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Mechanical characterization of aged recycled polymers and applications

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MECHANICAL CHARACTERIZATION OF AGED RECYCLED POLYMERS AND APPLICATIONS

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ABSTRACT

Mechanical Characterization Of Aged Recycled Polymers And Applications

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The research focuses on the evaluation of mechanical properties (tension, bending, compression, impact, hardness and creep) of recycled acrylonitrile butadiene styrene (ABS) and polycarbonate (PC) thermoplastics obtained as electronic shredder residue (ESR) from computer housings. Three forms of polymers, i.e., virgin, blend of virgin and recycled, and 100% recycled were investigated to establish their long term mechanical properties. Chopped and continuous glass fiber / fabric addition to the resins was evaluated to study the thermo-mechanical properties.

Mechanical characterization was carried out at freeze-thaw cycling aging. It was found that recycled polymers retain at least 70% of their tensile, bending and compressive strength after 18 months of aging under harsh environment (60 years in practice).

Offset block modules for highway guardrail systems were manufactured with recycled ABS and discarded rubber tires. Reinforced recycled plastic shapes were evaluated as possible post and rail for highway guardrail systems. Channel, trapezoidal, and box sections, and flat sheets made of recycled polypropylene (PP) and ABS were tested in tension, compression and bending.

Based on the manufacturing of laboratory specimens and test results, it is concluded that recycled polymers have significant potential for high-volume infrastructure and automotive applications.

To my wife, María José “Chiquitaja”

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CHAPTER 1

INTRODUCTION

1.1 General Remarks

Thermoplastics such as acrylonitrile-butadiene styrene (ABS) and polycarbonate (PC) are widely used to manufacture housings for small appliances (e.g., calculators, telephones, computers, etc.) as well as large equipment (e.g., automobiles). Development of new technologies and their applications make these appliances obsolete within a few years after their introduction into the consumer markets. One such obsolescence is the personal computers, which have a fast paced introduction into the consumer market. About 25 million computers are made in America each year and it is predicted that by 2005 the number of obsolete computers per year will exceed the number of new computers produced by 18% (Riverdeep, 2002). Recycling of polymers from discarded plastic housings of appliances and equipment, especially personal computers can be economical and environmental friendly.

In order to add value to recycled electronic (computer casings) shredder residue (ESR), it is essential to blend polymer ESR with virgin thermoplastics and further improve their properties with glass fiber addition, thus resulting in energy savings as well as substantial reductions in landfill space. Because of improved thermo-mechanical properties, structural and non-structural systems such as highway guardrail systems, automobile bumpers, headlight housings and other applications can be manufactured economically using blended recycled and virgin polymers. However, a comprehensive understanding of thermo-mechanical characterization is essential before developing a wide range of applications for recyclable materials.

1.2 Objectives

This research is a sequel to the research conducted by the Constructed Facilities Center at West Virginia University (CFC-WVU) on mechanical property characterization of recycled thermoplastics (Bargo, 2000). Long-term mechanical property retention and durability were evaluated for two types of thermoplastics, i.e., ABS and PC (virgin, blend of virgin and recycled, and 100% recycled) resins reinforced with glass fibers. Data collection of creep behavior was continued for additional 2 years in this research and those results are reported herein.

The objectives of this research are to:

- Evaluate long-term strength and stiffness retention of virgin/recycled ESR-ABS and ESR-PC polymers under tension, compression, bending, impact and hardness with and without glass fibers.
- Characterize creep behavior of glass fiber reinforced ABS and PC polymers that are virgin, blends of virgin and recycled, and 100% recycled ABS and PC. Continue the tests initiated by the CFC-WVU (Bargo, 2000) and analyze the results.
- Manufacture offset blocks for highway guardrail applications using recycled polymer composites and discarded tire strips.
- Evaluate bending, tensile and compressive properties of channel, trapezoidal and box section coupon specimens made of recycled polymers.

1.3 Scope

1.3.1 Coupon Specimens from Conditioned Recycled Thermoplastics

Based on availability, mechanical and manufacturing suitability, and cost issues, ABS and PC based polymers with and without chopped glass fibers were used in this research. Tests were carried out to evaluate tension, bending, compression, impact and hardness properties. Mechanical properties were evaluated at 2, 4, 10 and 18 months of aging. A total of 340 ABS and PC specimens were tested as part of this research. A summary of tests and specimen characteristics is shown in Table 1.1.

Table 1.1 Types of Coupon Specimens from Conditioned Recycled Thermoplastics, Tests and Aging Times

Test	Number of Tested Samples and Aging Times															
	2months				4 months				10 months				18 months			
	With Fibers		W/out Fibers		With Fibers		W/out Fibers		With Fibers		W/out Fibers		With Fibers		W/out Fibers	
	ABS	PC	ABS	PC	ABS	PC	ABS	PC	ABS	PC	ABS	PC	ABS	PC	ABS	PC
Tension	3	3	3	3	3	3	3	3	6	6	5	5	5	6	5	6
Bending	3	3	2	3	3	3	3	3	6	6	6	6	6	6	6	6
Compression	4	6	6	6	5	5	4	3	-	-	-	-	6	6	6	6
Impact	3	3	-	-	3	3	3	3	6	3	7	3	6	6	11	6
Hardness	3	3	3	3	3	3	3	3	6	6	6	6	6	6	6	6
Total	16	18	14	15	17	17	16	15	24	21	24	20	29	30	34	30
Grand Total	340															

In addition, monitoring of creep in ABS and PC specimens started by the CFC-WVU (Bargo, 2000) was continued. A total of 24 specimens were evaluated under creep as shown in Table 1.2.

Table 1.2 Creep Test Specimens

Type of creep load	Number of specimens	
	ABS	PC
20 % sustained load	6	6
50 % sustained load	6	6
Total	12	12
Grand Total		24

1.3.2 Guardrail Post, Rail and Offset Block

Offset block to be used between soil and post in a guardrail system was developed in this study. Manufacturing issues of these components such as shape, size and amount of recycled pellets, molding temperature, time and pressure were identified and characterized for mass production purposes.

Mechanical properties such as tension, bending and compression of recycled polypropylene channel section and trapezoidal section, and recycled ABS box section were also evaluated. This characterization will help in determining the possibility of manufacturing these shapes using recycled polymers for use as rails and posts in highway guardrail systems. To obtain optimized shapes, design, and manufacturing processes have to be further refined. However, such efforts are beyond the scope of this investigation.

With regards to the development of a highway guardrail system, various glass fiber composite materials were used. Recycled PP (polypropylene) channel and trapezoidal shapes as well as recycled ABS box shapes, sheets and belt-type strips were included in this evaluation. Tension, compression and bending tests were performed on these specimens. A virgin vinylester box section was also tested in bending for comparison purposes.

The offset block is the coupling element between the post and the rail of a guardrail system (Figure 1.1). The offset blocks manufactured during this research consisted of 4 modules joined together as shown in Figure 1.1. Materials used for manufacturing the offset block module consisted of recycled ABS pellets, glass fiber as reinforcement for the outer polymer shell, and rubber from tires for the inner core (Figure 1.1). Additional tests such as bond between ABS rubber surface, compression and impact on coupons from currently used wood offset block were also carried out. More information about materials and manufacturing of specimens can be found in chapters 3 and 4. A summary of tests and types of specimens is shown in Table 1.3.

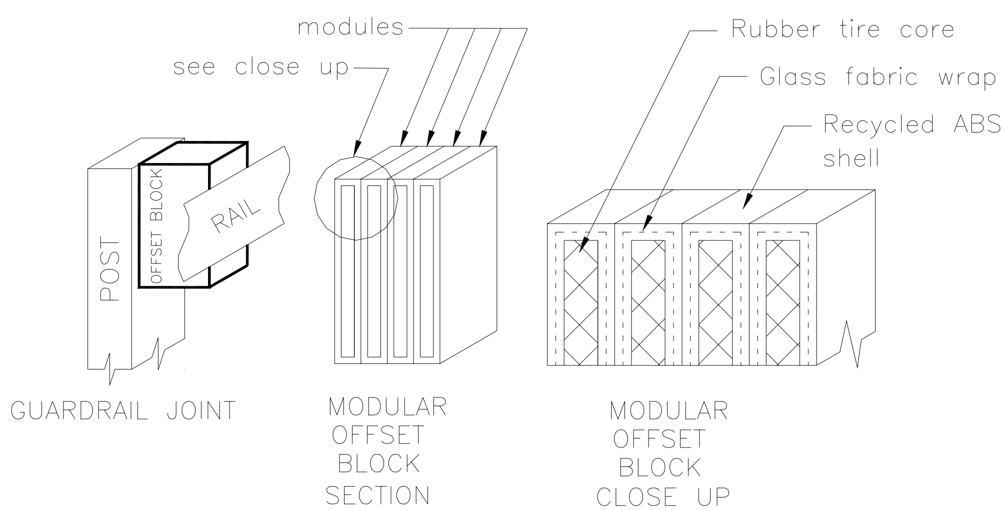


Figure 1.1 Typical Guardrail Joint Configuration and Modular Offset Block

Table 1.3 Guardrail Post, Rail and Offset Block Specimens Tested

Test	Channel section	Trapezoidal section	Box section		ABS sheets	ABS belt-type	Rubber-wood block	Wood from rubber-wood block	ABS-Rubber
	Polypropylene	Polypropylene	Recycled ABS	Virgin Vinylester	ABS	ABS	Rubber-wood	Wood	ABS-Rubber
Bending	1	1	3	2	4	-	-	-	-
Tension	-	5 (strips)	1	-	2	6	-	-	-
Compression	-	-	-	-	2	-	1	3(Pa)* 2(Pe)*	-
Impact	-	-	-	-	-	-	-	6	-
Bond strength	-	-	-	-	-	-	-	-	6
Total	1	6	4	2	8	6	1	11	6
Grand Total									45

*Pa= Parallel to grain, Pe= Perpendicular to grain

In Chapter 2, a summary on recycling of plastics, including processing and utilization is given. Also, examples of applications of recycled plastics in infrastructure are provided.

Chapters 3 and 4 include a detailed description of the materials as well as preparation and testing procedures of the standardized test specimens. A comprehensive description of the steps that led to manufacturing of offset block modules is provided in chapter 4 including details of recycled polymer post and rail specimens.

Test results, calculations, analysis of data and comparison of mechanical properties and accelerated aging of specimens are discussed in chapter 5. Chapter 6 describes results and analyses for recycled polymer shapes.

Finally, Chapters 7 and 8 include a summary of the results and findings on retention of thermo-mechanical properties of aged polymer coupons and evaluation of polymer shapes for highway guardrail applications. Suitability of recycled composites for infrastructure applications is discussed and recommendations towards future research are also provided.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Economics coupled with environmental factors of consumer products have been contributing to the growing preoccupation of people involved in industrial nations. To contain the waste, a variety of high-volume consumer products for potential recycling are: 1) soft drink bottles, 2) cans, 3) discarded appliances like computers, and 4) machinery such as heavy-duty equipment.

Experts have identified three main benefits attributable to recycling:

- Reduction in space for disposal capacity
- Lowered emissions from landfills and incinerators
- Reduction in litter and improper disposal

The three most important benefits resulting from the use of recycled materials are:

- Reduction in energy use and related emissions
- Reduction in emission of toxic gases due to reusability of polymers, and improvement in extraction and manufacturing processes
- Long-term value of conservation of raw materials (Ackerman, 1997)

Research in many areas of recycling of plastics and their applications is being conducted. Unfortunately, the development of new recycling techniques and applications has not received a major sponsorship from manufacturing industry, which would have helped making additional advances in this subject. Reasons for lack of participation of industry are low cost of virgin materials and limited amount of available raw materials needed for new sophisticated machines (Tall et al. 1998).

Two main topics are discussed in the following sections: 1) recycling process of plastics and 2) current utilization and practical examples of three uses of recycled plastic in infrastructure (guardrails, bridges and railroad ties). Discussion of these two topics will give an idea of what needs to be done in order to obtain the recycled plastics and what has been done in terms of recycled plastic applications.

Examples of recyclable materials and their recycle potential are given in Table 2.1 below from National Association of Recycling Industries NESS, (Barton, 1979).

Table 2.1 Types of Recyclable Materials

Material	Example	Recycle Potential	Recycle Rate, % of Potential
Manufacturing residues	Drosses, slags, skimmings	25-75% recoverable	Over 75
Manufacturing trimmings	Machining wastes, blanking and stamping trimmings, casting wastes	90% recoverable	Nearly 100
Manufacturing overruns	Obsolete new parts, extra parts	Variable compositions	Nearly 100
Manufacturing composite wastes	Galvanized trimmings, blended textile trimmings, coated paper wastes	Often not all constituents recovered	0-100
File dusts	Brass mill dust, steel furnace dust	Often not economical to recover	Under 25
Chemical wastes	Spent plating solutions: processing plant sludges, residues, and sewage	Often recoverable	Under 10
Old "pure" scrap	Cotton rags, copper tubing	Over 90% recoverable material	Over 75
Old composite scrap	Irony die castings, auto radiators, paper-based laminates	Often not economical to recover valuable materials	0-100
Old mixed scrap	Auto hulks, appliances, storage batteries	Not all materials recovered	Under 50
Solid wastes	Municipal refuse, industrial trash, demolition debris	Very low recovery rates now	Under 1

2.2 Recycling Aspects

The two principal steps on the recycling process are collection and sorting or separation.

By 1990 over 3000 curbside recycled programs existed in the USA. Campaigns promoting office and house recycling are being effective. By 1998 the number of people involved in recycling programs has risen (Powelson et al., 1992).

Many separation and sorting techniques have been developed in order to separate the collected materials (Bargo, 2000). Some existing methods include:

- Magnetic separator: Recovers ferrous material
- Eddy current device: Recovers aluminum material
- Disc screen: Separates smaller from larger material
- Trommel screen: Separates smaller from larger size particles of plastic material
- Vibrating screen: Separates material according to mesh size
- Oscillating screen: Similar to vibrating screen
- Traveling chain curtain: Separates high dense material from less dense material
- Air classifier: Separates light material from heavy material.

The amount of recyclable material collected in a certain community must meet the capacity of its separation facilities. Over collection must be avoided in order to prevent problems of recycled material storage (in small landfills). An example of an over collection problem was observed in Germany, one of the leading countries in recycling.

Recyclable plastic waste was supplied to steel industry to serve as a reducing agent (Ackerman, 1997). This practice was economically convenient but environmentally prejudicial.

2.3 Recycled Plastic Utilization

Polyethylene terephthalate (PET) is one of the most extensively recycled resins. Recycling of PET beverage containers grew more than 20 times in 10 years: from 8 million pounds in 1979 to 190 million pounds in 1989 (Bennet, 1992). Potential markets for recycled PET are:

- Civil engineering: geotextile and urethane foam
- Recreational industry: skis, surfboards and sailboats
- Other industries: carpets, fence posts, fiberfill, fuel pellets, industrial paints, strapping unsaturated polyester and paintbrushes.

Recycling of High Density Polyethylene (HDPE) used in milk jugs and water jugs, increased from 58 million pounds in 1986 to 145 millions in 1989 (Bennet, 1992). Potential markets for HDPE are:

- Civil engineering: building products, curb stops, pipes, signs and traffic-barrier cones
- General industry: kitchen drain boards, milk bottle carriers, soft drink base cups
- Agricultural, recreational and gardening industries: various products

In 1989, 60 million pounds of polypropylene (PP) were recycled. They were mainly used in manufacturing of automotive battery cases (Bennet, 1992). Other uses are bird feeders, furniture, pails, water meter boxes, slip-sheets, bag dispensers, flowerpots, golf equipment, pallets and carpets.

In 1989, 5 million pounds of polyvinyl chloride (PVC) were recycled, amounting to 0.06% of total PVC production (Bennet, 1992). PVC is used for downspouts, fencing corrals, handrails, hose siding, landscape timbers, sewer/drain pipes, telephone cables, and many more.

Around 20 million pounds of polystyrene (PS) were recycled in 1989, representing 0.4% of total production (Bennet, 1992). Potential uses for PS are: insulation board, appliance housings and trays.

2.4 Previous Research on Plastics in Infrastructure

A study on Fiber Reinforced Composites (FRC) for highway safety structures was conducted on composite W-beam guardrail and recycled composite offset blocks (Dutta, 1998).

<u>Composite W-beam guardrail:</u> Composites included both Fiber Reinforced Polyester and composites of recycled plastics with other fibrous additives, such as sawdust. Those composites were used to manufacture the 6.1 ft long w-beam by hand layup and vacuum bag technology. Three different thicknesses were produced and tested under bending and crash impact. Several issues were identified:

- Maximum tensile strength of 65,000 psi was obtained after producing a series of batches by trial and error, showing that this design process is more an "art than a science".

- Expected tensile strength of 70,000 psi was not achieved by this process. However, using a commercial fabrication process like pultrusion, the tensile strength can be increased.
- Stiffness was about one third of steel's stiffness. But this was not considered as a problem, since original shape of FRP beams is effectively recovered after load application, even after fracture of specimens.
- FRP shows higher fracture initiation energy than steel. Due to the brittle nature of FRP, lower post-fracture energy absorption was observed. However, geometrical arrangement of fibers in the composite can be controlled to provide progressive crushing failure.

Conclusions of the study (Dutta, 1998) were:

- It is possible to produce FRP W-beams with a desired strength, with the same profile, but with different thickness than the AASHTO steel beam.
- Early failures in pullout tests on joints (14% of laminate strength) showed that splicing and jointing mechanisms are a critical area of research.
- Other shapes, different from W-beams, must be considered for FRP beams, in order to identify the most efficient shape.

Recycled composite offset blocks: Recycled plastic composite consisting of a blend of 50% sawdust and 50% plastic waste was used to produce an offset block (Dutta, 1998). These blocks were tested under compression, tension and flexure. Several issues were identified:

- Large compression specimens showed less variability of test results than small tension and flexure specimens.
- Moisture on the recycled composite tended to increase compressive strength and reduce flexural strength.
- At low temperatures, strain at failure decreased indicating more brittleness. Stiffness and strength decreased as well.

As a result of the research, the author concludes that relating mechanical properties of offset blocks to design of guardrail systems is not straightforward. Analytical design involves many factors including post and rail structural response, as well as soil restraining forces. Research must be carried on this topic.

In the town of New Baltimore, New York, the first recycled plastic bridge (thermoplastic) in the world was designed and built. It is a single lane bridge, 11 ft wide with a 30 ft span, designed for AASHTO H-15 truck. Its primary load carrying structure was made out of Fiber Reinforced Plastic Lumber (FRPL) (McLaren, et.al. 2001). Superstructure consists of two parallel bowstring trusses with transverse floor beams framing into panel points.

Design of structural members was verified with flexural and tensile tests, while bolted connections were verified with tensile tests. Monitoring program is being conducted in order to confirm design predictions.

Material used for this bridge represents the recycling of 70,000 one-gallon milk jugs. The total weight of FRPL superstructure was 11,000 lb plus 5,400 lb of steel connection plates.

Another application of recycled plastics in infrastructure is railroad ties. Since 1994, Rutgers University has been developing polymer railroad ties as an alternative to wood ties (Plastics Resource, 2002). Around 700 million wooden ties are annually installed and nearly 14 million are replaced. In Altoona, PA, railroad ties made of 100% recycled high-density polyethylene (HDPE) showed a much better performance than wood ties. In addition, railroad ties installed in Pueblo, CO, with a train running 24 hours a day on a plastic railroad tie loop showed no signs of deterioration.

2.5 Conclusions

Recycling of plastic has been rapidly increasing in recent years. A variety of consumer applications for recycled plastics have been found. Beverage containers are believed to be one of the most widely used applications for recycled plastics. Applications in construction industry include traffic signboards, geotextiles, fence posts, and barrier cones.

Research conducted on fiber reinforced polyester (Dutta, 1998), demonstrated the suitability of plastics for use as W-beams in highway guardrail systems. Test results showed a good tensile strength (65,000psi). However, pullout tests showed low resistance (8,336 psi), and may affect the splices and joints of the rails.

Compression tests as well as non-standard flexural and tensile tests were also conducted on recycled offset blocks (Dutta, 1998). Even though specimens showed satisfactory compressive strength, it was concluded that the design and development of these blocks must include laboratory testing and analysis of forces acting on the block such as rail response and post-soil interaction.

As an example of a structural application, a recycled plastic bridge was designed and constructed (McLaren, et.al. 2001). The bridge designed for AASHTO H-15 truck is 11 ft wide and has a 30 ft. All of the structural members were made of reinforced plastic.

Another example of applications is the recycled plastic railroad ties installed in Altoona, PA. These ties showed no signs of deterioration neither on tests nor actual railroad lines.

Recycled polymers such as high density polyethylene, polypropylene, PVC and polyester are currently being recycled for infrastructure applications. Lightweight, corrosion resistance, easy transportation and installation, and durability are some of the reasons why recycled plastic products are advantageous for the construction industry.

From the three examples described, we can conclude that applications of recycled plastics in infrastructure are gradually being developed. Laboratory test and field monitoring have corroborated effectiveness of the design of structural members. In order to come up with adequate knock down factors of mechanical properties, further research has to be conducted on aging and long term evaluation of recycled thermoplastics.

CHAPTER 3

MATERIALS, PROCESS AND TEST PROCEDURE FOR CONDITIONED RECYCLED THERMOPLASTIC COUPONS

3.1 Introduction

Fiber reinforced polymers (FRP) and unreinforced polymers were tested during this research to evaluate long term retention of mechanical properties and to develop structural products using these recycled polymers. ABS and PC coupon specimens evaluated for long-term retention of mechanical properties were manufactured by injection molding process.

Specimen dimensions and test procedures used for this research were in accordance with ASTM standards (Table 3.5) to evaluate mechanical properties, i.e., tension, compression, bending, impact and hardness. Different types of recycled materials used in this process are:

- Chopped glass fibers as reinforcement
- Virgin and recycled thermoplastics as matrix

The following sections include a description of the materials (polymers and glass fibers) used in this research and a summary of the manufacturing process of the coupons. Also, in this chapter, aging procedure for polymer composite specimens is described. A detailed description of tension, bending, compression, impact, hardness and creep tests are provided, including specimen geometry, preparation and procedure.

3.2 Materials

ABS and PC resins (virgin and recycled) in the form of pellets/flakes were used to carry out the research. Chopped glass fibers were used as reinforcement to make composite test specimens for our research. Continuous fibers used to make structural shapes are described in chapter 4.

3.2.1 Virgin Polymers

Based on their feasibility for commercial applications and availability, Cycolac-GPM5500 acrylonitrile-butadiene-styrene (ABS) with ultimate tensile strength of 7,000 psi and Lexan-101 polycarbonate (PC) with ultimate strength of 9,000 psi were chosen for manufacturing the specimens.

3.2.2 Recycled Polymers

Recycled polymers from discarded computers, monitors and printers in the form of pellets with a maximum diameter of about 0.25" were supplied by MBA polymers. Purity levels of recycled polymers were above 90%. Approach shown in Appendix I can be used to theoretically calculate the stiffness of polymers with randomly oriented chopped fibers.

3.2.3 Glass Fibers

Two types of glass fibers were selected based on their sizing compatibility with different resins in this research. They were manufactured for the CFC-WVU by Owens Corning (for ABS resins) and PPG (for PC resins).

Glass reinforcement compatible with ABS consisted of 4mm long 408A-14C CRATEC chopped strands with a diameter of 14μ. The production process of these strands is made at a ISO 9002 register glass fiber facility, using the following steps:

strands were chopped to a specific length from continuous glass filaments gathered together in a single bundle and then dried, screened and cleared of metallic particles.

E-glass chopped strands 3762 MaxiChop® with length varying from 3mm to 13mm and 13μ diameter were used for polycarbonate specimens. The production process of these strands consisted of collimating of continuous fibers into strands and either chopping directly under the bushing or winding the strands into an intermediate package for chopping in a separate operation.

3.3 Manufacturing of Specimens

Based on the type of fabrics, resin, melt and cure temperature, cost effectiveness and type of part, different manufacturing methods such as compression and injection molding can be used. In this research, injection molding was selected. Chopped fiber addition of 25% of total weight of the composite was selected to increase the tensile and compressive strength of some of the specimens without a considerable reduction in impact strength.

3.3.1 Injection Molding Process

ABS injection molding was carried out by Owens Corning Inc., using a Cincinnati Milacron injection-molding machine with a 200-ton press as described in Table 3.1. PC samples were injection molded by PPG, as described in Table 3.2.

Table 3.1 Injection Molding Process for ABS Samples (CFC-WVU and Owens Corning Partnership)

Step	Description
Drying of pellets before injection process	GPM5500 standard drying specifications for general purpose: 2-4 hours drying time at 180-200°F
Melting and blending of resins	Pellets were melted and blended together at 530 to 535°F in a screw extruder with a L/D ratio of 24:1 and a compression ratio of 3.75:1, long enough to prevent non-homogeneous melting and degradation or discoloration (GE Plastics 1999)
Extrusion	At 530 to 535°F

Table 3.2 Injection Molding Process for PC Samples (CFC-WVU and PPG Partnership)

Step	Description
Drying of pellets before injection process	5 hours drying time at 200°F
Molding	Pellets were melted at 595°F in a screw with a speed of 3.65 inch/sec and a back pressure of 100psi
Extrusion	At 595°F

According to the type of resin (virgin, 100% recycled or blend) and chopped glass fiber addition (reinforced or non-reinforced), six types of samples were obtained for each resin (ABS and PC) from the injection process, as shown in Tables 3.3 and 3.4.

Table 3.3 Types of ABS Specimens

Specimens	Description	
	Resin	Fibers
A1	Virgin ABS polymer	Without fibers
A2	Virgin ABS polymer	With 25% (wt.%) (12% Fiber Volume Fraction) chopped fibers
A3	100% recycled ABS polymer	Without fibers
A4	100% recycled ABS polymer	With 25% (wt.%) (12% Fiber Volume Fraction) chopped fibers
A5	Recycled ABS (20%)/ Virgin ABS (80%) blend	Without fibers
A6	Recycled ABS (20%)/ Virgin ABS (80%) blend	With 25% (wt.%) (12% Fiber Volume Fraction) chopped fibers

Table 3.4 Types of PC Specimens

Specimens	Description	
	Resin	Fibers
P1	Virgin PC polymer	Without fibers
P2	Virgin PC polymer	With 25% (wt.%) (12% Fiber Volume Fraction) chopped fibers
P3	100% recycled PC polymer	Without fibers
P4	100% recycled PC polymer	With 25% (wt.%) (12% Fiber Volume Fraction) chopped fibers
P5	Recycled ABS (20%)/ Virgin ABS (80%) blend	Without fibers
P6	Recycled ABS (20%)/ Virgin ABS (80%) blend	With 25% (wt.%) (12% Fiber Volume Fraction) chopped fibers

Different shapes of coupon type samples without fibers and also with fibers (volume fraction of 12%) were obtained and tested under tension, compression, bending impact hardness and creep. Dimensions of the specimens and test procedures according to the ASTM standards are listed in Table 3.5

Table 3.5 Coupon Dimension and Test Procedure as per ASTM Standard

Test	Standard
Tension	ASTM D638-94b
Compression	ASTM D695-91
Bending	ASTM D790-92
Impact	ASTM D256-93[a]
Hardness	ASTM D2240-91
Creep	Sustained load, modified tension coupons were used.

3.4 Aging (conditioning)

In order to evaluate the long term mechanical property retention of the recycled materials, specimens were subjected to an accelerated aging process in a salt environment.

Samples were kept immersed in plastic containers consisting of a 3% NaCl (by weight) solution, placed inside an environmental chamber that runs the temperature cycle shown in Figure 3.1, throughout the year. Samples were removed for testing at 2, 4, 10 and 18 months of aging. Salt solution was selected because of its use as a deicing agent for roads and highways during winter periods. It was found that one day of aging in 3% salt solution at an average temperature of 34°F is equivalent to 17 days of weathering at normal environmental conditions (Vijay et al., 1999).

The study on creep behavior does not include aged samples. Creep tests started in February 2000 (Bargo, 2000) and data have been recorded since then.

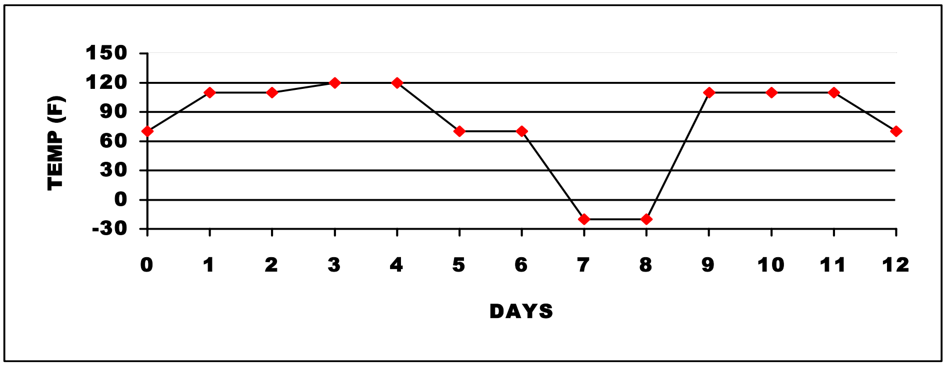


Figure 3.1 Conditioning (Aging) Temperature Cycle

3.5 Testing

In the following sections, a description of the tests carried out is given, which includes specimen, specimen preparation, test set up and procedure.

3.5.1 Tension Test

3.5.1.1 Test Specimen

For both ABS and PC, tension coupons tested were "dog-bone" shaped, as shown in Figure 3.2. Dimensions selected according to ASTM D638-94b for Type I specimen were as follows:

Width of narrow selection (W)	0.5"
Length of narrow section (L)	3.0"
Width overall (WO)	0.75"
Length overall (LO)	8.5"
Gage length (G)	1.0"
Distance between grips (D)	4.5"
Thickness (T)	0.125"

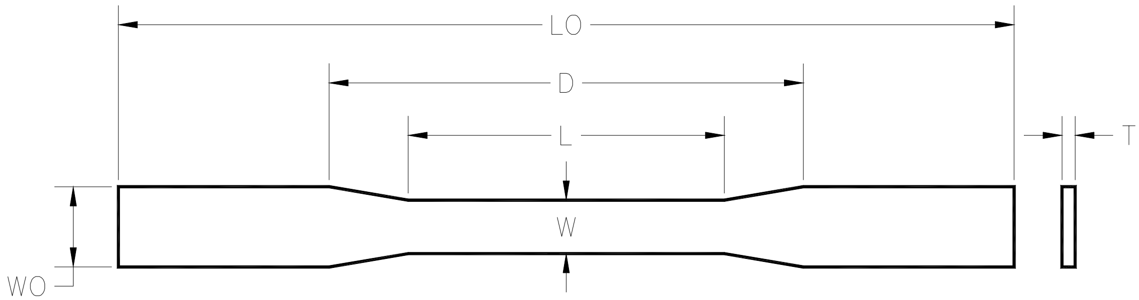


Figure 3.2 Tension Specimen Dimensions

Samples were labeled according to the type of test conducted, type of specimen tested and specimen number. For instance sample TA1-1 was a tension specimen (T), virgin ABS without fibers (A1, refer to Table 3.3), and specimen number was 1.

3.5.1.2 Specimen Preparation

In order to measure tensile strains on each tested sample, a series 2620 dynamic extensometer with a gage length of 1.00 inch was attached at the midsection of each sample as shown in Figure 3.3.

3.5.1.3 Test Set-up and Procedure

Test set-up and an Instron 8500 two-column load frame-testing machine are shown in Figures 3.3 and 3.4. The test was completely computer controlled, including the data recording of strain, deflection and testing time. "Wavemaker " software provided by the loading frame manufacturer was utilized to carry out the tests. Specimens were loaded to failure at a constant rate of 300 lb/min.

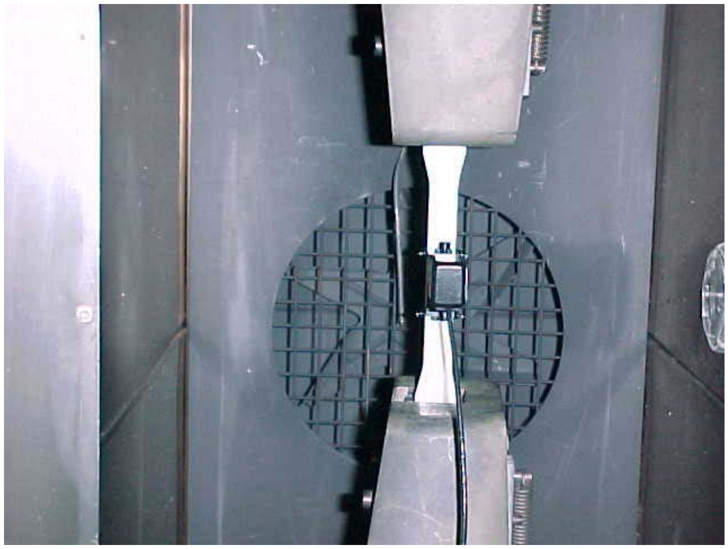


Figure 3.3 Close-up of Tension Test Set-up with Extensometer Attached

Figure 3.4 Test Set-up for Tension Test

3.5.2 Bending Test

3.5.2.1 Test Specimen

Rectangular specimens according to ASTM D790-92 test were manufactured for ABS and PC. Coupons tested under three-point bending were 5" long, 0.5" wide and 0.125" thick. Samples were labeled according to the type of test conducted, type of specimen tested and specimen number. For instance sample BA1-2 was a bending specimen (B), virgin ABS without fibers (A1, refer to Table 3.3), and specimen number was 2. A span of 3.75" was used for bending test to match ASTM requirements of span length and overhanging length.

3.5.2.2 Specimen Preparation

A strain gage was installed on the tension side at midspan on each specimen. Surface preparation consisted of: 1) sanding with a 320 grit sandpaper, 2) cleaning with an acid surface cleaner (degreaser), 3) cleaning with water-based alkaline solutions (conditioner and neutralizer) to remove oil residues and promote adhesion, 4) attaching the gage to the specimen using M-Bond 200 adhesive followed by overnight curing with proper clamping pressure to ensure adequate bond.

3.5.2.3 Test Set-up and Procedure

An Instron 8500 two-column load frame-testing machine was used. Test set-up and machine are shown in Figures 3.5 and 3.6. The test was computer controlled with the exception of recording strain data. Strain data were taken with the help of a strain indicator unit. “Wavemaker “ software was utilized to conduct the tests. Specimens were loaded at a constant rate of 0.25 in/min to failure or until deflections greater than one third of the span were attained.

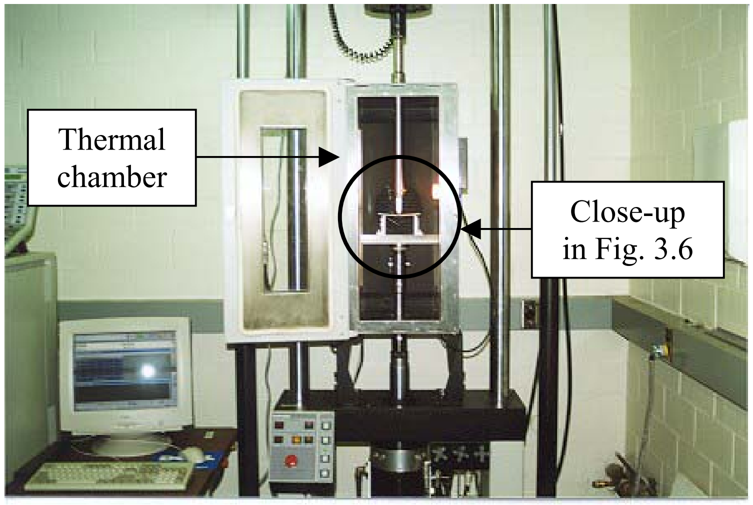


Figure 3.5 Test Set-up for Bending Test

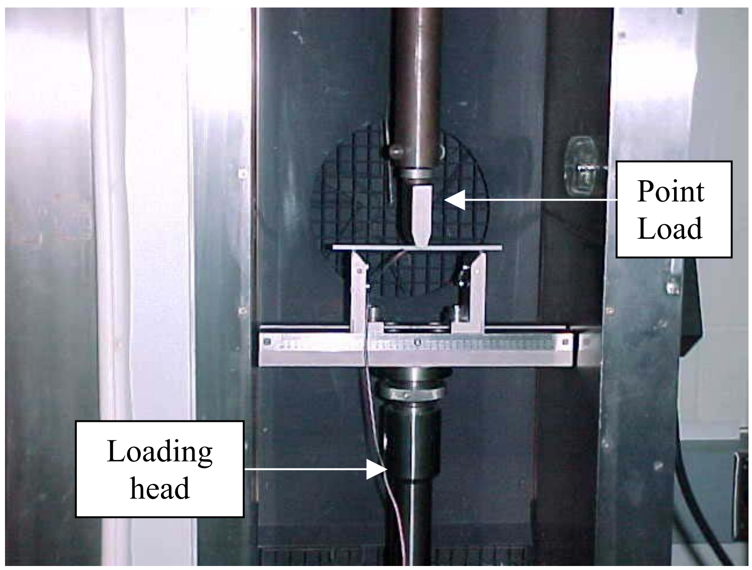


Figure 3.6 Close-up of Bending Test

3.5.3 Compression Test

3.5.3.1 Test Specimen

Rectangular specimens with cross section of 0.5" x 0.25", height of 0.5", and aspect ratio of 2 were selected as per ASTM D695-91 for both ABS and PC specimens. Samples were labeled according to the type of test conducted, type of specimen tested, and number of the specimen. For instance, sample CA1-3 was a compression specimen (C), virgin ABS without fibers (A1, refer to Table 3.3), and specimen number was 3.

3.5.3.2 Specimen Preparation

A strain gage on one of the wider faces was installed on each specimen. Surface preparation followed the same steps as described before for bending specimens.

3.5.3.3 Test Set-up and Procedure

Test set-up and an Instron 8500 two-column load frame-testing machine are shown in Figures 3.7 and 3.8. The test was computer controlled with the exception of strain data, which was recorded with the help of a strain indicator unit. Specimens were loaded at a constant rate of 0.05 in/min to failure.

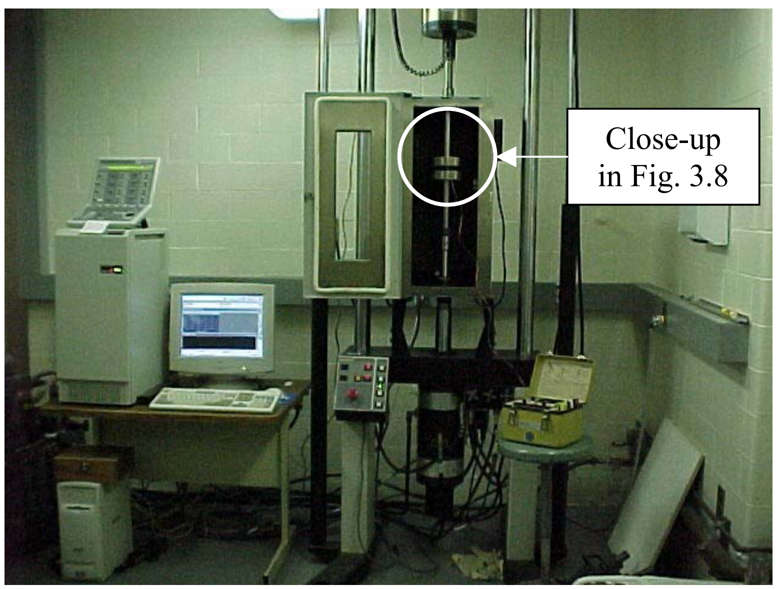


Figure 3.7 Test Set-up for Compression Test – Instron Machine

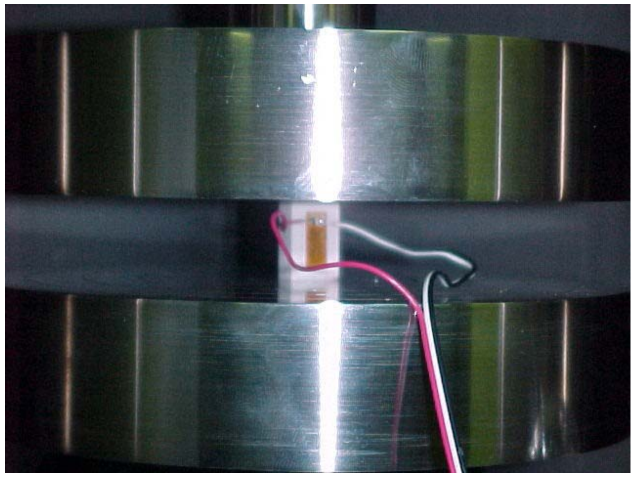


Figure 3.8 Close up for Compression Test

3.5.4 Impact Test

3.5.4.1 Test Specimen

Izod type test were carried out, specimen dimensions suitable for this type of test were selected according to ASTM D25-93a, as follows:

Width of notched section (A)	0.4085”
Notch location (B)	1.25”
Overall length (C)	2.5”
Depth of notch (D)	0.25R
Overall width (E)	0.5”
Thickness (F)	0.125”

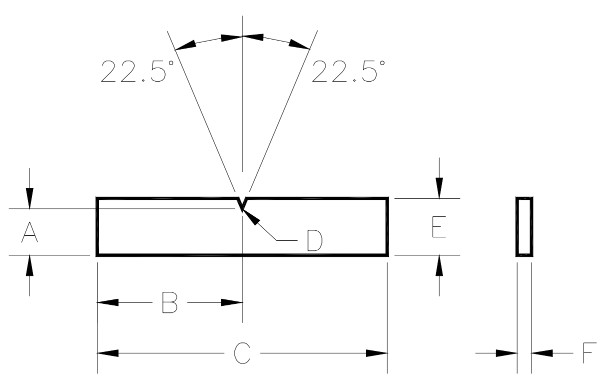


Figure 3.9 Impact Specimen Dimensions

Samples were labeled according to the type of test conducted, type of specimen tested and specimen number. For instance, sample IA1-4 was an impact specimen (I), virgin ABS without fibers (A1, refer to table 3.3), and specimen number was 4.

3.5.4.2 Specimen Preparation

Notching of specimens was performed by Owens Corning following ASTM specifications. No further preparation of the sample was required.

3.5.4.3 Test Set-up and Procedure

A BLI Series Impact Testing Machine was used for Izod type testing of PC and ABS specimens. No additional weight was attached to the pendulum. Test set-up is shown in Figures 3.10. After pendulum was released, impact energy was directly recorded from the machine's scale. Failure was noted by observation of the remaining portion of the specimen as hinge (H), complete (C) or partial (P). Readings were adjusted for pendulum friction and windage, using the standard correction chart supplied by the manufacturer (BLI Series Manual, 1999).

Figure 3.10 Test Set-up for Impact Test

3.5.5 Hardness Test

3.5.5.1 Test Specimen

Circular specimens meeting ASTM D2240-91 for dimensions and manufacturing were used. Diameters of ABS and PC specimens were 2" and 3" respectively, and both types of specimen thicknesses were 0.125". Samples were labeled according to the type of test conducted, type of specimen tested and number of the specimen. For instance, sample HA1-5 was a hardness specimen (H), virgin ABS without fibers (A1, refer to Table 3.3), and its number was 5.

3.5.5.2 Specimen Preparation

No preparation of the sample was required for this test.

3.5.5.3 Test Set-up and Procedure

A Duotronic Model 2000 Hardness Testing Machine was used for the hardness test as shown in Figure 3.11. For all PC and ABS specimens no extra weight was added to the hammer. Series of five hardness index readings at different locations on the surface of each specimen were directly recorded from the digital display on the machine.

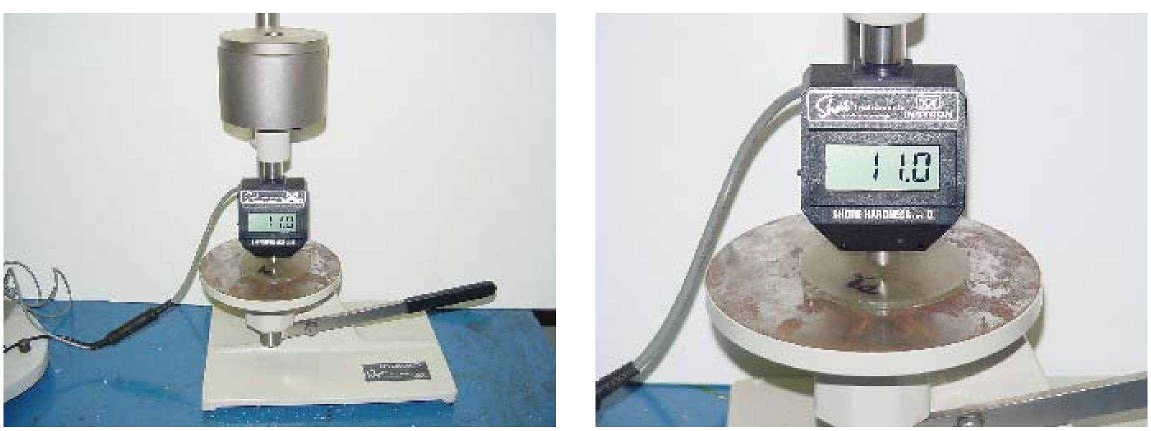


Figure 3.11 Test Set-up for Hardness Test

3.5.6 Creep Test

In order to determine the deformability of reinforced and unreinforced resins (composites) under constant state of stress, creep tests were initiated by the CFC-WVU and continued under this research.

3.5.6.1 Test Specimen

Dog-bone shaped tension specimens were selected to carry out creep tests. Dimensions used were as described in section 3.5.1.1 and Figure 3.2.

3.5.6.2 Specimen Preparation

In order to apply constant tensile force to the specimens, 3/8" diameter holes were drilled on each of the grips on the samples at 1.125" from the end and 0.375" from the sides as shown in Figure 3.12. Strain gages were attached at midlength of the specimens using the procedure described in section 3.5.2.2. Samples were suspended from the flange of a steel beam with a threaded bolt (0.375" diameter x 1.5" length) tightened in a threaded hole in the flange of the steel beam as shown in Figures 3.13 and 3.14. Bolts were passed through supporting steel plates on both sides of the grip and through the hole drilled on the specimen. Steel plates with a known weight were hung to provide the constant dead load at the other end of the specimen. Strain readings were recorded using a strain indicator unit.

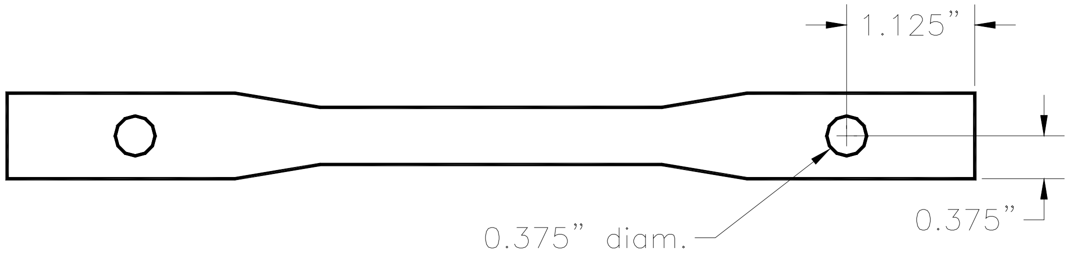


Figure 3.12 Creep Specimen

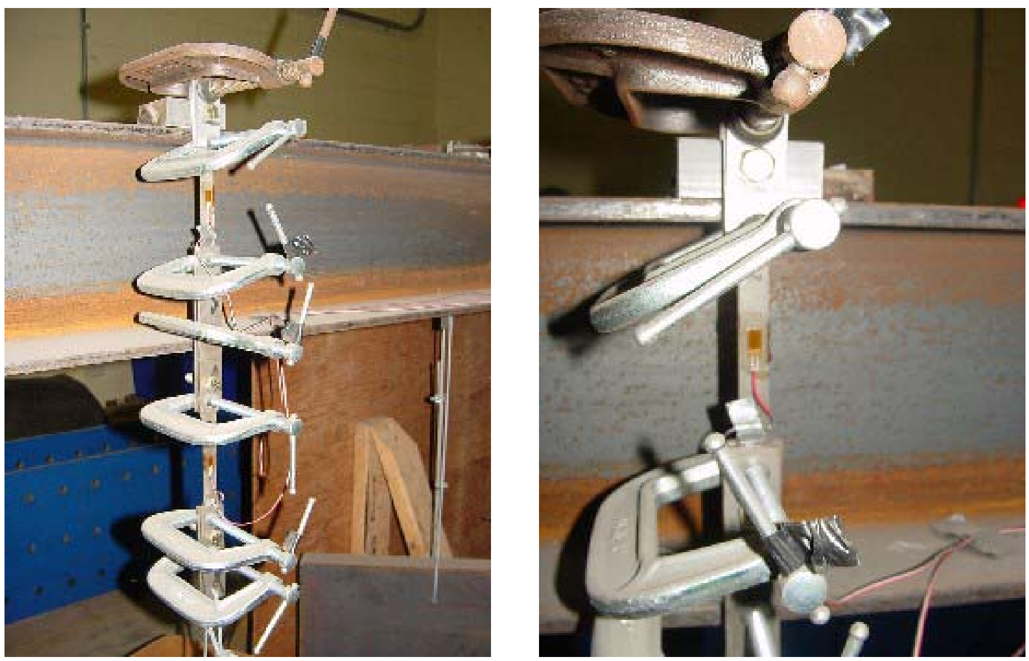


Figure 3.13 Creep Specimen Set-up

Figure 3.14 Creep Test Set-up

3.5.6.3 Test Set-up and Procedure

Strain readings were periodically recorded from a strain indicator unit connected to the strain gage. Creep coefficient for a given day of testing was calculated as:

$$Cc = \frac{\varepsilon_t}{\varepsilon_0}$$

Where,

Cc=Creep coefficient after t days of loading

ε_t=Strain after t days of loading

ε_0=Strain at the instance of loading

CHAPTER 4

MATERIALS, MANUFACTURING AND TEST PROCEDURE FOR GUARDRAIL POST, RAIL AND OFFSET BLOCK

4.1 Introduction

Recycled fiber reinforced polymers (FRP composites) were used as main materials during this research to develop an offset block, which is a structural product for highway guardrails. Different types of materials used for the offset block are:

- Recycled thermoplastic pellets as binding material
- Glass fiber as reinforcement for the offset block
- Rubber from automobile tires as a core to absorb the vehicular impact

Post and rail shapes tested in this study were manufactured by TPI Inc, Oklahoma in collaboration with CFC-WVU. Offset blocks were manufactured at CFC-WVU, using a compression molding process.

The following section includes a description of the materials used to manufacture the offset block as well as the polymer shapes, including polymers, glass fibers and rubber tires.

A detailed description of the steps that led to manufacturing of the offset block is provided in section 4.3, including

- Description of the compression molding procedure
- Manufacturing of the small blocks and modifications under compression molding process
- Discussion of heat transfer aspects
- Manufacturing of full size offset block modules

Bending, tension and compression test results on polymer channel, trapezoidal and box sections are summarized and analyzed in section 4.4. Comparisons between shapes are also provided. Additional test results of bond between ABS and rubber and wood for offset blocks are also presented in this section.

