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Mechanical property characterization of recycled thermoplastics

Johnny Edward Bargo
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MECHANICAL PROPERTY CHARACTERIZATION OF RECYCLED THERMOPLASTICS

Johnny E. Bargo

Thesis Submitted to the
College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements
for the degree of

**Master of Science
In
Civil Engineering**

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2000

Keywords: Recycled Polymers, ABS, PC, Tension, Compression, Bending,
Hardness, Impact, Creep

ABSTRACT

Mechanical Property Characterization of Recycled Thermoplastics

Johnny E. Bargo

Reuse of engineering thermoplastics retrieved from discarded computers, monitors and printers called as electronic shredder residue is described in the following thesis. Virgin, blend of virgin and recycled, and 100% recycled polymers such as acrylonitrile butadiene styrene (ABS) and polycarbonate (PC) are characterized for mechanical properties as part of this research. This research consists of characterization of mechanical properties such as tension, bending, compression, impact, hardness, and creep of ABS and PC plastics.

Long-term mechanical property retention and environmental durability are very important for infrastructure and automotive applications. The resins alone do not have the strength or stiffness to meet the requirements of certain automobile or construction applications. Hence, to obtain improved mechanical properties, the polymers in this research are characterized by adding fibers during the manufacturing process.

It was found that the recycled ABS and PC polymers retain at least 85% and in some cases over 90% of the tension, bending, and compression strength and stiffness properties compared to virgin polymers. Based on test results it is concluded that recycled polymers have significant potential for high-volume infrastructure and automotive applications because of a high percent of mechanical property retention under long-term loading conditions.

**This Thesis is dedicated to
My Wife, Heather, and My Parents**

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CHAPTER 1

INTRODUCTION

1.1 General Remarks

Developing high-volume applications of engineering thermoplastics (acrylonitrile-butadiene styrene, polycarbonate, and others) retrieved from discarded computers, monitors and printers is a major challenge. These thermoplastics may be blended with virgin plastics and elastomers and further reinforced with glass strands or glass fabrics or even glass rods to obtain economical products for high-volume usage.

For example, such fiber-reinforced composites (FRC) may be well suited for highway guardrail posts and guardrails because FRC can be designed for high impact strength because of their good damping properties. Other potential high-volume applications for recycled glass fiber reinforced thermoplastics are pallets and non-structural window and doorframes. These products can be easily assembled with mechanical and/or adhesive bonding. Similarly, ABS and PC are extensively used for automobile applications such as bumpers, fenders, longitudinal rails, transverse rails, cross members, suspension system components and others made with glass fiber/fabric reinforced thermoplastic composites.

This research consists of characterization of mechanical properties of ABS and PC plastics obtained from computer and monitor housings in three forms, i.e., virgin, blend of virgin and recycled, and 100% recycled polymers. Long-term mechanical property retention and durability are very important for infrastructure and automotive applications. The resins alone do not have the strength or stiffness to meet the

requirements of certain automobile or construction applications. Hence, to obtain improved mechanical properties, the polymers in this research are studied by adding fibers during the manufacturing process.

The most common type of fiber used in thermoplastic resin is glass. Glass fibers are available in many different forms such as mats, woven fabrics, rovings, chopped strands, etc. The mechanical and thermal properties of a composite depend on the fiber orientation, quantity, and fiber arrangement. A good understanding of processing composites with glass is essential so that an acceptable product can be obtained. For instance, selecting the correct melt temperature of the resin is a critical step in injection molding process for good finish. In addition, the type of resin and glass fibers must be compatible. Glass fibers need to have appropriate sizing to ensure proper adhesion of glass fibers to the resin. Many other factors such as screw speed, cycle time, injection pressure and drying parameters influence the outcome of a product. All these parameters have to be considered in order to manufacture products with consistent mechanical and structural properties. Hence, industrial quality manufacturing of test samples with and without glass fibers was carried out by CFC-WVU in collaboration with Owens Corning Company and PPG Industries.

1.2 Objectives

The main objectives of the research on both virgin and recycled polymers are the following:

- Characterize the strength and stiffness of recycled polymers obtained from electronic shredder residue (ESR) under tension, compression, bending, impact, hardness, and creep.

- Characterize virgin polymers, which are identical to the ESR polymers, and compare the strength and stiffness of recycled polymers and their blends with virgin polymers under tension, compression, bending, impact, hardness, and creep.
- Establish the impact properties and creep behavior of recycled and virgin polymers and their blends.

1.3 Scope

There are two main types of polymers, i.e. thermoplastics and thermosets. Thermosets such as polyurethane, polyester, and polyvinyl acetate are usually more brittle than thermoplastics and will not be dealt with in this research. Among the different types of thermoplastics, this research will be limited to polycarbonate (PC) and acrylonitrile-butadiene styrene (ABS).

Recycled ABS and PC were considered for evaluation purposes based on their availability, suitability for mass production and cost. Over 180 ABS samples manufactured by Owens Corning and over 180 PC specimens manufactured by PPG Industries were tested. Table 1.1 shows the type of test conducted and the number of samples tested for each along with the types of resins and fibers used in each sample. Additional information about the specimens, resins and fibers used in the testing is discussed in chapter 3. This report focuses on the results of both the ABS and PC specimens. Material selection, results of different tests and conclusions are provided in chapters 3, 4, and 6.

Test	Number of Test Samples				Type of Resin				Type of Chopped Fibers	
	With Fibers		Without Fibers		With Fibers		Without Fibers			
	ABS	PC	ABS	PC	ABS	PC	ABS	PC	ABS	PC
Tension	16	16	15	15	100% Virgin 100% Recycled 80% Virgin 20% Recycled				4mm 14μ	3.18mm 13μ
Bending	16	15	17	15						
Compression	20	19	15	16						
Impact	15	15	15	18						
Hardness	48	48	48	48						
Creep	7	6	8	6						

Table 1.1 Samples Tested, Resin Type, and Type of Fibers

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The need for developing suitable methods to recycle and reuse plastic products that are to compete economically with those of virgin polymers is becoming more and more evident. In 1990, an estimated 0.8% of the nearly 31 million tons of plastics consumed in the United States were recycled, leaving approximately 30.7 million tons finding their way into landfills (Powelson et al., 1992). It is also known that plastics are non-biodegradable (will not decompose naturally when in contact with soil, water and light over a period of time) and will remain in a landfill. The benefits of recycling plastic are:

- the reduction in landfill space requirements
- reduce air pollution from incineration emissions
- reduction in the amount of non-renewable resources needed to manufacture virgin materials (Tall et al., 1998).

On the other hand, there are several trends that are discouraging the mechanical recycling of plastics. The cost of virgin plastics is currently low, and lesser amounts of raw materials are needed for manufacturing due to the sophistication of newer machinery. This in turn promotes the use of mass produced virgin plastics and makes it more difficult for recycled material to compete economically with the virgin plastics (Tall et al. 1998). However, due to growing environmental concerns by both the public and the

government, research is being carried out to develop various recycled plastics that would closely match the mechanical and thermal properties of virgin plastics.

2.2 Recycling issues

In order to establish an acceptable way to recycle materials four main areas must be explored. They are:

- collection
- separation
- manufacturing
- consumption

These areas are briefly described in the following sections, 2.2.1 through 2.2.4.

2.2.1 Collection

The collection process is the most important step in recycling, without proper collection of post-consumer waste the recycling process would be much more difficult. In 1990, over 3,000 curbside recycling programs existed in communities across the United States (Powelson et al., 1992). By 1998 the number of community recycling programs, including collection, had risen sharply. In addition to community recycling programs, many businesses have adopted recycling programs to be used by their employees. Additional means of collecting recyclable products can be found in schools, parks, and government agencies.

2.2.2 Separation

Once the collection process is completed, the various materials must now be separated. There are several methods in which this process is completed, often times

incorporating several separation techniques. It must be pointed out that none of the following techniques is 100% effective.

In Europe and other developed countries, nearly 75% of a vehicle's total weight is recycled through a well-established dismantling operation. After the vehicle has been dismantled, 8% of the post-use plastics waste is currently being recycled with the Association of Plastics Manufacturers in Europe (APME) estimating that the number could rise to as much as 10% (Modern Plastics, Jan. 2000).

Separation techniques

1. Magnetic separator – Magnetic separation is a technique where the ferrous material is recovered from the waste stream using three configurations. These are as follows:

- the drum
- the magnetic belt
- the magnetic head pulley.

Feeding the waste stream, by means of a non-metallic conveyor system, near the magnets completes the process. The magnets will then lift the ferrous materials from the waste bed thus allowing the remaining nonferrous materials to pass. The effectiveness of the entire process depends upon bed depth and magnet strength (Swartzbaugh et al. 1993).

2. Eddy current device - This separation technique is designed specifically for aluminum materials. The process works by creating a magnetic field that ejects aluminum products (usually cans) from the waste stream into a collection container.

3. Disc screen - a disc screen is composed of parallel multiple shafts with discs mounted onto these shafts and spaced in such a manner that the discs on one shaft are midway between the discs on another shaft. This configuration allows smaller material (e.g., broken glass) to fall between the openings of the two shafts and larger material to continue through the separation process (Swartzbaugh et al. 1993).

4. Trommel screen - A Trommel screen is a large cylindrical perforated screen usually with a downward inclination. The waste stream is brought into the trommel by means of a conveyor belt. Once inside, the Trommel screen rotates, thus causing smaller particles to fall through the perforated openings in the screen and out of the waste stream (Swartzbaugh et al. 1993). A more effective configuration is to have two or more trommel screens in-line each with increasingly larger perforations. This would allow for faster separation of materials.

5. Vibrating screen - This technique incorporates a wire mesh or perforated plate screen that is vibrated in order to separate certain size materials from the waste stream.

6. Oscillating screen - The oscillating screen is much like the vibrating screen except that the screens motion is orbital rather than vibrating in plane.

7. Traveling chain curtain - A traveling chain curtain consists of a curtain made from common chain that is suspended from a revolving conveyor. The curtain provides a barrier that allows more dense material to pass while preventing less dense material (e.g., plastic and paper) from continuing through the waste stream. The less dense material is then collected from the curtain as it is directed to the side.

8. Air classifier - The air classifier uses an air stream that is directed upwards through a shaft. The waste stream is brought into the shaft by means of a conveyor and

then falls through the air stream. The lighter material (e.g., paper and plastic) is blown up through the shaft into a collection container while the heavier material (e.g., metals and glass) falls onto a conveyor at the bottom of the shaft for further separation (Swartzbaugh et al. 1993).

2.2.3 Manufacturing

In order to make recycling effective, manufactures must be willing to use comparable recycled materials over virgin materials. Throughout the 1990's, manufactures have become more aware of the increasing need to recycle and their role in the recycling industry. Companies such as Great White (laser printer and copier paper) and Procter & Gamble (plastic containers) are now using recycled materials over virgin materials in many of their products. As stated earlier, European automobile manufactures are currently recycling nearly 75% of a vehicles total weight of which 8% is post-use plastics, which enables product manufactures to have the recycled material needed in order to produce post consumer products like bottles and serving trays. Studies are being conducted by companies such as General Motors that will provide manufactures with the needed mechanical information about recycled products that will allow them to expand their production into the automotive and infrastructure industries.

2.2.4 Consumption

To achieve all the benefits that recycling has to offer, consumers must be willing to buy a product that has been manufactured from recycled materials. To stimulate consumption of recycled products, many government agencies and businesses give preference to recycled materials when making purchasing decisions (Powelson et al., 1992). Laws requiring the purchase of recycled materials are also on the rise.

Connecticut was one of the first states to enact a law targeted at the newspaper industry that required a specific percentage of their annual purchases to be recycled products (Powelson et al., 1992). The manufacturing industry is also assisting consumers in purchasing recycled products by placing symbols on their products to help identify them.

2.3 Previous research with recycled polymers

Liang (1999) conducted a literature search on the Recycling of Polymers and evaluated many different types of plastic waste and the recycling methods used in the recovery of the recycled resins.

High-density polyethylene (HDPE) was recycled from milk bottles and tested as a possible food packaging material. Untreated caustic-washed and caustic-washed/stem-stripped/air-dried recycled bottles were used in the tests. The untreated caustic-washed recycled material was found to be unsuitable as food packaging due to the high migration rate of some compounds. The steam-stripped recycled material was found to perform identical to the virgin material and could not be distinguished from such. Additional tests concluded that the mechanical properties of the recycled material remained unchanged during the recycling process (Liang, 1999).

Bottles made of polyvinyl chloride (PVC) and supermarket tray material made of pulverized PVC were recycled. Both the recycled materials were combined and co-extruded to produce cladding for the building industry. From experiments, it was found that the impact properties of the recycled plastic blend were actually superior to the virgin material due to the presence of high levels of an impact modifier in the original tray formations. Furthermore, using up to 100% recycled PVC bottles did not affect the impact properties of the extruded product (Liang, 1999).

It is often difficult to recycle a material that will exhibit the purity of that of a virgin material. Tall et al. (1998), in the article entitled “Improvements in the Properties of Mechanically Recycled Thermoplastics”, described the mechanical properties of some thermoplastics, i.e. HDPE, ABS, and ABS/PC blends, when contamination occurred during the recycling process (Tall et al., 1998).

During the recycling process, nearly all polymer mixtures will form separate phases. By forming these separate phases, a blend will usually become more brittle than that of a single-phase material. Tall et al. (1999) studied the effects on impact resistance of a mixture of ABS (acrylonitrile-butadiene styrene) and PC (polycarbonate). Because ABS and PC are such common engineering materials, it was probable that these two thermoplastics could be recycled as one blend. However, when recycled together, ABS and PC form separate phases and therefore the blend ratio must be controlled. In order to avoid the minimum impact resistance, it was concluded that a blend ratio of around 30% PC was to be avoided (Tall et al, 1999).

The effects on the mechanical properties and processing temperatures of various blends of high-density polyethylene (HDPE) with other thermoplastics were also discussed in the article by Tall et al. (1999). A general purpose extrusion grade (melt flow rate = 3.2 dg/min @230°C/2.16 kg) polypropylene (PP) was blended with HDPE in order to test the effects on both the tensile strength and the tear propagation resistance of the blended material. It was concluded that the tensile strength of the material increased while the tear propagation resistance decreased with increased PP content. Additional tests were conducted with an injection-molding grade (melt flow rate = 18 dg/min @230°C/2.16 kg) polypropylene (PP) blended with HDPE. The conclusions were that

both the tensile strength and the tear propagation resistance decreased with an increase in PP content and that the blend became very brittle when 30% PP-content was achieved.

Tall et al. (1999) also discussed how tensile properties were effected for blends of ABS (Ronfalin SRA36) with polypropylene (ME 210 U) and ABS with high-impact polystyrene (Polystyrene 552). The article found that ABS would shift from a ductile mode of failure to a brittle mode of failure at a contamination level of 6% polypropylene. For the ABS/HIPS blends, it was concluded that at a 4% HIPS-content, there were significant increases in elongation at break. However, at increasing HIPS-content, the amount of elongation would begin to decrease. For each of the tests, the tensile properties for 100% ABS was used as a standard.

The effects on the mechanical properties of continuous recycling thermoplastics is of great concern. Eriksson et al. (1997) discusses the effects on the tensile properties of continuous recycling 30 wt % glass-fiber reinforced polyamide 66. The study shows that with increasing molding operations, up to four to five, the specimens showed a faster deterioration rate in elongation at break. Furthermore, the onset of embrittlement and a decrease in tensile elongation at break became more evident with increasing molding operations.

In 1996, Norm Kakarala became the team leader of a group faced with the challenge of developing the first 100% recycled instrument panel for the 2000 Pontiac Boneville. The team was successful and in 1999 the program received the "Recycler of the Year" award from the Society of Plastics Engineers. The process uses 60% vacuum forming scrap for the interior layer, while the top layer is a virgin plastic so that color consistency and texture can be achieved. One of the most important aspects of the

application is that it eliminates solvent emissions by using water-borne coatings. The method also ensures grain retention, soft touch and deep draw (Modern Plastics, Jan. 2000).

2.4 Conclusions

From the above research work on virgin and recycled polymers, we can conclude that recycled polymers can be used for many applications with little or no effect on the mechanical properties necessary to achieve an acceptable product. In order to achieve the mechanical properties needed for a particular product, the way that recycled plastics are separated and processed is essential. Once recycled polymers have been processed they can then be used with virgin polymers in order to achieve color and texture consistency.

CHAPTER 3

MATERIALS, MANUFACTURING AND TEST PROCEDURE

3.1 Introduction

The mechanical properties (i.e. stiffness, strength, etc.) of thermoplastics are not of great concern when used in such products as computer housings or food service trays. However, in order to be a competitive value-added product in the construction or automotive industry, accurate and consistent evaluation of mechanical properties becomes much more relevant. The resins alone often times do not have the strength or stiffness needed for certain automobile or construction applications. Therefore, to gain higher mechanical properties, the resins are combined with fibers during the manufacturing process.

The most common type of fiber used in thermoplastic resin is based on glass. Glass fibers can be purchased in many different forms such as mats, woven or stitched fabrics, rovings, chopped strands, etc. The mechanical and thermal properties of a composite depend on the fiber orientation, quantity (i.e. volume percent in a composite), and fiber arrangement.

During the manufacturing of a composite, a good understanding of processing composites with glass is essential so that an acceptable product can be obtained. For instance, for the injection molding process, selecting the correct melt temperature of the resin is a critical step in producing a good final product. Also, the type of resin used must be compatible with the fibers. Therefore, selecting an appropriate sizing that will ensure proper adhesion of glass fibers to the resin is essential. Many other factors influence the

outcome of a product such as screw speed, cycle time, injection pressure and drying parameters, all of which are to be understood properly to manufacture high quality products with consistent mechanical and structural properties.

3.2 Materials

3.2.1 Virgin Polymers

Two types of thermoplastic resins were evaluated in this research: Lexan-101 polycarbonate (PC) and Cycolac-GPM5500 acrylonitrile-butadiene-styrene (ABS) manufactured by GE Plastics Company. Selection of these resins was based on availability of these materials as electronic shredder residue and their commercial viability for infrastructure and automobile applications.

Lexan-101 polycarbonate resins have good electrical, optical, thermal, and mechanical properties including durability. The combination of these physical properties makes it one of the toughest, most versatile of all engineering thermoplastics (GE Plastics, 1999). Lexan-101 resins are widely used in packaging, electronics, appliance and the automotive industries. Lexan-101 resins are available in different commercial grades to suit a wide range of requirements and applications such as flame resistance, wear resistance, and health care use.

Cycolac-GPM5500 ABS resins have excellent impact strength, hardness, rigidity, and toughness properties. The resin grades of Cycolac ABS consist of elastomeric blends of polybutadiene or a butadiene copolymer and an amorphous thermoplastic component of styrene and acrylonitrile (SAN) and are easy to process (GE Plastics 1999). Various other grades of ABS-Cycolac resins are commercially used to meet specific end-product requirements.

3.2.2 Recycled Polymers

Recycled polymers were received from sources such as computer, monitor and printer housings. These were made available to the CFC-WVU research team by the MBA polymers. The recycled polymers were granulated with a size of about 0.25” or less. Purity of these recycled polymers was well above 90%.

3.2.3 Glass Fibers

The chopped glass fibers available from Owens Corning were chosen in this research with suitable sizings compatible with ABS. The 408A-14C CRATEC chopped strands with a length of 4mm and diameter of 14 μ used in this study are general-purpose glass fiber reinforcement and have proven compatibility with many thermoplastic resins including ABS. The 408A CRATEC strands are produced at ISO 9002 registered glass fiber facilities. The chopped strands are manufactured from continuous glass filaments that have been gathered into a single bundle. The fiber bundles are then chopped into specific lengths, dried, screened, trace metals removed, and supplied for use. The characteristics of the 408A CRATEC strands include optimized strand integrity, good glass dispersion, excellent mechanical properties, and excellent coupling with polymer systems.

The chopped glass fibers available from PPG were chosen in this research with suitable sizing compatible with PC. The 3762 3mm MaxiChop® chopped strands are general-purpose glass reinforcement and have been proven compatible with both thermoplastic and thermoset resin including PC. The 3762 MaxiChop® E-glass fibers are chopped strands from 3mm (1/8 in) to 13mm (1/2 in) in length and 13 μ in diameter.

The fibers are produced by collimating the continuous fibers into strands and either chopping directly under the bushing, or winding the strands into an intermediate package for subsequent chopping in a separate operation. Proprietary silane-based finishes are applied to the surface of each fiber in order to enable processing and handling and maximize the glass-to-resin bond in the molded part.

3.3 Manufacturing

The choice of manufacturing process depends mainly on the type of fibers and resin, temperature required to form the part and cure the resin, and the cost effectiveness of the process involved. The injection molding process was used in the production of test specimens. A brief description of the different types of moldings carried out and the injection molding process is given below.

3.3.1 Injection Molding Process

Injection molding of the ABS samples was performed by Owens Corning. Six types of specimens, as described in Table 3.1, were manufactured by Owens Corning. Proper drying of the pellets was necessary before the molding process begins. Standard drying specifications for general-purpose GPM5500 ABS resin is 2-4 hours drying time at a temperature of 180-200°F. Resins in the form of pellets are uniformly blended by means of a screw extruder. Screws with L/D ratios of 24:1 were used (with a compression ratio of 3.75:1) because shorter screws can sacrifice melt homogeneity and lead to material degradation and discoloration at transition sections (GE Plastics 1999). The melt temperature used for both the extrusion process and the injection molding was 530° to 535°F. Molding was performed on a Cincinnati Milacron injection-molding machine with a 200-ton press.

Injection molding of the PC samples was performed by PPG. Six types of specimens, as shown in Table 3.2, were manufactured by PPG. Drying time of the Lexan 101 resin was 5 hours at 200°F. A melt temperature of 300° to 313°F was used for the extrusion process and a melt temperature of 595°F during the molding process. The injection screw speed was set at 3.65"/sec. with a back pressure of 100 psi.

Table 3.1 Description of Different Types of ABS Specimens

Specimens	Description of Different Specimens
A1	Virgin ABS polymer without fibers
A2	Virgin ABS polymer with 25% (wt. %) chopped fibers
A3	100% recycled ABS polymer without fibers
A4	100% recycled ABS polymer with 25% (wt. %) chopped fibers
A5	Recycled ABS/virgin ABS (20%/80%) blend without fibers
A6	Recycled ABS/virgin ABS (20%/80%) blend with 25% (wt. %) fibers

Table 3.2 Description of Different Types of PC Specimens

Specimens	Description of Different Specimens
P1	Virgin PC polymer without fibers
P2	Virgin PC polymer with 25% (wt. %) chopped fibers
P3	100% recycled PC polymer without fibers
P4	100% recycled PC polymer with 25% (wt. %) chopped fibers
P5	Recycled PC/virgin PC (20%/80%) blend without fibers
P6	Recycled PC/virgin PC (20%/80%) blend with 25% (wt. %) fibers

Coupon specimens manufactured through injection molding allowed the researchers to conduct six types of tests, i.e., tension, compression, bending, impact, hardness and creep. All ABS and PC specimens with fibers contained a fiber volume fraction of 12%. Dimensions of the coupon specimens and test procedures according to ASTM standards are listed in Table 3.3.

Table 3.3 ASTM Coupon Dimension and Test Procedure Specification

Specimens	Description of Different Specimens
Tension	ASTM D638-94b
Bending	ASTM D790-92
Compression	ASTM D695-91
Impact	ASTM D256-93a
Durometer Hardness	ASTM D2240-91
Creep	Sustained load application on modified tension coupons

3.4 Testing

Details of the test specimen, specimen preparation, test set-up, test procedure, test results and discussions for each type of test are provided in the following sections.

3.4.1 Tension Test

3.4.1.1 Test Specimen

The tension test specimens were manufactured to the dimensions as per ASTM D638-94b for a Type I specimen. Figure 3.1 and Table 3.4 show the typical design parameters of a Type I, II, III, & V tension specimen. Type I and II specimens have a thickness less than 0.28" and fall within the guidelines set by the ASTM standard. For a Type III specimen, the thickness must be between 0.28" to 0.55" along with other guidelines set by ASTM. Types IV and V specimens are special cases. A Type IV specimen must have a thickness of 0.16" or less and a narrow section (W) width of 0.25". Type V specimens must have a thickness of 0.16" or less and be machined or die cut according to the dimensions set by the ASTM standard. Each specimen was labeled according to the type of test conducted and the test number. For example, a specimen

designated as TA1-2 represents, tension test (T), sample group (A1 – 100% virgin sample without fibers), and the test number 2.

