JMEPEG (1999) 8:339-346

Analytical Modeling of the Mechanical Properties of Recycled Plastics

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(Submitted 17 December 1997; in revised form 1 February 1999)

The widespread use of recycled plastics has been restricted in part because of the limited state of knowledge about the behavior of this recycled material and the lack of unified design procedures. The material behaves differently in tension and compression, and the nonlinear nature of recycled plastic makes traditional terminology such as modulus of elasticity difficult to determine because generally there is no clearly defined yield point. Furthermore, the modulus of rupture, a property determined from beam tests, can vary for different portions of a fabricated beam making these terms specific to the particular beam rather than exclusively a material property. This article investigates the properties of recycled thermoplastics and methods of testing and analyzing recycled thermoplastic members in both axial compression and flexure. In an effort to provide means for analysis of recycled plastic, material tests of discrete portions of beams were performed to develop a uniaxial material model. The model was used to predict member response based on section geometry alone. This enables prediction of member response of sections not yet tested or even constructed with greater accuracy than previously possible, regardless of the differences in tension-compression behavior and material nonlinearities or variations in material properties among manufacturers.

Keywords compression tests, creep, mechanical properties, recycled thermoplastics, tension tests

1. Introduction

Solid waste is overloading the landfills and is a major contributor to the environmental problems facing this country. Every year the United States alone generates billions of pounds of municipal solid waste, and within this quantity, plastic is the fastest growing segment of solid wastes (Ref 1-2). Recycling is an environmentally acceptable means of reducing solid waste and conserving resources. Reprocessing industrial plastic waste (e.g., in-house scrap) has been a common practice for as long as the plastic industry has existed. There have recently been significant developments in the recycling technology of commingled plastic waste, but the key issue to be resolved is securing long-term, high-value markets for recycled polymers.

In the common procedure, collected plastic scrap (thermoplastics) is granulated, melted, and processed in an extruder. The molten plastic is then forced through a die of the shape and size of the final product. The product can be cut and shaped with the same tools and fastening devices used for wood, but it has been noted that most of the strength is in the outer surface, and manufacturers do not recommend planing (mechanical removal of a thin surface layer). These thermoplastics are resistant to attack from gas, oil, salt, sunlight, chemicals, and insects and will withstand human and mechanical abuse (Ref 3). Test results have shown that mixed plastics hold nails approximately 40% better than wood (Ref 4). Fiberglass and treated wood fiber, both classified as hazardous waste materials, have been successfully used to improve the mechanical properties (Ref 5) of recycled plastics. Previous work (Ref 6) has also revealed that the modulus of elasticity varies greatly among manufacturers. Creep effects (Ref 7) are thought to be significant, and it has been noted (Ref 8) that sample size and temperature affect material properties. It has also been shown (Ref 9) that these recycled plastics are virtually nontoxic, which is in sharp contrast to chemically pressure-treated lumber.

Although the extruded product can be virtually any shape, commonly produced sections resemble standard lumber shapes. Currently, molded shapes are used to make park benches, guardrail block outs, fences, road markers, landscape timbers, and a wide variety of other nonstructural applications. Although it has been highly anticipated that molded shapes will replace wood, concrete, and steel (Ref 10), structural applications of the product are practically nonexistent. This is mainly due to lack of knowledge about the mechanical and structural properties of the material, especially their relation to long term performance. Lack of specific testing standards and design specifications compound the problem.

2. Material Tests

The cross section of the standard recycled plastic lumber shape is visually nonhomogeneous, suggesting that the material properties also vary. Nonhomogeneity of the cross section (Fig. 1) is attributed to the cooling process during extrusion; the section normally cools from the outside first, causing the periphery to solidify before the center. Shrinkage of the center as it cools can also distort the final form of the section causing rounded corners and uneven surfaces. Although the degree of variation is different for various manufacturers and shapes, all products evaluated in this study exhibited this phenomenon. Material tests in tension and compression were conducted to

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investigate this difference, and the results were used to formulate a constitutive model for recycled plastic that can be employed in analytical studies. To validate the constitutive model and assess global behavior of structural components (such as stiffness, strength, and ductility) tests in bending and axial compression were performed, and the results were compared with the analytical results using the proposed material model.