4.2 Materials

In addition to thermoplastic resins and glass fibers used for manufacturing the components of the guardrail system (post, offset block and rail), rubber from discarded tires was used as a shock absorber and filler for the offset block.

4.2.1 Recycled Polymers

Two types of resins were used for the specimens tested for guardrail and post: Polypropylene specimens with trapezoidal and channel section and ABS specimens with box cross sections. In addition to these, ABS sheets were also tested at room temperature to identify the material behavior and quantify mechanical properties. All of the above specimens were pultruded using recycled thermoplastics by TPI Inc, Oklahoma and shipped to CFC-WVU before testing.

For the offset block, recycled ABS pellets with a maximum diameter of ½" were used as shown in Figure 4.1 ESR pellets were made available from MBA Polymer Inc, with a purity level above 90%.

Figure 4.1 ABS Recycled Pellets for Offset Block Manufacturing

4.2.2 Glass Fibers

For the offset block, several types of glass fabrics were used in the form of a continuous wrap inside the block itself.

4.2.3 Rubber Tires

To take advantage of the shock absorption property of rubber materials, discarded rubber tires were used to manufacture offset blocks. They were obtained from automobile and tire shops and cut to convenient shape and size, with a reciprocating saw or a high speed vertical saw, according to dimensional requirements. Art of steel belted tires was perfected by trial and error during this research.

4.3 Manufacturing of Offset Block

Compression molding process was selected for manufacturing the offset block for the guardrail system, based on availability of the equipment and suitability of glass fabric usage as reinforcement. A PHI molding machine model SO-230H with a maximum molding force of 30 ton was used. The molding machine consists of two hot platens (top and bottom) that apply pressure to a mold placed in between them. Machine and mold schematic is shown in Figure 4.2.

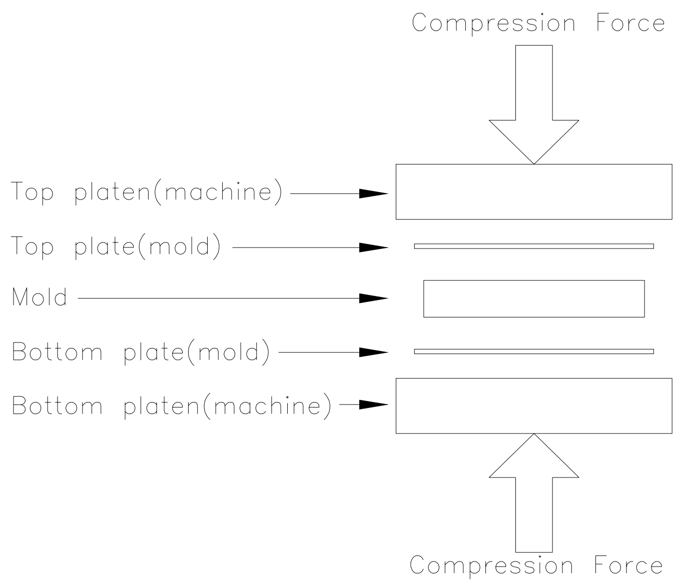


Figure 4.2 Schematic of Compression Molding

4.3.1 Molding Procedure

Different approaches were tried during this study in order to get an adequate homogeneity of the resin, adhesion of the fabric and final finish. The molds used in this study were made of steel and consisted of a closed rectangular box having opened bottom and top surfaces where the pellets were placed. Two pressure plates at the top and bottom surfaces close the mold and transfer the load applied by the hot platens of the molding machine. The main steps of a pressure molding process are:

- Hot platen set up: By means of a digital selector, hot plates are heated up to the desired molding temperature for the thermoplastic. In our case ABS was molded at 400ºF and this process required about 40 minutes.
- Mold set-up: Top and bottom plates were wrapped with aluminum foil or a similar wrap for easy cleaning of the plates after molding. During the molding stage, some of the resin dripped on the plates and adhered to

them, making it difficult to clean. Mold and plates can be oiled to de-mold the pressure-molded product after cooling.

- Positioning of pellets in the mold: Mold was placed over the bottom plate. Fillers such as wooden or rubber blocks and fabrics were placed in position inside the mold and pellets were poured into the mold filling as many voids as possible. Depending upon the desired final density of the molded product, the pellets will stand out of the mold, forming a pile. This pile will be forced into the mold during the pressure application stage (Figure 4.3).

Figure 4.3 Mold and Pellets for Pressure Molding

- Molding set-up: Top plate was placed over the pellet pile and aligned with the bottom plate. Mold and plates were placed and centered over the bottom hot platen (Figure 4.4). Pumping the machine jack with the lever brings hot platens together. Molding clock was set to the selected molding time, which varied depending upon the thickness of the mold.

Figure 4.4 Molding Set-up

- Pressure molding: Desired pressure was applied with the hydraulic pump, in our case, i.e. 20 Tons. The pressure was held constant during the molding time. Usually it took a few minutes for the pressure to stabilize due to air flowing out of the mold. In order to maintain the pressure constant, the hydraulic pump had to be activated until the pressure reached a steady state.

Figure 4.5 Pressure Molding Machine During Molding Process

- Cool down and de-mold: Once the molding time was over, pressure was released and mold was pulled out of the machine and placed in an isolated space for cooling. Cooling time was usually 20 to 25 minutes. A fan was used to reduce the cooling time, in our case to 15 minutes. Once the mold and product cooled down, top and bottom plates were removed. Excess resin on the edges of the mold was cleaned and the molded product was extracted by disassembling the mold or by hammering the final product out in the case of one-piece molds.

4.3.2 Small Block Molding

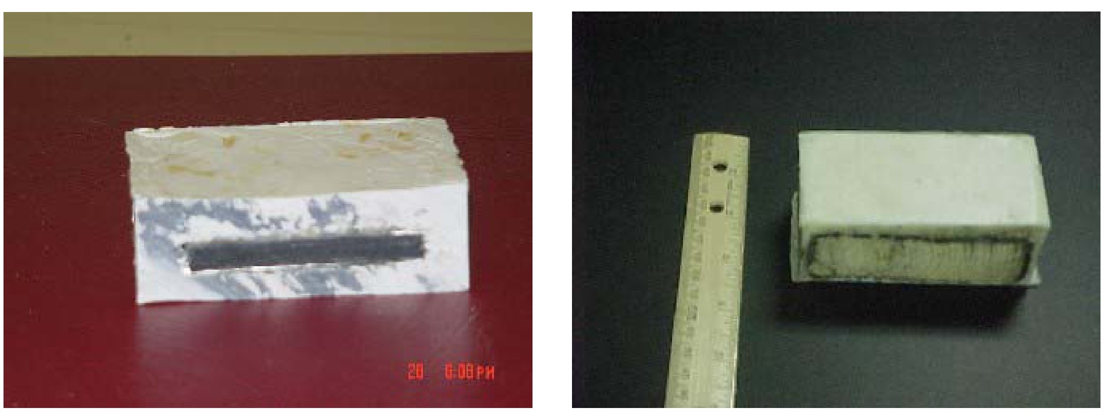
Small blocks were molded with and without core (rubber and wood), and also with and without fabric, to get a feel on the pressure molding process, manufacturing issues and compatibility of the resins with the core material (rubber and wood) and fabric.

Specimens and dimensions are described next:

- Solid recycled ABS small blocks: Neither fillers nor fabric were used in this block, measuring 3" x 3" and 0.5" thick. About 20 of these small blocks were produced with varying molding times and molding pressures in order to determine the optimum combination. Times varied between 2 and 5 minutes and pressures between 15 and 20 Ton. Finally, it was established that the optimum molding configuration for these small blocks was 4 minutes under 20 Ton pressure over the 3" x 3" area. Optimum parameters were determined in terms of homogeneity of the molded resin and final finish of the product. Small block specimens are shown in Figure 4.6.

Figure 4.6 Solid Recycled ABS Small Block

- Filled recycled ABS small blocks: Next step consisted of using a filler material inside the ABS block. Filler material consisted of neoprene, wooden and discarded rubber strips. In addition, glass fabric was also used to improve properties of the block. Primer was used to improve bond between rubber and glass fabric. A number of pull-out bond tests between rubber and ABS interface were conducted as described in section 4.4.6. Dimensions of the blocks were 3" x 3.5" with a thickness of 1". Specimens are shown in Figure 4.7



a) Neoprene Core **b) Wood Core**

c) Rubber tire Core

Figure 4.7 Filled Small Blocks

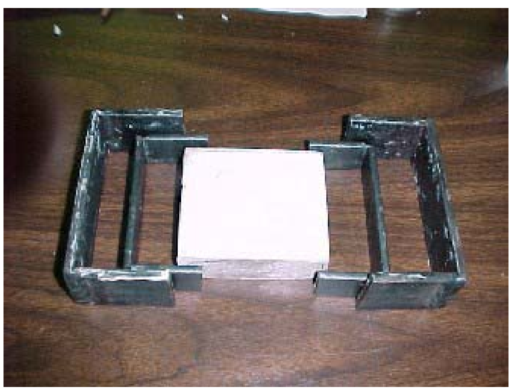
- Two stage molded small blocks: In order to properly embed the glass fabric in the resin and facilitate the positioning of pellets between the rubber core and the fabric, a two stage molding process was used as described below:

    1. An inner small block 3" x 3" x 1" with uneven rubber core and resin shell was molded to obtain a regular shape.
    2. Small block described in step 1 was wrapped with glass fabric. This step minimized the voids inside the specimens. The wrapped small block was then used as filler for the final product manufacturing.
    3. The filler described above was molded with ABS pellets in a bigger mold to obtain the final product. This final product was 4" x 4" and 1.5" thickness. The process is shown in Figure 4.8.

The two stage procedure was very important in this study because we found out that the heat transfer to the resin inside the wrap was not adequate during the second stage molding.

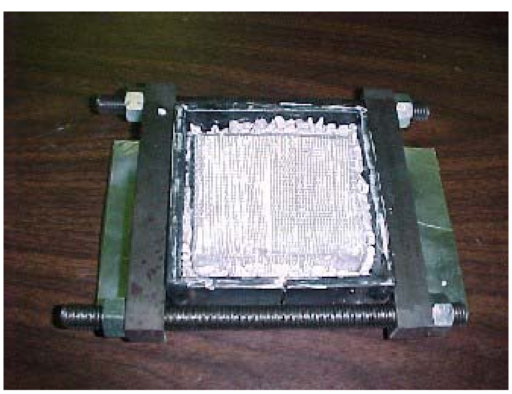
a) ABS Pellets For First Stage

b) Rubber Core Partially Covered With ABS Pellets



c) First Stage Inner Small Block and Molds

d) Fabric Wrapping of the Inner Small Block



e) ABS Pellets for Second Stage

f) Final Two Stage Small Block Molding

Figure 4.8 Two Stage Molding Process

- Rubber-Wood Block: An additional block made out of three rubber tire strips assembled between two wooden blocks with slots to hold the strips in place was also developed and tested. When tested under compression, this test specimen showed good compression strength but excessive deformation. This model demonstrated the need for a solid wrapping shell to prevent buckling of the core elements. Overall dimensions of the assembled block were 9½" x 6" x 8¾". Dimensions of wooden blocks were 9½" x 6" x 2"(thick) and slots were 1" deep. Dimensions of rubber strips were approximately 8½" x 7" x ¾"(thick). Block is shown in Figure 4.9.

Figure 4.9 Rubber-Wood Model

4.3.3 Heat Transfer Aspects

One of the major concerns while compression molding an offset block was heat transfer along the depth of the member. Temperature measurements using thermocouples attached to the sides, top, and bottom plates of the steel molds revealed that the entire mold heated up to its uniform temperature in less than a minute. However, it was evident that inner pellets along the depth of the block were not heated up to thermoplastic melting temperatures. Two possibilities were considered:

1- Increase in molding time, which led to over heating of the outside pellets causing the resin to lift up the upper plate and resin overflow during the release of the mold.

2- Pre heating of the mold with pellets, rubber and fabric properly positioned in the mold using an oven at the desired mold temperature and proceed with the molding stage with the whole product already at melting temperature. It is important to note that due to its high viscosity and low coefficient of thermal expansion, ABS at melting temperature does not easily flow without pressure application. Hence, after pre-heating, pellets become soft and sticky making it easier for them to bind together. This second approach was later refined and led us to a successful process.

4.3.4 Final Product - Small Scale

Same 4" x 4" mold with 1.5" thickness described in section 4.3.2 and used for the second stage of the two stage molding process was used to obtain small scale final product. Several runs were done following the pre-heating approach. In order to reduce voids and improve fabric wettability, virgin ABS tabs obtained from injection molding process (with a thickness of 0.125") were cut to dimensions needed to cover the rubber core in all directions. These tabs were placed on to the rubber core using instant glue to hold them in place and to facilitate wrapping as shown in Fig. 4.10.

Figure 4.10 Pre-molded ABS Tabs and Rubber Core

Once the rubber core with tabs was assembled, it was placed in the mold and gaps between the core and the sides of the mold were filled with recycled ABS pellets. Additional pellets were heaped up on the top surface to provide sufficient amount of resin to fill the mold. Following items were noted:

- It is very important to provide enough pellets; otherwise during melting under pressure, pellets will not have sufficient volume to fuse together and produce a solid block. An example of insufficient resin amount is shown in Fig. 4.11. Calculation of ABS weight that can be packed in must be done to provide sufficient amount of pellets. For our ABS, we took the maximum density of packed pellets to be 67 pcf.

Figure 4.11 Specimen Molded With Inadequate Amount of Pellets and Solidified After Melting Under Pressure

After placing pellets, the filled mold with top and bottom plates were placed in an oven at a temperature of 400ºF for 15 minutes of preheating. Following preheating, the mold was placed in the compression molding machine, and 20 Tons of pressure was applied for 6 minutes. Figure 4.12 shows a cross section of one of the manufactured blocks, where pellets were totally melted together with good fiber-resin adhesion.

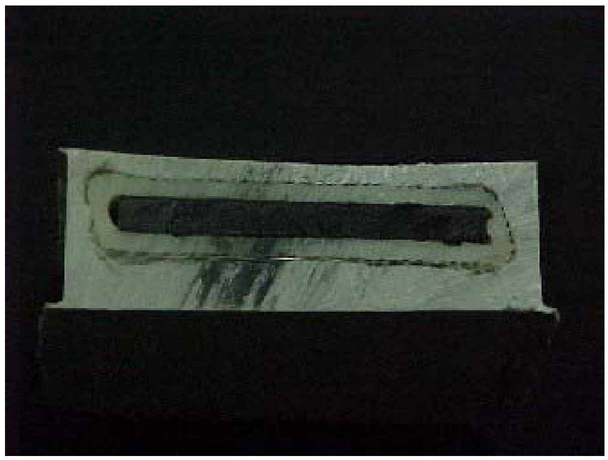


Figure 4.12 Pre-heated Molded Block

4.3.5 Final Product - Prototype

Schematic of standard dimension offset blocks being used in highways is shown in Figure 4.13. Manufactured offset blocks conformed to those dimensions.

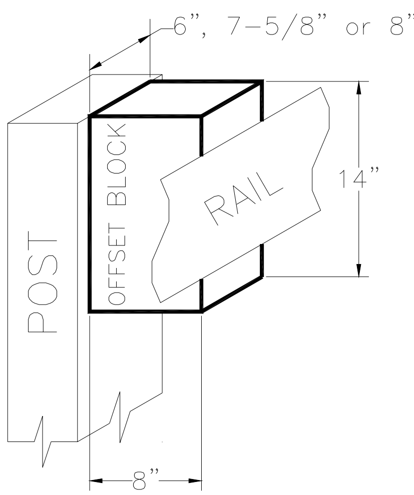


Figure 4.13 Offset Block Dimensions

While molding the offset block, two drawbacks were noted. Hot platen dimensions were 12.5" x 12.5" and maximum opening between hot platens was 5". Obviously, two of the dimensions were smaller than the required 14" x 8" x (6" or 7 5/8" or 8"). To overcome this problem following approach was used

1. The offset block was divided into four 14" x 8" x 2" modules, to get a final product (14" x 8" x 8" standard dimension for highway use). These blocks will be interlocked with bolts passing through holes drilled after molding the element.
2. The hot platen length was 1.5" shorter than the desired final product. By rotating the mold 180º, a second preheating and molding cycle would be carried out on the molded product in order to provide adequate molding pressure to the 1.5" (14" x 12.5" available in machine) portion projected out of the hot platens during the first molding phase.

For mass production of offset block, proper molding of the module in a single step can be accomplished using larger hot platens. Figure 4.14 shows the final design for the modular offset block

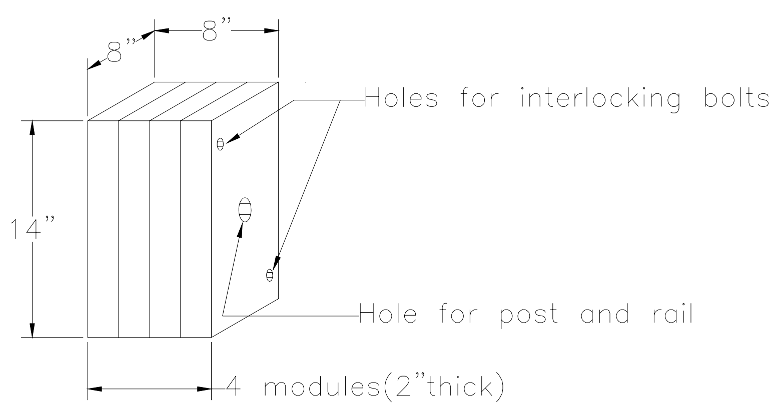


Figure 4.14 Modular Offset Block

4.3.6 Final Molding Procedure

In this section, final molding procedure for module is described. Two main molding stages were identified: molding of tabs and molding of module. Molds used in this research were manufactured at CFC-WVU laboratories.

4.3.6.1 Molding of Tabs

Tab mold preparing: The mold for manufacturing tabs consisted of a 9¼" x 10" and ¼" thick steel plate, with three slots machined in it: two for the side tabs (6¾" x 1" and 7" x 1") and the other one for the bottom and top tabs (6¾" x 7½"). Top and bottom steel plates were 10¼" x 11" and ¼" thick. Mold was cleaned and top and bottom plates were wrapped with aluminum foil or covered with a sheet of aluminum flashing (which gives a better finish). Figure 4.15 shows the mold preparation for tabs.

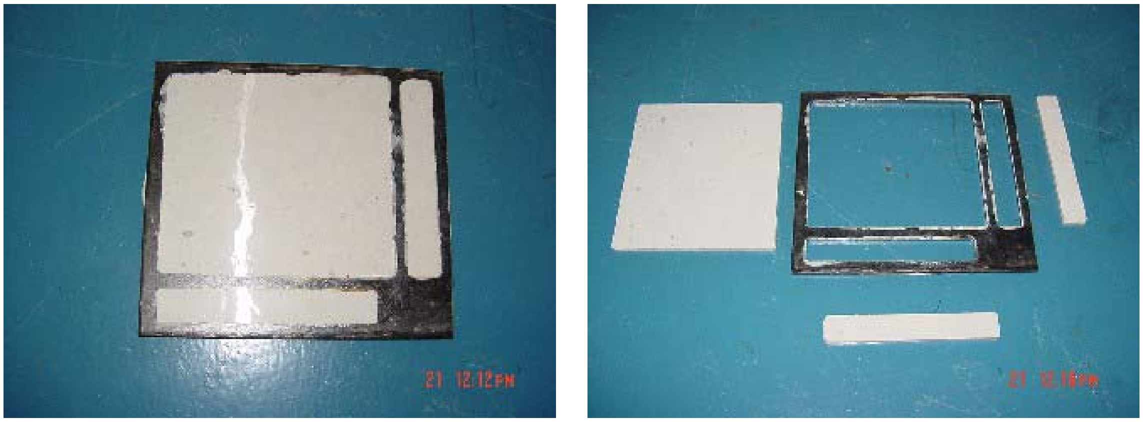
Figure 4.15 Tab Mold, Prepared for Molding

Placing of ABS pellets: For a target density of 67 pcf of compression molded resin, 29 grams (1.02 oz.) of ABS pellets were placed in each of the side slots and 212 grams (7.48 oz.) in the bigger square (Figure 4.16).

Figure 4.16 Mold for Tab Manufacturing With Recycled Pellets

Molding of Tabs: Mold with pellets and plates were placed on the bottom hot platen of the molding machine, heated to 400ºF. Top plate was then positioned over the pellet pile and bottom platen was pumped until mold made contact with the upper hot platen. At this point pressure began to be applied to the pellets that forced the plates into the mold slots, pressure application was continued until 20 Ton pressure was applied and retained at that pressure for 5 minutes. After 5 minutes of pressure application mold was taken out for cooling for 15 minutes and a fan was used to accelerate cooling. Finally, top and bottom plates were removed and ABS molded tabs were taken out. Figure 4.17 shows the molding process

a) Mold in molding machine **b) Cool Down**



c) Molded tabs before de-molding **d) Molded tabs taken out of the mold**

Figure 4.17 Molding of Tabs

For each module, the manufacturing operation has to be repeated 4 times to get enough ABS tabs to put all around the rubber tire core before wrapping with fabric.

4.3.6.2 Molding of Offset Block Module

Preparation of mold: A square steel frame with inner dimensions of 14" x 8", and a height of 2" was used. Thickness of mold walls was ½". The four walls were detachable to make it easy to de-mold the product after curing, by just releasing the bolts. Mold was cleaned and coated with oil on the inner walls for easy de-molding of the product. Top and bottom plates were covered with an aluminum flashing to protect plates against extra resin flow and provide a smooth finish to the final product. Mold prepared for module manufacturing is shown in figure 4.18.

Figure 4.18 Mold Prepared for Module Manufacturing (Wrapped Core Also Shown)

<u>Preparation of rubber core:</u> Using a reciprocating saw with a blade capable of cutting through high resistance steel, rectangular rubber strips (of size approximately 13" x 7") were cut from discarded rubber tires. Depending upon the tire selected, thickness usually varies between ½" and 1½". During the cutting operation, dimensions can vary ±½" along the edges of the strips. In order to have a top and bottom clear cover of ½" of resin, one or two rubber strips can be used based on the thickness, as shown in Figure 4.19. Volume of the rubber strips with varying thickness was calculated using the average dimensional measurements in order to estimate required amount of ABS pellets to completely fill the mold.

Figure 4.19 Rubber Tire Strips for Module Core

ABS molded tabs were cut as necessary to completely cover the rubber strips. Bottom tabs were placed first, followed by lateral plates and upper plates. Compatible glue was used for holding the tabs in place while assembling the core as shown in Figure 4.20. It is very important to use as many as required tabs to get a homogeneous melted resin inside the fabric wrap. An approximate volume of the total tabs used was measured in order to estimate the amount of pellets to fill rest of the mold.

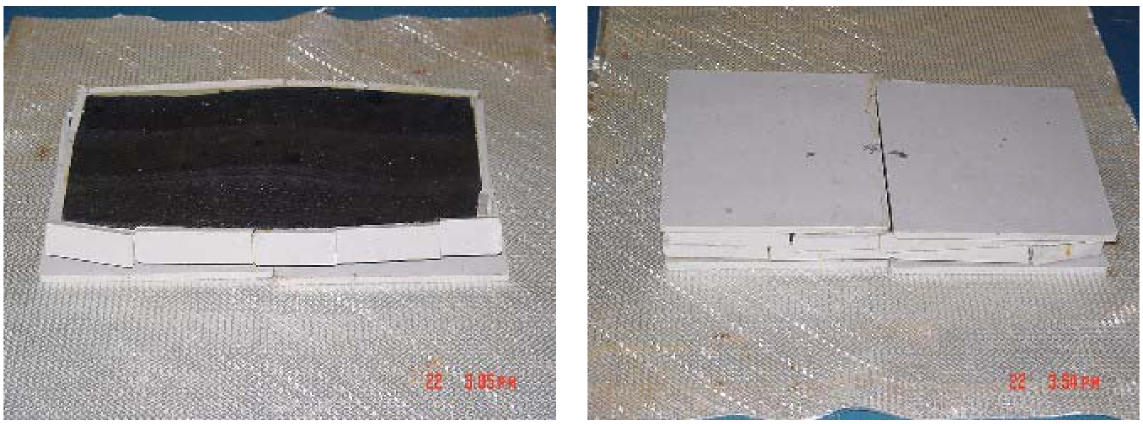


Figure 4.20 ABS Tabs Covering Rubber Core

Glass fabric was then cut as needed and wrapped around the rubber-ABS tabs core. Instant glue was used to hold the fabric in place during this operation (Figure 4.21)

Figure 4.21 Wrapped Rubber-ABS Core

<u>Filling of mold:</u> Wrapped block was placed inside the mold and centered with respect to the walls of the mold. With a target density of 67 pcf for compression molded

ABS, weight of pellets to be poured in to the mold was calculated by subtracting the volume of the wrapped core from the volume of the mold. Gaps were carefully filled with pellets and remaining pellets were piled on top of the wrapped block as shown in figure 4.22.

Figure 4.22 Filled Mold

Pre-heating: Pre-heating operation can be described as follows:

- Oven was preheated to 400ºF.
- Using proper protective gloves tray containing mold and bottom plate was carefully transferred to the oven, top plate was separately put inside the oven (Figure 4.23) for pre-heating as well.
- Mold and specimen were left for 25 minutes until melting temperature of 400ºF was reached. At this temperature pellets mantain their original shape but become soft and sticky and act as a single unit.
- After molding temperature was reached, mold was taken out of oven and placed in molding machine.

Figure 4.23 Pre-heating Procedure

Compression molding: Top mold plate was put on top of the pellet pile and aligned with respect to the bottom mold plate. Whole of the mold and plate assembly was carefully placed and centered on the bottom hot platen. Bottom platen was pumped up until top mold plate made contact with the upper hot platen. Pumping was continued until 20 Ton pressure was applied and the pressure was held constant for 10 minutes. Following the molding, pressure was released and mold was taken out, placed over wooden supports on the floor, and cooled with the help of a fan for 15 minutes. Finally, top and bottom mold plates were removed, and the mold was disassembled. Offset block module as shown in Figure 4.24.

Figure 4.24 Molded Offset Block Module

4.4 Testing

In the following sections, a description of tests carried out is given, including specimen, specimen preparation, test set up and procedure.

4.4.1 Bending Test

4.4.1.1 Test Specimens

Five types of FRP specimens were tested under bending as described in Table 4.1. All of the samples were made of recycled resins with the exception of the virgin vinylester box section.

Table 4.1 Types of Bending Specimens for Guardrail Systems

Section	Recycled Resin	Fiber volume fraction (%)	Length (in)	Test- Type
Channel	Polypropylene	43	16½	3-point bending
Trapezoidal	Polypropylene	41	16½	3-point bending
Box	ABS	25	20	3-point bending
Box	Virgin Vinylester*	41	20	3-point bending
Fabric wrapped Box	ABS	22	20	3-point bending 4-point bending
Flat specimens cut from sheets	ABS	25	4 (small coupons) 12.75 (big coupons)	3-point bending

* Not a recycled resin

For channel and trapezoidal beams a span of 14" was used and for box beams a span of 16" was used as recommended on ASTM D790-92. Figures 4.25, 4.26 and 4.27 show cross section for these specimens. Two types of flat specimens cut from recycled ABS sheets (12.75 in x 3 in x 3/8 in) were used as shown in figure 4.28. Dimensions of these specimens were:

- Plates: 4" long x ¾" wide x 3/8" thick
- Half sheet: 12.75" long x 1.5" wide x 3/8" thick

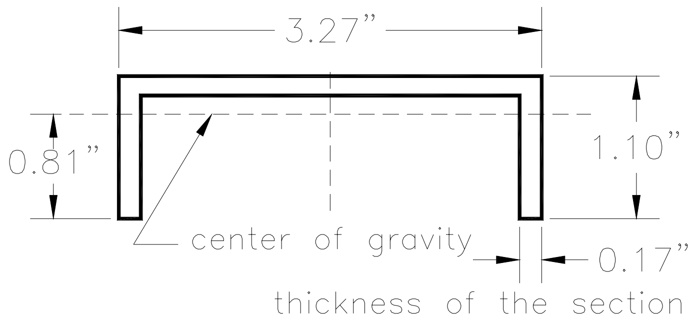


Figure 4.25 Channel Section Dimensions of Propylene Specimen

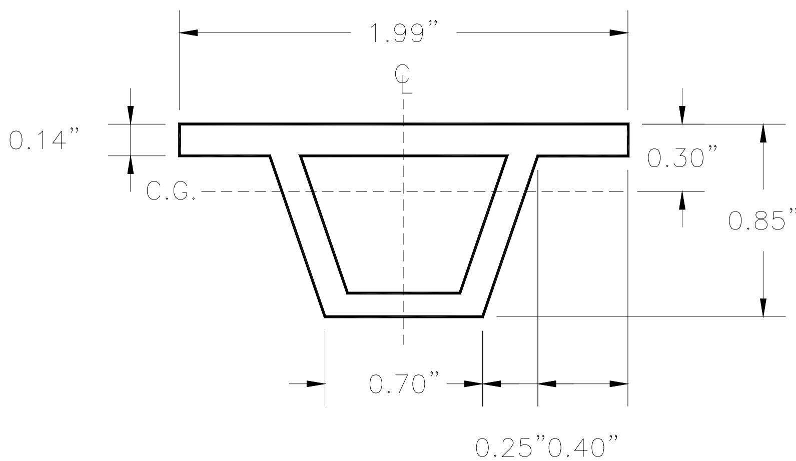


Figure 4.26 Trapezoidal Section Dimensions of Propylene Specimen

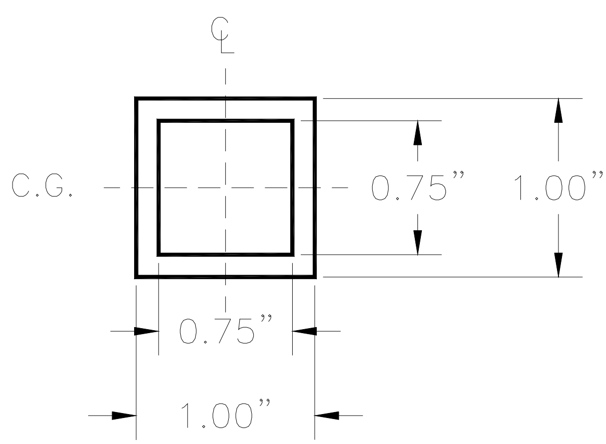


Figure 4.27 Box Section Dimensions of ABS Specimen

Figure 4.28 Short Plate and Long Plate Bending Specimens (With Strain Gage) Cut from Recycled ABS Sheets (Also Shown)

4.4.1.2 Specimen Preparation

For each of the shapes tested, strain gages were installed as follows:

- 5 gages for channel section (Fig. 4.29)
- 4 gages for trapezoidal section (Fig. 4.30)
- 2 gages for box section (Fig 4.31)
- One gage for ABS small plates on the compression side at midspan (Figure 4.28)
- 2 gages for ABS long plates at midspan one on the compression and one on the tension side. (Figure 4.28 shows only one side)

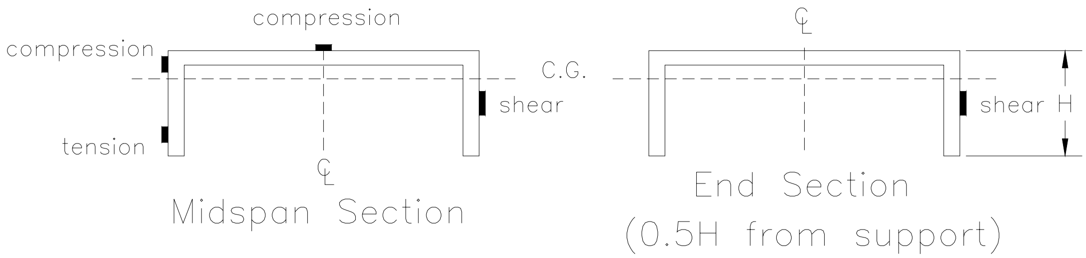


Figure 4.29 Strain Gage Locations for Bending Test on Channel Section

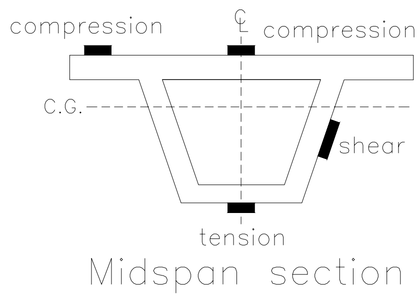


Figure 4.30 Strain Gage Locations for Bending Test on Trapezoidal Section

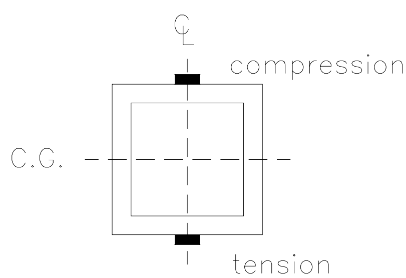


Figure 4.31 Strain Gage Locations for Bending Test on Box Sections (Midspan)

Surface preparation for strain gage bonding consisted of the following steps:

1) Sanding with a 320 grit sandpaper
2) Cleaning with an acid surface cleaner (degreaser)
3) Cleaning with water-based conditioner and neutralizer solutions to remove oil residues and help in the adhesion of the strain gage
4) Bonding the gage to the required specimen surface using M-Bond 200 adhesive

5) Allowing the adhesive cure overnight with proper clamping pressure to ensure adequate bond

Box sections were tested with and without glass fabric wrapping. Box sections required an additional surface preparation for glass fabric wrap installation as described below:

1) To ensure good adhesion, all four surfaces were lightly ground to remove the glossy finishing given during manufacturing process
2) Mbrace Primer supplied by Master Builders Technologies was applied on all of the surfaces
3) Resin was cured for 48 hours
4) A thin layer of Mbrace Saturant resin was applied
5) Fabric was coated with resin and wrapped around the specimens
6) A final coat of resin was applied

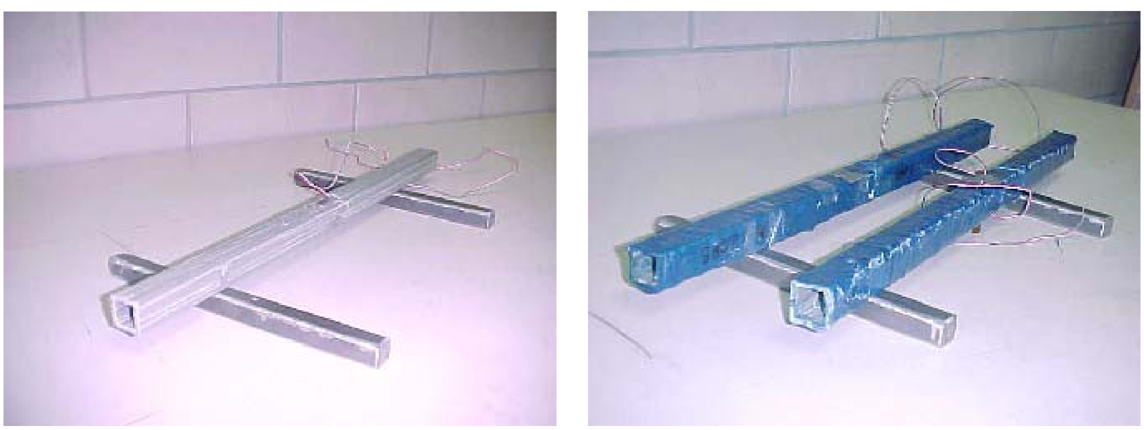


Figure 4.32 Non Wrapped and Wrapped Box Specimens for Bending Test

A wooden stiffener was placed inside the channel section (Figure 4.33) at both ends of the specimen, to prevent shear/punching failures at support points.

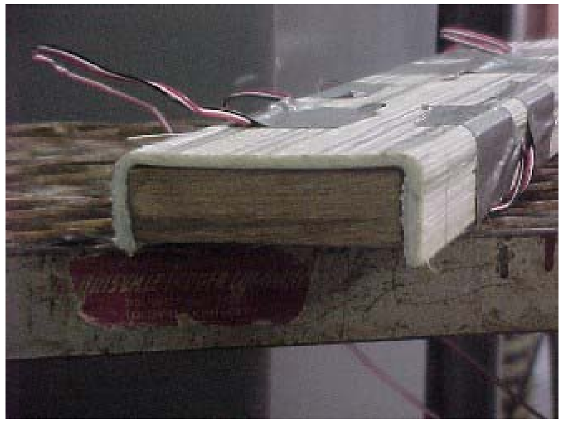


Figure 4.33 Wooden Stiffeners at Ends of Channel Section

4.4.1.3 Test Set-up and Procedure

Universal testing machine (UTM) shown in figure 4.34, was used to conduct the bending tests in channel, trapezoidal and box sections. ABS strips were tested as described on section 3.5.2.3. UTM was set to a low loading range of 0 to 10 kips. Test was carried out at a constant rate of ≈0.25 in/min until the test specimen failed. Deflections were manually recorded from a dial gage placed at midspan of the specimens, whereas load and strain readings were automatically recorded with a data acquisition system. Bending test set-up and specimens are shown in Figures 4.35 to 4.39.

Figure 4.34 Bending Test Set-up: Universal Testing Machine and Data Acquisition System

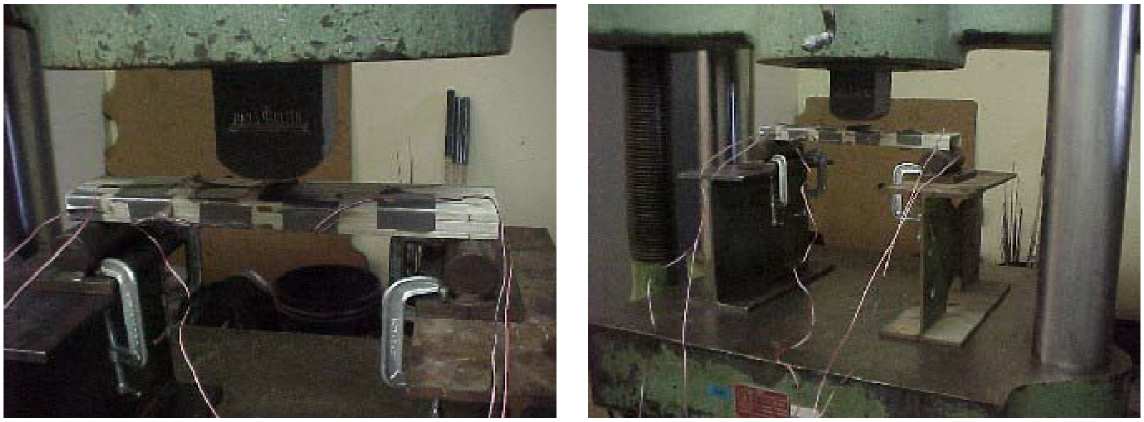


Figure 4.35 Channel Section Set-up for Bending Test

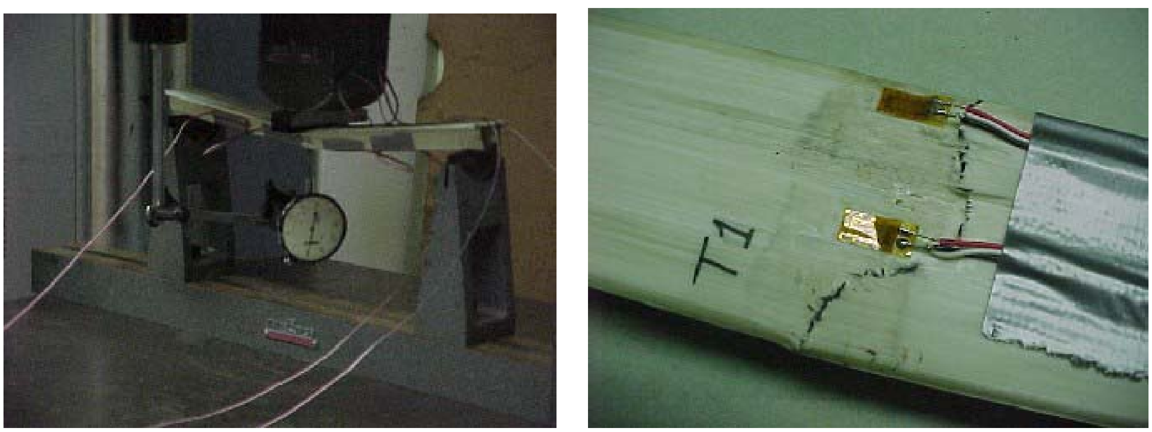


Figure 4.36 Trapezoidal Section Bending Test Set-up and Failure Mode

Figure 4.37 Wrapped Box Section Three and Four Point Bending Test Set-up

Figure 4.38 Virgin Vinylester Box Section Three Point Bending Test Set-up

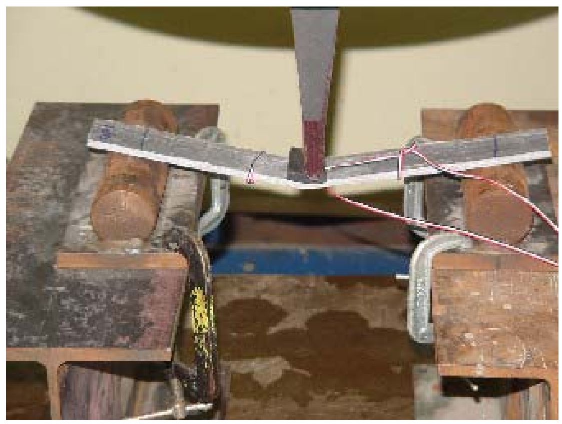


Figure 4.39 Recycled ABS Half Sheet Specimen Three Point Bending Test Set-up

4.4.2 Tension Test

4.4.2.1 Test Specimen

Strips cut from trapezoidal sections, ABS sheets, ABS belt-type specimens (flexible) and ABS box sections were tested under tension. For polypropylene samples from trapezoidal sections (Fig. 4.40), typical strip dimensions were 7" x ½" with variable thickness from 0.08" to 0.135" depending upon its location on the section from where it was extracted. For strips from ABS sheets (Fig 4.41), dimensions were 7" x ½" and thickness of 3/8". For strips from ABS belt-type specimens (flexible) (Fig 4.41 and 4.42), dimensions were 7" x ½" and thickness was around 0.01". For ABS box specimen, length was 42" and cross sectional dimensions were as shown in Fig. 4.3. Dimensions were selected based on ASTM D638-94b recommendation.

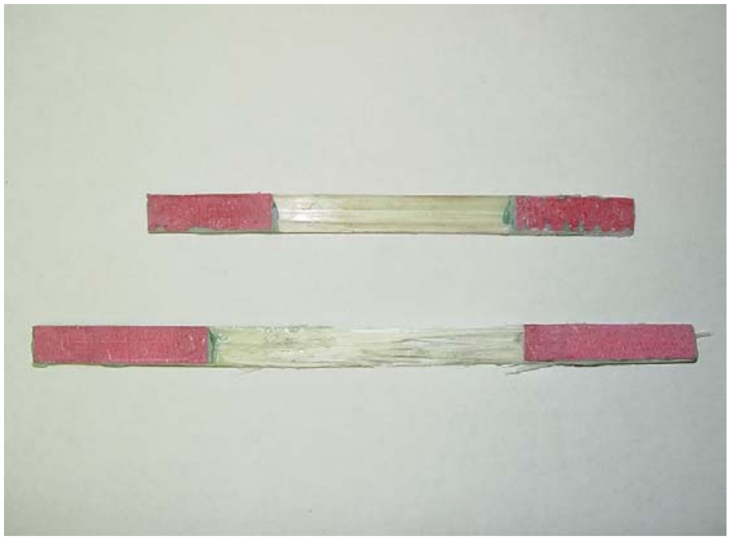


Figure 4.40 Polypropylene Strip Specimen from Trapezoidal Sections Used for Tension Tests (Before and After Testing)

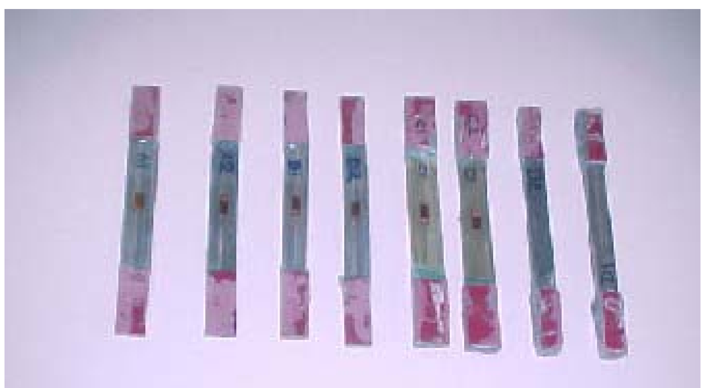


Figure 4.41 ABS Strip Tension Specimen from Belt Type (Flexible) Product and from Sheets (Last Two on the Right)

Figure 4.42 ABS Belt Type (Flexible) Product

4.4.2.2 Specimen Preparation

To prevent slipping of the specimen from the grips of testing machine and for effective force transfer during tension testing, plastic grips were attached to the specimens. Each of the grips was 2" long for strips and 12" long for box specimens. Details of grip preparation are as follows:

1) Grip length was lightly ground and grooves were cut on bonding area of both specimens and plastic tabs using a mechanical grinder or a file.
2) Tabs (grips) were bonded to specimens using Ashlands Plyogrip adhesive. The glue was applied and allowed to cure for at least 48 hours under pressure application by means of weights (for strips) or clamps (for box specimens).

In order to measure the tensile strains on each specimen, a series 2620 dynamic extensometer with a gage length of 1.00 inch was attached using rubber bands at the midsection as shown in Figure 3.3. Due to the flexibility of belt specimens, it was not possible to attach extensometer. Instead, strain gages were used to measure strains on these specimens. For box specimens, two strain gages were attached at midlength (Fig.

4.44), rectangular stiffeners were inserted at the grip length of the box section to prevent crushing of the hollow section.

4.4.2.3 Test Set-up and Procedure

Computer controlled Instron 8500 two-column load frame-testing machine was used to test the strip type specimens. Strain readings were taken with a strain indicator unit. "Wavemaker " software was utilized to carry out the tests. Specimens were loaded to failure or until deflections greater than one third of the span were attained at a constant rate of 0.25 in/min. Test set up for tensile strip specimens is shown in Figure 4.41

Figure 4.43 Strip Type Specimens Tension Test Set-up

Baldwin testing machine was used to test the box section (Figure 4.44). It was set to medium range loading mode of 0 to 50 kips. Test was carried to failure of the specimen at a constant rate of ≈0.25 in/min, load and strain readings were recorded using a data acquisition system.

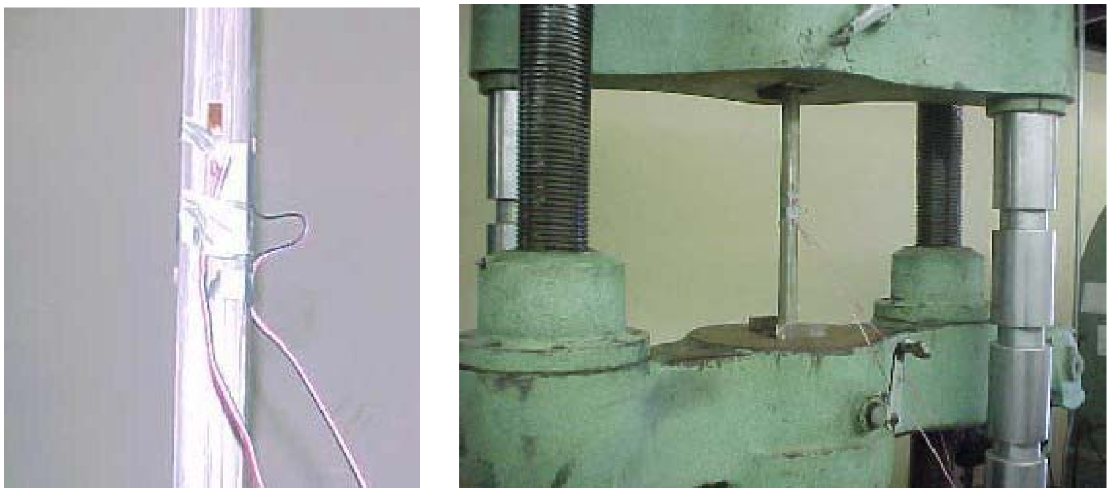


Figure 4.44 Box Specimen Tension Test Set-up

4.4.3 Compression Test

4.4.3.1 Test Specimen

Rectangular specimens cut from ABS sheets with cross section of 0.5" x 3/8" and height of 0.5" were used as per ASTM D695-91.

4.4.3.2 Specimen Preparation

No specimen preparation was necessary for these specimens.

4.4.3.3 Test Set-up and Procedure

Same Instron 8500 two-column load frame-testing machine was used. The set up is shown in Figures 3.7. Specimens were loaded to failure at a constant rate of 0.05 in/min.

4.4.4 Compression Test of Rubber-Wood Offset Block Model

4.4.4.1 Test Specimen

As discussed in section 4.3.2, this model consisted of rubber tires and wood. Dimensions of wooden blocks were 9½" x 6" with a thickness of 2", slots were 1" deep. Dimensions of rubber strips were approximately 8½" x 7" with an approx. thickness of ¾". Overall dimensions of the block were 9½" x 6" x 8¾"

4.4.4.2 Specimen Preparation

No specimen preparation was necessary for this test specimen.

4.4.4.3 Test Set-up and Procedure

Baldwin machine (UTM) was used to test the box section. Tests were carried out at an approximate deformation rate of 0.25 in/min. Load readings were manually recorded. The model was loaded until buckling of rubber strips and beyond. Test set-up is shown in Figure 4.45.

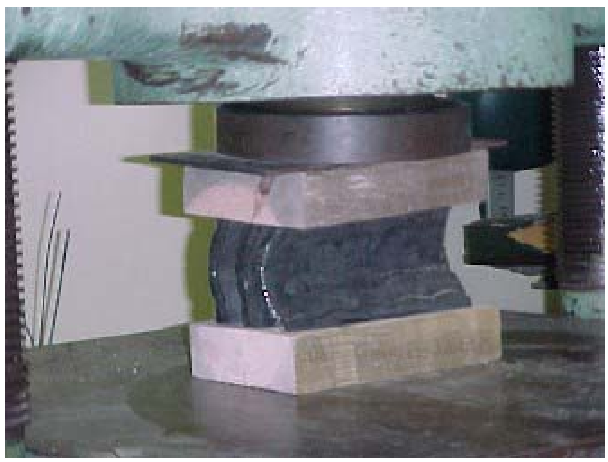


Figure 4.45 Compression Test on Rubber-Wood Offset Block Model

4.4.5 Tests on Wood from Rubber –Wood Block Model

In order to evaluate the strength of wooden blocks used for the rubber-wood model, compression tests parallel to grain and perpendicular to grain (as per ASTM D-143-94 procedures) and impact tests were performed on wooden specimens cut from actual prototype rubber -wood offset block.