Fig. 3.1 Tension Specimen Dimensions (Types I, II, III, & V)

Table 3.4 Dimensions of Injection Molded Tensile Test Specimens

Dimensions (see Fig. 3.1)	ABS Specimens	PC Specimens
W-Width of narrow section	0.5"	0.5"
L-Length of narrow section	3.0"	3.0"
WO-Width over-all	0.75"	0.75"
LO-Length over-all	8.5"	8.5"
G-Gage length	1.0"	1.0"
D-Distance between grips	4.5"	4.5"
T-Thickness	0.125"	0.125"

3.4.1.2 Specimen Preparation

A series 2620 dynamic strain gage extensometer was used at the midsection as shown in Fig. 3.3 to measure tensile strains. Each of the samples was marked with a permanent marker so that the correct grip location and extensometer position could be easily obtained.

3.4.1.3 Test Set-up and Procedure

Each of the tension specimens was tested using an Instron Series 8500 Two-Column Load Frame as per ASTM D638-94b as shown in Figure 3.2. The strains were

automatically recorded using 'wavemaker' software and with the use of extensometer having a gage length of one inch. The extensometer was attached to the tensile specimen by means of rubber bands supplied by the manufacture as shown in Figure 3.3. The tests were computer controlled using the same 'wavemaker' software and loaded to failure at a rate of 300 lbs./min. Other parameters recorded by the computer were time and displacement.

Figure 3.2 Test Set-Up for Tension Test

Figure 3.3 Test Set-Up for Extensometer

3.4.2 Bending Test

3.4.2.1 Test Specimen

Bending specimens were manufactured with the dimensions conforming to ASTM D790-92 for a three point bending test. The ABS and PC samples were rectangular in cross section with a length of 5", width of 0.5", and a thickness of 0.125". Each specimen was labeled according to the type of test conducted and the test number. For example, a specimen designated as BA1-14 represents, bending test (B), sample group (A1 – 100% virgin sample without fibers), and the test number 14. Test span of 3.75" was used for the bending tests.

3.4.2.2 Specimen Preparation

Each of the bending samples was marked with a permanent marker to locate the correct support points. The specimen surface at mid-length was prepared for strain gage application using a 320 grit sandpaper. A degreaser, an acidic surface cleaner followed by a water-based alkaline cleaner was used to remove any oil residues and to aid in the adhesion of the strain gage. Strain gages were then applied using M-Bond 200 adhesive, clamped, and allowed to cure overnight in order to achieve proper bond between the gage and the specimen surface. Gages were bonded at the center on both sides of the specimen to facilitate comparison of stiffnesses in bending or compression as well as tension faces.

3.4.2.3 Test Set-up and Procedure

Each of the bending specimens was tested using an Instron Series 8500 Two-Column Load Frame or the Instron Model 4411 as per ASTM D790-92. The rate of cross-head motion was set at 0.25 in./min. in accordance with the ASTM standard. ASTM Test Method I, threepoint bending, was performed on each specimen shown in

Figs. 3.4 and 3.5. The strain gage on the compression side of the test specimen was protected by placing a rubber cushion, with an indentation to match the gage size, on top of the strain gage during loading. Tensile and compressive strains were recorded, using a strain indicator, at predetermined intervals during the test. The specimens were loaded to failure or until significant deflections in excess of $1/3$ of the span were observed. Maximum load, displacement and strain values were recorded.

Fig. 3.4 Bending Test of ABS Specimens

Figure 3.5 Close-up of Bending Test

3.4.3 Compression Test

3.4.3.1 Test Specimen

The compression specimens were manufactured to the dimensions as per ASTM standards D695-91. The ABS and PC samples were rectangular with a cross-section of 0.5"x 0.25". Height of the specimens was 0.5". Additional samples with height 1" and 1.5" were also tested to establish the optimum height for minimizing and eliminating bending effects. Based on pilot testing, height of 0.5" was chosen, which provides an aspect ratio of 2. Each specimen was labeled according to the type of test conducted and the test number. For example, a specimen designated as CA1-2 represents, compression test (C), sample group (A1 – 100% virgin sample without fibers), and the test number 2.

3.4.3.2 Specimen Preparation

Surface of the specimens was prepared for strain gage bonding. The surface preparation and strain gage application were same as described under bending test.

3.4.3.3 Test Set-up and Procedure

Compression testing was performed using an Instron 8500 Two-Column Load Frame as per ASTM D695-91. Rate of cross-head motion was computer controlled using the Wavemaker software provided by Instron and set at 0.05 in./min. in accordance with the ASTM standard. The strain was recorded at predetermined intervals during the test using a strain indicator. Each specimen was loaded to maximum load and through the yield zone. Maximum load, strain and reduction in length were recorded. The test set-up and specimen orientation are shown in Figs. 3.6 and 3.7.

Figure 3.6 Test Set-Up for Compression Test

Figure 3.7 Compression Specimen Orientation

3.4.4 Impact Test

3.4.4.1 Test Specimen

The impact test specimens are in accordance with the standards set by ASTM D25-93a for an Izod type test. Figure 3.8 shows typical design parameters for an Izod impact test specimen. The actual dimensions of the specimen used in the impact testing are shown in Table 3.5.

Fig. 3.8 Impact Test Specimen

Table 3.5 Dimensions of Impact Test Specimen

Dimension (Fig. 3.8)	ABS Specimens	PC Specimens
A	0.4085"	0.4085"
B	1.25"	1.25"
C	2.5"	2.5"
D	0.25R	0.25R
E	0.5"	0.5"

3.4.4.2 Specimen Preparation

No specimen preparation was performed on the Izod impact specimens. Owens Corning carried out notching on the specimen as per ASTM specifications.

3.4.4.3 Test Set-up and Procedure

The impact testing was conducted as per ASTM D256-93a method A using a BLI Series Impact Testing Machine shown in Fig. 3.9. The test was conducted without any weight addition to the Izod pendulum. The final impact energy was obtained from the pointer reading and the type of break (i.e. H-hinge, C-complete, or P-Partial) was recorded. The results were calibrated using a standard correction chart supplied by Instron to account for pendulum friction and windage (BLI Series Manual, 1999).

Figure 3.9 BLI Series Impact Testing Machine

3.4.5 Creep Test

3.4.5.1 Test Specimen

The test specimens chosen for use in the creep test have the same dimensions as in tension. Additional modifications as explained under specimen preparation were carried out.

3.4.5.2 Specimen Preparation

Two 3/8" diameter holes were drilled at both ends with their centers at a distance of 1.125" from the end and 0.375" from the sides as shown in Fig. 3.10. On one end of the specimen, two 2.25"x1"x0.125" aluminum tabs with a 0.375" diameter hole in the center of the tabs were attached on each side. Surface preparation and strain gage application were similar as explained in bending tests. A threaded bolt measuring 0.375" in diameter and 1.5" in length was passed through the aluminum tabs and holes and tightened on to the flange of a steel beam with threaded holes as shown in Fig. 3.11. Thus, the specimen was suspended from the beam. Free end of the specimen was attached with 5"x1"x0.125" steel plates with a 0.375" diameter hole for suspending a known dead weight. To further ensure that no slippage occurred between the specimen and the tabs, two C-clamps were applied at each end of the specimen, one on each side of the bolt, as shown in Fig. 3.11.

Fig. 3.10 Creep Specimen with Drilled Holes

3.4.5.3 Test Set-up and Procedure

The load was applied by suspending large steel plates with known weights from the specimen by means of a 1/8" cables. In some cases, the same sustained load was used to simultaneously apply the sustained load on two different specimens connected in series. In Fig. 3.12, specimens at both ends of the steel beams are suspended in series.

Figure 3.11 Creep Specimen Set-Up Procedure

Figure 3.12 Test Set-Up for Creep Test

3.4.6 Hardness Test

3.4.6.1 Test Specimen

The hardness specimens are in accordance with the standards set by ASTM D2240-91. The ABS samples are of 2" diameter with a thickness of 0.125". The PC samples are of 3" diameter with a thickness of 0.125". Each specimen was labeled according to the type of test conducted and the test number. For example, a specimen designated as HP1-2 represents, hardness test (H), sample group (P1 – 100% PC virgin sample without fibers), and the test number 2.

3.4.6.2 Specimen Preparation

No specimen preparation was performed on the hardness test specimens.

3.4.6.3 Test Set-up and Procedure

The hardness testing was performed using a Duotronic Model 2000 hardness testing machine per ASTM D2240-91. Two tests were conducted on each specimen, one using a 626g weight and the other with no weight. The hardness number was recorded from the Duotronic's visual display for each test. The test set-up and specimen orientation can be seen on Figure 3.13.

Figure 3.13 Test Set-Up for Hardness Test

CHAPTER 4

TEST RESULTS, ANALYSIS, AND DISCUSSIONS

4.1 Introduction

Experimental evaluations of the strength and stiffness properties of PC and ABS plastics are very important for developing good design approaches for infrastructure and automotive applications. These resins alone often do not have the strength or stiffness to meet the requirements of certain automobile or construction applications. Hence, to obtain improved mechanical properties, the polymers are evaluated by adding fibers during the manufacturing process.

Experimental results and the analysis and discussion of those results based on coupon level testing are presented in this chapter. The stiffness values for ABS and PC is obtained from tension, compression, and bending tests from specimens with and without fibers. Other values presented in this chapter include maximum stress, impact strength, hardness values, and creep coefficients.

4.2 Tension Test

4.2.1 Results of Tension Tests on ABS

Strength and stiffness results from the tension tests are summarized in Table 4.1. Each result is an average of at least 5 specimens. Results for individual tests are shown in Appendix-A, including statistical analysis of the data. Virgin polymers and recycled polymers without fibers showed elongation in excess of 10%. Extensometer used in this study had a limit of 10% on strain measurements and hence the strain readings were discontinued at about 8% strain. Comparison of tensile stress and stiffness is shown in

Figs. 4.1 and 4.2. Typical stress-strain curves are shown in Figs. 4.3 and 4.4 for virgin ABS without and with fibers.

Table 4.1 Tension Test Results on ABS

Specimen	Maximum Load	Maximum Stress	Strain @ Max. Load	Tensile Stiffness (E)
	lbs.	psi	%	psi
TA1	385.88	6174.14	2.87	0.321E+06
TA2	643.71	10299.42	1.35	0.976E+06
TA3	348.68	5578.85	2.85	0.333E+06
TA4	550.03	8800.54	1.12	0.964E+06
TA5	369.75	5915.94	2.76	0.359E+06
TA6	556.96	8911.39	1.18	0.941E+06

Fig. 4.1 Comparison of Maximum Tensile Stresses in ABS (12% Fiber Volume Fraction)

Fig. 4.2 Comparison of Maximum Tensile Stiffness in ABS (12% Fiber Volume Fraction)

Fig. 4.3 Typical Stress-Strain Curve for Virgin ABS without Fibers in Tension

Fig. 4.4 Typical Stress-Strain Curve for Virgin ABS with 12% Fiber Volume Fraction in Tension

4.2.2 Analysis and Discussion of Tension Test Results on ABS

Stiffness of the specimens was evaluated through regression analysis by providing best-fit curve to the linear portion of the stress-strain curve. Analysis of test results is shown in Table 4.2.

Table 4.2 Analysis and Comparison of Tension Test Results on ABS (% Increase/Decrease)

Effect of	Specimen Type	Compared With	Max. Tensile Stress	Tensile Stiffness	Strain @ Max. Stress
			%	%	%
Recycling (Without Fibers)	TA3 (R)	TA1 (V)	-9.6	+3.7	-0.7
	TA5 (B)		-4.2	+11.8	-3.8
Recycling (With Fibers)	TA4 (R-F)	TA2 (V-F)	-14.6	-1.2	-17.0
	TA6 (B-F)		-13.5	-3.6	-12.6
Fiber Addition	TA2 (V-F)	TA1 (V)	+66.8	+204.0	-53.0
	TA4 (R-F)	TA3 (R)	+57.5	+189.5	-60.7
	TA6 (B-F)	TA5 (B)	+50.6	+162.1	-57.2

Note: T-Tension; A-ABS; V-Virgin; R-100% Recycled; B-Blend (80% virgin and 20% Recycled); F-Fiber; +ve sign –Increase; -ve sign- Reduction. Refer to Table 4.1 for absolute values.

- Compared to virgin polymers, maximum tensile stress in the blend and 100% recycled polymers reduced by 4.2% and 9.6% respectively. However, blend and recycled polymer stiffness increased by 11.8 and 3.7%, respectively.
- Compared to virgin polymers with fibers, maximum tensile stress reductions in the blend and 100% recycled polymers with fibers were found to be between 13.5 and 14.6%, respectively. Similarly, blend and 100% recycled polymer stiffness reductions were found to be 1.2 and 3.6%, respectively.
- Addition of 12% fiber volume fraction of randomly oriented and chopped glass fibers to virgin, blend and 100% recycled polymers resulted in a tensile stress increase of 66.8, 50.6, and 57.7% respectively. Similarly, stiffness increase was found to be 204.0, 162.1 and 189.5% respectively for the virgin, blend and 100% recycled polymers.
- Virgin polymers without fibers showed elongation in excess of 10%. Extensometer available with the Instron machine had a maximum capacity of 10%. Hence the, strain measurements were discontinued. Strain values of recycled and blend specimens were less than the strains of virgin polymers. Addition of fibers reduced the failure strain values in virgin, blend and 100% recycled polymers to 1.35, 1.18 and 1.12%, respectively.

4.2.3 Results of Tension Tests on PC

Strength and stiffness results of tension tests are summarized in Table 4.3. Each result is an average of at least 5 specimens. Results for individual tests are shown in Appendix-A, including statistical analysis of the data. Virgin polymers and recycled

polymers without fibers showed elongation in excess of 10%. Extensometer used in this study had a limit of 10% on strain measurements; hence the strain readings were discontinued at about 9% strain. Typical stress-strain curves are shown in Figs. 4.7 and 4.8 for virgin PC without and with fibers. It is noted that the PC polymer exhibits two stiffness values, E1 and E2, during testing. For the virgin, 100% recycled, and blend PC polymer with fibers, the second stiffness value, E2, is 41-47% of E1 and begins at approximately 72-78% of the maximum stress (≈ 12000 psi). For the virgin, 100% recycled, and blend PC polymer without fibers, the second stiffness value, E2, is 47-52% of E1 and begins at approximately 57% of the maximum stress (≈ 5000 psi). Comparison of tensile stress and stiffness is shown in Figs. 4.5 and 4.6.

Table 4.3 Tension Test Results on PC

Specimen	Maximum Load	Maximum Stress	Strain @ Max. Load	Tensile Stiffness (E1)	Tensile Stiffness (E2)	E2/E1	ϵ_1/ϵ_2
	lbs.	psi	%	psi	psi	%	%
TP1	556.21	8664.76	7.27	0.300E+06	0.147E+06	49.0	61.5
TP2	1057.82	16479.06	3.14	1.029E+06	0.431E+06	41.8	51.5
TP3	549.87	8566.05	7.33	0.293E+06	0.139E+06	47.4	66.7
TP4	976.58	15213.48	2.68	0.993E+06	0.417E+06	41.9	48.7
TP5	573.01	8926.44	7.03	0.329E+06	0.169E+06	51.3	58.8
TP6	1062.74	16555.71	2.95	1.046E+06	0.490E+06	46.8	48.9

Fig. 4.5 Comparison of Maximum Tensile Stresses in PC (12% Fiber Volume Fraction)

Fig. 4.6 Comparison of Maximum Tensile Stiffness in PC (12% Fiber Volume Fraction)

Fig. 4.7 Typical Stress-Strain Curve for Virgin PC without Fibers in Tension

Fig. 4.8 Typical Stress-Strain Curve for Virgin PC with 12% Fiber Volume Fraction in Tension

4.2.4 Analysis and Discussion of Tension Test Results on PC

Stiffness of the specimens was evaluated through regression analysis by providing best-fit curve to the linear portion of the stress-strain curve. Analysis of the test results is shown in Table 4.4.

**Table 4.4 Analysis and Comparison of Tension Test Results on PC
(% Increase/Decrease)**

Effect of	Specimen Type	Compared With	Max. Ten. Stress	Tensile Stiffness %		Strain @ Max. Stress
			%	E1	E2	%
Recycling (Without Fibers)	TP3 (R)	TP1 (V)	-1.1	-2.3	-5.4	+0.8
	TP5 (B)		+3.0	+9.7	+15.0	-3.3
Recycling (With Fibers)	TP4 (R-F)	TP2 (V-F)	-7.7	-3.4	-3.2	-14.6
	TP6 (B-F)		+0.5	+1.7	+13.7	-6.1
Fiber Addition	TP2 (V-F)	TP1 (V)	+90.2	+243.0	+193.0	-56.8
	TP4 (R-F)	TP3 (R)	+77.6	+238.7	+200.0	-63.4
	TP6 (B-F)	TP5 (B)	+85.5	+217.9	+189.9	-58.0

Note: T-Tension; P-PC; V-Virgin; R-100% Recycled; B-Blend (80% virgin and 20% Recycled); F-Fiber; E1-First Stiffness; E2-Second Stiffness; +ve sign -Increase; -ve sign-Reduction. Refer to Table 4.3 for absolute values.

- Compared to virgin polymers, maximum tensile stress in the blend increased by 3.0% whereas the 100% recycled polymers was nearly equal. Similarly, blend and 100% recycled polymer stiffness increased and decreased by 9.7 and 2.3%, respectively.
- Compared to virgin polymers with fibers, maximum tensile stress reductions in the 100% recycled polymers with fibers were found to be 7.7% and increased by 0.5% in the blend. Similarly, blend and 100% recycled polymer increased and decreased by 1.7 and 3.4%, respectively.

- Addition of 12% fiber volume fraction of randomly oriented and chopped glass fibers to virgin, blend and 100% recycled polymers resulted in a tensile stress increase of 90.2, 85.5, and 77.6% respectively. Similarly, stiffness increase for E1 was found to be 243.0, 217.9 and 238.7% respectively for the virgin, blend and 100% recycled polymers and 193.0, 189.9, and 200.0% for E2.
- Virgin polymers without fibers showed elongation in excess of 10%. Extensometer available with the Instron machine had a maximum capacity of 10% and hence the readings were discontinued. Strain values of recycled and blend specimens were less than the virgin polymers. It is noted that the PC polymer with fibers exhibited higher ductility than the ABS polymer with fibers. Addition of fibers in the PC polymer yielded maximum strain at failure values in virgin, blend and 100% recycled polymers of 3.23, 3.26 and 2.96%, respectively. For the ABS polymer with fibers, the maximum strain values at failure in virgin, blend and 100% recycled polymers was 1.51, 1.18 and 1.12%, respectively.

4.3 Bending Test

4.3.1 Results of Bending Tests on ABS

Strength and stiffness results of the bending tests are summarized in Table 4.5. Each result is an average of at least 5 specimens. Results for individual tests are shown in Appendix-B, including statistical analysis of the data. Virgin polymers and recycled polymers without fibers showed higher deflections in excess of $1/3^{\text{rd}}$ the test span of 3.75". Comparison of bending stress and stiffness is shown in Figs. 4.9 and 4.10. Typical load-deflection diagrams of polymer blend specimens without and with fibers are shown in Figs. 4.11 and 4.12.

Table 4.5 Results of Bending Tests on ABS

Specimen	Maximum Load	Maximum Stress	Deflection @ Max. Stress	Bending Stiffness (E)
	lbs.	psi	in.	psi
BA1	12.61	9080.23	0.67	0.40E+06
BA2	24.68	17771.04	0.50	1.02E+06
BA3	12.76	9187.20	0.69	0.40E+06
BA4	23.25	16740.00	0.48	1.08E+06
BA5	13.28	9558.72	0.70	0.40E+06
BA6	22.93	16509.60	0.47	1.11E+06

Fig. 4.9 Comparison of Maximum Bending Stresses in ABS (12% Fiber Volume Fraction)

Fig. 4.10 Comparison of Maximum Bending Stiffness in ABS (12% Fiber Volume Fraction)

Fig. 4.11 Load-Deflection in Bending for ABS Polymer Blend Specimen without Fibers

Fig. 4.12 Load-Deflection in Bending for ABS Polymer Blend Specimen with 12% Fiber Volume Fraction

4.3.2 Analysis and Discussion of Bending Test Results on ABS

Evaluation of stiffness was carried out using the slope of the load-deflection diagram in Euler's bending equation and the stiffness values were found to be lower than those recorded by strain gages. In this report bending stiffness values obtained through strain-gages are reported. Analysis of the test results is shown in Table 4.6.

Table 4.6 Analysis and Comparison of Bending Test Results on ABS (% Increase/Decrease)

Effect of	Specimen Type	Compared With	Max. Tensile Stress	Tensile Stiffness	Strain @ Max. Stress
			%	%	%
Recycling (Without Fibers)	BA3 (R)	BA1 (V)	+1.2	0.0	+3.0
	BA5 (B)		+5.3	0.0	+4.5
Recycling (With Fibers)	BA4 (R-F)	BA2 (V-F)	-5.8	+5.9	-4.0
	BA6 (B-F)		-7.1	+8.8	-6.0
Fiber Addition	BA2 (V-F)	BA1 (V)	+95.7	+155.0	-25.4
	BA4 (R-F)	BA3 (R)	+75.1	+170.0	-31.4
	BA6 (B-F)	BA5 (B)	+72.7	+177.5	-32.9

Note: B-Bending; A-ABS; V-Virgin; R-100% Recycled; B (within brackets)-Blend (80% virgin and 20% Recycled); F-Fiber; +ve sign -Increase; -ve sign- Reduction. Refer to Table 4.5 for absolute values.

- Compared to virgin polymers, maximum bending stress in the blend and 100% recycled polymers increased by 5.3% and 1.2% respectively. However, blend and 100% recycled polymer stiffnesses were identical to the virgin polymer.
- Compared to virgin polymers with fibers, maximum bending stress reductions in the blend and 100% recycled polymers with fibers were found to be 7.1 and 5.8%, respectively. However, blend and 100% recycled polymer stiffness increases were found to be 8.8 and 5.9%, respectively.
- Addition of 12% fiber volume fraction of randomly oriented and chopped glass fibers to virgin, blend and 100% recycled polymers resulted in a bending stress increase of 95.7, 72.7, and 75.1% respectively. Similarly, stiffness increase was found to be 155.0, 177.5 and 170.0% respectively for the virgin, blend and 100% recycled polymers.

4.3.3 Results of Bending Tests on PC

Strength and stiffness results of the bending tests are summarized in Table 4.7. Each result is an average of at least 5 specimens. Results for individual tests are shown in Appendix-B, including statistical analysis of the data. Virgin polymers and recycled polymers without fibers showed higher deflections in excess of $1/3^{\text{rd}}$ the test span of 3.75". Comparison of bending stress and stiffness is shown in Figs. 4.13 and 4.14. Typical load-deflection diagrams of polymer blend specimens without and with fibers are shown in Figs. 4.15 and 4.16.

Table 4.7 Results of Bending Tests on PC

Specimen	Maximum Load	Maximum Stress	Deflection @ Max. Stress	Bending Stiffness (E)
	lbs.	psi	in.	psi
BP1	14.23	10242.72	0.87	0.332E+06
BP2	34.12	24566.40	0.78	0.967E+06
BP3	14.39	10363.68	0.81	0.291E+06
BP4	32.22	23198.40	0.66	0.916E+06
BP5	15.51	11168.64	0.90	0.327E+06
BP6	34.56	24886.08	0.69	0.993E+06

Fig. 4.13 Comparison of Maximum Bending Stresses in PC (12% Fiber Volume Fraction)

Fig. 4.14 Comparison of Maximum Bending Stiffness in PC (12% Fiber Volume Fraction)

Fig. 4.15 Load-Deflection in Bending for PC Polymer Blend Specimen without Fibers

Fig. 4.16 Load-Deflection in Bending for PC Polymer Blend Specimen with 12% Fiber Volume Fraction

4.3.4 Analysis and Discussion of Bending Test Results on PC

Evaluation of stiffness was carried out using the slope of the load-deflection diagram in Euler's bending equation. Analysis of the test results is shown in Table 4.8.

