002)

Material	MFI (g/10m in)
HDPE (P-C)	1.59 ± 0.48
HDPE (P-IND)	0.88 ± 0.14
HDPE (VI)	1.03 ± 0.23
PP (P-C)	5.77 ± 0.48
PP (VI)	3.20 ± 0.32
PET (P-C)	62.04 ± 2.41
PET (P-IND)	57.93 ± 3.80
PET (VI)	63.27 ± 3.23

Table 2.3 shows crystallization and melting temperature values obtained from DSC thermograms of tested materials, % crystallinity values calculated from enthalpies of fusion in the second heating and table 2.4 shows mechanical properties for post consumer, post industrial and virgin HDPE, PP and PET materials.

Table.2.3

*Crystallization and melting temperature values obtained from DSC thermograms of tested materials, % crystallinity values calculated from enthalpies of fusion in the second heating*

(Baquero, Moreno, Ichazo, and Sabino.A.Marco, 2002)

M uestra	Tc (°C)		Tm (°C)		% Crist.
	Onset	Pico	Onset	Pico	
HDPE (P-C)	124.0	119.5	118.4	131.2	60
HDPE (P-IND)	123.6	119.9	118.7	129.7	59
HDPE (VI)	123.3	117.5	118.6	133.5	60
PP (P-C)	130.2	124.9	139.5	155.1	27
PP (VI)	125.4	120.7	122.5	148.2	34
PET (P-C)	199.2	192.1	230.8	246.0	29
PET (P-IND)	205.4	196.5	242.5	253.9	31
PET (VI)	196.9	183.8	235.1	247.0	32

Table 2.4

*Mechanical characterization results for Tested polymers*

(Baquero, Moreno, Ichazo, and Sabino.A.Marco, 2002)

M uestra	E (MPa)	$\sigma_y$ (MPa)	$\epsilon_y$ (%)	$\sigma_r$ (MPa)	$\epsilon_r$ (%)
HDPE (P-C)	234.3 ± 26.2	23.7 ± 0.5	16.5 ± 1.2	13.3 ± 0.6	78.1 ± 6.5
HDPE (P-IND)	272.6 ± 24.0	23.9 ± 0.6	14.9 ± 0.4	14.3 ± 1.0	218.1 ± 21.8
HDPE (VI)	175.4 ± 21.6	24.8 ± 0.5	23.9 ± 1.6	32.7 ± 0.7	550.2 ± 23.4
PP (P-C)	254.8 ± 16.6	29.4 ± 0.4	18.0 ± 0.7	25.3 ± 1.8	284.6 ± 18.0
PP (VI)	204.7 ± 8.9	24.7 ± 0.7	19.4 ± 0.8	35.2 ± 1.4	442.5 ± 31.0
PET (P-C)	7459.4 ± 384.1	555.9 ± 33.1	10.9 ± 0.5	585.9 ± 36.3	197.0 ± 17.2
PET (P-IND)	7180.7 ± 259.9	559.8 ± 29.3	13.6 ± 0.3	406.4 ± 17.2	140.8 ± 12.6
PET (VI)	6000.7 ± 87.9	533.4 ± 19.8	11.8 ± 0.5	476.2 ± 19.4	195.2 ± 7.2

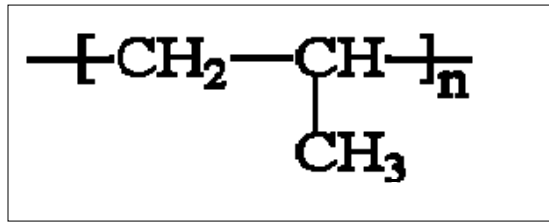
E = Young's modulus

P-C = post consumer

P-IND= Post Industrial

VI = Virgin

### 2.4.3. Polypropylene (P.P)



*Figure 2.6* Structure of PP  
(Source: Macrogalleria)

The repeating unit for polypropylene (PP) (virgin) is shown in [Figure 2.6]. The presence of a pendant  $\text{CH}_3$  group allows the formation of three different types of PP molecules. These types of molecules are called stereoisomers. These stereoisomers differ in the way the atoms are spatially arranged about the backbone of the carbons. Important among three different types of PP is ‘isotactic PP’. In the isotactic configuration, the pendant group is always attached to the tertiary carbon atom (Strong, Brent) (the carbon atom which has three other carbons attached to it) on the same side. “This results in a very regular structure( This arrangement can be compared to a line of people who are all facing the same direction, each holding a balloon in his/her right hand). Only isotactic arrangement allows the molecules to pack tightly into crystalline structures. The only PP of commercial importance is highly crystallized isotactic arrangement (Strong, 2006, p239).

PP and HDPE have similar properties and compete for many of the same applications. However PP differs from HDPE in a number respects of which the following are among the most important (Brydson, 1995, p245):

- It has lower density (0.9 g/cc)
- It is stiffer than HDPE and
- It has higher glass transition temperature and melting temperature.

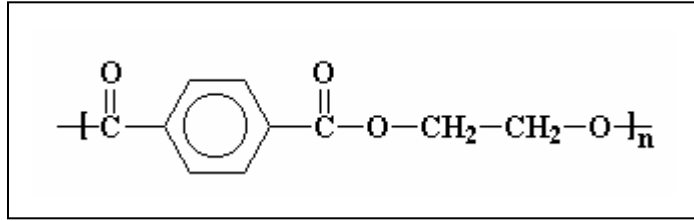
The influence of molecular weight on mechanical properties of PP is often opposite to that experienced with most other well known polymers. An increase in molecular weight leads to an increase in melt viscosity and impact strength, but leads to a lower yield strength, lower hardness, lower stiffness and lower softening point. The effect is believed to be due to the fact that a high molecular weight polymer doesn't crystallize so easily as lower molecular weight material and it is the difference in the degree of crystallization which affects the bulk properties.

The Differential Scanning Calorimetry (DSC) results of recycled PP show decrease in percentage crystallinity and increase in melt flow index (Baquero, Moreno, Ichazo, and Sabino.A.Marco, 2002) (please refer to the tables 2.1-2.2-2.3). These results show a change in structure of recycled PP. To be specific, recycled PP contains polymer chains that are smaller (lower molecular weight) obtained by chain-scission during recycling process (may be cross-linking too). An increase in mechanical properties like modulus of recycled PP compared to virgin material can be attributed to cross-linking of polymer chains by chain scission.

In order to improve mechanical properties of recycled PP to be used in structural applications, it is blended with HDPE and paper (80% of PP, 20% of HDPE and 30% of paper). The blending improves mechanical properties by about 63% (of [43 MPa] higher value of tensile strength range) and 68% [1551 MPa] of modulus of virgin mixture of same blend (Farahmand, 2001, 80: 2573-2577).



#### 2.4.4. PolyethyleneTeraphthalate (P.E.T)



*Figure 2.7* Structure of PET

(Source: Macrogalleria)

PET, in its virgin form, is a colorless, rigid crystalline polymer (density range: amorphous molding- film or fiber= 1.3 -1.38 g/cc) stemming from the high degree of structural regularity that may be present, depending on the processing steps undertaken during preparation, such as extrusion and drawing. The properties that particularly characterize PET are very high mechanical properties (tensile strength range: amorphous molding- fiber= 55 - 690 MPa), good toughness and shatter resistance and barrier resistance [(Azapagic, and Hamerton, 2003, pp52-53, 57-58)].

Recycling of blow molded PET bottles (by extrusion pelletizing and then injection molding into tensile specimens) subjected to thermal cycles of the processes has a positive effect on crystallization (also on structure of PET) as indicated by dynamic cooling crystallization of the DSC and in turn on mechanical properties(Fann,Huang and Lee(1996),61,1375-1385). The reason is that secondary bonds between chains are attacked rather than decreasing the chain length of recycled PET(R-PET) subjected to thermal cycling, retaining less amorphous structure (more crystalline structure). For semicrystalline polymers, most mechanical properties depend critically on crystallinity (McCrum, Buckley, and Bucknall (1988) and F. A. Bovey and F. H. Winslow (1979)).

The tensile property of R-PET from the following table 2.5 is 61 Mpa (or 623 kg/cm<sup>2</sup>), which is greater than the tensile strength of virgin amorphous PET molding material (55Mpa) (Azapagic, Adisa & Hamerton, 2003, pp52-53, 57-58). An increase in crystallization (and mechanical properties) of R-PET is also indirectly indicated by increase in melt flow index (MFI) (Baquero, Moreno, Ichazo, and Sabino.A.Marco, 2002).

Table 2.5 shows tensile strength of various blends of recycled PET and engineering PET

Table 2.5

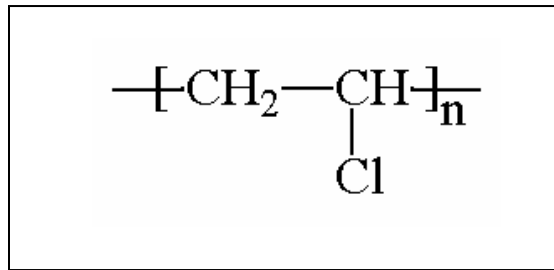
*Tensile strength of R-PET*

(Fann, Huang and Lee (1996), 61, 1375-1385)

Property	E-PET R-PET	100 0	80 20	50 50	20 80	0 100
Tensile (kg/cm <sup>2</sup> )	653	684	672	653	623	
Elongation (%)	20	264	187	190	295	
Impact (kg-cm/cm)	1.10	4.97	3.58	3.32	3.70	

E-PET = Engineering PET, R-PET = recycled PET

### 2.4.5. Polyvinyl Chloride (P.V.C)



*Figure 2.8 Structure of PVC*  
(Source: Macrogalleria)

Polyvinyl chloride in its virgin form is a clear or white flake or powder. The chlorine atom prevents close packing of the polymer and also provides a solvent sensitivity not seen in PE or PP because of high electro-negativity of the chlorine. PVC is available in two forms,

- Rigid PVC or unmodified PVC
- Plasticized PVC (solvent-modified) or vinyl

Compared to PE and PP, rigid PVC is more rigid and is stronger. The crystallinity of rigid PVC (density= 1.4 g/cc) is less than 10%. Intermolecular interference and polarity of Cl atom results in intermolecular attractions, thus increasing tensile strength (59Mpa) and modulus compared to PE (10-28 Mpa) and PP (28Mpa) (Azapagic, Adisa & Hamerton, 2003, pp52-53, 57-58).

Plasticized PVC (density= 1.31 g/cc) on the other hand, is flexible and has lower tensile strength (19MPa (Azapagic, Adisa & Hamerton, 2003, pp52-53, 57-58)) compared to rigid PVC (Strong, 2006, p242-247).

Pulverized recycled PVC powder obtained from PVC bottles containing small amount of PET and PE as impurities, has shown to have tensile and fatigue strength

similar to virgin materials. However, a decrease in strain to failure and Environmental Stress Crack Resistance (ESCR) can be attributed to the presence of impurities. Molecular weight distribution has shown no significant difference between recycled material and virgin material. However it can be noted that molecular weight distribution of pulverization of recycled PVC results in chain scission (Maund and Arnold, 1990).

Table 2.6

*The average ultimate tensile strength and standard deviation for samples tested at a strain rate of  $2.5 \times 10^{-3} \text{ s}^{-1}$*

(Maund and Arnold, 1990)

Material	Average UTS (MPa)	Standard Deviation (MPa)
Virgin	49.2	1.42
Bottle flake	52.0	0.84
Recycled powder	51.3	11.7
Recycled flake	32.6	1.19

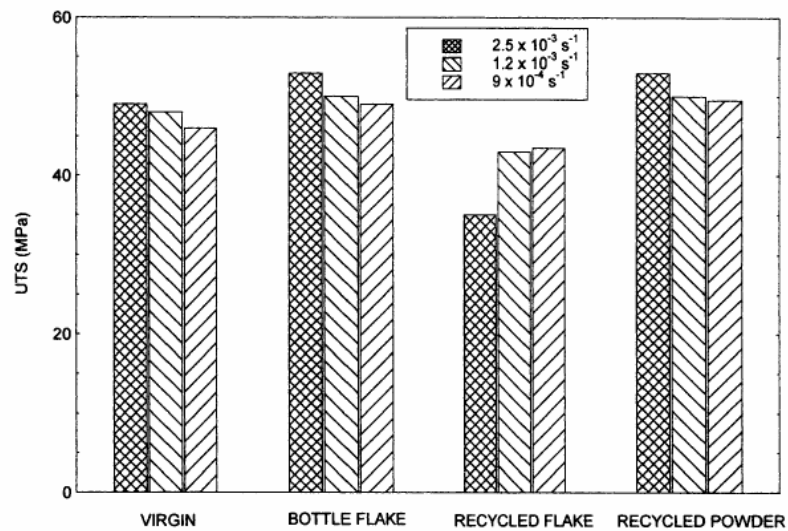
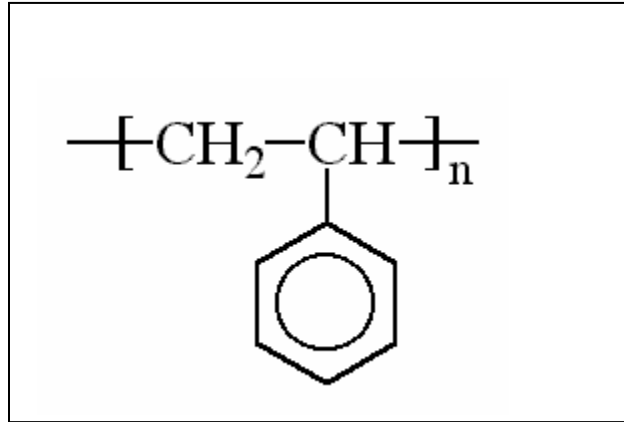


Figure 2.9 The average ultimate tensile strength studied at the strain rates indicated (Maund and Arnold, 1990).

### 2.4.6. Polystyrene (PS)



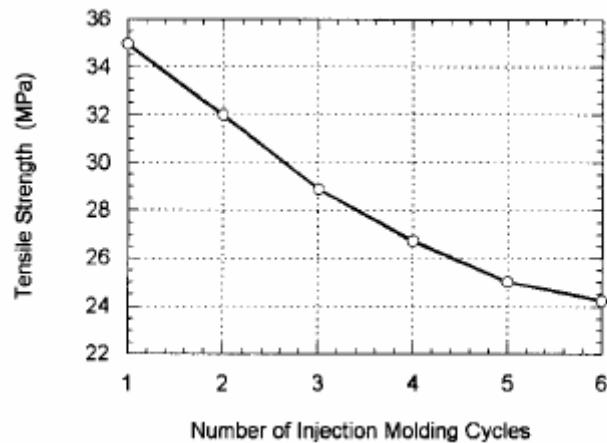
*Figure 2.10* Structure of Polystyrene  
(Source: Macrogalleria)

Polystyrene repeating unit is as shown in Fig: 2.10. The size of the pendant group is much larger than any of the other pendant groups (hydrogen, CH<sub>3</sub>, or Cl) associated with other commodity resins. “The benzene ring reduces the ability of the polymer chain to bend and interferes substantially with other parts of the molecule. These characteristics prevent crystallization and hence PS is 100% amorphous (density-PS general-Styrene acrylo nitrile (SAN) = 1.04-1.08 g/cc). The large aromatic ring not only prevents crystallization but also significantly increases tensile strength (42MPa), the cause being steric (shape) effect” (Strong, 2005, p 247- 248). The steric effect present in polystyrene is interference by the pendant groups on one chain with the movement of pendant groups of another chain. PS is quite brittle.

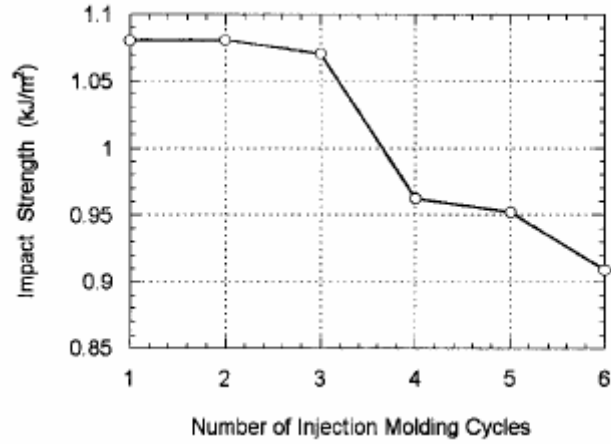
High impact polystyrene (HIPS) has more impact strength but has tensile strength (18MPa) lesser than that of rigid PS. ABS is a blend of PS containing butadiene rubber

and its properties (tensile strength= 37(high impact) – 40(medium impact) MPa) can be varied depending upon the application for which it's used.

A study on recycled expanded polystyrene (PS) (From table-2.1, density 1.04-1.07 g/cc), which was extruded and then injection molded into test specimens, shows that, the tensile strength decreased almost linearly with increasing the processing cycles. The tensile strength after one cycle was 35.0 MPa while the strength was reduced to 24.2 MPa after six cycles of injection molding (Fig. 2.11). The impact energy decreased drastically after three times of injection molding. The impact strength was reduced from 1.081 kJ m<sup>-2</sup> after one injection molding cycle to 0.909 kJ m<sup>-2</sup> after six (6) processing cycles (Fig. 2.12 ) Statistical testing showed that the changes in tensile strength and impact strength with increasing number of injection molding cycles were significant at a confidence level of 95% (Ciesielska,1998)

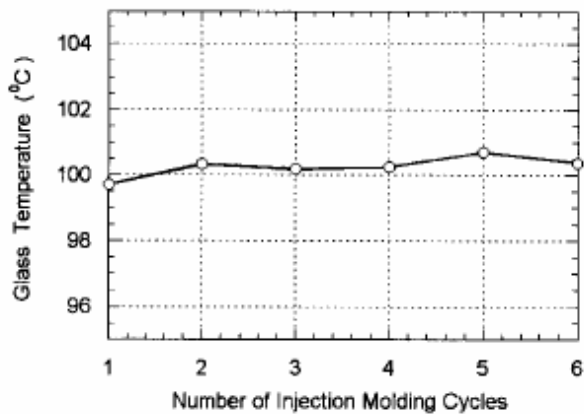


*Figure 2.11* Tensile strength of PS as a function of injection molding cycles (Ciesielska, 1998)



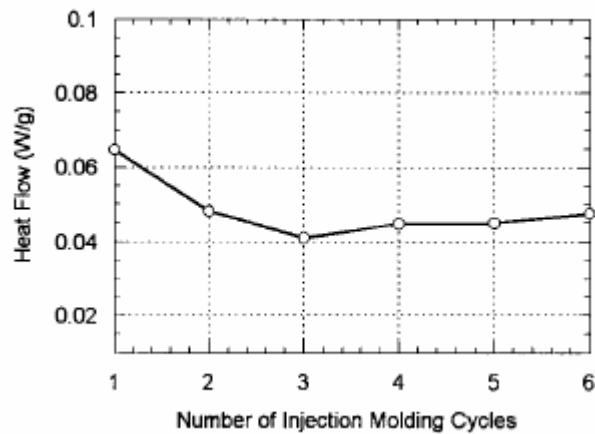
*Figure 2.12* Impact strength of recycled PS as a function of injection molding cycles (Ciesielska, 1998)

Durometer hardness of recycled polystyrene did not change significantly with number of recycling cycles. The glass transition temperature determined by DSC shows that, as the number of injection molding cycle is increased, the glass transition temperature increased (Fig.2.13).



*Figure 2.13* Variation of glass transition temperature of recycled PS with increasing of number of injection molding cycles (Ciesielska, 1998)

“(Fig.2.14) depicts the variation of heat flow at glass transition with the number of injection molding cycles for recycled PS. The heat of fusion decreased when the number of injection molding cycles increased. This fact suggests that the internal structure of the recycled polystyrene has been altered significantly due to the repeated processing or recycling” (Ciesielska, 1998).



*Figure 2.14* Variation of heat flow associate with glass transition of recycled PS with increasing of number of injection molding cycles  
(Ciesielska, 1998)

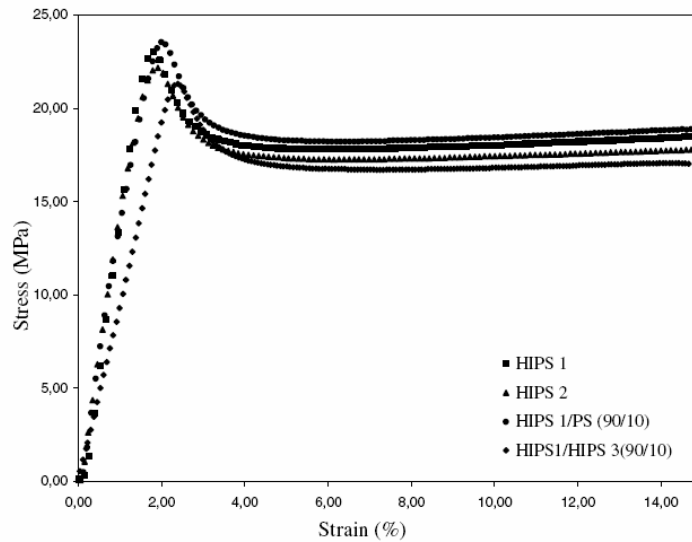
A study on 50/50 post consumer and post industrial recycled HIPS shows that neither mechanical properties nor melt flow index did change after recycling (Luna, Marcano, Marrero and Perera.Rosestela, 2004).