4.4.5.1 Test Specimen

<u>Compression parallel to grain:</u> Blocks with a cross section of 2" x 2" and a length of 8", placed on the 2" x 2" section were tested as per ASTM D-143-94

Compression perpendicular to grain: Blocks with a cross section of 2" x 2" and a length of 6", placed on a 2" x 6" face were tested as per ASTM D-143-94

Impact test: Specimens with dimensions described on section 3.5.4.1 and Figure 3.9 were manufactured as shown in Figure 4.46 and tested using the BLI machine described on section 3.5.4.3. Objective of tests is to compare results to those obtained for recycled thermoplastic resins (ABS and PC).

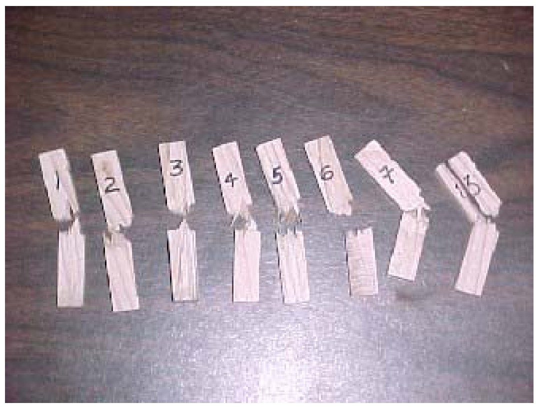


Figure 4.46 Tested Wooden Impact Specimens

4.4.5.2 Specimen Preparation

Strain gage was attached as described on section 4.4.1.2 on each of the compression specimens to measure strains in the direction of the compressive force that was applied on the specimens. Preparation was made following the procedures described on section 4.4.1.2.

Impact specimens were provided with V-notches as per ASTM D25-93a (Figure 3.9).

4.4.5.3 Test Set-up and Procedure

Compression parallel to grain: Initially, Instron 8500 two-column load frame-testing machine was used to conduct the compression as shown in Figure 4.47. The test was computer controlled with exception of strain readings. The strain readings were recorded by using a strain indicator unit. Specimens were loaded up to 16 kips, within the Instron's maximum loading capacity of 21 kips. Tests were continued in Baldwin machine until failure, at a rate of approximately 0.10 in/min.

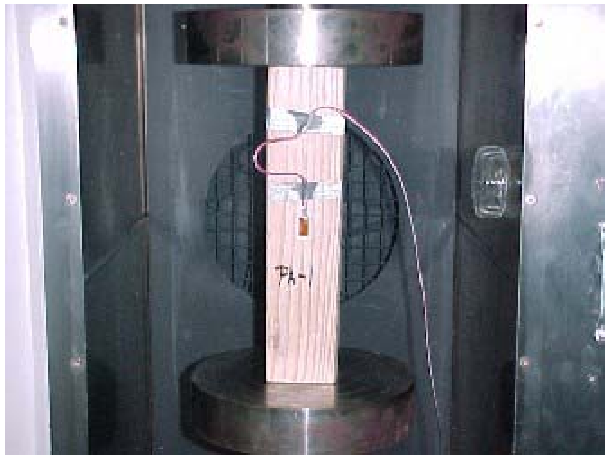


Figure 4.47 Compression Parallel to Grain Test Set-up

<u>Compression perpendicular to grain:</u> Instron 8500 two-column load frame-testing machine was used to conduct the compression test as shown in Figure 4.48. The test was computer controlled with the exception of strain readings. The strain readings were recorded using a strain indicator unit. Tests were loaded until failure, at a rate of approximately 0.10 in/min.

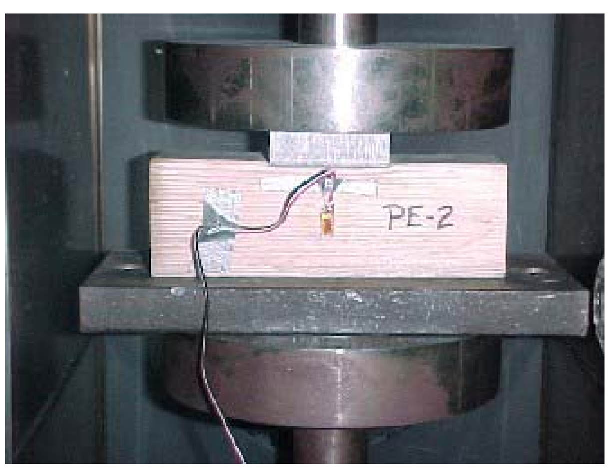


Figure 4.48 Compression Perpendicular to Grain Test Set-up

Impact test: test set-up and procedure was the same described in section 3.5.4.3

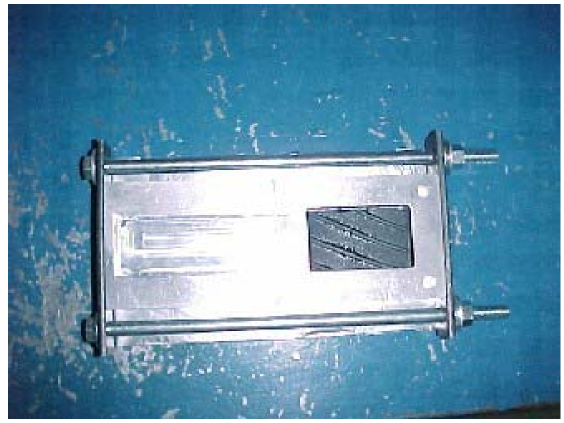
4.4.6 Bond Strength Test for Rubber- ABS Interface

While manufacturing the offset block for highway guardrail systems, we developed a compression molding process using ABS and rubber. In order to evaluate the bonding strength between rubber and molded ABS, pull out tests were performed. Additional details are given below.

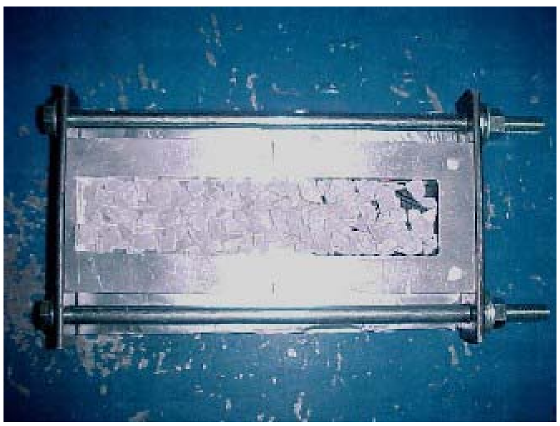
4.4.6.1 Test Specimen

An aluminum apparatus shown in Figure 4.49a was designed and constructed at CFC-WVU to facilitate molding of recycled thermoplastic pellets and samples required for testing. Specimens consisted of ABS molded strip 7" x 1½" and ¼" thick with a rubber block from discarded tires 2½" x 1½" and ½" thick. The mold consisted of a hollow space where the rubber block was placed during molding phase (Fig. 4.49b). A primer was coated on the rubber at the contact surface to improve bonding between ABS and rubber. Inner layer of pellets was first positioned in the hollow space (Fig. 4.49c) and a glass fabric was positioned over this layer (Fig. 4.49d). A final layer of pellets was piled over the fabric (Fig 4.49e). Top plate was placed over the pile of pellets and the specimen was compression molded under 20 Tons for 5 minutes, following the procedure described on section 4.3.1. The specimens are shown in Figure 4.49f and 4.50.

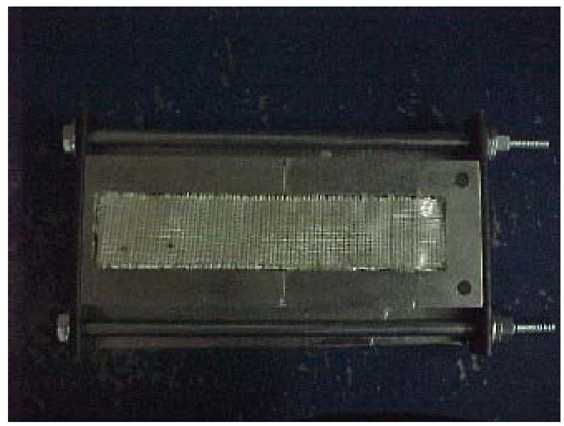
a) Mold and Materials



b) Positioning of Rubber Block Coated With Primer



c) Pellet Inner Layer



d) Glass Fabric on Inner Pellet Layer

e) Pellet Outer Pile

f) Molded Specimen in the Aluminum Apparatus

Figure 4.49 Compression Molding of Bond Specimen

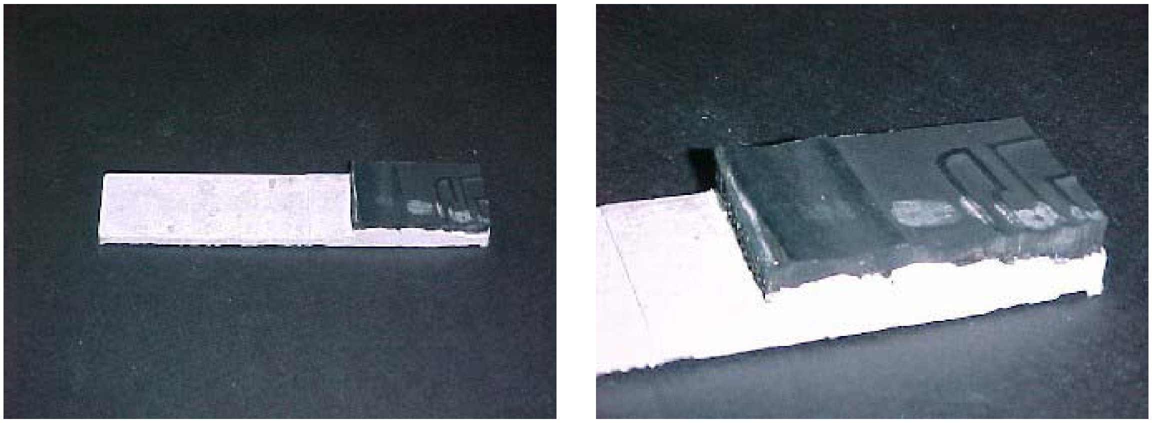


Figure 4.50 Rubber Tire-ABS Bond Specimen

4.4.6.2 Specimen Preparation

Excess resin from molding process on the ABS-rubber bond specimen was removed and edges were filed to prevent frictional resistance during pull out test. Inner walls of the mold were oiled to prevent undesired frictional resistance and the test sample was positioned in the mold (Fig. 4.51). The mold incidentally works as testing apparatus as well. Pulling grips were bolted on to the mold and attached with a hinged steel arm through a drilled hole on the ABS based specimen (Figure 4.51).

Figure 4.51 Bond Specimen Apparatus for Pull-out Test

4.4.6.3 Test Set-up and Procedure

Instron 8500 two-column load frame-testing machine was used to conduct the bond pull-out test as shown in Figure 4.52. The test was computer controlled, including gathering of load and displacement data. Specimens were loaded at a constant rate of 300 lb/min until bond resistance dropped down to near zero and rubber block had de bonded from ABS or considerably deformed in addition to debonding.

Figure 4.52 Bond Test Set-up

4.5 Conclusions

After trying different compression molding procedures and performing adequate modifications to the compression molding technique, an offset block for highway guardrails was successfully manufactured. Use of premolded tabs and preheat of offset block specimens prior to compression molding were necessary in order to obtain a satisfactory final product. Additional conclusions and recommendations are given in chapter 8.

CHAPTER 5

TEST RESULTS, ANALYSIS AND DISCUSSIONS ON CONDITIONED RECYCLED COUPONS

5.1 Introduction

As described in chapter 3, several static tests were performed on coupon specimens to determine their mechanical properties under tension, bending, compression, impact and hardness, for conditioned (aged) FRP specimens. In this section, test results are presented, discussed and compared to existing data from previous research (Bargo, 2000).

Characterization of aged coupon specimens will provide a better understanding about reduction in mechanical properties of the polymers due to environmental exposure. Based on the test results, it will be possible to determine knock down factors for tension, compression, bending, impact, and hardness that will be used for designing structural members.

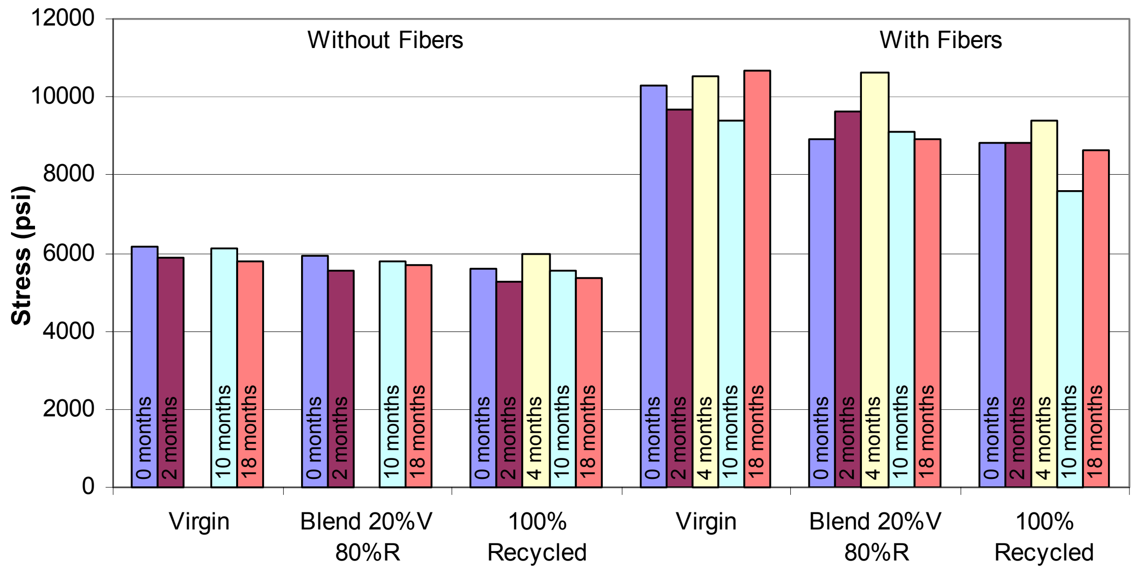
5.2 Tension Test

5.2.1 Results on ABS

Tables 5.1, 5.2, F.1, and F.2 show strength and stiffness results for ABS specimens under tension. Maximum tensile strength and stiffness are provided for each type of ABS and PC specimens (virgin, 100% recycled and virgin/recycled blend) and each aging period (2, 4, 10 and 18 months). Figures 5.1 and 5.2 show strength and stiffness variations, respectively, for different specimens and aging periods.

Table 5.1 Tensile Strength Variations in Aged ABS Specimens

Specimen Type	Max. Tensile Stress (psi)					% Change
	Months of aging					Maximum reduction in period
	0	2	4	10	18	
A1	6174	5866	-	6118	5809	-5.9
A2	10299	9683	10510	9410	10678	-8.6
A3	5578	5285	5988	5549	5360	-5.3
A4	8800	8802	9388	7602	8637	-13.6
A5	5916	5558	-	5790	5683	-6.1
A6	8911	9607	10619	9123	8916	No reduction
Average reduction without fibers (A1,A3,A5)						-5.7
Average reduction with fibers (A2,A4,A6)						-11.1

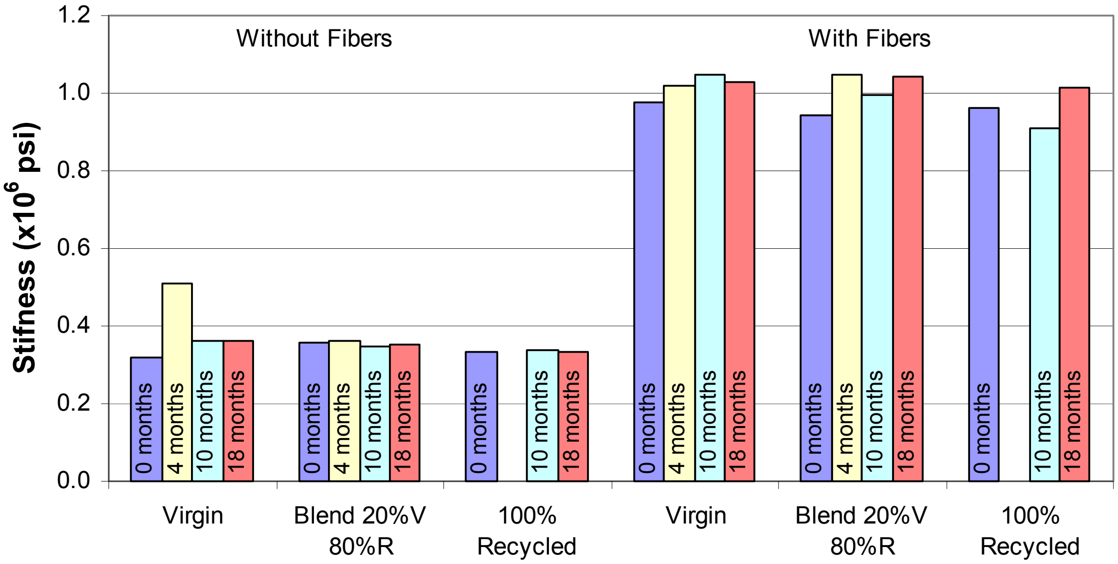


Note: Some intermittent results between 0 and 18 months may not be present due to no testing during that period

Figure 5.1 Tensile Strength in Aged ABS Specimens

Table 5.2 Tensile Stiffness Variations in Aged ABS Specimens

Specimen Type	Tensile Stiffness (psi x10^6)					% Change
	Months of aging					Maximum reduction in period
	0	2	4	10	18	
A1	0.321	-	0.510	0.360	0.362	No reduction
A2	0.976	-	1.019	1.047	1.027	No reduction
A3	0.333	-	-	0.337	0.331	-0.6
A4	0.964	-	-	0.909	1.012	-5.7
A5	0.359	-	0.360	0.347	0.351	-3.3
A6	0.941	-	1.050	0.993	1.041	No reduction
Average reduction without fibers (A1,A3,A5)						-2.0
Average reduction with fibers (A2,A4,A6)						-5.7



Note: Some intermittent results betw een 0 and 18 months may not be present due to no testing during that period

Figure 5.2 Tensile Stiffness in Aged ABS Specimens

5.2.2 Analysis and Discussion on ABS

Tables 5.1 and F.1 (in Appendix) show average reduction and average change in tensile strength for ABS samples.

Tensile Strength Variation in ABS at the End of the Aging Period:

- Reduction in tensile strength under conditioning varied from 3.9% to 5.9% for specimens without fibers and 1.9% to zero for specimens with fibers.
- Strength gain of 3.7% was observed in fiber reinforced specimen A2 having virgin resin.
- Average reduction in tensile strength after 18 months of conditioning for samples without fibers was 4.6% as compared to 1.9% in samples with fibers.

Tensile Strength Variation in ABS During the Aging Period:

- Maximum reductions were observed to range from 5.3% and 6.1% for specimens without fibers and 8.6 to 13.6% for specimens with fibers.

- Specimen A3, blend of recycled and virgin resins, was the only unreinforced specimen that showed a gain in strength with a maximum of 7.4% at 4 months of aging.
- Reinforced specimens showed gains ranging from 3.7% to 19.2%. Average reduction during the aging period was 5.7% for specimens without fibers as compared to 11.1% for specimens with fibers.

Tables 5.2 and F.2 show the average reduction and average change in tensile stiffness for ABS samples.

Tensile Stiffness Variation in ABS at the End of the Aging Period:

- Reduction in tensile stiffness under conditioning varied from 0.6% to 2.2% for specimens without fibers and no reductions were observed for specimens with fibers.
- Stiffness gain of 12.8% was observed for unreinforced specimen A1 with virgin resin, whereas reinforced specimens showed gain of 5.0% to 10.6%.
- After 18 months of conditioning, samples without fibers indicated a reduction of 1.4% and no reduction in specimens with fibers.

Tensile Stiffness Variation in ABS During the Aging Period:

- Reductions ranging from 0.6% to 3.3% for specimens without fibers, and 5.7% to zero for specimens with fibers were observed.
- Specimens without fibers showed a gain ranging from 0.3% to 58.9%. Reinforced specimens showed maximum gain from 5.0% to 11.6%.
- Average reduction during the aging period was 2.0% for specimens without fibers as compared to 5.7% for specimens with fibers.

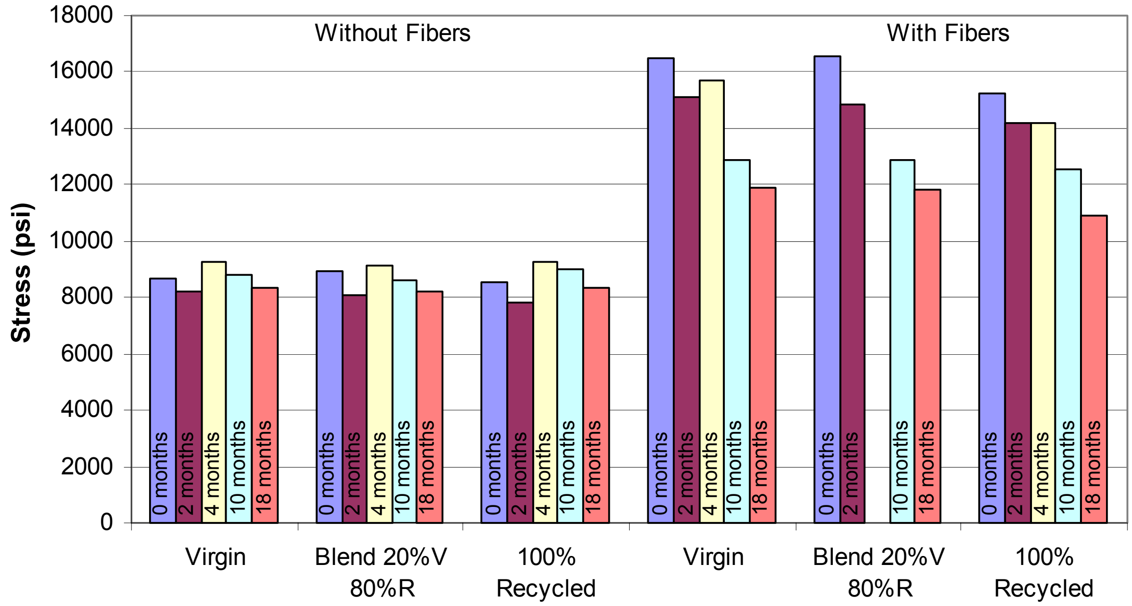
Gains observed in some of the specimens may be possibly due to secondary curing effects and improvement in force transfer across the resin/fiber interface. Additional comparisons to other mechanical properties are discussed in chapter 7.

5.2.3 Results on PC

Tables 5.3, 5.4, F.3, and F.4 show tensile strength and stiffness results for PC specimens. Maximum tensile strength and stiffness are provided for each type of specimen and each aging period. Figures 5.3 and 5.4 show maximum strength and stiffness, respectively, for each of the specimen types and aging periods..

Table 5.3 Tensile Strength Variations in Aged PC Specimens

Specimen Type	Max. Tensile Stress (psi)					% Change
	Months of aging					Maximum reduction in period
	0	2	4	10	18	
P1	8664	8210	9261	8817	8352	-5.2
P2	16479	15101	15721	12867	11892	-27.8
P3	8566	7813	9233	8983	8329	-8.8
P4	15213	14203	14205	12525	10920	-28.2
P5	8926	8072	9163	8589	8185	-9.6
P6	16555	14831	-	12877	11848	-28.4
Average reduction without fibers (A1,A3,A5)						-7.9
Average reduction with fibers (A2,A4,A6)						-28.2

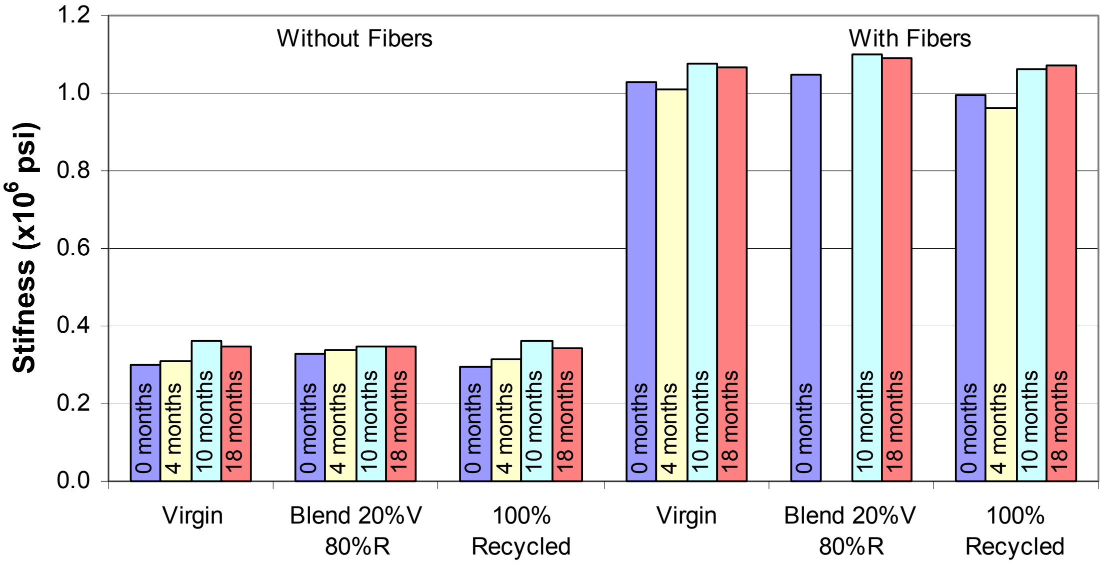


Note: Some intermittent results between 0 and 18 months may not be present due to no testing during that period

Figure 5.3 Tensile Strength in Aged PC Specimens

Table 5.4 Tensile Stiffness Variations in Aged PC Specimens

Specimen Type	**Tension Stiffness (psi x10^6)**					**% Change**
	Months of aging					**Maximum reduction in period**
	0	**2**	**4**	**10**	**18**	
P1	0.300	-	0.309	0.364	0.350	No reduction
P2	1.029	-	1.008	1.076	1.068	-2.0
P3	0.293	-	0.315	0.364	0.343	No reduction
P4	0.993	-	0.964	1.061	1.073	-2.9
P5	0.329	-	0.337	0.347	0.349	No reduction
P6	1.046	-	-	1.099	1.091	No reduction
Average reduction without fibers (A1,A3,A5)						No reduction
Average reduction with fibers (A2,A4,A6)						-2.5



Note: Some intermittent results between 0 and 18 months may not be present due to no testing during that period

Figure 5.4 Tensile Stiffness in Aged PC Specimens

5.2.4 Analysis and Discussion on PC

Tables 5.3 and F.3 (Appendix) show the change in tensile strength for PC specimens.

Tensile Strength Variation in PC at the End of the Aging Period

- Reduction in tensile strength under conditioning varied from 2.8% to 8.3% for specimens without fibers and 27.8% to 28.4% for specimens with fibers.
- Average reduction in tensile strength after 18 months of conditioning for samples without fibers was 4.9% as compared to 28.2% in samples with fibers.

Tensile Strength Variation in PC During the Aging Period

- Maximum tensile strength reductions between 5.2% and 9.6% for specimens without fibers and 27.8% to 28.4% for specimens with fibers were observed.
- Specimens without fibers showed maximum strength gains ranging from 2.7% to 7.8%. No gain was observed for specimens without fibers.
- Maximum reduction due to aging was 7.9% for specimens without fibers as compared to 28.2% for specimens with fibers.

Tables 5.4 and F.4 show the average reduction in tensile stiffness for PC samples.

Tensile Stiffness Variation in PC at the End of the Aging Period

No reduction was noted in tensile stiffness under conditioned state for specimens without fibers or even for specimens with fibers.

Tensile Stiffness Variation in PC During the Aging Period

- No stiffness reductions for specimens without fibers were observed, whereas specimens with fibers showed maximum reductions of 2.0% to 2.9%.
- Specimens without fibers showed maximum gain of 6.1% to 24.2% and specimens with fibers showed maximum gain of 4.6% to 8.1%
- Maximum reduction during the aging period was 2.5% for specimens with fibers.

Gains observed in some of the specimens may be possibly due to secondary curing effects and improvement in force transfer across the resin/fiber interface.

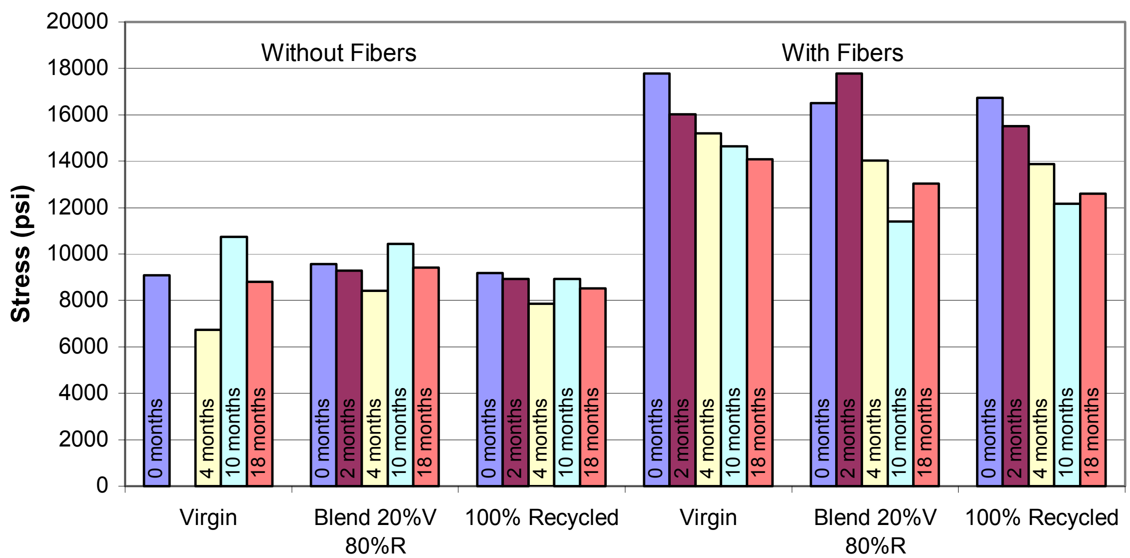
5.3 Bending Test

5.3.1 Results on ABS

Tables 5.5, 5.6, F.5, and F.6 show strength and stiffness results for aged ABS specimens under bending. Maximum bending strength and stiffness values are provided for each type of specimen and each aging period. Figures 5.5 and 5.6 show maximum strength and stiffness, respectively, for each of the specimen types and aging periods.

Table 5.5 Bending Strength Variations in Aged ABS Specimens

Specimen Type	Max. Bending Stress (psi)					% Change
	Months of aging					Maximum reduction in period
	0	2	4	10	18	
A1	9080	-	6728	10747	8971	-25.9
A2	17771	16033	15211	14631	14080	-20.8
A3	9187	8931	7862	8923	8511	-14.4
A4	16740	15522	13886	12162	12605	-27.3
A5	9558	9295	8412	10446	9419	-12.0
A6	16509	17793	14043	11400	13034	-30.9
Average reduction without fibers (A1,A3,A5)						-17.4
Average reduction with fibers (A2,A4,A6)						-26.4

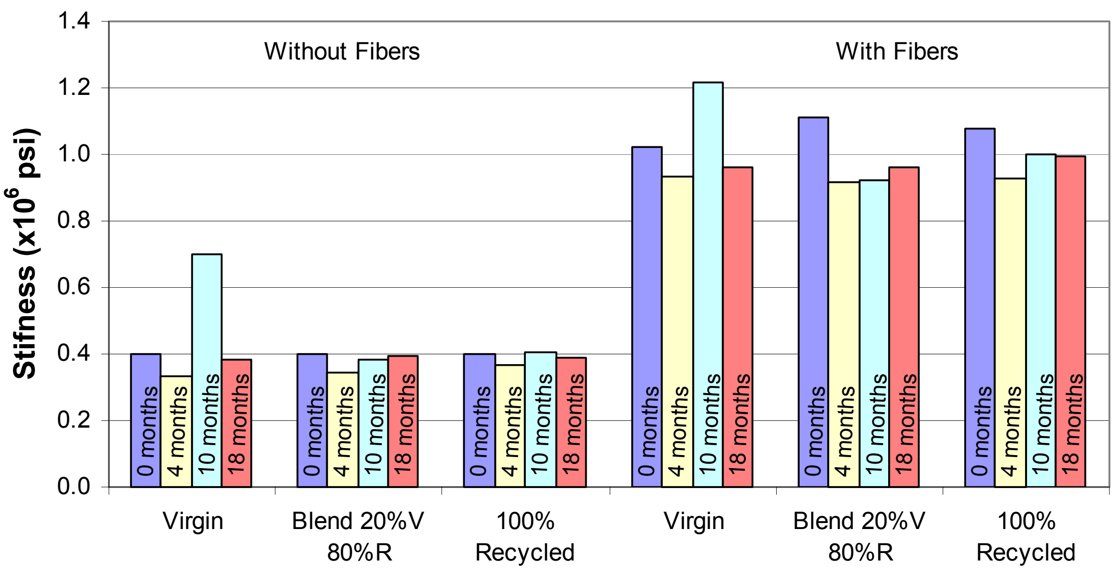


Note: Some intermittent results between 0 and 18 months may not be present due to no testing during that period

Figure 5.5 Bending Strength in Aged ABS Specimens

Table 5.6 Bending Stiffness Variations in Aged ABS Specimens

Specimen Type	Bending Stiffness (psi x10^6)					% Change
	Months of aging					Max red. in period
	0	2	4	10	18	
A1	0.40	-	0.334	0.699	0.381	-16.5
A2	1.02	-	0.932	1.215	0.960	-8.6
A3	0.40	-	0.364	0.408	0.391	-9.0
A4	1.08	-	0.930	0.998	0.996	-13.9
A5	0.40	-	0.346	0.385	0.395	-13.5
A6	1.11	-	0.917	0.925	0.962	-17.4
Average reduction without fibers (A1,A3,A5)						-13.0
Average reduction with fibers (A2,A4,A6)						-13.3



Note: Some intermittent results betw een 0 and 18 months may not be present due to no testing during that period

Figure 5.6 Bending Stiffness in Aged ABS Specimens

5.3.2 Analysis and Discussion on ABS

Tables 5.5 and F.5 shows the average reduction in bending strength for ABS samples.

Bending Strength Variation in ABS at the End of the Aging Period:

- Reduction in bending strength under conditioning varied from 1.5% to 7.4% for specimens without fibers and 20.8% to 24.7% for specimens with fibers.
- Average reduction in bending strength after 18 months of conditioning for specimens without fibers was 4.0% as compared to 22.2% for samples with fibers.

Bending Strength Variation in ABS During the Aging Period:

- Maximum reductions were noted between 12.0% and 25.9% for specimens without fibers and 20.8% to 30.9% for specimens with fibers.
- Specimens without fibers showed maximum gains of 9.3% to 18.4%.
- Average maximum reduction during the aging period was 17.4% for specimens without fibers as compared to 26.4% for specimens with fibers.

Tables 5.6 and F.6 show the average reduction in bending stiffness for ABS samples.

Bending Stiffness Variation in ABS at the End of the Aging Period:

- Reduction in bending stiffness is noted under conditioning which varied from 1.3% to 4.8% for specimens without fibers while the reductions were raging from 5.9% to 13.3% for specimens with fibers.
- Average reduction in bending stiffness after 18 months of conditioning for samples without fibers was 2.8% as compared to 9.0% for specimens with fibers.

Bending Stiffness Variation in ABS During the Aging Period:

- Maximum stiffness reductions were noted between 9.0% and 16.5% for specimens without fibers and 8.6% to 17.4% for specimens with fibers.
- Specimens without fibers showed maximum stiffness gains of 2% to 74%. Such high variation might be attributed to randomly oriented fibers in the specimens and possible manufacturing imperfections.
- Specimen A2 having virgin resin, was the only specimen with fibers that showed any gain, with a maximum of 19.1%.
- Average maximum reduction during the aging period was 13.0% for specimens without fibers as compared to 13.3% for specimens with fibers.

Gains observed in some of the specimens may be possibly due to secondary curing effects and improvement in force transfer across the resin/fiber interface. Additional comparisons to other mechanical properties are discussed in chapter 7.

5.3.3 Results on PC

Tables 5.7, 5.8, F.7, and F.8 show strength and stiffness results for PC specimens tested. Maximum bending strength and stiffness are provided for each type of specimen and each aging period. Figures 5.7 and 5.8 show maximum strength and stiffness for each of the specimen types and aging periods, respectively.

Table 5.7 Bending Strength Variations in Aged PC Specimens

Specimen Type	Max. Bending Stress (psi)					% Change
	Months of aging					Maximum reduction in period
	0	2	4	10	18	
P1	10242	7494	9283	14945	12506	-26.8
P2	24566	20228	21336	25370	19908	-19.0
P3	10363	8235	8398	17327	12117	-20.5
P4	23198	18830	17117	28586	19798	-26.2
P5	11168	10136	10602	15023	12366	-9.2
P6	24886	19606	21159	23909	20441	-21.2
Average reduction without fibers (A1,A3,A5)						-18.9
Average reduction with fibers (A2,A4,A6)						-22.1

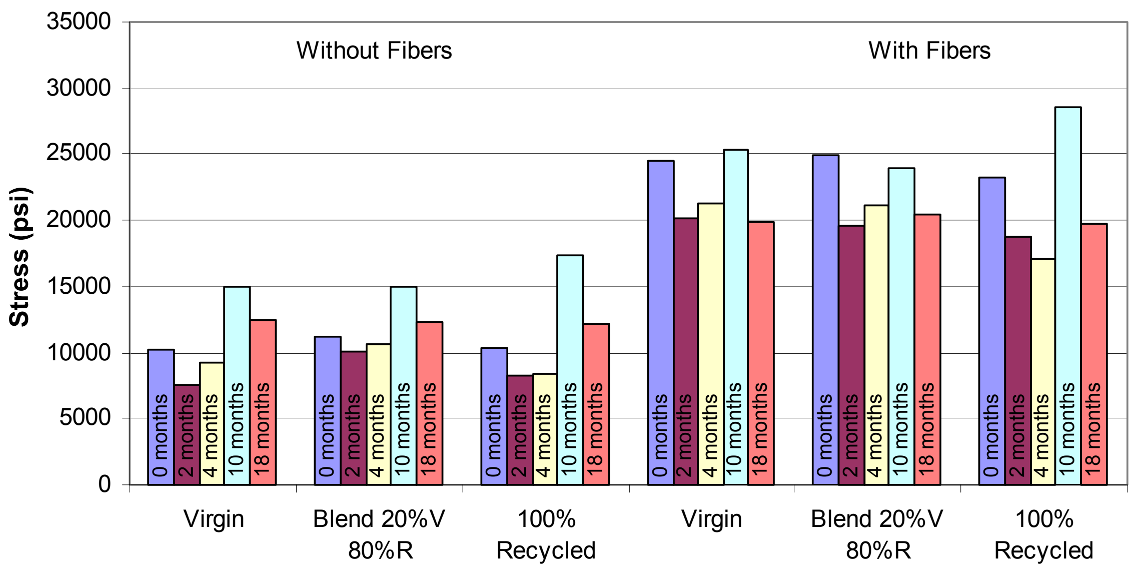


Figure 5.7 Bending Strength in Aged PC Specimens

Table 5.8 Bending Stiffness Variations in Aged PC Specimens

Specimen Type	Bending Stiffness (psi x10^6)					% Change
	Months of aging					Maximum reduction in period
	0	2	4	10	18	
P1	0.332	-	0.341	0.416	0.408	No reduction
P2	0.967	-	1.001	1.089	1.031	No reduction
P3	0.291	-	0.354	0.445	0.450	No reduction
P4	0.916	-	0.994	1.001	1.037	No reduction
P5	0.327	-	0.406	0.452	0.430	No reduction
P6	0.993	-	1.062	1.168	1.027	No reduction
Average reduction without fibers (A1,A3,A5)						No reduction
Average reduction with fibers (A2,A4,A6)						No reduction

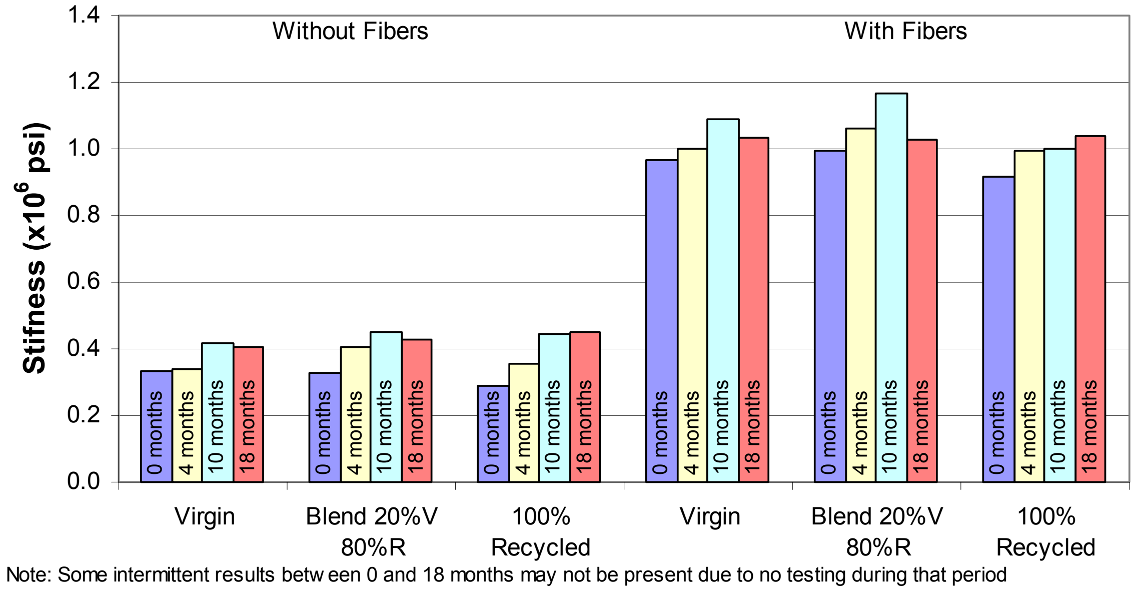


Figure 5.8 Bending Stiffness in Aged PC Specimens

5.3.4 Analysis and Discussion on PC

Table 5.7and F.7 shows the average reduction in bending strength for PC samples.

Bending Strength Variation in PC at the End of the Aging Period:

- No reduction in bending strength was noted under conditioning for specimens without fibers, whereas 14.7% to 19.0% reduction was obtained for specimens with fibers.
- Average reduction of 17.2% was noted in bending strength after 18 months of conditioning for samples with fibers.

Bending Strength Variation in PC During the Aging Period:

- Maximum bending strength reductions ranging between 9.2% and 26.8% were observed for specimens without fibers and 19.0% to 26.2% for specimens with fibers.

- Specimens without fibers showed maximum gains of 34.5% to 67.2%, whereas specimens with fibers showed maximum gains of 3.3% to 23.2%.
- Maximum average bending strength reduction during the aging period was 18.9% for specimens without fibers as compared to 22.1% for specimens with fibers.

Tables 5.8 and F.7 show the average reduction in bending stiffness for PC samples.

Bending Stiffness Variation in PC at the End of the Aging Period:

- No reductions in bending stiffness were observed under conditioning for specimens both without and with fibers.
- Stiffness gain ranging between 22.9% to 54.6% was observed for specimens without fibers and 3.4% to 13.2% for specimens with fibers.

Bending Stiffness Variation in PC During the Aging Period:

No reductions in bending stiffness were observed during the entire period of aging, whereas gains of 25.3% to 54.6% was observed for specimens without fibers and 12.6% to 17.6% for specimens with fibers.

Gains observed in some of the specimens may be possibly due to secondary curing effects and improvement in force transfer across the resin/fiber interface. However, it should be noted that the bending strength gains after 10 months of conditioning are high and the tests may have to be repeated to ascertain such high gains

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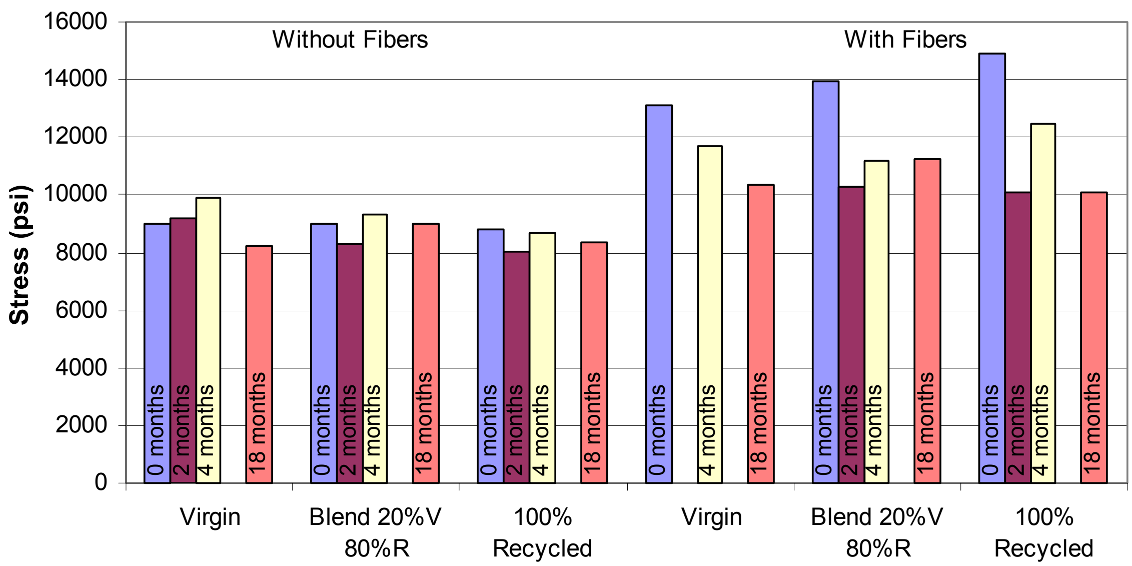
5.4 Compression Test

5.4.1 Results on ABS

Tables 5.9, 5.10, F.9, and F.10 show strength and stiffness results for ABS specimens tested. Maximum compressive strength and stiffness are provided for each type of specimen and each aging period. Figures 5.9 and 5.10 show maximum strength and stiffness for each of the specimen types and aging periods, respectively.

Table 5.9 Compressive Strength Variations in Aged ABS Specimens

Specimen Type	Max. Compressive Stress (psi)					% Change
	Months of aging					Maximum reduction in period
	0	2	4	10	18	
A1	8966	9208	9886	-	8244	-8.1
A2	13135	-	11698	-	10376	-21.0
A3	8792	8027	8670	-	8381	-8.7
A4	14891	10061	12440	-	10120	-32.4
A5	8972	8318	9287	-	9011	-7.3
A6	13920	10308	11151	-	11265	-25.9
Average reduction without fibers (A1,A3,A5)						-8.0
Average reduction with fibers (A2,A4,A6)						-26.5

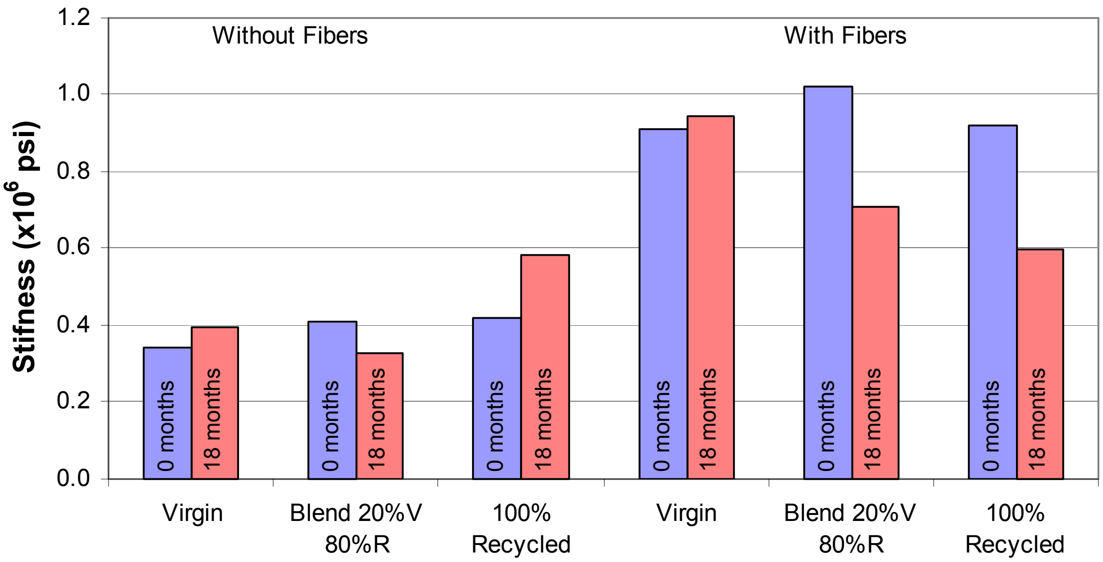


Note: Some intermittent results betw een 0 and 18 months may not be present due to no testing during that period

Figure 5.9 Compressive Strength in Aged ABS Specimens

Table 5.10 Compressive Stiffness Variations in Aged ABS Specimens

Specimen Type	Compressive Stiffness (psi)					% Change
	Months of aging					Maximum reduction in period
	0	2	4	10	18	
A1	0.34	-	-	-	0.397	No reduction
A2	0.91	-	-	-	0.943	No reduction
A3	0.42	-	-	-	0.583	No reduction
A4	0.92	-	-	-	0.600	-34.8
A5	0.41	-	-	-	0.330	-19.5
A6	1.02	-	-	-	0.709	-30.5
Average reduction without fibers (A1,A3,A5)						-19.5
Average reduction with fibers (A2,A4,A6)						-32.6



Note: Some intermittent results betw een 0 and 18 months may not be present due to no testing during that period

Figure 5.10 Compressive Stiffness in Aged ABS Specimens

5.4.2 Analysis and Discussion on ABS

Tables 5.9 and F.9 show average reduction in compressive strength for ABS samples.

Compressive Strength Variation in ABS at the End of the Aging Period:

- Reduction in compressive strength under conditioning varied from 4.7% to 8.1% for specimens without fibers and 19.1% to 32.0% for specimens with fibers.
- Average reduction in compressive strength after 18 months of conditioning for samples without fibers was 6.4% as compared to 24.0% in samples with fibers.

Compressive Strength Variation in ABS During the Aging Period:

- Maximum reductions were noted to range from 7.3% to 8.7% for specimens without fibers and 21.0% to 32.4% for specimens with fibers.
- Specimens without fibers showed maximum gains of 3.5% to 10.3%, whereas no gain was observed for specimens with fibers.
- Maximum average reduction during the aging period was 8.0% for specimens without fibers as compared to 26.5% for specimens with fibers.

Tables 5.10 and F.10 show the average reduction in compressive stiffness for ABS samples.

Compressive Stiffness Variation in ABS at the End of the Aging Period:

- Reduction in compressive stiffness under conditioning varied from 19.8% to zero for specimens without fibers whereas reductions of 30.5% to 34.8% were observed for specimens with fibers.

- Average reduction in bending stiffness after 18 months of conditioning of specimens without fibers was 19.8% as compared to 32.6% for specimens with fibers.
- Average gain in maximum compressive stiffness observed for specimens without fibers was 27.8% and 3.6% for specimens with fibers.