Table 4.8 Analysis and Comparison of Bending Test Results on PC (% Increase/Decrease)

Effect of	Specimen Type	Compared With	Max. Tensile Stress	Tensile Stiffness	Strain @ Max. Stress
			%	%	%
Recycling (Without Fibers)	BP3 (R)	BP1 (V)	+1.1	-12.3	-6.9
	BP5 (B)		+9.0	-1.5	+3.4
Recycling (With Fibers)	BP4 (R-F)	BP2 (V-F)	-5.8	-5.3	-15.4
	BP6 (B-F)		+1.3	+2.7	-11.5
Fiber Addition	BP2 (V-F)	BP1 (V)	+139.8	+191.3	-10.3
	BP4 (R-F)	BP3 (R)	+123.9	+214.8	-18.5
	BP6 (B-F)	BP5 (B)	+122.8	+203.7	-23.3

Note: B-Bending; P-PC; V-Virgin; R-100% Recycled; B (within brackets)-Blend (80% virgin and 20% Recycled); F-Fiber; +ve sign -Increase; -ve sign- Reduction. Refer to Table 4.7 for absolute values.

- Compared to virgin polymers, maximum bending stress in the blend and 100% recycled polymers increased by 9.0% and 1.1% respectively. However, blend and 100% recycled polymer stiffness decreased by 1.5 and 12.3% respectively.
- Compared to virgin polymers with fibers, maximum bending stress reduction in the 100% recycled polymers with fibers was found to be 5.8%, whereas the blend bending stress increased by 1.3%. Similarly, blend and 100% recycled polymer increased and decreased by 2.7 and 5.3%, respectively.
- Addition of 12% fiber volume fraction of randomly oriented and chopped glass fibers to virgin, blend and 100% recycled polymers resulted in a bending stress increase of 139.8, 122.8, and 123.9% respectively. Similarly, stiffness increase was found to be 191.3, 203.7 and 214.8% respectively for the virgin, blend and 100% recycled polymers.
- Compared to the ABS polymer without fibers, the virgin, blend and 100% recycled PC polymer without fibers exhibited 11.3, 14.4, and 11.4% higher maximum stress readings with 23.0, 14.8, and 22.2% more deflection at maximum stress, respectively.
- Compared to the ABS polymer with fibers, the virgin, blend and 100% recycled PC polymer with fibers exhibited 27.7, 33.7, and 27.8% higher maximum stress readings with 44.4, 31.9, and 27.3% more deflection at maximum stress, respectively.

4.4 Compression Test

4.4.1 Results of Compression Tests on ABS

Strength and stiffness results of the compression tests are summarized in Table 4.9. Each result is an average of at least 5 specimens with a height of 0.5” and a cross-

section of 0.5"x0.25". Each result is an average of at least 5 specimens. Results for individual tests are shown in Appendix-C, including statistical analysis of the data. Virgin polymers and recycled polymers without fibers showed significant deformations after the maximum load. Similar behavior was observed in specimens with chopped fibers. Comparison of compression stress and stiffness is shown in Figs. 4.17 and 4.18. Typical stress vs. change-in-height diagrams of 100% recycled polymer specimens without and with fibers are shown in Figs. 4.19 and 4.20.

Table 4.9 Results of Compression Tests on ABS

Specimen	Maximum Load lbs.	Maximum Stress psi	Reduction in Length @ Max. Stress in.	Compression Stiffness (E) psi
CA1	1120.75	8966.02	0.042	0.34E+06
CA2	1641.90	13135.22	0.034	0.91E+06
CA3	1099.03	8792.27	0.039	0.42E+06
CA4	1861.38	14891.01	0.034	0.92E+06
CA5	1121.55	8972.42	0.040	0.41E+06
CA6	1740.07	13920.55	0.033	1.02E+06

Fig. 4.17 Comparison of Maximum Compressive Stresses in ABS (12% Fiber Volume Fraction)

Fig. 4.18 Comparison of Maximum Compressive Stiffness in ABS (12% Fiber Volume Fraction)

Fig. 4.19 Stress versus Change-in-Height for 100% Recycled ABS specimen without Fibers in Compression

Fig. 4.20 Stress vs. Change-in-Height for 100% Recycled ABS specimen with 12% Fiber Volume Fraction in Compression

4.4.2 Analysis and Discussion of Compression Test Results on ABS

Evaluation of stiffness was carried out using the slope of the stress versus change-in-height diagrams in simple stress equation, and the stiffness values were found to be lower than those recorded by strain gages. In this report, stiffness values under compressive loads obtained through strain-gages are reported. Analysis of test results is shown in Table 4.10.

**Table 4.10 Analysis and Comparison of Compression Test Results on ABS
(% Increase/Decrease)**

Effect of	Specimen Type	Compared With	Max. Tensile Stress	Tensile Stiffness	Strain @ Max. Stress
			%	%	%
Recycling (Without Fibers)	CA3 (R)	CA1 (V)	-1.9	+23.5	-7.1
	CA5 (B)		+0.1	+20.6	-4.8
Recycling (With Fibers)	CA4 (R-F)	CA2 (V-F)	+13.4	+1.1	0.0
	CA6 (B-F)		+6.0	+12.1	-2.9
Fiber Addition	CA2 (V-F)	CA1 (V)	+46.5	+167.6	-19.0
	CA4 (R-F)	CA3 (R)	+66.0	+300.0	-15.0
	CA6 (B-F)	CA5 (B)	+55.1	+343.5	-17.5

Note: C-Compression; A-ABS; V-Virgin; R-100% Recycled; B-Blend (80% virgin and 20% Recycled); F-Fiber; +ve sign -Increase; -ve sign- Reduction. Refer to Table 4.9 for absolute values.

- Compared to virgin polymers, maximum compressive stress variations in the blend and 100% recycled polymers were found to be less than 2%. However, blend and 100% recycled polymer stiffnesses increased by 20.6 and 23.5%, respectively.
- Compared to virgin polymers with fibers, maximum compressive stress increases in the blend and 100% recycled polymers with fibers were found to be between 6 and 13.4%, respectively. Similarly, blend and 100% recycled polymer stiffness increase was found to be 12.1 and 1.1%, respectively.
- Addition of 12% fiber volume fraction of randomly oriented and chopped glass fibers to virgin, blend and 100% recycled polymers resulted in compressive stress increases of 46.5, 55.1, and 66.0% respectively. Similarly, stiffness increase was found to be 167.6, 343.5 and 300.0% respectively for the virgin, blend and 100% recycled polymers.

4.4.3 Results of Compression Tests on PC

Strength and stiffness results of the compression tests are summarized in Table 4.11. Each result is an average of at least 5 specimens with a height of 0.5" and a cross-section of 0.5"x0.25". Results for individual tests are shown in Appendix-C, including statistical analysis of the data. Virgin polymers and recycled polymers without fibers showed significant deformations after the maximum load. Similar behavior was observed in specimens with chopped fibers. Readings recorded by the Instron machine were found to be 95% higher than actual readings, as verified through a set of deflection gages having a least count of 0.0001" shown in Fig 4.21. It was noted that small deflections (of the order of 10^{-4} inches) of the stationary cross-head had a major contribution towards such discrepancy. The corrected stiffness readings were found to match with strain gage reading for ABS, therefore it was decided to use strain gage readings for the stiffness evaluation of ABS. The stiffness values for PC are based on the corrected machine readings as shown in Table 4.11. Comparisons of compression stress and stiffness with and without fibers are shown in Figs. 4.22 and 4.23. Typical stress vs. change-in-height diagrams of 100% recycled polymer specimens without and with fibers is shown in Figs. 4.24 and 4.25. The compression test was stopped between 0.03 to 0.04 inches deflection due to the specimen becoming compressed to a point that the original cross-section begins to change.

Fig. 4.21 Deflection gage set-up

Table 4.11 Results of Compression Tests on PC

Specimen	Maximum Load lbs.	Maximum Stress psi	Reduction in Length @ Max. Stress in.	Compression Stiffness (E) psi
CP1	1302.96	10423.66	0.043	0.41E+06
CP2	2541.60	20332.83	0.040	0.80E+06
CP3	1288.91	10311.28	0.044	0.39E+06
CP4	2593.40	20747.23	0.037	0.84E+06
CP5	1315.49	10523.94	0.044	0.41E+06
CP6	2640.52	21124.14	0.038	0.83E+06

Fig. 4.22 Comparison of Maximum Compressive Stresses in PC (12% Fiber Volume Fraction)

Fig. 4.23 Comparison of Maximum Compressive Stiffness in PC (12% Fiber Volume Fraction)

Fig. 4.24 Stress versus Change-in-Height for 100% Recycled PC specimen without Fibers in Compression

Fig. 4.25 Stress versus Change-in-Height for 100% Recycled PC specimen with 12% Fiber Volume Fraction in Compression

4.4.4 Analysis and Discussion of Compression Test Results on PC

Evaluation of stiffness was carried out using the slope of the stress versus corrected change-in-height diagrams. Analysis of test results is shown in Table 4.12.

**Table 4.12 Analysis and Comparison of Compression Test Results on PC
(% Increase/Decrease)**

Effect of	Specimen Type	Compared With	Max. Tensile Stress	Tensile Stiffness	Strain @ Max. Stress
			%	%	%
Recycling (Without Fibers)	CP3 (R)	CP1 (V)	-1.1	-4.8	+2.3
	CP5 (B)		+1.0	0.0	+2.3
Recycling (With Fibers)	CP4 (R-F)	CP2 (V-F)	+2.0	+5.0	-7.5
	CP6 (B-F)		+3.9	+3.8	-5.0
Fiber Addition	CP2 (V-F)	CP1 (V)	+95.1	+95.1	-7.0
	CP4 (R-F)	CP3 (R)	+101.2	+115.4	-15.9
	CP6 (B-F)	CP5 (B)	+100.7	+102.4	-13.6

Note: C-Compression; P-PC; V-Virgin; R-100% Recycled; B-Blend (80% virgin and 20% Recycled); F-Fiber; +ve sign -Increase; -ve sign- Reduction. Refer to Table 4.11 for absolute values.

- Compared to virgin polymers, maximum compressive stress variations in the blend and 100% recycled polymers were found to be less than 1.5%. However, 100% recycled polymer stiffnesses decreased by 4.8% whereas the blend was unchanged.
- Compared to virgin polymers with fibers, maximum compressive stress increases in the blend and 100% recycled polymers with fibers were found to be between 3.9 and 2.0%, respectively. Similarly, blend and 100% recycled polymer specimen stiffness increases were found to be 3.8 and 5.0%, respectively.

- Addition of 12% fiber volume fraction of randomly oriented and chopped glass fibers to virgin, blend and 100% recycled polymers resulted in compressive stress increases of 95.1, 100.7, and 101.2% respectively. Similarly, stiffness increase was found to be 95.1, 102.4 and 115.4% respectively for the virgin, blend and 100% recycled polymers.
- Compared to the ABS polymer without fibers, the virgin, blend and 100% recycled PC polymer without fibers exhibited 14.0, 14.7, and 14.7% higher maximum stress readings with similar deflections at maximum stress, respectively.
- Compared to the ABS polymer with fibers, the virgin, blend and 100% recycled PC polymer with fibers exhibited 35.4, 34.1, and 28.2% higher maximum stress readings with similar deflections at maximum stress, respectively.

4.5 Impact Test

4.5.1 Results, Analysis, and Discussion of Impact Tests on ABS

Impact strength results are summarized in Table 4.13 after averaging data of at least 5 specimens tested at a laboratory temperature of 72⁰F. Results for individual tests are shown in Appendix-D, including statistical analysis of the data. Virgin polymers and recycled polymers without fibers showed higher impact strength than those with fibers. Comparison of impact strength is shown in Fig. 4.26. Analysis of the test results is shown in Table 4.14.

Table 4.13 Results of Impact Tests on ABS

Specimen	Indicated Impact Strength	Corrected Impact Strength	Corrected Impact Strength	Observed Failure Types
	ft-lbs _f	ft-lbs _f	ft-lbs _f /in	
IA1	0.48	0.44	3.49	H
IA2	0.25	0.20	1.58	C
IA3	0.31	0.27	2.17	H
IA4	0.17	0.12	0.96	C
IA5	0.34	0.30	2.38	H(3), C(2)
IA6	0.20	0.15	1.20	C

Note: H-Hinge Break; C-Complete Break; corrections applied as per the chart supplied by the manufacturer for the impact testing machine to account for friction and windage.

Fig. 4.26 Comparison of Impact Strength in ABS (12% Fiber Volume Fraction)

**Table 4.14 Analysis and Comparison of Impact Test Results on ABS
(% Increase/Decrease)**

Effect of	Specimen Type	Compared with	Impact Strength
			%
Recycling (Without Fibers)	IA3 (R)	IA1 (V)	-37.8
	IA5 (B)		-31.8
Recycling (With Fibers)	IA4 (R-F)	IA2 (V-F)	-39.2
	IA6 (B-F)		-24.1
Fiber Addition	IA2 (V-F)	IA1 (V)	-54.7
	IA4 (R-F)	IA3 (R)	-59.7
	IA6 (B-F)	IA5 (B)	-49.6

Note: I-Impact; A-ABS; V-Virgin; R-100% Recycled; B-Blend (80% virgin and 20% Recycled); F-Fiber; +ve sign -Increase; -ve sign- Reduction. For absolute values refer to Table 4.13.

- Compared to virgin polymers, impact strength of the blend and 100% recycled polymers decreased by 31.8% and 37.8% respectively.
- Compared to virgin polymers with fibers, maximum impact strength reductions in the blend and 100% recycled polymers with fibers were found to be 24.1 and 39.2%, respectively.
- Addition of 25% by weight of randomly oriented and chopped glass fibers to virgin, blend and 100% recycled polymers resulted in impact strength reduction of 54.7, 49.6, and 59.7%.

4.5.2 Results, Analysis, and Discussion of Impact Tests on PC

Impact strength results are summarized in Table 4.15 after averaging data of at least 5 specimens tested at a laboratory temperature of 72⁰F. Results for individual tests are shown in Appendix-D, including statistical analysis of the data. Virgin polymers and

recycled polymers without fibers showed higher impact strength than those with fibers. Comparison of impact strength is shown in Fig. 4.27. Analysis of the test results is shown in Table 4.16.

Table 4.15 Results of Impact Tests on PC

Specimen	Indicated Impact Strength	Corrected Impact Strength	Corrected Impact Strength	Observed Failure Types
	ft-lbs _f	ft-lbs _f	ft-lbs _f /in	
IP1	1.79	1.77	14.40	P
IP2	0.42	0.38	3.01	C(4), H(1)
IP3	1.71	1.69	13.53	P
IP4	0.27	0.23	1.81	C
IP5	1.87	1.85	14.80	P
IP6	0.37	0.33	2.67	C

Note: H-Hinge Break; C-Complete Break; P-Partial Break corrections applied as per the chart supplied by the manufacturer for the impact testing machine to account for friction and windage.

Fig. 4.27 Comparison of Impact Strength in PC (12% Fiber Volume Fraction)

**Table 4.16 Analysis and Comparison of Impact Test Results on PC
(% Increase/Decrease)**

Effect of	Specimen Type	Compared with	Impact Strength
			%
Recycling (Without Fibers)	IP3 (R)	IP1 (V)	-4.4
	IP5 (B)		+4.5
Recycling (With Fibers)	IP4 (R-F)	IP2 (V-F)	-39.9
	IP6 (B-F)		-11.3
Fiber Addition	IP2 (V-F)	IP1 (V)	-78.7
	IP4 (R-F)	IP3 (R)	-86.6
	IP6 (B-F)	IP5 (B)	-82.0

Note: I-Impact; P-PC; V-Virgin; R-100% Recycled; B-Blend (80% virgin and 20% Recycled); F-Fiber; +ve sign -Increase; -ve sign- Reduction. For absolute values refer to Table 4.15.

- Compared to virgin polymers, impact strengths of the 100% recycled polymers and the blend were nearly the same, varying by as little as 4.5%.
- Compared to virgin polymers with fibers, maximum impact strength reductions in the blend and 100% recycled polymers with fibers were found to be 11.3 and 39.9%, respectively.
- Addition of 12% fiber volume fraction of randomly oriented and chopped glass fibers to virgin, blend and 100% recycled polymers resulted in impact strength reduction of 78.7, 82.0, and 86.6%.
- Compared to the ABS polymer without fibers, the virgin, blend and 100% recycled PC polymer without fibers exhibited 75.3, 84.0, and 83.9% higher impact readings, respectively.

- Compared to the ABS polymer with fibers, the virgin, blend and 100% recycled PC polymer with fibers exhibited 47.5, 55.1, and 47.0% higher impact readings, respectively.

4.6 Hardness Test

4.6.1 Results, Analysis, and Discussion of Hardness Tests on ABS

Hardness test results are summarized in Table 4.17. Each result is an average of 8 specimens carried out at a laboratory temperature of 72°F. Results for individual tests are shown in Appendix-E, including statistical analysis of the data. Comparison of the hardness values using no weight and using a 626g weight is shown in Figs. 4.28 and 4.29, respectively. All results are within 1.2% using a 626g weight, and 4% without the weight. Analysis of test results is shown in Table 4.18.

Table 4.17 Results of Hardness Tests on ABS

Specimen	Without Weight	With 626g Weight
HA1	10.9	25.7
HA2	11.3	25.8
HA3	11.1	25.6
HA4	11.2	25.7
HA5	11.2	25.9
HA6	11.2	25.8

Fig. 4.28 Comparison of Hardness Values of ABS w/o Weight (12% Fiber Volume Fraction)

Fig. 4.29 Comparison of Hardness Values of ABS with 626g Weight (12% Fiber Volume Fraction)

**Table 4.18 Analysis and Comparison of Hardness Test Results on ABS
(% Increase/Decrease)**

Effect of	Specimen Type	Compared with	Without Weight	With 626g Weight
			%	%
Recycling (Without Fibers)	HA3 (R)	HA1 (V)	+1.8	-0.4
	HA5 (B)		+2.8	+0.8
Recycling (With Fibers)	HA4 (R-F)	HA2 (V-F)	-0.9	-0.4
	HA6 (B-F)		-0.9	0.0
Fiber Addition	HA2 (V-F)	HA1 (V)	+3.7	+0.4
	HA4 (R-F)	HA3 (R)	+0.9	+0.4
	HA6 (B-F)	HA5 (B)	0.0	-0.4

Note: H-Hardness; A-ABS; V-Virgin; R-100% Recycled; B-Blend (80% virgin and 20% Recycled); F-Fiber; +ve sign -Increase; -ve sign- Reduction. For absolute values refer to Table 4.17.

- Compared to virgin polymers, hardness values of the blend and 100% recycled polymers increased by 2.8 and 1.8% respectively, using no weight. The hardness value of the 100% recycled polymer decreased by 0.4% whereas the blend increased by 0.8% using the 626g weight.
- Compared to virgin polymers with fibers, hardness values of the blend and 100% recycled polymers decreased by 0.9% using no weight, whereas the 100% recycled decreased by 0.4% and the blend remained unchanged using the 626g weight.
- Addition 12% fiber volume fraction of randomly oriented and chopped glass fibers to virgin, blend and 100% recycled polymers resulted in hardness values increasing 3.7%, 0.9% and remaining unchanged respectively, using no weight. Using the 626g weight, the virgin and 100% recycled increased 0.4%, and the blend decreased 0.4%.

4.6.2 Results, Analysis, and Discussion of Hardness Tests on PC

Hardness test results are summarized in Table 4.19. Each result is an average of 8 specimens carried out at a laboratory temperature of 72°F. Results for individual tests are shown in Appendix-E, including statistical analysis of the data. Comparison of the hardness values using no weight and using a 626g weight is shown in Figs. 4.30 and 4.31, respectively. All results are within 1.0% with and without using a 626g weight. Analysis of test results is shown in Table 4.20.

Table 4.19 Results of Hardness Test on PC

Specimen	Without Weight	With 626g Weight
HP1	10.6	25.3
HP2	10.7	25.3
HP3	10.6	25.4
HP4	10.7	25.3
HP5	10.7	25.5
HP6	10.7	25.5

Fig. 4.30 Comparison of Hardness Values of PC w/o Weight (12% Fiber Volume Fraction)

Fig. 4.31 Comparison of Hardness Values of PC with 626g Weight (12% Fiber Volume Fraction)

**Table 4.20 Analysis and Comparison of Hardness Test Results on PC
(% Increase/Decrease)**

Effect of	Specimen Type	Compared with	Without Weight	With 626g Weight
			%	%
Recycling (Without Fibers)	HP3 (R)	HP1 (V)	0.0	+0.4
	HP5 (B)		+0.9	+0.8
Recycling (With Fibers)	HP4 (R-F)	HP2 (V-F)	0.0	0.0
	HP6 (B-F)		0.0	+0.8
Fiber Addition	HP2 (V-F)	HP1 (V)	+0.9	0.0
	HP4 (R-F)	HP3 (R)	+0.9	+0.4
	HP6 (B-F)	HP5 (B)	0.0	0.0

Note: H-Hardness; P-PC; V-Virgin; R-100% Recycled; B-Blend (80% virgin and 20% Recycled); F-Fiber; +ve sign -Increase; -ve sign- Reduction. For absolute values refer to Table 4.19.

- Compared to virgin polymers, hardness values of the 100% recycled polymers were unchanged whereas the blend increased by 0.9% using no weight, and increased by 0.8 and 0.4% respectively, using the 626g weight.
- Compared to virgin polymers with fibers, hardness values of the blend and 100% recycled polymers with fibers were unchanged using no weight, and increased by 0.8 and remained unchanged respectively, using the 626g weight.
- Addition of 12% fiber volume fraction of randomly oriented and chopped glass fibers to virgin, blend and 100% recycled polymers resulted in hardness values increasing 0.9%, 0.9% and remaining unchanged respectively, using no weight and remained unchanged, increased 0.4%, and remained unchanged using the 626g weight.
- Compared to the ABS polymer, the hardness values for the PC polymer with and without fibers was nearly identical.

4.7 Creep Test

4.7.1 Results, Analysis, and Discussion of Creep Tests on ABS

Results of the creep study are briefly summarized in the following section. Creep coefficients in Table 4.21 and 4.22 refer to the ratio of creep strain to initial strain at the instant of load application with 50% and 20% sustained loading, respectively. The designations in the following tables and charts of A1, A3, and A5 refer to the virgin, 100% recycled, and blend ABS polymers without fibers respectively, whereas A2, A4, and A6 refer to the virgin, 100% recycled, and blend ABS polymers with fibers. At 50% of ultimate loading, ABS specimens with recycled polymer blend and 100% recycled polymer without fibers failed at 38 days. Both of these specimens were connected in series. At 20% of ultimate loading, the blend and 100% recycled polymer without fibers are at 0.860 and 1.179, respectively at 130 days. The virgin polymer specimen without fibers at a stress level of 50%, failed at 45 days. At 20% of loading, the virgin polymer specimen without fibers is 0.812 at 90 days. Creep testing on the specimens with fibers is currently being conducted at both 50% and 20% of the loading. It is to be noted that these specimens are performing well under these sustained loads. In practice, sustained stress on the fiber-reinforced polymers is limited to less than 20%. In Figs 4.32 to 4.35, the primary and secondary creep is clearly visible. Furthermore, if the specimens are tested at a greater duration, the tertiary creep should become recognizable. During the creep testing, it was concluded that the variation in temperature, sometimes as much as 10-15°F, was responsible for the excessive rise and fall of the creep values at various times throughout the test. Further testing is necessary to determine the degree to which

the creep values are effected by this temperature variation. Complete creep data is shown in Appendix-F.