Table 2.7

*Different mechanical properties of 50/50 post consumer/post industrial HIPS*  
(Luna, Marcano, Marrero and Perera.Rosestela, 2004)

Materials	Young Modulus (MPa)	Tensile Strength (MPa)	Tensile Strain (%)	Yield Stress (MPa)	Yield Strain (%) $\pm 0.1$
HIPS <sub>1</sub>	1870 $\pm$ 123	20 $\pm$ 1	27 $\pm$ 2	24 $\pm$ 1	1,9
HIPS <sub>1</sub> /PS (90/10)	1812 $\pm$ 30	19 $\pm$ 1	19 $\pm$ 3	23.4 $\pm$ 0.4	2,1
HIPS <sub>2</sub>	1869 $\pm$ 184	17 $\pm$ 1	21 $\pm$ 4	22 $\pm$ 1	1,8
HIPS <sub>1</sub> /HIPS <sub>3</sub> (90/10)	1570 $\pm$ 386	17 $\pm$ 1	17 $\pm$ 3	21.7 $\pm$ 0.3	2,2



*Figure 2.15 Stress-Strain curve for post consumer/post industrial HIPS*  
(Luna, Marcano, Marrero and Perera,Rosestela, 2004)

Note: HIPS 1(Post consumer/Post industrial) = 50/50

Table 2.8

*Melt flow index value of 50/50 post consumer/post industrial HIPS*  
(Luna, Marcano, Marrero and Perera.Rosestela, 2004)

Material	MFI (g/10min)
HIPS <sub>1</sub>	3,5
10/90 PS / HIPS <sub>1</sub>	3,8
10/90 HIPS <sub>3</sub> / HIPS <sub>1</sub>	4,1
HIPS <sub>2</sub>	2,7
HIPS <sub>3</sub>	5
PS	7

The research involving granulated recycled ABS (99.9% purity) obtained from printer housing and compression molded into sheets to make tensile specimens, shows that, the mechanical property yield strength (37MPa) doesn't change appreciably compared to virgin ABS [Tensile strength: virgin ABS (high impact grade) = 37 MPa and virgin ABS (medium impact grade) = 40 MPa] exception to it would be recycled ABS with significant amount of impurities (Gupta and Liang, 2001)

However, impact strength (210 J/m) decreases with recycling [Izod impact strength: virgin ABS (high impact grade) = 400 J/m MPa and virgin ABS (medium impact grade) = 270 J/m] (Gupta and Liang, 2001)

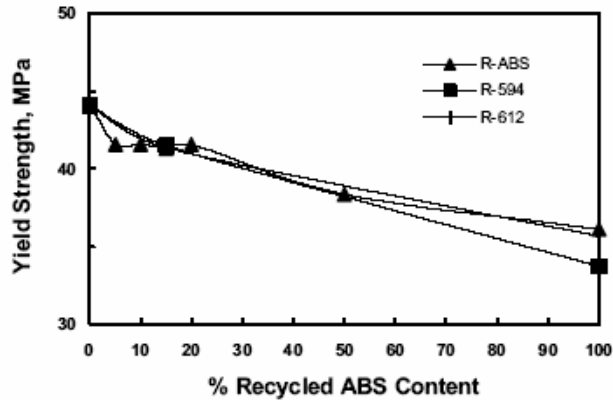


Figure 2.16 Effect of recycled ABS content and residual impurities on tensile yield strength  
(Gupta and Liang, 2001)

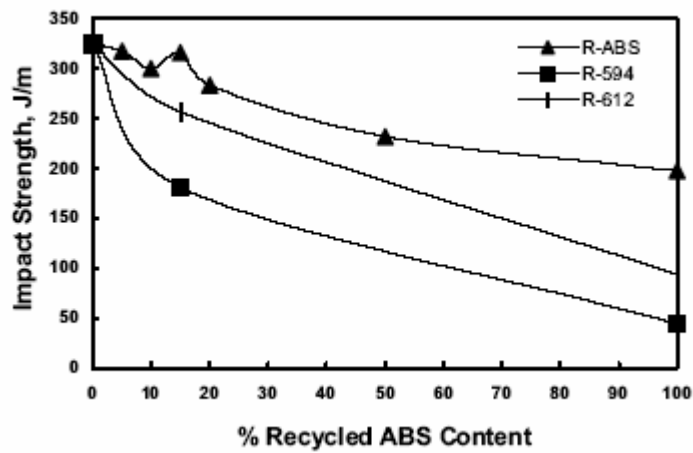


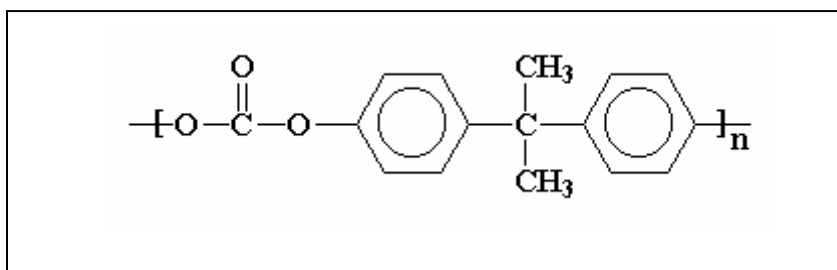
Figure 2.17 Effect of recycled ABS content and residual impurities on Izod impact strength  
(Gupta and Liang, 2001)

Table 2.9

*Recycled ABS with different purity level*  
(Gupta and Liang, 2001)

Recycled ABS I R-ABS	99.9%	No appreciable Contamination
Recycled ABS II R-594ABS	96%	HIPS 2.4% PPO + Nylon 1.3%
Recycled ABS III R-612ABS	88%	ABS-FR 9.8% HIPS 1.4% PC/ABS 0.2%

#### 2.4.7. Polycarbonate (P.C)



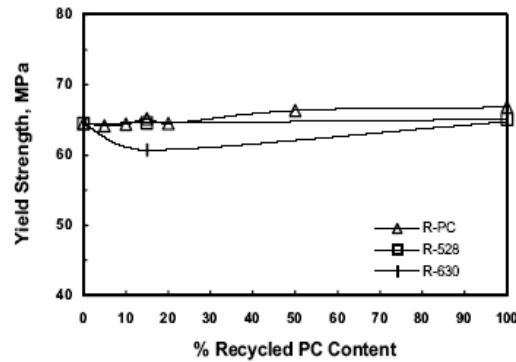
*Figure 2.18* Structure of Polycarbonate  
(Source: Macrogalleria)

The large, complex, aromatic structure of polycarbonate (density = 1.2 g/cc) determines the physical and mechanical properties of the molecule. Polycarbonate is non-crystalline yet is nearly as strong (tensile modulus = 2400 MPa and tensile strength = 64.5 MPa) as the highly crystalline nylon and acetal plastics and is some what tougher. This mechanical performance is due to the large aromatic content of the polymer, leading

to backbone stiffness coupled with moderately large pendant groups and the hydrogen bonds that form between polar carbonates on adjacent molecules. All these factors increase the resistance to intermolecular movement that is needed for high strength.

The research involving granulated recycled PC (greater than 99% purity), obtained from monitor housing and compression molded into sheets to make tensile specimens, shows that the mechanical property yield strength (67MPa) doesn't change compared to virgin PC [virgin PC = 64.5 MPa] exception would be recycled PC with significant amount of impurities (Gupta and Liang, 2001)

However, impact strength (1090J/m) of granulated recycled PC (greater than 99% purity) increases with recycling [Izod impact strength: virgin PC = 730 J/m] (Gupta and Liang, 2001). The exact reason for the increase is not known. However, impact strength of recycled PC decreases depending on the amount of impurities present in it.



*Figure 2.19* Effect of recycled PC content and residual impurities on tensile yield strength

(Gupta and Liang, 2001)

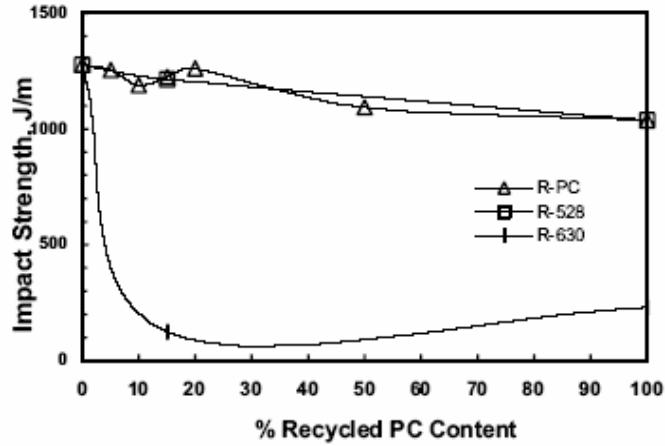


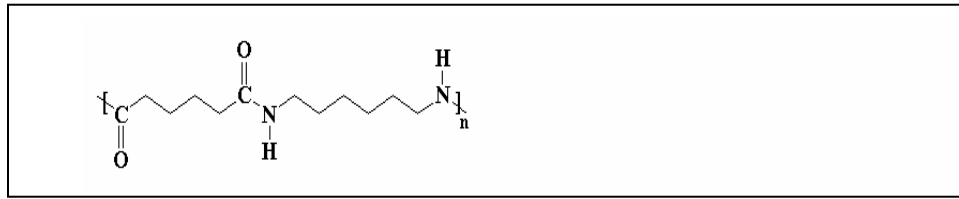
Figure 2.20 Effect of recycled PC content and residual impurities on Izod impact strength (Gupta and Liang, 2001)

Table 2.10

Recycled PC with different purity level  
(Gupta and Liang, 2001)

Designation	Purity Level	Contaminants
Recycled PC I R-PC	>99%	No appreciable Contamination
Recycled PC II R-528PC	99%	HIPS 0.016% PC/ABS 0.03% PMMA 0.05% PE 0.07%
Recycled PC III R-630PC	98%	HIPS 0.29% PC/ABS 0.11% PMMA 0.25% PE 0.07% ABS 0.6% POM 0.16%

### 2.4.8. Nylon (Polyamide)



*Figure 2.21* Structure of Nylon  
(Source: Macrogalleria)

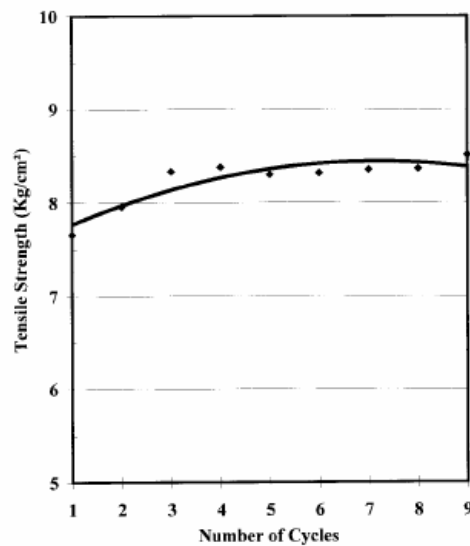
“Nylons are formed by condensation polymerization of reactants (monomers) that combine to make amide groups with water as a by-product. Nylon66 is most widely used in many commercial applications. Both C-O and N-H bonds are polar, with the N and the O being the negative ends. This polarity induces the formation of secondary bonds between adjacent nylon molecules. The secondary bonds restrict the movement of the nylon molecules relative to each other, thus increasing the tensile strength. The secondary bonding also facilitates the close packing of nylon molecules, resulting in high crystallinity. This crystallinity leads to high strength, high stiffness and good toughness” (Strong, 2005, p263-264).

Research on recycling of nylon-6 by injection molding revealed that tensile strength increases as a function of number of processes (as much as 11% from nylon-6 virgin to the ninth cycle). The flexural modulus of the nylon-6 with 10 cycles was 10% higher than the nylon-6 virgin. The increase of tensile strength and modulus flexural property during reprocessing can be explained by an increase of molecular weight (Valko and chilkis (1965), Pavlov, Kudrjajtseva, Abramova, Vasileja, Zezina and Kazaryan (1989)). Percentage elongation as a function of number of processes decreases and

overall decrement was 70% for 10 processes (Lez Gonza- Lozano, Hernandez-Rodriguez, Los Santos and Olmos-Villalpando, 2000, 76, 851–858).

It can be observed that the MFI decreases with the number of injection cycles. As is known, the chains of material with high molecular weight are tangled more easily than the chains of material with low molecular weight, and therefore the flow resistance goes higher. If the MFI decreases, the viscosity of the material is high (degradation by increasing the molecular weight and by cross-linking); and if the MFI increases it indicates less viscosity of the polymer (degradation by broken chain) (Miller, 1993)

“The impact resistance had no significant change until the 7th cycle; after this, a decrease in the impact resistance is observed” (Lozano-Gonzalez, Rodriguez- Hernandez, Gonzalez-De Los Santos and Villalpando-Olmos, 2000, p4).



*Figure 2.22* Tensile strength of nylon-6 as a function of number of cycles.

(Lez Gonza- Lozano, Hernandez-Rodriguez, Los Santos and Olmos-Villalpando, 2000, 76, 851–858).



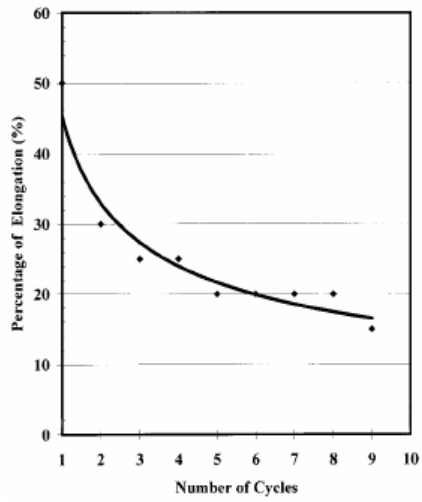


Figure 2.23 Changes in elongation (%) values obtained with each process (Lez Gonza- Lozano, Hernandez-Rodriguez, Los Santos and Olmos-Villalpando, 2000, 76, 851–858).

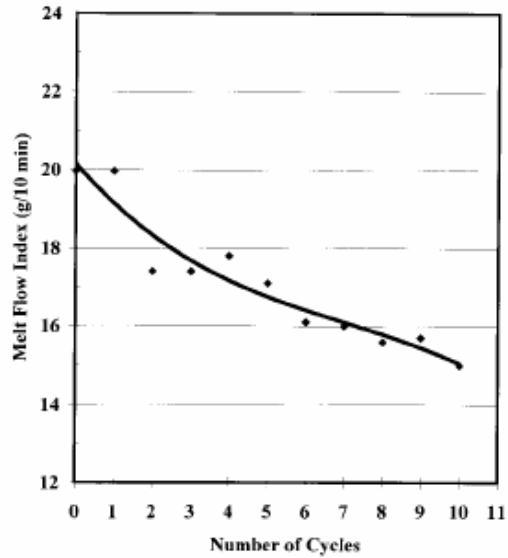


Figure 2.24 Decrement of the nylon-6 MFI with the increment in the number of cycles (Lez Gonza- Lozano, Hernandez-Rodriguez, Los Santos and Olmos-Villalpando, 2000, 76, 851–858).

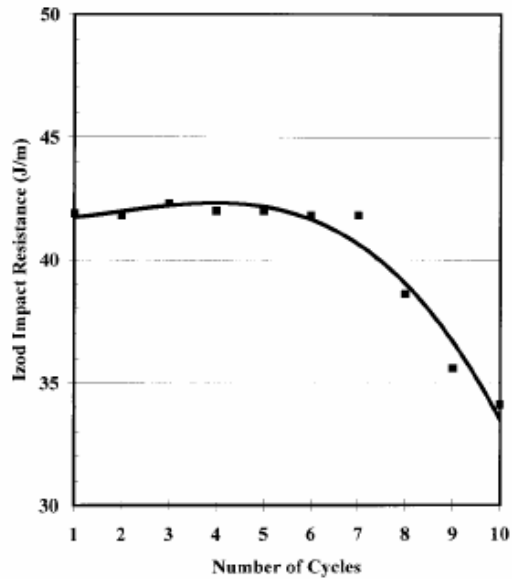


Figure 2.25 Effect on impact properties of nylon-6 as a function of the number of cycles (Lez Gonza- Lozano, Hernandez-Rodriguez, Los Santos and Olmos-Villalpando, 2000, 76, 851–858).

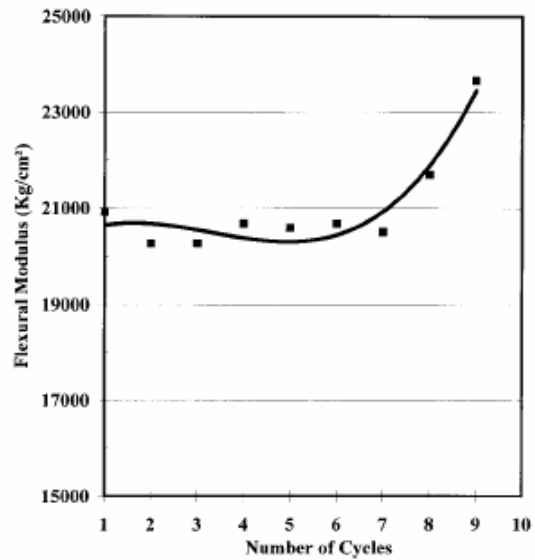
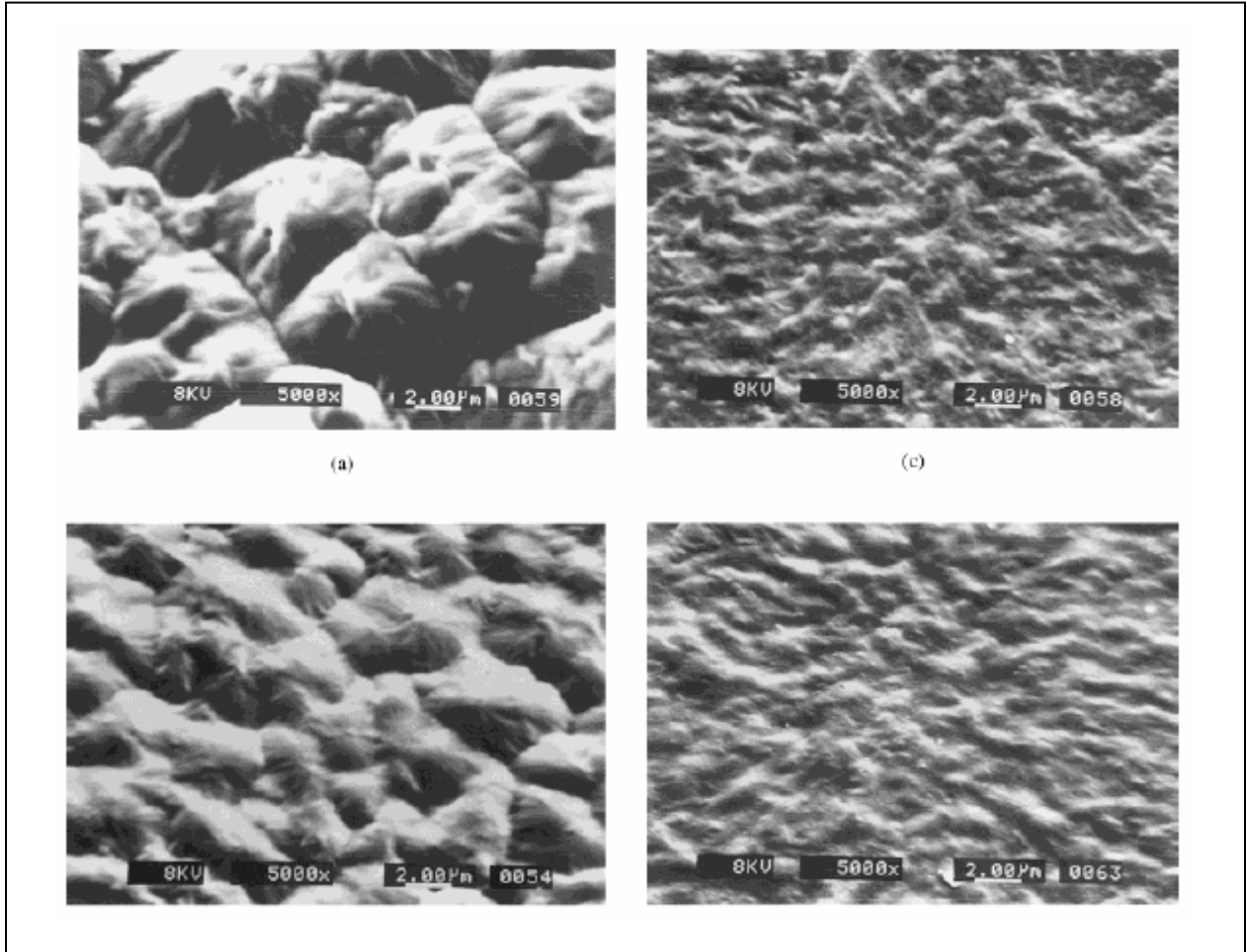


Figure 2.26 Flexural modulus of nylon-6 as a function of number of cycles (Lez Gonza- Lozano, Hernandez-Rodriguez, Los Santos and Olmos-Villalpando, 2000, 76, 851–858).



*Figure 2.27* Microphotographs of spherulites obtained by SEM at 5000x magnifications: (a) nylon-6 virgin, (b) first cycle, (c) fifth cycle, and (d) tenth cycle of injection molding (Lez Gonza- Lozano, Hernandez-Rodriguez, Los Santos and Olmos-Villalpando, 2000, 76, 851–858).

#### **2.4.9. Polyurethane (PU)**

“Polyurethanes are by far the most versatile group of polymers, because the products range from soft thermoplastic elastomer to hard thermoset rigid forms. A major part of automotive plastics is PU, which is used for car upholstery, front, rear and side

coverings. Though most PU plastics are cross-linked polymers, they cannot be regarded as ordinary thermosetting plastics, owing to their chemical structure and physical domain structure. Thus in contrast to typical thermosetting plastics, various methods are available today for recycling PU scrap and used products.

There are basically two methods for recycling polyurethane scrap and used parts, namely, material recycling (primary, secondary, and tertiary recycling) and energy recycling (quaternary recycling). The former methods are preferred since in this way material resources are replenished. After multiple uses the material can finally be used for energy recovery by high temperature combustion or gasification.

Among several processes described for PU material, thermo-pressing and kneader recycling have attracted much attention (Meister and Schaper, 1990, 80(11):1260). By thermo-pressing process, granulated PU wastes can be converted into new molded parts, while in the kneader recycling process a thermo-mechanical operation causes partial chemical breakdown of PU polymer chains to smaller-size segments that can be subsequently cross-linked by reacting with polyisocyanates. Hydrolysis and glycolysis are important tertiary recycling processes for PU wastes.

“The parts obtained by thermo-pressing of granulated PU waste exhibit only slight reduction in hardness and impact strength but significant reduction in elongation at break. Elongation at break drops about 10% of the original value if painted PU wastes are used” (Chanda and Roy, 1998, pp969-970).

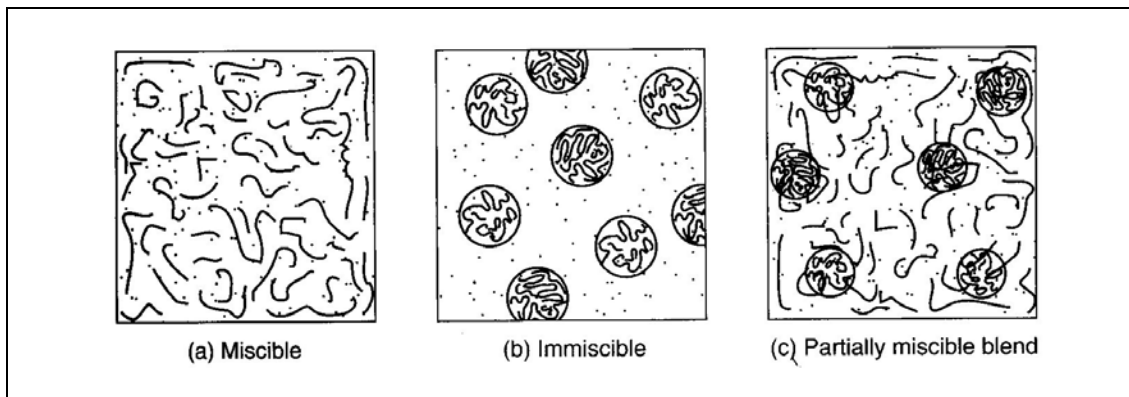
Partial breakdown of the PU network in the kneader process results in highly branched molecules and addition of polyisocyanates in relatively high concentration for subsequent cross-linking, thus yields products of high hardness (shore hardness up to

80) and high tensile strength ( 30 MPa), but small elongation at break ( 6 to 8 % )”  
(Chanda, 1998, p969-971) .