Gains observed in some of the specimens may be possibly due to secondary curing effects and improvement in force transfer across the resin/fiber interface.

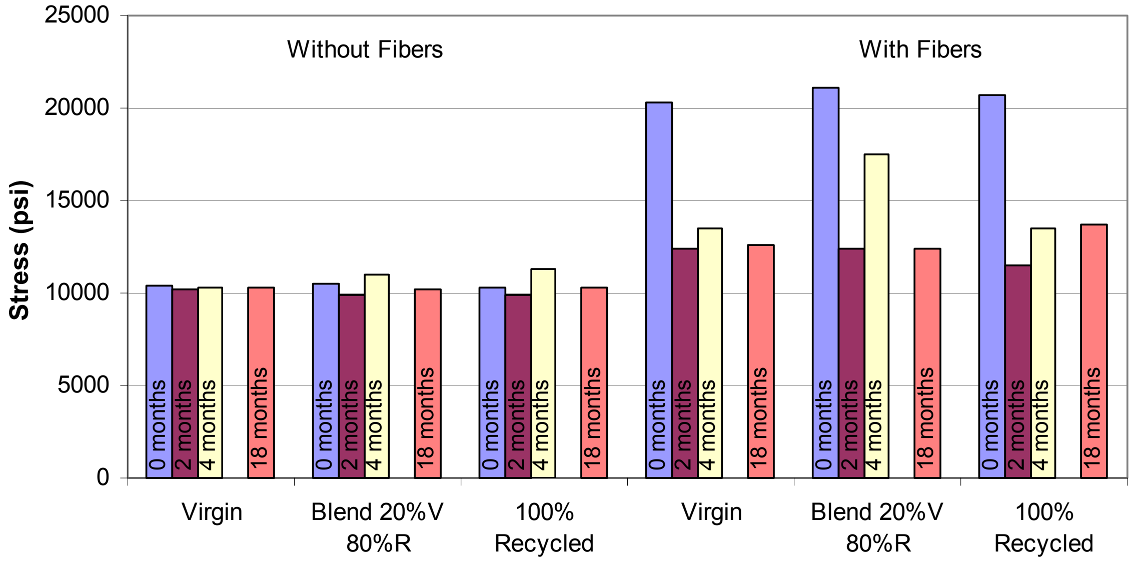
It should be noted that the compressive strength was not measured after 10 months of conditioning and tests may have to be conducted to obtain further results.

5.4.3 Results on PC

Tables 5.11, 5.12, F.11, and F.12 show strength and stiffness results for PC specimens. Maximum compressive strength and stiffness are provided for each type of specimen and aging period. Figures 5.11 and 5.12 show maximum strength and stiffness, respectively, for different specimen types and aging period.

Table 5.11 Compressive Strength Variations in Aged PC Specimens

Specimen Type	Max. Compressive Stress (psi)					% Change
	Months of aging					Maximum reduction in period
	0	2	4	10	18	
P1	10423	10234	10259	-	10344	-1.8
P2	20332	12408	13539	-	12587	-39.0
P3	10311	9894	11348	-	10296	-4.0
P4	20747	11463	13509	-	13749	-44.7
P5	10523	9931	10979	-	10221	-5.6
P6	21124	12412	17500	-	12422	-41.2
Average reduction without fibers (A1,A3,A5)						-3.8
Average reduction with fibers (A2,A4,A6)						-41.7



Note: Some intermittent results between 0 and 18 months may not be present due to no testing during that period

Figure 5.11 Compressive Strength in Aged PC Specimens

Table 5.12 Compressive Stiffness Variations in Aged PC Specimens

Specimen Type	Compressive Stiffness (psi)					% Change
	Months of aging					Maximum reduction in period
	0	2	4	10	18	
P1	0.21	-	0.283	-	0.320	No reduction
P2	0.41	-	0.481	-	0.511	No reduction
P3	0.20	-	0.302	-	0.344	No reduction
P4	0.43	-	0.463	-	0.494	No reduction
P5	0.21	-	0.355	-	-	No reduction
P6	0.43	-	0.481	-	0.477	No reduction
Average reduction without fibers (A1,A3,A5)						No reduction
Average reduction with fibers (A2,A4,A6)						No reduction

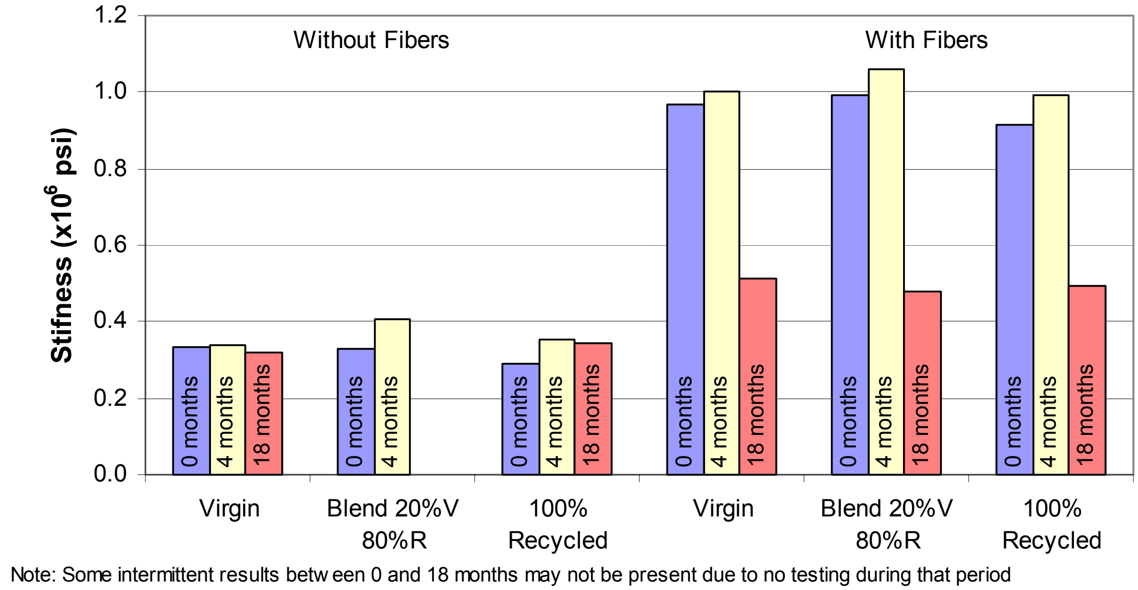


Figure 5.12 Compressive Stiffness in Aged PC Specimens

5.4.4 Analysis and Discussion on PC

Tables 5.11 and F.11 show the average reduction in compressive strength for PC specimens.

Compressive Strength Variation in PC at the End of the Aging Period:

- Reduction in compressive strength under conditioning varied from 0.1% to 2.9% for specimens without fibers and 33.7% to 41.2% for specimens with fibers.
- Average reduction in compressive strength after 18 months of conditioning for specimens without fibers was 1.3% as compared to 37.7% in specimens with fibers.

Compressive Strength Variation in ABS During the Aging Period:

- Maximum reductions were noted to be between 1.8% and 5.6% for specimens without fibers and 39.0% to 44.7% for specimens with fibers.

- Specimens without fibers showed maximum gains of 4.3% to 10.1% whereas no gain was observed for specimens with fibers.
- Average maximum reduction during the aging period was 3.8% for specimens without fibers as compared to 41.7% for specimens with fibers.

Tables 5.12, F.12 show average reduction and average change in compressive stiffness for PC samples.

Compressive Stiffness Variation in PC at the End of the Aging Period:

- No reduction in compressive stiffness under conditioned state was observed for specimens without fibers or specimens with fibers.
- Compressive stiffness gains of 52.4% to 72.0% were observed for specimens without fibers and 10.9% to 24.6% for specimens with fibers.

Compressive Stiffness Variation in PC During the Aging Period:

No reductions in bending stiffness were observed. Stiffness gain ranging from 52.4% to 72.0% was noted for specimens without fibers as compared to 11.9% to 24.6% for specimens with fibers.

Gains observed in some of the specimens may be possibly due to secondary curing effects and improvement in force transfer across the resin/fiber interface.

It should be noted that the compressive stiffness was not measured after 10 months of conditioning and tests may have to be conducted to obtain further results.

5.5 Impact Test

5.5.1 Results on ABS

Tables 5.13 and 5.14 show impact strength results for aged ABS specimens. Impact strength is provided for each type of specimen and aging period. Figure 5.13 shows impact strength variation for each of the specimen types under aging.

Table 5.13 Impact Strength Variations in ABS Specimens

Specimen Type	Impact Strength (ft-lbs$_f$)					% Change
	Months of aging					Maximum reduction in period
	0	2	4	10	18	
A1	3.49	3.67	3.76	3.44	3.41	-2.3
A2	1.58	1.31	1.40	1.32	1.24	-21.5
A3	2.17	1.91	1.24	0.83	0.87	-61.6
A4	0.96	0.90	0.83	0.75	0.75	-21.7
A5	2.38	2.86	2.54	1.77	1.46	-38.8
A6	1.20	1.04	1.08	1.00	0.87	-27.2
Average reduction without fibers (A1,A3,A5)						-34.2
Average reduction with fibers (A2,A4,A6)						-23.5

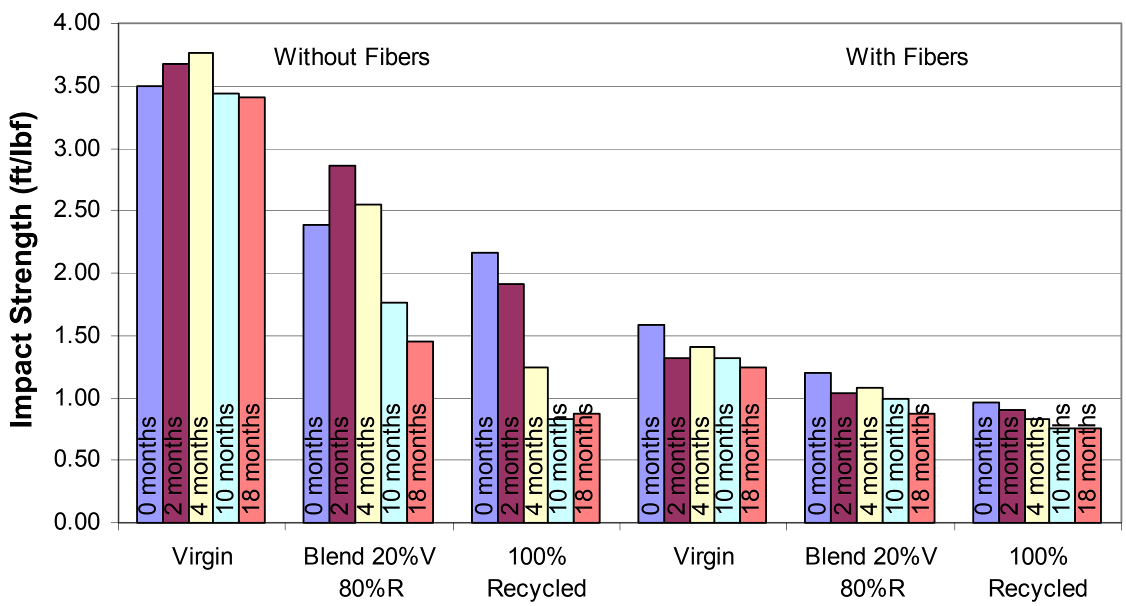


Figure 5.13 Impact Strength in Aged ABS Specimens

5.5.2 Analysis and Discussion on ABS

Tables 5.13 and F.13 show the average reduction in impact strength for ABS specimens.

Impact Strength Variation in ABS at the End of the Aging Period:

- Reduction in impact strength under conditioning varied from 2.3% to 59.7% for specimens without fibers and 21.5% to 21.7% for specimens with fibers.
- Average reduction in impact strength after 18 months of conditioning for specimens without fibers was 33.6% as compared to 23.5% for specimens with fibers.

Impact Strength Variation in ABS During the Aging Period:

- Maximum reductions were noted to be ranging from 2.3% to 61.6% for specimens without fibers, and 21.5% to 27.2% for specimens with fibers.
- Specimens without fibers showed maximum gains of 7.8% to 20.3%, whereas no gain was observed for specimens with fibers.
- Average maximum reduction during the aging period was 34.2% for specimens without fibers as compared to 23.5% for specimens with fibers.

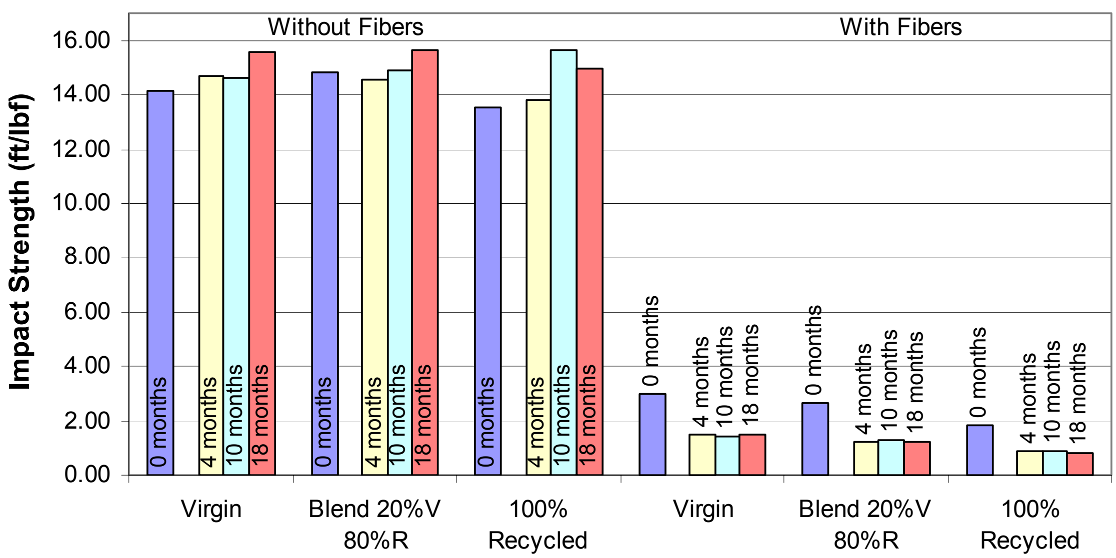
Gains observed in some of the specimens may be possibly due to secondary curing effects and improvement in force transfer across the resin/fiber interface.

5.5.3 Results on PC

Tables 5.14 and F.14 show impact strength results for aged PC specimens. Impact strength is provided for each type of specimen and each aging period. Figure 5.14 shows impact strength for aged PC specimens.

Table 5.14 Impact Strength Variations in Aged PC Specimens

Specimen Type	Impact Strength ($ft\text{-}lbs_f$)					% Change
	Months of aging					Maximum reduction in period
	0	2	4	10	18	
P1	14.15	-	14.67	14.59	15.56	No reduction
P2	3.01	-	1.48	1.40	1.48	-53.4
P3	13.53	-	13.77	15.65	14.99	No reduction
P4	1.81	-	0.91	0.91	0.79	-56.2
P5	14.80	-	14.58	14.91	15.65	-1.5
P6	2.67	-	1.24	1.32	1.20	-55.1
Average reduction without fibers (A1,A3,A5)						-1.5
Average reduction with fibers (A2,A4,A6)						-54.9



Note: Some intermittent results between 0 and 18 months may not be present due to no testing during that period

Figure 5.14 Impact Strength in Aged PC Specimens

5.5.4 Analysis and Discussion on PC

Tables 5.14 and F.14 show the average reduction in impact strength for PC samples.

Impact Strength Variation in PC at the End of the Aging Period:

- No reduction in impact strength under conditioning was observed for specimens without fibers and a reduction of 50.7% to 56.2% was noted for specimens with fibers.
- Average reduction in impact strength was 54.0% after 18 months of conditioning for samples with fibers.

Impact Strength Variation in PC During the Aging Period:

- Maximum reductions were noted to be ranging from 1.5% to zero for specimens without fibers and 53.4% to 56.2% for specimens with fibers.
- Specimens without fibers showed maximum gains of 5.7% to 15.6% whereas no gain was observed for specimens with fibers.
- Maximum average reduction after aging was 1.5% for specimens without fibers as compared to 54.9% for specimens with fibers.

Gains observed in some of the specimens may be possibly due to secondary curing effects and improvement in force transfer across the resin/fiber interface.

5.6 Hardness Test

5.6.1 Results on ABS

Tables 5.15 and F.15 show hardness test data for ABS specimens. Hardness index is provided for each type of specimen and each aging period. Figure 5.15 shows hardness index for each of the specimen types and aging periods, respectively.

Table 5.15 Hardness Index Variations in Aged ABS Specimens

Specimen Type	Hardness Index					% Change
	Months of aging					Maximum reduction in period
	0	2	4	10	18	
A1	10.90	12.44	11.70	12.10	12.00	No reduction.
A2	11.30	12.80	11.50	11.00	10.90	-3.5
A3	11.10	12.58	11.40	11.10	11.00	-0.9
A4	11.20	11.76	11.30	10.80	10.60	-5.4
A5	11.20	12.44	10.80	11.10	10.90	-3.6
A6	11.20	12.16	11.00	10.90	10.80	-3.6
Average reduction without fibers (A1,A3,A5)						-2.2
Average reduction with fibers (A2,A4,A6)						-4.2

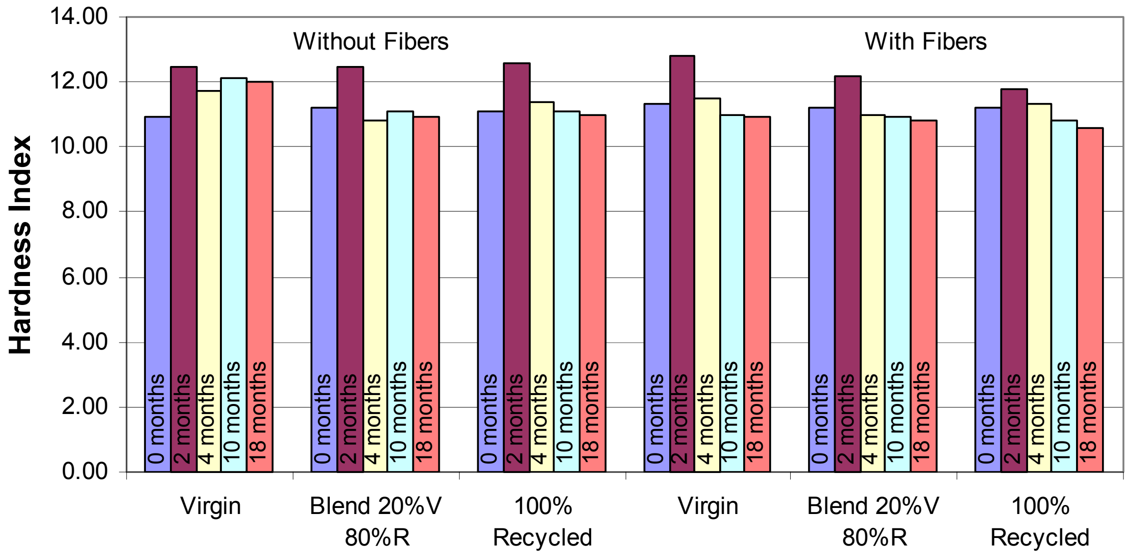


Figure 5.15 Hardness Index in Aged ABS Specimens

5.6.2 Analysis and Discussion on ABS

Tables 5.15 and F.15 show average reduction in hardness index for ABS samples.

Hardness Index Variation in ABS at the End of the Aging Period:

- Reduction in hardness index under conditioning varied from 0.9% to 2.7% for specimens without fibers and 3.5% to 5.4% for specimens with fibers.

- Average reduction in impact strength after 18 months of conditioning for specimens without fibers was 1.8% as compared to 4.2% for specimens with fibers.

Hardness Index Variation in ABS During the Aging Period:

- Maximum reductions ranged from 0.9% to 3.6% for specimens without fibers and 3.5% to 5.4% for specimens with fibers.
- Specimens without fibers showed maximum gains of 11.1% to 14.1%, whereas gains of 5.0% to 13.3% were observed for specimens with fibers.
- Maximum average reduction during the aging period was 2.2% for specimens without fibers as compared to 4.2% for specimens with fibers.

Gains observed in some of the specimens may be possibly due to secondary curing effects and improvement in force transfer across the resin/fiber interface.

5.6.3 Results on PC

Tables 5.16 and F.16 show hardness results for aged PC specimens. Hardness index is provided for each type of specimen and each aging period. Figure 5.16 shows hardness index for each of the specimen types and aging periods, respectively.

Table 5.16 Hardness Index Variations in Aged PC Specimens

Specimen Type	Hardness Index					% Change
	Months of aging					Maximum reduction in period
	0	2	4	10	18	
P1	10.60	12.00	11.30	11.10	11.00	No reduction
P2	10.70	11.10	11.20	11.30	11.30	No reduction
P3	10.60	11.50	10.80	11.10	11.00	No reduction
P4	10.70	11.44	10.80	10.90	10.80	No reduction
P5	10.70	10.74	11.20	10.90	10.90	No reduction
P6	10.70	11.38	11.40	10.90	10.80	No reduction
Average reduction without fibers (A1,A3,A5)						No reduction
Average reduction with fibers (A2,A4,A6)						No reduction

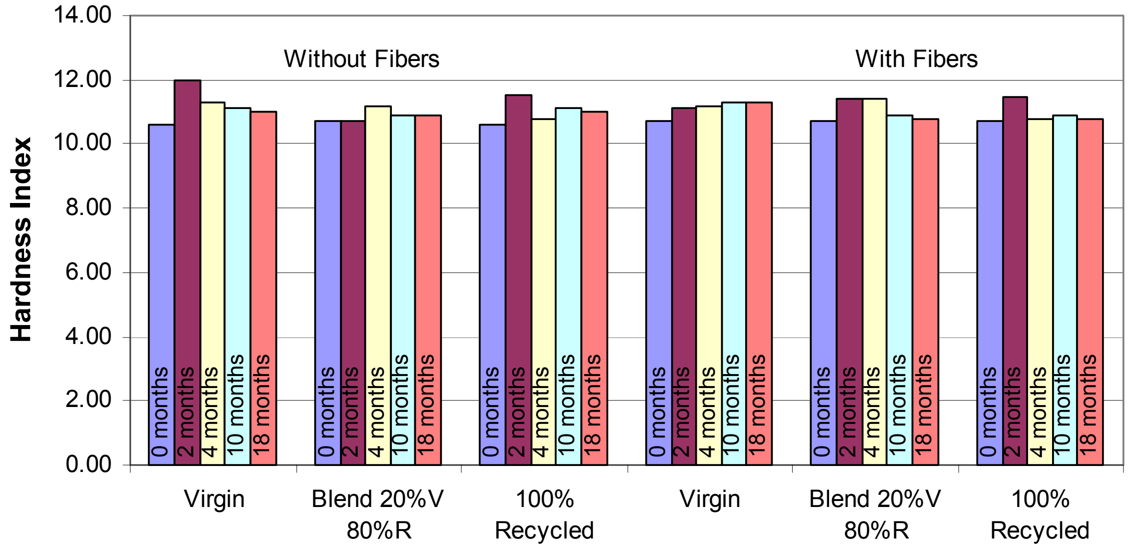


Figure 5.16 Hardness Index in Aged PC Specimens

5.6.4 Analysis and Discussion on PC

Tables 5.16 and F.16 show the average reduction in hardness index for PC specimens.

Hardness Index Variation in PC at the End of the Aging Period:

- Hardness index under conditioning did not vary either for specimens without fibers or for specimens with fibers.
- Gain in hardness index for specimens without fibers varied from 1.9% to 3.8% and from 0.9% to 5.6% for specimens with fibers.

Hardness Index Variation in PC During the Aging Period:

No reductions in hardness index were observed for any types of specimens. Specimens without fibers showed maximum gains of 4.7% to 13.2%, whereas gains of 5.6% to 6.9% were observed for specimens with fibers.

Gains observed in some of the specimens may be possibly due to secondary curing effects and improvement in force transfer across the resin/fiber interface.

5.7 Creep Test

5.7.1 Results on ABS

Tables 5.17 and 5.18 show creep results for ABS specimens tested at sustained load levels of 20% and 50% of ultimate (failure) load. Creep coefficient (creep strain / initial strain) is provided for each type of specimen for the testing period. Figures 5.17 and 5.18 show creep coefficient for each of the specimen types during the testing period for sustained loads of 20% and 50% of ultimate load, respectively.

Table 5.17 Creep Test Results for 20% Sustained Load on ABS Specimens

Type of Specimen	Days	Creep Coefficient
A1 – Virgin without fibers	896	1.62
A2 – Virgin with 25%(wt.%) chopped fibers	896	0.82
A3 – 100% recycled without fibers	924	1.73
A4 – 100% recycled with 25%(wt.%) chopped fibers	896	0.72
A5 – Recycled (20%) / virgin (80%) blend without fibers	924	2.07
A6 - Recycled (20%) / virgin (80%) blend with 25%(wt.%) chopped fibers	896	0.95

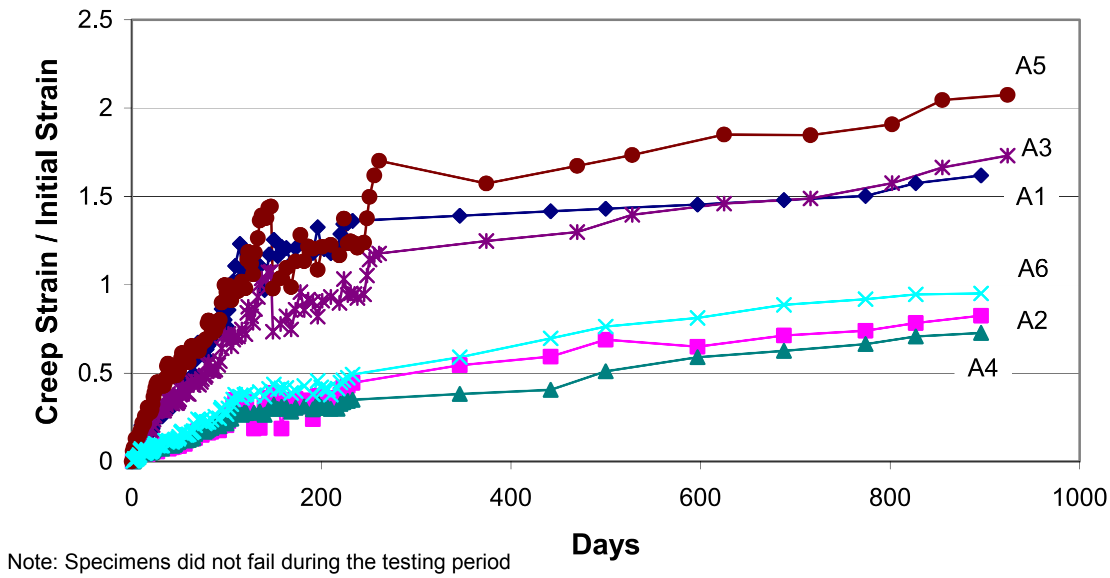
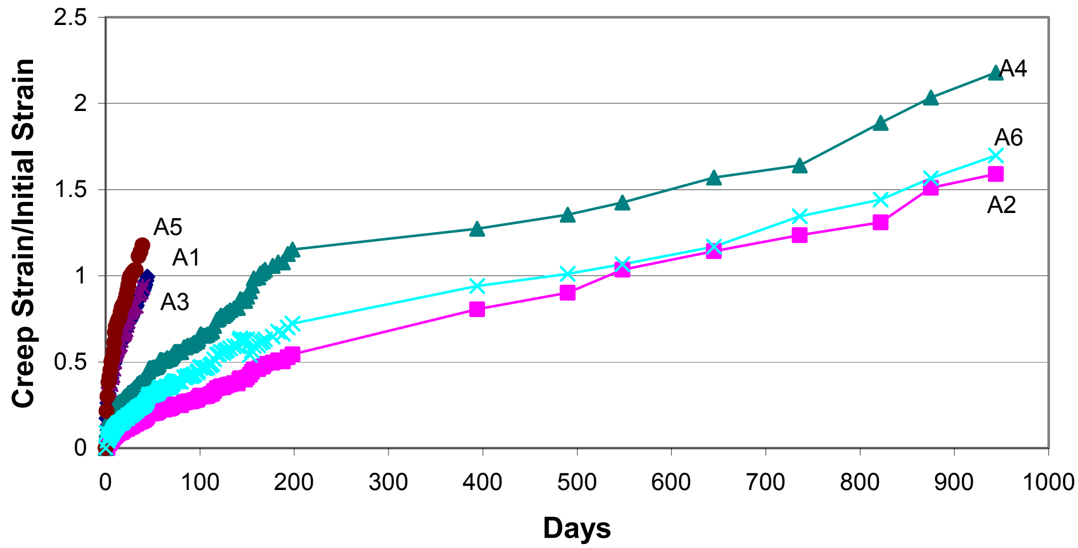


Figure 5.17 Creep Test on ABS Specimens for 20% Sustained Load

Table 5.18 Creep Test Results for 50% Sustained Load on ABS Specimens

Type of Specimen	**Days**	**Creep Coefficient**
A1 – Virgin without fibers	44 (Failed)	0.99 (Failed)
A2 – Virgin with 25%(wt.%) chopped fibers	944	1.59
A3 – 100% recycled without fibers	39 (Failed)	0.94 (Failed)
A4 – 100% recycled with 25%(wt.%) chopped fibers	944	2.18
A5 – Recycled (20%) / virgin (80%) blend without fibers	39 (Failed)	1.18 (Failed)
A6 - Recycled (20%) / virgin (80%) blend with 25%(wt.%) chopped fibers	944	1.70



Note: Specimens A2, A4 and A6 (with fibers) did not fail during the testing period

Figure 5.18 Creep Test on ABS Specimens for 50% Sustained Load

5.7.2 Analysis on ABS

For ABS specimens tested under 20% sustained load, creep coefficient varied from 1.62 to 2.07 for specimens without fibers on 924th day and 0.72 to 0.95 for specimens with fibers on 896th day of testing. Average creep coefficient after 924 days of testing for samples without fibers was 1.81 as compared to 0.83 for samples with fibers after 896 days.

ABS specimens without fibers tested at 50% sustained load failed with a maximum creep coefficient of 0.94 and 1.18 on 39th day for 100% recycled and blend specimens, respectively, and 0.99 on 44th day for virgin ABS specimens.

Specimens with fibers tested at 50% sustained load, showed a creep coefficient between 1.59 and 2.18 on the 944th day. Average creep coefficient of 1.82 was observed for ABS specimens with fibers.

For ABS specimens with fibers, average creep coefficient after 924 days increased from 0.83 when tested under 20% sustained load to 1.82 for 50% sustained load.

ABS specimens without fabrics failed within a short period (39 to 44 days) when tested under 50% sustained load. However, ABS specimens without fabrics tested under 20% sustained load showed an average creep coefficient of 1.81 after 924 days without fail.

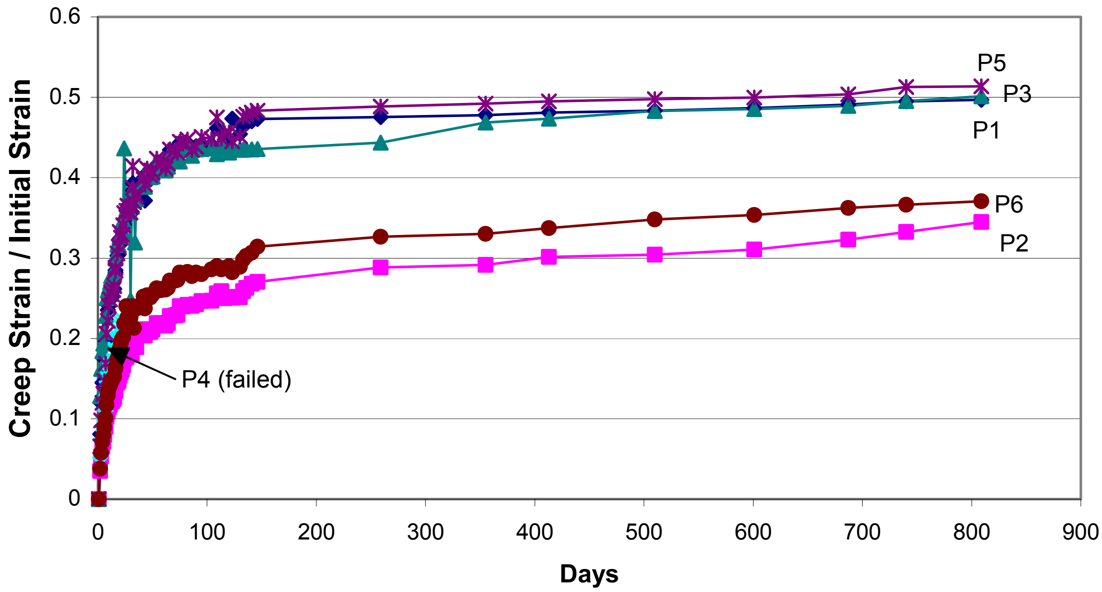
During the testing period, higher creep strains were observed for specimens without fibers, indicating that the addition of fibers decreases the long-term deformation of ABS specimens under sustained loads.

5.7.3 Results on PC

Tables 5.19 and 5.20 show creep results for PC specimens tested at sustained load levels of 20% and 50% of ultimate load. Creep coefficient (creep strain / initial strain) is provided for each type of specimen for the testing period. Figures 5.19 and 5.20 show creep coefficient for each of the specimen types during the testing period for sustained loads of 20% and 50% of ultimate load, respectively.

Table 5.19 Creep Test Results for 20% Sustained Load on PC Specimens at 809 Days

Type of Specimen	Creep Coefficient
P1 – Virgin without fibers	0.50
P2 – Virgin with 25%(wt.%) chopped fibers	0.35
P3 – 100% recycled without fibers	0.50
P4 – 100% recycled with 25%(wt.%) chopped fibers	0.22 (failed on 23rd day)
P5 – Recycled (20%) / virgin (80%) blend without fibers	0.51
P6 - Recycled (20%) / virgin (80%) blend with 25%(wt.%) chopped fibers	0.37



Note: Specimens P1, P2, P3, P5 and P6 did not fail during the testing period

Figure 5.19 Creep Test on PC Specimens for 20% Sustained Load

Table 5.20 Creep Test Results for 50% Sustained Load on PC Specimens at 809 Days

Type of Specimen	Creep Coefficient
P1 – Virgin without fibers	0.77
P2 – Virgin with 25%(wt.%) chopped fibers	0.47
P3 – 100% recycled without fibers	0.86
P4 – 100% recycled with 25%(wt.%) chopped fibers	0.44
P5 – Recycled (20%) / virgin (80%) blend without fibers	0.80
P6 - Recycled (20%) / virgin (80%) blend with 25%(wt.%) chopped fibers	0.40

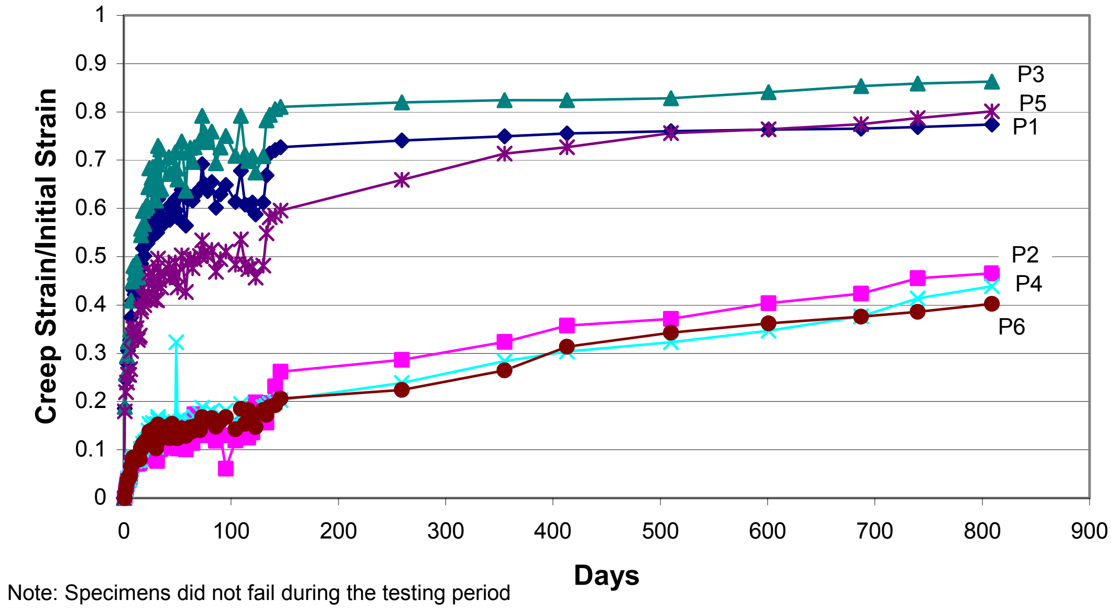


Figure 5.20 Creep Test on PC Specimens for 50% Sustained Load

5.7.4 Analysis on PC

Specimen P4 (100% recycled with chopped fibers) tested under 20% sustained load failed with a maximum creep coefficient of 0.22 on 23rd day.

On the 809th day of testing, specimens P2 and P6 (remaining specimens with fibers) tested at 20% sustained load showed a creep coefficient between 0.35 and 0.37 as compared to 0.50 to 0.51 for specimens without fibers at 20% sustained load. Average creep coefficient of 0.36 was observed for PC specimens with fibers and 0.50 for specimens without fibers.

For PC specimens tested under 50% sustained load, creep coefficient on 809th day of testing varied from 0.77 to 0.86 for specimens without fibers and 0.40 to 0.47 for specimens with fibers. Average creep coefficient after 809 days of testing for samples without fibers was 0.81 as compared to 0.44 for samples with fibers.

For PC specimens with fibers, average creep coefficient after 809 days increased from 0.36 when tested under 20% sustained load to 0.44 for 50% sustained load.

For PC specimens without fibers, average creep coefficient after 809 days increased from 0.50 when tested under 20% sustained load to 0.81 for 50% sustained load.

Similar to ABS specimens, higher creep strains were observed for PC specimens without fibers, indicating that the addition of fibers decreases the long-term deformation under sustained loads.

At 20% of sustained load, PC specimens without fibers showed one-third the creep coefficient of ABS specimens (0.50 vs. 1.81). With fiber addition, creep coefficient in PC was near one half the creep coefficient in ABS specimens at 20% load, i.e., (0.36 vs. 0.83).

Sustained load level on ABS specimens is suggested to be limited to 20%. At 50% of sustained load, PC specimens showed better capacity to carry sustained load than ABS specimens, either with or without fibers.

For reinforced concrete, creep coefficient at a given time with respect to initial loading time can be computed as (Nilson, 1986):

$$C_{ct} = \frac{t^{0.60}}{10 + t^{0.60}} C_{cu}$$

Where,

Cct= Creep coefficient after t days of loading

t= time in days after loading

Ccu= Ultimate creep coefficient (2.9 for a 4,000 psi reinforced concrete)

Calculated creep coefficients for reinforced concrete at the 809th, 896th, and 924th day after loading are 2.46, 2.48, and 2.49, respectively. Compared to ABS and PC specimens tested on this research, concrete creep coefficient is at least 13% higher than that observed for ABS and PC specimens without fibers and more than 1.5 times higher than that of ABS and PC specimens with fibers.

CHAPTER 6

TEST RESULTS, ANALYSIS AND DISCUSSIONS ON GUARDRAIL POST, RAIL AND OFFSET BLOCK

6.1 Introduction

As described in chapter 4, several static tests such as tension, compression and bending were performed on coupon and prototype specimens made of recycled polymer and discarded rubber tires to determine their suitability for highway guardrail system. In this chapter, test results on different types of specimens including shapes are presented, discussed and compared.

6.2 Recycled Polypropylene Channel Section

6.2.1 Test Results on Recycled Polypropylene Channel Section

Compressive and tensile gage locations and stress-strain variations for the channel section are shown in Figures 6.1 and 6.2, respectively. The response shown in Figure 6.2 is for a 3 point bending test on the recycled polypropylene channel section. Maximum experimental stress and stiffness values of the section are shown in Table 6.1. Punching failure occurred on the top member. Fiber volume fraction of the section was found to be 43% based on ignition test. Stiffnesses were computed from the slope of strain versus stress plots for tensile and compressive stress (Figure 6.2) using linear curve fit. Computation of stresses was made as follows:

$$\sigma = \frac{Mc}{I}$$

Where,

σ= Compressive or tensile bending stress

M= Moment at midspan for 3-point bending

$$M = \frac{PL}{4}$$

P=Applied load

L= Span length

c= Distance from section centroid to point of stress calculation (Figure 6.1).

I= Moment of inertia about centroid of section= 0.0841 in^4

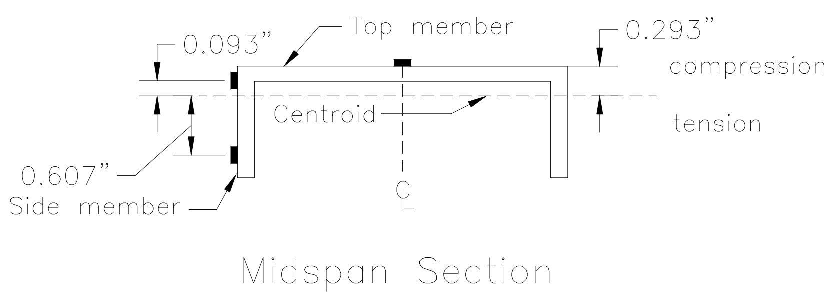


Figure 6.1 Distances from Centroid of Channel Section to Locations of Strain Gages

Table 6.1 Maximum Tensile and Compressive Stresses and Stiffnesses of Polypropylene Channel Section Under Three Point Bending Test

Location	**Type of stress**	**Stiffness, E (psi)**	**Maximum Stress (psi)**	**Failure mode**
Top @ midspan and center of channel width	Compression	2.45 x10^6	6,686	Punching on compression side
Bottom @ midspan on bottom-most fiber on the side of the channel	Tension	2.55 x10^6	13,831	

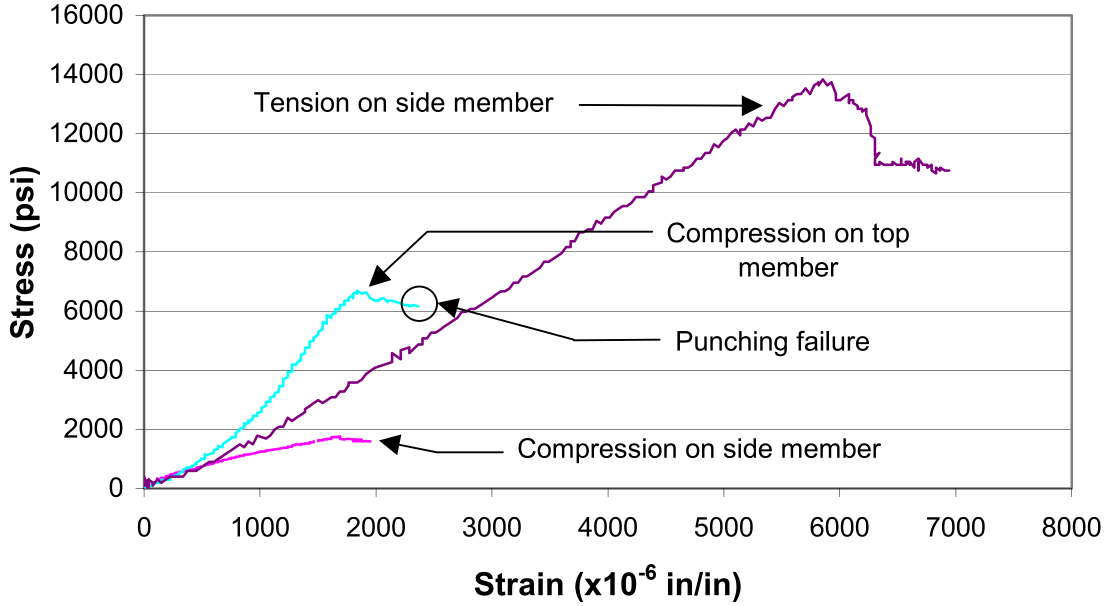


Figure 6.2 Compressive and Tensile Stresses in Recycled Polypropylene Channel Section Under Three Point Bending Test

6.2.2 Analysis and Discussion of Test Results on a Recycled Polypropylene Channel Section

Figure 6.2 shows the stress versus strain for a channel section under bending loads. Tensile stresses on the bottom were found to be higher than the top compressive stresses. This is due to the fact that the fiber area in tension zone is less than the fiber area in the compression zone, which consists of both horizontal portion and vertical legs (Figure 6.1). Failure occurred on the top of the channel, when compressive stress reached 6,686 psi, and tensile stress was 13,831 psi. Considering that the entire section was uniformly reinforced, it was evident from the failure type that the section with a thickness of 0.17" was punched through under the loading point.

6.3 Recycled Polypropylene Trapezoidal Section

6.3.1 Test Results on Recycled Polypropylene Trapezoidal Section

Trapezoidal section with recycled polypropylene is shown in Figure 6.3. This section had 43% fiber volume fraction as determined by ignition test.

Bending: Compressive and tensile stresses at the locations shown in Figure 6.3 during 3 point bending tests are plotted in Figure 6.4. Bending tests were conducted on the trapezoidal section and tension tests were conducted on the plates cut from trapezoidal section. Maximum stress and stiffness values are shown in Table 6.2. A combination of compression and punching failure was observed on the top member. Stiffnesses were computed from the slope of the linear curve fit of the stress versus strain plots for compressive and tensile stress (Figure 6.4). Moment of inertia of the section (I) was computed and the value is 0.0433 in^4. Bending stresses were calculated as described for the channel section. Outer fiber distances from neutral axis for stress calculations are given in Figure 6.3.

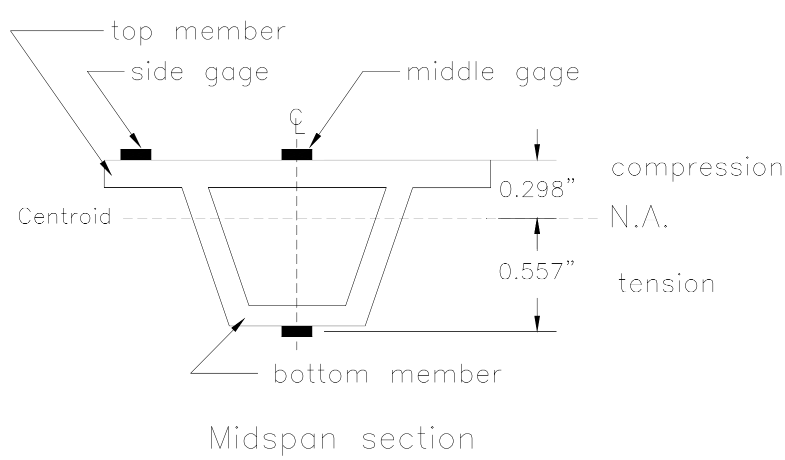


Figure 6.3 Distances from Centroid of Trapezoidal Section to Locations of Strain Gages

Table 6.2 Maximum Tensile and Compressive Stresses and Stiffnesses of Polypropylene Trapezoidal Section Under Three Point Bending Test

Location	Type of stress	Stiffness, E (psi)	Maximum Stress (psi)	Failure mode
Top member @ center of the section	Compression	3.04 x10^6	23,722	Punching
Bottom member @ center of the section	Tension	3.16 x10^6	45,049	

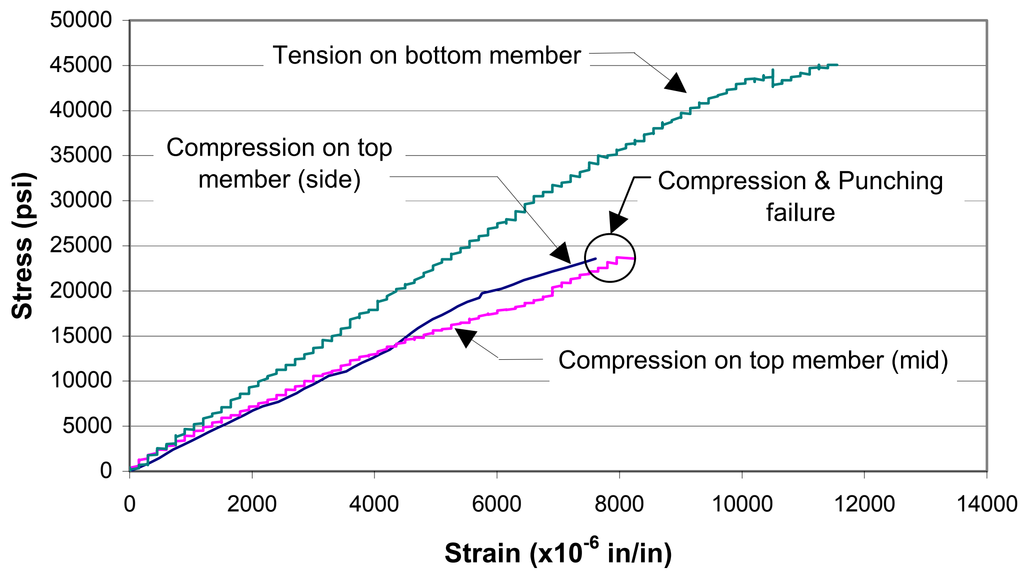


Figure 6.4 Compressive and Tensile Bending Stresses on Recycled Polypropylene Trapezoidal Section Under Three Point Bending Test

<u>Tension tests on plates cut from trapezoidal section:</u> For the tension specimens described in section 4.4.1, tension tests were carried out using three different grip configurations and lengths: 1) no grips, 2) 1¾ in, and 3) 2½ in. Results of the tension tests are summarized in Table 6.3. Stiffnesses were computed from the slope of the linear curve fit of the stress vs. strain curves (Figure 6.5). Tensile stresses were computed as follows:

$$\sigma = \frac{P}{A}$$

Where

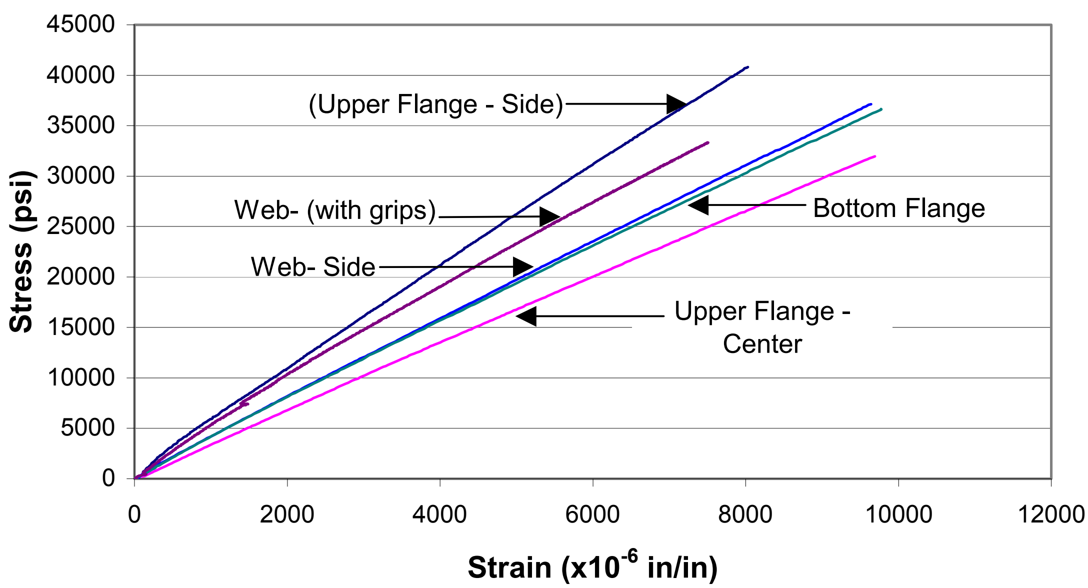
σ= Tensile stress

P= Applied load

A= Area of cross section

Table 6.3 Maximum Tensile Stresses and Stiffnesses on Polypropylene Plates from Trapezoidal Section - Tension Test

Location from where the plate was cut	Grips	Stiffness, E (psi)	Maximum Stress (psi)
Upper Flange - Side	NO	5.00 $x10^6$	53,240
Upper Flange – Center	1 ¾"	3.30 $x10^6$	39,124
Web	2 ½"	3.83 $x10^6$	82,897
Web	NO	4.40 $x10^6$	55,000
Bottom Flange	1 ¾"	3.73 $x10^6$	72,811



Note: Failure point not shown

Figure 6.5 Linear Portion of Stress vs. Strain for Tension Tests on Recycled Polypropylene Plates from Trapezoidal Section

6.3.2 Analysis and Discussion of Test Results on Recycled Polypropylene Trapezoidal Section

Bending: Figure 6.4 shows compressive and tensile stresses in the trapezoidal section. Similar to channel section, tensile stress on the bottom is higher than the compressive stress for any given load level. Again, this is due to the fact that higher compressive area results in lower compressive stress, i.e., satisfying force equilibrium requirements. Failure occurred in the top of the member with failure compressive stress being 23,722 psi while the tensile stress was 45,049 psi. Overall average thickness of the section was 0.14 inches. This small thickness has contributed to the observed punching failure.