Table 4.21 Creep Data of 145 Days for ABS Specimens with $\approx 50\%$ Sustained Loading

Specimen	Duration					
	3 Days	7 Days	16 Days	45 Days	90 Days	145 Days
A1	0.322	0.428	0.609	0.996	-	-
A2	0.083	0.116	0.152	0.259	0.335	0.472
A3	0.371	0.483	0.681	-	-	-
A4	0.161	0.201	0.269	0.436	0.595	0.861
A5	0.215	0.284	0.405	-	-	-
A6	0.140	0.173	0.230	0.365	0.497	0.710

Table 4.22 Creep Data of 130 Days for ABS Specimens with $\approx 20\%$ Sustained Loading

Specimen	Duration					
	3 Days	7 Days	16 Days	45 Days	90 Days	130 Days
A1	0.096	0.126	0.214	0.381	0.812	-
A2	0.049	0.062	0.088	0.118	0.221	-
A3	0.043	0.083	0.160	0.350	0.541	0.860
A4	0.030	0.045	0.069	0.108	0.222	-
A5	0.100	0.152	0.260	0.512	0.762	1.179
A6	0.049	0.058	0.089	0.181	0.291	-

Fig. 4.32 Creep Curves for ABS with 12% Fiber Volume Fraction ($\approx 50\%$ Ultimate Load)

Fig. 4.33 Creep Curves for ABS without Fibers ($\approx 50\%$ Ultimate Load)

Fig. 4.34 Creep Curves for ABS with 12% Fiber Volume Fraction ($\approx 20\%$ Ultimate Load)

Fig. 4.35 Creep Curves for ABS without Fibers ($\approx 20\%$ Ultimate Load)

- For ABS specimens without fibers at 16 days duration and $\approx 50\%$ sustained load, the creep values are 0.609, 0.681, and 0.405 for the virgin, 100% recycled, and blend respectively. For 90 days duration and $\approx 20\%$ sustained load, the creep values are 0.812, 0.541, and 0.762 for the virgin, 100% recycled, and blend respectively.
- For ABS specimens with fibers at 145 days duration and $\approx 50\%$ sustained load, the creep values are 0.472, 0.861, and 0.710 for the virgin, 100% recycled, and blend respectively. For 90 days duration and $\approx 20\%$ sustained load, the creep values are 0.221, 0.222, and 0.291 for the virgin, 100% recycled, and blend respectively.
- Polymers alone, i.e., without glass fibers, are not suitable for high-sustained load applications. Creep of polymers is limited by the use of fibers.
- Recycled polymers and their blends showed creep-life of about 40% of those of virgin polymers without fibers at a high-sustained load of 50%. These results are based on single specimen tests and further tests need to be carried out with additional samples.

4.7.2 Results, Analysis, and Discussion of Creep Tests on PC

Results of the creep study are briefly summarized in the following section. Creep coefficients in Table 4.23 and 4.24 refer to the ratio of creep strain to initial strain at the instant of load application with 50% and 20% sustained loading, respectively. The designations in the following tables and charts of P1, P3, and P5 refer to the virgin, 100% recycled, and blend PC polymers without fibers respectively, whereas P2, P4, and P6 refer to the virgin, 100% recycled, and blend PC polymers with fibers. Due to time constraints, the PC creep test was conducted for a period of 16 days. In Figs. 4.36 to

4.39, the primary and secondary creep is clearly visible. Furthermore, if the specimens are tested at a greater duration, the tertiary creep should become recognizable. During the creep testing, it was concluded that the variation in temperature, sometimes as much as 10-15°F, was responsible for the excessive rise and fall of the creep values at various times throughout the test. Further testing is necessary to determine the degree to which the creep values are effected by this temperature variation. Complete creep data is shown in Appendix-F.

Table 4.23 Creep Data of 16 Days for PC Specimens with ≈50% Sustained Loading

Specimen	Duration		
	3 Days	7 Days	16 Days
P1	0.429	0.499	0.612
P2	0.170	0.207	0.253
P3	0.396	0.455	0.539
P4	0.211	0.263	0.333
P5	0.390	0.469	0.610
P6	0.183	0.225	0.290

Table 4.24 Creep Data of 16 Days for PC Specimens with ≈20% Sustained Loading

Specimen	Duration		
	3 Days	7 Days	16 Days
P1	0.291	0.386	0.471
P2	0.077	0.109	0.139
P3	0.308	0.426	0.537
P4	0.114	0.151	0.185
P5	0.191	0.263	0.329
P6	0.081	0.115	0.148

Fig. 4.36 Creep Curves for PC with 12% Fiber Volume Fraction ($\approx 50\%$ Ultimate Load)

Fig. 4.37 Creep Curves for PC without Fibers ($\approx 50\%$ Ultimate Load)

Fig. 4.38 Creep Curves for PC with 12% Fiber Volume Fraction ($\approx 20\%$ Ultimate Load)

Fig. 4.39 Creep Curves for PC without Fibers ($\approx 20\%$ Ultimate Load)

- For PC specimens without fibers at 16 days duration and $\approx 50\%$ sustained load, the creep values are 0.612, 0.539, and 0.610 for the virgin, 100% recycled, and blend respectively. For 16 days duration and $\approx 20\%$ sustained load, the creep values are 0.471, 0.537, and 0.329 for the virgin, 100% recycled, and blend respectively.
- For PC specimens with fibers at 16 days duration and $\approx 50\%$ sustained load, the creep values are 0.253, 0.333, and 0.290 for the virgin, 100% recycled, and blend respectively. For 16 days duration and $\approx 20\%$ sustained load, the creep values are 0.139, 0.185, and 0.148 for the virgin, 100% recycled, and blend respectively.
- Polymers alone, i.e., without glass fibers, are not suitable for high sustained load applications. Creep of polymers is limited by the use of fibers.
- For both 50% and 20% sustained loading, the ABS specimens exhibited lower creep values than those of the PC at a 16-day duration in all cases except for the P3 specimen at 50% ultimate loading. In this case the creep value of the ABS was 0.681 at 16 days whereas the PC was 0.539.
- Further testing is necessary in order to determine if the PC specimens will continue to exhibit higher creep values than the ABS specimens for extended duration's.

CHAPTER 5

ANALYTICAL COMPARISONS AND EVALUATIONS

5.1 Theoretical Analysis and Comparisons of Tension Test Results

The following is a comparison of the theoretical equation used in obtaining the tension moduli for both the ABS and PC specimens with fibers to that of experimentally obtained data. Determination of the random modulus of these specimens is shown in Table 5.1. Table 5.2 is a comparison of experimental data of glass fiber reinforced ABS and PC specimens, with those computed from theoretical analysis. The tensile stiffness model for short-fiber randomly oriented composites is used for theoretical predictions (Agarwal and Broutman, 1980). Randomly oriented short-fiber composites are essentially isotropic in a plane and are produced by injection or compression molding. Analysis of unidirectional fiber composites requires knowledge of the elastic properties of the isotropic layers within the unidirectional composite. Predicting the tensile properties of randomly oriented short-fiber composites is much more complex. The following empirical formula is used to predict the tension modulus of such a composite (Agarwal and Broutman, 1980):

$$E_{\text{random}} = (3/8)E_L + (5/8)E_T \quad (5.1)$$

where E_L is the longitudinal moduli and E_T is the transverse moduli of a short-fiber composite and can be determined experimentally or calculated using the Halpin-Tsai equations. The following is an explanation along with sample calculations to find tension stiffness using equation 5.1. Calculate the tension modulus, E_L using the following Halpin-Tsai equation for longitudinal moduli (Agarwal and Broutman, 1980):

$$E_L = E_m[(1+(2L/d)\eta_L V_f)/(1-\eta_L V_f)] \quad (5.2)$$

Where, V_f is the fiber volume fraction, which is about 12% in our case

l = fiber length, 4mm for the ABS composite

d = fiber diameter, 0.014mm for the ABS composite

$$\eta_L = [(E_f/E_m)-1]/[(E_f/E_m)+(2l/d)] \quad (\text{Agarwal and Broutman, 1980}) \quad (5.3)$$

Where, E_f is the fiber modulus and E_m is the matrix modulus, which is 72.4 Gpa (10.5×10^6 psi) and 2.21 Gpa (0.321×10^6 psi), respectively.

Thus,

$$\eta_L = [(72.4/2.21)-1]/[(72.4/2.21)+(2*4/0.014)] = 0.053$$

and

$$E_L = 2.21[(1+(2*4/0.014)0.053*0.12)/(1-0.053*0.12)] = 9.80 \text{ Gpa } (1.42 \times 10^6 \text{ psi})$$

Calculate the transverse modulus, E_T using the following Halpin-Tsai equation for transverse moduli (Agarwal and Broutman, 1980):

$$E_T = E_m[(1+2\eta_T V_f)/(1-\eta_T V_f)] \quad (5.4)$$

where

$$\eta_T = [(E_f/E_m)-1]/[(E_f/E_m)+2] \quad (\text{Agarwal and Broutman, 1980}) \quad (5.5)$$

Therefore,

$$\eta_T = [(72.4/2.21)-1]/[(72.4/2.21)+2] = 0.914$$

and

$$E_T = 2.21[(1+2*0.914*0.12)/(1-0.914*0.12)] = 2.98 \text{ Gpa } (0.43 \times 10^6 \text{ psi})$$

Now the random modulus is calculated from equation 5.1 as follows,

$$E_{\text{random}} = (3/8)*9.80 + (5/8)*2.98 = 5.53 \text{ Gpa } (0.802 \times 10^6 \text{ psi})$$

Computation of the random modulus using properties of each type of resin and fibers is shown in Table 5.1. A value of E_f is constant throughout the ABS and PC polymers and is 72.4 GPa. Values for E_m can be found in Appendix A for both ABS and PC resins. Values of V_f are listed in Table 5.1. For the ABS polymers, glass fibers having a fiber length of 4.0mm diameter of 14 μ were used, whereas for the PC polymers, glass fibers having a length of 3.18mm and diameter of 13 μ were used. Comparisons of E_{random} using the theoretical equation versus experimental results are shown in Table 5.2.

Table 5.1 Determination of Random Modulus, E_{random}

Specimen		V_f	E_L	E_T	E_{random}
		%	GPa ($\times 10^6$ psi)	GPa ($\times 10^6$ psi)	GPa ($\times 10^6$ psi)
ABS with Fibers	Virgin	11.3	9.80 (0.142)	2.98 (0.043)	5.53 (0.802)
	Blend	12.3	10.76 (0.156)	3.41 (0.049)	6.19 (0.898)
	100% Rec.	12.5	10.65 (0.154)	3.18 (0.046)	5.98 (0.867)
PC with Fibers	Virgin	12.1	10.10 (0.146)	2.88 (0.042)	5.59 (0.811)
	Blend	12.4	10.54 (0.153)	3.18 (0.046)	5.94 (0.862)
	100% Rec.	11.4	9.60 (0.139)	2.73 (0.040)	5.31 (0.770)

Table 5.2 Analysis and Comparison of E_{random} for Theoretical versus Experimental Results (% Increase/Decrease)

Specimen		E_{random} (Theoretical)	E_{random} (Experimental)	Difference
		GPa ($\times 10^6$ psi)	GPa ($\times 10^6$ psi)	%
ABS with Fibers	Virgin	5.53 (0.802)	6.73 (0.976)	17.8
	Blend	6.19 (0.898)	6.49 (0.941)	4.6
	100% Rec.	5.98 (0.867)	6.65 (0.964)	10.1
PC with Fibers	Virgin	5.59 (0.811)	7.09 (1.029)	21.1
	Blend	5.94 (0.862)	7.21 (1.046)	17.6
	100% Rec.	5.31 (0.770)	6.85 (0.993)	22.5

Experimental values of the tensile moduli in ABS and PC were found to be higher than theoretical values by as much as 22.5% as shown in Table 5.2. This difference is

attributed to randomness of the fiber orientation that could have resulted in better fiber alignment in some specimens in comparison to other specimens or the presence of a more accurate equation than equation 5.1. This observation is based on the fact that variations in some specimens are as low as 4.6% and in others as high as 22.5%. Though manufacturing methods and sizing were not the primary focus of this research, it appears that higher experimental values in PC specimens with fibers may be due to better processing, curing, and fiber compatibility (Table 5.2). Fiber content of the specimens shown in Table 5.1 were based on actual verification through Loss On Ignition (LOI) test, independently conducted with the help of Owens Corning Science and Technology Division (Schweizer, 2000).

5.2 Theoretical Equations used in Bending Test Results

The following are sample calculations for obtaining bending stress and stiffness values of ABS and PC specimens described in chapter 4 (Tables 4.5 and 4.7). The equation used to obtain the stiffness value is based on the deflection equation for three-point bending. In order to calculate stress, the Euler bending equation was used. The sample calculation is shown for a virgin PC sample, BP1-8 (Appendix B7), without fibers. Equation 5.6 was used to determine the maximum bending stress,

$$\sigma = Mc/I \quad (5.6)$$

Where, M = the applied moment, $PL/4$ in our case

c = the perpendicular distance from the neutral axis to a point farthest away from the neutral axis, where $\sigma_{\max}$ acts.

I = the moment of inertia of the cross sectional area, $bh^3/12$ in our case

Therefore,

$$\sigma = ((PL/4)*c)/(bh^3/12) \quad (5.7)$$

Where, P = maximum load taken by the specimen, 13.98 lbs for our case

L = span length, 3.75"

b = specimen base dimension, 0.5"

h = specimen height, 0.125"

Hence,

$$\sigma = ((13.98*3.75/4)*(.125/2))/((.5*.125^3)/12) = 10065.60 \text{ psi}$$

Equation 5.8 was rearranged, shown in equation 5.9, to determine the stiffness value,

$$\delta = PL^3/48EI \quad (5.8)$$

Where, δ = deflection at maximum load

P = maximum load

L = span length

E = stiffness value

I = moment of inertia of the cross sectional area, $bh^3/12$ in our case

Rearranging equation 5.8 to solve for the stiffness value,

$$E = (P/\delta)*(L^3/48I) \quad (5.9)$$

the quantity (P/δ) is obtained from the slope of the linear regression line on the P- δ curve

as shown in Figure 5.1. Therefore,

$$E = (22.336)*(3.75^3/48*(.5*.125^3/12)) = 0.302 \times 10^6 \text{ psi}$$

Fig. 5.1 Typical P- δ Plot with Linear Regression

5.3 Theoretical Analysis of Compression Testing

It is stated that no formulas are available for predicting compressive, inplane shear, and interlaminar shear strengths of random composites (Barbero, 1999). Several of the available models on aligned short-fiber composites were used for predicting the moduli of random short-fiber composites. The result of these attempts was as much as 50% different than the experimental values and will not be reported in this paper. Hence, further study is necessary for establishing a theoretical equation for the compressive modulus of random short-fiber composites.

5.4 Theoretical Analysis of Impact and Hardness Testing

No theoretical analysis was performed on the impact or hardness test specimens. The Izod impact test was conducted on a machine that had previously been calibrated to the specific height and kinetic energy required for this type of specimen. The values were obtained directly from the machines dial gage reading and then corrected using a

chart provided by Instron for that particular machine (Fig 3.9). The hardness values were also obtained directly from the hardness-testing machine through a digital display located on the machine (Fig 3.13). With both the impact and hardness test, the readings have previously been calibrated through the manufacturer and are assumed correct.

5.5 Conclusions

- Experimental tensile moduli of PC and ABS specimens with fibers were as much as 22.5% greater than those obtained using theoretical equations.
- The bending moduli of both the ABS and PC specimens were found to be slightly higher than the tensile modulus.
- Currently no theoretical equation is available for the prediction of compressive modulus of random short-fiber composites (Barbero, 1999).

CHAPTER 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

Summary of tension, bending, compression, impact, hardness, and creep test results of virgin, blend, and 100% recycled ABS and PC specimens are provided in section 6.2 of this chapter. Conclusions and recommendations based on theoretical and experimental data are also included in section 6.3 and 6.4, respectively.

6.2 Summary

6.2.1 Summary of Tension Test Results

The following is a summary of typical values obtained through experimental tension tests for ABS specimens with and without fibers. Further explanation of these results can be found in section 4.2.1. Table 4.2 shows an analysis and comparison between the various specimens and the percent difference of each. A complete listing of each specimen's maximum load, maximum stress, and stiffness values is given in appendix A.

ABS:

- Typical maximum stress values for ABS specimens without fibers are on the order of 5500 to 6200 psi with stiffness values ranging from 0.321×10^6 to 0.359×10^6 psi. For ABS specimens with fibers, typical maximum stress values vary between 8800 to 10300 psi with stiffness values ranging from 0.941×10^6 to 0.976×10^6 psi.

- Compared to virgin polymers without fibers and with fibers, maximum stress reductions were under 15% for the blend and 100% recycled polymers. Similarly, stiffness variations were found to be within 12%.
- Addition of 12% fiber volume fraction of chopped fibers to virgin, blend and 100% recycled polymers resulted in a tensile stress increase ranging between 50.6 and 68.8%. Similarly, stiffness increase ranging between 162.1 to 204% was observed.
- Recycled polymers and blends were found to have slightly lower elongation than virgin polymers. However, both the materials showed elongations in excess of 8%. Addition of fibers reduced the maximum strain values at failure to under 1.35%.
- Addition of unidirectional and continuous fibers is expected to provide higher strength and stiffness increase.

The following is a summary of typical values obtained through experimental tension tests for PC specimens with and without fibers. Further explanation of these results can be found in section 4.2.3. Table 4.4 shows an analysis and comparison between the various specimens and the percent difference of each. A complete listing of each specimen's maximum load, maximum stress, and stiffness values is given in appendix A.

PC:

- Typical maximum stress values for PC specimens without fibers are on the order of 8500 to 9000 psi with stiffness values ranging from 0.293×10^6 to 0.329×10^6

- psi. For ABS specimens with fibers, typical maximum stress values vary between 15200 to 16600 psi with stiffness values ranging from 0.993×10^6 to 1.046×10^6 psi.
- Compared to virgin polymers without fibers and with fibers, maximum stress reductions were under 8% for the blend and 100% recycled polymers. Similarly, stiffness variations were found to be within 10% for the first stiffness, E1, and within 15% for the second stiffness value, E2.
 - Addition of 12% fiber volume fraction of chopped fibers to virgin, blend and 100% recycled polymers resulted in a tensile stress increase ranging between 77.6 and 90.2%. Similarly, with the addition of 12% fiber volume fraction, stiffness increase ranging between 217.9 to 243% was observed for the first stiffness value, E1, and between 189.9 and 200% for the second stiffness value, E2.
 - Recycled polymers and blends were found to have slightly lower elongation than virgin polymers due to impurities in the material. However, both the materials showed elongations in excess of 8%. Addition of fibers reduced the maximum strain values at failure to under 3.14%.
 - Virgin polymers without fibers showed elongation in excess of 10%. Extensometer available with the Instron machine had a maximum capacity of 10% and hence the readings were discontinued. Strain values of recycled and blend specimens were less than the virgin polymers. It is noted that the PC polymer with fibers exhibited higher ductility than the ABS polymer with fibers. Addition of fibers in the PC polymer yielded maximum strain at failure values in virgin, blend and 100% recycled polymers of 3.23, 3.26 and 2.96%, respectively.

For the ABS polymer with fibers, the maximum strain values at failure in virgin, blend and 100% recycled polymers was 1.51, 1.18 and 1.12%, respectively.

- As with ABS, addition of unidirectional and continuous fibers is expected to provide higher strength and stiffness increase for PC.

6.2.2 Summary of Bending Test Results

The following is a summary of typical values obtained through experimental bending tests for ABS specimens with and without fibers. Further explanation of these results can be found in section 4.3.1. Table 4.6 shows an analysis and comparison between the various specimens and the percent difference of each. A complete listing of each specimen's maximum load, maximum stress, and stiffness values is given in appendix B.

ABS:

- Typical maximum stress values for ABS specimens without fibers vary between 9000 to 9600 psi with stiffness values of 0.40×10^6 psi. For ABS specimens with fibers, typical maximum stress values are on the order of 16500 to 17800 psi with stiffness values ranging from 1.02×10^6 to 1.11×10^6 psi.
- Compared to virgin polymers without fibers and with fibers maximum bending stress reductions or increases were within 7.1% for the blends and 100% recycled polymers. Stiffness increase in the blend and 100% recycled polymer were found to be within 8.8%.
- Addition of 12% fiber volume fraction of chopped fibers to virgin, blend and 100% recycled polymers resulted in a bending stress increase ranging between

72.7 and 95.7%. Similarly, stiffness increase ranging between 155.0 to 177.5% was observed with the addition of 12% fiber volume fraction.

- Bending strength and stiffness values were found to be higher than the corresponding tensile values for all three types of polymers considered in this study.

The following is a summary of typical values obtained through experimental bending tests for PC specimens with and without fibers. Further explanation of these results can be found in section 4.3.3. Table 4.8 shows an analysis and comparison between the various specimens and the percent difference of each. A complete listing of each specimen's maximum load, maximum stress, and stiffness values is given in appendix B.

PC:

- Typical maximum stress values for PC specimens without fibers vary between 10200 to 11200 psi with stiffness values ranging from 0.291×10^6 to 0.332×10^6 psi. For ABS specimens with fibers, typical maximum stress values are on the order of 23200 to 24900 psi with stiffness values ranging from 0.916×10^6 to 0.993×10^6 psi.
- Compared to virgin polymers without fibers and with fibers maximum bending stress reductions or increases were within 9% for the blends and 100% recycled polymers. Stiffness increase in the blend and 100% recycled polymer were found to be within 12.3%.
- Addition of 12% fiber volume fraction of chopped fibers to virgin, blend and 100% recycled polymers resulted in a bending stress increase ranging between

122.8 and 139.8%. Similarly, stiffness increase ranging between 191.3 to 214.8% was observed with the addition of 12% fiber volume fraction.

- Compared to the ABS polymer without fibers, the virgin, blend and 100% recycled PC polymer without fibers exhibited 11.3, 14.4, and 11.4% higher maximum stress readings with 23.0, 14.8, and 22.2% more deflection at maximum stress, respectively.
- Compared to the ABS polymer with fibers, the virgin, blend and 100% recycled PC polymer with fibers exhibited 27.7, 33.7, and 27.8% higher maximum stress readings with 44.4, 31.9, and 27.3% more deflection at maximum stress, respectively.
- Similar to ABS, PC bending strength and stiffness values were found to be higher than the corresponding tensile values for all three types of polymers considered in this study.

6.2.3 Summary of Compression Test Results

The following is a summary of typical values obtained through experimental compression tests for ABS specimens with and without fibers. Further explanation of these results can be found in section 4.4.1. Table 4.10 shows an analysis and comparison between the various specimens and the percent difference of each. A complete listing of each specimen's maximum load, maximum stress, and stiffness values is given in appendix C.

ABS:

- Typical maximum stress values for ABS specimens without vary between 8800 to 9000 psi with stiffness values ranging from 0.34×10^6 to 0.41×10^6 psi. For ABS

specimens with fibers, typical maximum stress values are on the order of 13100 to 14900 psi with stiffness values ranging from 0.91×10^6 to 1.02×10^6 psi.

- Compared to virgin polymers without fibers and with fibers, maximum compressive stress increase up to 13.4% was observed for the blend and 100% recycled polymers. Stiffness increase up to 23.5% was also observed.
- Addition of 12% fiber volume fraction of chopped fibers to virgin, blend and 100% recycled polymers resulted in a compressive stress increase ranging between 46.5 and 66%. Similarly, stiffness increase ranging between 167.6 to 343.5% was observed with the addition of 12% fiber volume fraction.
- Virgin polymers without fibers showed significant compressive strains in excess of 10%. Strain values of recycled and blend specimens were less than the virgin polymers.

The following is a summary of typical values obtained through experimental compression tests for PC specimens with and without fibers. Further explanation of these results can be found in section 4.4.3. Table 4.12 shows an analysis and comparison between the various specimens and the percent difference of each. A complete listing of each specimen's maximum load, maximum stress, and stiffness values is given in appendix C.