There is currently no industry standard for the manufacture of recycled plastic products, so there is variation among the manufacturers in composition as well as the methods of acquiring materials. To represent the range of compositions available, three manufacturers were selected for testing and referred to as A, B, and C. Manufacturer A mixed fiberglass with the recycled plastic, manufacturer B used only recycled plastic, and manufacturer C used 50% wood fiber in addition to the recycled plastic. It should be mentioned that variations in material strength among manufacturers were not a problem in developing structural applications, but consistency (reliability) of the mechanical properties and long term performance were. The cross section of the extruded product can have any shape, but only standard lumber shapes were used in testing because these are commonly produced and available. The cross section of the standard lumber shapes used in this study were 38 by 241 mm, 89 by 89 mm, 140 by 140 mm, and 140 by 191 mm. In this article they will be referred to by their trade availability names, which are 2 by 10, 4 by 4, 6 by 6, and 6 by 8, respectively.

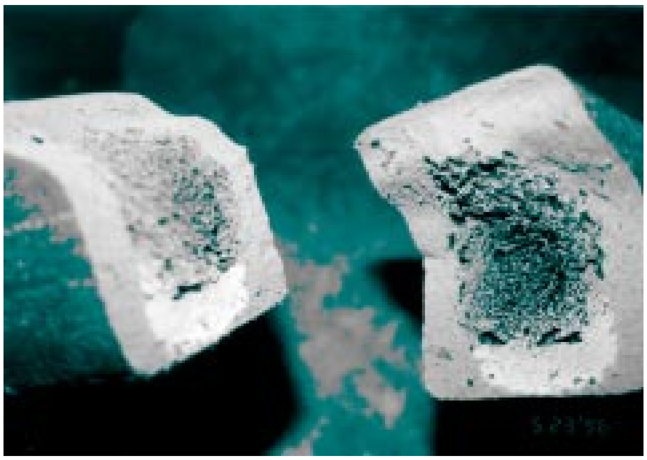

Fig. 1 Picture of cross section of fractured 4 by 4 (100 by 100 mm) sample

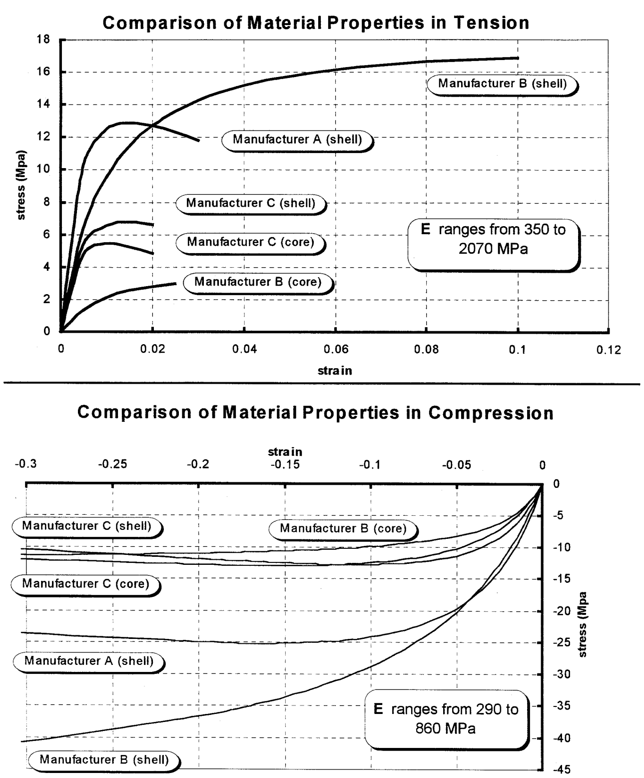

Fig. 2 Stress-strain diagrams for recycled material from three different suppliers. Data for core and shell samples are shown.

2.1 Stress-Strain

Material tests were performed to assess the variation of material properties within the material as well as the variation among manufacturers. The material stress-strain behavior is discussed in later sections to model the member response.

Selection of Coupons and Test Setup. To investigate the apparent nonhomogeneity, visually consistent sections were cut from 4 by 4, 6 by 6, and 6 by 8 shapes and termed core or shell coupons based on their origin. Coupons were also cut from 2 by 10 shapes, but the visually consistent shell section was too thin (typically less than 1 cm) to be used for standard coupons. Cutting was done with power tools designed for wood (circular saw), and no machining was done after the cutting. The core and shell coupons were not only visually different but also were noted to have different dry densities after they were weighed and measured. The dry density of the shell coupons was found to range between 910 to 1090 kg/m^3. Depending on manufacturer (and lumber size for manufacturer B), the core coupons typically had 50% the density of the shell.