Tension tests on plates cut from trapezoidal section: Tension coupon plates cut from the trapezoidal section were tested with and without grips on the end. Lower strength values were obtained for the specimens tested without grips due to premature failure near the gripping areas. Tension failure at 39,124 psi for specimens with 1¾ in grips was caused by bond problems at the interface between the composite and grip. This value was discarded and additional tests were conducted. Maximum tensile stress value of 82,897 psi was obtained for a grip length of 2½ in. This value can be considered as the absolute maximum tensile strength for this type of material. It can be seen that the section under bending did not reach its full tensile strength value due to premature failure.

6.4 Recycled ABS Box Sections

6.4.1 Test Results on Recycled ABS Box Section

Bending: Tables 6.4 and 6.5 show the box dimensions and test results, respectively, under three and four point bending tests for FRP wrapped and unwrapped box sections. Both recycled and virgin polymer specimens were tested and evaluated. For all the test configurations, stiffness and ultimate strength values are shown in Table 6.6 and Figure 6.7, respectively. Punching failure occurred on the top member at loading points for recycled ABS specimens. Tensile and compressive stiffnesses were computed from the stress versus strain plots (Figure 6.7). Bending stresses were calculated as described for channel section. The distance from the neutral axis to strain gage location for non-wrapped specimens, wrapped specimens, and virgin vinylester non wrapped specimens were 0.487 in, 0.586 in, and 0.496 in, respectively. Moment of inertia of non wrapped section was the section was I=0.044 in^4, for wrapped specimens was I=0.084 in^4 and for virgin Vinylester specimens I=0.056 in^4. Specimen cross sections are shown in Figure 6.6. Fiber content and dimensional properties of the specimens are summarized in Table 6.4. For 4-point bending tests maximum moment (between loads) was computed as follows:

$$M = Pa$$

Where

M= Moment in the middle third zone

P= Applied load (Max load/2)

a= Distance from supports to each point of load application = 5 in.

Table 6.4 Fiber Volume Fraction and Dimensional Properties for ABS Box Sections

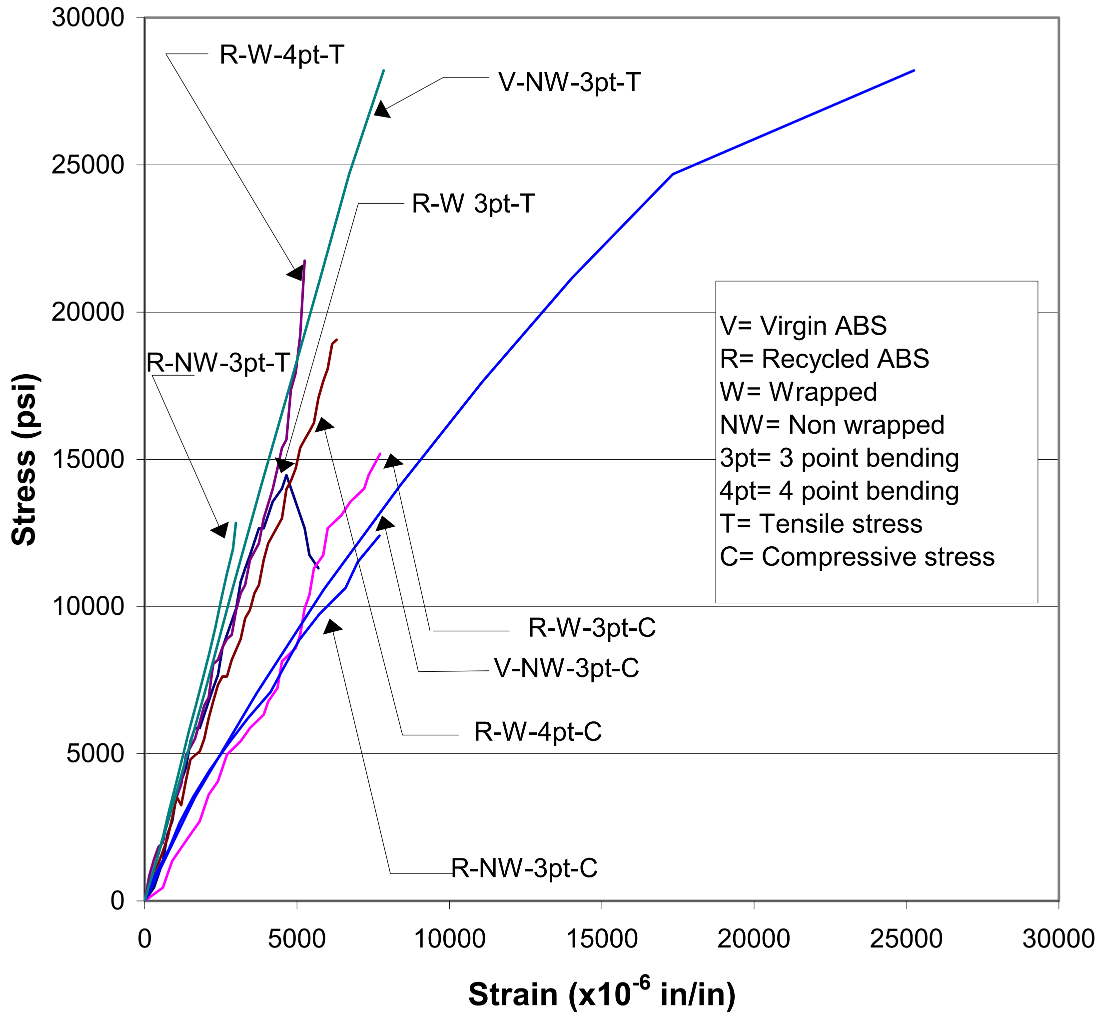
Specimen	Fiber Volume Fraction (%)	Average thickness (in)	Area of cross section (in^2)	Moment of Inertia (in^4)
Non-wrapped recycled	25	0.10	0.348	0.0440
Wrapped recycled	22	0.16	0.586	0.0837
Non-wrapped virgin*	41	0.13	0.437	0.0562

* Vinylester Specimen

Figure 6.6 Box Sections (from Left to Right) Recycled ABS, Wrapped Recycled ABS and Virgin Vinylester

Table 6.5 Maximum Tensile and Compressive Stresses and Stiffnesses in Box Sections

Specimen	Type of test	Tensile Stiffness, E (psi)	Compressive Stiffness, E (psi)	Maximum Stress (psi)	Load on loading point at failure. (lb)
Non-wrapped recycled ABS	3-point	3.86×10^6	2.28×10^6	12,845	280
Wrapped recycled ABS	3-point	3.24×10^6	1.90×10^6	12,953	504
Wrapped recycled ABS	4-point	3.42×10^6	2.94×10^6	19,733	589
Non-wrapped virgin Vinylester	3-point	3.60×10^6	2.52×10^6	29,972	850



Note: Recycled ABS specimens failed in compression and punching
Virgin PP specimens failed in compression

Figure 6.7 Compressive and Tensile Bending Stresses in Recycled ABS Box Section Under Three and Four Point Bending Test

<u>Tension:</u> ABS box section as described in section 4.4.1 was tested under tension. Results of ultimate strength and stiffness are summarized in Table 6.6. Tensile stresses were calculated by dividing the applied force by the area of cross section. Stiffness was calculated from the stress versus strain curve (Figure 6.8).

Table 6.6 Maximum Tensile Stress and Stiffness for Recycled ABS Box Section - Tension Test

Stiffness, E (psi)	Maximum Stress (psi)
3.21 x10^6	19,960

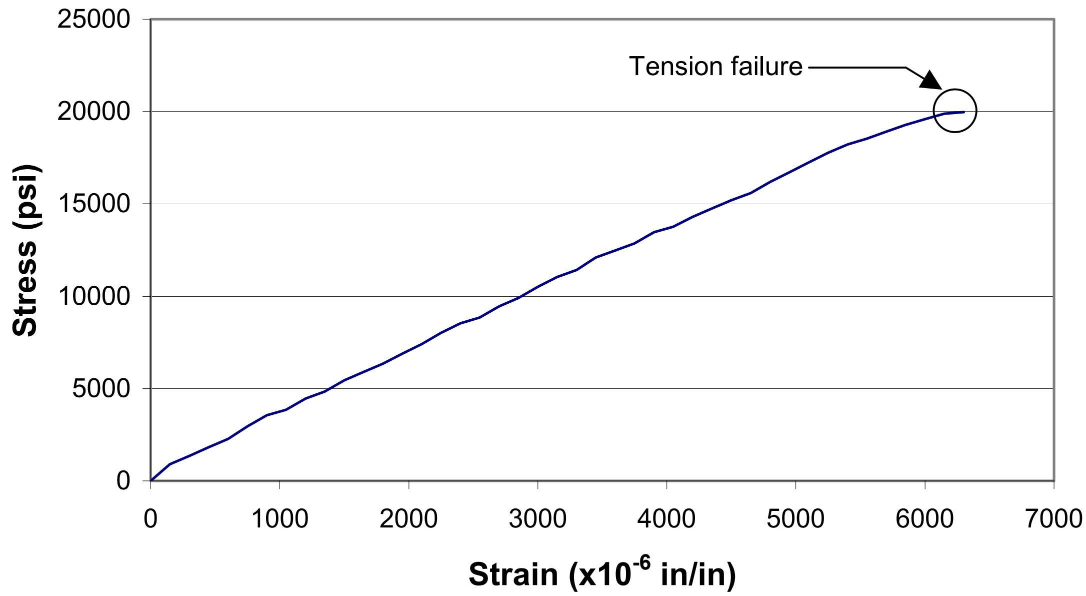


Figure 6.8 Tensile Stress vs. Strain for Tension Tests on Recycled ABS Box Section

6.4.2 Analysis and Discussion of Test Results on Recycled ABS Box Section

Bending: Tensile strains were observed to be higher than the compressive strains in box sections as seen in Figure 6.7. For the unwrapped specimens with a thickness of 0.10 in, ultimate stress under 3-point bending was 12,845 psi. For wrapped section with a thickness of 0.16 in, ultimate stress under 3 point bending was 12,953 psi. Ultimate stress for 4-point bending test was 19,733 psi. For virgin box section with a thickness of 0.13 in, 3 point bending ultimate stress was 29,972 psi.

Failure mode observed for the recycled specimens was a compression failure coupled with punching at the loading point. Both 3-point and 4-point bending stresses were well below the maximum stress values. However, punching ultimate stress under single location in 3-point bending was more critical than that under two locations in 4-point bending. Test results indicate the effectiveness of wrap in terms of strength increase.

Virgin vinylester box specimen failed in compression at a much larger strain than the recycled ABS box sections. Higher strength of the virgin vinylester composite box section is attributed to the higher fiber volume fraction (41% versus 25%). It has to be noted that the fiber reinforced virgin vinylester specimen was an optimized design for a thermoset that can be looked as a final objective for recycled thermoplastic shapes.

From the bending results of three sections tested under this research, trapezoidal section showed better bending resistance and higher stress levels. Reinforcement at loading points in a prototype (i.e., junction of post and railing) is also a critical issue that needs to be properly accounted for when designing an actual size of a highway post or rail.

Tension: Ultimate tensile strength of 19,960 psi was obtained for the box section when tested as a single unit. Stiffness obtained was $3.21x10^6$ psi. Tension value shows that box specimens under bending failed before they reached their maximum tensile stress capacity.

6.5 Plates from Recycled ABS Sheets

6.5.1 Test Results on Plates with Recycled ABS Sheets

Bending: Table 6.7 shows the results for recycled ABS sheets tested under three point bending. Fiber volume fraction of 25% for recycled ABS sheets was determined by ignition test. Failure mode observed for short plates was longitudinal shearing delamination of the composite at an interlaminar shear stress of 874 psi. This low value is attributed to a poor wet out of the fabric during manufacturing process. For long plates, crushing on the compression surface of the plate was observed. Stiffnesses were computed from the stress versus strain plots (Figure 6.9). Bending stresses were calculated as described for the channel section. For short plates, distance from the neutral axis to top of the plate was 0.113 in, and moment of inertia was I=0.00072 in^4. For long plates, distance value was 0.100 in. and I=0.00101 in^4. Interlaminar shear stress due to bending was calculated as follows:

$$\tau = \frac{VQ}{I}$$

Where

τ= Interlaminar shear stress

V= Shear force at point of stress calculation

Q= Moment of area about centroid of shear area

I= Moment of inertia

For a rectangular section, the interlaminar shear stress can be calculated as:

$$\tau = 1.5\frac{V}{A}$$

Where

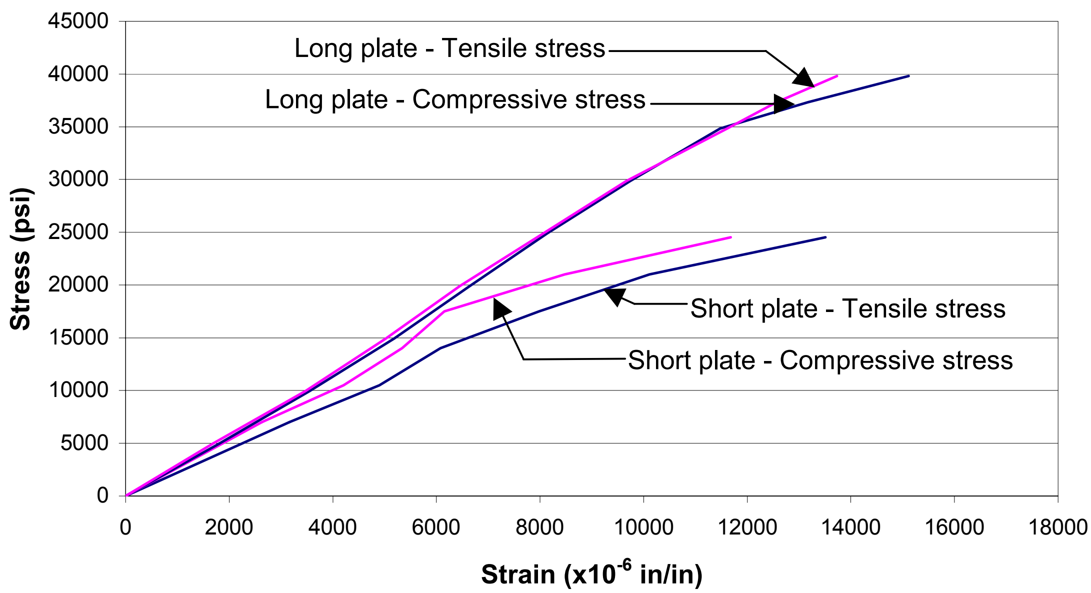
V=0.5P =Shear at midspan for a simply supported beam under point load P

A= total area

Table 6.7 Maximum Tensile and Compressive Stresses and Stiffnesses in Recycled ABS Plates - Three Point Bending Test

Specimen	Tensile Stiffness, E (psi)	Compressive Stiffness, E (psi)	Maximum stress (psi)	Load at failure (lb)	Interlaminar shear stress (psi)
Short plates	2.59×10^6	2.33×10^6	27,991	197	874*
Long plates	3.025×10^6	2.91×10^6	39,518	160	400**

* Separation of fabric from resin (interlaminar shear failure)
** Not an interlaminar shear failure



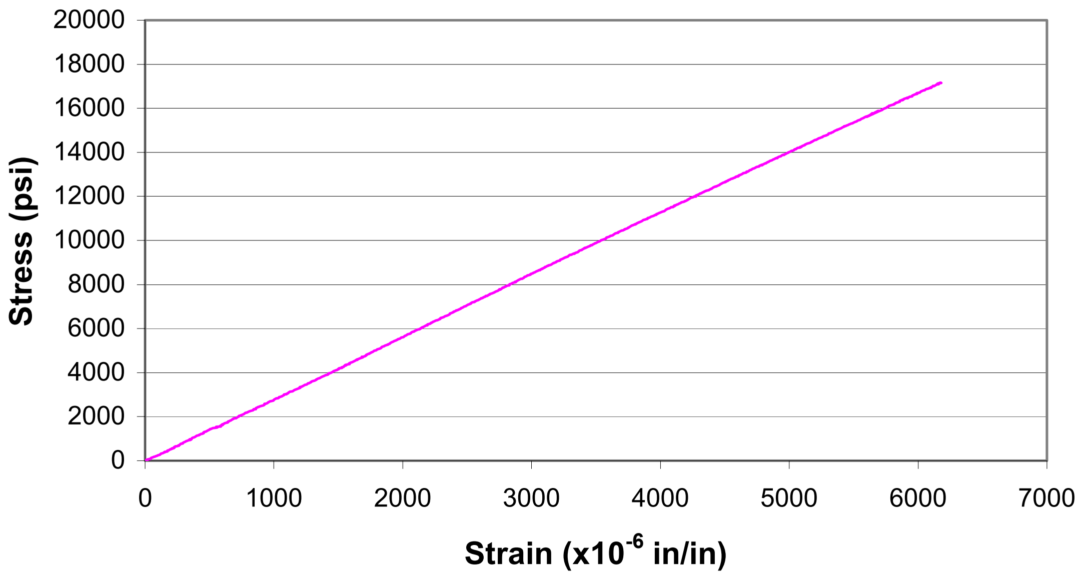
Note: Long plates failed in compression - Short plates failed in interlaminar shear

Figure 6.9 Tensile and Compressive Bending Stress in Recycled ABS Plates and Under Three Point Bending Test

Tension: Results of ultimate strength and stiffness on ABS plates cut from sheets are provided in Table 6.8. Stiffnesses were computed from the stress versus strain curves (Figure 6.10). Tensile stresses were computed as described for plates cut from trapezoidal section (Section 6.3.1)

Table 6.8 Maximum Tensile Stress and Stiffness on Plates from ABS Sheets - Tension Test

Stiffness, E (psi)	Maximum Stress (psi)
2.68×10^6	21,950



Note: Failure point not shown

Figure 6.10 Linear Portion of Stress vs. Strain for Tension Tests on ABS Plates from Recycled ABS Sheets

Compression: Small rectangular coupons cut from ABS sheets with cross section of 0.5" x 3/8" and height of 0.5" as per ASTM D695-91 were tested under compression. Results are shown in Table 6.9. Stiffnesses were computed from the stress versus strain curves (Figure 6.11). Compressive stresses were computed as follows:

$$\sigma = \frac{P}{A}$$

Where

σ= Compressive stress

P= Applied load

A= Area of cross section

Table 6.9 Maximum Compressive Stress and Stiffness on Plates from ABS Sheets

Stiffness, E (psi)	Maximum Stress (psi)
3.58 x10^6	6,900

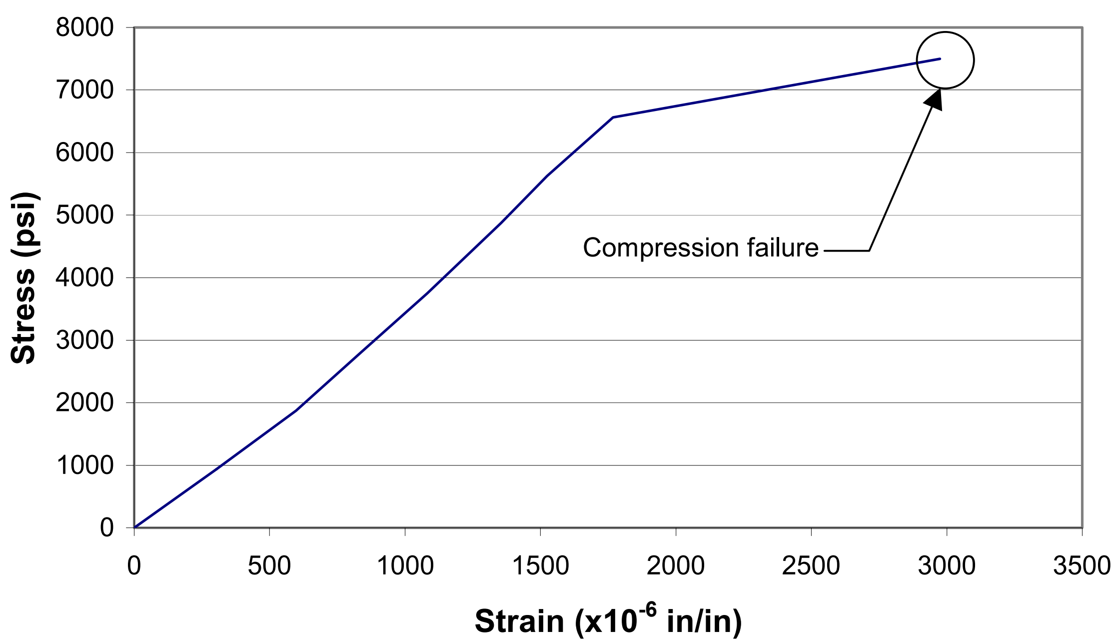


Figure 6.11 Compressive Stress vs. Strain for Compression Tests on Plates from Recycled ABS Sheets

6.5.2 Analysis and Discussion of Plate Test Results from Recycled ABS Sheets

Bending: Ultimate bending strength of recycled ABS plates with a thickness of 3/8 in. was 39,518 psi. . Failure consisted of crushing on the compression surface, which is different from the observed punching of the other shapes described before. Short plate mode of failure was shear delamination at a maximum interlaminar shear stress of 874 psi, indicating a poor wet out of the fabric during manufacturing process.

Tension: Maximum average tensile strength of 21,950 was observed for ABS plates cut from sheets.

Compression: Under compression, specimen split open, showing buckling delamination and thus a low compression strength value of 6,900 psi was obtained. Most likely, delamination was caused because of the small thickness of 3/8 of the specimens tested. It should be noted that ASTM recommends a thickness of at least ½ in. In addition, some fiber wet out problems were also noted.

6.6 Strips from Recycled ABS Belt-Type Specimens

6.6.1 Test Results on Strips from Recycled ABS Belt-Type Specimens

Tension: Three different belt-type specimens were received for testing. Results of tension tests on strips cut from the belt type specimens are shown in Table 6.10. Stiffnesses were computed from the slope of the stress vs. strain curves (Figure 6.12). Tensile stresses were computed as described for plates from trapezoidal section (Section 6.3.1).

Table 6.10 Maximum Stress and Stiffness of Strips from ABS Belt –Type Specimens - Tension Test

Type of Specimen	Fiber volume fraction (%)	Stiffness, E (psi)	Maximum Stress (psi)
A	20	2.92 $x10^6$	29,800
B	24	2.65 $x10^6$	37,150
C	19	$2.09x10^6$	24,450

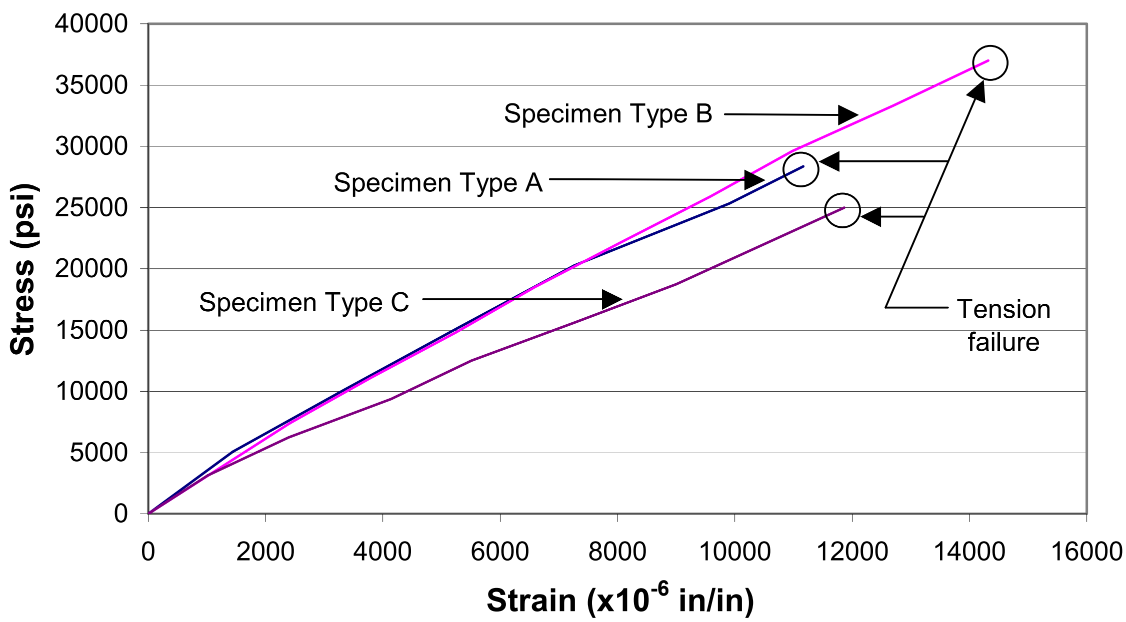


Figure 6.12 Tensile Stress vs. Strain of Recycled ABS Strips from Belt-Type Specimens

6.6.2 Analysis and Discussion of Test Results on Strips from Recycled ABS Belt-Type Specimens

Tension: Tensile strength of specimens varied from 24,450 psi for type C specimens up to 37,150 psi for Type B specimens. Type A specimens showed an ultimate strength of 29,800 psi. Lowest stiffness of $2.09x10^6$ psi was obtained for Type C specimens as compared to $2.65x10^6$ psi for Type B specimens and $2.92x10^6$ psi for Type A samples.

6.7 Compression Tests of Rubber-Wood Offset Block Model

6.7.1 Results on Compression Test of Rubber-Wood Offset Block Model

A maximum load of 5,250 lb was applied to the joint block. Test was stopped because of excessive deformation (buckling) of the rubber strips. This buckling was due to the fact that the strips were tested about weak axis with a high slenderness ratio. However, when compression tests were performed on the rubber block (3" x 3") compressive stress in excess of 50 ksi was noted. Compressive stress on the block at this point was 595 psi.

6.7.2 Analysis and Discussion of Compression Test of Rubber-Wood Offset Block Model

As expected, block without lateral support buckled at a very low applied load (Figure 4.45). Tests showed good performance of the materials (rubber and wood). However, applied load was well below the maximum value for individual components of the block. Interaction of the parts was satisfactory, none of the parts suffered any damage. In addition, strips were not placed one over the other in a stack, which would have enormously increased the total compressive load.

6.8 Tests on Wood from Rubber – Wood Block Model

6.8.1 Results of Tests on Wood from Rubber – Wood Block Model

In order to evaluate the strength of wood used for the rubber-wood prototype and compare to polymer strength, compression and impact tests were carried out.

<u>Compression parallel to grain:</u> Ultimate strength and stiffness of wood samples tested in compression with load applied parallel to grain are shown in Table 6.11.

Stiffnesses were computed from the slope of the stress vs. strain curves (Figure 6.13). Compressive stresses parallel to grain were computed as follows:

$$\sigma = \frac{P}{A}$$

Where

σ= Compressive stress

P= Applied load

A= Area of cross section parallel to grain

Table 6.11 Maximum Compressive Stress and Stiffness of Wooden Blocks from Rubber – Wood Block Model – Compression Parallel to Grain Test

Stiffness, E (psi)	Maximum Stress (psi)
1.63×10^6	8,399

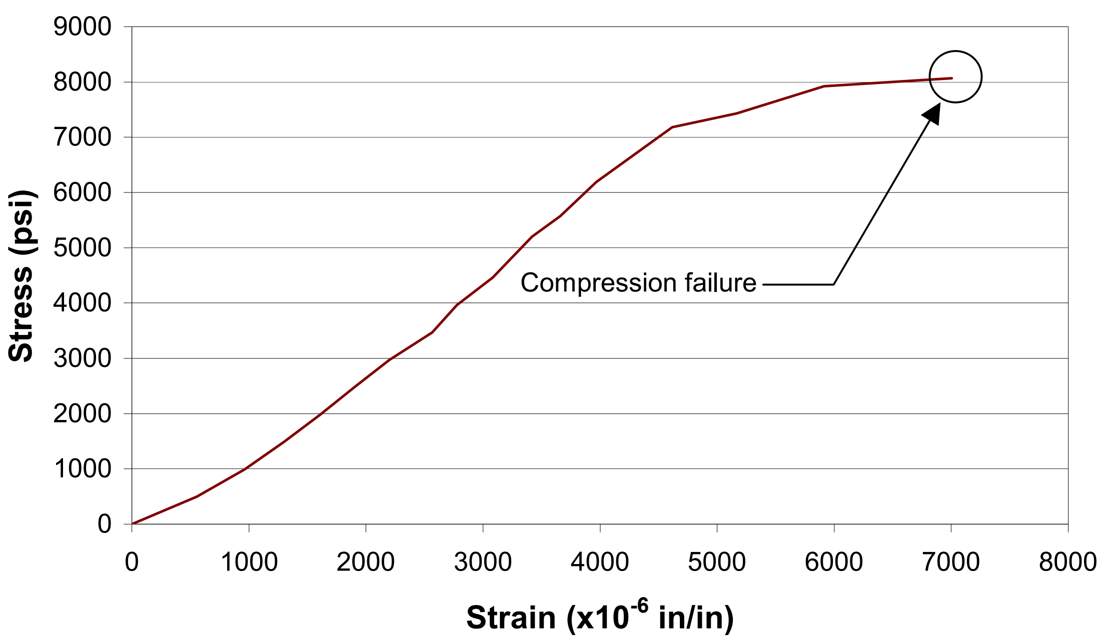


Figure 6.13 Compressive Stress vs. Strain for Compression Parallel to Grain Tests on Wooden Blocks from Rubber – Wood Block Model

Compression perpendicular to grain: Ultimate strength and stiffness of wood samples tested in compression with load applied perpendicular to grain are shown in Table 6.12. Stiffnesses were computed from the stress versus strain curves (Figure 6.14). Compressive stresses parallel to grain were computed as follows:

$$\sigma = \frac{P}{A}$$

Where

σ= Compressive stress

P= Applied load

A= Area of cross section perpendicular to grain

Table 6.12 Maximum Compressive Stress and Stiffness of Wood Blocks from Rubber – Wood Block Model – Compression Perpendicular to Grain Test

Stiffness, E (psi)	Maximum Stress (psi)
0.197×10^6	1,472

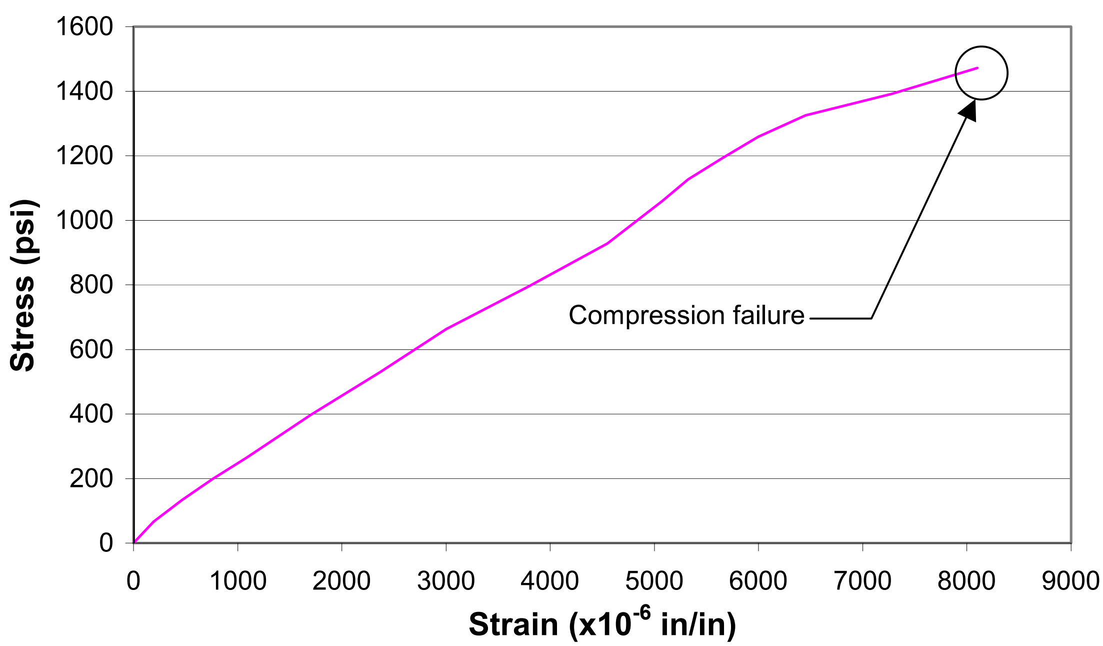


Figure 6.14 Stress vs. Strain for Compression Perpendicular to Grain Tests on Wooden Blocks from Rubber – Wood Block Model

Impact: Average value of Izod impact strength obtained from the notched specimens was 1.82 ft-lb/in. Values varied from 0.07 to 4.31 ft-lb/in. Impact strength was calculated as follows:

$$S = \frac{I}{b}$$

Where

S=Impact strength

I= Wind and friction corrected impact strength from Izod impact apparatus

b=Thickness of the specimen

6.8.2 Analysis and Discussion of Tests on Wood from Rubber – Wood Block Model

Compression: As expected, compression resistance parallel to grain of the wood used for the rubber block is 5.7 times greater than compression perpendicular to grain. Stiffness parallel to grain was 8.3 times greater than the stiffness perpendicular to grain. Values obtained from these tests will be used only as a reference for later comparison to polymer composite offset blocks.

Impact: Lower values for impact resistance were obtained for wood samples than virgin and recycled polymers such as ABS or PC. Figure 6.15 shows a comparison of impact strength between wood, ABS and PC (both virgin and recycled).

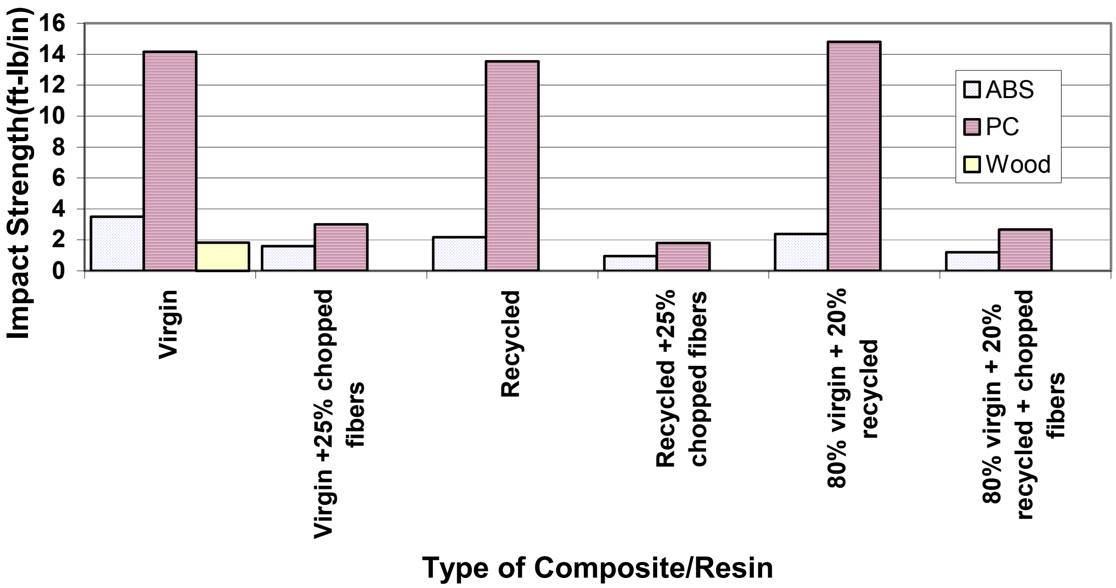


Figure 6.15 Comparison of Impact Strength Between Virgin and Combinations of Recycled ABS and PC, and Wood

As shown in Figure 6.15, wood impact strength of 1.82 ft-lb/in is about 8 times less than virgin PC (14.15 ft-lb/in) and about 2 times less than virgin ABS (3.19 ft-lb/in). When compared to recycled and blended (virgin/recycled) resins, wood impact strength is at least 7.4 times less than that of PC and at least 1.2 times less than that of ABS specimens. Impact strength in all three kinds of PC specimens with fiber addition was equal to or higher than impact stress in wood (1.81 to 3.01 ft-lb/in vs. 1.82 ft-lb/in). However impact strength in wood was higher than that in chopped fiber reinforced ABS specimens (0.96 to 1.59 ft-lb/in vs. 1.82 ft-lb/in). This gives us an idea on the efficiency of some polymer composites for future impact strength designs, which is one of the main concerns when designing guardrail systems.

6.9 Bond Strength Test on Rubber-ABS Interface

As part of the development of an offset block for highway guardrail systems, a number of tests were performed to characterize the bond strength between rubber tire surface and molded recycled ABS. In this section test results are presented and discussed.

6.9.1 Results of Bond Strength Test on Rubber-ABS Interface

Bond pull out tests were conducted with and without applying primer to the surface of rubber prior to molding the recycled ABS sample to obtain good interfacial contact between ABS and rubber. Figure 6.16 shows stress vs. deflection during bond pull out test conducted for different curing-bonding configurations. Test results are summarized in Table 6.13 and illustrated in Figure 6.17. Bond stress was calculated as follows:

$$\tau = \frac{P}{A}$$

Where

τ= Bond stress

P= Pulling load

A= Bond area (rubber surface in contact with ABS)

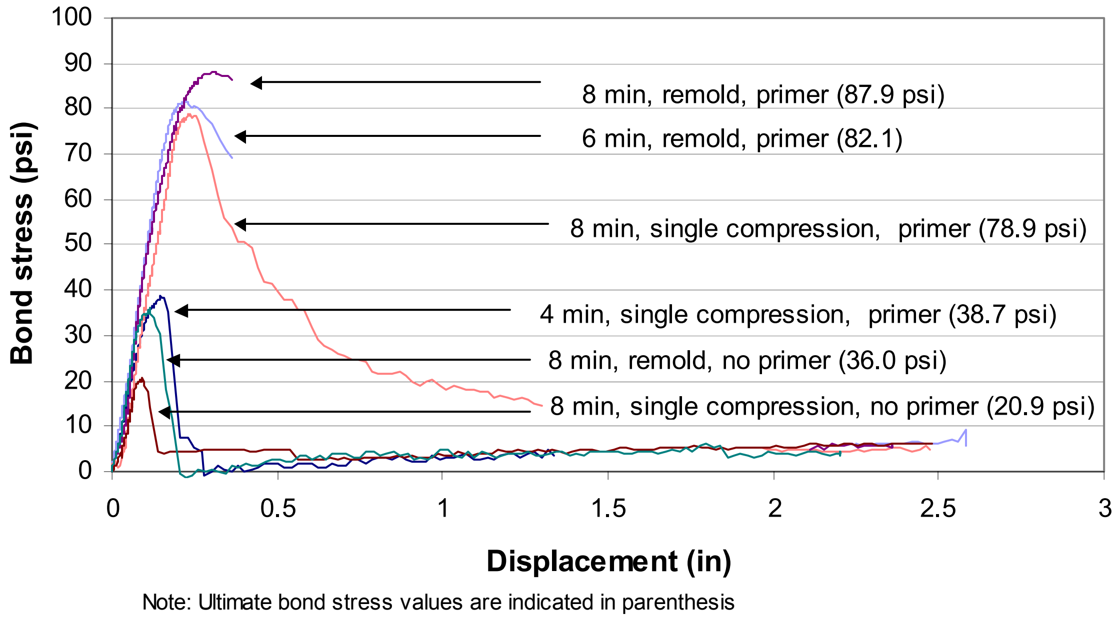


Figure 6.16 Bond Stress vs. Deflection for Pull Out Tests on ABS – Rubber Interface

Table 6.13 Bond Strength Test Results ABS-Rubber Interface

Bond mechanism	Molding Process	Molding Time	Ultimate bond stress (psi)
No primer	Single compression	8	20.9
	Remolded	8	36.0
Primer	Single compression	4	38.7
	Remolded	6	82.1
	Single compression	8	78.9
	Remolded	8	87.9

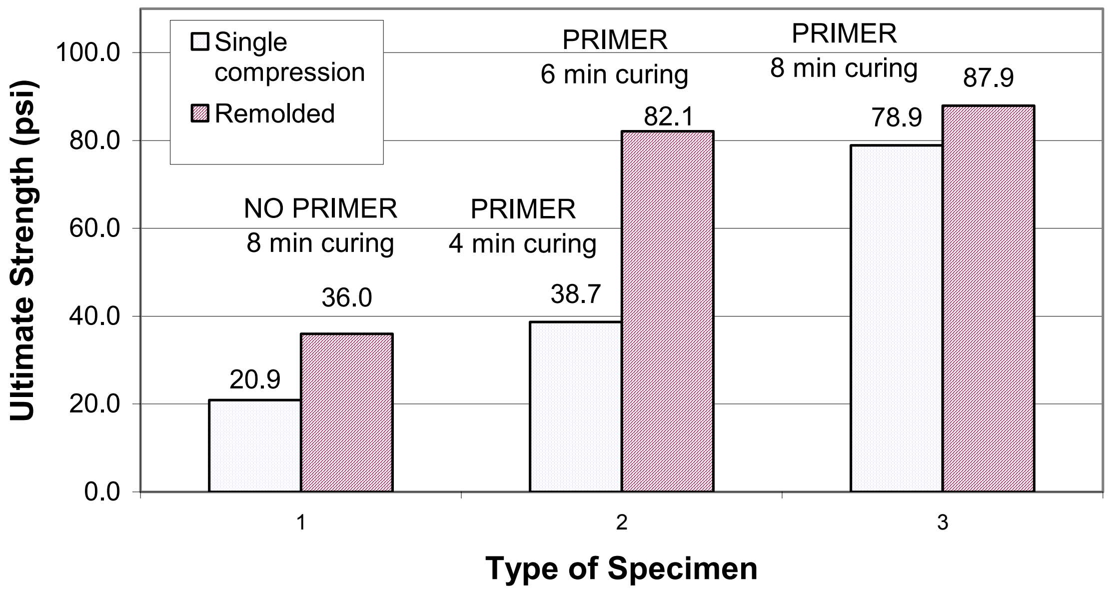


Figure 6.17 Results of Bond Strength Tests on ABS – Rubber Interface With and Without Primer for Different Molding (Curing) Duration

6.9.2 Analysis and Discussion of Bond Strength Test on Rubber-ABS Interface

From the pull out tests, it was observed that:

- Better bond stress between rubber and ABS interface was obtained when the specimens were compression molded for 8 minutes. Specimens with 4 minute cure showed bond strength of 38.7 psi as compared to 78.9 psi for specimens with 8 minute cure. Specimens cured for 6 minutes showed bond strength of 82.1 psi as compared to 87.9 psi for specimens cured for 8 minutes
- Use of primer increased the bond strength. Specimens without primer had bond strength of 20.9 psi as compared to 78.9 psi for a single molding cycle with 8 minute curing. For specimens with primer, samples cured for just 4

minutes showed bond strength of 38.7 psi which is 85% higher than the bond strength (20.9 psi) obtained for the 8 minute cured sample without primer.

- Remolding increased the bond strength significantly. Specimens without primer showed an increase from 20.9 psi to 36.0 psi (72% increase) in bond strength when remolded. Samples with primer showed an increase from 78.9 psi to 87.9 psi in bond strength when remolded.

It can be concluded that the optimum bond strength can be obtained when primer is applied to the rubber surface and specimens are remolded. However, taking into account that under a mass production operation, remolding of products will double the processing time and eventually increase the cost, remolding of samples should be avoided if possible. Remolding may increase the bond strength by up to 10%.

CHAPTER 7

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR COUPON SPECIMENS FROM CONDITIONED RECYCLED THERMOPLASTICS

7.1 Introduction

Aging (conditioning) of fiber reinforced (chopped) and non- fiber reinforced ABS and PC thermoplastics specimens manufactured from virgin and recycled electronic shredder residue (ESR) was carried out for a period of 18 months which is equivalent to more than 60 years of natural weathering. Based on the accelerated aging study by Vijay and GangaRao (1999), glass fiber reinforced sand coated bars subjected to salt and alkaline conditioning indicated maximum strength reductions of 21.9% and 37.5%, respectively, over 30 months duration. Based on the most severe alkaline conditioning, the authors predict the serviceability of those GFRP bars with urethane modified vinylester (thermoset) resins to be at least 60 years with 20% sustained stress. In our experiments, based on 30% maximum strength reduction without sustained stress over 18 months, it would be safe to assume at least 60 years of service life for products made of recycled polymers. However, careful considerations has to be given to type of fibers, purity of resins, pH, and sustained stress values, and quality control in manufacturing, before applying such conclusions to a particular recycled product. After conditioning, the coupon specimens were tested to evaluate tension, bending, compression, impact, and hardness properties.

7.2 Summary of Tension Test Results

Specimens without chopped fibers conditioned for 18 months:

- Maximum reduction in tensile strength without chopped fibers was 6.1% and 9.6% for ABS and PC specimens, respectively. Average maximum tensile strength reduction in those ABS and PC specimens during the aging period was 5.7% and 7.9%, respectively.
- Maximum reduction in tensile stiffness of ABS specimens without chopped fibers was 3.3%. Average maximum reduction in those ABS specimens during the aging period was 2.0%. No reductions (some gains) in tensile stiffness were observed for PC specimens without chopped fibers.

Specimens with chopped fibers conditioned for 18 months:

- Maximum reduction in tensile strength with chopped fibers was 13.6% and 28.4% for ABS and PC specimens, respectively. Average maximum tensile strength reduction in those ABS and PC specimens was 11.1% and 28.2%.
- Maximum reduction in tensile stiffness with chopped fibers was 5.7% and 2.9% for ABS and PC specimens, respectively. Average maximum tensile strength reduction in those ABS and PC specimens during aging period was 5.7% and 2.5%, respectively.

7.3 Summary of Bending Test Results

Specimens without chopped fibers conditioned for 18 months:

- Maximum reduction in bending strength without chopped fibers was 25.9% and 26.8% for ABS and PC specimens, respectively. Average maximum bending strength reduction in those ABS and PC specimens during the aging period was 17.4% and 18.94%, respectively.

- Maximum reduction in bending stiffness of ABS specimens was 16.5% for specimens without chopped fibers. Average maximum reduction in the aging period was 13.0%. No reductions in bending stiffness of PC were observed for specimens without chopped fibers during the aging period.

Specimens with chopped fibers conditioned for 18 months:

- Maximum reduction in bending strength with chopped fibers was 30.9% and 26.2% for ABS and PC specimens, respectively. Average maximum bending strength reduction in those ABS and PC specimens during the aging period was 26.4% and 22.1%, respectively.
- Maximum reduction in bending stiffness of ABS specimens was 17.4% for specimens with chopped fibers. Average maximum reduction in the aging period was 13.3%. No reductions in bending stiffness of PC were observed for specimens with chopped fibers during the aging period.

7.4 Summary of Compression Test Results

Specimens without chopped fibers conditioned for 18 months:

- Maximum reduction in compressive strength without chopped fibers was 8.7% and 5.6% for ABS and PC specimens, respectively. Average maximum compressive strength in those ABS and PC specimens during the aging period was 8.0% and 3.8%, respectively.

- Maximum reduction in compressive stiffness of ABS specimens was 19.5% for specimens without chopped fibers. Average maximum reduction in the aging period was 19.5%. No reductions in compressive stiffness of PC were observed for specimens without chopped fibers during the aging period.

<u>Specimens with chopped fibers conditioned for 18 months:</u>

- Maximum reduction in compressive strength with chopped fibers was 32.4% and 44.7% for ABS and PC specimens, respectively. Average maximum compressive strength reduction in those ABS and PC specimens during the aging period was 26.5% and 41.7%, respectively.
- Maximum reduction in compressive stiffness of ABS specimens was 34.8% for specimens with chopped fibers. Average maximum reduction in the aging period was 32.63%. No reductions in compressive stiffness of PC were observed for specimens with chopped fibers during the aging period.

7.5 Summary of Impact Test Results

<u>Specimens without chopped fibers conditioned for 18 months:</u>

- Maximum reduction in impact strength without chopped fibers was 2.3%, 61.6% and 38.8% for virgin, 100% recycled, and blended (20% virgin / 80% recycled) ABS specimens, respectively.
- Maximum reduction in impact strength of PC specimens was 1.5% for specimens without chopped fibers. Average maximum reduction in the aging period was 1.5%.

Specimens with chopped fibers conditioned for 18 months:

- Maximum reduction in impact strength of ABS specimens was 27.2% for specimens with chopped fibers. Average maximum reduction in the aging period was 23.5%.
- Maximum reduction in impact strength of PC specimens was 56.2% for specimens with chopped fibers. Average maximum reduction in the aging period was 54.9%.

7.6 Summary of Hardness Test Results

Specimens without chopped fibers conditioned for 18 months:

- Maximum reduction in hardness index of ABS specimens was 3.6% for specimens without chopped fibers. Average maximum reduction in the aging period was 2.2%. No reductions in hardness index of PC were observed for specimens without chopped fibers during the aging period.

Specimens with chopped fibers conditioned for 18 months:

- Maximum reduction in hardness index of ABS specimens was 5.4% for specimens with chopped fibers. Average maximum reduction in the aging period was 4.2%. No reductions in hardness index of PC were observed for specimens with chopped fibers during the aging period.