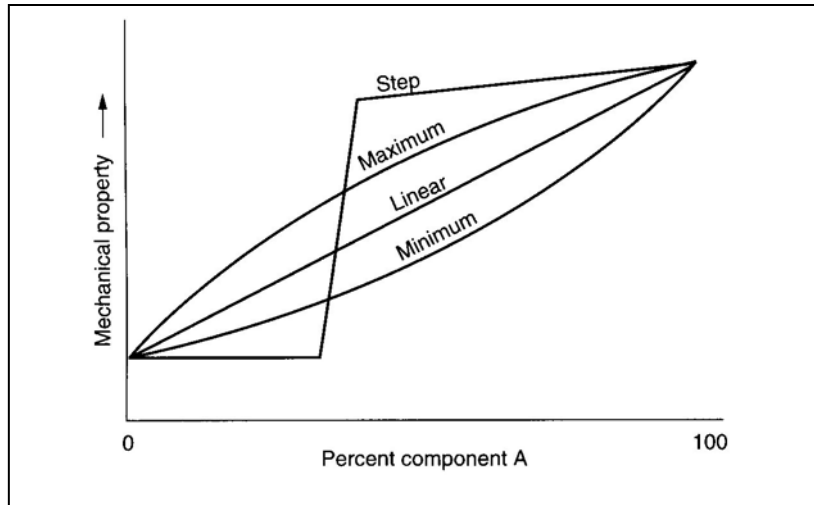
#### 2.4.10. Recycled Polymeric blends (RPB)

“As plastics technology has progressed, polymer blends and alloys have become increasingly important material subgroups because they offer unique combinations of properties of each of their parent polymers. Polymer blends fall into three main categories:

- Miscible
- Immiscible and
- Partially miscible



*Figure 2.28* Recycled Polymeric blends  
(Trantina, and Nimmer, 1994, p15-16)



*Figure 2.29* potential responses for the mechanical properties of a recycled polymer blend

(Trantina, and Nimmer, 1994, p15-16)

### **Miscible blends**

A miscible blend consists of a single polymer phase- two or more polymers that are completely soluble in each other. The mechanical properties of a miscible blend are usually weighted averages of the properties of the two components. Polyphenylene ether (PPE) and polystyrene (PS) form miscible blends over the entire composition range of both components. PPE brings the benefits of high use temperature and flame retardancy; PS adds improved flow and processability, resulting in good properties for extrusion, blow-molding, or injection molding applications.

## **Immiscible blends**

Immiscible blends result from mixing two materials with little affinity for each other. The polymer with the smallest volume fraction is usually a poorly dispersed second phase with little adhesion between the phases. However, compatibilization improves dispersion and phase adhesion, yielding blends with useful engineering properties. These properties are ideally the best properties of each material, varying as a step function (Trantina, and Nimmer, 1994, p17-18) as shown in Fig.2.29. Addition of glass fibers, for example, is found (Vezzoli, Beretta, and Lamperti, 1993) to yield products with very high stiffness (e.g., elastic modulus  $E \approx 2800$  Mpa with 30% glass fiber), higher than with talc ( $E \approx 1250$  Mpa with 20% talc) and far better than that of the original mixture ( $E \approx 950$  MPa). Addition of LDPE and styrene-butadiene-styrene copolymer, on the other hand improves tenacity (showing, typically, a 30-90% increase in elongation at break) (Chanda and Roy, 1998, p984). The most practiced example of combining two immiscible polymers is for the purpose of impact resistance. Examples of such immiscible blends are high-impact polystyrene (HIPS), some ABS materials, and toughened polyamide. Another example where chemical compatibilization of two immiscible polymers has led to a successful new polymer is the blend of PPE with nylon. This blend improves the dimensional stability, high glass transition temperature, and electrical properties of PPE with the improved flow and solvent resistance of nylon.

## **Partially miscible blends**

Some blends are neither completely miscible nor immiscible. These partially miscible blends show limited mutual affinity, but small amounts of one polymer are

soluble in the other. The best properties of each blend may be combined, often without the challenge of developing a compatibilization mechanism. Partially miscible blends of crystalline polyesters such as polybutylene terephthalate (PBT) with polycarbonate (PC) yield materials with dimensional stability and toughness of the PC and the solvent resistance and processability of the crystalline polyester. Impact modification gives these blends low temperature toughness” (Trantina and Nimmer, 1994, p17-18).

“It is well established that a strong incompatibility is typical of polymers usually found in commingled wastes (PE, PP, PET, PVC, and PS)” (Chanda and Roy, 1998, p984). Particularly, mixtures that are known to be potentially immiscible (or only sparingly miscible) include PS/SAN, PS/ABS, PS/PVC, PS/PP, PS/LDPE, PS/HDPE, PET/PVC, and PET/HDPE, etc (Lemmens, 1995, p315-326).

## **2.5 RECYCLING PROCESSES**

### **Thermo kinetic recycling process (TKR)**

Thermo kinetic recycling (compounding) is the process of combining plastics through the particles by motion. Essentially, old plastic which has been chipped into pieces by a chopper is then accelerated in a mixer chamber. The acceleration of the pieces causes them to collide with each other and the chamber walls to create heat. Once the material is heated, it is removed from the chamber and formed into a part through either compression molding or some other appropriate plastics forming method (Brough, 2001, p1-11).



This process is vastly different from most other plastic molding processes. The unique heating process of thermo-kinetic compounding, presents several advantages and a few limitations.

### **Advantages**

- “Thermosets do not need to melt:

In TKR, the materials are raised in temperature only until they can be molded. For amorphous plastics and thermosets, this means that they are raised just above their  $T_g$ . For crystalline thermoplastics, the temperature is raised until it is close to, but still under the melting temperature,  $T_m$ . Because the process is not aiming for a specific temperature, but rather a range of temperature, different melting point materials can be processed together. This gives the system the ability to reprocess almost any combination of plastics.

- Different melt temperature materials can be processed together.
- Non-plastics materials can be processed in the mix:
- The non-plastics materials become blended throughout the mix in the process.
- Heating is rapid, thus decreasing the effect of heat history

### **Limitations**

- Thermo kinetic compounding does not heat to a specific homogeneous Temperature
- The mixture of different materials will not act as homogeneous material”  
(Brough, 2001, p1-11).

## Comparison of properties of TKR plastics with virgin plastics

Table 2.11

*Comparison of properties of TKR plastics with virgin plastics*

Material	Tensile Strength @ yield MPa
Recycled PVC	7.58 - 29.65
Virgin PVC	(19-59)
Recycled LDPE	13- 27.58
Virgin LDPE	(10 )
Recycled Nylon	28.96 - 59.98
Virgin Nylon	(76-79)

## 2.6 DESIGN GUIDE LINES FOR DESIGNING WITH RECYCLED PLASTICS

“The goal of utilizing recycled resins in a design is that, in use, they should be indistinguishable from virgin grades. The degree to which this goal is achieved depends on careful consideration of both the design and the manufacturing processes that will be employed. Some of the guidelines are as follows (Lintell and Smith, 1997, p194);

- Because recycled plastics tend to suffer some loss in mechanical properties (such as tensile strength and impact resistance), wall thickness in the design should be increased to compensate. This will increase the material’s load carrying ability and should prevent the possibility of unexpected failure.
- The incorporation of additional strengthening ribs in the molding can also help overcome shortcoming in mechanical properties of the material.

The effect of the above measures is to increase the safety margin on the design and can be applied where exact mechanical properties of the recycled material are not available, or cannot be guaranteed” (Lintell and Smith, 1997, p194).

## **2.7 FINITE ELEMENT ANALYSIS (FEA) OF RECYCLED PLASTICS**

“One of the foundations of structural mechanics is Hooke’s discovery that, for many structures, the relationship between force and deflection could be practically approximated as linear in nature. Using a simple spring as an example of a structure, its stiffness is simply the force divided by the deflection, as long as the spring remains linearly elastic and does not yield or break. A bar of cross-sectional area ‘A’ and length ‘L’ made of a material with Young’s modulus ‘E’ is one specific and simple example of a structural spring. For such a bar loaded in tension by force P the structural stiffness can be written as

$$S = P/\delta = EA/L$$

Where  $\delta$  = change in length. As can be seen in this equation, the structural stiffness is dependent on both material properties such as ‘E’ and geometric properties such as ‘A’ and ‘L’.

Although the stiffness of a bar is easily defined in terms of its geometric properties, most engineering exhibit far more complex geometry, making accurate structural analysis much more difficult. In mid-1950’s, American and European aeronautical engineers independently developed the finite-element method as an approach to analyzing such structures (Stokes, 1998, p2772-2785). Using this approach, a structure can be idealized as being composed of small, discrete pieces called ‘Finite elements’. These engineers

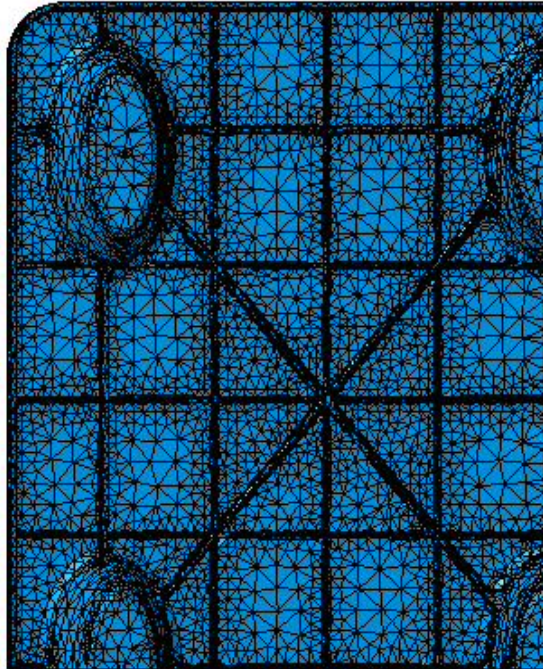
extended Hooke's basic idea of linear springs into a general approach capable of analyzing extremely large structures. As a direct result of breaking the complex structure down into smaller, simpler pieces, the problem now became characterized by large numbers of simultaneous equations. The advent of the first generation of computers has made the solution of these equations straightforward" (Trantina and Nimmer, 1994, p-33-34).

As technology of FEA for analysis, including plastics field available, many areas apart from the one for which it was invented started using it. As plastics became popular in structural applications, it offered new challenges to engineers. For example, properties such as tensile strength are less than metals and unpredictable (since properties can be modified by compounding) making the use of FEA inevitable to establish design guide lines. As far as recycled plastics are concerned, challenges are greater as they loose some of their mechanical properties compared to their virgin counter-parts during recycling, which make FEA a valuable tool for establishing design guidelines both in structural and other engineering applications.

## **Fundamentals**

"The basic theory of FEA is to reduce a large, complex structure into a network of small, simple geometric elements, such as beams, two dimensional (2-D) elements, shells, or solids (3-D elements). Each finite element is connected to an adjacent finite element by definition points of the element called 'nodes'. Within any of these elements, relatively simple equations can be used to describe measures of deformation, e.g., stress, strain, and displacement. The behavior of entire structure is calculated by combining the

element equations into a large set of simultaneous equations representing the behavior of the structure.



*Figure 2.30* Structure divided into finite elements

In order to gain a general understanding of FEA theory, consider its application to above shown structure in Figure 2.30. When load is applied to the structure, all of the elements deform in a fashion that guarantees equilibrium of forces between the elements. In addition, the deformation of the modeled structure remains compatible. This latter requirement must be fulfilled in order to ensure that discontinuities in displacement do not develop at elemental boundaries. Let us consider development of these equations for the structure modeled with elements as shown in above Figure 2.30.

The first step in developing these equations is to establish the expression for element stiffness, relating forces and displacements at the nodes of an element.

The sequence in this process is as follows:

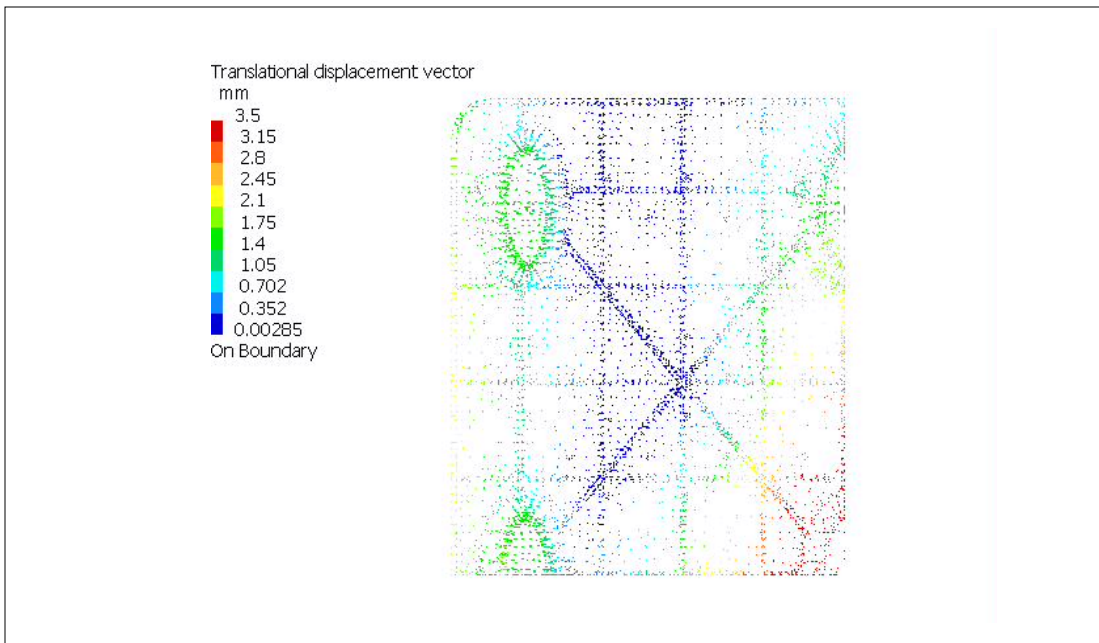
- Assume an approximate displacement function for the element. This function is defined in-terms of the displacements at the nodes of the element and should ensure compatibility of displacements with neighboring elements along its entire boundary.
- Apply the kinematic equations defining strain in terms of the approximate displacement functions
- Use the constitutive relationship appropriate for the material to determine stresses in terms of strains
- Develop equilibrium equations relating internal element nodal forces to externally applied nodal forces

### **Global equilibrium**

Equation for an element as from above, establishes relationship between the nodal displacements of an element and corresponding nodal forces. When individual elements are joined at common nodes to model a structure such that shown in Fig.2.30 above, global equilibrium must be ensured at each node. This requirement means that the summation of the forces associated with all the elements attached to that node must be equal in magnitude and opposite in the direction to the externally applied force at that node.

To construct these equations, individual element stiffnesses are assembled using matrix algebra techniques into a global stiffness matrix representing the stiffness of

the entire structure. Since different elements in the model will share common nodes individual components of element stiffness matrices are added to form the global set of matrix equations. This global set of equations relates all the nodal degrees of freedom in the structure to the externally applied nodal forces. If the externally applied forces are known, a solution for the nodal degree of freedom can be obtained using linear algebra once the required boundary equations are applied. When the displacements of all the nodes are known, the state of deformation of each element is also defined. Thus, the state of stress and strain within each element can be calculated using equations for each element. However, since equilibrium is only guaranteed at a finite number of nodal points in the structure, the finite-element method is a numerical approximation rather than exact solution. The accuracy of the approximation will depend on the number of nodes and elements in the structure (Trantina and Nimmer, 1993, p33-41).



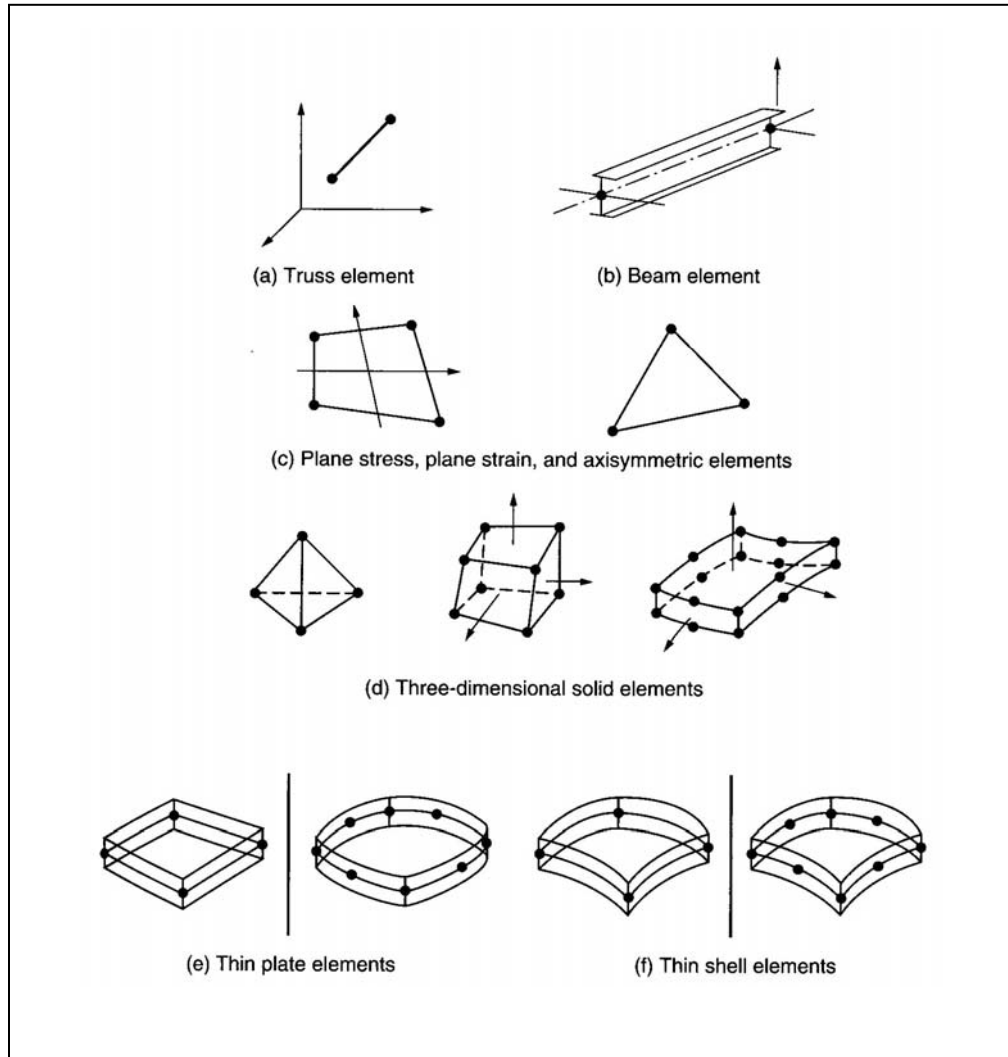
*Figure 2.31* FEA model showing summarized deflections of elements

## **Types of Finite elements**

The choice of the type of element to use for a particular problem is often a trade-off between reality and simplicity. Elements can be categorized as one, two, and three-dimensional solid elements and beam, plate and shell elements. The complexity of the analysis and the amount of engineering and computer time required increase significantly when moving from 1-D to 2-D to 3-D analysis. Many real part geometries and loadings are certainly 3-D in nature. When 2-D or 1-D elements are used, assumptions must be made relative to the distribution of stress and strain in the other directions. Since plastic parts tend to have thin walls (recycled plastics too) relative to their overall dimensions, plate-, or shell-type elements are often most suitable. Plate or shell analysis can treat the geometric complexity adequately and offer the flexibility to change the wall thickness of the model easily during engineering parameter studies, whereas with fully 3-D analysis, a thickness change requires the nodes of the finite-element mesh to be moved, which is usually a more time-consuming process. However, plate and shell elements are complex and vary widely in their formulations. Arguments continue to persist with respect to the relative ability of the different commercially available elements to accurately predict part performance” (Trantina and Nimmer, 1994, p33-41).

Manual finite-element calculation consumes enormous time and hence computers are used for the same purpose. In this section of literature review, mathematical equations are not presented, as calculations are done by commercial FEA software and are beyond the scope of this thesis. The exact procedure used in FEA using a computer will be presented in the next chapter.





*Figure 2.32* Types of Finite elements  
 (Trantina and Nimmer, 1994, p33-41)

## **CHAPTER 3**

### **METHODOLOGY**

#### **3.1 SUMMARY**

The purpose of this thesis is to evaluate the commercial applicability of six recycled plastics blends using FEA (finite element analysis) and experimental testing. The first step in evaluating the commercial applicability is to test six recycled plastics blends for different physical and mechanical properties. These physical and mechanical properties include density, tensile and impact properties. The second step is to compare the properties of the six blends of recycled plastics. The third step is to determine the service performance of a product made from the six blends of recycled plastics using CATIA FEA.

#### **3.2 TESTED MATERIAL BLENDS**

The six different types of thermo-kinetically recycled plastics blends are:

1. Pop bottles made of PolyethyleneTerephthalate (PET), milk jugs made of High-Density Polyethylene (HDPE)
2. Vinyl seats made of Poly Vinyl Chloride (PVC) and a small amount of Polypropylene (PP) and Urethane (PU)

3. Electronic scrap made of engineering resins like Acrylo-Nitrile-Butadiene Styrene (ABS), Polystyrene (PS) and Polycarbonate (PC)
4. Agriculture waste consisting of Low Density Polyethylene (LDPE)
5. Industrial waste consisting of Nylon (PA) and PolyethyleneTeraphthalate (PET)
6. Household waste consisting of Polystyrene (PS)

### **3.3 TESTING**

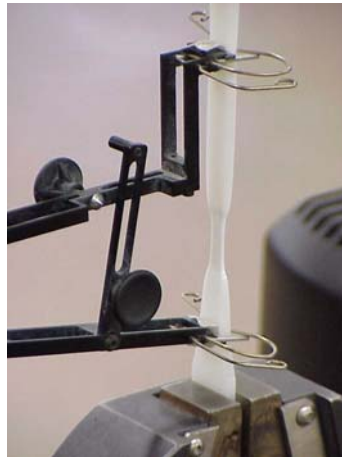
#### **3.3.1 Tensile test (ASTM D 638)**

**Scope:**

“The tensile test measures the force required to break a specimen and the extent to which the specimen stretches or elongates to that breaking point. The tensile test is used to produce a stress-strain diagram, which is used to determine tensile modulus and yield strength and Poisson’s ratio. The data are often used to specify a material, to design parts to withstand application force and as input for material properties used in FEA. Since the physical properties of many materials (especially thermoplastics) can vary depending on ambient temperature, it is sometimes appropriate to test materials at temperatures that simulate the intended end use environment” (source: Plastics Technology Laboratories, Inc., 2005). Please refer to Figure 3.1 and 3.2.

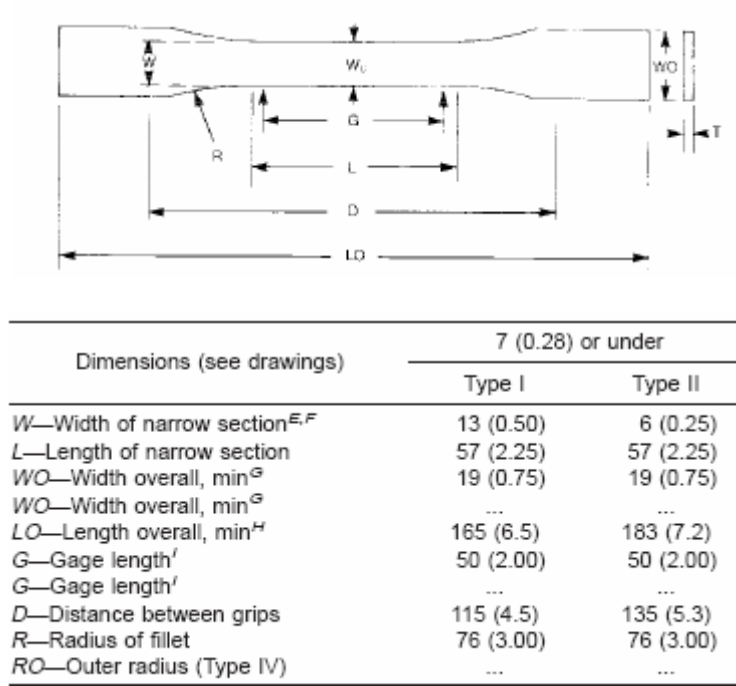


*Figure 3.1* Tensile testing machine  
(Source: Testlopedia)



*Figure 3.2* Necking of tensile specimen  
(Source: Testlopedia)

## Test Specimen and conditioning:



*Figure 3.3 Tensile test specimen type-I*

*(Source: American Society of Testing and Materials testing standard D-638-02a, 2002)*

Ten test specimens of each blend were prepared by water-jet cutting of compression-molded, recycled plastics sheets. Test specimen dimensions vary considerably depending upon the requirements and are described in detail in the ASTM book of standards. Fig.3.3 shows ASTM D 638 Type I tensile test specimen most commonly used for testing rigid and semi-rigid plastics, which are the types used in the current work.