Core and shell coupons for tension tests were 1.3 by 4 by 20 cm nominal, and the compression coupons were 1.3 by 4 by 2 cm nominal. Because ASTM is still developing recycled plastic test standards, procedures for wood and plastic were used. Ten tension tests were conducted, generally similar to ASTM D 638, and ten compression tests were conducted similar to ASTM D 695 for each manufacturer. Tension strain was measured with a clip-on type gage over a 5 cm initial gage length, and the load was recorded. Stress was computed by dividing the recorded load by the original cross sectional area, and the strain rate was 0.02 in./in./min.

Results. Figure 2 shows tension and compression stress-strain diagrams for both core and shell coupons for all three manufacturers. The compression test results are plotted only to a maximum of 30% strain because data beyond this point are considered large strain and are not intended for design development. It should be noted that beyond 30% strain, the materials exhibit hyperelastic behavior; there was no point of maximum stress but rather the stress continued to increase after the material visually failed. This was also characterized by a softening (lower modulus of elasticity) followed by a stiffening of the material. Figure 3 shows a typical full-scale compression test for manufacturer B, which marks the point of inflection (change in curvature) and indicates the minimum stiffness. This stiffening is likely attributed to the size of the sample used rather than it being representative of true material characteristics for large deformations. For rectangular wood samples, the ASTM procedure recommends that the height be no greater than two times the minimum thickness, but it is believed that these recommendations are not appropriate for compression testing of plastics where large deformations are expected. The coupons appeared to be approaching a point that would require the material to undergo viscous flow for continued deformation, which is, of course, entirely apart from the objective of these tests. The results of this method are applicable for small to moderate strain (less than 10%), but if large deformation results are desired, a different sample size may provide more representative results.

The stress-strain diagrams show that there is a significant difference in both the tension and compression behavior as well as the core and shell materials. It can also be seen that all materials are nonlinear throughout the range, and none were noted to have a clearly defined yield point. For all manufacturers tested, the core was found to have a lower initial tangent modulus of elasticity, E, and lower ultimate strength. Manufacturer A foam fills the core for aesthetic purposes, so these coupons were not tested. Table 1 shows the variation in material properties between shell and core coupons in tension and compression for all three manufacturers tested. For manufacturer B, the material properties varied with the size of the section. The core coupons from 4 by 4 sizes had a smaller E than that of the 6 by 6 and 6 by 8. It was also noted that the core density of the 4 by 4 (370 kg/m^3) was nearly half that of the 6 by 6 and 6 by 8 (670 kg/m^3). This suggests a correlation between density and stiffness; higher density corresponds to a higher stiffness, but variations in density of less than 5% do not appear to be significant. Although it is unclear if manufacturer B uses different raw materials to form different shapes, it is thought that the variation in density and stiffness is caused by the size and shape of the section. While it is beyond the scope of this article, the rate of cooling is thought to have an important effect on the material properties, and because the section will cool from the outside first, the shell will impose boundary conditions on the core as it cools. Noting that only the core properties are different for the 4 by 4 sections and that the 6 by 6 and 6 by 8 have the same minimum center to perimeter distance supports this notion.

Coupons from all manufacturers were seen to contain varying amounts of impurities; tension failure usually occurred at these locations. Impurities are typically materials such as bottle tops that are inadvertently collected and granulated with the recyclables but melt at a different (normally higher) temperature. The amount of bond adhesion for these impurities is unknown. The size of the impurities varied, but typically comprised less than 5% of the coupon cross sectional area for A and C, while they contributed as much as 10% for B. This is believed to be a factor in the divergence from theory mentioned in later sections.