7.7 Summary of Creep Test Results

Specimens without chopped fibers conditioned for 18 months:

- At 20% sustained load, average creep coefficient for ABS specimens was 1.81 and 0.50 for PC samples.

- At 50% sustained loading, ABS specimens failed before 44 days. On the other hand, average creep coefficient for PC samples was 0.81.

Specimens with chopped fibers conditioned for 18 months:

- At 20% sustained loading, average creep coefficient for ABS specimens was 0.83 and 0.36 for PC samples.
- At 50% sustained loading, average creep coefficient for ABS specimens was 1.82 and 0.44 for PC samples.

7.8 Conclusions and Recommendations

- In general, virgin polymers were less susceptible to harsh environment as compared to 100% recycled and blend of virgin and recycled resins.
- Among tensile, bending, and compressive properties, compressive strength reductions were higher in terms of both strength and stiffness.
- Reductions in tensile strength and stiffness were less than those in bending strength and stiffness.
- Impact strength was most sensitive to aging among all the mechanical properties evaluated. For every type of ABS and PC specimens, a decrease in impact strength was observed varying from 1.5% (PC without fibers) to 61.6% (100% recycled ABS without fibers). Variability can be attributed in part to the random orientation of chopped fibers.
- Hardness properties of both ABS and PC specimens were not significantly affected in many of the specimens after aging.

- Reductions observed in tensile, bending and compressive strength and stiffness of PC specimens were generally higher than those in tensile, bending and compressive strength and stiffness of ABS specimens.
- Based on test results, recycled thermoplastic polymers with no fiber addition were found to retain at least 92% of their tensile strength, 81% of their bending strength and 92% of their compressive strength when conditioned up to 18 months under harsh environment.
- Based on test results, chopped fiber reinforced recycled thermoplastic polymers were found to retain at least 71% of their tensile strength, 73% of their bending strength and 58% of their compressive strength when conditioned under harsh environment.
- The aging process effect on stiffness of PC specimens with and without fibers was not significant. However stiffness of ABS specimens was more sensitive to aging under harsh environment than PC specimens.
- Based on test results, recycled thermoplastic polymers with no fiber addition were found to retain at least 98% of their tensile stiffness, 87% of their bending stiffness, and 80% of their compressive stiffness when conditioned under harsh environment.
- Based on test results, chopped fiber reinforced recycled thermoplastic polymers were found to retain at least 96% of their tensile stiffness, 86% of their bending stiffness and 64% of their compressive stiffness when conditioned under harsh environment.

- Higher reductions in strength and stiffness of specimens with chopped fibers are due to existence of moisture "channels" that facilitate moisture diffusion along fiber/resin interface resulting in higher deterioration in specimens with chopped fibers.
- Use of continuous fibers or proper surface coating to seal off the open interfaces is expected to reduce moisture related degradation problems.
- Based on the test results, it is concluded that the recycled polymers can be appropriately used with chopped or continuous fibers for long term structural or automobile applications with suitable knock-down factors.
- Further investigation using continuous fibers is highly recommended in order to evaluate a possible mitigation of aging effects and reduction on variability of test results.
- At 20% of sustained loading, PC specimens without fibers showed one-third the creep coefficient of ABS specimens (0.50 vs. 1.81). With fiber addition, creep coefficient in PC was near one half the creep coefficient in ABS specimens at 20% loading, i.e., (0.36 vs. 0.83).
- Sustained load level on ABS specimens is suggested to be limited to 20%. At 50% of sustained loading, PC specimens showed better capacity to carry sustained load than ABS specimens, either with or without fibers.
- Trends observed for the creep tests can be suitably used for knock-down factors. More tests with different fibers, sizing chemistry and stress levels are necessary for suggesting definitive creep coefficients.

CHAPTER 8

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR GUARDRAIL POST, RAIL AND OFFSET BLOCK

8.1 Introduction

As a result of this research, an FRP offset block made of recycled polymers and discarded rubber tire strips for joining posts and rails in highway guardrail systems was developed. FRP channel, trapezoidal and box shapes made of recycled resins were tested under tension, bending and compression. A prototype rubber-wood offset block was developed and tested in compression. Issues such as strength of wood for offset blocks and bond stress between rubber and ABS were also evaluated. In the following sections, summary of test results, conclusions and recommendation are given.

8.2 Summary of Offset Block Manufacturing

- Three different types of small size offset blocks were manufactured before producing prototype specimens:
  - Solid recycled ABS
  - Rubber and wood filled recycled ABS
  - Two stage molded rubber or wood filled recycled ABS

  Optimum combination of molding time and molding pressure was established through the manufacturing of small size solid blocks. For the best homogeneity and finish of the molded product, it was established that a 4 minute molding time and 20 Ton molding pressure is required.

  Wrapping glass fabric as well as rubber and wood core inclusion was carried out during the manufacturing of small size filled blocks. Based on these blocks, further research on bonding of ABS and rubber was conducted. Manufacturing difficulties such as proper packing of the required amount of pellets and filling the inner zone of the wrap were successfully sorted out during the development of small size filled blocks.

During two stage molding of coupons, it was found that heat transfer through the resin was not effective enough to melt the innermost portion of the specimens. This aspect led to the development of pre-heating concept, which resulted in finalizing a successful molding process.

- Temperature measurements on the mold during molding process showed good heat transfer through the top, bottom and side plates of the mold. However, heat transfer problem was noted based on poor melting of the pellets inside the wrap. Thus, heat transfer through the resin was inadequate to melt the inner pellets within an optimum molding time. Hence, pre-heating of mold and resin prior to compression molding was used as a successful solution to the problem.
- Pre-heated coupons with pre-molded inner tabs (tabs inside the wrap) were compression molded with satisfactory results leading to the manufacture of offset block module.
- A compression molding process was developed to obtain successful prototype offset block modules. The final process includes the following features:
  - Rubber core made of discarded automobile tires, which provides good shock absorption to the offset block module.

- Pre-molding of inner tabs to adequately fill the space and voids between rubber tire core and wrap.
- Pre-heating of mold and ABS pellets to facilitate the melting process during compression molding.

8.3 Summary of Recycled Polypropylene Channel Section

- Maximum bending stress of polypropylene (PP) channel section specimens was 13,831 psi. Considering that the specimens were very thin and failed at a low compressive strain, this premature failure can be attributed to combination of compression and punching at the loading point.
- Bending stiffness observed on the channel specimens was 2.45×10^6 psi. for compressive stress and 2.55×10^6 for tensile stress.
- Pure tension properties were not evaluated for polypropylene channel section, due to the similarity of the composite with the trapezoidal section material. Values obtained for trapezoidal polypropylene sections are also valid for channel section.

8.4 Summary of Recycled Polypropylene Trapezoidal Section

<u>Bending</u>

- Maximum bending stresses of polypropylene (PP) trapezoidal section specimens were 45,049 psi for tensile stress and 23,722 psi for compressive stress. Failure was due to compression and punching at the loading point. Tension strength of coupons showed a higher stress value of 72,000 psi to 82,000 psi.

- Bending stiffness observed on the trapezoidal specimens was 3.04×10^6 psi for compressive stress and 3.16×10^6 psi for tensile stresses.

Tension

- Maximum tensile stress of strips from PP trapezoidal section specimens was 82,897 psi.
- Tensile stiffness observed on the strips from PP trapezoidal specimens was 3.83×10^6 psi

Table 8.1 summarizes the mechanical properties established.

Table 8.1 Mechanical Properties of Recycled Trapezoidal Section

Type of test	Stiffness, E (psi)	Ultimate Stress (psi)
Bending	3.16×10^6 (tensile)	45,059 (tensile)
	3.04×10^6 (compressive)	23,722 (compressive)
Tension	3.83×10^6	82,897

8.5 Summary of Recycled and Virgin ABS Box Sections

Bending

- For three point bending tests, maximum bending stress of non-wrapped recycled ABS box section specimens was 12,845 psi. Maximum load under loading point was 280 lb.
- For three point bending tests, maximum bending stress of wrapped ABS box section specimens was 12,953 psi. Maximum load under loading point was 504 lb.

- For four point bending tests, maximum bending stress of wrapped ABS box section specimens was 19,733 psi. Maximum load at the point of failure was 589 lb.
- Ultimate stress increased from 12,953 psi in 3-point bending to 19,733 psi in 4-point bending. However, applied load at loading points just increased from 504 lbs. to 589 lbs. This fact indicates that for the wrapped recycled ABS box sections a punching failure occurs between 504 to 589 lbs. The difference between the two punching loads is possibly due to the non-uniform section thickness.
- Ultimate tensile bending stress for virgin ABS box sections failing in compression was 29,972 psi.
- Tensile bending stiffness for virgin ABS box sections was 3.60×10^6 psi whereas compressive bending stiffness was 2.52×10^6 psi.

Tension

- Maximum tensile stress of recycled ABS box section was 19,960 psi.
- Tensile stiffness of recycled ABS box section was 3.21×10^6 psi.

Mechanical properties of box sections are summarized in Table 8.2

Table 8.2 Mechanical Properties of Recycled and Virgin Box Sections

Type of ABS box section	Mechanical Property	Stiffness, E (psi)	Ultimate Stress (psi)
Recycled	Bending	$3.86x10^6$ (tensile)	12,845
		$2.28x10^6$ (compressive)	
	Tension	$3.21x10^6$	19,960
Recycled (wrapped)	Bending	$3.42x10^6$ (tensile)	19,733
		$2.94x10^6$ (compressive)	
Virgin	Bending	$3.60x10^6$ (tensile)	29,972
		$2.52x10^6$ (tensile)	

8.6 Summary of Recycled ABS Sheets

Bending

- Maximum bending stress of recycled ABS sheets for short plates was 27,991 psi. A shear failure causing a delamination of the plate was noted at a stress of 874 psi.
- Bending stiffness of recycled ABS short plates was $2.59x10^6$ psi for tensile bending stress and $2.33x10^6$ psi for compressive bending stress.
- Long sheet recycled ABS specimens had an ultimate bending stress of 39,518 psi. Compression failure (crushing) was observed. Shear stress between laminates at this bending stress level was 400 psi.
- Bending stiffness of recycled ABS sheets was $3.03x10^6$ psi for tensile bending stress and $2.91x10^6$ psi for compressive bending stress.

Tension

- Maximum tensile stress of recycled ABS sheets was 21,950 psi.
- Tensile stiffness of recycled ABS sheets was $2.68x10^6$ psi.

Compression

- Maximum compressive stress of strips from ABS sheet specimens was 6,900 psi. Specimens delaminated instead of crushing due to its large aspect ratio.
- Compressive stiffness for recycled ABS sheets was $3.58x10^6$ psi.

Mechanical properties of recycled ABS sheets are summarized in Table 8.3

Table 8.3 Mechanical Properties of Recycled ABS Sheets

Mechanical property	Stiffness, E (psi)	Ultimate Stress (psi)
Bending	$3.03x10^6$ (tensile)	39,518
	$2.91x10^6$ (compressive)	
Shear (between laminates)	-	874
Tension	$2.68 x10^6$	21,950
Compression	$3.58 x10^6$	6,900 (premature failure due to delamination)

8.7 Summary of Recycled ABS Belt-Type Material

- Maximum tensile stress of strips from ABS belt-type specimens were 29,800 for type A, 37,150 psi for type B and 24,450 for type C. Fiber volume fractions for each type of specimens were: 20% for A, 24% for B and 19% for specimen type C.
- Tensile stiffness observed on the strips from ABS belt-type specimens was $2.92x10^6$ psi for type A, $2.65x10^6$ psi for type B, and $2.09x10^6$ psi for type C.

8.8 Summary of Rubber-Wood Offset Block Model

Performance of the block was considered satisfactory, holding together during the compression test. Buckling of rubber strips at 5,250 lbs was expected as they were not laterally restrained. No damage was noted in the wood or rubber parts.

8.9 Summary of Tests on Wood Used in Rubber – Wood Model

Compression

- Maximum compressive stress parallel to grain of wood was found to be 8,399 psi. Maximum compressive stress perpendicular to grain was 1,472 psi.
- Compressive stiffness parallel to grain was 1.63×10^6 psi while compressive stiffness perpendicular to grain was 0.197×10^6 psi.

Impact

- Izod impact strength was 1.82 ft-lb/in. This value is very low compared to non- reinforced and virgin polymers.

Mechanical properties of recycled ABS sheets are summarized in Table 8.4

Table 8.4 Mechanical Properties of Wood from Rubber-Wood Model

Mechanical property	Stiffness, E (psi)	Ultimate Stress (psi)
Compression parallel to grain	1.63×10^6	8,399
Compression perpendicular to grain	0.197×10^6	1,472
Impact Strength (Izod)	-	1.82*

* Impact strength is in ft-lb/in

8.10 Summary of Bond Strength on Rubber-ABS Interface

- Primer application on rubber surface increased the bond strength between 2.44 to 3.76 times.

- Specimens cured during 8 minutes showed increase 2.04 times in bond strength as compared to specimens cured for 4 minutes. 7% gain in bond strength (1.07 times) was observed for specimens cured for 8 minutes as compared to specimens cured for 6 minutes.
- Remolding of specimens (secondary curing) increased the bond strength between 1.11 to 1.72 times.

8.11 Conclusions and Recommendations

Offset block manufacturing

- For a molding temperature of 400°F, optimum molding time and molding pressure were established by trying different combinations. For a 3"x3"x0.5" ABS product 4 minute molding gave best results. However, for larger samples optimum molding time is higher. For the final offset block module measuring 14"x8"x2" an optimum molding time of 10 minutes was determined.
- Heating the specimens for more than 12 minutes at 400°F is not recommended. It was observed throughout this research that samples molded for more than 12 minutes will have a brown finish (burn marks) on top and bottom surfaces. Also, overheated resins will try to expand out of the mold after releasing the molding pressure, thus lifting up the top plate and leading to a product with rough finish and voids.
- It was observed that the smaller the size of the pellets, the easier it is to fill the voids in the mold. However, this may be a disadvantage in terms of handling the specimen before preheating, because keeping the pellet pile in place becomes more difficult. No improvement on the final product finish or

homogeneity is expected from using small (ground) pellets if adequate melting and cure time are utilized.

- In order to overcome the heat transfer problems through the resin, an alternate approach to pre-heating of the pellets is the use of smaller pellets, this would facilitate the heat transfer through the resin. A minimum effective pellet size has to be determined by trial. Other approach would be blanketing the polymer with an inert gas. This would cool down the outside pellets to prevent degradation from overheating while the heat is transferred to the inner pellets in the mold. Installation of thermocouples inside the specimens and thermography procedures will help in understanding the heat transfer through the polymer molded samples.
- Discarded rubber tire strips used in this research were manually cut with a reciprocating saw. Cut edges obtained were non-uniform and posed placement problems for lateral pre-molded tabs. In a mass production process, it is recommended to improve the uniformity of rubber tire edges by means of a different cutting mechanism such as shearing or heating. Use of uniform rubber cores will also lead to the use of uniform ABS pre-cast tabs.
- The compression molding machine (12.5" x 12.5") available at WVU-CFC was not large enough to conduct compression molding of a module in a single heating stage. A compression molding machine with hot platens at least 15" x 10" must be used to avoid additional compression molding of the portion left out of the plates.

- Use of aluminum flashing as a cover for mold plates gave smoother finish than aluminum foil that gave a wrinkly finish. In addition, ease of de-molding was observed when aluminum flashing was used.
- Caution must be used at every stage of the process due to the manufacturing of large and heavy mold blocks at high temperatures. High temperature resistance gloves must be worn when handling hot elements. Special attention must be taken when carrying the pre-heated specimen from the oven to the molding machine. Pre-heated parts at 400°F (bottom plate + mold + pellets) weigh around 25 pounds. Use of a cart is recommended for moving these heavy mold and block assembly.
- One of the difficulties in the specimen preparation was to adequately fill the gap between rubber core and fabric wrap with ABS pellets. Pre-casting ABS tabs, which constitutes an additional step to be carried out before compression molding of the modules solved this problem. Molds that allow air escape from the specimens while molding would also contribute to void reduction.
- Alternate molding methods can be considered to overcome manufacturing difficulties. Injection molding process may demand less manufacturing effort. However, a proper injection mold capable of holding a core and a fiber wrap has to be developed.
- A successful procedure for compression molding of offset block was developed. Efforts need to be concentrated in characterizing the mechanical properties (tension, compression, bending and impact) of the modules and the offset block as a whole through standard but expensive crash tests.

- A new use for discarded rubber tires was found taking advantage of its shock absorption properties. Discarded rubber tires rubber is heavier than ABS resin. Weight of the finished module was around 7 lbs. Other core materials such as sawdust can also be evaluated to obtain a lighter final product.
- It is recommended that further optimization and improvement of the offset block can be carried out through finite element modeling.

Post and Rail

- Recycled Polypropylene channel and trapezoidal sections as well as recycled ABS box sections were tested. The three shapes, when tested in bending exhibited a combination of compression and punching failure. This failure mode is mostly due to small section thickness of 0.10" to 0.16". Testing of actual size specimens will give a better knowledge of punching behavior. Also, additional reinforcement at loading points (joints) can be implemented in actual guardrail systems to improve the load transfer and effectiveness of the sections.
- Stress and strain values obtained from the tests indicate suitability of all the shapes for use in highway guardrail systems. Recycled polypropylene shapes (channel and trapezoidal) showed better performance than recycled ABS box shape. However PP specimens had a fiber volume fraction of 41 to 43%, while ABS samples had 25%. Trapezoidal shape was the most effective section in terms of bending resistance.

- Tensile strength of recycled PP specimens was found to be 82,897 psi. This indicates that if punching problems are avoided, the material strength can be utilized more effectively.
- From the available sections of different shapes, it was difficult to obtain representative compression specimens due to the small thickness. Compression strength can be determined from specimens cut from actual size shapes for guardrails.
- Recycled ABS box section showed lower bending resistance as compared to other shapes tested. However, it was noted that these sections had a non-uniform thickness from 0.05" to 0.15". Improvements in the manufacturing process will lead to more uniform section with better mechanical properties.
- Wrapping of recycled ABS box sections contributed to an increase in the ultimate strength and punching resistance of the section.
- Recycled ABS sheets having a fiber volume fraction of 25% performed well under bending. Failure mode observed was crushing of the compression surface. Thickness of 0.375" for these sheets prevented a punching failure, which was observed for box sections with 0.10" thickness. Bending of short plates led to interlaminar shear failure at a maximum shear stress of 874 psi. Slender specimens in compression also failed in shear. It is recommended to improve the wet-out of fibers during manufacturing process to increase the shear strength.
- Recycled ABS belt-type specimens (tension elements) showed tensile resistance of 24,450 to 37,150 psi. Based on these results, it was concluded

that belt-type elements are suitable for carrying tensile loads on structural systems. However, due to their reduced thickness, they might be very sensitive to external agents such as lateral impact forces or harsh environment. Use of protective coating can alleviate this anticipated problem.

- A rubber-wood offset block prototype with no lateral restraint was manufactured and tested in compression. The need for lateral restraint to prevent buckling and a change in rubber-wood block considerations was evident from the tests.
- Wood from rubber – wood prototype was tested in compression parallel and perpendicular to grain. Compressive stress parallel to grain of 8,399 psi was comparable to virgin and recycled ABS compressive stress of 8,792 psi to 8,972 psi reported by (Bargo,2000). However, wood compressive strength was less than compressive stress for virgin and recycled PC (10,311 psi to 10,523 psi).
- Compressive stress of wood (8,399 psi) was also found to be less than compressive strength of reinforced polymers. Values established by (Bargo, 2000) are 13,135 psi to 14,891 psi for virgin and recycled ABS and 20,332 psi to 21,124 psi for virgin and recycled PC.
- Impact strength of wood for offset block was less than virgin ABS and PC impact resistance. However, impact strength of wood is comparable to that of recycled ABS and higher than fiber reinforced ABS.

- Impact strength of all combinations of virgin and recycled PC with and without fiber addition evaluated by (Bargo,2000), showed higher values than those obtained for wood specimens from offset blocks.
- It was determined that better bond strength between ABS and rubber was obtained when primer was applied to the bonding surface. Curing time of 8 minute also showed better results than 6 and 4 minute curing. Remolding of specimens resulted in a gain of 10% in bond strength.
- Based on test results and manufacturing issues, it is concluded that recycled polymers are suitable for developing highway and automotive applications.

Recommendation for Future Research:

Further research should be carried out on:

- Use of continuous fiber / fabrics for product manufacturing
- Development of a more efficient offset block in terms of lighter weight
- Crash testing of manufactured offset blocks
- Improvement of recycled polymer shapes in terms of fiber / fabric architecture and manufacturing
- Testing of actual size polymer shapes
- Developing design philosophies for recycled polymer posts, rails and offset blocks for highway guardrail systems

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APPENDIX A

TENSION TEST RESULTS FOR CONDITIONED SPECIMENS

Table A.1 Tension Test Results for 2 Months of Aging

Type	Specimen	Maximum Load lbs.	Maximum Stress psi	Average Max. Stress psi	Strain @ Max. load %	Max. Strain @ Failure %	Stiffness, E psi x 10^6	Average Stiffness, E psi x 10^6
ABS	TA1-9	341	5866	5866	No strains were recorded at 2 months of aging			
	TA2-12	582	9683	9683				
	TA3-11	308	5285	5285				
	TA4-14	513	8802	5285				
	TA5-10	325	5558	5558				
	TA6-12	561	9607	9607				
PC	TP1-6	510	8210	8210				
	TP2-7	959	15101	15101				
	TP3-6	504	7813	7813				
	TP4-6	893	14203	14203				
	TP5-7	532	8072	8072				
	TP6-6	964	14831	14831				

Table A.2 Tension Test Results for 4 Months of Aging

Type	Specimen	Maximum Load lbs.	Maximum Stress psi	Average Max. Stress psi	Strain @ Max. load %	Max. Strain @ Failure %	Stiffness, E psi x 10^6	Average Stiffness, E psi x 10^6
ABS	TA1-10	-	-	-	-	-	-	-
	TA2-13	606	10510	10510	-	-	1.019	1.019
	TA3-13	337	5988	5988	0.96	5.08	-	-
	TA4-15	550	9388	9388	-	-	-	-
	TA5-11	-	-	-	0.99	1.08	0.360	0.360
	TA6-13	608	10619	10619	-	-	1.050	1.050
PC	TP1-10	578	9261	9261	-	-	0.309	0.309
	TP2-8	994	15721	15721	-	-	1.008	1.008
	TP3-8	570	9233	9233	-	-	0.315	0.315
	TP4-9	891	14205	14205	-	-	0.964	0.964
	TP5-8	606	9163	9163	-	-	0.337	0.337

Table A.3 Tension Test Results for 10 Months of Aging

Type	Specimen	Maximum Load lbs.	Maximum Stress psi	Average Max. Stress psi	Strain @ Max. load %	Max. Strain @ Failure %	Stiffness, E psi x 10^6	Average Stiffness, E psi x 10^6
ABS	TA1-12	348	6118	6118	2.02	2.12	0.360	0.360
	TA2-14	506	9084		0.97	1.70	1.005	
	TA2-15	542	9736	9410	1.09	1.09	1.089	1.047
	TA3-16	317	5580		2.07	2.71	0.336	
	TA3-17	320	5518	5549	2.39	8.18	0.338	0.337
	TA4-16	417	7346		0.85	0.85	0.969	
	TA4-17	447	7858	7602	0.60	0.60	0.849	0.909
	TA5-12	313	5693		1.79	1.79	0.343	
	TA5-13	325	5888	5790	1.97	1.98	0.351	0.347
	TA6-15	-	-	-	-	-	1.019	
	TA6-16	518	9124	9124	1.04	1.04	0.967	0.993
PC	TP1-10	541	8817	8817	6.88	13.56	0.364	0.364
	TP2-12	812	12975		1.79	1.79	1.072	
	TP2-15	802	12758	12867	1.74	1.74	1.080	1.076
	TP3-10	539	8978		6.56	13.62	0.374	
	TP3-11	540	8989	8983	6.74	13.57	0.353	0.364
	TP4-10	751	12454		1.60	1.60	1.104	
	TP4-11	772	12596	12525	1.68	1.68	1.018	1.061
	TP5-10	521	8160		3.57	3.58	0.343	
	TP5-11	580	9019	8589	7.07	13.53	0.350	0.347
	TP6-12	786	12619		1.57	1.57	1.098	
	TP6-16	822	13135	12877	1.65	1.84	1.099	1.099

Table A.4 Tension Test Results for 18 Months of Aging

Type	Specimen	Maximum Load lbs.	Maximum Stress psi	Average Max. Stress psi	Strain @ Max. load %	Max. Strain @ Failure %	Stiffness, E psi x 10^6	Average Stiffness, E psi x 10^6
ABS	TA1-13	336	5728		1.97	2.83	0.348	
	TA1-14	337	5890	5809	1.90	2.77	0.375	0.362
	TA2-16	593	10439		1.23	1.23	1.010	
	TA2-17	614	10917	10678	1.27	1.28	1.043	1.027
	TA3-19	311	5319		1.93	4.10	0.334	
	TA3-20	312	5402	5360	1.96	4.14	0.328	0.331
	TA4-18	498	8516		1.02	1.04	1.001	
	TA4-19	493	8759	8637	1.00	1.59	1.022	1.012
	TA5-14	332	5838		1.93	3.56	0.348	
	TA5-15	316	5528	5683	1.81	1.87	0.353	0.351
	TA6-16	524	9000		1.07	1.07	1.029	
	TA6-17	210	8832	8916	1.04	1.04	1.053	1.041
PC	TP1-18	527	8320		5.17	9.12	0.349	
	TP1-21	521	8383	8352	5.34	9.21	0.350	0.35
	TP2-16	749	11931		1.65	1.65	1.029	
	TP2-20	744	11853	11892	1.61	1.61	1.107	1.068
	TP3-12	515	8352		5.46	8.90	0.344	
	TP3-13	512	8307	8329	5.36	9.40	0.341	0.343
	TP4-16	665	10498		1.43	1.43	1.050	
	TP4-21	719	11343	10920	1.71	1.71	1.095	1.073
	TP5-12	538	8239		5.11	9.79	0.345	
	TP5-17	548	8132	8185	5.12	9.13	0.352	0.349
	TP6-17	753	11855		1.67	1.68	1.094	
	TP6-21	753	11842	11848	1.65	1.65	1.087	1.091

APPENDIX B

BENDING TEST RESULTS FOR CONDITIONED SPECIMENS

Table B.1 Bending Test Results for 2 Months of Aging

Type	Specimen	Maximum Load lbs.	Maximum Stress psi	Deflection at Max. Stress in	Max. Deflection Recorded in	Stiffness, E Psi x 10^6
ABS	BA2-18	25.2	16033	0.41	0.43	-
	BA3-19	13.5	8931	0.49	0.49	-
	BA4-18	23.2	15522	0.33	0.37	-
	BA5-18	13.7	9295	0.49	0.49	-
	BA6-19	26.1	17793	0.41	0.45	-
PC	BP1-11	11.1	7494	0.43	0.45	-
	BP2-12	30.6	20228	0.42	0.47	-
	BP3-11	11.8	8235	0.45	0.46	-
	BP4-12	27.1	18830	0.45	0.46	-
	BP5-11	16.2	10136	0.44	0.45	-
	BP6-11	29.6	19606	0.44	0.45	-

Table B.2 Bending Test Results for 4 Months of Aging

Type	Specimen	Maximum Load lbs.	Maximum Stress psi	Deflection at Max. Stress in	Max. Deflection Recorded in	Stiffness, E psi x 10^6
ABS	BA1-5	35.2	6728	0.30	0.37	0.334
	BA2-19	36.2	15211	0.38	0.39	0.932
	BA3-20	11.4	7862	0.50	0.80	0.364
	BA4-19	19.2	13886	0.31	0.33	0.93
	BA5-19	12.2	8412	0.57	0.82	0.346
	BA6-20	20.6	14043	0.34	0.36	0.917
PC	BP1-13	13.5	9283	0.63	0.94	0.341
	BP2-13	29.6	21336	0.47	0.50	1.001
	BP3-12	11.7	8398	0.59	0.67	0.354
	BP4-13	23.5	17117	0.38	0.42	0.994
	BP5-12	14.5	10602	0.77	0.78	0.406
	BP6-12	28.8	21159	0.44	0.45	1.062

Table B.3 Bending Test Results for 10 Months of Aging

Type	Specimen	Maximum Load lbs.	Maximum Stress psi	Average Max. Stress psi	Deflection at Max. Stress in	Max. Deflection Recorded in	Stiffness, E psi x 10^6
ABS	BA1-8	Not tested to failure			-	-	0.699
	BA1-9	60.1	10747	10747	0.51	0.95	-
	BA2-6	Not tested to failure			-	-	1.215
	BA2-7	82.2	14631	14631	0.22	0.22	-
	BA3-6	Not tested to failure			-	-	0.408
	BA3-7	50.5	8923	8923	0.32	0.32	-
	BA4-3	64.0	11235		0.15	0.15	0.998
	BA4-6	74.5	13088	12162	0.20	0.20	-
	BA5-3	57.7	10107		0.40	0.44	0.385
	BA5-4	61.1	10785	10446	0.50	0.79	-
	BA6-3	65.1	11263		0.19	0.19	0.925
	BA6-4	66.0	11537	11400	0.27	0.28	-
PC	BP1-14	18.4	12476		0.64	0.65	0.416
	BP1-16	25.4	17414	14945	1.08	1.23	-
	BP2-14	29.7	20185		0.40	0.40	1.089
	BP2-15	45.9	30555	25370	0.48	0.48	-
	BP3-13	24.4	16368		0.93	1.00	0.445
	BP3-14	26.1	18286	17327	1.22	1.24	-
	BP4-16	49.1	33187		0.43	0.43	1.001
	BP4-17	35.5	23985	28586	0.48	0.48	-
	BP5-13	20.6	13306		0.64	0.64	0.452
	BP5-14	26.9	16740	15023	1.24	1.24	-
	BP6-13	32.8	21537		0.41	0.52	1.168
	BP6-15	38.9	26281	23909	0.45	0.47	-

Table B.4 Bending Test Results for 18 Months of Aging

Type	Specimen	Maximum Load lbs.	Maximum Stress psi	Average Max. Stress psi	Deflection at Max. Stress in	Max. Deflection Recorded in	Stiffness, E psi x 10^6
ABS	BA1-11	44.0	7817		0.23	0.35	0.381
	BA1-12	56.7	10124	8971	0.41	0.82	-
	BA2-12	75.9	13551		0.19	0.19	0.960
	BA2-13	81.5	14609	14080	0.19	0.19	-
	BA3-8	45.2	8229		0.27	0.33	0.391
	BA3-11	46.8	8793	8511	0.17	0.38	-
	BA4-9	68.9	12544		0.17	0.17	0.996
	BA4-10	71.1	12665	12605	0.15	0.15	-
	BA5-10	46.8	8466		0.28	0.34	0.395
	BA5-11	58.0	10372	9419	0.42	0.55	-
	BA6-10	68.0	12174		0.18	0.18	0.962
	BA6-11	76.6	13894	13034	0.19	0.19	-
PC	BP1-17	18.3	11377		0.65	0.66	0.408
	BP1-18	19.4	13635	12506	0.79	0.99	-
	BP2-16	28.1	20275		0.40	0.43	1.031
	BP2-17	27.6	19540	19908	0.37	0.38	-
	BP3-15	15.9	11513		0.60	0.63	0.450
	BP3-16	17.6	12720	12117	0.92	0.99	-
	BP4-18	25.6	19030		0.37	0.39	1.037
	BP4-19	28.5	20566	19798	0.43	0.47	-
	BP5-15	19.4	12155		0.71	0.79	0.430
	BP5-16	19.1	12577	12366	0.84	0.99	-
	BP6-16	29.0	20021		0.39	0.39	1.027
	BP6-19	28.8	20861	20441	0.37	0.38	-

APPENDIX C

COMPRESSION TEST RESULTS FOR CONDITIONED SPECIMENS

Table C.1 Compression Test Results for 2 Months of Aging

Type	Specimen	Maximum Load lbs.	Maximum Stress psi	Average Max. Stress psi	Reduction in Length at Max. Stress in	Stiffness, E psi x 10^6
ABS	CA1-6a	1120	8547		0.058	-
	CA1-6b	1313	9870	9208	0.080	-
	CA3-4a	1076	8054		0.055	-
	CA3-4b	1069	8001	8027	0.046	-
	CA4-4a	1290	9998		0.051	-
	CA4-4b	1360	10125	10062	0.045	-
	CA5-6a	1088	8482		0.045	-
	CA5-6b	1048	8154	8318	0.050	-
	CA6-5a	1351	10309		0.047	-
	CA6-5b	1356	10307	10308	0.047	-
PC	CP1-3a	1294	10210		0.071	-
	CP1-3b	1313	10259	10234	0.080	-
	CP2-3a	1587	12671		0.142	-
	CP2-3b	1607	12146	12408	0.103	-
	CP3-4a	1257	9780		0.057	-
	CP3-4b	1246	10008	9894	0.061	-
	CP4-3a	1617	12389		0.057	-
	CP4-3b	1445	10538	11463	0.068	-
	CP5-4a	1285	10018		0.070	-
	CP5-4b	1305	9844	9931	0.067	-
	CP6-12a	1544	12230		0.069	-
	CP6-12b	1568	12595	12412	0.067	-

Table C.2 Compression Test Results for 4 Months of Aging

Type	Specimen	Maximum Load lbs.	Maximum Stress psi	Average Max. Stress psi	Reduction in Length at Max. Stress in	Stiffness, E psi x 10^6
ABS	CA1-7a	1217	9341		0.070	-
	CA1-7b	1290	10430	9886	0.086	-
	CA2-5a	1462	11238		0.068	-
	CA2-5b	1556	12157	11698	0.060	-
	CA3-5a	1121	8670	8670	0.066	-
	CA4-7a	1584	12301		0.066	-
	CA4-7b	1588	12579	12440	0.063	-
	CA5-7a	1207	9287	9287	0.032	-
	CA6-6a	1388	11151	11151	0.065	-
PC	CP1-4a	1359	10259	10259	0.058	0.283
	CP2-4a	1671	13613		0.068	0.481
	CP2-4b	1663	13465	13539	0.063	-
	CP3-6a	1356	11348	11348	0.074	0.302
	CP4-6a	1668	13612		0.055	0.463
	CP4-6b	1642	13405	13509	0.068	-
	CP5-14a	1394	10979	10979	0.063	0.355
	CP6-14a	2364	17500	17500	0.053	0.481

Table C.3 Compression Test Results for 18 Months of Aging

Type	Specimen	Maximum Load lbs.	Maximum Stress psi	Average Max. Stress psi	Reduction in Length at Max. Stress in	Stiffness, E psi x 10^6
ABS	CA1-10a	1151	7678		0.041	-
	CA1-10b	1206	8810	8244	0.061	0.397
	CA2-11a	1245	9825		0.053	-
	CA2-11b	1424	10927	10376	0.085	0.943
	CA3-12a	1064	8429		0.040	-
	CA3-12b	1073	8332	8381	0.067	0.053
	CA4-11a	1316	10241		0.045	-
	CA4-11b	1331	9999	10120	0.044	0.600
	CA5-5a	1143	9165		0.045	-
	CA5-5b	1125	8857	9011	0.060	0.330
	CA6-7a	1420	10834		0.068	-
	CA6-7b	1415	11696	11265	0.051	0.709
PC	CP1-5a	1280	10364		0.082	-
	CP1-5b	1304	10323	10344	0.074	0.320
	CP2-7a	1520	12753		0.077	-
	CP2-7b	1606	12421	12587	0.084	0.511
	CP3-13a	1304	10432		0.063	-
	CP3-13b	1282	10159	10296	0.069	0.344
	CP4-20a	1880	15257		0.067	-
	CP4-20b	1548	12240	13749	0.063	0.494
	CP5-16a	1176	9360		0.071	-
	CP5-16b	1363	11081	10221	0.077	-
	CP6-24a	1589	12375		0.068	-
	CP6-24b	1555	12469	12422	0.084	0.477

APPENDIX D

IMPACT TEST RESULTS FOR CONDITIONED SPECIMENS

Table D.1 Impact Test Results for 2 Months of Aging

Type	Specimen	Indicated Impact Strength ft-lbs$_f$	Corrected Impact Strength ft-lbs$_f$	Impact Strength ft-lbs$_f$/in	Failure Type
ABS	IA1-7	0.51	0.46	3.67	H
	IA2-8	0.22	0.17	1.31	C
	IA3-8	0.29	0.25	1.91	C
	IA4-7	0.17	0.12	0.90	C
	IA5-8	0.41	0.37	2.86	H
	IA6-7	0.18	0.13	1.04	C

Table D.2 Impact Test Results for 4 Months of Aging

Type	Specimen	Indicated Impact Strength ft-lbs$_f$	Corrected Impact Strength ft-lbs$_f$	Impact Strength ft-lbs$_f$/in	Failure Type
ABS	IA1-8	0.52	0.47	3.76	H
	IA2-9	0.23	0.18	1.40	C
	IA3-9	0.21	0.15	1.24	C
	IA4-10	0.16	0.10	0.83	C
	IA5-9	0.37	0.32	2.54	C
	IA6-8	0.19	0.13	1.08	C
PC	IP1-19	1.86	1.83	14.67	P
	IP2-20	0.24	0.19	1.48	C
	IP3-18	1.75	1.72	13.77	P
	IP4-21	0.17	0.11	0.91	C
	IP5-18	1.85	1.82	14.59	C
	IP6-20	0.21	0.15	1.24	C

Table D.3 Impact Test Results for 10 Months of Aging

Type	Specimen	Indicated Impact Strength ft-lbs$_f$	Corrected Impact Strength ft-lbs$_f$	Impact Strength ft-lbs$_f$/in	Average Impact Strength ft-lbs$_f$/in	Failure Type
ABS	IA1-7	0.52	0.47	3.76		H
	IA1-9	0.46	0.41	3.27		H
	IA1-10	0.46	0.41	3.27	3.44	H
	IA2-4	0.22	0.17	1.32		C
	IA2-10	0.22	0.17	1.32	1.32	C
	IA3-4	0.16	0.10	0.83		C
	IA3-16	0.16	0.10	0.83	0.83	C
	IA4-7	0.15	0.09	0.75		C
	IA4-8	0.15	0.09	0.75	0.75	C
	IA5-7	0.26	0.21	1.65		C
	IA5-16	0.29	0.24	1.89	1.77	C
	IA6-9	0.17	0.11	0.91		C
	IA6-10	0.19	0.13	1.08	1.00	C
PC	IP1-21	1.85	1.82	14.59	14.59	P
	IP2-22	0.23	0.18	1.40	1.40	C
	IP3-19	1.98	1.96	15.65	15.65	C
	IP4-22	0.17	0.11	0.91	0.91	C
	IP5-19	1.89	1.86	14.91	14.91	P
	IP6-21	0.22	0.17	1.32	1.32	C

Table D.4 Impact Test Results for 18 Months of Aging

Type	Specimen	Indicated Impact Strength ft-lbs$_f$	Corrected Impact Strength ft-lbs$_f$	Impact Strength ft-lbs$_f$/in	Average Impact Strength ft-lbs$_f$/in	Failure Type
ABS	IA1-8	0.52	0.47	3.76		H
	IA1-9	0.45	0.40	3.19		H
	IA1-10	0.46	0.41	3.27	3.41	H
	IA2-5	0.21	0.15	1.24		C
	IA2-6	0.21	0.15	1.24	1.24	C
	IA3-5	0.16	0.10	0.83		C
	IA3-6	0.17	0.11	0.91	0.87	C
	IA4-9	0.15	0.09	0.75		C
	IA4-10	0.15	0.09	0.75	0.75	C
	IA5-1	0.21	0.15	1.24		C
	IA5-2	0.21	0.15	1.24		C
	IA5-3	0.22	0.17	1.32		C
	IA5-4	0.27	0.22	1.73		C
	IA5-5	0.27	0.22	1.73		C
	IA5-6	0.24	0.19	1.48	1.46	C
	IA6-6	0.16	0.10	0.83		C
	IA6-7	0.17	0.11	0.91	0.87	C
PC	P1-21	1.97	1.95	15.56	15.56	P
	P2-18	0.23	0.18	1.40		C
	P2-22	0.25	0.20	1.57	1.48	C
	P3-17	1.90	1.87	14.99	14.99	P
	P4-20	0.16	0.10	0.83		C
	P4-22	0.15	0.09	0.75	0.79	C
	P5-17	1.98	1.96	15.65	15.65	P
	P6-17	0.21	0.15	1.24		C
	P6-21	0.20	0.14	1.16	1.20	C

APPENDIX E

HARDNESS TEST RESULTS FOR CONDITIONED SPECIMENS

Table E.1 Hardness Test Results for 2 Months of Aging

Type	Specimen	Hardness Index
ABS	HA1-1	12.44
	HA2-1	12.80
	HA3-1	12.58
	HA4-1	11.76
	HA5-1	12.44
	HA6-1	12.16
PC	HP1-3	12.00
	HP2-3	11.10
	HP3-3	11.50
	HP4-3	11.44
	HP5-4	10.74
	HP6-2	11.38

Table E.2 Hardness Test Results for 4 Months of Aging

Type	Specimen	Hardness Index
ABS	HA1-2	11.70
	HA2-2	11.50
	HA3-2	11.40
	HA4-2	11.30
	HA5-2	10.80
	HA6-2	11.00
PC	HP1-4	11.30
	HP2-4	11.20
	HP3-4	10.80
	HP4-4	10.80
	HP5-5	11.20
	HP6-3	11.40

Table E.3 Hardness Test Results for 10 Months of Aging

Type	Specimen	Hardness Index	Average Hardness Index
ABS	HA1-3	12.30	
	HA1-4	11.90	12.10
	HA2-3	10.30	
	HA2-4	11.70	11.00
	HA3-3	11.70	
	HA3-4	10.50	11.10
	HA4-3	10.00	
	HA4-4	11.60	10.80
	HA5-3	11.40	
	HA5-4	10.80	11.10
	HA6-3	10.10	
	HA6-4	11.70	10.90
PC	HP1-5	10.90	
	HP1-6	11.30	11.10
	HP2-5	10.70	
	HP2-6	11.90	11.30
	HP3-5	10.60	
	HP3-6	11.60	11.10
	HP4-5	11.50	
	HP4-6	10.30	10.90
	HP5-6	11.00	
	HP5-7	10.80	10.90
	HP6-4	10.90	
	HP6-6	10.90	10.90

Table E.4 Hardness Test Results for 18 Months of Aging

Type	Specimen	Hardness Index	Average Hardness Index
ABS	HA1-3	11.80	
	HA1-4	12.20	12.00
	HA2-3	10.70	
	HA2-4	11.10	10.90
	HA3-3	11.50	
	HA3-4	10.50	11.00
	HA4-3	11.20	
	HA4-4	10.00	10.60
	HA5-3	10.20	
	HA5-4	11.60	10.90
	HA6-3	11.60	
	HA6-4	10.00	10.80
PC	HP1-5	10.60	
	HP1-6	11.40	11.00
	HP2-5	11.70	
	HP2-6	10.90	11.30
	HP3-5	11.00	
	HP3-6	11.00	11.00
	HP4-5	10.90	
	HP4-6	10.70	10.80
	HP5-6	10.50	
	HP5-7	11.30	10.90
	HP6-4	10.90	
	HP6-6	10.90	10.90

APPENDIX F

COMPARISON CHARTS OF TEST RESULTS ON CONDITIONED RECYCLED COUPONS

Table F.1 Tensile Strength Variations in Aged ABS Specimens

Specimen Type	Max. Tensile Stress (psi)					% Change		
	Months of aging					End of period	Max gain in period	Max red. in period
	0	2	4	10	18			
A1	6174	5866	-	6118	5809	-5.9	No gain	-5.9
A2	10299	9683	10510	9410	10678	+3.7	+3.7	-8.6
A3	5578	5285	5988	5549	5360	-3.9	+7.4	-5.3
A4	8800	8802	9388	7602	8637	-1.9	+6.7	-13.6
A5	5916	5558	-	5790	5683	-3.9	No gain	-6.1
A6	8911	9607	10619	9123	8916	+0.1	+19.2	No red.
Average reduction (-ve values only) without fibers (A1,A3,A5)						-4.6		
Average change (+ve and –ve values) without fibers (A1,A3,A5)						-4.6	+7.4	-5.7
Average reduction (-ve values only) with fibers (A2,A4,A6)						-1.9		
Average change (+ve and –ve values) with fibers (A2,A4,A6)						+0.6	+9.8	-11.1

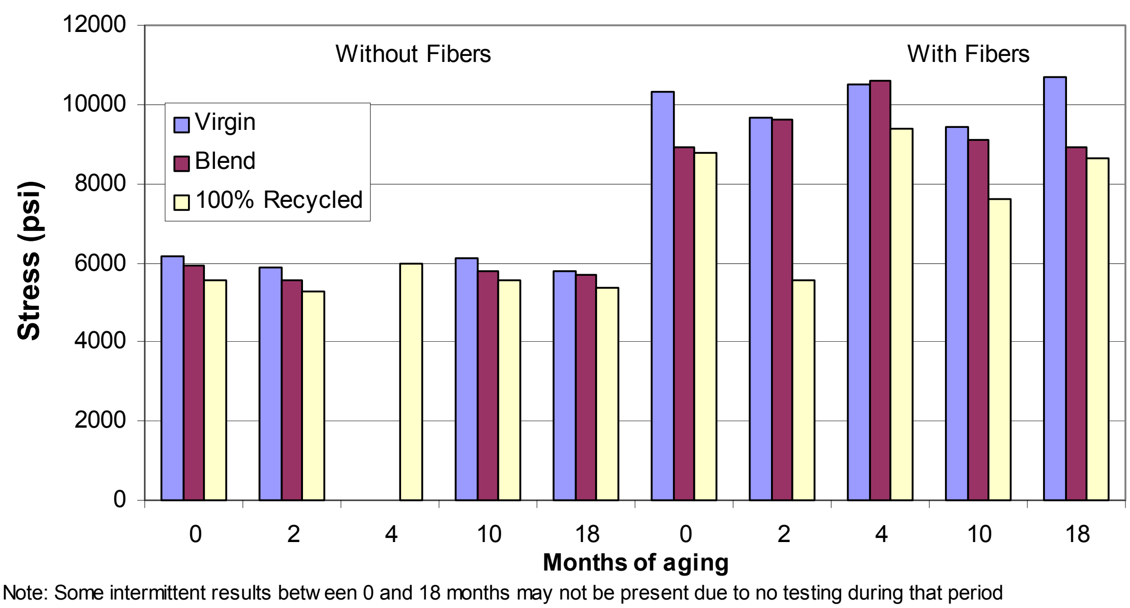
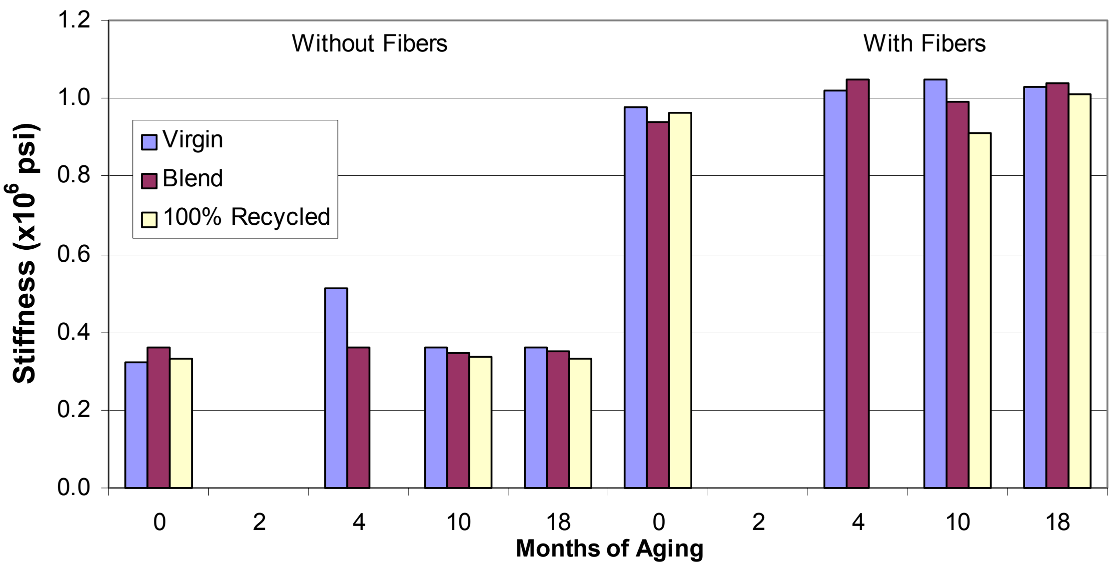


Figure F.1 Tensile Strength in Aged ABS Specimens

Table F.2 Tensile Stiffness Variations in Aged ABS Specimens

Specimen Type	Tensile Stiffness (psi x10^6)					% Change		
	Months of aging					End of period	Max gain in period	Max red. in period
	0	2	4	10	18			
A1	0.321	-	0.510	0.360	0.362	+12.8	+58.9	No red.
A2	0.976	-	1.019	1.047	1.027	+5.2	+7.3	No red.
A3	0.333	-	-	0.337	0.331	-0.6	+1.2	-0.6
A4	0.964	-	-	0.909	1.012	+5.0	+5.0	-5.7
A5	0.359	-	0.360	0.347	0.351	-2.2	+0.3	-3.3
A6	0.941	-	1.050	0.993	1.041	+10.6	+11.6	No red.
Average reduction (-ve values only) without fibers (A1,A3,A5)						-1.4		
Average change (+ve and –ve values) without fibers (A1,A3,A5)						+3.3	+20.1	-2.0
Average reduction (-ve values only) with fibers (A2,A4,A6)						0		
Average change (+ve and –ve values) with fibers (A2,A4,A6)						+6.9	+7.9	-5.7



Note: Some intermittent results between 0 and 18 months may not be present due to no testing during that period

Figure F.2 Tensile Stiffness in Aged ABS Specimens

Table F.3 Tensile Strength Variations in Aged PC Specimens

Specimen Type	Max. Tensile Stress (psi)					% Change		
	Months of aging					End of period	Max gain in period	Max red. in period
	0	2	4	10	18			
P1	8664	8210	9261	8817	8352	-3.6	+6.9	-5.2
P2	16479	15101	15721	12867	11892	-27.8	No gain	-27.8
P3	8566	7813	9233	8983	8329	-2.8	+7.8	-8.8
P4	15213	14203	14205	12525	10920	-28.2	No gain	-28.2
P5	8926	8072	9163	8589	8185	-8.3	+2.7	-9.6
P6	16555	14831	-	12877	11848	-28.4	No gain	-28.4
Average reduction (-ve values only) without fibers (A1,A3,A5)						-4.9		
Average change (+ve and –ve values) without fibers (A1,A3,A5)						-4.9	+5.8	-7.9
Average reduction (-ve values only) with fibers (A2,A4,A6)						-28.2		
Average change (+ve and –ve values) with fibers (A2,A4,A6)						-28.2	No gain	-28.2