PC:

- Typical maximum stress values for ABS specimens without fibers vary between 10300 to 10550 psi with stiffness values ranging from 0.39×10^6 to 0.41×10^6 psi. For ABS specimens with fibers, typical maximum stress values are on the order of 20300 to 21200 psi with stiffness values ranging from 0.80×10^6 to 0.84×10^6 psi.

- Compared to virgin polymers without fibers and with fibers, maximum compressive stress increase up to 3.9% was observed for the blend and 100% recycled polymers. Stiffness increase up to 5.0% was also observed.
- Addition of 12% fiber volume fraction of chopped fibers to virgin, blend and 100% recycled polymers resulted in a compressive stress increase ranging between 95.1 and 101.2%. Similarly, stiffness increase ranging between 95.1 to 115.4% was observed with the addition of 12% fiber volume fraction.
- Compared to the ABS polymer without fibers, the virgin, blend and 100% recycled PC polymer without fibers exhibited 14.0, 14.7, and 14.7% higher maximum stress readings with similar deflections at maximum stress, respectively.
- Compared to the ABS polymer with fibers, the virgin, blend and 100% recycled PC polymer with fibers exhibited 35.4, 34.1, and 28.2% higher maximum stress readings with similar deflections at maximum stress, respectively.
- As with ABS, virgin PC polymers without fibers showed significant compressive strains in excess of 10%. Strain values of recycled and blend specimens were less than the virgin polymers.

6.2.4 Summary of Impact Test Results

The following is a summary of typical values obtained through experimental impact tests for ABS specimens with and without fibers. Further explanation of these results can be found in section 4.5.1. Table 4.14 shows an analysis and comparison between the various specimens and the percent difference of each. A complete listing of each specimen's impact strength and failure type is given in appendix D.

ABS:

- Typical impact strength values for ABS specimens without vary between 0.96 to 1.58. For ABS specimens with fibers, typical impact strength values are on the order of 2.17 to 3.50.
- Compared to virgin polymers with or without fibers, impact strength of the blend and 100% recycled polymers decreased by a maximum of 39.2%.
- Addition of 12% fiber volume fraction of randomly oriented and chopped glass fibers to virgin, blend and 100% recycled polymers resulted in maximum impact strength reduction of 59.7%.

The following is a summary of typical values obtained through experimental impact tests for PC specimens with and without fibers. Further explanation of these results can be found in section 4.5.2. Table 4.16 shows an analysis and comparison between the various specimens and the percent difference of each. A complete listing of each specimen's impact strength and failure type is given in appendix D.

PC:

- Typical impact strength values for PC specimens without vary between 1.81 to 3.01. For ABS specimens with fibers, typical impact strength values are on the order of 13.53 to 14.80.
- Compared to virgin polymers with or without fibers, impact strength of the blend and 100% recycled polymers decreased by a maximum of 39.9%.

- Addition of 12% fiber volume fraction of randomly oriented and chopped glass fibers to virgin, blend and 100% recycled polymers resulted in maximum impact strength reduction of 86.6%.
- Compared to the ABS polymer without fibers, the virgin, blend and 100% recycled PC polymer without fibers exhibited 75.3, 84.0, and 83.9% higher impact readings, respectively.
- Compared to the ABS polymer with fibers, the virgin, blend and 100% recycled PC polymer with fibers exhibited 47.5, 55.1, and 47.0% higher impact readings, respectively.

6.2.5 Summary of Hardness Test Results

The following is a summary of typical values obtained through experimental hardness tests for ABS specimens with and without fibers. Further explanation of these results can be found in section 4.6.1. Table 4.18 shows an analysis and comparison between the various specimens and the percent difference of each. A complete listing of each specimen's hardness values, with and without the 626g weight, is given in appendix E.

ABS:

- Typical hardness values for ABS specimens without fibers vary between 10.9 to 11.2 without weight and 25.6 to 25.9 with 626g weight. For ABS specimens with fibers, typical hardness values are on the order of 11.2 to 11.3 without weight and 25.7 to 25.8 with 626g weight.

- Compared to virgin polymers with or without fibers, hardness values of the blend and 100% recycled polymers were within 2.8% using no weight, and within 0.8% using a 626g weight.
- Addition of 12% fiber volume fraction of randomly oriented and chopped glass fibers to virgin, blend and 100% recycled polymers resulted in maximum hardness value increase of 3.7% using no weight, and 0.4% using a 626g weight.

The following is a summary of typical values obtained through experimental hardness tests for PC specimens with and without fibers. Further explanation of these results can be found in section 4.6.2. Table 4.20 shows an analysis and comparison between the various specimens and the percent difference of each. A complete listing of each specimen's hardness values, with and without the 626g weight, is given in appendix E.

PC:

- Typical hardness values for PC specimens without fibers vary between 10.6 to 10.7 without weight and 25.3 to 25.5 with 626g weight. For ABS specimens with fibers, typical hardness values are on the order of 10.7 without weight and 25.3 to 25.5 with 626g weight.
- Compared to virgin polymers with or without fibers, hardness values of the blend and 100% recycled polymers were within 0.9% using no weight, and within 0.8% using a 626g weight.
- Addition of 12% fiber volume fraction of randomly oriented and chopped glass fibers to virgin, blend and 100% recycled polymers resulted in maximum hardness value increase of 0.9% using no weight, and 0.4% using a 626g weight.

- Compared to the ABS polymer, the hardness values for the PC polymer with and without fibers was nearly identical.

6.2.6 Summary of Creep Test Results

The following is a summary of the creep test data of ABS specimens under sustained loads of 50% and 20% of the maximum. Tables 4.21 and 4.22 show creep coefficients for various intervals throughout the test. Further explanation of the creep data can be found in section 4.7.1. A complete listing creep data is shown in Appendix-F, in terms of microstrains.

ABS:

- For ABS specimens without fibers at 16 days duration and $\approx 50\%$ sustained load, the creep values are 0.609, 0.681, and 0.405 for the virgin, 100% recycled, and blend respectively. For 90 days duration and $\approx 20\%$ sustained load, the creep values are 0.812, 0.541, and 0.762 for the virgin, 100% recycled, and blend respectively.
- For ABS specimens with fibers at 145 days duration and $\approx 50\%$ sustained load, the creep values are 0.472, 0.861, and 0.710 for the virgin, 100% recycled, and blend respectively. For 90 days duration and $\approx 20\%$ sustained load, the creep values are 0.221, 0.222, and 0.291 for the virgin, 100% recycled, and blend respectively.
- Recycled polymers and their blends showed creep-life of about 40% of those of virgin polymers without fibers at a high-sustained load of 50%. These results are based on single specimen tests and further tests need to be carried out with additional samples.

- For sustained load applications, fibers have to be used to reduce creep strain rate and enhance rupture of the specimen.
- Virgin polymers have a better creep-life compared to recycled polymers and their blends due to fewer impurities in the specimens.
- Recycled polymers and their blends showed creep-life of about 40% of those of virgin polymers without fibers at a high-sustained load of 50%. These results are based on single specimen tests and further tests need to be carried out with additional samples.

The following is a summary of the creep test data of PC specimens under sustained loads of 50% and 20% of the maximum. Tables 4.23 and 4.24 show creep coefficients for various intervals throughout the test. Further explanation of the creep data can be found in section 4.7.2. A complete listing creep data is shown in Appendix-F, in terms of microstrains.

PC:

- For PC specimens without fibers at 16 days duration and $\approx 50\%$ sustained load, the creep values are 0.612, 0.539, and 0.610 for the virgin, 100% recycled, and blend respectively. For 16 days duration and $\approx 20\%$ sustained load, the creep values are 0.471, 0.537, and 0.329 for the virgin, 100% recycled, and blend respectively.
- For PC specimens with fibers at 16 days duration and $\approx 50\%$ sustained load, the creep values are 0.253, 0.333, and 0.290 for the virgin, 100% recycled, and blend respectively. For 16 days duration and $\approx 20\%$ sustained load, the creep values are 0.139, 0.185, and 0.148 for the virgin, 100% recycled, and blend respectively.

- For both 50% and 20% sustained loading, the ABS specimens exhibited lower creep values than those of the PC at a 16 day duration in all cases except for the P3 specimen at 50% ultimate loading. In this case the creep value of the ABS was 0.681 at 16 days whereas the PC was 0.539.
- Further testing is necessary in order to determine if the PC specimens will continue to exhibit higher creep values than the ABS specimens for extended duration's.
- The higher creep values for PC compared to ABS at the 16 day interval is most likely attributed to the temperature at the time of measurement. The 16 day interval for the ABS polymer was during the winter months (average temperature of 32°F), whereas the PC polymer's 16 day interval was during the summer months (average temperature of 75°F). Because the testing facility is unable to control the temperature fluctuation within the building, the higher temperature had more effect on the PC polymer and thus allowed it to creep more than that of the ABS polymer.
- Polymers alone, i.e., without glass fibers, are not suitable for high-sustained load applications. Fibers are essential to control creep of polymers for sustained load applications.

6.3 Conclusions

Results of this study indicate the potential of using recycled polymers for infrastructure and automotive applications. Use of 100% recycled ABS polymers resulted in tensile, bending and compressive strength and stiffness reduction on an average of about 10% and a maximum of 15%. Reduction in impact strength of the blend and

recycled polymers was more than the reductions in tensile, bending and compressive stresses in ABS polymers. Compared to virgin ABS polymers with and without fibers, impact strength of the blended polymers with and without fibers was less by 24.1 and 31.8%, respectively. Maximum impact strength reductions up to 39.2% were observed in 100% recycled ABS polymer. Hardness values of the blended and 100% recycled ABS polymers were within 2.8% when compared to virgin PC polymer with and without fibers. The use of fibers is essential to control the creep of different types of ABS virgin and recycled polymers for sustained load applications.

For PC polymers, use of 100% recycled polymers resulted in tensile, bending, and compressive strength and stiffness reduction within 13%. Reduction in impact strength of the blended and recycled PC polymers was more than the reductions in tensile, bending and compressive stresses. Compared to virgin PC polymers with and without fibers, impact strengths of the blended polymers with and without fibers was less than 11.3% and 4.5%, respectively. Maximum impact strength reductions up to 39.9% were observed in 100% recycled PC polymers. Hardness values of the blend and 100% recycled PC polymers were within 0.9% when compared to virgin PC polymer with and without fibers. Use of fibers is essential to control creep in virgin and recycled PC polymers, as in ABS, for sustained load applications.

Throughout the testing, virgin ABS and PC specimens with and without fibers consistently performed better than the blended and 100% recycled polymeric materials. Several factors contribute to lower mechanical properties in the blended and 100% recycled specimens. These factors effect the molecular structure of the material and include physical effects such as ultraviolet radiation and thermal differences. Other

factors include chemical effects such as water absorption, which can lead to hydration and oxidation in PC materials and cross-linking in the ABS material. As the ABS and PC materials are recycled several times, i.e. 4 or 5 times, these factors will further degrade the material to a point where the mechanical properties are inadequate for usage in the infrastructure or automotive fields (Liang 2000).

Throughout the research, bending stresses were found to be higher than those in tension. There are many different failure modes that are identified in the literature to establish failure stress. Obviously the bending failure mode is more complex than tension because non-uniform stress distribution, shear stress, and secondary effects from axial stresses are induced under three-point bending loads. Therefore such theories as Tsai-Wu and Tsai-Hill may better fit and provide a better correlation between bending and tension than the failure theories corresponding to the principal stress theory.

During testing, the impact test results did not follow the same trend as found with tension, bending, compression, and hardness tests. The large differences in impact results of the blended and 100% recycled materials, when compared to the virgin material, are attributed to more impurities found within these materials. With the introduction of fibers into the blended and 100% recycled materials, impact values are much lower than those without fibers because of stress concentrations effects caused by the fibers as well as impurities in recycled products. During a static test, such as tension, bending, compression, and hardness, the load is applied in a gradual manner, thus allowing the energy within the system to go around the impurities, whereas in dynamic tests, such as impact, kinetic energy is applied to the specimen at high velocities. The high velocity stress wave transmittal does not provide sufficient time for stresses to pass around the

impurities, but develops high stresses near impurities through the propagating wave resulting in failure at lower values than those corresponding to the virgin materials. In order to achieve better results for recycled resins under impact, rubber must be added to the test specimens in addition to chopped fibers.

Based on the data from this research, recycled ABS and PC polymers in relation to virgin resins were found to retain at least 85% of their tensile, bending and compressive strength and stiffness properties. Proper design of recycled polymer blends with and without glass fibers has significant potential for nonstructural composite applications in infrastructure and automotive applications.

The results attained through this research are based on a first time recycling operation of the ABS and PC resins. The mechanical properties of these materials do change with additional recycling operations. Furthermore, aging and exposure to moisture during service of recycled polymers would further reduce these mechanical properties.

What Have We Learned?

- During creep testing, the blended and 100% recycled ABS specimen failed much sooner than the virgin specimen under identical sustained stresses. This is attributed to the fact that through the recycling operation, cross-linking within the ABS occurred along with the introduction of impurities into the material. Thus, ABS has become stiffer than the virgin resins, resulting in lower load to failure.
- Impurities within the blend and 100% recycled materials reduce the impact values significantly. As stated previously, addition of rubber along with fibers will

reduce the effects of these impurities and allow the recycled material to produce better impact results compared to the virgin material.

- Virgin and first time recycled resins achieved similar results in tension, bending, compression, and hardness testing. Additional recycling operations will reduce the mechanical properties of the recycled resins due to factors such as water absorption, cross-linking, and oxidation of the ABS and PC polymers.
- First time recycling of ABS and PC polymers have similar mechanical properties in tension, bending, compression, and hardness as virgin materials. Therefore, these recycled ABS and PC resins would be suitable to replace virgin materials in automobile and infrastructure applications where color consistency is not a concern.

6.4 Recommendations

- The use of unidirectional fibers and effect of fiber volume fraction should be studied to characterize the increase in strength, stiffness and other mechanical properties of recycled ABS and PC.
- Further study is necessary for establishing a theoretical equation for the compressive modulus of random short-fiber composites using varying fiber volume fractions to validate the result..
- Care in manufacturing methods and sizing selection along with better processing, curing, and fiber compatibility need to be addressed in order to achieve better mechanical properties.
- Additional creep tests need to be conducted on both ABS and PC specimens to achieve a more precise creep coefficient of virgin, blend, and 100% recycled

specimens with and without fibers in terms of fiber volume fraction and fiber architecture.

- Further study is needed to determine the fatigue behavior of recycled plastics with and without fibers.
- Automotive applications require a class "A" glossy finish; therefore achieving the same with recycled plastics needs to be studied.
- Additional testing of recycled plastics in terms of crash-worthiness (Automobile 5 mph bumper impact tests) is needed.
- Further investigation is needed to develop mathematical models for predicting failure modes of recycled composites with and without fibers having different types of fillers (e.g. nanomers) and additives (e.g. fire retardants).
- The effect of secondary and tertiary recycling of plastics and its effect on mechanical properties needs additional study.
- Further evaluation of economical and environmental benefits in terms of life-cycle costs for recycled plastics is needed.
- Further study is necessary to determine the effects on the molecular and mechanical properties of recycling a material over and over.

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APPENDIX-A

TENSION TEST RESULTS

Table A-1 Tension Test Results for Virgin ABS

Specimen	Maximum Load	Maximum Stress	Strain @ Max. Load	Max. Strain @ Failure	Slope of the stress-strain curve (Stiffness, E)
	lbs.	psi	%	%	psi
TA1-1	391.17	6258.72	2.70	3.31	0.316E+06
TA1-2	387.66	6202.56	2.86	5.36	0.319E+06
TA1-3	385.44	6167.04	2.91	4.80	0.330E+06
TA1-4	385.79	6172.64	2.99	4.81	0.320E+06
TA1-5	379.36	6069.76	2.88	6.17	0.323E+06
Average	385.88	6174.14	2.87	4.89	0.321E+06
Std. Dev.	4.30	68.76	0.11	1.05	0.551E+04

Table A-2 Tension Test Results for Virgin ABS with 25% by Weight of Chopped Fibers

Specimen	Maximum Load	Maximum Stress	Strain @ Max. Load	Max. Strain @ Failure	Slope of the stress-strain curve (Stiffness, E)
	lbs.	psi	%	%	psi
TA2-1	624.80	9996.80	1.31	1.31	0.924E+06
TA2-2	624.59	9993.44	1.31	1.69	0.966E+06
TA2-3	646.96	10351.36	1.29	1.43	1.020E+06
TA2-4	662.77	10604.32	1.42	1.67	0.979E+06
TA2-5	659.45	10551.20	1.43	1.43	0.993E+06
Average	643.71	10299.42	1.35	1.51	0.976E+06
Std. Dev.	18.34	293.37	0.07	0.17	3.530E+04

Table A-3 Tension Test Results for 100% Recycled ABS

Specimen	Maximum Load	Maximum Stress	Strain @ Max. Load	Max. Strain @ Failure	Slope of the stress-strain curve (Stiffness, E)
	lbs.	psi	%	%	psi
TA3-1	354.64	5674.24	2.83	5.02	0.348E+06
TA3-2	347.97	5567.52	2.91	6.49	0.338E+06
TA3-3	347.86	5565.76	2.82	5.37	0.338E+06
TA3-4	347.15	5554.40	3.02	7.42	0.329E+06
TA3-5	345.77	5532.32	2.68	8.09	0.314E+06
Average	348.68	5578.85	2.85	6.48	0.333E+06
Std. Dev.	3.45	55.14	0.13	1.31	1.274E+04

Table A-4 Tension Test Results for 100% Recycled ABS with 25% by Weight of Chopped Fibers

Specimen	Maximum Load	Maximum Stress	Strain @ Max. Load	Max. Strain @ Failure	Slope of the stress-strain curve (Stiffness, E)
	lbs.	psi	%	%	psi
TA4-1	515.56	8248.96	1.06	1.06	0.926E+06
TA4-2	563.76	9020.16	1.20	1.20	0.926E+06
TA4-3	548.06	8768.96	1.10	1.10	0.964E+06
TA4-4	563.87	9021.92	1.13	1.13	1.020E+06
TA4-5	558.92	8942.72	1.13	1.13	0.984E+06
Average	550.03	8800.54	1.12	1.12	0.964E+06
Std. Dev.	20.32	325.07	0.05	0.05	4.018E+04

Table A-5 Tension Test Results for ABS Polymer Blend

Specimen	Maximum Load	Maximum Stress	Strain @ Max. Load	Max. Strain @ Failure	Slope of the stress-strain curve (Stiffness, E)
	lbs.	psi	%	%	psi
TA5-1	384.18	6146.88	2.53	2.64	0.404E+06
TA5-2	369.58	5913.28	2.77	4.03	0.371E+06
TA5-3	363.50	5816.00	2.99	6.10	0.336E+06
TA5-4	361.86	5789.76	2.85	7.50	0.336E+06
TA5-5	369.61	5913.76	2.67	6.38	0.349E+06
Average	369.75	5915.94	2.76	5.33	0.359E+06
Std. Dev.	8.80	140.76	0.17	1.96	2.874E+04

Table A-6 Tension Test Results for ABS Polymer Blend with 25% by Weight of Chopped Fibers

Specimen	Maximum Load	Maximum Stress	Strain @ Max. Load	Max. Strain @ Failure	Slope of the stress-strain curve (Stiffness, E)
	lbs.	psi	%	%	psi
TA6-1	565.20	9043.20	1.27	1.27	0.885E+06
TA6-3	516.54	8264.64	1.20	1.20	0.848E+06
TA6-4	556.12	8897.92	1.20	1.20	0.907E+06
TA6-5	576.83	9229.28	1.12	1.12	1.014E+06
TA6-6	570.12	9121.92	1.10	1.10	1.048E+06
Average	556.96	8911.39	1.18	1.18	0.941E+06
Std. Dev.	23.82	381.19	0.07	0.07	8.609E+04

Table A-7 Tension Test Results for Virgin PC

Specimen	Maximum Load	Maximum Stress	Strain @ Max. Load	Max. Strain @ Failure	Slope of the stress-strain curve (Stiffness, E)	
	lbs.	psi	%	%	psi	
					E1	E2
TP1-1	560.40	8730.06	7.50	10.75	0.300E+06	0.146E+06
TP1-2	555.16	8648.43	7.32	9.97	0.305E+06	0.147E+06
TP1-3	553.52	8622.88	7.22	10.39	0.297E+06	0.145E+06
TP1-4	555.86	8659.33	7.31	8.00	0.299E+06	0.147E+06
TP1-5	556.10	8663.07	7.00	10.50	0.298E+06	0.148E+06
Average	556.21	8664.76	7.27	9.92	0.300E+06	0.147E+06
Std. Dev.	2.55	39.74	0.18	1.11	0.321E+04	0.114E+04

Table A-8 Tension Test Results for Virgin PC with 25% by Weight of Chopped Fibers

Specimen	Maximum Load	Maximum Stress	Strain @ Max. Load	Max. Strain @ Failure	Slope of the stress-strain curve (Stiffness, E)	
	lbs.	psi	%	%	psi	
					E1	E2
TP2-2	1062.49	16551.75	2.96	3.11	1.063E+06	0.450E+06
TP2-3	1058.43	16488.50	3.28	3.33	1.007E+06	0.420E+06
TP2-4	1057.02	16466.54	3.12	3.23	1.009E+06	0.424E+06
TP2-5	1055.00	16435.07	3.13	3.23	1.037E+06	0.428E+06
TP2-6	1056.18	16453.45	3.21	3.25	1.031E+06	0.435E+06
Average	1057.82	16479.06	3.14	3.23	1.029E+06	0.431E+06
Std. Dev.	2.89	45.06	0.12	0.08	2.267E+04	1.178E+04

Table A-9 Tension Test Results for 100% Recycled PC

Specimen	Maximum Load	Maximum Stress	Strain @ Max. Load	Max. Strain @ Failure	Slope of the stress-strain curve (Stiffness, E)	
	lbs.	psi	%	%	psi	
					E1	E2
TP3-1	550.91	8582.22	7.58	8.89	0.291E+06	0.137E+06
TP3-2	550.48	8575.52	7.33	9.85	0.288E+06	0.138E+06
TP3-3	548.60	8546.24	7.61	9.82	0.291E+06	0.140E+06
TP3-4	550.45	8575.06	6.91	9.63	0.307E+06	0.138E+06
TP3-5	548.92	8551.22	7.23	9.53	0.289E+06	0.141E+06
Average	549.87	8566.05	7.33	9.54	0.293E+06	0.139E+06
Std. Dev.	1.04	16.16	0.29	0.39	0.792E+04	0.164E+04

Table A-10 Tension Test Results for 100% Recycled ABS with 25% by Weight of Chopped Fibers

Specimen	Maximum Load	Maximum Stress	Strain @ Max. Load	Max. Strain @ Failure	Slope of the stress-strain curve (Stiffness, E)	
	lbs.	psi	%	%	psi	
					E1	E2
TP4-1	978.29	15240.06	2.80	2.85	0.967E+06	0.422E+06
TP4-2	976.94	15219.03	2.66	3.11	1.008E+06	0.433E+06
TP4-3	973.31	15162.48	2.61	2.97	0.987E+06	0.408E+06
TP4-4	977.41	15226.35	2.68	2.71	1.007E+06	0.412E+06
TP4-5	976.97	15219.50	2.63	3.15	0.997E+06	0.411E+06
Average	976.58	15213.48	2.68	2.96	0.993E+06	0.417E+06
Std. Dev.	1.91	29.75	0.07	0.18	1.694E+04	1.028E+04

Table A-11 Tension Test Results for PC Polymer Blend

Specimen	Maximum Load	Maximum Stress	Strain @ Max. Load	Max. Strain @ Failure	Slope of the stress-strain curve (Stiffness, E)	
	lbs.	psi	%	%	psi	
					E1	E2
TP5-1	573.71	8937.41	6.79	8.20	0.350E+06	0.172E+06
TP5-2	570.93	8894.10	7.34	9.35	0.313E+06	0.165E+06
TP5-3	573.16	8928.84	6.98	9.19	0.323E+06	0.166E+06
TP5-4	573.39	8932.42	7.07	9.18	0.327E+06	0.171E+06
TP5-5	573.84	8939.43	6.99	9.30	0.330E+06	0.172E+06
Average	573.01	8926.44	7.03	9.04	0.329E+06	0.169E+06
Std. Dev.	1.19	18.55	0.20	0.48	1.360E+04	0.342E+04