The specimens were conditioned using standard conditioning procedures. Since the tensile properties of some plastics change rapidly with small changes in temperature, the testing was carried out at standard laboratory atmosphere of 23+/- 2<sup>0</sup>C and 50+/-5 percent relative humidity.

### **Test Procedure:**

#### **Tensile strength:**

“The speed of testing is the relative rate of motion of the grips during the test. There are basically five different testing speeds specified in the ASTM D 638 standard. The most frequently employed speed of testing is 0.2 in/min. Whenever possible, the speed indicated by the specification for the material being tested should be used. If a test speed is not given, an appropriate speed that causes rupture between 30 sec and 5 min. should be chosen. The test specimen was positioned vertically in the grips of the testing machine. The grips [were] tightened evenly and firmly to prevent any slippage” (Shah, 1998, p17-23). The speed of the testing machine was set at the proper rate (0.2 in/min) and the machine was started. As the specimen elongates the resistance of the specimen increased and was detected by a load cell. This load value (force) was recorded by the instrument. This machine also records the maximum (peak) load obtained by the specimen, which was recalled after the completion of the test. The elongation of the specimen was continued until a rupture of the specimen was observed. Load value at break was also recorded. The tensile strengths at yield and break (ultimate tensile strength) were calculated (Shah, Vishu, 1998, p17-23)).

$$\text{Tensile strength} = \frac{\text{Maximum load recorded (load)(lb)}}{\text{cross - section area (sq.in)}}$$

$$\text{Tensile strength at yield (psi)} = \frac{\text{Force (load) (lb)}}{\text{Cross - section area (sq.in)}}$$

**Tensile modulus:**

Tensile modulus and elongation values were derived from a stress-strain curve. The stress-strain curve was plotted using an MS-Excel sheet in the computer connected to tensile testing machine. The following procedure is generally used to carry out the calculations. Please refer to the Fig.3.4

- “Mark off the units of stress in lb/in<sup>2</sup> on the y-axis of the chart. This is done by dividing the force by cross-sectional area of the specimen
- Mark off the units of strain in inch/inch on the x-axis. These values are obtained by dividing chart value by the magnification selected.
- Carefully draw a tangent KL to the initial straight line portion of the stress-strain curve (If the curve is not straight select the portion of the curve where the curve actually starts rising)

- Select any two convenient points on the tangent ( point P and L are selected in this case)
- Draw straight line PQ and LM connecting points P and L with the y axis of the chart
- Stress value at L = 8000 psi, corresponding strain value at M= 0.08 in/in. Stress value at P = 3200 psi, corresponding strain value at Q= 0.04.

$$\text{Tensile modulus} = \frac{\text{Difference in stress}}{\text{Difference in corresponding strain}}$$

Or

$$\text{Tensile modulus} = 8000-3200 / (0.08-0.04) = \frac{4800}{0.04} = 120,000 \text{ psi}'' \text{ (Shah, 1998, p20-23)}$$

For accuracy, modulus values were determined from ten stress-strain curves obtained by testing ten specimens of each recycled blend.



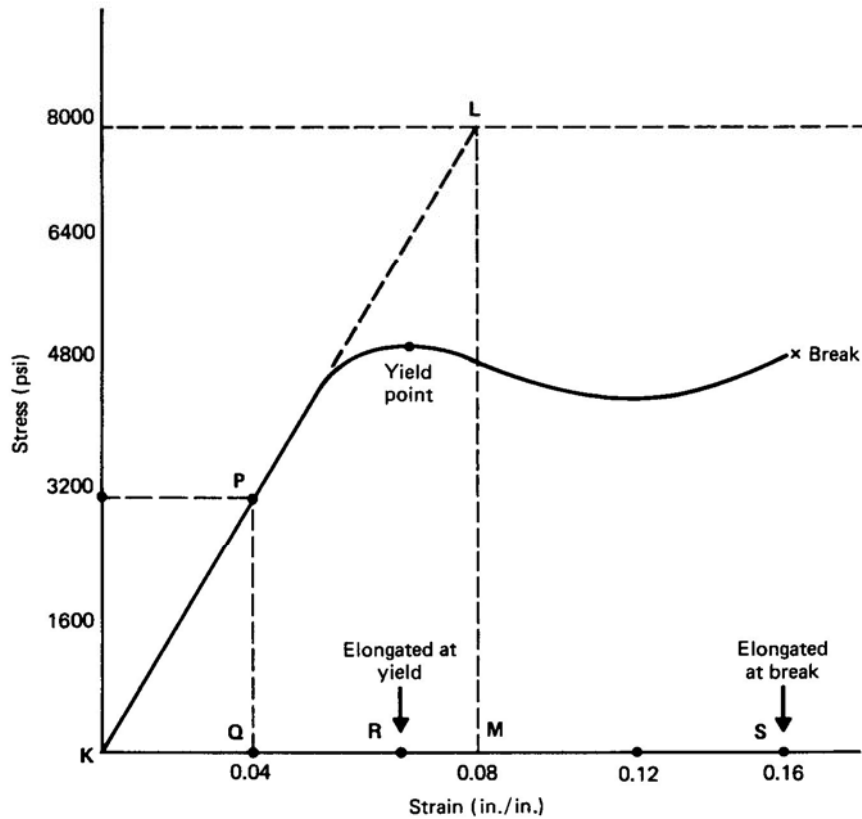


Figure 3.4 Tensile test curve  
(Shah, 1993, p17-23)

### 3.3.2 Density (Specific Gravity) test (ASTM D 792)

Specific gravity is defined as the ratio of the weight of the given volume of a material to that of an equal volume of water (or the reference liquid) at a stated temperature. The temperature selected for determining specific gravity of recycled plastic parts is 23<sup>0</sup>C (Shah, 1998, p257-260).

Density (specific gravity) values represent the difference between recycled plastics, its blends and virgin plastics. Along with melt flow index, density of recycled plastics blends can provide useful information about the structure of the recycled plastic blends.

**Method:**

“This method, which is suitable for pellets, or powder, requires the use of analytical balance, a pycnometer, a vacuum pump and a vacuum desiccator. This test was started by first weighing the empty pycnometer. The pycnometer was filled with Isopropyl alcohol and placed in a water bath until temperature equilibrium with the bath was attained. The weight of the pycnometer filled with Isopropyl alcohol was determined. After cleaning and drying the pycnometer, 1-5 g of recycled plastics material was added and weight of the specimen plus the pycnometer was determined. The pycnometer filled with Isopropyl alcohol in a vacuum desiccator. The vacuum was applied until all the air had been removed from between the particles of the specimen. Last, the weight of the pycnometer filled with Isopropyl alcohol and the specimen was recorded. The specific gravity is calculated as follows:

$$\text{Specific gravity} = \frac{a}{(b + a - m)}$$

Where a= weight of the specimen; b= weight of the pycnometer filled with Isopropyl alcohol; m = weight of the pycnometer containing the specimen and filled with Isopropyl alcohol.

Note: If another suitable immersion liquid is substituted for the water the specific gravity of the immersion liquid must be determined and taken into account in calculating specific gravity.” (Shah, 1998, p257-260).

Hence, the density of recycled plastics was found by multiplying the specific gravity value thus obtained above by the density of isopropyl alcohol (0.778 g/cc).



*Figure 3.5 Pycnometer*



*Figure 3.6 Analytical balance*

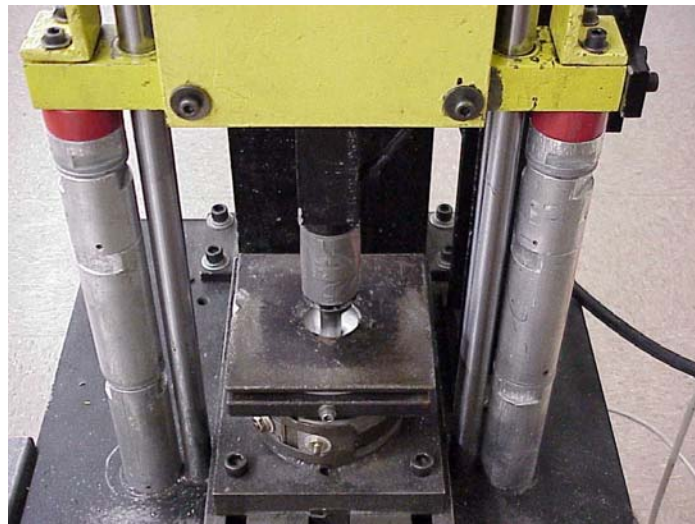
*(Source: Plastics Technology Laboratories, Inc.)*

### 3.3.3 Instrumented impact test (ASTM D 3763)



*Figure 3.7* Tup impact tester

*(Source: Plastics Technology Laboratories, Inc.)*



*Figure 3.8* Tup impact tester- a closer look

*(Source: Plastics Technology Laboratories, Inc.)*

**Scope:**

The impact properties of the recycled polymeric material are directly related to the overall toughness of the material. Toughness is defined as the ability of the polymer to absorb applied energy. The higher the impact energy of the material higher is the toughness and vice versa. Impact resistance is the ability of a material to resist breaking under a shock loading or the ability to resist the fracture under stress applied at high speed (Shah, Vishu, 1998, p50-71).

**Test specimen:**

About ten specimens of each recycled plastic blend were used for this testing, each of which had 2.5” diameter.

**Impact strength:**

- A free-falling tup was allowed to strike a supported specimen directly. The tup having a fixed mass was dropped from various heights (See Fig. 3.7).
- The impact tester was attached to a computer capable of monitoring the entire impact event, starting from acceleration (from rest) to the initial impact and plastic bending to fracture initiation and propagation to complete failure. The instrumentation was done by mounting the load cell onto the tup. During the test, a fiber-optic device triggered the oscilloscope just before striking the specimen. The output of the load cell was recorded by oscilloscope, depicting the variation of the load applied to the specimen throughout the entire fracturing process (Shah, 1998, p50-71).

- The procedure determines the impact energy at which the specimens fail. The impact strength was directly read from the computer and a printout of the same was taken.
- Each test method permits the use of different tup and test specimen geometries to obtain different modes of failure, permit easier sampling, or test limited amounts of material. There is no known means for correlating the results of tests made by different impact methods or procedures (source: ASTM D5628-96 (re-approved 2001), 2001). Please refer to Figure 3.8.

### **3.4 FINITE ELEMENT ANALYSIS (FEA)**

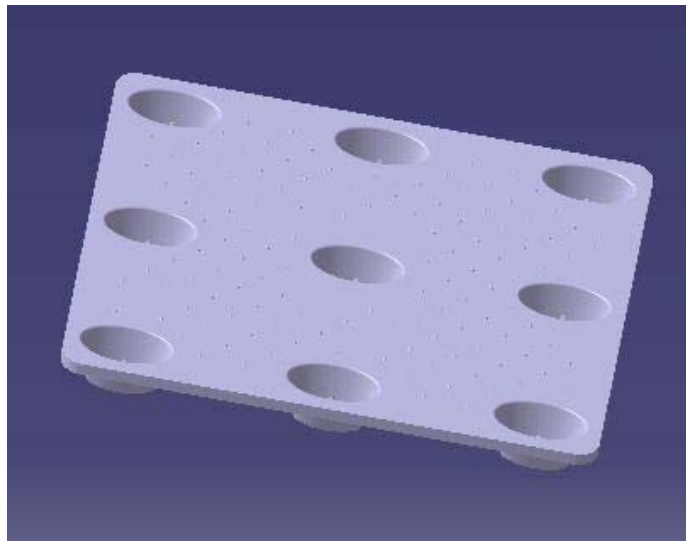
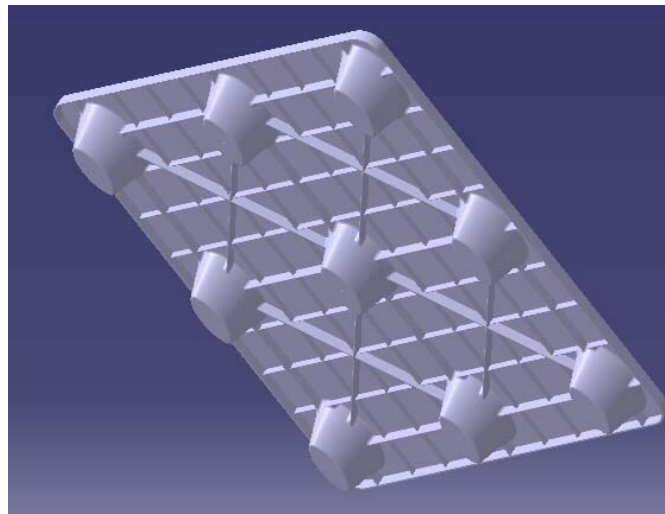
#### **Geometry creation:**

The first step in the FEA procedure was to model the part geometry. “There are many ways to define geometry, ranging from two-dimensional drawings to three-dimensional computer-aided design (CAD). Computer-aided drafting permits easy generation and editing of two-dimensional geometry. In general this process involves placing lines, rectangles, arcs, circles and other basic geometric shapes on a display screen and then moving, rotating and scaling these shapes to define a part outline. Often, there is a need to describe a part in three dimensions so that it can be more easily understood and converted to a discretized finite-element definition. 3-D parts include wire frame, surface and solid models. Among these, solid model provides the most unambiguous description of part geometry by mathematically describing the interior and exterior of the part. A significant amount of engineering judgment is required to produce

an effective geometric representation of a complex part” (Trantina and Nimmer, 1994, p 45-48).

A pallet such as that used in industries for material handling was selected as the product for FEA. The CAD/FEA software choice for FEA was CATIA.

For this thesis, a solid model of the pallet in Solid Works was imported into CATIA using the IGES format.



*Figure 3.9* CAD Isometric views of plastics pallet

Since the pallet has a symmetrical shape, only 1/4<sup>th</sup> of pallet was considered for FEA.

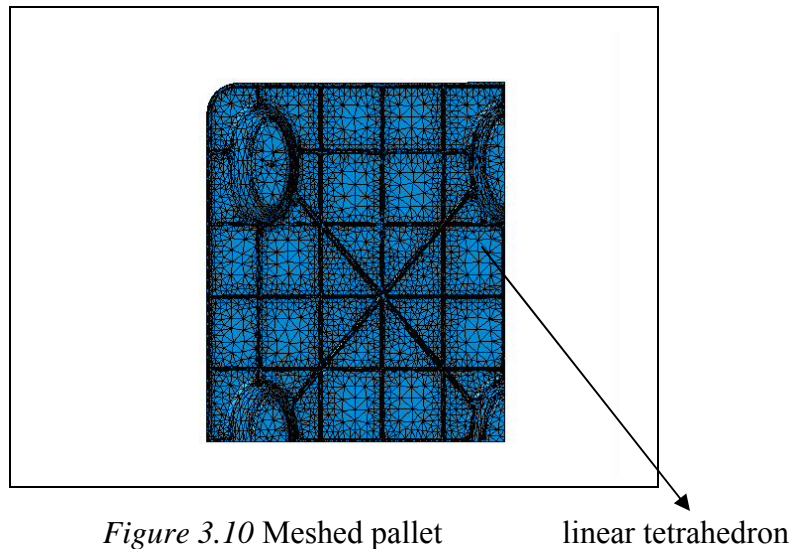
### **Mesh creation and element selection:**

“No matter how the geometry is created, it must eventually be described discretely in terms of nodal points and elements in order to apply finite-element analysis. This division of geometry into a set of elements is referred to as a mesh. Engineering judgment is required to select an appropriate element type and also in determining the mesh density, the number and size of the elements. Coarser meshes result in faster solution times but also limit the accuracy of the analysis. For complex parts, this process is usually accomplished by using an automated finite-element mesh generator to represent a part discretely in terms of nodes and elements” (Trantina and Nimmer, 1994, p45-48).

Three-dimensional linear tetrahedra were used with an automated meshing routine available in CATIA to specify the mesh density.

The areas of most interest on the model were of course the high stress regions. These regions generally occurred in the areas where there was an abrupt change in the geometry. This occurred in the transition area of the rib to the body of the pallet and around small notches created for applying boundary conditions in the bottom (Jensen Budge, 1992, p30-38).





**Boundary and load conditions:**

**Symmetry, constraint boundary conditions and loads:**

The boundary conditions include the loads, constraints and the symmetry boundary conditions. “Boundary conditions on a structure appear as applied displacements at points of support. For static problems, the stiffness matrix associated with the linear equations of equilibrium for the complete structure will be singular, and therefore un-invertible, unless all rigid body motion is prohibited. As a result a fundamental requirement for solution of the linear equations governing a problem is that the structure must be prevented from freely translating or rotating in space” (Trantina and Nimmer, 1994, p 45-48).

“One feature of FEA modeling and solving is the ability of the software to model portions of a symmetric object representing the total model by imposing boundary conditions” (Jensen Budge, Lawrence, 1992, p37). These boundary conditions are known as symmetric boundary conditions. These conditions cause the partial model to behave as if the whole object has been modeled. The symmetry conditions allow the ability to

model part of the pallet. These boundaries must be defined about geometry and loading conditions that are symmetrical. The pallet was symmetrical along its main axis and an axis perpendicular (minor axis) to the main axis and lying in the same horizontal plane of the pallet. Hence, only one quarter of the pallet needed to be modeled. This greatly reduced the size and the time required to solve the model. Fig.3.11 shows the model with symmetrical boundary conditions and constraints applied along main axis (longer edge) and shorter edge (minor axis).

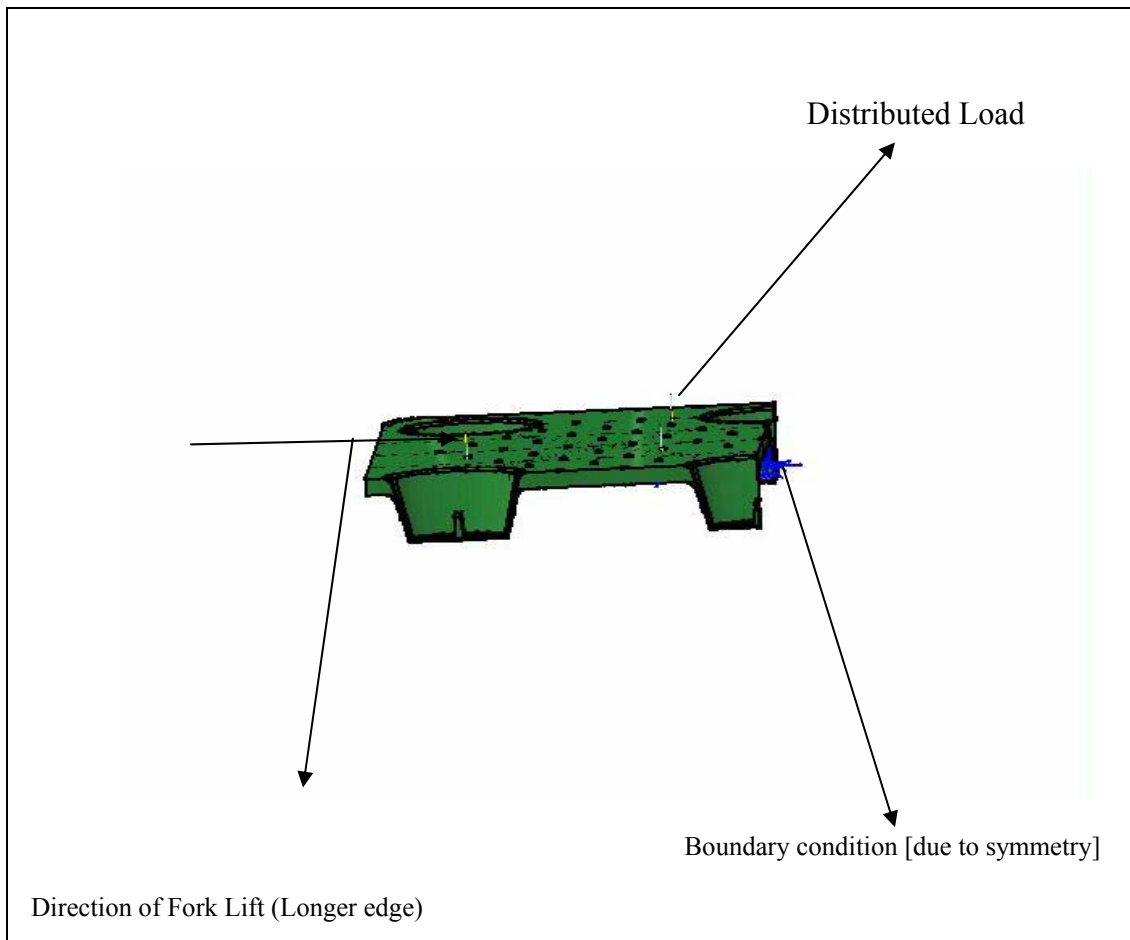
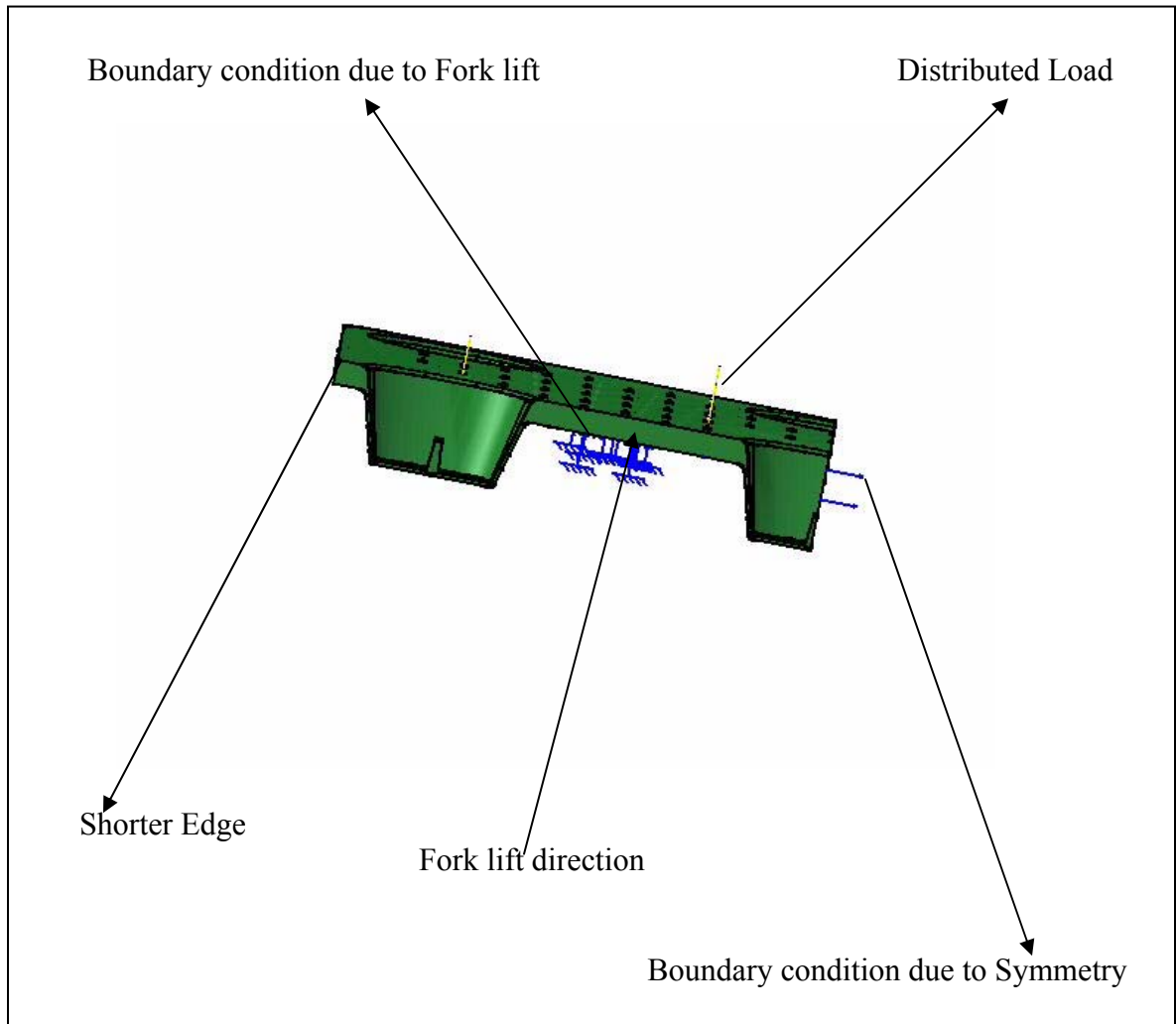


Figure 3.11 Boundary conditions along longer edge (main axis)



*Figure 3.12* Boundary conditions along minor axis (or shorter edge)

**Constraints:**

To simulate the pallet lifted off of the ground by a forklift from the bottom side, the correct forklift constraints had to be modeled. This forklift that contacted the bottom side of the pallet was best modeled by not allowing nodal displacement or rotation at any point of contact between the forklift and the bottom of the pallet. This is probably not a

perfect representation of the pallet but approximates the ‘real world’ situation reasonably well. The forklift that came in contact with the bottom side of the pallet allowed translation along directions other than out of the plane vertical axis. Loads were applied to the pallet model in the form of applied force. The applied force was in the form of distributed force (pressure). When these pallets are used in industrial settings to transport or store stacked objects, they encounter downward pressure due to weight of the stacked objects.