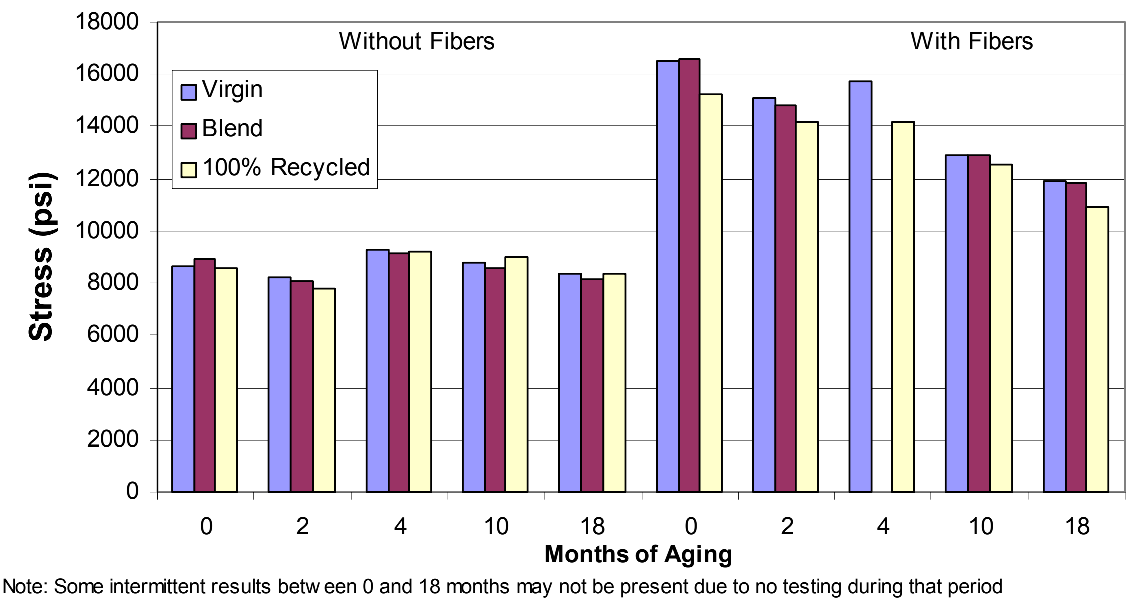
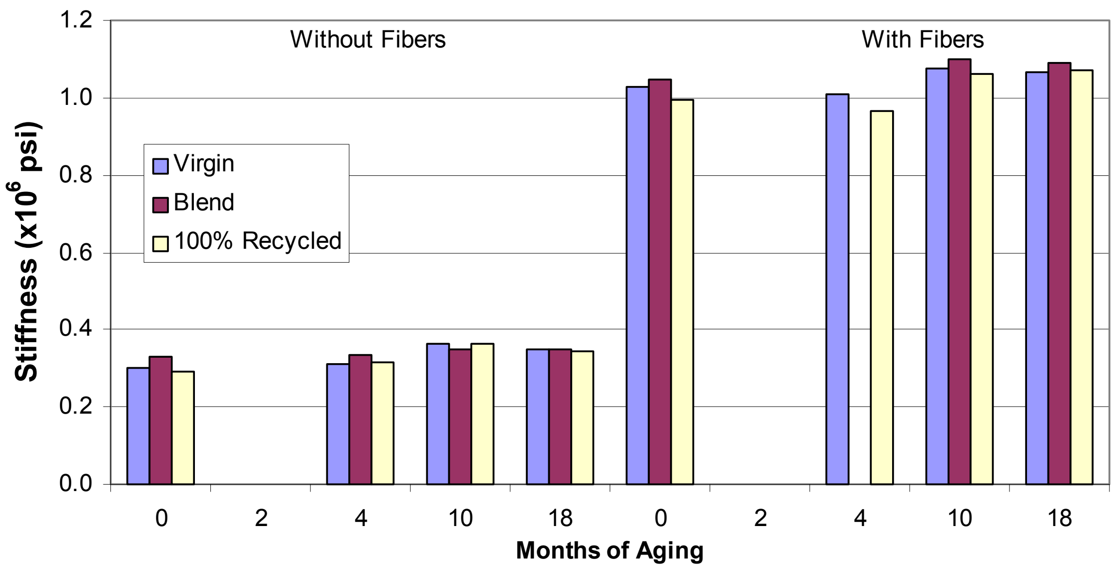


Figure F.3 Tensile Strength in Aged PC Specimens

Table F.4 Tensile Stiffness Variations in Aged PC Specimens

Specimen Type	Tension Stiffness (psi x10^6)					% Change		
	Months of aging					End of period	Max gain in period	Max red. in period
	0	2	4	10	18			
P1	0.300	-	0.309	0.364	0.35	+16.7	+21.3	No red.
P2	1.029	-	1.008	1.076	1.068	+3.8	+4.6	-2.0
P3	0.293	-	0.315	0.364	0.343	+17.1	+24.2	No red.
P4	0.993	-	0.964	1.061	1.073	+8.1	+8.1	-2.9
P5	0.329	-	0.337	0.347	0.349	+6.1	+6.1	No red.
P6	1.046	-	-	1.099	1.091	+4.3	+5.1	No red.
Average reduction (-ve values only) without fibers (A1,A3,A5)						0		
Average change (+ve and –ve values) without fibers (A1,A3,A5)						+13.3	+17.2	No red.
Average reduction (-ve values only) with fibers (A2,A4,A6)						0		
Average change (+ve and –ve values) with fibers (A2,A4,A6)						+5.4	+5.9	-2.5

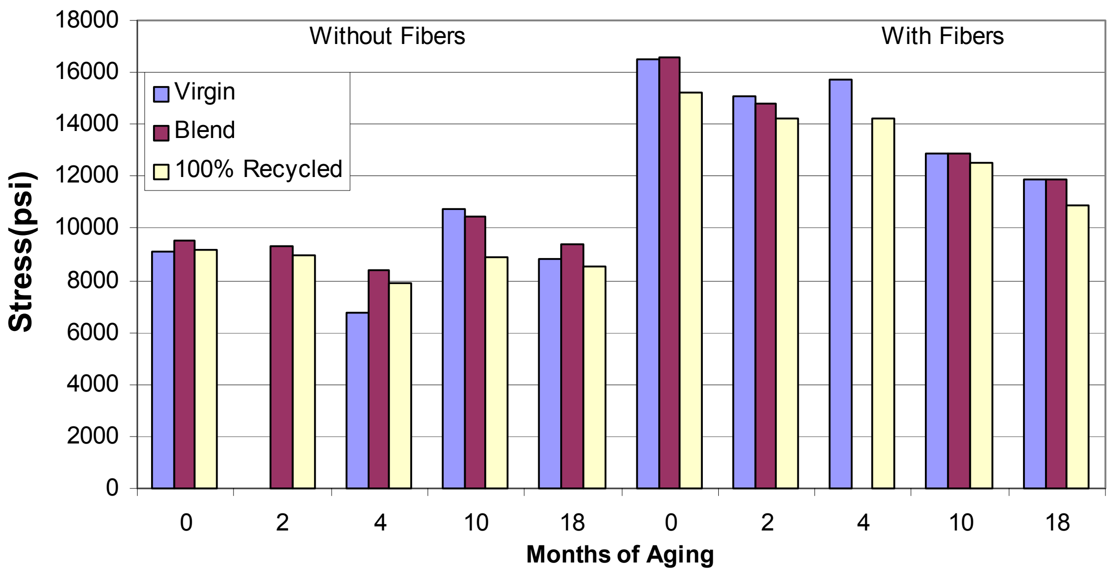


Note: Some intermittent results between 0 and 18 months may not be present due to no testing during that period

Figure F.4 Tensile Stiffness in Aged PC Specimens

Table F.5 Bending Strength Variations in Aged ABS Specimens

Specimen Type	Max. Bending Stress (psi)					% Change		
	Months of aging					End of period	Max gain in period	Max red. in period
	0	2	4	10	18			
A1	9080	-	6728	10747	8971	-3.2	+18.4	-25.9
A2	17771	16033	15211	14631	14080	-20.8	No gain	-20.8
A3	9187	8931	7862	8923	8511	-7.4	No gain	-14.4
A4	16740	15522	13886	12162	12605	-24.7	No gain	-27.3
A5	9558	9295	8412	10446	9419	-1.5	+9.3	-12.0
A6	16509	17793	14043	11400	13034	-21.0	No gain	-30.9
Average reduction (-ve values only) without fibers (A1,A3,A5)						-4.0		
Average change (+ve and –ve values) without fibers (A1,A3,A5)						-4.0	+13.8	-17.4
Average reduction (-ve values only) with fibers (A2,A4,A6)						-22.2		
Average change (+ve and –ve values) with fibers (A2,A4,A6)						-22.2	No gain	-26.4

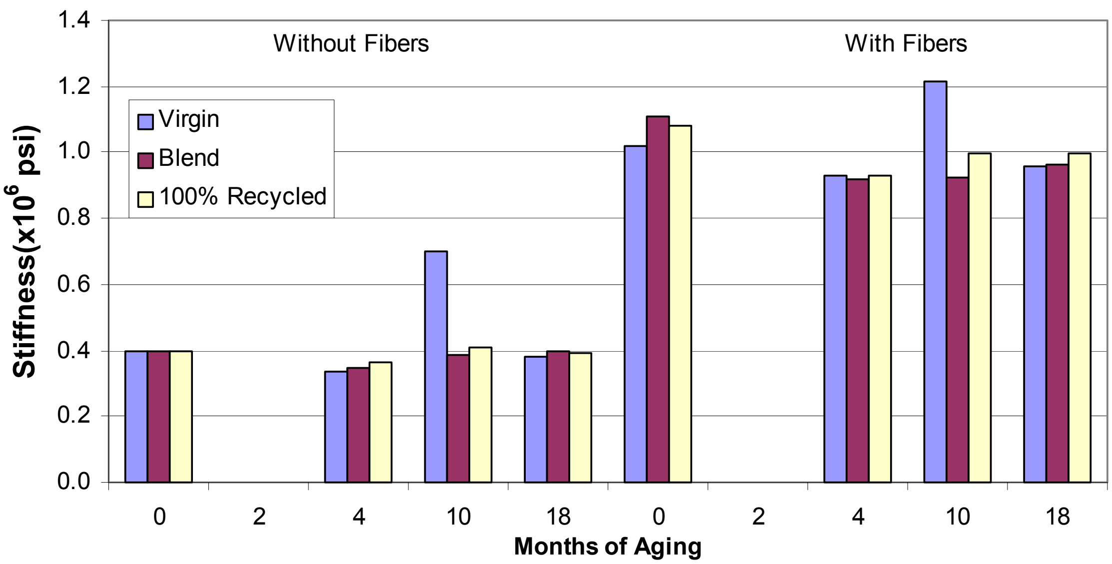


Note: Some intermittent results between 0 and 18 months may not be present due to no testing during that period

Figure F.5 Bending Strength in Aged ABS Specimens

Table F.6 Bending Stiffness Variations in Aged ABS Specimens

Specimen Type	Bending Stiffness (psi x10^6)					% Change		
	Months of aging					End of period	Max gain in period	Max red. in period
	0	2	4	10	18			
A1	0.40	-	0.334	0.699	0.381	-4.8	+74.8	-16.5
A2	1.02	-	0.932	1.215	0.960	-5.9	+19.1	-8.6
A3	0.40	-	0.364	0.408	0.391	-2.3	+2.0	-9.0
A4	1.08	-	0.930	0.998	0.996	-7.8	No gain	-13.9
A5	0.40	-	0.346	0.385	0.395	-1.3	No gain	-13.5
A6	1.11	-	0.917	0.925	0.962	-13.3	No gain	-17.4
Average reduction (-ve values only) without fibers (A1,A3,A5)						-2.8		
Average change (+ve and –ve values) without fibers (A1,A3,A5)						-2.8	+38.4	-13.0
Average reduction (-ve values only) with fibers (A2,A4,A6)						-9.0		
Average change (+ve and –ve values) with fibers (A2,A4,A6)						-9.0	+19.1	-13.3



Note: Some intermittent results betw een 0 and 18 months may not be present due to no testing during that period

Figure F.6 Bending Stiffness in Aged ABS Specimens

Table F.7 Bending Strength Variations in Aged PC Specimens

Specimen Type	Max. Bending Stress (psi)					% Change		
	Months of aging					End of period	Max gain in period	Max red. in period
	0	2	4	10	18			
P1	10242	7494	9283	14945	12506	+22.1	+45.9	-26.8
P2	24566	20228	21336	25370	19908	-19.0	+3.3	-19.0
P3	10363	8235	8398	17327	12117	+16.9	+67.2	-20.5
P4	23198	18830	17117	28586	19798	-14.7	+23.2	-26.2
P5	11168	10136	10602	15023	12366	+10.7	+34.5	-9.2
P6	24886	19606	21159	23909	20441	-17.9	No gain	-21.2
Average reduction (-ve values only) without fibers (A1,A3,A5)						0		
Average change (+ve and –ve values) without fibers (A1,A3,A5)						+16.6	+49.2	-18.9
Average reduction (-ve values only) with fibers (A2,A4,A6)						-17.2		
Average change (+ve and –ve values) with fibers (A2,A4,A6)						-17.2	+13.2	-22.1

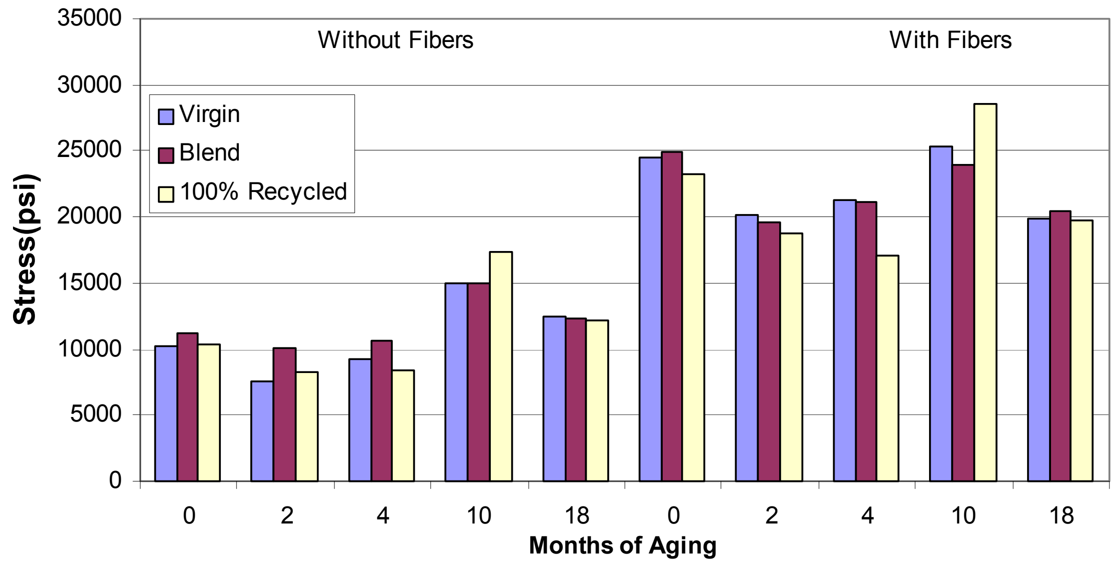
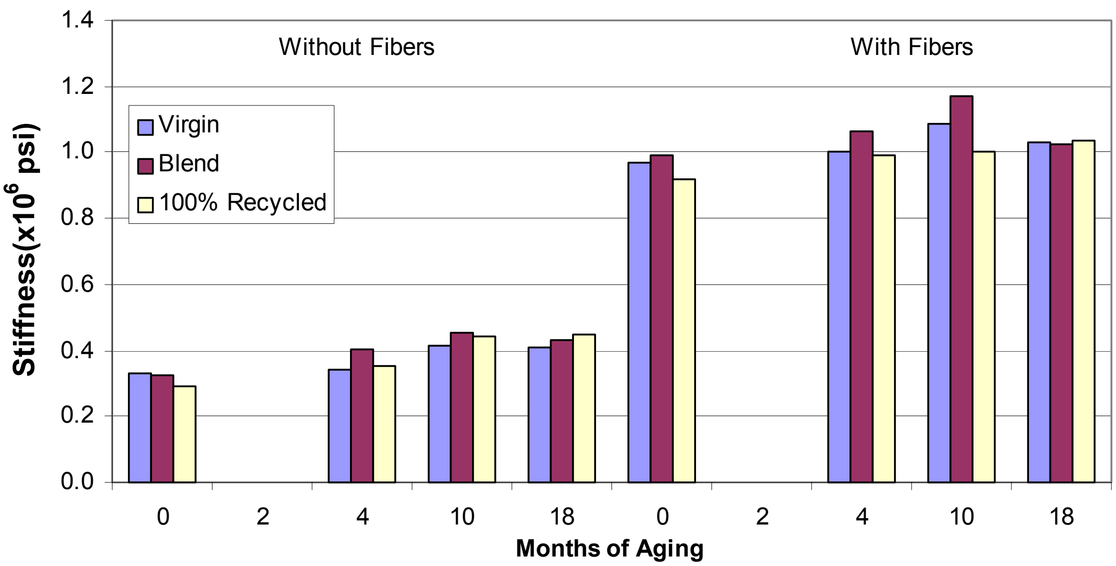


Figure F.7 Bending Strength in Aged PC Specimens

Table F.8 Bending Stiffness Variations in Aged PC Specimens

Specimen Type	Bending Stiffness (psi x10^6)					% Change		
	Months of aging					End of period	Max gain in period	Max red. in period
	0	2	4	10	18			
P1	0.332	-	0.341	0.416	0.408	+22.9	+25.3	No red.
P2	0.967	-	1.001	1.089	1.031	+6.6	+12.6	No red.
P3	0.291	-	0.354	0.445	0.450	+54.6	+54.6	No red.
P4	0.916	-	0.994	1.001	1.037	+13.2	+13.2	No red.
P5	0.327	-	0.406	0.452	0.430	+31.5	+38.2	No red.
P6	0.993	-	1.062	1.168	1.027	+3.4	+17.6	No red.
Average reduction (-ve values only) without fibers (A1,A3,A5)						0		
Average change (+ve and –ve values) without fibers (A1,A3,A5)						+36.3	+39.4	No red.
Average reduction (-ve values only) with fibers (A2,A4,A6)						0		
Average change (+ve and –ve values) with fibers (A2,A4,A6)						+7.8	+14.5	No red.

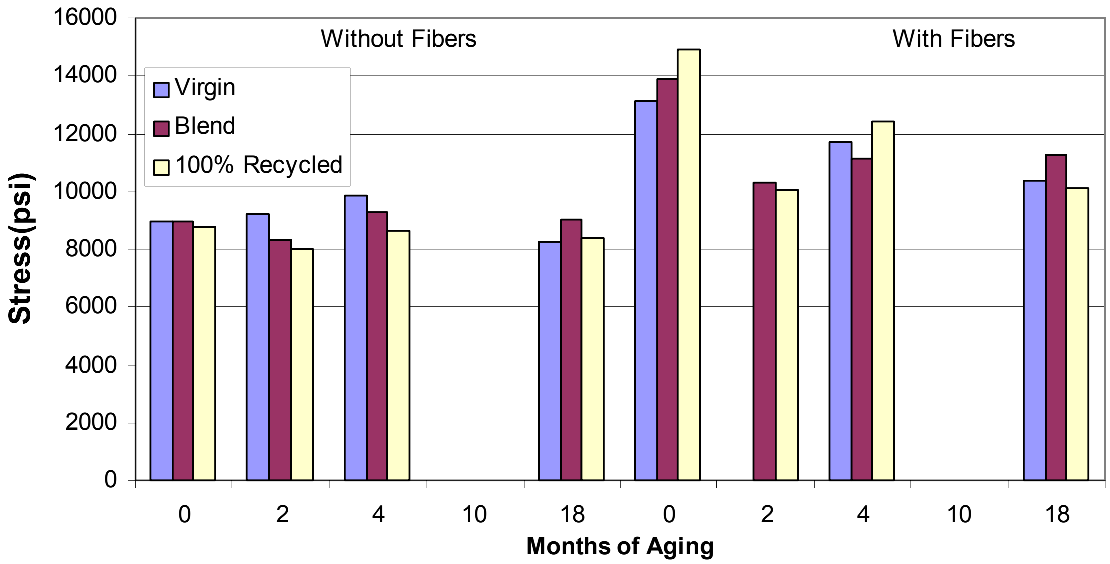


Note: Some intermittent results betw een 0 and 18 months may not be present due to no testing during that period

Figure F.8 Bending Stiffness in Aged PC Specimens

Table F.9 Compressive Strength Variations in Aged ABS Specimens

Specimen Type	Max. Compressive Stress (psi)					% Change		
	Months of aging					End of period	Max gain in period	Max red. in period
	0	2	4	10	18			
A1	8966	9208	9886	-	8244	-8.1	+10.3	-8.1
A2	13135	-	11698	-	10376	-21.0	No gain	-21.0
A3	8792	8027	8670	-	8381	-4.7	No gain	-8.7
A4	14891	10061	12440	-	10120	-32.0	No gain	-32.4
A5	8972	8318	9287	-	9011	+0.4	+3.5	-7.3
A6	13920	10308	11151	-	11265	-19.1	No gain	-25.9
Average reduction (-ve values only) without fibers (A1,A3,A5)						-6.4		
Average change (+ve and –ve values) without fibers (A1,A3,A5)						-4.1	+6.9	-8.0
Average reduction (-ve values only) with fibers (A2,A4,A6)						-24.0		
Average change (+ve and –ve values) with fibers (A2,A4,A6)						-24.0	No gain	-26.5

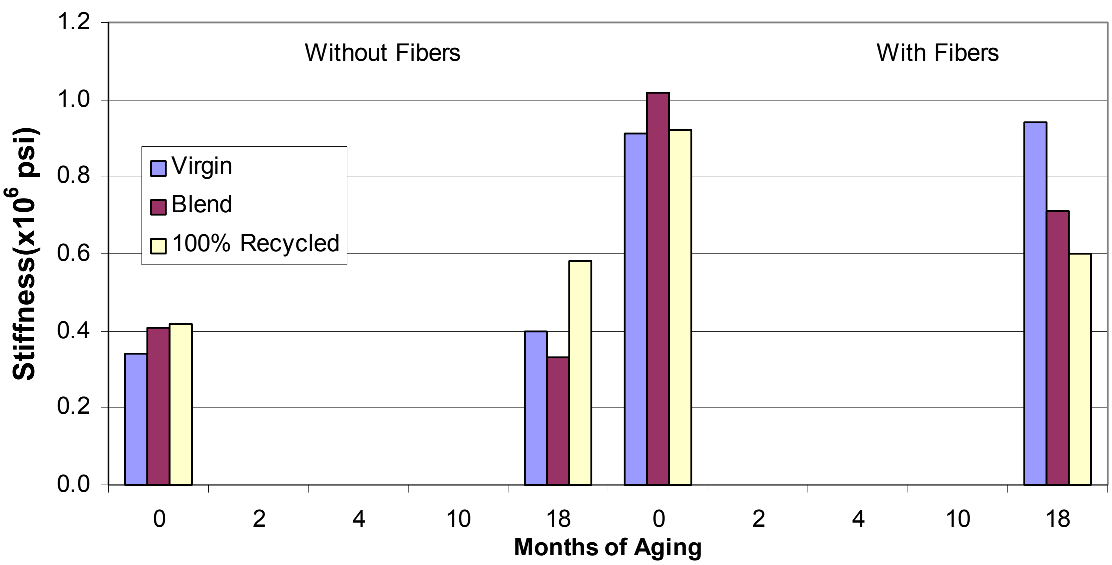


Note: Some intermittent results between 0 and 18 months may not be present due to no testing during that period

Figure F.9 Compressive Strength in Aged ABS Specimens

Table F.10 Compressive Stiffness Variations in Aged ABS Specimens

Specimen Type	Compressive Stiffness (psi)					% Change		
	Months of aging					End of period	Max gain in period	Max red. in period
	0	2	4	10	18			
A1	0.34	-	-	-	0.397	+16.8	+16.8	No red.
A2	0.91	-	-	-	0.943	+3.6	+3.6	No red.
A3	0.42	-	-	-	0.583	+38.8	+38.8	No red.
A4	0.92	-	-	-	0.600	-34.8	No gain	-34.8
A5	0.41	-	-	-	0.330	-19.5	No gain	-19.5
A6	1.02	-	-	-	0.709	-30.5	No gain	-30.5
Average reduction (-ve values only) without fibers (A1,A3,A5)						-19.5		
Average change (+ve and –ve values) without fibers (A1,A3,A5)						+12.0	+27.8	-19.5
Average reduction (-ve values only) with fibers (A2,A4,A6)						-32.6		
Average change (+ve and –ve values) with fibers (A2,A4,A6)						-20.5	+3.6	-32.6



Note: Some intermittent results between 0 and 18 months may not be present due to no testing during that period

Figure F.10 Compressive Stiffness in Aged ABS Specimens

Table F.11 Compressive Strength Variations in Aged PC Specimens

Specimen Type	Max. Compressive Stress (psi)					% Change		
	Months of aging					End of period	Max gain in period	Max red. in period
	0	2	4	10	18			
P1	10423	10234	10259	-	10344	-0.8	No gain	-1.8
P2	20332	12408	13539	-	12587	-38.1	No gain	-39.0
P3	10311	9894	11348	-	10296	-0.1	+10.1	-4.0
P4	20747	11463	13509	-	13749	-33.7	No gain	-44.7
P5	10523	9931	10979	-	10221	-2.9	+4.3	-5.6
P6	21124	12412	17500	-	12422	-41.2	No gain	-41.2
Average reduction (-ve values only) without fibers (A1,A3,A5)						-1.3		
Average change (+ve and –ve values) without fibers (A1,A3,A5)						-1.3	+7.2	-3.8
Average reduction (-ve values only) with fibers (A2,A4,A6)						-37.7		
Average change (+ve and –ve values) with fibers (A2,A4,A6)						-37.7	No gain	-41.7

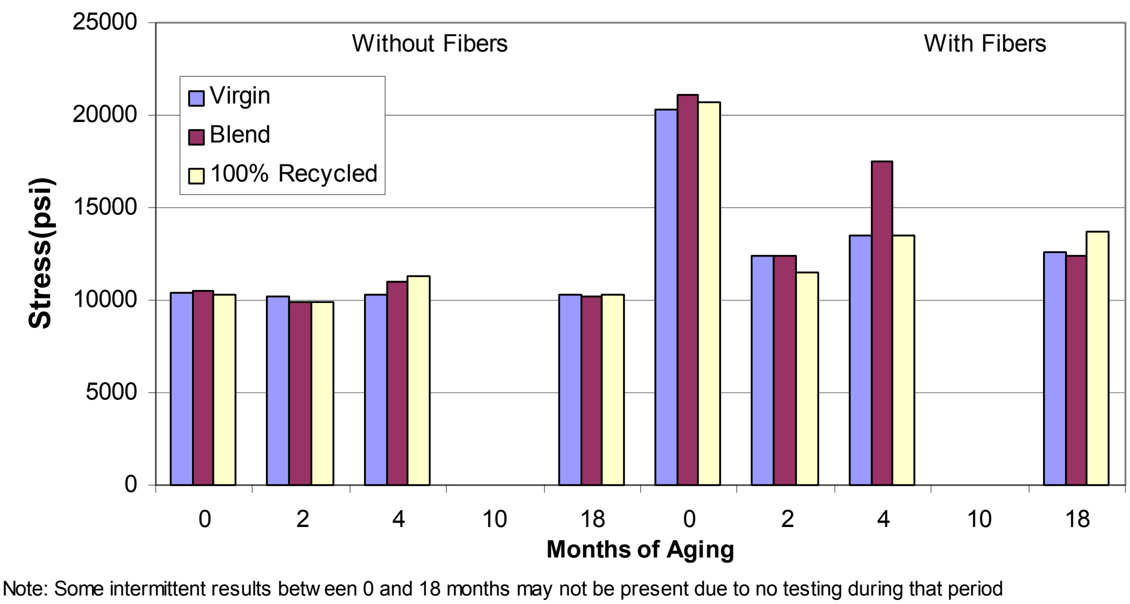
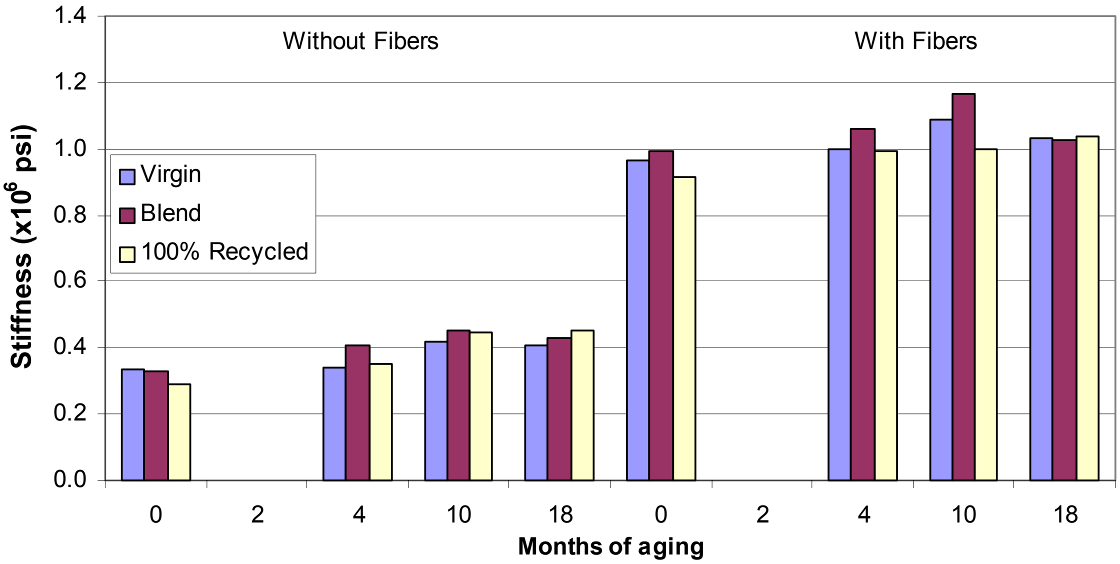


Figure F.11 Compressive Strength in Aged PC Specimens

Table F.12 Compressive Stiffness Variations in Aged PC Specimens

Specimen Type	Compressive Stiffness (psi)					% Change		
	Months of aging					End of period	Max gain in period	Max red. in period
	0	2	4	10	18			
P1	0.21	-	0.283	-	0.320	+52.4	+52.4	No red.
P2	0.41	-	0.481	-	0.511	+24.6	+24.6	No red.
P3	0.20	-	0.302	-	0.344	+72.0	+72.0	No red.
P4	0.43	-	0.463	-	0.494	+14.9	+14.9	No red.
P5	0.21	-	0.355	-	-	+69.0	+69.0	No red.
P6	0.43	-	0.481	-	0.477	+10.9	+11.9	No red.
Average reduction (-ve values only) without fibers (A1,A3,A5)						0		
Average change (+ve and –ve values) without fibers (A1,A3,A5)						+64.5	+64.5	No red.
Average reduction (-ve values only) with fibers (A2,A4,A6)						0		
Average change (+ve and –ve values) with fibers (A2,A4,A6)						+16.8	+17.1	No red.



Note: Some intermittent results between 0 and 18 months may not be present due to no testing during that period

Figure F.12 Compressive Stiffness in Aged PC Specimens

Table F.13 Impact Strength Variations in Aged ABS Specimens

Specimen Type	Impact Strength (ft-lbs$_f$)					% Change		
	Months of aging					End of period	Max gain in period	Max red. in period
	0	2	4	10	18			
A1	3.49	3.67	3.76	3.44	3.41	-2.3	+7.8	-2.3
A2	1.58	1.31	1.40	1.32	1.24	-21.5	No gain	-21.5
A3	2.17	1.91	1.24	0.83	0.87	-59.7	No gain	-61.6
A4	0.96	0.90	0.83	0.75	0.75	-21.7	No gain	-21.7
A5	2.38	2.86	2.54	1.77	1.46	-38.8	+20.3	-38.8
A6	1.20	1.04	1.08	1.00	0.87	-27.2	No gain	-27.2
Average reduction (-ve values only) without fibers (A1,A3,A5)						-33.6		
Average change (+ve and –ve values) without fibers (A1,A3,A5)						-33.6	+14.1	-34.2
Average reduction (-ve values only) with fibers (A2,A4,A6)						-23.5		
Average change (+ve and –ve values) with fibers (A2,A4,A6)						-23.5	No gain	-23.5

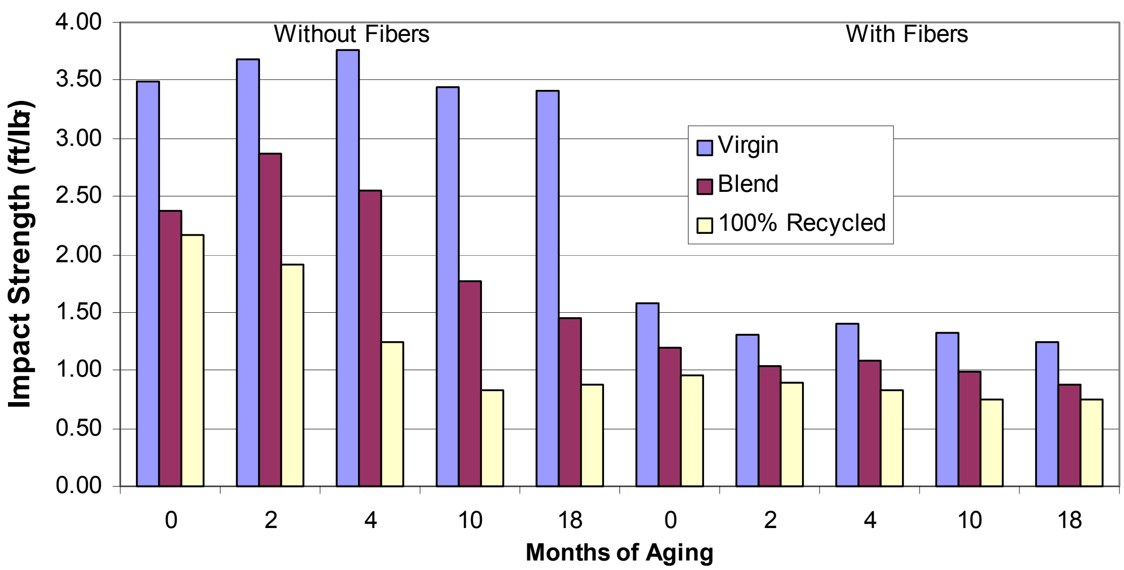


Figure F.13 Impact Strength in Aged ABS Specimens

Table F.14 Impact Strength Variations in Aged PC Specimens

Specimen Type	Impact Strength (ft-lbs$_f$)					% Change		
	Months of aging					End of period	Max gain in period	Max red. in period
	0	2	4	10	18			
P1	14.15	-	14.67	14.59	15.56	+10.0	+10.0	No red.
P2	3.01	-	1.48	1.40	1.48	-50.7	No gain	-53.4
P3	13.53	-	13.77	15.65	14.99	+10.8	+15.6	No red.
P4	1.81	-	0.91	0.91	0.79	-56.2	No gain	-56.2
P5	14.80	-	14.58	14.91	15.65	+5.7	+5.7	-1.5
P6	2.67	-	1.24	1.32	1.20	-55.1	No gain	-55.1
Average reduction (-ve values only) without fibers (A1,A3,A5)						0		
Average change (+ve and –ve values) without fibers (A1,A3,A5)						+8.8	+10.4	-1.5
Average reduction (-ve values only) with fibers (A2,A4,A6)						-54.0		
Average change (+ve and –ve values) with fibers (A2,A4,A6)						-54.0	No gain	-54.9

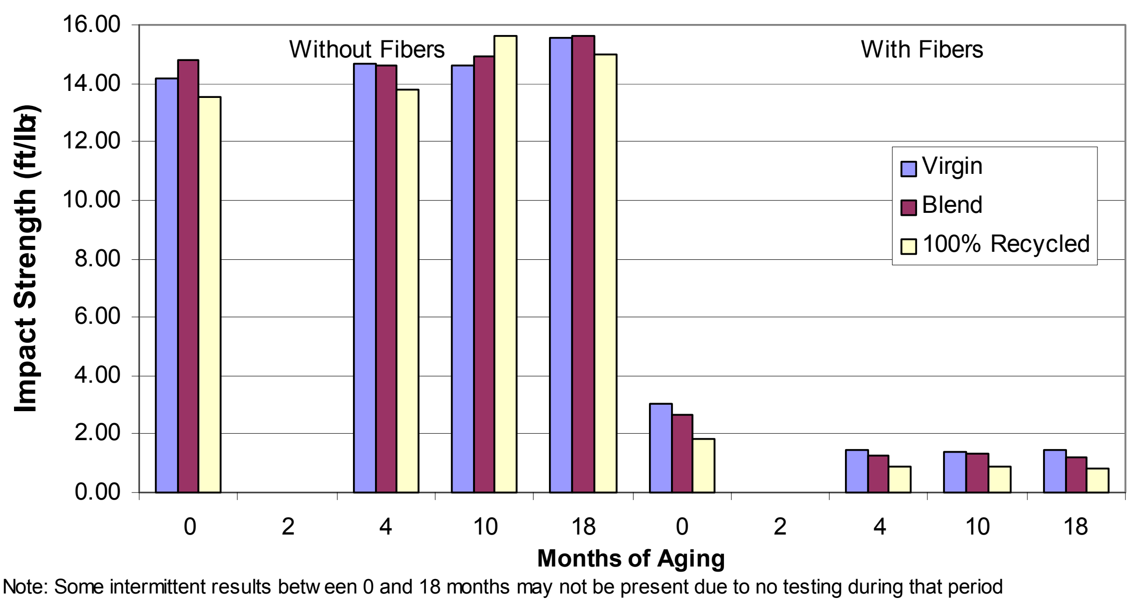


Figure F.14 Impact Strength in Aged PC Specimens

Table F.15 Hardness Index Variations in Aged ABS Specimens

Specimen Type	Hardness Index					% Change		
	Months of aging					End of period	Max gain in period	Max red. in period
	0	2	4	10	18			
A1	10.90	12.44	11.70	12.10	12.00	+10.1	+14.1	No red.
A2	11.30	12.80	11.50	11.00	10.90	-3.5	+13.3	-3.5
A3	11.10	12.58	11.40	11.10	11.00	-0.9	+13.3	-0.9
A4	11.20	11.76	11.30	10.80	10.60	-5.4	+5.0	-5.4
A5	11.20	12.44	10.80	11.10	10.90	-2.7	+11.1	-3.6
A6	11.20	12.16	11.00	10.90	10.80	-3.6	+8.6	-3.6
Average reduction (-ve values only) without fibers (A1,A3,A5)						-1.8		
Average change (+ve and –ve values) without fibers (A1,A3,A5)						+2.2	+12.8	-2.2
Average reduction (-ve values only) with fibers (A2,A4,A6)						-4.2		
Average change (+ve and –ve values) with fibers (A2,A4,A6)						-4.2	+8.9	-4.2

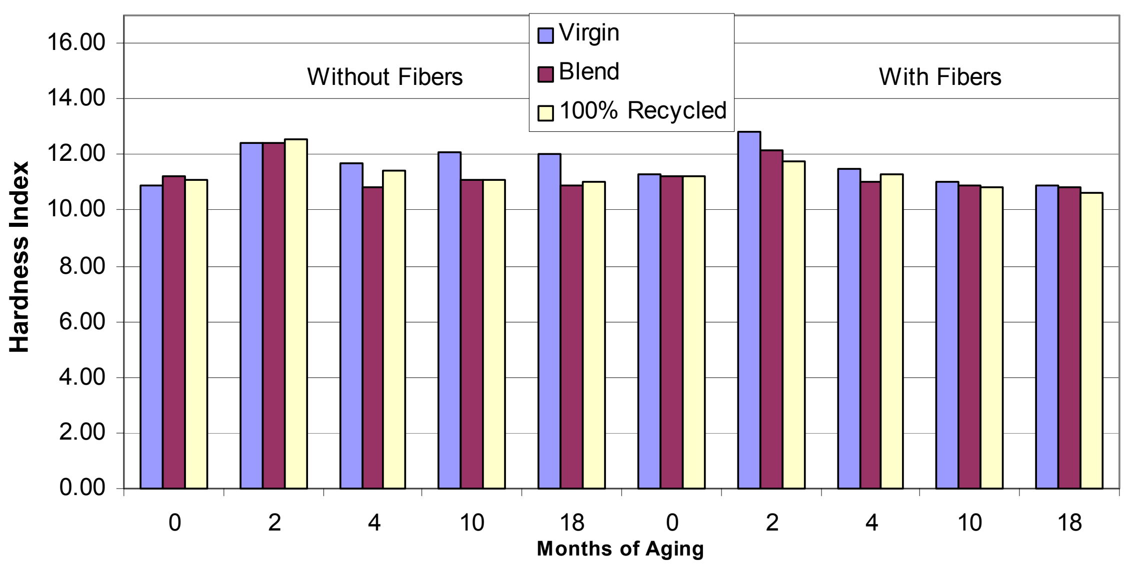


Figure F.15 Hardness Index in Aged ABS Specimens

Table F.16 Hardness Index Variations in Aged PC Specimens

Specimen Type	Hardness Index					% Change		
	Months of aging					End of period	Max gain in period	Max red. in period
	0	2	4	10	18			
P1	10.60	12.00	11.30	11.10	11.00	+3.8	+13.2	No red.
P2	10.70	11.10	11.20	11.30	11.30	+5.6	+5.6	No red.
P3	10.60	11.50	10.80	11.10	11.00	+3.8	+8.5	No red.
P4	10.70	11.44	10.80	10.90	10.80	+0.9	+6.9	No red.
P5	10.70	10.74	11.20	10.90	10.90	+1.9	+4.7	No red.
P6	10.70	11.38	11.40	10.90	10.80	+0.9	+6.5	No red.
Average reduction (-ve values only) without fibers (A1,A3,A5)						0		
Average change (+ve and –ve values) without fibers (A1,A3,A5)						+3.1	+8.8	No red.
Average reduction (-ve values only) with fibers (A2,A4,A6)						0		
Average change (+ve and –ve values) with fibers (A2,A4,A6)						+2.5	+6.4	No red.

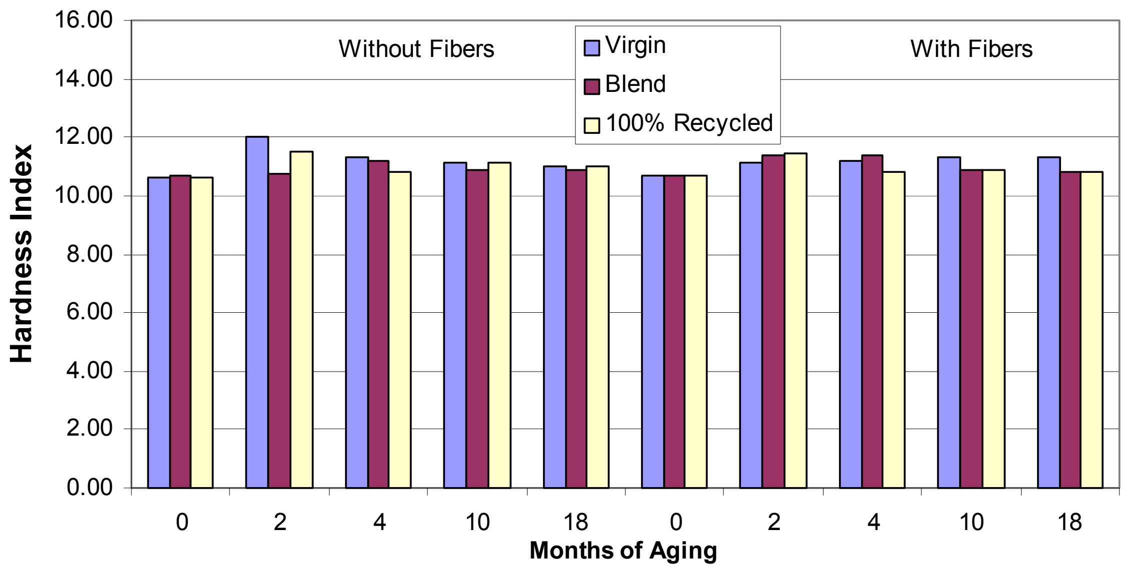


Figure F.16 Hardness Index in Aged PC Specimens

APPENDIX G

CREEP TEST RESULTS

Table G.1 Creep Test Results for 100% Recycled and Blend ABS without Fibers at 20% Sustained Load

Date	Days	Specimens			
		Strain Reading (μs)		Creep Coefficient	
		A3	A5	A3	A5
01/31/2000	0	4116	3130	0.000	0.000
02/01/2000	1	4187	3313	0.017	0.058
02/02/2000	2	4242	3374	0.031	0.078
02/03/2000	3	4251	3385	0.033	0.081
02/04/2000	4	4384	3530	0.065	0.128
02/05/2000	5	4372	3528	0.062	0.127
02/06/2000	6	4391	3544	0.067	0.132
02/07/2000	7	4426	3586	0.075	0.146
02/08/2000	8	4451	3610	0.081	0.153
02/09/2000	9	4511	3667	0.096	0.172
02/10/2000	10	4550	3709	0.105	0.185
02/11/2000	11	4654	3810	0.131	0.217
02/12/2000	12	4620	3774	0.122	0.206
02/13/2000	13	4645	3805	0.129	0.216
02/14/2000	14	4761	3927	0.157	0.255
02/15/2000	15	4758	3928	0.156	0.255
02/16/2000	16	4782	3945	0.162	0.260
02/17/2000	17	4885	4085	0.187	0.305
02/18/2000	18	4874	4035	0.184	0.289
02/19/2000	19	4836	4006	0.175	0.280
02/20/2000	20	4837	4002	0.175	0.279
02/21/2000	21	4871	4045	0.183	0.292
02/22/2000	22	4965	4145	0.206	0.324
02/23/2000	23	5090	4276	0.237	0.366
02/24/2000	24	5182	4345	0.259	0.388
02/25/2000	25	5279	4431	0.283	0.416
02/26/2000	26	5332	4502	0.295	0.438
02/27/2000	27	5370	4536	0.305	0.449
02/28/2000	28	5335	4513	0.296	0.442
02/29/2000	29	5305	4478	0.289	0.431
03/01/2000	30	5346	4503	0.299	0.439
03/02/2000	31	5305	4470	0.289	0.428
03/03/2000	32	5305	4469	0.289	0.428
03/04/2000	33	5301	4465	0.288	0.427
03/05/2000	34	5302	4472	0.288	0.429
03/06/2000	35	5350	4529	0.300	0.447

03/07/2000	36	5432	4609	0.320	0.473
03/08/2000	37	5630	4816	0.368	0.539
03/09/2000	38	5684	4864	0.381	0.554
03/10/2000	39	5520	4706	0.341	0.504
03/11/2000	40	5555	4766	0.350	0.523
03/12/2000	41	5480	4630	0.331	0.479
03/13/2000	42	5470	4645	0.329	0.484
03/14/2000	43	5465	4639	0.328	0.482
03/15/2000	44	5539	4718	0.346	0.507
03/16/2000	45	5592	4773	0.359	0.525
03/17/2000	46	5491	4682	0.334	0.496
03/18/2000	47	5470	4651	0.329	0.486
03/19/2000	48	5478	4667	0.331	0.491
03/20/2000	49	5516	4705	0.340	0.503
03/21/2000	50	5562	4739	0.351	0.514
03/22/2000	51	5670	4845	0.378	0.548
03/23/2000	52	5773	4955	0.403	0.583
03/24/2000	53	5863	5052	0.424	0.614
03/25/2000	54	5830	5020	0.416	0.604
03/26/2000	55	5743	4945	0.395	0.580
03/27/2000	56	5752	4950	0.397	0.581
03/29/2000	58	5700	4901	0.385	0.566
03/30/2000	59	5694	4890	0.383	0.562
03/31/2000	60	5690	4885	0.382	0.561
04/03/2000	63	5978	5175	0.452	0.653
04/05/2000	65	5896	5080	0.432	0.623
04/07/2000	67	5993	5168	0.456	0.651
04/10/2000	70	5920	5107	0.438	0.632
04/11/2000	71	5902	5090	0.434	0.626
04/13/2000	73	5971	5195	0.451	0.660
04/14/2000	74	6034	5231	0.466	0.671
04/17/2000	77	6082	5262	0.478	0.681
04/18/2000	78	6117	5295	0.486	0.692
04/20/2000	80	6363	5574	0.546	0.781
04/21/2000	81	6432	5626	0.563	0.797
04/24/2000	84	6224	5407	0.512	0.727
04/26/2000	86	6217	5412	0.510	0.729
04/28/2000	88	6256	5454	0.520	0.742
05/01/2000	91	6365	5565	0.546	0.778
05/03/2000	93	6453	5640	0.568	0.802
05/05/2000	95	6755	5946	0.641	0.900
05/08/2000	98	7072	6253	0.718	0.998
05/10/2000	100	6980	6130	0.696	0.958
05/12/2000	102	7089	6251	0.722	0.997
05/15/2000	105	6800	5983	0.652	0.912
05/17/2000	107	6955	6122	0.690	0.956
05/19/2000	109	7009	6140	0.703	0.962
05/22/2000	112	7030	6150	0.708	0.965

05/26/2000	116	7193	6316	0.748	1.018
05/30/2000	120	7076	6201	0.719	0.981
06/01/2000	122	7579	6709	0.841	1.143
06/02/2000	123	7720	6845	0.876	1.187
06/05/2000	126	7497	6636	0.821	1.120
06/07/2000	128	7346	6450	0.785	1.061
06/09/2000	130	7665	6829	0.862	1.182
06/12/2000	133	7950	7089	0.931	1.265
06/14/2000	135	8247	7400	1.004	1.364
06/16/2000	137	8381	7492	1.036	1.394
06/21/2000	142	8350	7446	1.029	1.379
06/23/2000	144	8521	7625	1.070	1.436
06/26/2000	147	8539	7650	1.075	1.444
06/28/2000	149	7138	6195	0.734	0.979
07/06/2000	157	7318	6382	0.778	1.039
07/12/2000	163	7500	6559	0.822	1.096
07/17/2000	168	7194	6223	0.748	0.988
07/22/2000	173	7650	6673	0.859	1.132
07/27/2000	178	8062	7142	0.959	1.282
07/31/2000	182	7642	6680	0.857	1.134
08/04/2000	186	7894	6942	0.918	1.218
08/09/2000	191	7839	6900	0.905	1.204
08/14/2000	196	7491	6528	0.820	1.086
08/19/2000	201	7860	6935	0.910	1.216
08/28/2000	210	7949	6970	0.931	1.227
09/06/2000	219	7808	6783	0.897	1.167
09/11/2000	224	8365	7435	1.032	1.375
09/15/2000	228	7994	6999	0.942	1.236
09/18/2000	231	8035	7029	0.952	1.246
09/22/2000	235	8015	6997	0.947	1.235
09/25/2000	238	7928	6917	0.926	1.210
10/02/2000	245	8010	7011	0.946	1.240
10/05/2000	248	8452	7437	1.053	1.376
10/08/2000	251	8821	7816	1.143	1.497
10/13/2000	256	8923	8199	1.168	1.619
10/18/2000	261	8965	8456	1.178	1.702
02/08/2001	374	9256	8056	1.249	1.574
05/15/2001	470	9462	8365	1.299	1.673
07/12/2001	528	9863	8562	1.396	1.735
10/17/2001	625	10125	8921	1.460	1.850
01/16/2002	716	10245	8912	1.489	1.847
04/12/2002	802	10598	9105	1.575	1.909
06/04/2002	855	10965	9532	1.664	2.045
08/12/2002	924	11245	12658	1.732	2.075