Table A-12 Tension Test Results for PC Polymer Blend with 25% by Weight of Chopped Fibers

Specimen	Maximum Load	Maximum Stress	Strain @ Max. Load	Max. Strain @ Failure	Slope of the stress-strain curve (Stiffness, E)	
	lbs.	psi	%	%	psi	
					E1	E2
TP6-1	1059.03	16497.85	2.88	2.94	1.077E+06	0.489E+06
TP6-2	1065.02	16591.16	3.11	3.43	1.025E+06	0.478E+06
TP6-3	1064.92	16589.61	2.98	3.04	1.031E+06	0.492E+06
TP6-4	1061.61	16538.04	2.83	3.53	1.048E+06	0.501E+06
TP6-5	1063.14	16561.88	2.94	3.37	1.052E+06	0.489E+06
Average	1062.74	16555.71	2.95	3.26	1.046E+06	0.490E+06
Std. Dev.	2.51	39.06	0.11	0.26	2.039E+04	0.823E+04

APPENDIX-B

BENDING TEST RESULTS

Table B-1 Bending Test Results for Virgin ABS

Specimen	Maximum Load	Maximum Stress	Deflection @ Max. Stress	Max. Deflection Recorded	Stiffness, E
	lbs.	psi	in.	in.	psi
BA1-12	10.54	7588.80	0.62	1.30	0.42E+06 0.38E+06
BA1-13	13.35	9612.00	0.72	1.42	
BA1-14	13.58	9777.60	0.71	1.42	
BA1-15	13.25	9540.00	0.68	1.16	
BA1-17	11.47	8258.40	0.67	1.40	
BA1-18	12.53	9021.60	0.64	1.42	
BA1-19	13.56	9763.20	0.69	1.22	
Average	12.61	9080.23	0.67	-	0.40E+06
Std. Dev.	1.09	788.32	0.04	-	-

Table B-2 Bending Test Results for Virgin ABS with 25% by Weight of Chopped Fibers

Specimen	Maximum Load	Maximum Stress	Deflection @ Max. Stress	Max. Deflection Recorded	Stiffness, E
	lbs.	psi	in.	in.	psi
BA2-11	24.94	17956.80	0.45	0.47	1.05E+06 0.99E+06
BA2-12	25.06	18043.20	0.49	0.52	
BA2-13	24.00	17280.00	0.51	0.51	
BA2-16	24.82	17870.40	0.50	0.52	
BA2-17	24.59	17704.80	0.53	0.54	
Average	24.68	17771.04	0.50	-	1.02E+06
Std. Dev.	0.37	269.80	0.03	-	-

Table B-3 Bending Test Results for 100% Recycled ABS

Specimen	Maximum Load	Maximum Stress	Deflection @ Max. Stress	Max. Deflection Recorded	Stiffness, E
	lbs.	psi	in.	in.	psi
BA3-12	13.93	10029.60	0.70	1.41	0.42E+06 0.38E+06
BA3-13	14.40	10368.00	0.84	1.48	
BA3-15	11.12	8006.40	0.62	1.38	
BA3-17	11.47	8258.40	0.57	1.39	
BA3-18	12.88	9273.60	0.70	1.48	
Average	12.76	9187.20	0.69	-	0.40E+06
Std. Dev.	2.43	1749.19	0.10	-	-

Table B-4 Bending Test Results for 100% Recycled ABS with 25% by Weight of Chopped Fibers

Specimen	Maximum Load	Maximum Stress	Deflection @ Max. Stress	Max. Deflection Recorded	Stiffness, E
	lbs.	psi	in.	in.	psi
BA4-11	21.54	15508.80	0.51	0.51	1.11E+06 1.04E+06
BA4-12	24.59	17704.80	0.49	0.49	
BA4-13	23.65	17028.00	0.46	0.46	
BA4-16	21.89	15760.80	0.46	0.48	
BA4-17	24.58	17697.60	0.49	0.50	
Average	23.25	16740.00	0.48	-	1.08E+06
Std. Dev.	1.46	1049.46	0.02	-	-

Table B-5 Bending Test Results for ABS Polymer Blend

Specimen	Maximum Load	Maximum Stress	Deflection @ Max. Stress	Max. Deflection Recorded	Stiffness, E
	lbs.	psi	in.	in.	psi
BA5-11	12.41	8935.20	0.70	1.38	0.43E+06 0.38E+06
BA5-12	13.58	9777.60	0.68	1.43	
BA5-13	13.82	9950.40	0.68	1.47	
BA5-16	13.46	9691.20	0.73	1.41	
BA5-17	13.11	9439.20	0.69	1.37	
Average	13.28	9558.72	0.70	-	0.40E+06
Std. Dev.	0.55	394.31	0.02	-	-

Table B-6 Bending Test Results for ABS Polymer Blend with 25% by Weight of Chopped Fibers

Specimen	Maximum Load	Maximum Stress	Deflection @ Max. Stress	Max. Deflection Recorded	Stiffness, E
	lbs.	psi	in.	in.	psi
BA6-11	21.08	15177.60	0.49	0.49	1.15E+06 1.08E+06
BA6-12	22.95	16524.00	0.44	0.44	
BA6-13	23.88	17193.60	0.55	0.56	
BA6-15	23.42	16862.40	0.47	0.48	
BA6-17	23.77	17114.40	0.45	0.46	
BA6-18	22.48	16185.60	0.45	0.46	
Average	22.93	16509.60	0.47	-	1.11E+06
Std. Dev.	1.05	753.33	0.04	-	-

Table B-7 Bending Test Results for Virgin PC

Specimen	Maximum Load	Maximum Stress	Deflection @ Max. Stress	Max. Deflection Recorded	Stiffness, E
	lbs.	psi	in.	in.	psi
BP1-6	13.70	9864.00	0.81	1.43	0.329E+06
BP1-7	14.19	10216.80	0.94	1.21	0.345E+06
BP1-8	13.98	10065.60	0.94	1.16	0.302E+06
BP1-9	15.04	10828.80	0.83	1.34	0.355E+06
BP1-10	14.22	10238.40	0.81	1.29	0.329E+06
Average	14.23	10242.72	0.87	-	0.332E+06
Std. Dev.	0.50	360.20	0.07	-	2.022E+04

Table B-8 Bending Test Results for Virgin PC with 25% by Weight of Chopped Fibers

Specimen	Maximum Load	Maximum Stress	Deflection @ Max. Stress	Max. Deflection Recorded	Stiffness, E
	lbs.	psi	in.	in.	psi
BP2-6	33.90	24408.00	0.73	0.80	0.929E+06
BP2-7	34.69	24976.80	0.78	0.82	1.009E+06
BP2-8	34.22	24638.40	0.79	0.82	0.956E+06
BP2-9	34.07	24530.40	0.84	0.84	0.981E+06
BP2-10	33.72	24278.40	0.75	0.79	0.961E+06
Average	34.12	24566.40	0.78	-	0.967E+06
Std. Dev.	0.37	265.96	0.04	-	2.974E+04

Table B-9 Bending Test Results for 100% Recycled PC

Specimen	Maximum Load	Maximum Stress	Deflection @ Max. Stress	Max. Deflection Recorded	Stiffness, E
	lbs.	psi	in.	in.	psi
BP3-6	14.28	10281.60	0.87	1.26	0.302E+06
BP3-7	14.10	10152.00	0.77	1.28	0.289E+06
BP3-8	14.99	10792.80	0.73	1.47	0.297E+06
BP3-9	14.75	10620.00	0.93	1.44	0.281E+06
BP3-10	13.85	9972.00	0.73	1.33	0.286E+06
Average	14.39	10363.68	0.81	-	0.291E+06
Std. Dev.	0.47	337.20	0.09	-	0.860E+04

Table B-10 Bending Test Results for 100% Recycled PC with 25% by Weight of Chopped Fibers

Specimen	Maximum Load	Maximum Stress	Deflection @ Max. Stress	Max. Deflection Recorded	Stiffness, E
	lbs.	psi	in.	in.	psi
BP4-6	32.55	23436.00	0.66	0.67	0.864E+06
BP4-7	32.17	23162.40	0.65	0.69	0.909E+06
BP4-8	32.50	23400.00	0.68	0.71	0.958E+06
BP4-9	32.03	23061.60	0.67	0.73	0.928E+06
BP4-10	31.85	22932.00	0.66	0.70	0.924E+06
Average	32.22	23198.40	0.66	-	0.916E+06
Std. Dev.	0.30	216.84	0.01	-	3.424E+04

Table B-11 Bending Test Results for PC Polymer Blend

Specimen	Maximum Load	Maximum Stress	Deflection @ Max. Stress	Max. Deflection Recorded	Stiffness, E
	lbs.	psi	in.	in.	psi
BP5-6	14.81	10663.20	0.79	1.31	0.303E+06
BP5-7	15.25	10980.00	0.95	1.38	0.338E+06
BP5-8	15.43	11109.60	0.79	1.47	0.343E+06
BP5-9	16.27	11714.40	0.99	1.49	0.326E+06
BP5-10	15.80	11376.00	0.96	1.43	0.326E+06
Average	15.51	11168.64	0.90	-	0.327E+06
Std. Dev.	0.55	398.56	0.10	-	1.545E+04

Table B-12 Bending Test Results for PC Polymer Blend with 25% by Weight of Chopped Fibers

Specimen	Maximum Load	Maximum Stress	Deflection @ Max. Stress	Max. Deflection Recorded	Stiffness, E
	lbs.	psi	in.	in.	psi
BP6-6	34.90	25128.00	0.66	0.75	1.000E+06
BP6-7	33.95	24444.00	0.66	0.79	0.991E+06
BP6-8	35.79	25768.80	0.72	0.75	1.026E+06
BP6-9	34.85	25092.00	0.67	0.80	0.999E+06
BP6-10	33.33	23997.60	0.73	0.73	0.950E+06
Average	34.56	24886.08	0.69	-	0.993E+06
Std. Dev.	0.95	682.82	0.03	-	2.752E+04

APPENDIX-C

COMPRESSION TEST RESULTS

Table C-1 Compression Test Results for Virgin ABS

Specimen	Maximum Load	Maximum Stress	Reduction in Length @ Max. Stress	Stiffness, E	Stiffness, E
	lbs.	psi	in.	psi	psi
CA1-1	1127.47	9019.76	0.041	0.22E+06	0.34E+06
CA1-2	1079.71	8637.68	0.044	0.21E+06	
CA1-3	1108.39	8867.12	0.049	0.23E+06	
CA1-4	1133.32	9066.56	0.035	0.23E+06	
CA1-5	1154.87	9238.96	0.039	0.24E+06	
Average	1120.75	8966.02	0.042	0.23E+06	0.34E+06
Std. Dev.	28.30	226.43	0.01	1.21E+04	-

Table C-2 Compression Test Results for Virgin ABS with 25% by Weight of Chopped Fibers

Specimen	Maximum Load	Maximum Stress	Reduction in Length @ Max. Stress	Stiffness, E	Stiffness, E
	lbs.	psi	in.	psi	psi
CA2-1	1929.22	15433.76	0.032	0.45E+06	0.91E+06
CA2-2	1352.89	10823.12	0.037	0.32E+06	
CA2-3	1413.83	11310.64	0.034	0.33E+06	
CA2-4	1526.10	12208.80	0.034	0.34E+06	
CA2-5	1908.93	15271.44	0.035	0.44E+06	
CA2-6	1734.02	13872.16	0.031	0.40E+06	
CA2-7	1812.90	14503.20	0.033	0.44E+06	
CA2-8	1457.33	11658.64	0.038	0.33E+06	
Average	1641.90	13135.22	0.034	0.38E+06	0.91E+06
Std. Dev.	231.33	1850.66	0.002	5.80E+04	-

Table C-3 Compression Test Results for 100% Recycled ABS

Specimen	Maximum Load	Maximum Stress	Reduction in Length @ Max. Stress	Stiffness, E	Stiffness, E
	lbs.	psi	in.	psi	psi
CA3-1	1098.21	8785.68	0.038	0.23E+06	0.42E+06
CA3-2	1109.34	8874.72	0.040	0.23E+06	
CA3-3	1094.00	8752.00	0.041	0.22E+06	
CA3-4	1102.08	8816.64	0.038	0.24E+06	
CA3-5	1091.54	8732.32	0.038	0.23E+06	
Average	1099.03	8792.27	0.039	0.23E+06	0.42E+06
Std. Dev.	7.03	56.24	0.001	5.31E+04	-

Table C-4 Compression Test Results for 100% Recycled ABS with 25% by Weight of Chopped Fibers

Specimen	Maximum Load	Maximum Stress	Reduction in Length @ Max. Stress	Stiffness, E	Stiffness, E
	lbs.	psi	in.	psi	psi
CA4-1	1849.32	14794.56	0.037	0.43E+06	0.92E+06
CA4-2	1710.23	13681.84	0.032	0.39E+06	
CA4-3	1681.42	13451.36	0.034	0.39E+06	
CA4-4	1988.06	15904.48	0.034	0.46E+06	
CA4-5	1984.89	15879.12	0.034	0.45E+06	
CA4-6	1954.34	15634.72	0.035	0.46E+06	
Average	1861.38	14891.01	0.034	0.43E+06	0.92E+06
Std. Dev.	138.07	1104.59	0.002	3.22E+04	-

Table C-5 Compression Test Results for ABS Polymer Blend

Specimen	Maximum Load	Maximum Stress	Reduction in Length @ Max. Stress	Stiffness, E	Stiffness, E
	lbs.	psi	in.	psi	psi
CA5-1	1124.22	8993.76	0.038	0.22E+06	0.41E+06
CA5-2	1119.07	8952.56	0.045	0.22E+06	
CA5-3	1090.27	8722.16	0.037	0.23E+06	
CA5-4	1098.35	8786.80	0.042	0.23E+06	
CA5-5	1175.85	9406.80	0.031	0.25E+06	
Average	1121.55	8972.42	0.04	0.23E+06	0.41E+06
Std. Dev.	33.46	267.68	0.005	1.20E+04	-

Table C-6 Compression Test Results for ABS Polymer Blend with 25% by Weight of Chopped Fibers

Specimen	Maximum Load	Maximum Stress	Reduction in Length @ Max. Stress	Stiffness, E	Stiffness, E
	lbs.	psi	in.	psi	psi
CA6-1	1850.19	14801.52	0.033	0.45E+06	1.02E+06
CA6-2	1848.79	14790.32	0.032	0.46E+06	
CA6-3	1881.33	15050.64	0.031	0.45E+06	
CA6-4	1356.63	10853.04	0.036	0.34E+06	
CA6-5	1791.07	14328.56	0.033	0.44E+06	
CA6-6	1712.40	13699.20	0.030	0.41E+06	
Average	1740.07	13920.55	0.033	0.42E+06	1.02E+06
Std. Dev.	197.13	1577.01	0.002	4.34E+04	-

Table C-7 Compression Test Results for Virgin ABS

Specimen	Maximum Load	Maximum Stress	Reduction in Length @ Max. Stress	Recorded Stiffness, E	Corrected Stiffness, E
	lbs.	psi	in.	psi	psi
CP1-1	1294.30	10354.40	0.050	0.19E+06	0.36E+06
CP1-2	1317.36	10538.88	0.045	0.22E+06	0.42E+06
CP1-3	1288.79	10310.32	0.040	0.22E+06	0.42E+06
CP1-4	1301.90	10415.20	0.039	0.21E+06	0.41E+06
CP1-5	1312.44	10499.52	0.043	0.22E+06	0.43E+06
Average	1302.96	10423.66	0.043	0.21E+06	0.41E+06
Std. Dev.	11.98	95.84	0.004	1.43E+04	2.79E+04

Table C-8 Compression Test Results for Virgin ABS with 25% by Weight of Chopped Fibers

Specimen	Maximum Load	Maximum Stress	Reduction in Length @ Max. Stress	Stiffness, E	Stiffness, E
	lbs.	psi	in.	psi	psi
CP2-1	2654.60	21236.80	0.043	0.38E+06	0.75E+06
CP2-2	2431.77	19454.16	0.038	0.41E+06	0.80E+06
CP2-3	2564.28	20514.24	0.037	0.41E+06	0.80E+06
CP2-4	2536.19	20289.52	0.038	0.42E+06	0.82E+06
CP2-5	2580.91	20647.28	0.036	0.42E+06	0.82E+06
CP2-6	2481.87	19854.96	0.045	0.39E+06	0.76E+06
Average	2541.60	20332.83	0.040	0.41E+06	0.80E+06
Std. Dev.	78.09	624.70	0.004	1.58E+04	3.07E+04

Table C-9 Compression Test Results for 100% Recycled ABS

Specimen	Maximum Load	Maximum Stress	Reduction in Length @ Max. Stress	Stiffness, E	Stiffness, E
	lbs.	psi	in.	psi	psi
CP3-1	1302.14	10471.12	0.043	0.19E+06	0.37E+06
CP3-2	1294.06	10352.48	0.044	0.20E+06	0.38E+06
CP3-3	1290.90	10327.20	0.045	0.20E+06	0.40E+06
CP3-4	1264.21	10113.68	0.051	0.18E+06	0.34E+06
CP3-5	1276.97	10215.76	0.039	0.21E+06	0.42E+06
CP3-6	1305.18	10441.44	0.039	0.21E+06	0.42E+06
Average	1288.91	10311.28	0.044	0.20E+06	0.39E+06
Std. Dev.	15.64	125.11	0.004	1.49E+05	2.90E+05

Table C-10 Compression Test Results for 100% Recycled ABS with 25% by Weight of Chopped Fibers

Specimen	Maximum Load	Maximum Stress	Reduction in Length @ Max. Stress	Stiffness, E	Stiffness, E
	lbs.	psi	in.	psi	psi
CP4-1	2643.83	21150.64	0.044	0.42E+06	0.82E+06
CP4-2	2533.38	20267.04	0.034	0.42E+06	0.82E+06
CP4-3	2520.74	20165.92	0.033	0.43E+06	0.84E+06
CP4-4	2651.26	21210.08	0.038	0.42E+06	0.83E+06
CP4-5	2637.21	21097.68	0.038	0.44E+06	0.85E+06
CP4-6	2574.00	20592.00	0.033	0.44E+06	0.86E+06
Average	2593.40	20747.23	0.037	0.43E+06	0.84E+06
Std. Dev.	58.43	467.42	0.004	0.76E+04	1.47E+04

Table C-11 Compression Test Results for ABS Polymer Blend

Specimen	Maximum Load	Maximum Stress	Reduction in Length @ Max. Stress	Stiffness, E	Stiffness, E
	lbs.	psi	in.	psi	psi
CP5-1	1314.55	10516.40	0.045	0.20E+06	0.40E+06
CP5-2	1324.74	10597.92	0.048	0.21E+06	0.42E+06
CP5-3	1310.23	10481.84	0.043	0.21E+06	0.41E+06
CP5-4	1317.95	10543.60	0.046	0.21E+06	0.41E+06
CP5-5	1309.99	10479.92	0.040	0.21E+06	0.42E+06
Average	1315.49	10523.94	0.044	0.21E+06	0.41E+06
Std. Dev.	6.13	49.06	0.003	0.44E+04	0.85E+04

Table C-12 Compression Test Results for ABS Polymer Blend with 25% by Weight of Chopped Fibers

Specimen	Maximum Load	Maximum Stress	Reduction in Length @ Max. Stress	Stiffness, E	Stiffness, E
	lbs.	psi	in.	psi	psi
CP6-1	2580.67	20645.36	0.039	0.41E+06	0.80E+06
CP6-2	2642.83	21142.64	0.037	0.44E+06	0.87E+06
CP6-3	2624.49	20995.92	0.037	0.41E+06	0.81E+06
CP6-4	2722.51	21780.08	0.040	0.44E+06	0.86E+06
CP6-5	2642.54	21140.32	0.039	0.43E+06	0.83E+06
CP6-6	2540.35	20322.80	0.038	0.41E+06	0.80E+06
CP6-7	2730.23	21841.84	0.038	0.44E+06	0.86E+06
Average	2640.52	21124.14	0.038	0.43E+06	0.83E+06
Std. Dev.	69.10	552.84	0.001	1.56E+04	3.04E+04

APPENDIX-D

IMPACT TEST RESULTS

Table D-1 Impact Test Results for Virgin ABS

Specimen	Indicated Impact Strength	Corrected Impact Strength	Impact Strength	Failure Type
	ft-lbs _f	ft-lbs _f	ft-lbs _f /in	
IA1-2	0.46	0.42	3.36	H
IA1-3	0.48	0.44	3.52	H
IA1-4	0.46	0.42	3.36	H
IA1-5	0.49	0.45	3.60	H
IA1-6	0.49	0.45	3.60	H
Average	0.48	0.44	3.49	-
Std. Dev.	0.02	0.02	0.12	-

Table D-2 Impact Test Results for Virgin ABS with 25% by Weight of Chopped Fibers

Specimen	Indicated Impact Strength	Corrected Impact Strength	Impact Strength	Failure Type
	ft-lbs _f	ft-lbs _f	ft-lbs _f /in	
IA2-2	0.25	0.20	1.60	C
IA2-3	0.25	0.20	1.60	C
IA2-4	0.25	0.20	1.60	C
IA2-5	0.24	0.19	1.52	C
IA2-6	0.25	0.20	1.60	C
Average	0.25	0.20	1.58	-
Std. Dev.	0.00	0.00	0.04	-

Table D-3 Impact Test Results for 100% Recycled ABS

Specimen	Indicated Impact Strength	Corrected Impact Strength	Impact Strength	Failure Type
	ft-lbs _f	ft-lbs _f	ft-lbs _f /in	
IA3-2	0.32	0.28	2.24	H
IA3-3	0.30	0.26	2.04	H
IA3-4	0.30	0.26	2.08	H
IA3-5	0.32	0.28	2.24	H
IA3-6	0.32	0.28	2.24	H
Average	0.31	0.27	2.17	-
Std. Dev.	0.01	0.01	0.10	-

Table D-4 Impact Test Results for 100% Recycled ABS with 25% by Weight of Chopped Fibers

Specimen	Indicated Impact Strength	Corrected Impact Strength	Impact Strength	Failure Type
	ft-lbs _f	ft-lbs _f	ft-lbs _f /in	
IA4-2	0.17	0.12	0.96	C
IA4-3	0.17	0.12	0.96	C
IA4-4	0.18	0.13	1.06	C
IA4-5	0.16	0.11	0.88	C
IA4-6	0.17	0.12	0.96	C
Average	0.17	0.12	0.96	-
Std. Dev.	0.01	0.01	0.06	-

Table D-5 Impact Test Results for ABS Polymer Blend

Specimen	Indicated Impact Strength	Corrected Impact Strength	Impact Strength	Failure Type
	ft-lbs _f	ft-lbs _f	ft-lbs _f /in	
IA5-2	0.28	0.23	1.84	H
IA5-3	0.30	0.26	2.08	C
IA5-4	0.36	0.32	2.56	C
IA5-5	0.36	0.32	2.56	H
IA5-6	0.40	0.36	2.85	H
Average	0.34	0.30	2.38	-
Std. Dev.	0.05	0.05	0.41	-

Table D-6 Impact Test Results for ABS Polymer Blend with 25% by Weight of Chopped Fibers

Specimen	Indicated Impact Strength	Corrected Impact Strength	Impact Strength	Failure Type
	ft-lbs _f	ft-lbs _f	ft-lbs _f /in	
IA6-2	0.19	0.14	1.12	C
IA6-3	0.20	0.15	1.20	C
IA6-4	0.20	0.15	1.20	C
IA6-5	0.20	0.15	1.20	C
IA6-6	0.21	0.16	1.28	C
Average	0.20	0.15	1.20	-
Std. Dev.	0.01	0.01	0.06	-