### **Material properties:**

“In addition to the geometric detail of the component and the applied loads, the material (constitutive) relationship between stress and strain must also be defined. For simple isotropic, linear-elastic stress analysis, only the material elastic modulus and Poisson’s ratio need to be provided. In some cases, more detailed constitutive models may be desirable.

In general, material properties represent the fundamental measurements that relate the performance of a material to the performance of a geometrically complex structural component. It should be emphasized that they play two roles in structural analysis. First, the material properties that define the deformation behavior of a material are used within the framework of the material’s constitutive model, to relate stress to strain in the finite-element method. Second, the material properties that define failure limits are used to interpret the results of analysis in-terms of likelihood of failure” (Trantina and Nimmer, 1994, p 45-48).

In this thesis, only elastic modulus and Poisson's ratio were provided as this FEA was assumed to be isotropic, linear-elastic stress analysis for each recycled blend. Other details such as density and yield strength along with coefficient of thermal expansion were used to provide additional information about the suitability of these materials for use as a pallet. The above said details also hold good for the analysis of virgin blends that are used for comparison with recycled blends.

Virgin plastics blends consist of same type of plastics compared to corresponding recycled plastics blend, the only difference being virgin plastics are not reprocessed or recycled.

In this thesis, to represent final result for each recycled plastics blend (also for each virgin plastics blend) statistically, two values of elastic modulus were considered.

- Mean elastic modulus
- Mean-3  $\sigma$  value of elastic modulus

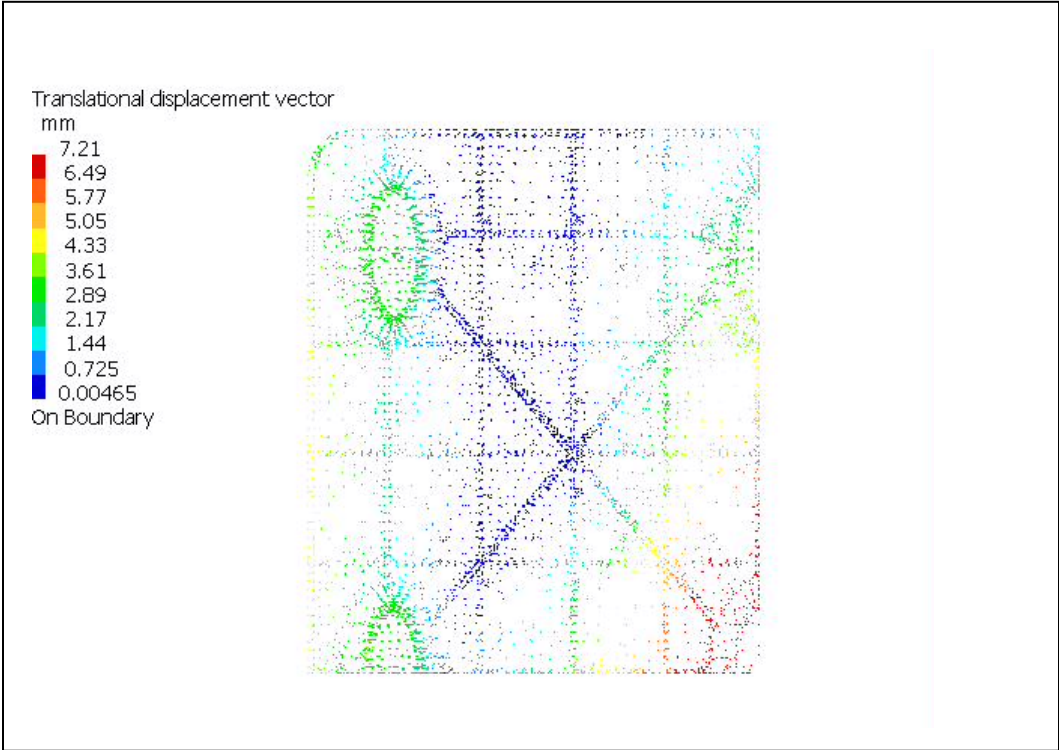
The elastic modulus mean-3  $\sigma$  is obtained by subtracting -3  $\sigma$  from mean value of elastic modulus obtained from tensile testing (mean modulus -3  $\sigma$ ). The purpose of the above said procedure was to establish a lower limit for elastic modulus of each recycled plastics blend, below which the recycled plastics cannot be used in commercial applications.

In addition to the above, since the exact Poisson's ratio for each blend of recycled plastics was unknown, analysis was done using Poisson's ratios available from material properties chart and in some cases lower, average and higher values of Poisson's ratios (based on intuition) were considered in combination with above said elastic moduli.

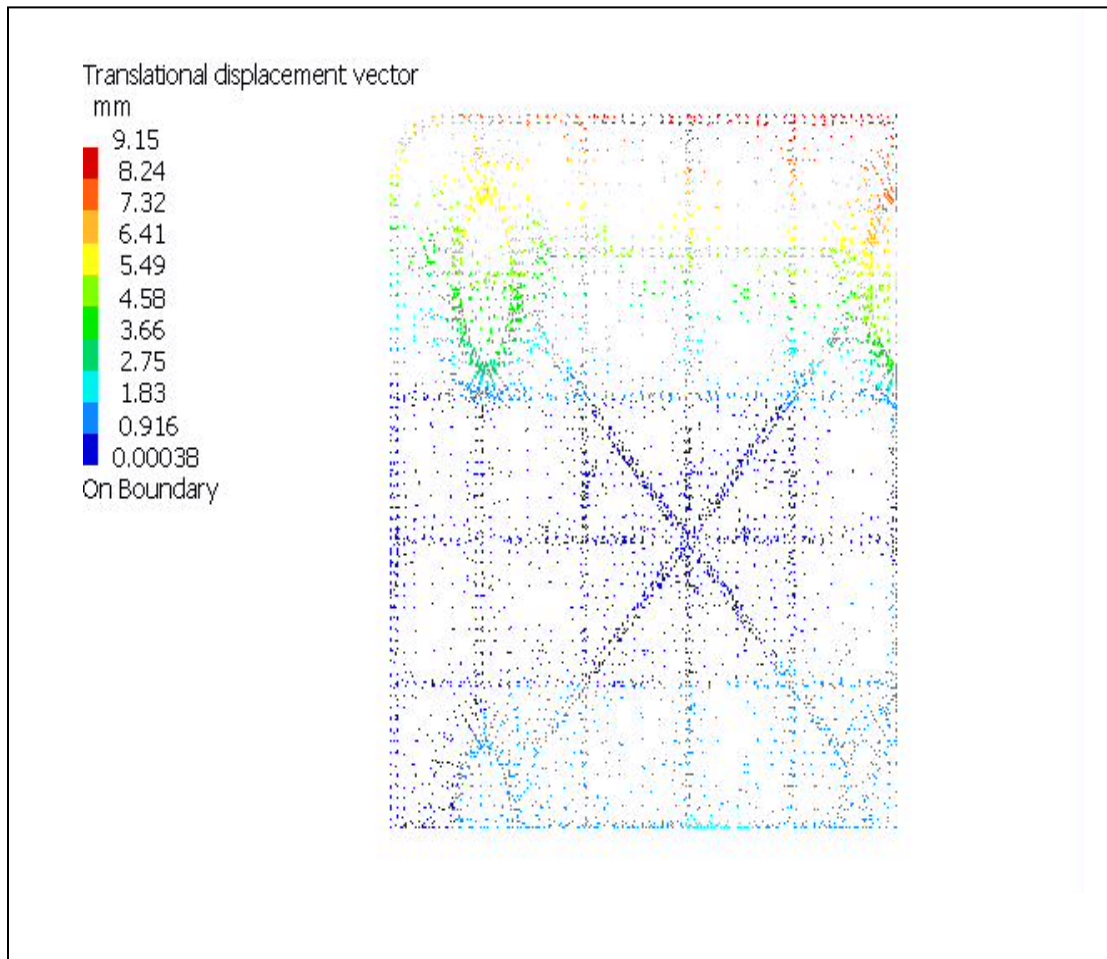
As mentioned previously, in simple linear, static analysis, CATIA doesn't consider yield strength in its calculations. However, yield strength in the ratio yield strength to maximum von Mises stress decides whether the material under consideration is yielded or not. If the ratio is less than one, i.e., maximum von Mises stress (resultant stress in the pallet) is more than that of yield strength of the material under consideration, then material yields rendering the material unsuitable to be used in pallet. Mean value of the yield strength was considered for this analysis.

### **Solving:**

For each set of elastic modulus and Poisson's ratio, the analysis of each recycled plastics blend was performed along main axis and minor axis. The failure limit considered for each recycled plastic blend along main axis and minor axis was, "deflection" and the material was said to have failed if the deflection exceeded one inch (25.4 mm). In addition to deflection as failure limit, another important failure limit "ratio of yield strength to maximum von Mises stress (Value  $\geq 1$  represents 'No Yielding of material under applied load')" for each recycled plastics blend was considered along main axis and minor axis to make sure that the material didn't yield under applied load (though the deflection lies within 1 inch). The results of the same are provided in the next chapter.



*Figure 3.13* FEA model showing Deflection (along main axis)  
(Red color represents highest deflection and blue the lower limit)



*Figure 3.14* FEA model showing deflection (along minor axis)  
(Red color represents highest deflection and blue the lower limit)



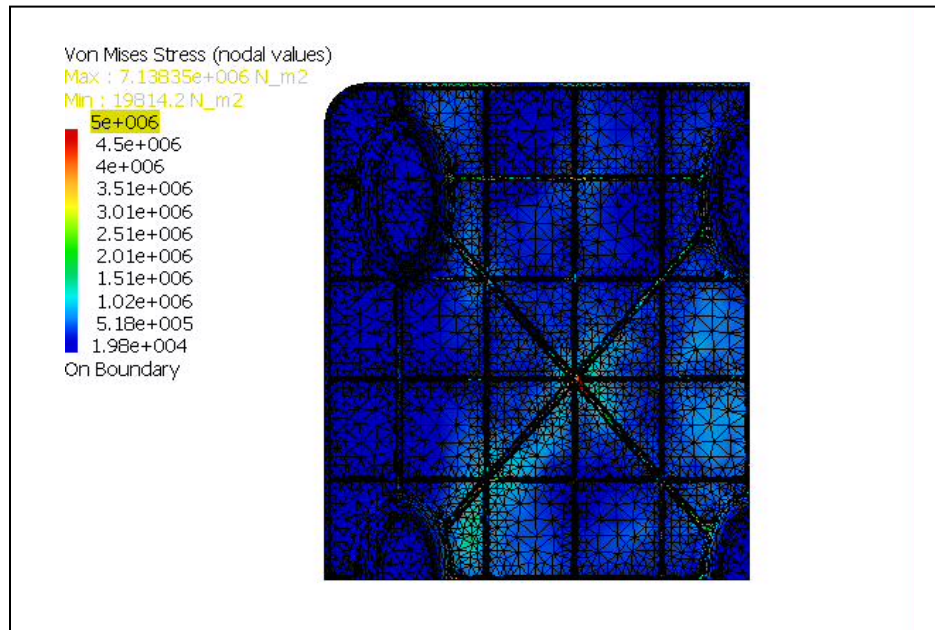


Figure 3.15 FEA model showing von Mises stress distribution (major axis)  
 (Red color represents highest von Mises stress and blue the lower limit)

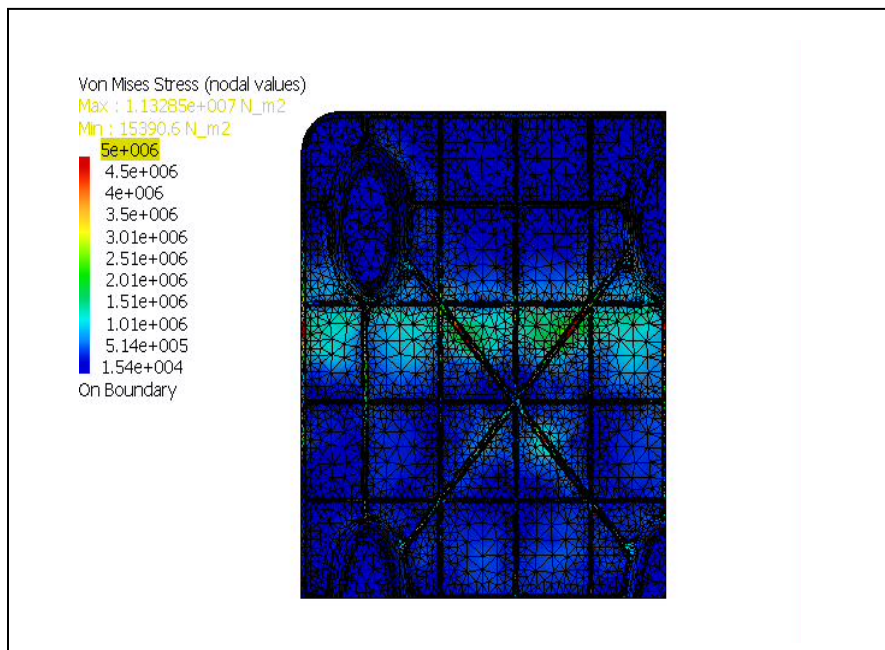


Figure 3.16 FEA model showing von Mises stress distribution (minor axis)  
 (Red color represents highest von Mises stress and blue the lower limit)

## **CHAPTER 4**

### **RESULTS AND ANALYSIS**

The focus of this research is to find out whether recycled plastics can be used for commercial applications such as a molded pallet and to establish guide lines that serve as standards for establishing the suitability of recycled plastics materials for commercial products. To achieve the same, six available recycled plastics blends were tested for adequate mechanical strength, ability to withstand impact and finally analyzed for maximum allowable deflections and stress level under load. Deflection along with ratio of yield strength to maximum von Mises stress obtained by stress analysis was used as the test statistic to determine the suitability of each of six recycled plastics blends. The acceptable limit of deflection was one inch (or 25.4 mm) and the acceptable ratio of yield strength to maximum von Mises stress should be greater than one.

Each of the following sections (each of the five recycled blends) contains the results of density and impact tests along with the material properties obtained from tensile testing needed as input for finite element analysis. Following are the results of finite element analysis of the pallet as discussed in the previous chapter.

Blend #2, consisting of vinyl seats made of poly vinyl chloride, a small amount of polypropylene, and urethane was eliminated in early testing for its poor mechanical properties.

A detailed report of the FEA is shown only for the recycled plastics blend #1 along with its results. For the rest of the four recycled plastics blends, only tables containing values of deflection and ratio of yield strength to maximum von Mises stress are presented, since the results of FEA are similar for deflection and stress distribution (though magnitudes may differ).

The next section consists of analysis and comparison of FEA results of the five recycled plastics blends with their virgin counterparts.

Finally, sensitivity analysis for the five blends is presented to see the effect of changes in Poisson's ratio on pallet deflection. A comparison of the properties of five recycled plastics blends with those of their respective virgin blends.

Note: 1. The following words can be interchangeably used in this chapter:

a) Major axis= main axis = along length = along longer edge

b) Minor axis = along width = along shorter edge

2. Lower limit of modulus is applicable only for virgin plastics blends.

It represents the smallest modulus value of virgin plastics in the blend.

3. Lower value of modulus for Recycled blend= mean modulus -  $3\sigma$

4. Value of ' $\sigma$ ' for Recycled blend was found from sample standard deviation 'S' obtained from tensile testing of ten specimens of each recycled blend.

5. Lower limit of ratio yield stress to max.von Mises stress= 1

## 4.1 PROPERTIES OF RECYCLED BLENDS

The properties of the six recycled plastics blends selected for this research along with their virgin counter parts are shown in Table 4.1. The properties include density (for virgin plastics blends it includes lower value and higher value), impact resistance, elastic modulus (lower limit and mean value) and yield strength.

Table 4.1

*Properties of recycled plastic blends along with their virgin counter parts*

Note: 1. Recycled plastics blends are represented in ‘**BOLD**’ fonts

2. Virgin plastics blends are represented in ‘*ITALIC*’

<u>Blend</u>	<u>Material</u> <b>Recycled</b>  <i>Virgin</i>	<u>Density</u> (Kg/cu.m) <i>Lower limit – higher limit</i>	<u>Impact</u> <u>strength</u> (m-kgf )  Mean value	<u>Modulus</u> (Mpa) lower limit- mean value	<u>Yield</u> <u>Strength</u> (Mpa) Mean value
1	<b>HDPE - PET</b>  <i>HDPE-PET</i>	<b>1153</b> <i>(HDPE) 918- 1400(PET)</i>	<b>2.262</b>	<b>334 - 443</b> <i>(HDPE) 1551.3- 2845.65</i>	<b>4.22</b>  <i>31.2</i>
2	<b>PVC,PP, PU</b>  <i>PVC,PP, PU</i>	<b>1149</b> <i>(PP) 895- 1400(PVC)</i>	<b>5.136</b>	-  -	-  -
3	<b>ABS,PS,PC</b>  <i>ABS,PS,PC</i>	<b>1078</b> <i>(ABS)1018.62- 1339.71(PC)</i>	<b>2.316</b>	<b>477.61-757</b> <i>(ABS) 1792.64- 4895.28</i>	<b>5.56</b>  <i>47</i>
4	<b>LDPE</b>  <i>LDPE</i>	<b>856</b>  <i>910</i>	<b>8.912</b>	<b>79-97.7</b> <i>139.27- 244.76</i>	<b>8.4</b>  <i>15.93</i>
5	<b>Nylon &amp; PET</b>  <i>Nylon &amp; PET</i>	<b>1251</b> <i>(Nylon)1079.52- 1400(PET)</i>	<b>2.63</b>	<b>635-1028.71</b> <i>(PET)2760- 3450</i>	<b>8.05</b>  <i>49.92</i>
6	<b>PS</b>  <i>PS</i>	<b>1004</b>  <i>1040.764</i>	<b>2.172</b>	<b>425-634</b> <i>1792.64- 2585.53</i>	<b>6.342</b>  <i>47</i>

**Recycled blend (RB) #1 (PET and HDPE):**

From table 4.1, it can be seen that the density of RB #1 (1153 kg/cu.m) is 126% of the density of HDPE (918 kg/cu.m) constituent in corresponding virgin plastics blend and that of the mean value of elastic modulus of RB #1 (443 MPa) is about 29% of the elastic modulus of HDPE (1551.3 MPa) constituent in corresponding virgin plastics. The mean value of yield strength of the RB #1 (4.22 MPa) is about 13.5% of corresponding virgin plastics blend (31.2 MPa).

**Recycled blend (RB) #3 (ABS, PS and PC):**

From Table 4.1, it can be seen that the density of RB #3 (1078 kg/cu.m) is 106% of the density of ABS (1018.6 kg/cu.m) constituent in corresponding virgin plastics blend and that of the mean value of elastic modulus of RB #3 (757 MPa) is about 42.2% of the elastic modulus of ABS (1792.6 MPa) constituent in corresponding virgin plastics. The mean value of yield strength of the RB #3 (5.56 MPa) is about 12% of corresponding virgin plastics blend (47 MPa).

**Recycled blend (RB) #4 (LDPE):**

From Table 4.1, it can be seen that the density of RB #4 (856 kg/cu.m) is 94% of the density (910 kg/cu.m) of corresponding virgin plastics blend and that of the mean value of elastic modulus of RB #4 (97.7 MPa) is about 70% of the elastic modulus (139.27 MPa) of corresponding virgin plastics. The mean value of yield strength of the RB #4 (8.4 MPa) is about 53% of the corresponding virgin plastics blend (15.9 MPa).

### **Recycled blend (RB) #5 (Nylon and PET):**

From table 4.1, it can be seen that the density of RB #5 (1251 kg/cu.m) is 116% of the density of Nylon (1079.5 kg/cu.m) constituent in corresponding virgin plastics blend and that of the mean value of elastic modulus of RB #5 (1028.7 MPa) is about 37.27% of the elastic modulus of PET (2760 MPa) constituent in corresponding virgin plastics blend. The mean value of yield strength of the RB #5 (8.05 MPa) is about 16.12% of the corresponding virgin plastics blend (49.92 MPa).

### **Recycled blend (RB) #6 (PS):**

From table 4.1, it can be seen that the density of RB #6 (1004 kg/cu.m) is 96.5% of the density (1040 kg/cu.m) of corresponding virgin plastics blend and that of the mean value of elastic modulus of RB #6 (634 MPa) is about 35.4% of the elastic modulus (1792.6 MPa) of the corresponding virgin plastics blend. The mean value of yield strength of the RB #6 (6.3 MPa) is about 13.4% of the corresponding virgin plastics blend (47 MPa).