Table 1 Material properties

Manufacturer and type	E_t, MPa	E_c, MPa	Maximum tension stress, MPa	Compression stress at inflection point, psi
A				
Shell	2070	860	12.9	22.4
Core	NA	NA	NA	NA
B				
Shell	1860	690	16.8	42.2
Core (4 by 4)	350	290	3.1	12.4
Core (6 by 6, 6 by 8)	1030	500	4.0	13.2
C				
Shell	2200	620	6.9	13.8
Core	1800	450	5.5	13.1

E_t, initial tangent modulus in tension; E_c initial tangent modulus in compression; NA, not applicable

Table 2 Summary of creep strain

Manufacturer	Initial strain (immediate), %	Creep strain after seven months, %	Increase from initial strain, %
A	0.008	0.13	1625
B	0.01	0.13	1300
C	0.01	0.13	1300

2.2 Creep

Standard shell compression coupons were subjected to a constant dead load that produced a stress level of 68.9 kPa (10 psi). This is a typical dead load stress level at the base of a 6.1 m (20 ft) high wall created with recycled plastic and was chosen in anticipation of traffic noise barrier applications. The temperature was held constant at 35 °C throughout, and strains were recorded at 14 day intervals. After seven months, the creep strain for all manufacturers was less than 0.15%, and no creep strain was measured in the last four months for manufacturer A. If this strain was (conservatively) considered constant throughout the height, it equates to a creep deflection of only 0.76 cm for a 6.1 m high wall. Although this is acceptable for applications such as traffic noise barriers, Table 2 shows it is extremely large when compared to the initial strain (immediate

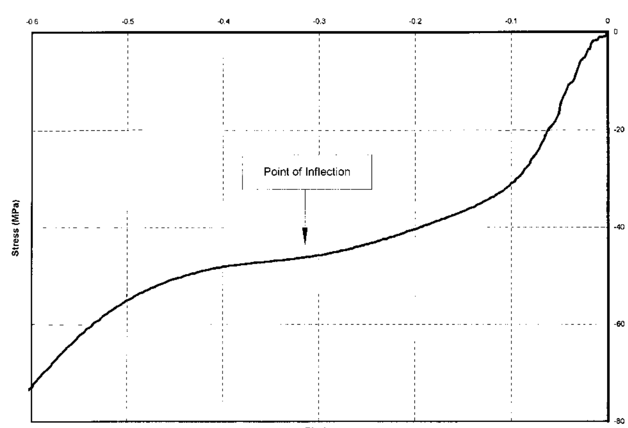

Fig. 3 Full scale compression test for manufacturer B

strain) obtained from the test data. Creep deflection comprises the larger portion of the total deflection by far, even for low stress levels. Noting that 68.9 kPa is much less than the ultimate compressive stress found in the material tests for all manufacturers, it is apparent that creep deflection can be very significant and needs further investigation.

2.3 Freeze/Thaw

To help assess the effects of long term outdoor exposure, all materials were exposed to freeze/thaw cycles. Standard tension and compression coupons were submerged in water for six days and then put into a chamber that regulated the temperature. One cycle consisted of at least 12 h frozen (–15 °C) and at least 12 h thawed (20 °C). The relative humidity was between 65 and 75% at all times. All coupons were subjected to at least 60 freeze/thaw cycles before performing the same material tests as before. Figure 4 indicates that after this exposure, both strength and stiffness were reduced in materials containing wood fibers (manufacturer C) by as much as 50%, while materials containing all plastic (manufacturer B) or mixed with fiberglass (manufacturer A) were not affected significantly. This indicates that plastics containing wood fibers are not a good choice for long term outdoor exposure where structural considerations are important.