Table D-7 Impact Test Results for Virgin PC

Specimen	Indicated Impact Strength	Corrected Impact Strength	Impact Strength	Failure Type
	ft-lbs _f	ft-lbs _f	ft-lbs _f /in	
IP1-2	1.82	1.80	14.40	P
IP1-3	1.74	1.72	13.76	P
IP1-4	1.81	1.79	14.32	P
IP1-5	1.79	1.77	14.16	P
IP1-6	1.75	1.73	13.84	P
IP1-7	1.82	1.80	14.40	P
Average	1.79	1.77	14.15	-
Std. Dev.	0.04	0.35	0.28	-

**Table D-8 Impact Test Results for Virgin PC with 25% by
Weight of Chopped Fibers**

Specimen	Indicated Impact Strength	Corrected Impact Strength	Impact Strength	Failure Type
	ft-lbs _f	ft-lbs _f	ft-lbs _f /in	
IP2-2	0.41	0.37	2.96	C
IP2-3	0.42	0.38	3.04	C
IP2-4	0.42	0.38	3.04	C
IP2-5	0.41	0.37	2.96	C
IP2-6	0.42	0.38	3.04	H
Average	0.42	0.38	3.01	-
Std. Dev.	0.01	0.01	0.04	-

Table D-9 Impact Test Results for 100% Recycled PC

Specimen	Indicated Impact Strength	Corrected Impact Strength	Impact Strength	Failure Type
	ft-lbs _f	ft-lbs _f	ft-lbs _f /in	
IP3-2	1.70	1.68	13.44	P
IP3-3	1.70	1.68	13.44	P
IP3-4	1.57	1.54	12.32	P
IP3-5	1.79	1.77	14.16	P
IP3-6	1.74	1.72	13.76	P
IP3-7	1.75	1.73	13.84	P
IP3-8	1.74	1.72	13.76	P
Average	1.71	1.69	13.53	-
Std. Dev.	0.07	0.07	0.59	-

Table D-10 Impact Test Results for 100% Recycled PC with 25% by Weight of Chopped Fibers

Specimen	Indicated Impact Strength	Corrected Impact Strength	Impact Strength	Failure Type
	ft-lbs _f	ft-lbs _f	ft-lbs _f /in	
IP4-2	0.26	0.22	1.76	C
IP4-3	0.29	0.25	2.00	C
IP4-4	0.26	0.22	1.76	C
IP4-5	0.25	0.21	1.68	C
IP4-6	0.27	0.23	1.84	C
Average	0.27	0.23	1.81	-
Std. Dev.	0.02	0.02	0.12	-

Table D-11 Impact Test Results for PC Polymer Blend

Specimen	Indicated Impact Strength	Corrected Impact Strength	Impact Strength	Failure Type
	ft-lbs _f	ft-lbs _f	ft-lbs _f /in	
IP5-2	1.87	1.85	14.80	P
IP5-3	1.87	1.85	14.80	P
IP5-4	1.86	1.84	14.72	P
IP5-5	1.87	1.85	14.80	P
IP5-6	1.88	1.86	14.88	P
Average	1.87	1.85	14.80	-
Std. Dev.	0.01	0.01	0.06	-

Table D-12 Impact Test Results for PC Polymer Blend with 25% by Weight of Chopped Fibers

Specimen	Indicated Impact Strength	Corrected Impact Strength	Impact Strength	Failure Type
	ft-lbs _f	ft-lbs _f	ft-lbs _f /in	
IP6-2	0.37	0.33	2.64	C
IP6-3	0.36	0.32	2.56	C
IP6-4	0.37	0.33	2.64	C
IP6-5	0.38	0.34	2.72	C
IP6-6	0.39	0.35	2.80	C
Average	0.37	0.33	2.67	-
Std. Dev.	0.01	0.01	0.09	-

APPENDIX-E

HARDNESS TEST RESULTS

Table E-1 Hardness Test Results for Virgin ABS

Specimen	Without Weight	With 626g Weight
HA1-1	11.0	25.5
HA1-2	11.0	25.0
HA1-3	10.7	26.0
HA1-4	10.6	26.0
HA1-5	11.0	25.8
HA1-6	10.9	26.0
HA1-7	11.0	25.8
HA1-8	10.9	25.8
Average	10.9	25.7
Std. Dev.	0.2	0.3

Table E-2 Hardness Test Results for Virgin ABS with 25% by Weight of Chopped Fibers

Specimen	Without Weight	With 626g Weight
HA2-1	11.3	25.9
HA2-2	11.3	25.8
HA2-3	11.3	25.6
HA2-4	11.2	25.8
HA2-5	11.2	25.8
HA2-6	11.2	25.9
HA2-7	11.2	25.8
HA2-8	11.3	25.7
Average	11.3	25.8
Std. Dev.	0.1	0.1

Table E-3 Hardness Test Results for 100% Recycled ABS

Specimen	Without Weight	With 626g Weight
HA3-1	11.2	25.6
HA3-2	11.1	25.6
HA3-3	11.1	25.8
HA3-4	10.9	25.5
HA3-5	11.1	25.5
HA3-6	11.2	25.5
HA3-7	11.2	25.4
HA3-8	11.2	25.5
Average	11.1	25.6
Std. Dev.	0.1	0.1

Table E-4 Hardness Test Results for 100% Recycled ABS with 25% by Weight of Chopped Fibers

Specimen	Without Weight	With 626g Weight
HA4-1	11.2	25.8
HA4-2	11.1	25.7
HA4-3	11.2	25.7
HA4-4	11.2	25.7
HA4-5	11.2	25.4
HA4-6	11.2	25.8
HA4-7	11.1	25.6
HA4-8	11.2	25.7
Average	11.2	25.7
Std. Dev.	0.0	0.1

Table E-5 Hardness Test Results for ABS Polymer Blend

Specimen	Without Weight	With 626g Weight
HA5-1	11.3	25.7
HA5-2	11.0	25.9
HA5-3	11.3	25.7
HA5-4	11.3	26.0
HA5-5	11.2	26.1
HA5-6	11.3	25.8
HA5-7	11.3	25.8
HA5-8	11.0	25.8
Average	11.2	25.9
Std. Dev.	0.1	0.1

Table E-6 Hardness Test Results for ABS Polymer Blend with 25% by Weight of Chopped Fibers

Specimen	Without Weight	With 626g Weight
HA6-1	11.2	25.9
HA6-2	11.2	25.9
HA6-3	11.1	25.8
HA6-4	11.1	25.9
HA6-5	11.3	25.8
HA6-6	11.2	25.7
HA6-7	11.2	25.8
HA6-8	11.1	25.8
Average	11.2	25.8
Std. Dev.	0.1	0.1

Table E-7 Hardness Test Results for Virgin PC

Specimen	Without Weight	With 626g Weight
HP1-1	10.6	25.3
HP1-2	10.6	25.3
HP1-3	10.6	25.3
HP1-4	10.6	25.1
HP1-5	10.6	25.3
HP1-6	10.7	25.1
HP1-7	10.6	25.3
HP1-8	10.6	25.3
Average	10.6	25.3
Std. Dev.	0.0	0.1

Table E-8 Hardness Test Results for Virgin PC with 25% by Weight of Chopped Fibers

Specimen	Without Weight	With 626g Weight
HP2-1	10.7	25.2
HP2-2	10.7	25.6
HP2-3	10.6	25.5
HP2-4	10.7	25.2
HP2-5	10.6	25.2
HP2-6	10.7	25.4
HP2-7	10.7	25.3
HP2-8	10.6	25.2
Average	10.7	25.3
Std. Dev.	0.1	0.2

Table E-9 Hardness Test Results for 100% Recycled PC

Specimen	Without Weight	With 626g Weight
HP3-1	10.7	25.4
HP3-2	10.8	25.5
HP3-3	10.6	25.5
HP3-4	10.7	25.3
HP3-5	10.6	25.4
HP3-6	10.6	25.4
HP3-7	10.5	25.3
HP3-8	10.6	25.5
Average	10.6	25.4
Std. Dev.	0.1	0.1

Table E-10 Hardness Test Results for 100% Recycled PC with 25% by Weight of Chopped Fibers

Specimen	Without Weight	With 626g Weight
HP4-1	10.7	25.3
HP4-2	10.6	25.4
HP4-3	10.6	25.4
HP4-4	10.7	25.5
HP4-5	10.8	25.2
HP4-6	10.7	25.3
HP4-7	10.7	25.3
HP4-8	10.8	25.2
Average	10.7	25.3
Std. Dev.	0.1	0.1

Table E-11 Hardness Test Results for PC Polymer Blend

Specimen	Without Weight	With 626g Weight
HP5-1	10.8	25.6
HP5-2	10.6	25.4
HP5-3	10.7	25.5
HP5-4	10.8	25.6
HP5-5	10.6	25.4
HP5-6	10.7	25.4
HP5-7	10.8	25.5
HP5-8	10.7	25.6
Average	10.7	25.5
Std. Dev.	0.1	0.1

Table E-12 Hardness Test Results for PC Polymer Blend with 25% by Weight of Chopped Fibers

Specimen	Without Weight	With 626g Weight
HP6-1	10.7	25.4
HP6-2	10.6	25.4
HP6-3	10.8	25.6
HP6-4	10.7	25.3
HP6-5	10.8	25.4
HP6-6	10.8	25.5
HP6-7	10.7	25.4
HP6-8	10.8	25.6
Average	10.7	25.5
Std. Dev.	0.1	0.1

APPENDIX-F

CREEP TEST RESULTS

**Table F-1 Creep Test Results for 100% Recycled and Blend ABS without Fibers at
≈20% Sustained Loading (Values in Microstrains)**

Date	Time	A3	A5
1/31/11	11:00 AM	4116	3130
	12:00 PM	4137	3201
	1:00 PM	4142	3229
	2:00 PM	4147	3242
	3:00 PM	4151	3249
	4:00 PM	4153	3252
	6:00 PM	4153	3259
	9:00 PM	4162	3276
2/1/00	12:00 AM	4187	3313
	6:00 AM	4188	3313
	9:00 AM	4187	3314
	12:00 PM	4190	3315
	3:00 PM	4238	3362
	6:00 PM	4235	3362
	9:00 PM	4231	3361
2/2/00	12:00 AM	4242	3374
	6:00 AM	4232	3369
	9:00 AM	4230	3363
	3:00 PM	4190	3332
	9:00 PM	4253	3389
2/3/00	6:00 AM	4251	3385
	9:00 AM	4192	3371
	12:00 PM	4293	3445
	3:00 PM	4357	3506
	6:00 PM	4359	3511
	9:00 PM	4364	3518
2/4/00	6:00 AM	4384	3530
	9:00 AM	4388	3533
	12:00 PM	4319	3479
	3:00 PM	4384	3545
	6:00 PM	4387	3545
	9:00 PM	4365	3517
2/5/00	6:00 AM	4372	3528
	9:00 AM	4374	3531
	12:00 PM	4369	3521
	6:00 PM	4406	3546
	9:00 PM	4402	3545

2/6/00	9:00 AM	4391	3544
	3:00 PM	4409	3569
	9:00 PM	4417	3578
2/7/00	9:00 AM	4426	3586
	3:00 PM	4465	3631
	9:00 PM	4481	3634
2/8/00	9:00 AM	4451	3610
	3:00 PM	4504	3669
	9:00 PM	4519	3675
2/9/00	9:00 AM	4511	3667
	3:00 PM	4572	3718
	9:00 PM	4568	3717
2/10/00	9:00 AM	4550	3709
	3:00 PM	4604	3769
	9:00 PM	4639	3810
2/11/00	9:00 AM	4654	3810
	3:00 PM	4645	3804
	9:00 PM	4658	3810
2/12/00	9:00 AM	4620	3774
	3:00 PM	4637	3796
	9:00 PM	4662	3828
2/13/00	9:00 AM	4645	3805
	3:00 PM	4696	3853
	9:00 PM	4721	3884
2/14/00	3:00 PM	4761	3927
	9:00 PM	4758	3927
2/15/00	9:00 AM	4758	3928
	9:00 PM	4768	3941
2/16/00	3:00 PM	4782	3945
	9:00 PM	4804	3974
2/17/00	3:00 PM	4885	4085
	9:00 PM	4870	4081
2/18/00	9:00 PM	4874	4035
2/19/00	3:00 PM	4836	4006
	9:00 PM	4849	4029
2/20/00	3:00 PM	4837	4002
	9:00 PM	4827	3990
2/21/00	3:00 PM	4871	4045
	9:00 PM	4897	4059
2/22/00	9:00 PM	4965	4145
2/23/00	9:00 PM	5090	4276
2/24/00	9:00 PM	5182	4345
2/25/00	9:00 PM	5279	4431
2/26/00	9:00 PM	5332	4502
2/27/00	9:00 PM	5370	4536

2/28/00	9:00 PM	5335	4513
2/29/00	9:00 PM	5305	4478
3/1/00	9:00 PM	5346	4503
3/2/00	9:00 PM	5305	4470
3/3/00	9:00 PM	5305	4469
3/4/00	9:00 PM	5301	4465
3/5/00	9:00 PM	5302	4472
3/6/00	9:00 PM	5350	4529
3/7/00	9:00 PM	5432	4609
3/8/00	9:00 PM	5630	4816
3/9/00	9:00 PM	5684	4864
3/10/00	9:00 PM	5520	4706
3/11/00	9:00 PM	5555	4766
3/12/00	9:00 PM	5480	4630
3/13/00	9:00 PM	5470	4645
3/14/00	9:00 PM	5465	4639
3/15/00	9:00 PM	5539	4718
3/16/00	9:00 PM	5592	4773
3/17/00	9:00 PM	5491	4682
3/18/00	9:00 PM	5470	4651
3/19/00	9:00 PM	5478	4667
3/20/00	9:00 PM	5516	4705
3/21/00	3:00 PM	5562	4739
3/22/00	3:00 PM	5670	4845
3/23/00	3:00 PM	5773	4955
3/24/00	3:00 PM	5863	5052
3/25/00	3:00 PM	5830	5020
3/26/00	3:00 PM	5743	4945
3/27/00	3:00 PM	5752	4950
3/29/00	3:00 PM	5700	4901
3/30/00	3:00 PM	5694	4890
3/31/00	3:00 PM	5690	4885
4/3/00	3:00 PM	5978	5175
4/5/00	3:00 PM	5896	5080
4/7/00	3:00 PM	5993	5168
4/10/00	3:00 PM	5920	5107
4/11/00	3:00 PM	5902	5090
4/13/00	3:00 PM	5971	5195
4/14/00	3:00 PM	6034	5231
4/17/00	3:00 PM	6082	5262
4/18/00	3:00 PM	6117	5295
4/20/00	3:00 PM	6363	5574
4/21/00	3:00 PM	6432	5626
4/24/00	3:00 PM	6224	5407
4/26/00	3:00 PM	6217	5412
4/28/00	3:00 PM	6256	5454

5/1/00	3:00 PM	6365	5565
5/3/00	3:00 PM	6453	5640
5/5/00	3:00 PM	6755	5946
5/8/00	3:00 PM	7072	6253
5/10/00	3:00 PM	6980	6130
5/12/00	3:00 PM	7089	6251
5/15/00	3:00 PM	6800	5983
5/17/00	3:00 PM	6955	6122
5/19/00	3:00 PM	7009	6140
5/22/00	3:00 PM	7030	6150
5/26/00	3:00 PM	7193	6316
5/30/00	3:00 PM	7076	6201
6/1/00	3:00 PM	7579	6709
6/2/00	3:00 PM	7720	6845
6/5/00	3:00 PM	7497	6636
6/7/00	3:00 PM	7346	6450
6/9/00	3:00 PM	7665	6829

Table F-2 Creep Test Results for Virgin ABS without Fibers; Virgin, Blend, and 100% Recycled with Fibers at $\approx$ 20% Sustained Loading (Values in Microstrains)

Date	Time	A1	A2	A4	A6
2/28/00	11:30 AM				
	12:00 PM	3270			1980
	12:30 PM	3304	2750		2400
	1:00 PM	3332	2777		2411
	2:00 PM	3364	2788		2415
	3:00 PM	3379	2813		2424
	4:00 PM	3391	2826		2426
	5:00 PM	3397	2831		2426
	7:00 PM	3411	2840		2429
	9:00 PM	3424	2841		2432
2/29/00	12:00 AM	3424	2839		2431
	8:00 AM	3430	2840		2429
	11:00 AM	3440	2839	3400	2433
	12:00 PM			3428	
	1:00 PM	3451	2854	3432	2440
	2:00 PM			3440	
	3:00 PM	3461	2857	3442	2434
	4:00 PM			3442	
	5:00 PM	3460	2857	3441	2434
	7:00 PM	3471	2871	3453	2444
	9:00 PM	3481	2863	3451	2443
3/1/00	12:00 AM	3472	2856	3451	2442

	9:00 AM	3460	2847	3449	2440
	11:00 AM	3483	2847	3456	2444
	1:00 PM	3512	2843	3469	2454
	3:00 PM	3517	2842	3469	2454
	7:00 PM	3551	2843	3482	2464
	9:00 PM	3556	2853	3482	2467
3/2/00	9:00 AM	3549	2874	3482	2467
	11:00 AM	3573	2881	3508	2467
	1:00 PM	3592	2886	3508	2467
	3:00 PM	3592	2886	3507	2466
	9:00 PM	3573	2888	3507	2462
3/3/00	9:00 AM	3568	2886	3504	2456
	1:00 PM	3568	2894	3506	2458
	5:00 PM	3584	2901	3508	2460
	9:00 PM	3598	2905	3508	2470
3/4/00	1:00 PM	3592	2901	3505	2465
	9:00 PM	3603	2905	3512	2468
3/5/00	9:00 PM	3660	2918	3526	2479
3/6/00	9:00 PM	3718	2928	3540	2495
3/7/00	9:00 PM	3816	2941	3568	2521
3/8/00	9:00 PM	4027	2990	3619	2579
3/9/00	9:00 PM	4126	3007	3649	2601
3/10/00	9:00 PM	4002	2993	3620	2564
3/11/00	9:00 PM	4008	2981	3627	2571
3/12/00	9:00 PM	3942	2976	3607	2547
3/13/00	9:00 PM	3942	2987	3607	2550
3/14/00	9:00 PM	3939	2987	3607	2553
3/15/00	9:00 PM	4014	2998	3629	2575
3/16/00	9:00 PM	4078	2955	3644	2594
3/17/00	9:00 PM	4019	3008	3631	2572
3/18/00	9:00 PM	3975	3008	3623	2561
3/19/00	9:00 PM	3995	3000	3624	2568
3/20/00	9:00 PM	4049	2991	3635	2577
3/21/00	3:00 PM	4065	2991	3645	2594
3/22/00	3:00 PM	4173	2996	3676	2617
3/23/00	3:00 PM	4289	3043	3702	2648
3/24/00	3:00 PM	4387	3033	3730	2675
3/25/00	3:00 PM	4383	3029	3730	2670
3/26/00	3:00 PM	4300	3000	3715	2651
3/27/00	3:00 PM	4302	3048	3713	2651
3/29/00	3:00 PM	4300	3063	3709	2650
3/30/00	3:00 PM	4300	3078	3703	2651
3/31/00	3:00 PM	4300	3075	3702	2652
4/3/00	3:00 PM	4527	3100	3768	2715
4/5/00	3:00 PM	4475	3109	3760	2700
4/7/00	3:00 PM	4572	3045	3779	2716

4/10/00	3:00 PM	4501	3068	3772	2705
4/11/00	3:00 PM	4483	3064	3760	2702
4/13/00	3:00 PM	4563	3076	3774	2721
4/14/00	3:00 PM	4640	3085	3797	2734
4/17/00	3:00 PM	4680	3084	3824	2742
4/18/00	3:00 PM	4702	3084	3844	2770
4/20/00	3:00 PM	4990	3130	3895	2827
4/21/00	3:00 PM	5057	3131	3909	2846
4/24/00	3:00 PM	4831	3122	3861	2796
4/26/00	3:00 PM	4859	3199	3861	2798
4/28/00	3:00 PM	4901	3190	3867	2805
5/1/00	3:00 PM	5015	3203	3895	2830
5/3/00	3:00 PM	5116	3205	3915	2850
5/5/00	3:00 PM	5390	3214	3990	2930
5/8/00	3:00 PM	5730	3325	4083	3013
5/10/00	3:00 PM	5652	3297	4074	2983
5/12/00	3:00 PM	5732	3266	4081	3003
5/15/00	3:00 PM	5469	3312	4029	2953
5/17/00	3:00 PM	5596	3304	4056	2975
5/19/00	3:00 PM	5674	3300	4085	2978
5/22/00	3:00 PM	5750	3315	4106	3009
5/26/00	3:00 PM	5910	3376	4158	3048
5/30/00	3:00 PM	5964	3335	4140	3026
6/1/00	3:00 PM	6236	3409	4242	3140
6/2/00	3:00 PM	6379	3473	4273	3170
6/5/00	3:00 PM	6167	3423	4221	3116
6/7/00	3:00 PM	6047	3418	4197	3081
6/9/00	3:00 PM	6361	3484	4269	3160

**Table F-3 Creep Test Results for 100% Recycled and Blend ABS without Fibers at
≈50% Sustained Loading (Values in Microstrains)**

Date	Time	A3	A5
2/28/00	10:30 AM	9265	8770
	11:30 AM	9605	9497
	12:30 PM	9801	9680
	1:00 PM	9876	9756
	2:00 PM	10022	9896
	3:00 PM	10166	10034
	4:00 PM	10272	10133
	5:00 PM	10341	10183
	7:00 PM	10450	10324
	9:00 PM	10623	10482
2/29/00	12:00 AM	10801	10651

	8:00 AM	11020	10871
	11:00 AM	11143	10999
	1:00 PM	11239	11082
	3:00 PM	11285	11119
	5:00 PM	11331	11162
	7:00 PM	11441	11264
	9:00 PM	11471	11308
3/1/00	12:00 AM	11573	11402
	9:00 AM	11719	11554
	11:00 AM	11758	11608
	1:00 PM	11877	11703
	3:00 PM	11882	11732
	7:00 PM	12014	11865
	9:00 PM	12048	11911
3/2/00	9:00 AM	12146	12102
	11:00 AM	12183	12143
	1:00 PM	12236	12189
	3:00 PM	12236	12189
	9:00 PM	12279	12260
3/3/00	9:00 AM	12401	12396
	1:00 PM	12458	12470
	5:00 PM	12548	12554
	9:00 PM	12584	12608
3/4/00	1:00 PM	12711	12748
	9:00 PM	12842	12884
3/5/00	9:00 PM	13067	13172
3/6/00	12:00 PM	13193	13310
	9:00 PM	13339	13474
3/7/00	3:00 PM	13525	13670
	9:00 PM	13656	13821
3/8/00	2:00 PM	13926	14140
	9:00 PM	14117	14402
3/9/00	2:00 PM	14298	14651
	9:00 PM	14455	14882
3/10/00	1:00 PM	14463	14955
	9:00 PM	14493	14979
3/11/00	1:00 PM	14568	15088
	9:00 PM	14688	15210
3/12/00	2:00 PM	14706	15240
	9:00 PM	14708	15251
3/13/00	3:00 PM	14781	15352
	9:00 PM	14848	15413
3/14/00	3:00 PM	14849	15413
	9:00 PM	14967	15558
3/15/00	3:00 PM	15080	15692
	9:00 PM	15163	15781

3/16/00	3:00 PM	15319	15922
	9:00 PM	15367	15991
3/17/00	9:00 PM	15370	16025
3/18/00	9:00 PM	15397	16061
3/19/00	9:00 PM	15506	16192
3/20/00	9:00 PM	15639	16350
3/21/00	3:00 PM	15879	16565
3/22/00	3:00 PM	16085	16810
3/23/00	3:00 PM	16310	17069
3/24/00	3:00 PM	16558	17345
3/25/00	3:00 PM	16666	17525
3/26/00	3:00 PM	16675	17541
3/27/00	3:00 PM	16800	17672
3/29/00	3:00 PM	16891	17773
3/30/00	3:00 PM	16922	17821
3/31/00	3:00 PM	16921	17833
4/3/00	3:00 PM	17540	18536
4/5/00	3:00 PM	17672	18764
4/7/00	3:00 PM	17957	19087
		Failure	Failure

Table F-4 Creep Test Results for Virgin ABS without Fibers; Virgin, Blend, and 100% Recycled with Fibers at $\approx$ 50% Sustained Loading (Values in Microstrains)