Table G.2 Creep Test Results for Virgin ABS without Fibers; Virgin, Blend, and 100% Recycled with Fibers at 20% Sustained Load

Date	Days	Specimens							
		Strain Reading (ms)				Creep Coefficient			
		A1	A2	A4	A6	A1	A2	A4	A6
02/28/2000	0	0	0		0				
02/29/2000	1	3424	2839	0	2431	0.000	0.000		0.000
03/01/2000	2	3472	2856	3451	2442	0.014	0.006	0.000	0.005
03/02/2000	3	3549	2874	3482	2467	0.037	0.012	0.009	0.015
03/03/2000	4	3568	2886	3504	2456	0.042	0.017	0.015	0.010
03/04/2000	5	3592	2901	3505	2465	0.049	0.022	0.016	0.014
03/05/2000	6	3660	2918	3526	2479	0.069	0.028	0.022	0.020
03/06/2000	7	3718	2928	3540	2495	0.086	0.031	0.026	0.026
03/07/2000	8	3816	2941	3568	2521	0.114	0.036	0.034	0.037
03/08/2000	9	4027	2990	3619	2579	0.176	0.053	0.049	0.061
03/09/2000	10	4126	3007	3649	2601	0.205	0.059	0.057	0.070
03/10/2000	11	4002	2993	3620	2564	0.169	0.054	0.049	0.055
03/11/2000	12	4008	2981	3627	2571	0.171	0.050	0.051	0.058
03/12/2000	13	3942	2976	3607	2547	0.151	0.048	0.045	0.048
03/13/2000	14	3942	2987	3607	2550	0.151	0.052	0.045	0.049
03/14/2000	15	3939	2987	3607	2553	0.150	0.052	0.045	0.050
03/15/2000	16	4014	2998	3629	2575	0.172	0.056	0.052	0.059
03/16/2000	17	4078	2955	3644	2594	0.191	0.041	0.056	0.067
03/17/2000	18	4019	3008	3631	2572	0.174	0.060	0.052	0.058
03/18/2000	19	3975	3008	3623	2561	0.161	0.060	0.050	0.053
03/19/2000	20	3995	3000	3624	2568	0.167	0.057	0.050	0.056
03/20/2000	21	4049	2991	3635	2577	0.183	0.054	0.053	0.060
03/21/2000	22	4065	2991	3645	2594	0.187	0.054	0.056	0.067
03/22/2000	23	4173	2996	3676	2617	0.219	0.055	0.065	0.077
03/23/2000	24	4289	3043	3702	2648	0.253	0.072	0.073	0.089
03/24/2000	25	4387	3033	3730	2675	0.281	0.068	0.081	0.100
03/25/2000	26	4383	3029	3730	2670	0.280	0.067	0.081	0.098
03/26/2000	27	4300	3000	3715	2651	0.256	0.057	0.076	0.090
03/27/2000	28	4302	3048	3713	2651	0.256	0.074	0.076	0.090
03/29/2000	30	4300	3063	3709	2650	0.256	0.079	0.075	0.090
03/30/2000	31	4300	3078	3703	2651	0.256	0.084	0.073	0.090
03/31/2000	32	4300	3075	3702	2652	0.256	0.083	0.073	0.091
04/03/2000	35	4527	3100	3768	2715	0.322	0.092	0.092	0.117
04/05/2000	37	4475	3109	3760	2700	0.307	0.095	0.090	0.111
04/07/2000	39	4572	3045	3779	2716	0.335	0.073	0.095	0.117
04/10/2000	42	4501	3068	3772	2705	0.315	0.081	0.093	0.113
04/11/2000	43	4483	3064	3760	2702	0.309	0.079	0.090	0.111
04/13/2000	45	4563	3076	3774	2721	0.333	0.083	0.094	0.119
04/14/2000	46	4640	3085	3797	2734	0.355	0.087	0.100	0.125
04/17/2000	49	4680	3084	3824	2742	0.367	0.086	0.108	0.128
04/18/2000	50	4702	3084	3844	2770	0.373	0.086	0.114	0.139
04/20/2000	52	4990	3130	3895	2827	0.457	0.103	0.129	0.163

04/21/2000	53	5057	3131	3909	2846	0.477	0.103	0.133	0.171
04/24/2000	56	4831	3122	3861	2796	0.411	0.100	0.119	0.150
04/26/2000	58	4859	3199	3861	2798	0.419	0.127	0.119	0.151
04/28/2000	60	4901	3190	3867	2805	0.431	0.124	0.121	0.154
05/01/2000	63	5015	3203	3895	2830	0.465	0.128	0.129	0.164
05/03/2000	65	5116	3205	3915	2850	0.494	0.129	0.134	0.172
05/05/2000	67	5390	3214	3990	2930	0.574	0.132	0.156	0.205
05/08/2000	70	5730	3325	4083	3013	0.673	0.171	0.183	0.239
05/10/2000	72	5652	3297	4074	2983	0.651	0.161	0.181	0.227
05/12/2000	74	5732	3266	4081	3003	0.674	0.150	0.183	0.235
05/15/2000	77	5469	3312	4029	2953	0.597	0.167	0.167	0.215
05/17/2000	79	5596	3304	4056	2975	0.634	0.164	0.175	0.224
05/19/2000	81	5674	3300	4085	2978	0.657	0.162	0.184	0.225
05/22/2000	84	5750	3315	4106	3009	0.679	0.168	0.190	0.238
05/26/2000	88	5910	3376	4158	3048	0.726	0.189	0.205	0.254
05/30/2000	92	5964	3335	4140	3026	0.742	0.175	0.200	0.245
06/01/2000	94	6236	3409	4242	3140	0.821	0.201	0.229	0.292
06/02/2000	95	6379	3473	4273	3170	0.863	0.223	0.238	0.304
06/05/2000	98	6167	3423	4221	3116	0.801	0.206	0.223	0.282
06/07/2000	100	6047	3418	4197	3081	0.766	0.204	0.216	0.267
06/09/2000	102	6361	3484	4269	3160	0.858	0.227	0.237	0.300
06/12/2000	105	6609	3640	4287	3216	0.930	0.282	0.242	0.323
06/14/2000	107	6915	3730	4367	3282	1.020	0.314	0.265	0.350
06/16/2000	109	7217	3825	4437	3352	1.108	0.347	0.286	0.379
06/21/2000	114	7645	3705	4380	3323	1.233	0.305	0.269	0.367
06/23/2000	116	6999	3722	4365	3304	1.044	0.311	0.265	0.359
06/26/2000	119	7107	3781	4406	3346	1.076	0.332	0.277	0.376
06/28/2000	121	7107	3791	4395	3358	1.076	0.335	0.274	0.381
07/06/2000	129	7108	3367	4398	3342	1.076	0.186	0.274	0.375
07/12/2000	135	7216	3377	4423	3387	1.107	0.190	0.282	0.393
07/17/2000	140	6752	3733	4360	3325	0.972	0.315	0.263	0.368
07/22/2000	145	7437	3861	4481	3431	1.172	0.360	0.298	0.411
07/27/2000	150	7725	3936	4553	3493	1.256	0.386	0.319	0.437
07/31/2000	154	7408	3860	4477	3420	1.164	0.360	0.297	0.407
08/04/2000	158	7589	3368	4518	3437	1.216	0.186	0.309	0.414
08/09/2000	163	7559	3826	4504	3443	1.208	0.348	0.305	0.416
08/14/2000	168	7264	3679	4425	3371	1.121	0.296	0.282	0.387
08/19/2000	173	7560	3846	4500	3399	1.208	0.355	0.304	0.398
08/28/2000	182	7623	3820	4526	3468	1.226	0.346	0.312	0.427
09/06/2000	191	7469	3518	4471	3353	1.181	0.239	0.296	0.379
09/11/2000	196	7966	3891	4605	3539	1.327	0.371	0.334	0.456
09/15/2000	200	7588	3856	4511	3453	1.216	0.358	0.307	0.420
09/18/2000	203	7545	3854	4496	3419	1.204	0.358	0.303	0.406
09/22/2000	207	7538	3854	4492	3426	1.202	0.358	0.302	0.409
09/25/2000	210	7461	3806	4476	3348	1.179	0.341	0.297	0.377
10/02/2000	217	7531	3828	4484	3434	1.199	0.348	0.299	0.413
10/05/2000	220	7831	3908	4572	3516	1.287	0.377	0.325	0.446
10/08/2000	223	8025	4025	4605	3548	1.344	0.418	0.334	0.459

10/13/2000	228	8047	4054	4634	3583	1.350	0.428	0.343	0.474
10/18/2000	233	8089	4102	4656	3625	1.362	0.445	0.349	0.491
02/08/2001	346	8187	4385	4768	3864	1.391	0.545	0.382	0.589
05/15/2001	442	8274	4525	4852	4125	1.416	0.594	0.406	0.697
07/12/2001	500	8324	4795	5212	4287	1.431	0.689	0.510	0.763
10/17/2001	597	8402	5648	5487	4406	1.454	0.650	0.590	0.812
01/16/2002	688	8492	5864	5612	4585	1.480	0.713	0.626	0.886
04/12/2002	774	8570	5956	5741	4664	1.503	0.739	0.664	0.919
06/04/2002	827	8820	6104	5892	4731	1.576	0.783	0.707	0.946
08/12/2002	896	8965	6250	5912	6685	1.618	0.825	0.727	0.952

Table G.3 Creep Test Results for 100% Recycled and Blend ABS without Fibers 50% Sustained Load

Date	Days	Specimens			
		Strain Reading (ms)		Creep Coefficient	
		A3	A5	A3	A5
02/28/2000	0	9265	8770	0.000	0.000
02/29/2000	1	10801	10651	0.166	0.214
03/01/2000	2	11573	11402	0.249	0.300
03/02/2000	3	12146	12102	0.311	0.380
03/03/2000	4	12401	12396	0.338	0.413
03/04/2000	5	12711	12748	0.372	0.454
03/05/2000	6	13067	13172	0.410	0.502
03/06/2000	7	13193	13310	0.424	0.518
03/07/2000	8	13525	13670	0.460	0.559
03/08/2000	9	13926	14140	0.503	0.612
03/09/2000	10	14298	14651	0.543	0.671
03/10/2000	11	14463	14955	0.561	0.705
03/11/2000	12	14568	15088	0.572	0.720
03/12/2000	13	14706	15240	0.587	0.738
03/13/2000	14	14781	15352	0.595	0.751
03/14/2000	15	14849	15413	0.603	0.757
03/15/2000	16	15080	15692	0.628	0.789
03/16/2000	17	15319	15922	0.653	0.816
03/17/2000	18	15370	16025	0.659	0.827
03/18/2000	19	15397	16061	0.662	0.831
03/19/2000	20	15506	16192	0.674	0.846
03/20/2000	21	15639	16350	0.688	0.864
03/21/2000	22	15879	16565	0.714	0.889
03/22/2000	23	16085	16810	0.736	0.917
03/23/2000	24	16310	17069	0.760	0.946
03/24/2000	25	16558	17345	0.787	0.978
03/25/2000	26	16666	17525	0.799	0.998
03/26/2000	27	16675	17541	0.800	1.000
03/27/2000	28	16800	17672	0.813	1.015
03/29/2000	30	16891	17773	0.823	1.027
03/30/2000	31	16922	17821	0.826	1.032
03/31/2000	32	16921	17833	0.826	1.033
04/03/2000	35	17540	18536	0.893	1.114
04/05/2000	37	17672	18764	0.907	1.140
04/07/2000	39	17957	19087	0.938	1.176
		Failure	Failure	Failure	Failure

Table G.4 Creep Test Results for Virgin ABS without Fibers; Virgin, Blend, and 100% Recycled with Fibers at 50% Sustained Load

Date	Days	Specimens							
		Strain Reading (ms)				Creep Coefficient			
		A1	A2	A4	A6	A1	A2	A4	A6
01/11/2000	0	9490		3759	4102	0.000		0.000	0.000
01/12/2000	1	11123		4150	4471	0.172		0.104	0.090
01/13/2000	2	11972	6514	4293	4278	0.262	0.000	0.142	0.043
01/14/2000	3	12483	6691	4363	4341	0.315	0.027	0.161	0.058
01/15/2000	4	12778	6694	4397	4372	0.346	0.028	0.170	0.066
01/16/2000	5	13171	6768	4462	4428	0.388	0.039	0.187	0.079
01/17/2000	6	13323	6790	4477	4433	0.404	0.042	0.191	0.081
01/18/2000	7	13577	6838	4518	4477	0.431	0.050	0.202	0.091
01/19/2000	8	13899	6896	4573	4528	0.465	0.059	0.217	0.104
01/20/2000	9	14159	6946	4617	4568	0.492	0.066	0.228	0.114
01/21/2000	10	14308	6967	4636	4581	0.508	0.070	0.233	0.117
01/22/2000	11	14519	6995	4666	4612	0.530	0.074	0.241	0.124
01/23/2000	12	14712	7031	4694	4636	0.550	0.079	0.249	0.130
01/24/2000	13	14909	7067	4730	4673	0.571	0.085	0.258	0.139
01/25/2000	14	15105	7098	4758	4698	0.592	0.090	0.266	0.145
01/26/2000	15	15131	7096	4755	4694	0.594	0.089	0.265	0.144
01/27/2000	16	15291	7122	4777	4715	0.611	0.093	0.271	0.149
01/28/2000	17	15367	7124	4779	4712	0.619	0.094	0.271	0.149
01/29/2000	18	15505	7150	4800	4732	0.634	0.098	0.277	0.154
01/30/2000	19	15749	7197	4845	4775	0.660	0.105	0.289	0.164
01/31/2000	20	15889	7217	4868	4795	0.674	0.108	0.295	0.169
02/01/2000	21	16021	7239	4891	4820	0.688	0.111	0.301	0.175
02/02/2000	22	16106	7252	4899	4826	0.697	0.113	0.303	0.176
02/03/2000	23	16132	7240	4898	4818	0.700	0.111	0.303	0.175
02/04/2000	24	16416	7307	4956	4876	0.730	0.122	0.318	0.189
02/05/2000	25	16459	7308	4959	4878	0.734	0.122	0.319	0.189
02/06/2000	26	16538	7317	4970	4888	0.743	0.123	0.322	0.192
02/07/2000	27	16652	7337	4991	4907	0.755	0.126	0.328	0.196
02/08/2000	28	16748	7352	5000	4920	0.765	0.129	0.330	0.199
02/09/2000	29	16873	7374	5022	4937	0.778	0.132	0.336	0.204
02/10/2000	30	17000	7392	5045	4957	0.791	0.135	0.342	0.208
02/11/2000	31	17200	7431	5081	4992	0.812	0.141	0.352	0.217
02/12/2000	32	17264	7430	5083	4995	0.819	0.141	0.352	0.218
02/13/2000	33	17350	7444	5097	5006	0.828	0.143	0.356	0.220
02/14/2000	34	17624	7493	5151	5053	0.857	0.150	0.370	0.232
02/15/2000	35	17661	7495	5151	5055	0.861	0.151	0.370	0.232
02/16/2000	36	17845	7526	5182	5081	0.880	0.155	0.379	0.239
02/17/2000	37	17844	7521	5179	5078	0.880	0.155	0.378	0.238
02/18/2000	38	17945	7533	5188	5088	0.891	0.156	0.380	0.240
02/19/2000	39	18158	7567	5227	5123	0.913	0.162	0.391	0.249
02/20/2000	40	18188	7561	5226	5117	0.917	0.161	0.390	0.247
02/21/2000	41	18324	7587	5247	5143	0.931	0.165	0.396	0.254

02/22/2000	42	18490	7622	5283	5176	0.948	0.170	0.405	0.262
02/23/2000	43	18720	7666	5328	5217	0.973	0.177	0.417	0.272
02/24/2000	44	18938	7698	5363	5253	0.996	0.182	0.427	0.281
02/25/2000	45	Failure	7778	5433	5322	Failure	0.194	0.445	0.297
02/26/2000	46		7821	5498	5375		0.201	0.463	0.310
02/27/2000	47		7826	5500	5376		0.201	0.463	0.311
02/28/2000	48		7820	5492	5368		0.200	0.461	0.309
02/29/2000	49		7818	5493	5364		0.200	0.461	0.308
03/01/2000	50		7838	5513	5384		0.203	0.467	0.313
03/02/2000	51		7836	5515	5384		0.203	0.467	0.313
03/03/2000	52		7844	5517	5389		0.204	0.468	0.314
03/04/2000	53		7846	5524	5393		0.204	0.470	0.315
03/05/2000	54		7858	5534	5401		0.206	0.472	0.317
03/06/2000	55		7879	5559	5422		0.210	0.479	0.322
03/07/2000	56		7909	5590	5456		0.214	0.487	0.330
03/08/2000	57		7971	5650	5513		0.224	0.503	0.344
03/09/2000	58		8000	5687	5546		0.228	0.513	0.352
03/10/2000	59		7976	5656	5520		0.224	0.505	0.346
03/11/2000	60		7986	5678	5533		0.226	0.511	0.349
03/12/2000	61		7968	5657	5515		0.223	0.505	0.344
03/13/2000	62		7974	5664	5521		0.224	0.507	0.346
03/14/2000	63		7974	5668	5520		0.224	0.508	0.346
03/15/2000	64		8004	5695	5546		0.229	0.515	0.352
03/16/2000	65		8029	5720	5569		0.233	0.522	0.358
03/17/2000	66		8010	5701	5550		0.230	0.517	0.353
03/18/2000	67		8005	5696	5545		0.229	0.515	0.352
03/19/2000	68		8015	5707	5546		0.230	0.518	0.352
03/20/2000	69		8032	5724	5573		0.233	0.523	0.359
03/21/2000	70		8054	5751	5599		0.236	0.530	0.365
03/22/2000	71		8086	5783	5629		0.241	0.538	0.372
03/23/2000	72		8122	5820	5663		0.247	0.548	0.381
03/24/2000	73		8157	5854	5696		0.252	0.557	0.389
03/25/2000	74		8155	5857	5697		0.252	0.558	0.389
03/26/2000	75		8143	5845	5683		0.250	0.555	0.385
03/27/2000	76		8150	5856	5694		0.251	0.558	0.388
03/29/2000	78		8147	5856	5688		0.251	0.558	0.387
03/30/2000	79		8144	5854	5686		0.250	0.557	0.386
03/31/2000	80		8138	5849	5679		0.249	0.556	0.384
04/03/2000	83		8246	5960	5787		0.266	0.586	0.411
04/05/2000	85		8241	5958	5782		0.265	0.585	0.410
04/07/2000	87		8274	5994	5814		0.270	0.595	0.417
04/10/2000	90		8277	6000	5814		0.271	0.596	0.417
04/11/2000	91		8279	6003	5814		0.271	0.597	0.417
04/13/2000	93		8304	6038	5841		0.275	0.606	0.424
04/14/2000	94		8327	6053	5862		0.278	0.610	0.429
04/17/2000	97		8340	6082	5896		0.280	0.618	0.437
04/18/2000	98		8396	6136	5936		0.289	0.632	0.447
04/20/2000	100		8480	6219	6015		0.302	0.654	0.466

04/21/2000	101		8502	6242	6038		0.305	0.661	0.472
04/24/2000	104		8460	6207	6004		0.299	0.651	0.464
04/26/2000	106		8472	6218	6007		0.301	0.654	0.464
04/28/2000	108		8489	6234	6024		0.303	0.658	0.469
05/01/2000	111		8542	6278	6064		0.311	0.670	0.478
05/03/2000	113		8564	6312	6102		0.315	0.679	0.488
05/05/2000	115		8671	6426	6209		0.331	0.709	0.514
05/08/2000	118		8780	6558	6324		0.348	0.745	0.542
05/10/2000	120		8790	6582	6335		0.349	0.751	0.544
05/12/2000	122		8843	6644	6390		0.358	0.767	0.558
05/15/2000	125		8817	6637	6363		0.354	0.766	0.551
05/17/2000	127		8857	6674	6405		0.360	0.775	0.561
05/19/2000	129		8890	6715	6443		0.365	0.786	0.571
05/22/2000	132		8925	6765	6480		0.370	0.800	0.580
05/26/2000	136		8969	6809	6525		0.377	0.811	0.591
05/30/2000	140		8962	6814	6526		0.376	0.813	0.591
06/01/2000	142		9106	6959	6661		0.398	0.851	0.624
06/02/2000	143		9153	7009	6713		0.405	0.865	0.637
06/05/2000	146		9124	6997	6685		0.401	0.861	0.630
06/07/2000	148		9096	6970	6658		0.396	0.854	0.623
06/09/2000	150		9185	7065	6688		0.410	0.879	0.630
06/12/2000	153		9286	7180	6315		0.426	0.910	0.539
06/14/2000	155		9388	7300	6418		0.441	0.942	0.565
06/16/2000	157		9491	7461	6533		0.457	0.985	0.593
06/21/2000	162		9503	7483	6543		0.459	0.991	0.595
06/23/2000	164		9582	7570	6618		0.471	1.014	0.613
06/26/2000	167		9601	7608	6641		0.474	1.024	0.619
06/28/2000	169		9689	7655	6689		0.487	1.036	0.631
07/06/2000	177		9746	7733	6753		0.496	1.057	0.646
07/12/2000	183		9824	7810	6876		0.508	1.078	0.676
07/17/2000	188		9794	7813	6821		0.504	1.078	0.663
07/22/2000	193		9947	7993	6973		0.527	1.126	0.700
07/27/2000	198		10062	8093	7067		0.545	1.153	0.723
07/31/2000	202		9951	-	-		0.528	-	-
08/04/2000	206		10048	-	-		0.543	-	-
08/09/2000	211		10041	-	-		0.541	-	-
08/14/2000	216		9971	-	-		0.531	-	-
08/19/2000	221		10072	-	-		0.546	-	-
08/28/2000	230		10105	-	-		0.551	-	-
09/06/2000	239		10133	-	-		0.556	-	-
09/11/2000	244		10352	-	-		0.589	-	-
09/15/2000	248		10302	-	-		0.582	-	-
09/18/2000	251		10302	-	-		0.582	-	-
09/22/2000	255		10309	-	-		0.583	-	-
09/25/2000	258		10301	-	-		0.581	-	-
10/02/2000	265		10307	-	-		0.582	-	-
10/05/2000	268		10512	-	-		0.614	-	-
10/08/2000	271		10696	-	-		0.642	-	-

10/13/2000	276		10815	-	-		0.660	-	-
10/18/2000	281		11026	-	-		0.693	-	-
02/08/2001	394		11758	8542	7965		0.805	1.272	0.942
05/15/2001	490		12384	8853	8254		0.901	1.355	1.012
07/12/2001	548		13261	9114	8482		1.036	1.425	1.068
10/17/2001	645		13967	9658	8897		1.144	1.569	1.169
01/16/2002	736		14563	9928	9623		1.236	1.641	1.346
04/12/2002	822		15047	10857	10021		1.310	1.888	1.443
06/04/2002	875		16352	11406	10524		1.510	2.034	1.566
08/12/2002	944		16879	11953	11065		1.591	2.180	1.697

Table G.5 Creep Test Results for Virgin, Blend, and 100% Recycled PC with and without Fibers at 20% Sustained Load

Date	Days	Specimens											
		Strain Reading (ms)						Creep Coefficient					
		P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
05/25/2000	0												
05/26/2000	1	15060	8816	15232	7250	15660	8335	0.000	0.000	0.000	0.000	0.000	0.000
05/27/2000	2	16275	9125	17185	7565	16690	8651	0.081	0.035	0.128	0.043	0.066	0.038
05/28/2000	3	16859	9282	17699	7733	17191	8815	0.119	0.053	0.162	0.067	0.098	0.058
05/29/2000	4	17245	9391	18032	7855	17536	8932	0.145	0.065	0.184	0.083	0.120	0.072
05/30/2000	5	17436	9444	18177	7928	17711	8995	0.158	0.071	0.193	0.094	0.131	0.079
05/31/2000	6	17679	9520	18399	8006	17958	9077	0.174	0.080	0.208	0.104	0.147	0.089
06/01/2000	7	18028	9609	18707	8108	18306	9173	0.197	0.090	0.228	0.118	0.169	0.101
06/02/2000	8	18410	9718	19038	8249	18886	9312	0.222	0.102	0.250	0.138	0.206	0.117
06/03/2000	9	18601	9772	19184	8332	19134	9409	0.235	0.108	0.259	0.149	0.222	0.129
06/04/2000	10	18681	9820	19249	8380	19424	9476	0.240	0.114	0.264	0.156	0.240	0.137
06/05/2000	11	18798	9853	19336	8414	19551	9518	0.248	0.118	0.269	0.161	0.248	0.142
06/06/2000	12	18930	9895	19450	8455	19689	9566	0.257	0.122	0.277	0.166	0.257	0.148
06/07/2000	13	18845	9885	19404	8455	19650	9564	0.251	0.121	0.274	0.166	0.255	0.147
06/08/2000	14	18960	9909	19460	8480	19740	9594	0.259	0.124	0.278	0.170	0.261	0.151
06/09/2000	15	18998	9928	19486	8498	19810	9605	0.261	0.126	0.279	0.172	0.265	0.152
06/10/2000	16	19306	10004	19790	8585	20113	9690	0.282	0.135	0.299	0.184	0.284	0.163
06/10/2000	16	19345	10015	19832	8601	20166	9703	0.285	0.136	0.302	0.186	0.288	0.164
06/12/2000	18	19622	10093	20053	8683	20451	9789	0.303	0.145	0.317	0.198	0.306	0.174
06/13/2000	19	19646	10115	20048	8702	20579	9817	0.305	0.147	0.316	0.200	0.314	0.178
06/14/2000	20	19828	10168	20213	8764	20868	9891	0.317	0.153	0.327	0.209	0.333	0.187
06/15/2000	21	19911	10207	20290	8802	20753	9958	0.322	0.158	0.332	0.214	0.325	0.195
06/16/2000	22	19968	10236	20329	8833	20807	9990	0.326	0.161	0.335	0.218	0.329	0.199
06/17/2000	23	20159	10281	20518	8862	21000	10015	0.339	0.166	0.347	0.222	0.341	0.202
06/18/2000	24	20206	10355	21876	Failure	21232	10152	0.342	0.175	0.436	Failure	0.356	0.218
06/20/2000	26	20467	10370	20727	Failure	21279	10337	0.359	0.176	0.361		0.359	0.240
06/21/2000	27	20512	10428	20824	Failure	21380	10218	0.362	0.183	0.367		0.365	0.226
06/22/2000	28	20426	10418	20730	Failure	21276	10210	0.356	0.182	0.361		0.359	0.225
06/23/2000	29	20388	10402	20668	Failure	21245	10193	0.354	0.180	0.357		0.357	0.223
06/24/2000	30	20412	10398	19002	Failure	21248	10216	0.355	0.179	0.248		0.357	0.226
06/25/2000	31	20436	10403	20916	Failure	21361	10270	0.357	0.180	0.373		0.364	0.232
06/26/2000	32	20976	10531	21000	Failure	22151	10301	0.393	0.195	0.379		0.414	0.236
06/26/2000	32	20849	10545	21111	Failure	21724	10337	0.384	0.196	0.386		0.387	0.240
06/27/2000	33	20641	10511	20891	Failure	21446	10110	0.371	0.192	0.372		0.369	0.213
06/28/2000	34	20701	10538	20097	Failure	21602	10321	0.375	0.195	0.319		0.379	0.238
06/29/2000	35	20676	10483	20918	Failure	21546	10310	0.373	0.189	0.373		0.376	0.237
07/06/2000	42	21081	10619	21206	Failure	21893	10436	0.400	0.205	0.392		0.398	0.252
07/07/2000	43	20653	10610	21153	Failure	21786	10314	0.371	0.203	0.389		0.391	0.237
07/09/2000	45	21177	10679	21465	Failure	22101	10450	0.406	0.211	0.409		0.411	0.254
07/12/2000	48	21049	10648	21330	Failure	21970	10427	0.398	0.208	0.400		0.403	0.251
07/13/2000	49	21161	10677	21441	Failure	22066	10454	0.405	0.211	0.408		0.409	0.254
07/14/2000	50	21112	10677	21346	Failure	22018	10456	0.402	0.211	0.401		0.406	0.254

07/18/2000	54	21324	10746	21641	Failure	22293	10522	0.416	0.219	0.421		0.424	0.262
07/22/2000	58	21284	10745	21519	Failure	22178	10503	0.413	0.219	0.413		0.416	0.260
07/24/2000	60	21330	10741	21580	Failure	22247	10518	0.416	0.218	0.417		0.421	0.262
07/26/2000	62	21306	10720	21461	Failure	22101	10508	0.415	0.216	0.409		0.411	0.261
07/28/2000	64	21443	10748	21534	Failure	22194	10524	0.424	0.219	0.414		0.417	0.263
07/30/2000	66	21602	10825	21786	Failure	22475	10602	0.434	0.228	0.430		0.435	0.272
08/04/2000	71	21530	10829	21751	Failure	22454	10601	0.430	0.228	0.428		0.434	0.272
08/06/2000	73	21485	10838	21697	Failure	22406	10608	0.427	0.229	0.424		0.431	0.273
08/08/2000	75	21741	10934	21633	Failure	22626	10684	0.444	0.240	0.420		0.445	0.282
08/11/2000	78	21649	10930	21852	Failure	22589	10675	0.438	0.240	0.435		0.442	0.281
08/15/2000	82	21731	10947	21920	Failure	22668	10691	0.443	0.242	0.439		0.448	0.283
08/19/2000	86	21536	10935	21742	Failure	22460	10647	0.430	0.240	0.427		0.434	0.277
08/23/2000	90	21671	10952	21862	Failure	22524	10686	0.439	0.242	0.435		0.438	0.282
08/28/2000	95	21713	10987	21868	Failure	22719	10669	0.442	0.246	0.436		0.451	0.280
09/06/2000	104	21705	10991	21879	Failure	22674	10718	0.441	0.247	0.436		0.448	0.286
09/11/2000	109	22011	11072	21772	Failure	23100	10751	0.462	0.256	0.429		0.475	0.290
09/15/2000	113	21638	11099	21898	Failure	22688	10717	0.437	0.259	0.438		0.449	0.286
09/18/2000	116	21757	11021	21907	Failure	22793	10731	0.445	0.250	0.438		0.455	0.287
09/22/2000	120	21790	11034	21800	Failure	22808	10751	0.447	0.252	0.431		0.456	0.290
09/25/2000	123	22191	11023	21884	Failure	22631	10688	0.474	0.250	0.437		0.445	0.282
10/02/2000	130	21899	11032	21854	Failure	22732	10743	0.454	0.251	0.435		0.452	0.289
10/05/2000	133	22053	11099	21856	Failure	23110	10817	0.464	0.259	0.435		0.476	0.298
10/08/2000	136	22102	11132	21859	Failure	23154	10858	0.468	0.263	0.435		0.479	0.303
10/13/2000	141	22142	11178	21863	Failure	23189	10889	0.470	0.268	0.435		0.481	0.306
10/18/2000	146	22185	11201	21867	Failure	23231	10954	0.473	0.271	0.436		0.483	0.314
02/08/2001	259	22219	11356	21989		23312	11056	0.475	0.288	0.444		0.489	0.326
05/15/2001	355	22257	11385	22369		23369	11087	0.478	0.291	0.469		0.492	0.330
07/12/2001	413	22305	11474	22440		23408	11145	0.481	0.301	0.473		0.495	0.337
10/17/2001	510	22338	11499	22587		23456	11235	0.483	0.304	0.483		0.498	0.348
01/16/2002	601	22387	11554	22627		23486	11281	0.487	0.311	0.485		0.500	0.353
04/12/2002	687	22456	11663	22687		23547	11356	0.491	0.323	0.489		0.504	0.362
06/04/2002	740	22515	11748	22776		23689	11389	0.495	0.333	0.495		0.513	0.366
08/12/2002	809	22546	11854	22865		23704	11423	0.497	0.345	0.501		0.514	0.370

Table G.6 Creep Test Results for Virgin, Blend, and 100% Recycled PC with and without Fibers at 50% Sustained Load

Date	Days	Specimens											
		Strain Reading (ms)						Creep Coefficient					
		P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
05/25/2000	0	4151		2980		4434		0.000		0.000		0.000	
05/26/2000	1	4921	3176	3544	3088	5232	3021	0.185	0.000	0.189	0.000	0.180	0.000
05/27/2000	2	5170	3230	3748	3141	5408	3076	0.245	0.017	0.258	0.017	0.220	0.018
05/28/2000	3	5312	3266	3857	3183	5495	3116	0.280	0.028	0.294	0.031	0.239	0.031
05/29/2000	4	5421	3295	3949	3213	5569	3146	0.306	0.037	0.325	0.040	0.256	0.041
05/30/2000	5	5452	3295	3955	3208	5566	3145	0.313	0.037	0.327	0.039	0.255	0.041
05/31/2000	6	5508	3315	4020	3230	5619	3165	0.327	0.044	0.349	0.046	0.267	0.048
06/01/2000	7	5707	3367	4200	3283	5788	3218	0.375	0.060	0.409	0.063	0.305	0.065
06/02/2000	8	5846	3399	4318	3330	5932	3260	0.408	0.070	0.449	0.078	0.338	0.079
06/03/2000	9	5943	3407	4413	3346	5992	3275	0.432	0.073	0.481	0.084	0.351	0.084
06/04/2000	10	5903	3402	4370	3325	5950	3255	0.422	0.071	0.466	0.077	0.342	0.077
06/05/2000	11	5932	3411	4403	3335	5956	3265	0.429	0.074	0.478	0.080	0.343	0.081
06/06/2000	12	5970	3425	4437	3352	5995	3281	0.438	0.078	0.489	0.085	0.352	0.086
06/07/2000	13	5870	3401	4341	3330	5886	3260	0.414	0.071	0.457	0.078	0.327	0.079
06/08/2000	14	5902	3408	4372	3331	5914	3263	0.422	0.073	0.467	0.079	0.334	0.080
06/09/2000	15	5902	3407	4354	3336	5928	3264	0.422	0.073	0.461	0.080	0.337	0.080
06/10/2000	16	6133	3467	4602	3397	6147	3323	0.477	0.092	0.544	0.100	0.386	0.100
06/10/2000	16	6166	3474	4642	3404	6184	3333	0.485	0.094	0.558	0.102	0.395	0.103
06/12/2000	18	6297	3505	4752	3438	6280	3359	0.517	0.104	0.595	0.113	0.416	0.112
06/13/2000	19	6231	3494	4672	3422	6208	3349	0.501	0.100	0.568	0.108	0.400	0.109
06/14/2000	20	6322	3452	4768	3450	6286	3376	0.523	0.087	0.600	0.117	0.418	0.118
06/15/2000	21	6336	3507	4783	3445	6276	3380	0.526	0.104	0.605	0.116	0.415	0.119
06/16/2000	22	6342	3525	4787	3462	6285	3385	0.528	0.110	0.606	0.121	0.417	0.120
06/17/2000	23	6402	3560	4899	3521	6317	3400	0.542	0.121	0.644	0.140	0.425	0.125
06/18/2000	24	6585	3527	5015	3564	6503	3437	0.586	0.111	0.683	0.154	0.467	0.138
06/20/2000	26	6521	3504	4956	3543	6439	3420	0.571	0.103	0.663	0.147	0.452	0.132
06/21/2000	27	6592	3529	5024	3569	6494	3450	0.588	0.111	0.686	0.156	0.465	0.142
06/22/2000	28	6460	3502	4884	3536	6351	3424	0.556	0.103	0.639	0.145	0.432	0.133
06/23/2000	29	6420	3464	4820	3517	6261	3354	0.547	0.091	0.617	0.139	0.412	0.110
06/24/2000	30	6456	3431	4816	3416	6258	3331	0.555	0.080	0.616	0.106	0.411	0.103
06/25/2000	31	6434	3420	5039	3564	6250	3361	0.550	0.077	0.691	0.154	0.410	0.113
06/26/2000	32	6639	3532	5061	3589	6553	3452	0.599	0.112	0.698	0.162	0.478	0.143
06/26/2000	32	6722	3628	5154	3609	6633	3482	0.619	0.142	0.730	0.169	0.496	0.153
06/27/2000	33	6512	3613	4879	3501	6437	3412	0.569	0.138	0.637	0.134	0.452	0.129
06/28/2000	34	6582	3498	5132	3563	6500	3449	0.586	0.101	0.722	0.154	0.466	0.142
06/29/2000	35	6487	3503	4888	3543	6369	3437	0.563	0.103	0.640	0.147	0.436	0.138
07/06/2000	42	6656	3560	5085	3587	6580	3472	0.603	0.121	0.706	0.162	0.484	0.149
07/07/2000	43	6543	3516	4981	3487	6460	3396	0.576	0.107	0.671	0.129	0.457	0.124
07/09/2000	45	6582	3545	4982	3569	6464	3485	0.586	0.116	0.672	0.156	0.458	0.154
07/12/2000	48	6720	3580	5115	3576	6599	3450	0.619	0.127	0.716	0.158	0.488	0.142
07/13/2000	49	6623	3523	5014	4086	6484	3432	0.596	0.109	0.683	0.323	0.462	0.136
07/14/2000	50	6563	3502	4947	3528	6368	3395	0.581	0.103	0.660	0.142	0.436	0.124

07/18/2000	54	6802	3609	5182	3606	6663	3457	0.639	0.136	0.739	0.168	0.503	0.144
07/22/2000	58	6494	3496	4877	3528	6329	3410	0.564	0.101	0.637	0.142	0.427	0.129
07/24/2000	60	6720	3644	5112	3569	6586	3455	0.619	0.147	0.715	0.156	0.485	0.144
07/26/2000	62	6742	3566	5141	3586	6630	3464	0.624	0.123	0.725	0.161	0.495	0.147
07/28/2000	64	6707	3539	5055	3570	6544	3439	0.616	0.114	0.696	0.156	0.476	0.138
07/30/2000	66	6752	3728	5145	3606	6624	3469	0.627	0.174	0.727	0.168	0.494	0.148
08/04/2000	71	6807	3628	5189	3631	6657	3445	0.640	0.142	0.741	0.176	0.501	0.140
08/06/2000	73	7022	3621	5340	3667	6802	3527	0.692	0.140	0.792	0.188	0.534	0.167
08/08/2000	75	6852	3600	5235	3600	6685	3514	0.651	0.134	0.757	0.166	0.508	0.163
08/11/2000	78	6792	3588	5177	3631	6657	3506	0.636	0.130	0.737	0.176	0.501	0.161
08/15/2000	82	6868	3614	5242	3645	6714	3522	0.655	0.138	0.759	0.180	0.514	0.166
08/19/2000	86	6649	3552	5048	3583	6514	3468	0.602	0.118	0.694	0.160	0.469	0.148
08/23/2000	90	6763	3589	5143	3614	6627	3502	0.629	0.130	0.726	0.170	0.495	0.159
08/28/2000	95	6844	3370	5215	3648	6698	3528	0.649	0.061	0.750	0.181	0.511	0.168
09/06/2000	104	6698	3556	5092	3582	6578	3452	0.614	0.120	0.709	0.160	0.484	0.143
09/11/2000	109	6964	3653	5339	3690	6810	3580	0.678	0.150	0.792	0.195	0.536	0.185
09/15/2000	113	6675	3662	5100	3605	6583	3485	0.608	0.153	0.711	0.167	0.485	0.154
09/18/2000	116	6666	3575	5061	3602	6537	3572	0.606	0.126	0.698	0.166	0.474	0.182
09/22/2000	120	6693	3608	5089	3605	6557	3511	0.612	0.136	0.708	0.167	0.479	0.162
09/25/2000	123	6590	3806	4989	3589	6461	3465	0.588	0.198	0.674	0.162	0.457	0.147
10/02/2000	130	6692	3800	5091	3672	6568	3571	0.612	0.196	0.708	0.189	0.481	0.182
10/05/2000	133	6925	3674	5311	3678	6866	3542	0.668	0.157	0.782	0.191	0.548	0.172
10/08/2000	136	7112	3802	5345	3692	7014	3592	0.713	0.197	0.794	0.196	0.582	0.189
10/13/2000	141	7143	3912	5381	3701	7028	3601	0.721	0.232	0.806	0.199	0.585	0.192
10/18/2000	146	7167	4008	5395	3715	7075	3645	0.727	0.262	0.810	0.203	0.596	0.207
02/08/2001	259	7225	4086	5422	3826	7358	3699	0.741	0.287	0.819	0.239	0.659	0.224
05/15/2001	355	7261	4203	5436	3965	7598	3821	0.749	0.323	0.824	0.284	0.714	0.265
07/12/2001	413	7285	4312	5437	4025	7656	3968	0.755	0.358	0.824	0.303	0.727	0.313
10/17/2001	510	7306	4356	5448	4086	7787	4056	0.760	0.372	0.828	0.323	0.756	0.343
01/16/2002	601	7320	4459	5486	4158	7821	4115	0.763	0.404	0.841	0.347	0.764	0.362
04/12/2002	687	7328	4521	5523	4252	7869	4156	0.765	0.423	0.853	0.377	0.775	0.376
06/04/2002	740	7340	4623	5539	4365	7925	4186	0.768	0.456	0.859	0.414	0.787	0.386
08/12/2002	809	7363	4654	5551	4444	7986	4237	0.774	0.465	0.863	0.439	0.801	0.403

APPENDIX H

TEST RESULTS FOR FIBER REINFORCED PLASTIC SPECIMENS FOR HIGHWAY APPLICATIONS

Table H.1 Recycled Polypropylene Channel Section Bending Test Results

Gage Location At Midspan Section	Stress	Maximum Load lbs.	Maximum Stress psi	Strain at Max. Load μs	Max. Strain Recorded μs	Stiffness, E psi x 10^6
Side, bottom-most fiber	Tensile	548	13831	5854	6942	2.55
Top, center of width	Compressive	548	6686	1839	3865	2.45
Side, upper-most fiber	Compressive	548	1761	453	4428	2.21

Table H.2 Recycled Polypropylene Trapezoidal Section Bending Test Results

Gage Location at Midspan Section	Stress	Maximum Load lbs.	Maximum Stress psi	Strain at Max. Load μs	Max. Strain Recorded μs	Stiffness, E psi x 10^6
Bottom, center of width	Tensile	1001	45049	11554	11554	3.16
Top, center of width	Compressive	1001	23722	7952	7952	3.04
Top, side	Compressive	1001	23595	7608	7608	3.02

Table H.3 Plates from Recycled Polypropylene Trapezoidal Section Tension Test Results

Gage Location	Grips	Maximum Load lbs.	Maximum Stress psi	Stiffness, E psi x 10^6
Upper flange - side	No	3702	53240	5.00
Upper flange - center	1 ¾"	3202	39124	3.30
Web	2 ½	5173	82897	3.83
Web	No	3300	55000	4.40
Bottom flange	1 ¾"	3418	72811	3.73

Table H.4 Recycled ABS Box Section Bending Test Results

Type of Specimen	Stress	Maximum Load lbs.	Maximum Stress psi	Strain at Max. Load μs	Max. Strain Recorded μs	Stiffness, E psi x 10^6
Non-wrapped 3-point bending	Tensile	290	12845	3087	3087	3.86
	Compressive	280	12402	7703	7703	2.28
Wrapped 3-point bending	Tensile	504	12953	4652	9309	3.24
	Compressive	504	12953	7354	7653	1.90
Wrapped 4-point bending	Tensile	1230	19733	5251	5251	3.42
	Compressive	1230	19733	5852	6302	2.94

Table H.5 Virgin Vinylester Box Section 3-Point Bending Test Results

Specimen No.	Stress	Maximum Load lbs.	Maximum Stress Psi	Strain at Max. Load μs	Max. Strain Recorded μs	Stiffness, E psi x 10^6
1	Tensile	900	31735	8801	8801	2.52
	Compressive	900	31735	18000	18000	3.60
2	Tensile	800	28209	7837	7837	1.96
	Compressive	800	28209	25250	25250	3.65

Table H.6 Recycled ABS Box Section Tension Test Results

Gage Location	Maximum Load lbs.	Maximum Stress psi	Strain at Max. Load μs	Max. Strain Recorded μs	Stiffness, E psi x 10^6
Front face	3702	6300	6600	8550	3.37
Lateral face	3202	6300	6450	8100	3.04
AVERAGE					3.21

Table H.7 Recycled ABS Short Plates Cut from Sheets Bending Test Results

Specimen No.	Stress	Maximum Load lbs.	Maximum Stress psi	Strain at Max. Load μs	Max. Strain Recorded μs	Stiffness, E psi x 10^6
1	Tensile	195	27240	14300	14300	2.59
	Compressive	195	27240	16911	16911	2.33
2	Tensile	200	28745	-	-	-
	Compressive	200	28745	-	-	-

Table H.8 Recycled ABS Long Plates Cut from Sheets Bending Test Results

Specimen No.	Stress	Maximum Load lbs.	Maximum Stress Psi	Strain at Max. Load μs	Max. Strain Recorded μs	Stiffness, E psi x 10^6
1	Tensile	160	39815	13734	13734	3.01
	Compressive	160	39815	15118	15118	2.92
2	Tensile	160	39815	13718	13718	3.04
	Compressive	160	39815	14832	14832	2.90

Table H.9 Recycled ABS Sheets Tension Test Results

Specimen No.	Maximum Load lbs.	Maximum Stress psi	Stiffness, E psi x 10^6
1	2261	20727	2.68
2	2669	23194	2.69

Table H.10 Recycled ABS Sheets Compression Test Results

Specimen No.	Maximum Load lbs.	Maximum Stress psi	Strain at Max. Load μs	Stiffness, E psi x 10^6
1	800	7497	2974	3.36
2	700	6255	2593	3.80
AVERAGE		6876		3.58

Table H.11 Recycled ABS Belt-Type Specimens Tension Test Results

Specimen Type	Specimen No.	Maximum Load lbs.	Maximum Stress psi	Strain at Max. Load μs	Stiffness, E psi x 10^6
A	A1	495	25085	9909	2.86
	A2	618	34497	12662	2.98
	AVERAGE		29791		2.92
B	B1	497	36808	14320	2.68
	B2	517	37482	13605	2.62
	AVERAGE		37145		2.65
C	C1	332	20771	9001	2.17
	C2	439	28053	13171	2.02
	AVERAGE		24412		2.09

Table H.12 Wooden Blocks from Rubber-Wood Block Model Compression Test Results

Specimen Type	Specimen No.	Maximum Load lbs.	Maximum Stress psi	Strain at Max. Load μs	Stiffness, E psi x 10^6
Parallel to grain	Pa1	35312	8749	4553	1.63
	Pa3	32570	7931	4543	1.81
	Pa4	34400	8517	7824	1.45
	AVERAGE		8399		1.63
Perpendicular to grain	Pe1	6500	1474	9640	0.196
	Pe2	6555	1472	8100	0.198
	AVERAGE		1473		0.197

Table H.13 Wooden Specimens from Rubber-Wood Block Model Impact Test Results

Specimen No.	Thickness in	Indicated Impact Strength ft-lb	Correction ft-lb	Corrected Impact Strength ft-lb	Impact Strength ft-lb/in	Failure Type
1	0.26	0.67	0.39	0.28	1.10	C
2	0.27	0.58	0.41	0.17	0.62	C
3	0.25	0.85	0.37	0.48	1.96	H
4	0.24	1.02	0.34	0.68	2.85	H
5	0.28	0.45	0.43	0.02	0.07	C
6	0.29	1.52	0.27	1.25	4.31	H
AVERAGE					1.82	

Table H.14 ABS-Rubber Pull-Out Test Results

Molding Process	Curing Time	Primer	Maximum Load lbs	Maximum Stress psi	Displacement at Max. Load in
Single compression	4	Yes	133	38.7	0.146
Remolded	6	Yes	281	82.1	0.221
Single compression	8	Yes	267	78.9	0.232
Remolded	8	Yes	297	87.9	0.313
Single compression	8	No	73	20.9	0.090
Remolded	8	No	126	36.0	0.114

Table H.15 Fiber Reinforced Plastics Ignition Test Results

Section	Resin	Weight of Fibers gr	Fiber Volume in^3	Specimen Volume in^3	Fiber Volume Fraction %
Trapezoidal	Recycled Polypropylene	9.28	0.199	0.484	41
Channel	Recycled Polypropylene	4.40	0.094	0.221	43
Box	Recycled ABS	0.60	0.013	0.052	25
Box	Virgin Vinylester	9.68	0.208	0.503	41
Wrapped Box	Recycled ABS	5.68	0.122	0.556	22
Sheet	Recycled ABS	1.27	0.027	0.107	25
Belt-type A	Recycled ABS	0.30	0.006	0.032	20
Belt-type B	Recycled ABS	0.38	0.008	0.034	24
Belt-type B	Recycled ABS	0.22	0.005	0.025	19

APPENDIX I

THEORETICAL CALCULATION OF TENSILE MODULUS FOR RANDOMLY ORIENTED CHOPPED FIBER REINFORCED PLASTICS

The following empirical formula proposed by (Agarwal and Broutman, 1980) can be used to estimate the tensile module of a randomly oriented chopped fiber reinforced plastic:

$E_{random}=(3/8)E_L+(5/8)E_T$

Where,

E_{random}= Tensile module of reinforced plastic

E_L= Longitudinal module

E_T= Transverse module

Longitudinal and transverse modulus can be determined by the Halpin-Tsai equation (Agarwal and Broutman, 1980). Calculations for our ABS reinforced specimens are as follows:

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

Where,

E_f= Fiber module, 72.4 Gpa ($10.5x10^6$ psi)

E_m= Matrix module, 2.21 Gpa ($0.321x10^6$ psi)

V_f= Fiber volume fraction = 12%

L= Fiber length, 4mm

d= Fiber diameter, 0.014mm

η_L= $[(E_f/E_m)-1]/[(E_f/E_m)+(21/d)]$ (Agarwal and Broutman, 1980)

replacing,

η_L= [(72.4/2.21)-1]/[(72.4/2.21)+(2x4/0.014)]= 0.053

and

E_L=2.21[(1+(1x4/0.014)0.053x0.12)/1-0.053x0.12)]= 9.80 Gpa (1.42x10^6 psi)

Transverse module is given by

$E_T=E_m[(l+(2\eta_T V_f)/(l-\eta_T V_f)]$

Where,

η_T= [(E_f/E_m)-1]/[(E_f/E_m)+2] (Agarwal and Broutman, 1980)

Thus,

η_T= [(72.4/2.21)-1]/[(72.4/2.21)+2]= 0.914

and

E_T=2.21[(1+2.21x0.914x0.12)/1-0.914x0.12)]=2.98 Gpa (0.43x10^6 psi)

And finally, the the random modulus is calculated as:

E_{random}= (3/8)x9.80+(5/8)x2.98= 5.53 Gpa (0.802x10^6 psi)