## **4.2 BLEND #1: *Recycled blend containing PET and HDPE***

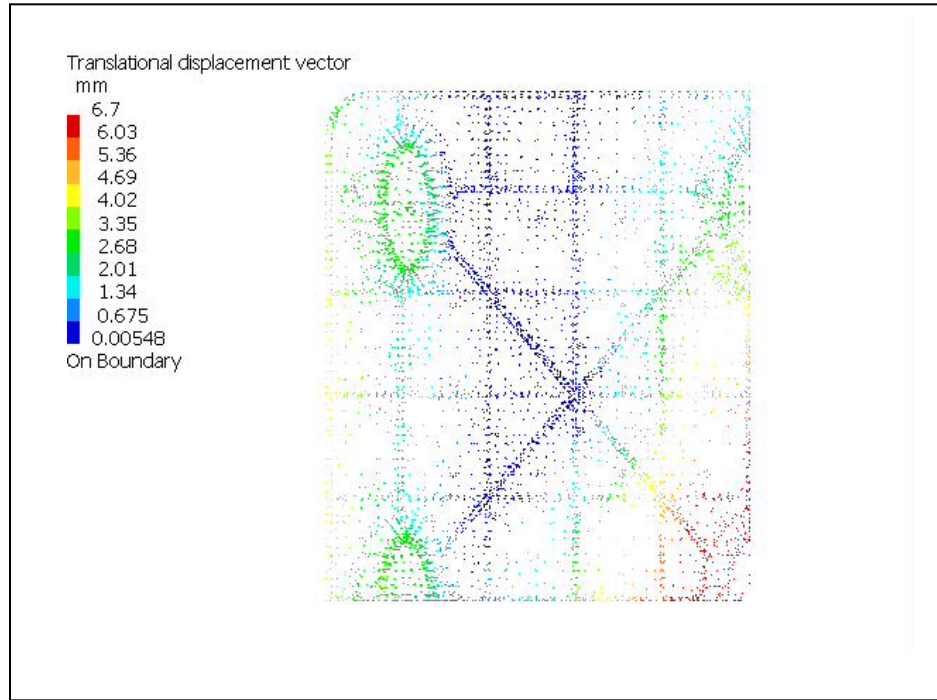
### **4.2.1. Mean value of tensile modulus and mean yield strength**

#### **Finite element analysis results:**

a) Along main axis:

The Figure 4.1 shows the deflection of the pallet subjected to a distributed load (example: weight due to a stack of sheet metal blanks stored on the pallet) of 255 lbs (1000 lbs for the whole pallet) along major axis. The deflection is high towards the center

of the pallet as shown in red color. However, the magnitude (6.67 mm as shown in the Table 4.2 below) of it is well under the established failure limit of 25.4 mm (or one inch).



*Figure 4.1* FEA model of pallet showing Deflection (Along main axis)  
(Red color represents highest deflection and blue the lower limit)

Table 4.2

*Deflection value for mean modulus and mean yield strength of material blend #1 along main axis*

	<b>Yield strength</b>	<b>Mean</b>
Modulus:		Deflection along main axis (longer edge of the pallet) (mm)
<b>Mean</b>		6.67

Fig.4.2 shows the FEA model of pallet showing stress distribution due to application of distributed load 255 lbs along major axis. The maximum stress occurs along the rib as shown in Fig.4.2. However, the ratio of yield stress to maximum von Mises stress, is greater than one indicating that material did not yield ( as shown in the table 4.3 below).

Table 4.3

*Ratio of yield stress to maximum stress for mean modulus and mean yield strength of material blend #1 along main axis*

	Yield strength	Mean
Modulus:		<i>Ratio of Yield stress to Max.stress</i> along main axis (longer edge of the pallet)
<b>Mean</b>		1.31

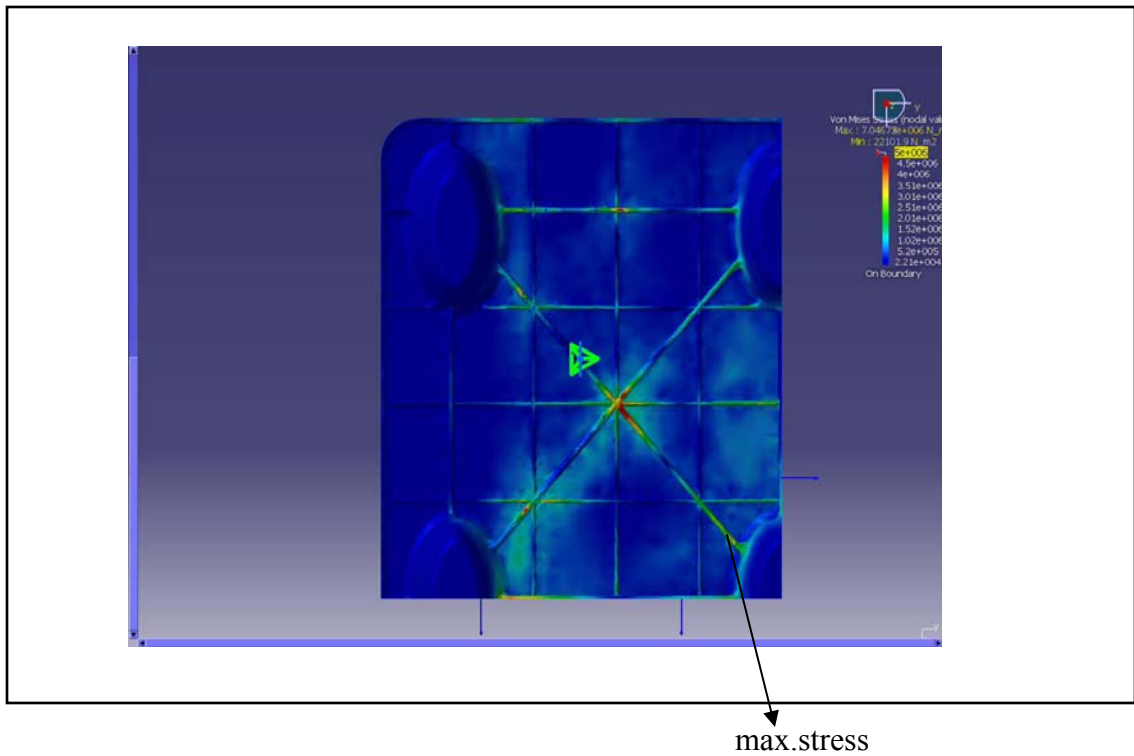
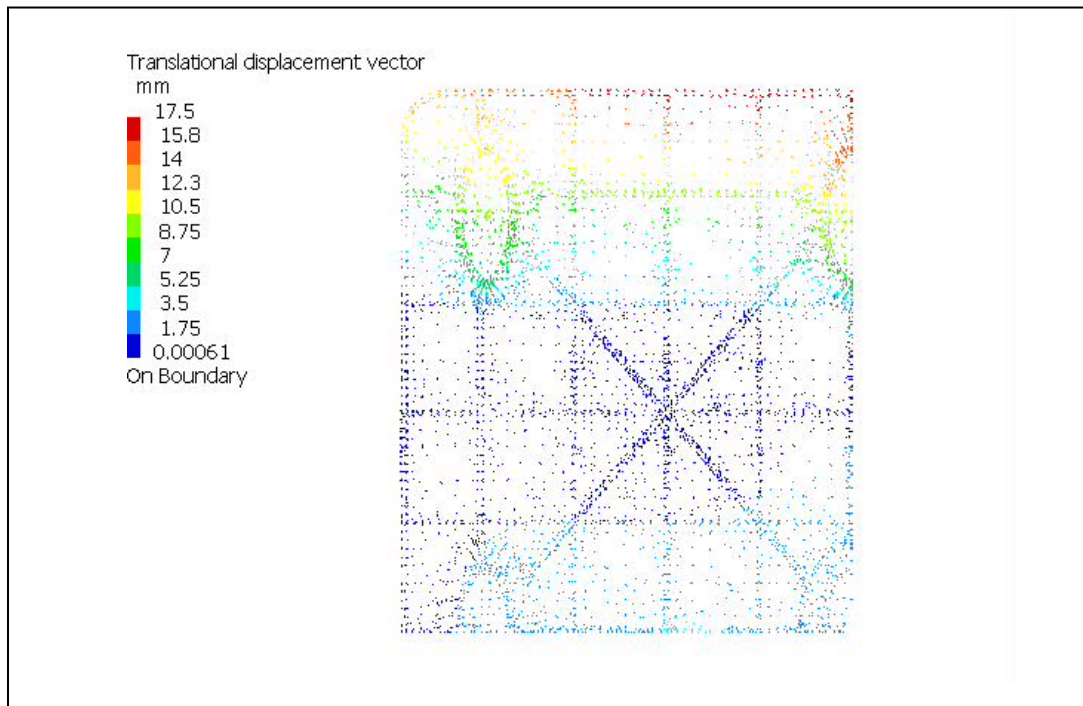


Figure 4.2 FEA model of pallet showing stress distribution (along main axis)



b) Along minor axis:

The Figure 4.3 shows the deflection of the pallet subjected to a distributed load of 255 lbs (1000 lbs for the whole pallet) along minor axis. The deflection is high towards the edge of the pallet, as shown in red color in the Fig. 4.3. However, the magnitude [(17.5 mm) as shown in the table 4.4 below] of it is less than the established failure limit [of 25.4 mm (or one inch)].



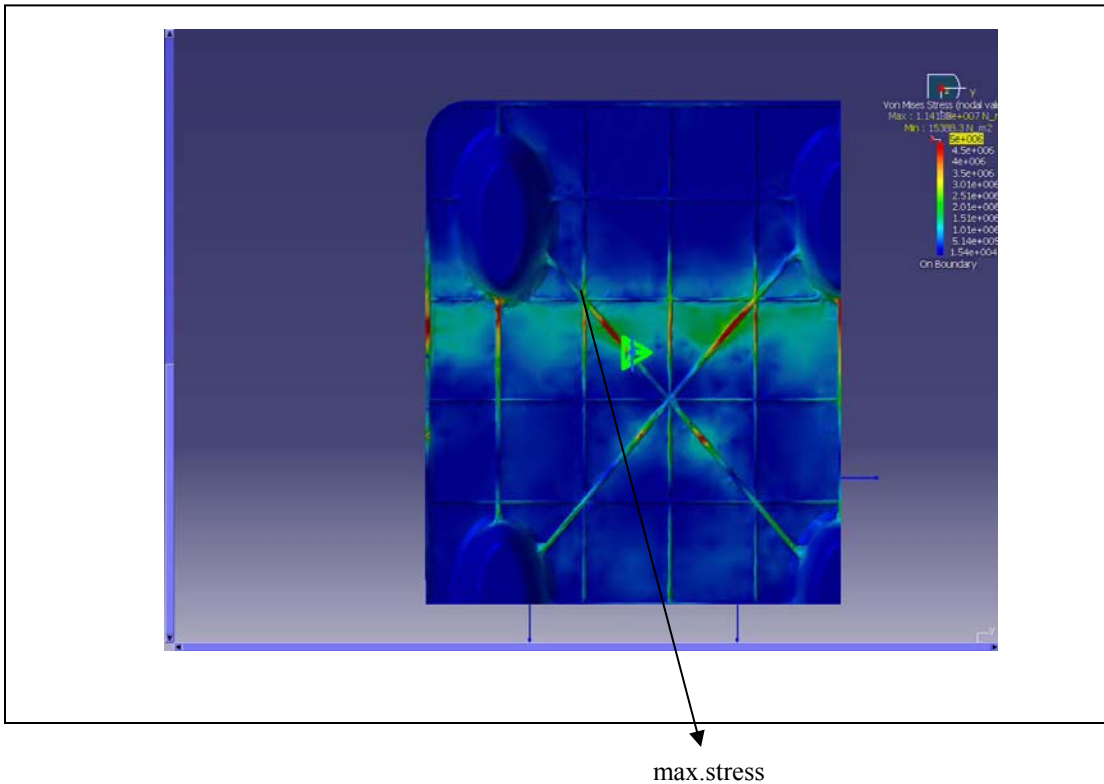
*Figure 4.3* FEA model of pallet showing deflection (along minor axis)  
(Red color represents highest deflection and blue the lower limit)

Table 4.4

*Deflection value for mean modulus and mean yield strength of material blend #1 along minor axis*

	<b>Yield strength</b>	<b>Mean</b>
Modulus:		<b>Deflection</b> along minor axis (shorter edge of the pallet) (mm)
<b>Mean</b>		17.5

Fig. 4.4 shows the FEA model of pallet showing stress distribution due to application of distributed load 255 lbs along minor axis. The maximum stress occurs along the rib as shown in Fig.4.4. the ratio of yield stress to maximum von Mises stress, is less than one (as shown in the table 4.5 below) indicating that material has yielded, eliminating the blend #1 with mean modulus and mean yield strength to be used in pallet



*Figure 4.4 FEA model of pallet showing stress distribution (along minor axis)*

Table 4.5

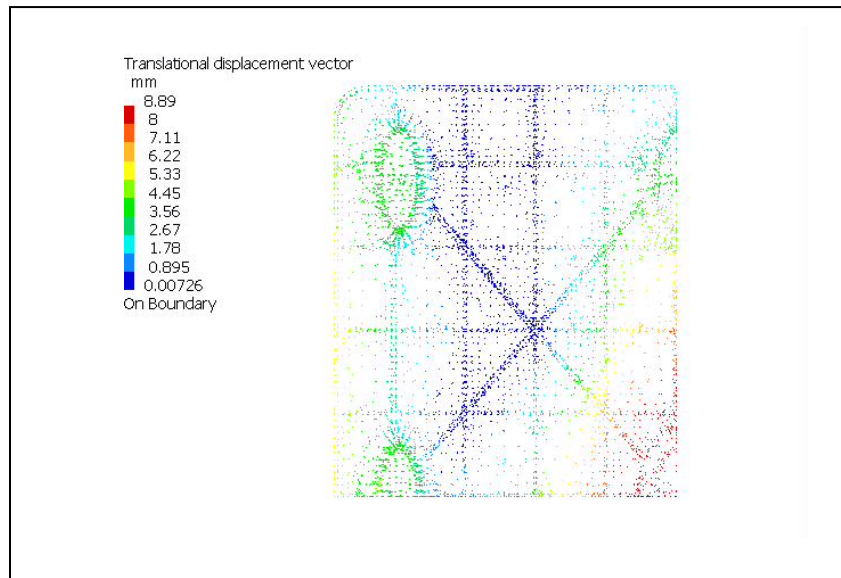
*Ratio of yield stress to Maximum stress for mean modulus and mean yield strength of material blend #1 along minor axis*

	Yield strength	Mean
Modulus:	<i>Ratio of Yield stress to Max.stress</i> along minor axis (shorter edge of the pallet)	
Mean	0.7	

#### 4.2.2. Lower limit of tensile modulus and mean yield strength

a) Along main axis:

The Figure 4.5 shows the deflection of the pallet subjected to a distributed load of 255 lbs (1000 lbs for the whole pallet) along major axis. The deflection is high towards the center of the pallet, as shown in red color in the Fig. 4.5. However, the magnitude [(8.89 mm) as shown in table 4.6 below] is less than the established failure limit of 25.4 mm (or one inch).



*Figure 4.5 FEA model of pallet showing deflection (along main axis)  
(Red color represents highest deflection and blue the lower limit)*

Table 4.6

*Deflection value for lower limit modulus and mean yield strength of material blend #1 along major axis*

	<b>Yield strength</b>	<b>Mean</b>
Modulus:		<b>Deflection</b> along main axis (longer edge of the pallet) (mm)
<b>mean-3<math>\sigma</math></b>		8.89

Fig. 4.6 shows the FEA model of pallet showing stress distribution due to application of distributed load 255 lbs along major axis. The maximum stress occurs along the rib as shown in Fig.4.6. However, the ratio of yield stress to maximum von Mises stress is greater than one ( as shown in table 4.7 below) indicating that material has not yielded.

Table 4.7

*Ratio of yield stress to maximum stress for lower limit of modulus and mean yield strength of material blend #1 along major axis*

	<b>Yield strength</b>	<b>Mean</b>
Modulus:		<b>Ratio of Yield stress to Max.stress</b> along main axis (longer edge of the pallet)
<b>mean-3<math>\sigma</math></b>		1.1

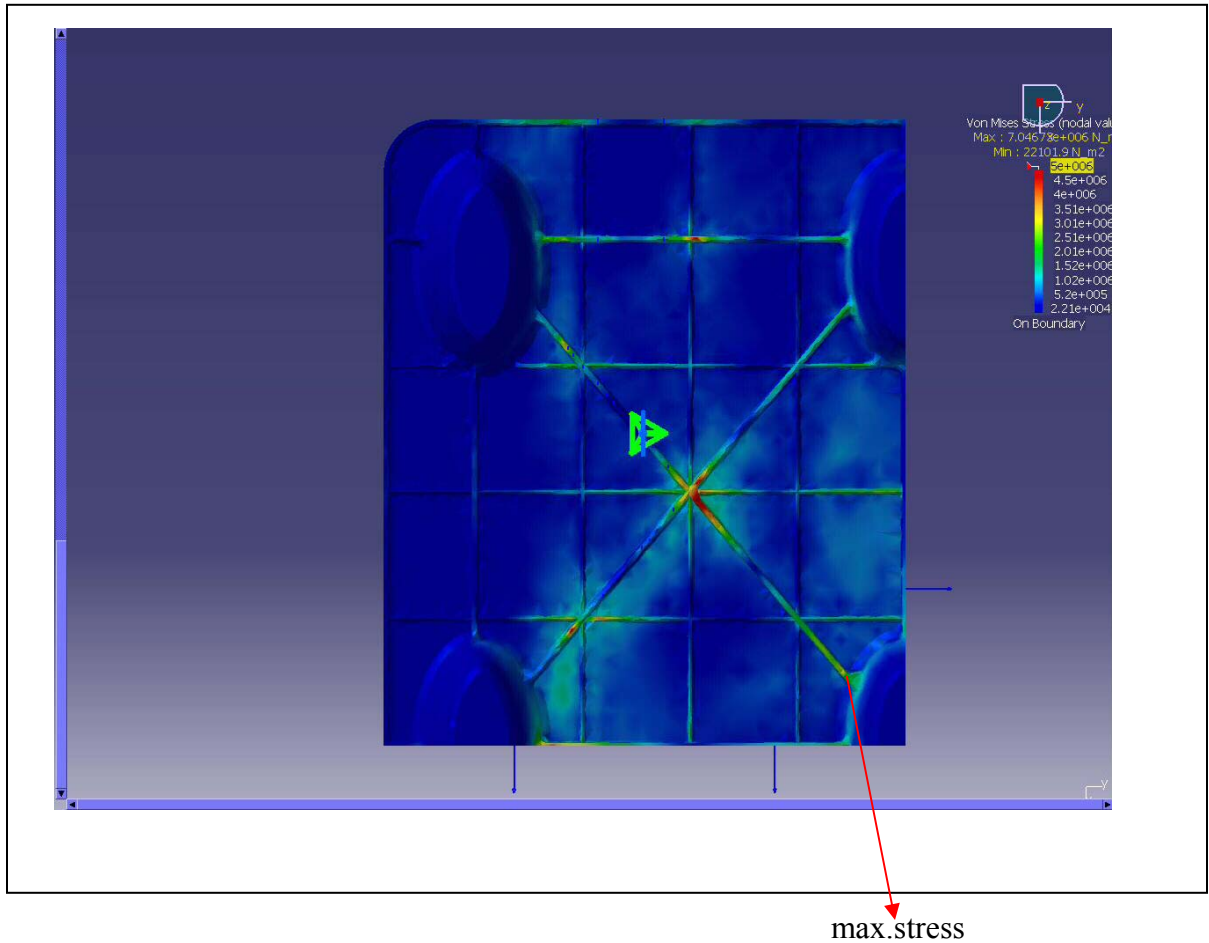


Figure 4.6 FEA model of pallet showing stress distribution (along major axis)

b) Along minor axis:

The Figure 4.7 shows the deflection of the pallet subjected to a distributed load of 255 lbs (1000 lbs for the whole pallet) along minor axis. The deflection is high towards the edge of the pallet, as shown in red color in the Fig. 4.7. The magnitude [(23.2 mm) as shown in the table 4.8 below] though huge, is less than the established failure limit of 25.4 mm (or one inch).

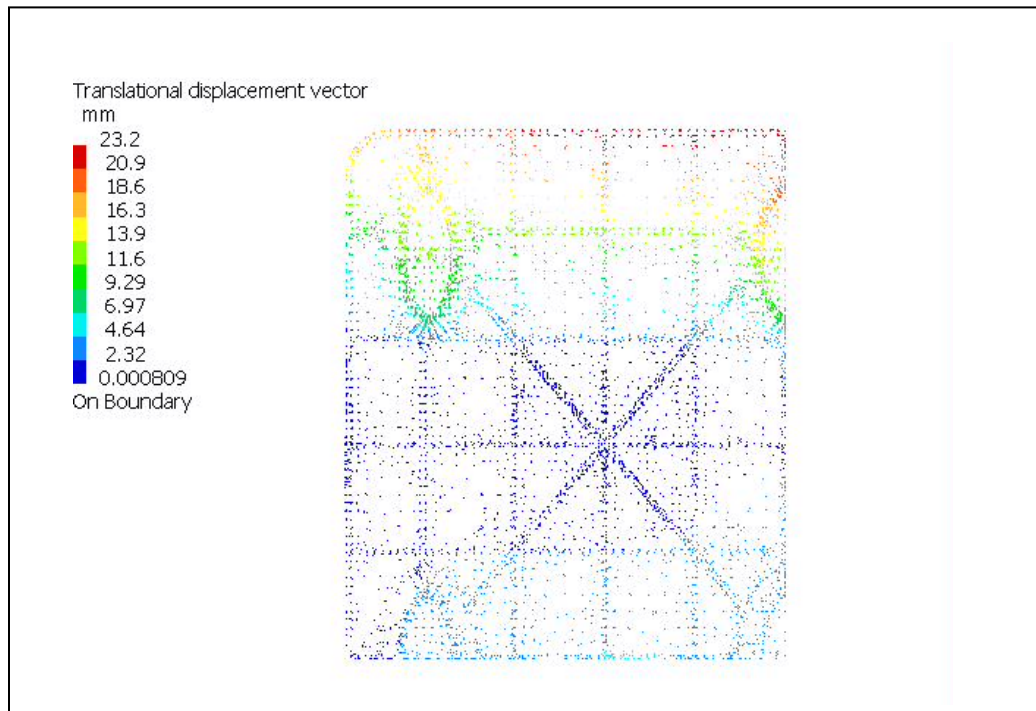


Figure 4.7 FEA model of pallet showing deflection (along minor axis)  
 (Red color represents highest deflection and blue the lower limit)

Table 4.8

*Deflection value for lower limit of modulus and mean yield strength of material blend #1 along minor axis*

	<b>Yield strength</b>	<b>Mean</b>
Modulus:		<b>Deflection</b> along minor axis (shorter edge of the pallet) (mm)
<b>mean-3σ</b>		23.2

Fig. 4.8 shows the FEA model of pallet showing stress distribution due to application of distributed load 255 lbs along minor axis. The maximum stress occurs along the rib as shown in Fig.4.8. the ratio of yield stress to maximum von Mises stress,

is less than one (as in table 4.9 below) indicating that material has yielded, eliminating the blend #1 with lower limit of modulus and mean yield strength to be used in pallet

Table 4.9

*Ratio of yield stress to maximum stress for lower limit of modulus and mean yield strength of material blend #1 along minor axis*

	yield strength	mean
modulus:	<i>ratio of yield stress to max.stress</i> along minor axis (shorter edge of the pallet)	
<b>mean-3σ</b>		0.69

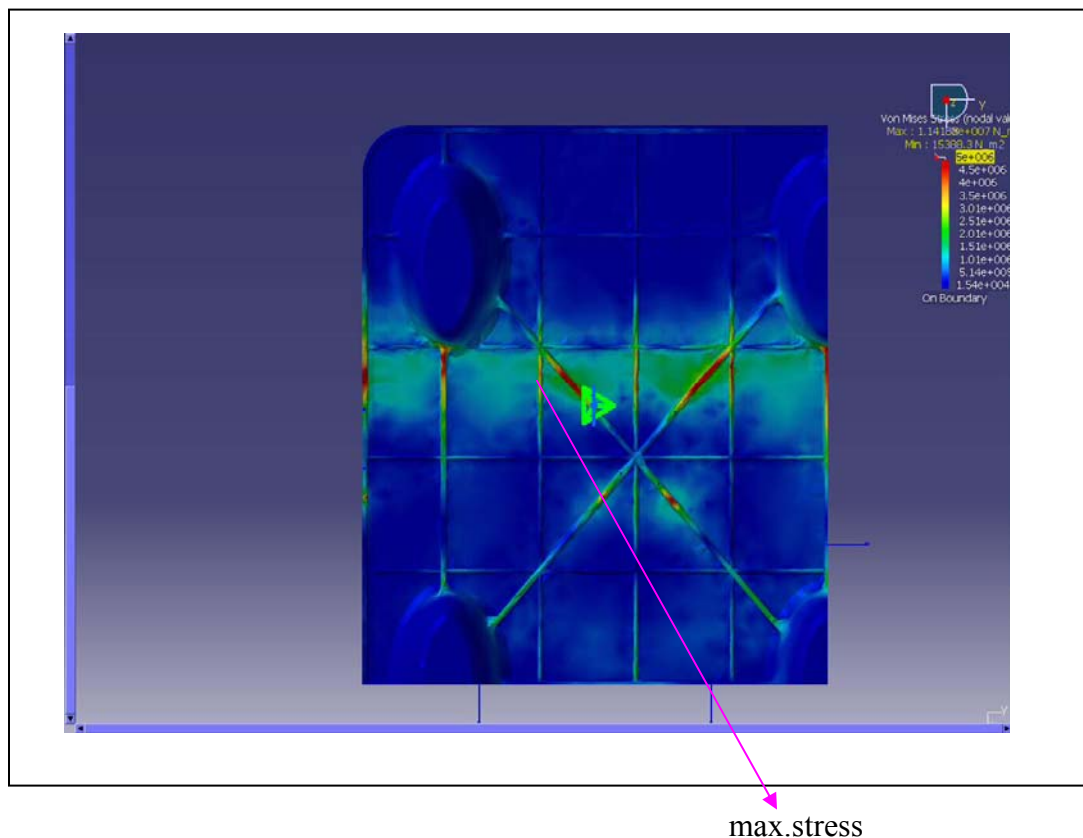


Figure 4.8 FEA model of pallet showing stress distribution (along minor axis)

### **4.3 COMPARISON OF THE PERFORMANCE OF RECYCLED PLASTICS AND VIRGIN PLASTICS**

This section contains comparison of the performance of recycled plastics blends and their virgin counter parts. This section essentially is a summary of results of finite element analysis for the five recycled plastics blends along the same lines of to the finite element analysis procedure followed for blend #1 (PET and HDPE) presented in the previous section; the only addition here includes results of the finite element analysis of corresponding virgin plastics blends.