Date	Time	A1	A2	A4	A6
1/11/00	9:30 AM	9490		3759	4102
	10:00 AM	9899		3929	4265
	10:30 AM	10012		3948	4253
	11:00 AM	10136		3963	4302
	11:30 AM	10230		3994	4320
	12:00 PM	10288		4009	4336
	12:30 PM	10379		4023	4349
	1:00 PM	10418		4032	4353
	2:00 PM	10493		4035	4361
	2:30 PM	10510		4050	4372
	3:00 PM	10559		4060	4379
	3:30 PM	10610		4068	4382
	4:00 PM	10612		4069	4387
	4:30 PM	10667		4081	4396
	5:00 PM	10740		4073	4398
	5:30 PM	10754		4081	4416
	6:00 PM	10807		4098	4416
	8:00 PM	10924		4122	4443
	10:00 PM	11024		4140	4457

1/12/00	12:00 AM	11123		4150	4471
	6:00 AM	11352		4177	4497
	8:00 AM	11432		4205	4505
	9:00 AM	11469		4215	4515
	10:00 AM	11492		4223	4521
	11:00 AM	11528		4228	4563
	12:00 PM	11580		4228	4554
	1:00 PM	11640		4236	4228
	2:00 PM	11661	6197	4246	4231
	3:00 PM	11698	6313	4251	4250
	4:00 PM	11745	6377	4254	4232
	5:00 PM	11760	6440	4262	4232
	6:00 PM	11812	6461	4267	4257
	7:00 PM	11852	6479	4274	4273
	8:00 PM	11888	6480	4279	4274
	9:00 PM	11910	6481	4283	4274
	10:00 PM	11918	6480	4285	4276
1/13/00	12:00 AM	11972	6514	4293	4278
	8:00 AM	12162	6541	4309	4292
	9:00 AM	12198	6550	4312	4295
	10:00 AM	12240	6583	4318	4300
	11:00 AM	12260	6642	4320	4304
	12:00 PM	12293	6603	4331	4308
	1:00 PM	12339	6668	4331	4319
	2:00 PM	12344	6681	4337	4319
	4:00 PM	12361	6692	4339	4314
	6:00 PM	12386	6693	4343	4316
	8:00 PM	12428	6692	4360	4337
	10:00 PM	12459	6695	4362	4341
1/14/00	12:00 AM	12483	6691	4363	4341
	6:00 AM	12516	6693	4365	4342
	10:00 AM	12548	6695	4368	4345
	2:00 PM	12643	6693	4386	4361
	6:00 PM	12712	6696	4395	4366
	10:00 PM	12739	6692	4396	4370
1/15/00	6:00 AM	12778	6694	4397	4372
	10:00 AM	12824	6698	4405	4376
	2:00 PM	12892	6713	4418	4390
	6:00 PM	12993	6734	4437	4405
	10:00 PM	13065	6755	4450	4418
1/16/00	6:00 AM	13171	6768	4462	4428
	10:00 AM	13237	6779	4475	4441
	3:00 PM	13310	6797	4490	4454
	7:00 PM	13328	6800	4491	4456
	11:00 PM	13328	6800	4491	4456
1/17/00	6:00 AM	13323	6790	4477	4433

	10:00 AM	13335	6791	4478	4442
	6:00 PM	13527	6832	4517	4477
	10:00 PM	13517	6832	4517	4477
1/18/00	6:00 AM	13577	6838	4518	4477
	2:00 PM	13658	6857	4536	4491
	10:00 PM	13789	6879	4556	4513
1/19/00	6:00 AM	13899	6896	4573	4528
	2:00 PM	14015	6919	4593	4548
	10:00 PM	14099	6935	4607	4559
1/20/00	6:00 AM	14159	6946	4617	4568
	2:00 PM	14237	6955	4628	4578
	10:00 PM	14293	6965	4635	4580
1/21/00	6:00 AM	14308	6967	4636	4581
	2:00 PM	14390	6978	4649	4593
	10:00 PM	14473	6991	4660	4605
1/22/00	6:00 AM	14519	6995	4666	4612
	2:00 PM	14599	7013	4680	4623
	10:00 PM	14675	7025	4684	4627
1/23/00	6:00 AM	14712	7031	4694	4636
	2:00 PM	14805	7054	4715	4661
	10:00 PM	14851	7056	4723	4663
1/24/00	6:00 AM	14909	7067	4730	4673
	2:00 PM	15025	7088	4747	4688
	10:00 PM	15040	7091	4748	4689
1/25/00	6:00 AM	15105	7098	4758	4698
	2:00 PM	15045	7078	4740	4680
	10:00 PM	15094	7090	4751	4690
1/26/00	6:00 AM	15131	7096	4755	4694
	2:00 PM	15287	7120	4777	4714
	10:00 PM	15266	7113	4771	4707
1/27/00	6:00 AM	15291	7122	4777	4715
	2:00 PM	15329	7132	4787	4720
	9:00 PM	15368	7132	4787	4720
1/28/00	9:00 AM	15367	7124	4779	4712
	9:00 PM	15527	7157	4808	4741
1/29/00	9:00 AM	15505	7150	4800	4732
	9:00 PM	15643	7176	4826	4754
1/30/00	9:00 AM	15749	7197	4845	4775
	9:00 PM	15831	7211	4861	4789
1/31/00	9:00 AM	15889	7217	4868	4795
	9:00 PM	15986	7237	4886	4814
2/1/00	9:00 AM	16021	7239	4891	4820
	9:00 PM	16093	7253	4901	4829
2/2/00	9:00 AM	16106	7252	4899	4826
	9:00 PM	16162	7260	4909	4833
2/3/00	9:00 AM	16132	7240	4898	4818

	9:00 PM	16342	7295	4945	4868
2/4/00	9:00 AM	16416	7307	4956	4876
	9:00 PM	16424	7306	4955	4876
2/5/00	9:00 AM	16459	7308	4959	4878
	9:00 PM	16505	7309	4960	4881
2/6/00	9:00 AM	16538	7317	4970	4888
	9:00 PM	16615	7331	4983	4901
2/7/00	9:00 AM	16652	7337	4991	4907
	9:00 PM	16734	7355	5002	4922
2/8/00	9:00 AM	16748	7352	5000	4920
	9:00 PM	16860	7374	5022	4937
2/9/00	9:00 AM	16873	7374	5022	4937
	9:00 PM	16952	7387	5039	4590
2/10/00	9:00 AM	17000	7392	5045	4957
	9:00 PM	17147	7423	5074	4984
2/11/00	9:00 AM	17200	7431	5081	4992
	9:00 PM	17273	7440	5093	5006
2/12/00	9:00 AM	17264	7430	5083	4995
	9:00 PM	17347	7447	5101	5009
2/13/00	9:00 AM	17350	7444	5097	5006
	9:00 PM	17484	7472	5126	5036
2/14/00	9:00 PM	17624	7493	5151	5053
2/15/00	9:00 AM	17661	7495	5151	5055
	9:00 PM	17735	7508	5163	5065
2/16/00	9:00 PM	17845	7526	5182	5081
2/17/00	9:00 AM	17844	7521	5179	5078
2/18/00	9:00 AM	17945	7533	5188	5088
	9:00 PM	18075	7557	5215	5114
2/19/00	9:00 PM	18158	7567	5227	5123
2/20/00	9:00 PM	18188	7561	5226	5117
2/21/00	9:00 PM	18324	7587	5247	5143
2/22/00	9:00 PM	18490	7622	5283	5176
2/23/00	9:00 PM	18720	7666	5328	5217
2/24/00	9:00 PM	18938	7698	5363	5253
2/25/00	9:00 PM	Failure	7778	5433	5322
2/26/00	9:00 PM		7821	5498	5375
2/27/00	9:00 PM		7826	5500	5376
2/28/00	9:00 PM		7820	5492	5368
2/29/00	9:00 PM		7818	5493	5364
3/1/00	9:00 PM		7838	5513	5384
3/2/00	9:00 PM		7836	5515	5384
3/3/00	9:00 PM		7844	5517	5389
3/4/00	9:00 PM		7846	5524	5393
3/5/00	9:00 PM		7858	5534	5401
3/6/00	9:00 PM		7879	5559	5422
3/7/00	9:00 PM		7909	5590	5456

3/8/00	9:00 PM	7971	5650	5513
3/9/00	9:00 PM	8000	5687	5546
3/10/00	9:00 PM	7976	5656	5520
3/11/00	9:00 PM	7986	5678	5533
3/12/00	9:00 PM	7968	5657	5515
3/13/00	9:00 PM	7974	5664	5521
3/14/00	9:00 PM	7974	5668	5520
3/15/00	9:00 PM	8004	5695	5546
3/16/00	9:00 PM	8029	5720	5569
3/17/00	9:00 PM	8010	5701	5550
3/18/00	9:00 PM	8005	5696	5545
3/19/00	9:00 PM	8015	5707	5546
3/20/00	9:00 PM	8032	5724	5573
3/21/00	3:00 PM	8054	5751	5599
3/22/00	3:00 PM	8086	5783	5629
3/23/00	3:00 PM	8122	5820	5663
3/24/00	3:00 PM	8157	5854	5696
3/25/00	3:00 PM	8155	5857	5697
3/26/00	3:00 PM	8143	5845	5683
3/27/00	3:00 PM	8150	5856	5694
3/29/00	3:00 PM	8147	5856	5688
3/30/00	3:00 PM	8144	5854	5686
3/31/00	3:00 PM	8138	5849	5679
4/3/00	3:00 PM	8246	5960	5787
4/5/00	3:00 PM	8241	5958	5782
4/7/00	3:00 PM	8274	5994	5814
4/10/00	3:00 PM	8277	6000	5814
4/11/00	3:00 PM	8279	6003	5814
4/13/00	3:00 PM	8304	6038	5841
4/14/00	3:00 PM	8327	6053	5862
4/17/00	3:00 PM	8340	6082	5896
4/18/00	3:00 PM	8396	6136	5936
4/20/00	3:00 PM	8480	6219	6015
4/21/00	3:00 PM	8502	6242	6038
4/24/00	3:00 PM	8460	6207	6004
4/26/00	3:00 PM	8472	6218	6007
4/28/00	3:00 PM	8489	6234	6024
5/1/00	3:00 PM	8542	6278	6064
5/3/00	3:00 PM	8564	6312	6102
5/5/00	3:00 PM	8671	6426	6209
5/8/00	3:00 PM	8780	6558	6324
5/10/00	3:00 PM	8790	6582	6335
5/12/00	3:00 PM	8843	6644	6390
5/15/00	3:00 PM	8817	6637	6363
5/17/00	3:00 PM	8857	6674	6405
5/19/00	3:00 PM	8890	6715	6443

5/22/00	3:00 PM	8925	6765	6480
5/26/00	3:00 PM	8969	6809	6525
5/30/00	3:00 PM	8962	6814	6526
6/1/00	3:00 PM	9106	6959	6661
6/2/00	3:00 PM	9153	7009	6713
6/5/00	3:00 PM	9124	6997	6685
6/7/00	3:00 PM	9096	6970	6658
6/9/00	3:00 PM	9185	7065	6688

Table F-5 Creep Test Results for Virgin, Blend, and 100% Recycled PC with and without Fibers at $\approx 20\%$ Sustained Loading (Values in Microstrains)

Date	Time	P1	P2	P3	P4	P5	P6
5/25/00	11:30 AM	4151		2980			
	12:30 PM	4402		3128		4640	
	1:00 PM	4430		3151	2870	4701	
	2:00 PM	4480		3176	3005	4794	
	3:00 PM	4538	3050	3235	3012	4891	2902
	4:00 PM	4648	3105	3325	3019	4998	2953
	5:00 PM	4672	3116	3348	3028	5028	2962
	6:00 PM	4740	3133	3408	3042	5092	2981
	7:00 PM	4782	3144	3444	3053	5122	2991
	8:00 PM	4817	3151	3464	3061	5150	2998
	9:00 PM	4855	3160	3500	3069	5183	3006
	10:00 PM	4892	3168	3529	3074	5214	3014
	11:00 PM	4905	3172	3538	3083	5228	3019
5/26/00	12:00 AM	4921	3176	3544	3088	5232	3021
	6:00 AM	4955	3181	3560	3093	5239	3029
	7:00 AM	4970	3183	3567	3091	5245	3035
	9:00 AM	4991	3168	3594	3104	5278	3041
	10:00 AM	5030	3195	3624	3106	5286	3044
	11:00 AM	5032	3199	3632	3110	5305	3050
	12:00 PM	5049	3203	3643	3115	5319	3052
	1:00 PM	5054	3205	3646	3116	5321	3052
	2:00 PM	5071	3208	3658	3120	5338	3055
	3:00 PM	5086	3211	3677	3121	5350	3063
	4:00 PM	5094	3213	3683	3124	5353	3062
	5:00 PM	5106	3213	3698	3126	5367	3082
	6:00 PM	5130	3220	3713	3130	5380	3068
	7:00 PM	5133	3221	3713	3132	5381	3068
	8:00 PM	5132	3223	3717	3133	5380	3068
	9:00 PM	5133	3221	3713	3132	5382	3067
	10:00 PM	5162	3228	3742	3138	5403	3076
	11:00 PM	5168	3228	3747	3141	5402	3075

5/27/00	12:00 AM	5170	3230	3748	3141	5408	3076
	12:00 PM	5260	3255	3821	3167	5467	3102
	4:00 PM	5281	3258	3834	3173	5477	3107
	8:00 PM	5307	3265	3851	3180	5487	3112
5/28/00	12:00 AM	5312	3266	3857	3183	5495	3116
	12:00 PM	5361	3281	3900	3195	5524	3128
	4:00 PM	5386	3286	3922	3203	5544	3138
	8:00 PM	5409	3292	3945	3209	5563	3143
5/29/00	12:00 AM	5421	3295	3949	3213	5569	3146
	6:00 AM	5416	3290	3937	3208	5554	3143
	9:00 AM	5421	3289	3938	3208	5554	3143
	12:00 PM	5430	3295	3950	3208	5560	3146
	3:00 PM	5453	3301	3971	3213	5581	3151
	6:00 PM	5455	3301	3983	3213	5591	3150
	9:00 PM	5452	3301	3981	3213	5592	3150
5/30/00	12:00 AM	5452	3295	3955	3208	5566	3145
	7:00 AM	5415	3288	3927	3201	5525	3135
	11:00 AM	5435	3300	3960	3210	5558	3149
	3:00 PM	5444	3300	3960	3210	5575	3150
	6:00 PM	5477	3308	4000	3219	5608	3156
	9:00 PM	5494	3311	4008	3222	5610	3160
	11:00 AM	5508	3315	4020	3230	5619	3165
5/31/00	3:00 PM	5594	3340	4105	3253	5709	3187
	6:00 PM	5623	3349	4135	3259	5735	3196
	9:00 PM	5650	3350	4153	3268	5759	3200
	9:00 AM	5707	3367	4200	3283	5788	3218
6/1/00	12:00 PM	5756	3375	4250	3296	5844	3230
	3:00 PM	5793	3384	4297	3306	5888	3237
	6:00 PM	5829	3389	4319	3314	5915	3245
	9:00 PM	5864	3399	4350	3324	5930	3253
	9:00 AM	5846	3399	4318	3330	5932	3260
6/2/00	12:00 PM	5942	3419	4383	3340	5956	3267
	3:00 PM	5962	3422	4443	3352	6013	3278
	6:00 PM	6040	3426	4485	3356	6033	3275
	9:00 PM	5942	3404	4393	3352	5993	3275
	9:00 AM	5943	3407	4413	3346	5992	3275
6/3/00	12:00 PM	5943	3412	4429	3340	5992	3275
	3:00 PM	5946	3410	4434	3356	6020	3200
	9:00 PM	5932	3402	4407	3331	5980	3260
	12:00 PM	5903	3402	4370	3325	5950	3255
6/4/00	3:00 PM	5915	3409	4396	3330	5959	3262
	7:00 PM	5935	3412	4418	3336	5978	3267
	9:00 AM	5932	3411	4403	3335	5956	3265
6/5/00	12:00 PM	5918	3409	4387	3334	5946	3265
	3:00 PM	5960	3420	4434	3345	5998	3277
	6:00 PM	5915	3397	4363	3319	5902	3248

6/6/00	9:00 PM	5979	3425	4442	3350	6004	3280
	9:00 AM	5970	3425	4437	3352	5995	3281
	12:00 PM	5969	3425	4438	3350	5991	3281
6/7/00	3:00 PM	5960	3423	4433	3349	5981	3281
	9:00 AM	5870	3401	4341	3330	5886	3260
	12:00 PM	5864	3400	4342	3321	5875	3257
	3:00 PM	5885	3404	4360	3327	5910	3265
6/8/00	6:00 PM	5900	3406	4380	3326	5925	3263
	9:00 PM	5911	3408	4383	3333	5939	3265
	9:00 AM	5902	3408	4372	3331	5914	3263
	12:00 PM	5925	3414	4399	3336	5945	3270
	3:00 PM	5968	3426	4440	3346	5994	3289
	6:00 PM	5975	3427	4450	3350	6002	3281
6/9/00	9:00 PM	5992	3432	4468	3353	6021	3286
	9:00 AM	5902	3407	4354	3336	5928	3264
	12:00 PM	5970	3429	4448	3346	5979	3285
	3:00 PM	6074	3452	4549	3377	6094	3305
	6:00 PM	6077	3454	4550	3380	6105	3305
6/10/00	9:00 PM	6095	3457	4568	3382	6126	3318
	10:00 AM	6133	3467	4602	3397	6147	3323
	3:00 PM	6166	3474	4642	3404	6184	3333

Table F-6 Creep Test Results for Virgin, Blend, and 100% Recycled PC with and without Fibers at $\approx 50\%$ Sustained Loading (Values in Microstrains)

Date	Time	P1	P2	P3	P4	P5	P6
5/25/00	11:30 AM					12503	
	12:30 PM	11950		12820		13636	
	2:00 PM	13270	7990	14380	6450	14002	7520
	3:00 PM	13540	8340	14680	6725	14283	7875
	4:00 PM	13889	8488	15066	6897	14649	8006
	5:00 PM	14066	8533	15386	6950	14797	8056
	6:00 PM	14285	8599	15425	7027	14976	8125
	7:00 PM	14482	8650	15601	7083	15121	8175
	8:00 PM	14591	8687	15725	7120	15223	8210
	9:00 PM	14779	8736	15890	7172	15371	8258
5/26/00	10:00 PM	14918	8770	15999	7205	15488	8291
	11:00 PM	14997	8793	16074	7229	15574	8313
	12:00 AM	15060	8816	16160	7250	15660	8335
	6:00 AM	15497	8917	16498	7368	16050	8453
	7:00 AM	15523	8927	16516	7373	16075	8460
	9:00 AM	15658	8962	16642	7408	16185	8483
	10:00 AM	15703	8973	16689	7420	16218	8496
	11:00 AM	15752	8985	16735	7433	16259	8508

	12:00 PM	15792	8996	16781	7445	16295	8519
	1:00 PM	15838	9010	16807	7472	16328	8533
	2:00 PM	15889	9023	16863	7473	16386	8548
	3:00 PM	15930	9036	16902	7484	16429	8561
	4:00 PM	15976	9046	16936	7496	16456	8571
	5:00 PM	16009	9057	16970	7504	16488	8582
	6:00 PM	16065	9070	17028	7519	16528	8596
	7:00 PM	16103	9078	17060	7527	16553	8606
	8:00 PM	16125	9089	17076	7538	16581	8618
	9:00 PM	16163	9095	17096	7543	16608	8623
	10:00 PM	16208	9109	17143	7557	16645	8634
	11:00 PM	16244	9117	17170	7566	16678	8645
5/27/00	12:00 AM	16275	9125	17185	7565	16690	8651
	12:00 PM	16628	9219	17506	7669	17033	8752
	4:00 PM	16714	9246	17582	7694	17076	8779
	8:00 PM	16810	9267	17656	7720	17151	8804
5/28/00	12:00 AM	16859	9282	17699	7733	17191	8815
	12:00 PM	17069	9337	17882	7795	17384	8877
	4:00 PM	17135	9356	17940	7817	17439	8897
	8:00 PM	17197	9371	17992	7837	17496	8916
5/29/00	12:00 AM	17245	9391	18032	7855	17536	8932
	6:00 AM	17290	9404	18064	7873	17579	8947
	9:00 AM	17312	9412	18077	7882	17591	8956
	12:00 PM	17336	9416	18116	7893	17625	8965
	3:00 PM	17381	9428	18145	7902	17663	8975
	6:00 PM	17412	9437	18172	7916	17695	8987
	9:00 PM	17427	9444	18174	7921	17705	8992
5/30/00	12:00 AM	17436	9444	18177	7928	17711	8995
	7:00 AM	17436	9449	18170	7928	17712	9001
	11:00 AM	17489	9465	18230	7946	17759	9018
	3:00 PM	17515	9473	18261	7955	17798	9025
	6:00 PM	17564	9484	18304	7967	17834	9039
	9:00 PM	17600	9495	18329	7979	17858	9049
5/31/00	11:00 AM	17679	9520	18399	8006	17958	9077
	3:00 PM	17796	9549	18514	8036	18073	9107
	6:00 PM	17838	9561	18549	8051	18144	9122
	9:00 PM	17892	9573	18592	8066	18160	9135
6/1/00	9:00 AM	18028	9609	18707	8108	18306	9173
	12:00 PM	18105	9628	18769	8135	18379	9196
	3:00 PM	18164	9647	18833	8152	18444	9217
	6:00 PM	18222	9661	18891	8173	18493	9237
	9:00 PM	18286	9678	18931	8207	18545	9253
6/2/00	9:00 AM	18410	9718	19038	8249	18886	9312
	12:00 PM	18424	9729	19064	8257	18976	9327
	3:00 PM	18526	9753	19147	8285	19066	9356
	6:00 PM	18575	9767	19196	8307	19119	9383

	9:00 PM	18525	9750	19111	8294	19053	9372
6/3/00	9:00 AM	18601	9772	19184	8332	19134	9409
	12:00 PM	18637	9793	19230	8349	19177	9438
	3:00 PM	18659	9819	19241	8353	19381	9402
	9:00 PM	18673	9810	19240	8367	19399	9460
6/4/00	12:00 PM	18681	9820	19249	8380	19424	9476
	3:00 PM	18714	9833	19283	8392	19465	9496
	7:00 PM	18758	9840	19320	8401	19515	9500
6/5/00	9:00 AM	18798	9853	19336	8414	19551	9518
	12:00 PM	18796	9855	19339	8419	19554	9520
	3:00 PM	18850	9870	19394	8434	19624	9537
	6:00 PM	18848	9862	19410	8436	19627	9536
	9:00 PM	18889	9895	19431	8438	19521	9553
6/6/00	9:00 AM	18930	9895	19450	8455	19689	9566
	12:00 PM	18931	9895	19455	8463	19697	9570
	3:00 PM	18932	9594	19454	8464	19697	9569
6/7/00	9:00 AM	18845	9885	19404	8455	19650	9564
	12:00 PM	18883	9885	19402	8456	19653	9565
	3:00 PM	18904	9893	19430	8465	19698	9573
	6:00 PM	18921	9896	19440	8466	19712	9576
	9:00 PM	18940	9902	19459	8470	19727	9580
6/8/00	9:00 AM	18960	9909	19460	8480	19740	9594
	12:00 PM	18985	9916	19494	8488	19769	9598
	3:00 PM	19032	9928	19535	8501	19833	9608
	6:00 PM	19050	9932	19554	8503	19842	9613
	9:00 PM	19063	9936	19568	8510	19859	9617
6/9/00	9:00 AM	18998	9928	19486	8498	19810	9605
	12:00 PM	19077	9946	19588	8519	19875	9632
	3:00 PM	19189	9971	19683	8545	19996	9656
	6:00 PM	19223	9974	19693	8610	20027	9659
	9:00 PM	19221	9979	19718	8657	20032	9663
6/10/00	10:00 AM	19306	10004	19790	8585	20113	9690
	3:00 PM	19345	10015	19832	8601	20166	9703