The values of density and impact tests along with the material properties needed as input for finite element analysis of virgin plastics blends were obtained from material property data sheets.

#### **4.3.1 Mean modulus and mean yield strength of recycled blends and their virgin counterparts**

The following table 4.10 consists of finite element analysis results (for the values of mean modulus and mean yield strength combination) of the five recycled plastics blends along with their virgin counterparts. Note that we do not know the exact composition of the recycled plastics; therefore, we have used mean values of the constituents as an estimate of the virgin plastics properties.



Table 4.10

*Summary of finite element results of recycled/virgin plastics blends (for mean modulus and mean yield strength)*

Results	Recycled blends (Virgin plastics blends)					
	1	2	3	4	5	6
<b>Deflection along length of pallet ( mm)</b>	<b>6.7</b>	-	<b>4.02</b>	<b>30.4</b>	<b>2.95</b>	<b>4.8</b>
<i>Deflection along length of pallet– (mm)</i>	<i>1.04</i>	-	<i>0.62</i>	<i>12.1</i>	<i>0.88</i>	<i>1.18</i>
<b>Deflection along width of pallet (mm)</b>	<b>17.5</b>	-	<b>10.4</b>	<b>79.4</b>	<b>7.66</b>	<b>12.5</b>
<i>Deflection along width of pallet– (mm)</i>	<i>2.72</i>	-	<i>1.61</i>	<i>31.7</i>	<i>2.28</i>	<i>3.06</i>
<b>Ratio of yield stress / Max. Von Mises stress along length (&gt;1 will be better)</b>	<b>1.3</b>	-	<b>1.69</b>	<b>2.6</b>	<b>2.45</b>	<b>1.93</b>
<i>Ratio of yield stress / Max. Von Mises stress along length</i>	<i>9.65</i>	-	<i>14.2</i>	<i>4.9</i>	<i>15.2</i>	<i>14.3</i>
<b>Ratio of yield stress / Max. Von Mises stress along width (&gt;1 will be better)</b>	<b>0.7</b>	-	<b>0.9</b>	<b>1.4</b>	<b>1.31</b>	<b>1.02</b>
<i>Ratio of yield stress / Max. Von Mises stress along width</i>	<i>6.3</i>	-	<i>7.6</i>	<i>2.7</i>	<i>50</i>	<i>7.6</i>

Note:

1. Values in “**Bold**” represent values of recycled blends
2. Values in “*Italics*” represent values of corresponding virgin plastics blend
3. Blend 1 = PET and HDPE (Recycled/virgin)  
 Blend 2= PVC, PP and PU (Recycled/virgin)  
 Blend 3= ABS, PS and PC (Recycled/virgin)  
 Blend 4= LDPE (Recycled/virgin)  
 Blend 5= Nylon and PET (Recycled/virgin)  
 Blend 6= PS (Recycled/virgin)

The following graphs are the graphical representation of finite element analysis results that are summarized in the table 4.10.

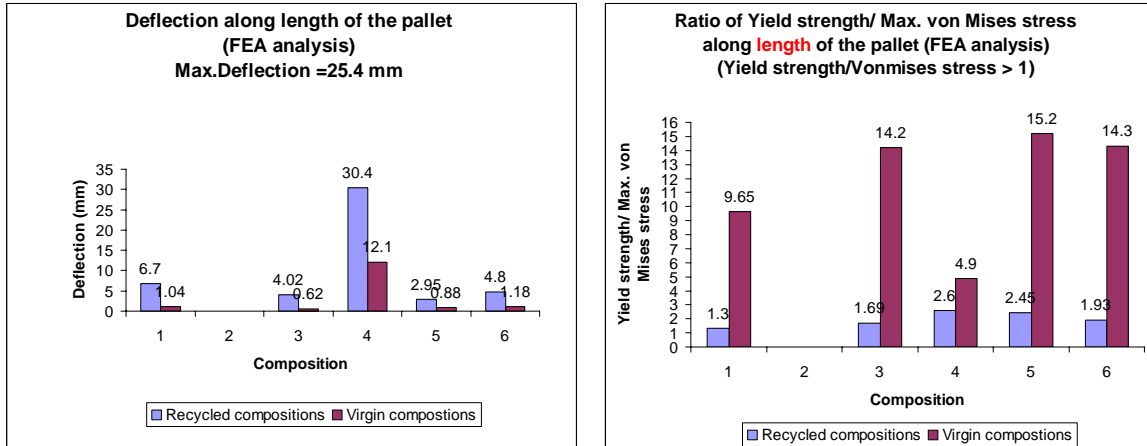


Figure 4.9 Deflection and ratio of yield strength to max.von Mises stress for five recycled blends along with their virgin counter parts (along major axis)

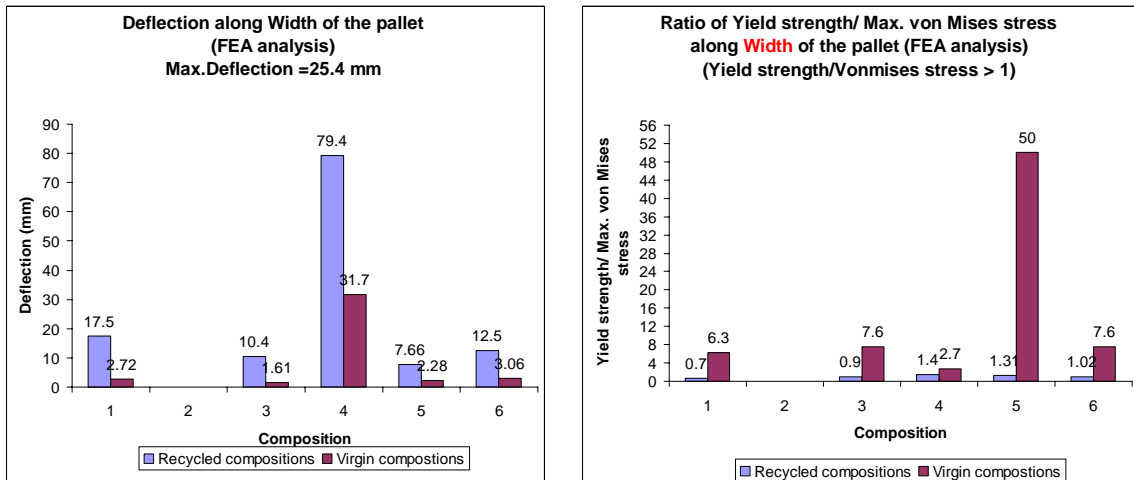


Figure 4.10 Deflection and ratio of yield strength to max.von Mises stress for five recycled blends along with their virgin counter parts (along minor axis)

### **a) Recycled plastics blend (RPB) #1:**

From the Fig. 4.9 it can be noted that the deflection along length (6.7 mm) though slightly more than its virgin counter part (1.04 mm), is well below the failure limit (25.4 mm). The ratio of yield stress to max.von Mises stress for RPB #1 (1.3) is smaller than its virgin counter part (9.65), is greater than the lower limit 1, indicating that RPB #1 along major axis, did not fail either by deflection or by yielding during finite element analysis of the pallet.

However, from the Fig. 4.10 it can be noted that, the deflection along width (17.5 mm) though more than its virgin counter part (2.72 mm), is well under the failure limit (25.4 mm). The ratio of yield stress to max.von Mises stress for the RPB #1 along minor axis (0.7) is far less than its virgin counter part (6.3) and the lower limit 1. This indicates that RPB #1 along minor axis did not fail by deflection but by yielding during finite element analysis of the pallet.

### **b) Recycled plastics blend (RPB) #2:**

Recycled plastics blend #2 consisting of vinyl seats made of poly vinyl chloride, a small amount of polypropylene and urethane, was eliminated for its poor performance (low tensile strength).

### **c) Recycled plastics blend (RPB) #3:**

From the Fig. 4.9 it can be noted that, the deflection along length (4.02 mm) though more than its virgin counter part (0.62 mm), is well below the failure limit (25.4 mm). The ratio of yield stress to max.von Mises stress for RPB #3(1.69) though smaller than its virgin counter part (14.2), is more than the established lower limit 1, indicating

that RPB #3 along major axis, did not fail either by deflection or by yielding during finite element analysis of the pallet.

From the Fig. 4.10 it can be noted that, the deflection along width (10.4 mm) though more than its virgin counter part (1.61 mm), is well under the failure limit (25.4 mm). The ratio of yield stress to max.von Mises stress for the RPB #3 along minor axis (0.9) is far less than its virgin counter part (7.6) still, is closer to the lower limit 1. This indicates that RPB #3 along minor axis did not fail either by deflection or by yielding during finite element analysis of the pallet.

#### **d) Recycled plastics blend (RPB) #4:**

From the Fig. 4.9 it can be noted that, the deflection along length (30.4 mm) is far more than its virgin counter part (12.1 mm) and is well above the failure limit (25.4 mm). The ratio of yield stress to max.von Mises stress for RPB #4 (2.6) though smaller than its virgin counter part (4.9), is still more than the established lower limit 1. This indicates that RPB #4 along major axis did fail by deflection and not by yielding during finite element analysis of the pallet.

From the Fig. 4.10 it can be noted that, the deflection along width (79.4 mm) is more than its virgin counter part (31.7 mm) as well as the failure limit (25.4 mm). The ratio of yield stress to max.von Mises stress for the RPB #4 along minor axis (1.4) is less than its virgin counter part (2.7) but is more than the lower limit 1. This indicates that RPB #4 along minor axis did not fail either by deflection or by yielding during finite element analysis of the pallet.

#### **e) Recycled plastics blend (RPB) #5:**

From the Fig. 4.9 it can be noted that, the deflection along length (2.95 mm) is more than its virgin counter part (0.88 mm) still, is well below the failure limit (25.4 mm). The ratio of yield stress to max.von Mises stress for RPB #5(2.45) though smaller than its virgin counter part (15.2) is still more than the established lower limit 1. This indicates that RPB #5 along major axis did not fail by either deflection or by yielding during finite element analysis of the pallet.

From the Fig. 4.10 it can be noted that, the deflection along width (7.66 mm) is more than its virgin counter part (2.28 mm) but well below the failure limit (25.4 mm). The ratio of yield stress to max.von Mises stress for the RPB #5 along minor axis (1.31) is far less than its virgin counter part (50) but is more than the lower limit 1. This indicates that RPB #5 along minor axis did not fail either by deflection or by yielding during finite element analysis of the pallet.

#### **f) Recycled plastics blend (RPB) #6:**

From the Fig. 4.9 it can be noted that, the deflection along length (4.8 mm) is more than its virgin counter part (1.18 mm) still, is well below the failure limit (25.4 mm). The ratio of yield stress to max.von Mises stress for RPB #6(1.93) though smaller than its virgin counter part (14.3) still, is more than the established lower limit 1. This indicates that RPB #6 along major axis did not fail by either deflection or by yielding during finite element analysis of the pallet.

From the Fig. 4.10 it can be noted that, the deflection along width (12.5 mm) is more than its virgin counter part (3.06 mm) but well below the failure limit (25.4 mm). The ratio of yield stress to max.von Mises stress for the RPB #6 along minor axis (1.02)

is far less than its virgin counter part (7.6) but is more than the lower limit 1. This indicates that RPB #6 along minor axis did not fail either by deflection or by yielding during finite element analysis of the pallet.

### 4.3.2 Lower limit modulus and mean yield strength of recycled blends and their virgin counterparts

The following table 4.11 consists of finite element analysis results (for the values of lower limit modulus and mean yield strength combination) of the five recycled plastics blends along with their virgin counterparts.

Table 4.11

*Summary of finite element results of recycled/virgin plastics blends (for lower limit of modulus and mean yield strength)*

Properties	Recycled blends (Virgin plastics blends)					
	1	2	3	4	5	6
<b>Deflection along length of pallet ( mm)</b>	<b>8.89</b>	-	<b>6.37</b>	<b>37.6</b>	<b>4.77</b>	<b>7.15</b>
<i>Deflection along length of pallet– (mm)</i>	<i>1.91</i>	-	<i>1.7</i>	<i>21.4</i>	<i>1.1</i>	<i>1.7</i>
<b>Deflection along width of pallet (mm)</b>	<b>23.2</b>	-	<b>16.5</b>	<b>98.2</b>	<b>12.4</b>	<b>18.6</b>
<i>Deflection along width of pallet– (mm)</i>	<i>5</i>	-	<i>4.41</i>	<i>55.8</i>	<i>2.92</i>	<i>4.41</i>
<b>Ratio of yield stress to max.von Mises stress along length (&gt;1 will be better)</b>	<b>1.1</b>	-	<b>1.04</b>	<b>2.5</b>	<b>1.7</b>	<b>1.2</b>
<i>Ratio of yield stress to max.von Mises stress along length</i>	<i>9.66</i>	-	<i>14.29</i>	<i>4.93</i>	<i>15.17</i>	<i>14.2</i>
<b>Ratio of yield stress to max.von Mises stress along width</b>	<b>0.6</b>	-	<b>0.55</b>	<b>1.34</b>	<b>0.9</b>	<b>0.6</b>
<i>Ratio of yield stress to max.von Mises stress along width</i>	<i>5.2</i>	-	<i>9.29</i>	<i>2.65</i>	<i>8.1</i>	<i>7.59</i>

Note:

1. Values in “**Bold**” represent values of recycled blends
2. Values in “*Italics*” represent values of corresponding virgin plastics blend

- 3. Blend 1 = PET and HDPE (Recycled/virgin)
- Blend 2= PVC, PP and PU (Recycled/virgin)
- Blend 3= ABS, PS and PC (Recycled/virgin)
- Blend 4= LDPE (Recycled/virgin)
- Blend 5= Nylon and PET (Recycled/virgin)
- Blend 6= PS (Recycled/virgin)

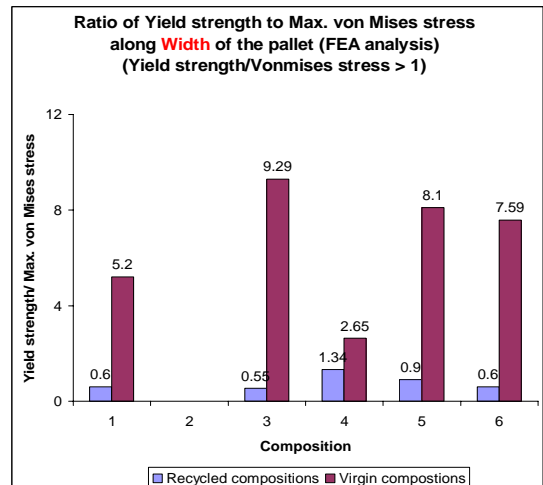
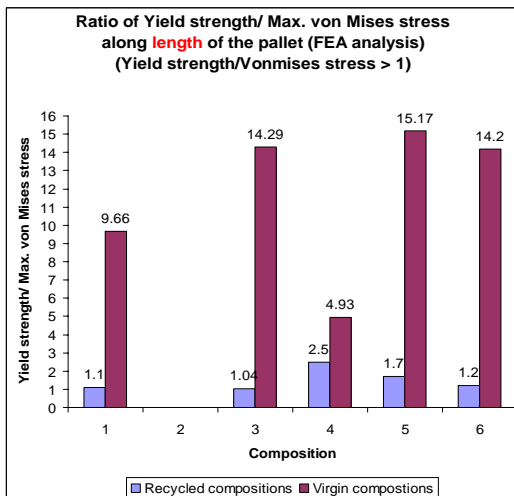
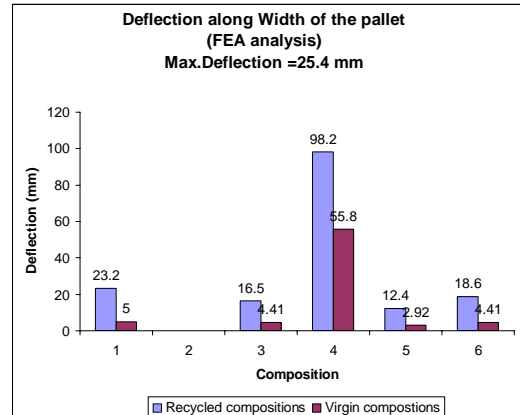
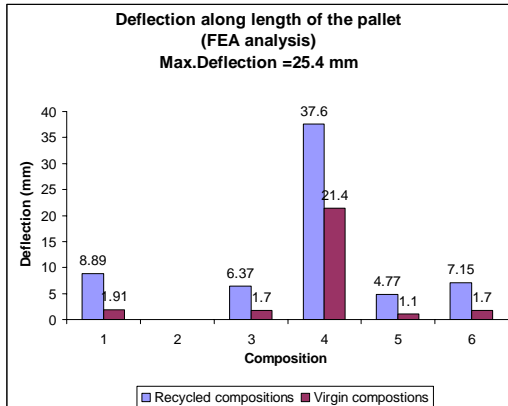


Figure 4.11 Deflection and ratio of yield strength to max.von Mises stress for five recycled blends along with their virgin counter parts (along major and minor axis)

### **a) Recycled plastics blend (RPB) #1:**

From the Fig. 4.11 it can be noted that the deflection along length (8.89 mm) though slightly more than its virgin counter part (1.91 mm), is well below the failure limit (25.4 mm). The ratio of yield stress to max.von Mises stress for RPB #1 (1.1) is smaller than its virgin counter part (9.66) but is greater than the lower limit 1, indicating that RPB #1 along major axis, did not fail either by deflection or by yielding during finite element analysis of the pallet.

From the Fig. 4.11 it can be noted that, the deflection along width (23.2 mm) though more than its virgin counter part (5 mm) still, is under the failure limit (25.4 mm). However, the ratio of yield stress to max.von Mises stress for the RPB #1 along minor axis (0.6) is far less than its virgin counter part (5.2) and the established lower limit 1. This indicates that RPB #1 along minor axis did not fail by deflection but by yielding during finite element analysis of the pallet.

### **b) Recycled plastics blend (RPB) #2:**

Recycled plastics blend #2 consisting of vinyl seats made of poly vinyl chloride, a small amount of polypropylene and urethane, was eliminated for its poor performance (low tensile strength).

### **c) Recycled plastics blend (RPB) #3:**

From the Fig. 4.11 it can be noted that, the deflection along length (6.37 mm) though more than its virgin counter part (1.7 mm), is still well below the failure limit (25.4 mm). The ratio of yield stress to max.von Mises stress for RPB #3 (1.04) though smaller than its virgin counter part (14.29), is more than the established lower limit 1,



indicating that RPB #3 along major axis, did not fail either by deflection or by yielding during finite element analysis of the pallet.

From the Fig. 4.11 it can be noted that, the deflection along width (16.5 mm) though more than its virgin counter part (4.41 mm), is still well under the failure limit (25.4 mm). However, the ratio of yield stress to max.von Mises stress for the RPB #3 along minor axis (0.55) is far less than its virgin counter part (9.29) also less than the established lower limit 1. This indicates that RPB #3 along minor axis did not fail by deflection but by yielding during finite element analysis of the pallet.

#### **d) Recycled plastics blend (RPB) #4:**

From the Fig. 4.11 it can be noted that, the deflection along length (37.6 mm) is far more than its virgin counter part (21.4 mm) and is well above the failure limit (25.4 mm). The ratio of yield stress to max.von Mises stress for RPB #4 (2.5) though smaller than its virgin counter part (4.93), is still more than the established lower limit 1. This indicates that RPB #4 along major axis did fail by deflection and not by yielding during finite element analysis of the pallet.

From the Fig. 4.11 it can be noted that, the deflection along width (98.2 mm) is more than its virgin counter part (55.8 mm) as well as the failure limit (25.4 mm). The ratio of yield stress to max.von Mises stress for the RPB #4 along minor axis (1.34) is less than its virgin counter part (2.65) but is more than the lower limit 1. This indicates that RPB #4 along minor axis did not fail either by deflection or by yielding during finite element analysis of the pallet.

#### **e) Recycled plastics blend (RPB) #5:**

From the Fig. 4.11 it can be noted that, the deflection along length (4.77 mm) is more than its virgin counter part (1.1 mm), is still well below the failure limit (25.4 mm). The ratio of yield stress to max.von Mises stress for RPB #5 (1.7) though smaller than its virgin counter part (15.17) still, is more than the established lower limit 1. This indicates that RPB #5 along major axis did not fail by either deflection or by yielding during finite element analysis of the pallet.

From the Fig. 4.11 it can be noted that, the deflection along width (12.4 mm) is more than its virgin counter part (2.92 mm) but well below the failure limit (25.4 mm). The ratio of yield stress to max.von Mises stress for the RPB #5 along minor axis (0.9) is far less than its virgin counter part (8.1) but is closer to the lower limit 1. This indicates that RPB #5 along minor axis did not fail either by deflection or by yielding during finite element analysis of the pallet.

#### **f) Recycled plastics blend (RPB) #6:**

From the Fig. 4.11 it can be noted that, the deflection along length (7.15 mm) is more than its virgin counter part (1.7 mm), is still well below the failure limit (25.4 mm). The ratio of yield stress to max.von Mises stress for RPB #6 (1.2) though smaller than its virgin counter part (14.2), is still more than the established lower limit 1. This indicates that RPB #6 along major axis did not fail by either deflection or by yielding during finite element analysis of the pallet.

From the Fig. 4.11 it can be noted that, the deflection along width (18.6 mm) is more than its virgin counter part (4.41 mm) but well below the failure limit (25.4 mm). The ratio of yield stress to max.von Mises stress for the RPB #6 along minor axis (0.6) is

far less than its virgin counter part (7.59) but is closer to the lower limit 1. This indicates that RPB #6 along minor axis did not fail either by deflection or by yielding during finite element analysis of the pallet.

#### **4.4 SENSITIVITY ANALYSIS OF RECYCLED BLENDS**

(Mean modulus and mean yield strength but different applicable Poisson's ratios)

In this research, the exact Poisson's ratio for each of the six recycled plastics blends was unknown. Since exact Poisson's ratio for each blend of recycled plastics was unknown, finite analysis was carried out using Poisson's ratios available from material properties chart.

In order to study the effect of Poisson's ratio on the finite element analysis results of five of the six available recycled plastics blends, a sensitivity analysis was carried out involving lower, actual and higher limit (based on intuition) values of Poisson's ratio in combination (exception would be the blend #4) with mean value of elastic modulus and yield strength for the finite element analysis of the pallet.

The sensitivity analysis of Poisson's ratio for each of the five recycled plastics blend consists of comparing deflection and ratio of yield stress to maximum von Mises stress values for lower, actual and higher values Poisson's ratios.

#### 4.4.1 BLEND #1:

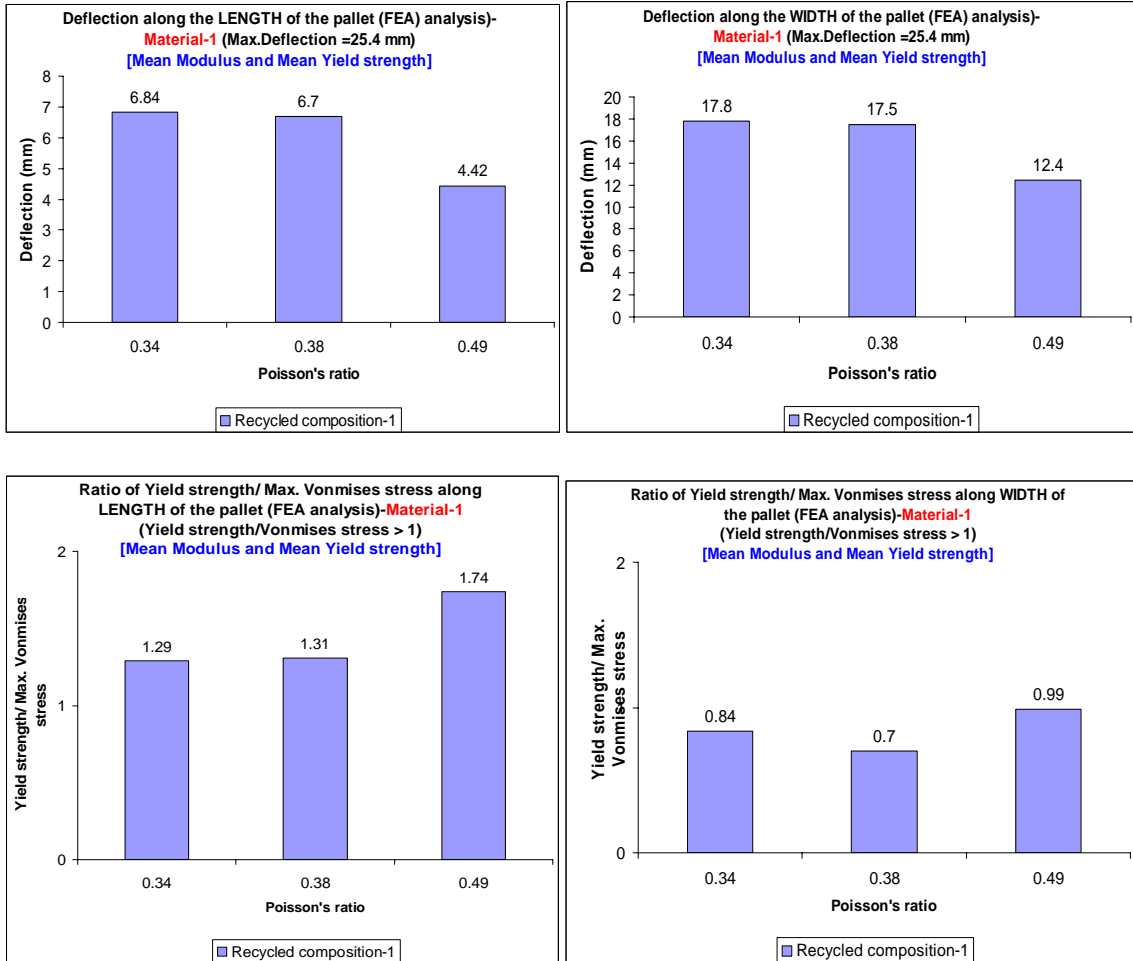


Figure 4.12 Deflection and ratio of yield strength to max.von Mises stress for recycled blend #1 for different Poisson's ratios

The sensitivity analysis for most part shows a general trend of decrease in deflection and increase in ratio of yield stress to maximum von Mises stress with increase in Poisson's ratio of blend #1. Hence, determining actual Poisson's ratio is essential.

### 4.4.2 BLEND #3:

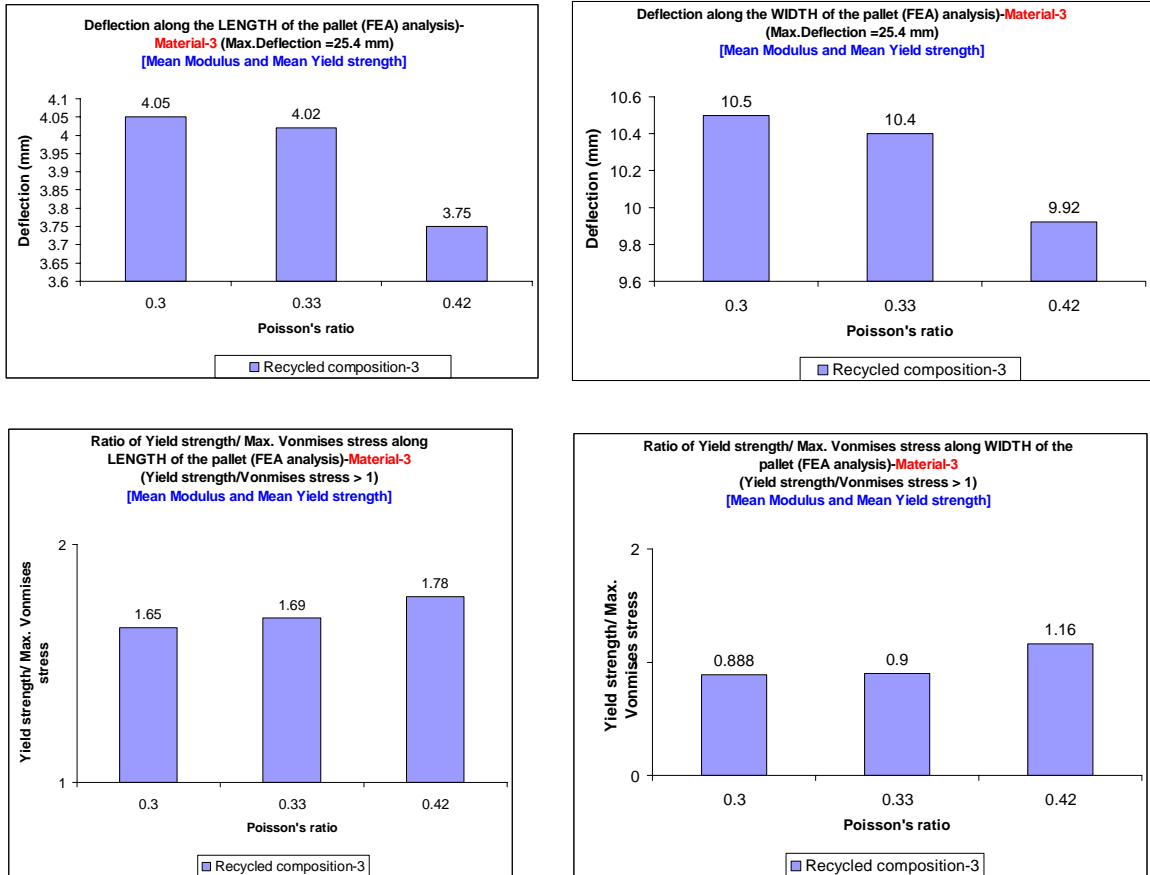


Figure 4.13 Deflection and ratio of yield strength to max.von Mises stress for Recycled blend #3 for different Poisson's ratios

The sensitivity analysis for most part shows a general trend of decrease in deflection and increase in ratio of yield stress to maximum von Mises stress with increase in Poisson's ratio of blend #3. Observable difference is Poisson's ratio of 0.42 makes it useful to be used in pallet.

### 4.4.3 BLEND #4:

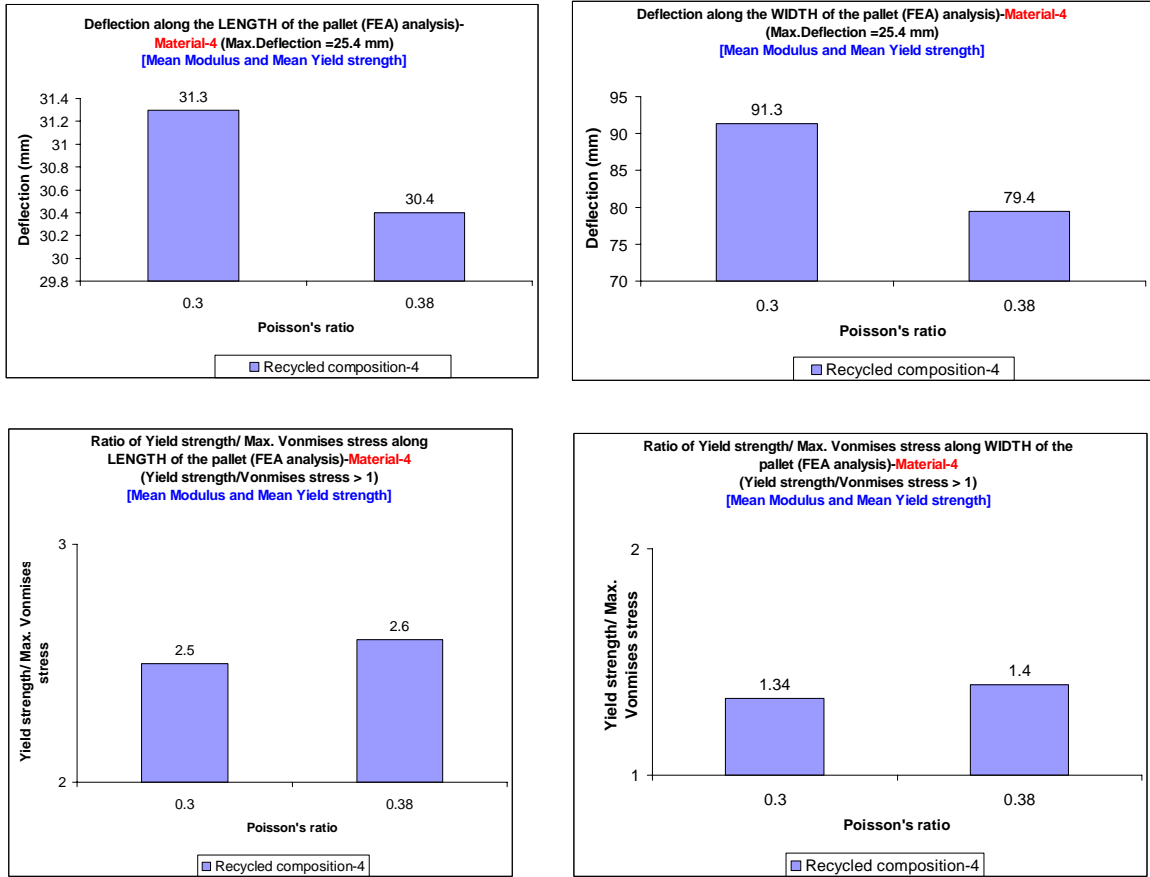


Figure 4.14 Deflection and ratio of yield strength to max.von Mises stress for Recycled blend #4 for different Poisson's ratios

The sensitivity analysis for most part shows a general trend of decrease in deflection and increase in ratio of yield stress to maximum von Mises stress with increase in Poisson's ratio of blend # 4.

#### 4.4.4 BLEND #5:

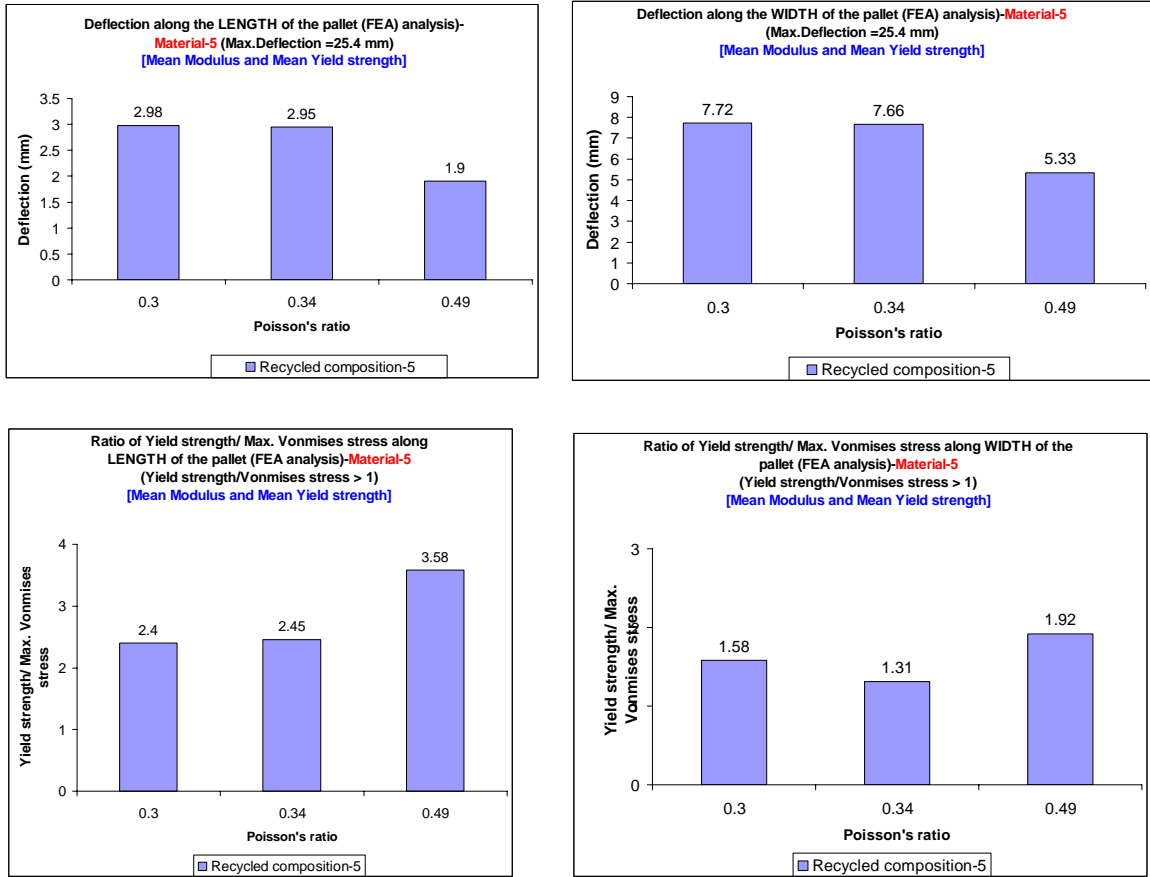


Figure 4.15 Deflection and ratio of yield strength to max.von Mises stress for recycled blend #5 for different Poisson's ratios

The sensitivity analysis for most part shows a general trend of decrease in deflection and increase in ratio of yield stress to maximum von Mises stress with increase in Poisson's ratio of blend #5.

#### 4.4.5 BLEND #6:

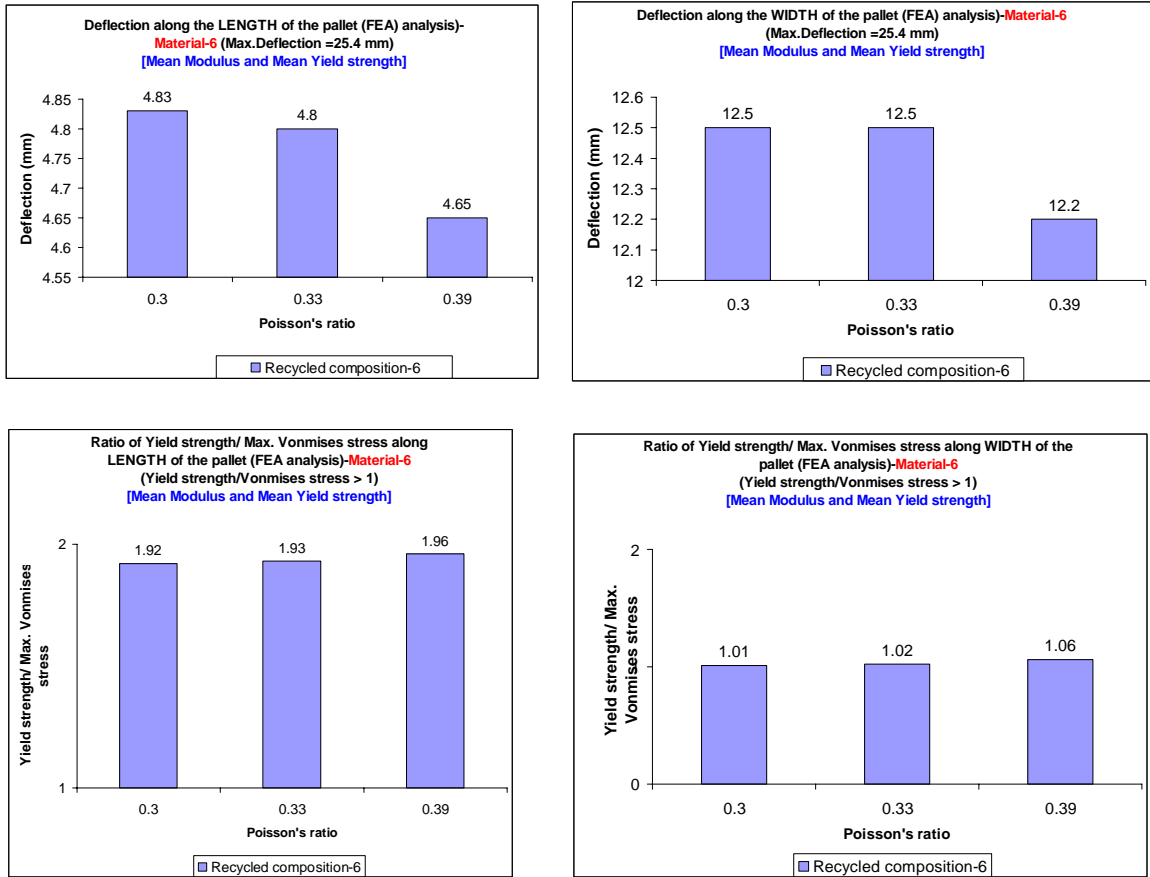


Figure 4.16 Deflection and ratio of yield strength to max.von Mises stress for Recycled blend #6 for different Poisson's ratios

The sensitivity analysis for most part shows a general trend of decrease in deflection and increase in ratio of yield stress to maximum von Mises stress with increase in Poisson's ratio of blend #6.





## **CHAPTER 5**

### **CONCLUSION AND RECOMMENDATIONS**

As recycling of plastics becomes inevitable for sustainable development, the challenges of using these recycled materials to make useful products will increase. The challenges are significant with recycled plastics because as their properties are usually not as good as their virgin counterparts. In order to characterize the properties of a given batch of recycled plastic extensive testing of each blend needs to be done. Once the testing establishes the properties, the next step is to establish the suitability of a given blend for use in a commercial application. Suitability of recycled plastics can be established either by building a prototype similar to the targeted product and then testing it, which is tedious and time consuming, or by performing finite element analysis (FEA) using a CAD model of the targeted product.

This research has made an attempt to establish the suitability for commercial applications of recycled plastics blends using FEA. A case study of a pallet was carried out in order to evaluate 6 different blends of recycled plastics. Two variables from the FEA were considered in order to gauge suitability for commercial application. They were:

- Pallet deflection under load, and
- Ratio of yield stress to maximum von Mises stress

From Figures 4.9 – 4.11, it can be concluded that Recycled blend #1 consisting of PET and HDPE in its original form (without additives to improve properties) fails by yielding [the ratio of yield stress to von Mises stress =0.6(<<1 lower limit for yielding) from Fig.4.11] along the minor axis of the pallet (lower limit of modulus and mean yield strength).

Recycled plastics blend #2 consisting of vinyl seats made of poly vinyl chloride, a small amount of polypropylene and urethane, was judged unsuitable for the pallet application for its poor mechanical properties (low tensile strength).

From Figures 4.9 – 4.11, it can be concluded that Recycled blend #3 containing PVC, PP and PU fails by yielding [the ratio of yield stress to von Mises stress =0.55(<<1 lower limit for yielding) from Fig.4.11] along the minor axis of the pallet. However, the failure is more pronounced at lower limit value of the modulus and mean yield strength. This blend is better compared to blend #1 in performance.

From Figures 4.9 – 4.11 and it can be concluded that Recycled blend #4 consisting of LDPE fails by high deflection [highest deflection =98.2 mm>> 25.4mm (failure limit) (lower limit of modulus and mean yield strength) from Figure 4.11] for both the values of modulus (mean and lower limit) and mean yield strength along both major and minor axes.

From Figures 4.9 – 4.11 it can be easily concluded that Recycled blend #5 consisting of Nylon and PET did better for both values of the modulus (mean and lower

limit) along with mean yield strength. It is very clear that blend #5 can be used for the pallet.

From Figures 4.9 – 4.11, Recycled blend #6 consisting of PS has performed well. It can be concluded that blend #6 with little modification in product design of pallet can be used in the pallet. From Figures 4.9 – 4.11, it is clear that material blend #5 has performed slightly better compared to blend #6 and it can be concluded that both the blends can be used for the pallet.

Some of the blends that failed to meet the requirements for the pallet might be used if the following modifications were made:

- Improving compatibilization between various recycled plastics of blend
- Adding additives such as fillers and reinforcing agents to improve stiffness (modulus) of recycled blends.
- Addition of LDPE and styrene-butadiene-styrene copolymer and other compatibilizing agents for improving strength
- Redesigning of all pallet ribs to be of same height

## **5.1 RECOMMENDATIONS FOR FURTHER STUDY**

During this study of finding commercial application for recycled plastics blends using FEA several other opportunities for further study became apparent. Further study would strengthen the understanding of thermo-kinetically recycled plastics.

These ideas for further study are presented below:

- Perform a research study to better understand the elemental structure of the thermo-kinetically recycled blends

- Conduct a study of the thermo-kinetic recycling process to check whether it is routine and well controlled
- Perform a research for understanding the relationship between the thermo-kinetically, recycled blends morphology and its mechanical properties
- Conduct a study to recognize the specific advantages offered recycled blends properties and manufacturing processes for achieving the functional requirements of a part
- Create a part design that will function satisfactorily in commercial applications that use thermo-kinetically recycled blends
- Carry out an experiment to establish the exact Poisson's ratio for each of the six available thermo-kinetically recycled blends

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## **APPENDIX**

## **CALCULATIONS AND FINITE ELEMENT ANALYSIS RESULTS**