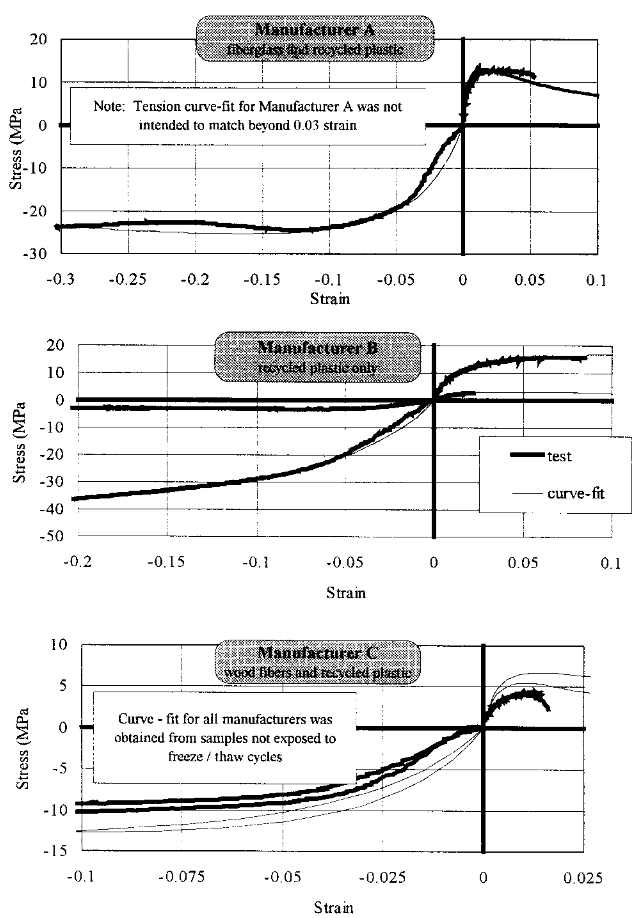

Fig. 4 Material tests after freeze/thaw exposure

3. Proposed Constitutive Model

Based on analyses of the test results under both tension and compression stresses for all manufacturers, the following equation is proposed to define the stress-strain behavior of recycled plastics:

$$\sigma = \frac{A\varepsilon}{B\varepsilon^2 + C\varepsilon + D} \qquad \text{(Eq a)}$$

where σ represents the stress, ε represents the strain, and *A, B, C,* and *D* are material constants. The material constants need to be determined for each type of material, that is, tension and compression of core and shell. This requires sixteen constants for each manufacturer to fully define the section behavior. These constants were determined using a Chi-square minimization method (Ref 11). The model was not fit to the compression curves beyond the point of inflection.

For all three manufacturers the proposed model can simulate the experimental results with high accuracy. In Fig. 5, a stress-strain diagram from material tests of manufacturer B is plotted along with the proposed model, which shows a good match. Table 3 lists the material model constants for all three manufacturers.

With knowledge of the stress-strain behavior, it is possible to predict member response. The material model was used to represent material behavior in computer programs that numerically integrate the stress-strain curve over the cross section. Two programs were developed, one for flexure and one for compression. The flexure program operates by assuming that the strain varies linearly throughout the cross section and maintaining force equilibrium within the section. Load-deflection data was generated by developing a theoretical moment-curvature relation and using it in a moment-area beam analysis. The algorithm for one moment-curvature data point is:

- Select an arbitrary tension strain at the outer fiber.
- Find the corresponding outer fiber compression strain that will maintain tension-compression force equilibrium within the section. Force is computed at thin layers within the section by multiplying the stress from the material model with the corresponding area.

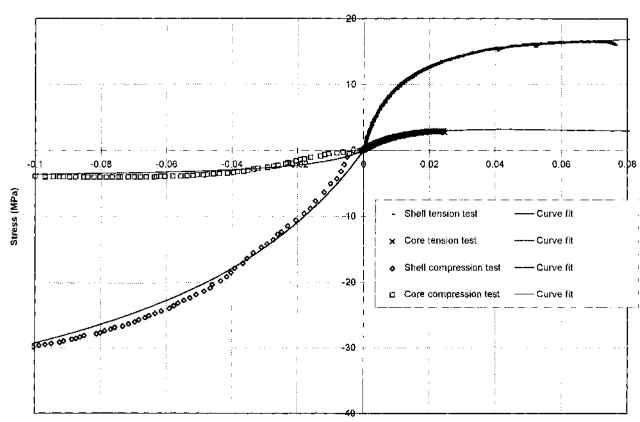

Fig. 5 Material tests and curve fit for manufacturer B

- Compute the curvature in the section: outer fiber strain divided by the distance to the neutral axis.
- Compute the bending moment by summing the product of stress, area, and distance from the neutral axis for all discrete layers in the section.

The compression program operates in a similar manner but uses the following algorithm:

- Select an arbitrary compression strain, assumed to be uniform across the entire section.
- Find the internal force generated by this strain by multiplying the stress and area of the appropriate sections. This is the theoretical load.
- Multiply strain by original sample height for the theoretical deflection at this load.

It should be clear that neither of these programs provide for inelastic unloading or other factors such as creep. They are intended to predict member response to quasi-static loadings. Both programs assume that there is a distinct division between core and shell and that the section is perfectly rectangular (i.e., roundness of the corners is ignored).

4. Member Tests

4.1 Flexure

Four point bending tests were performed on 4 by 4 sections, and three point bending tests were conducted on 6 by 6 and 6 by 8 sections in accordance with ASTM D 198. A 68.6 cm (27 in.) span was used for the 4 by 4 sections with 22.9 cm (9 in.) between the load points, while the larger sections were supported on a 152 cm (60 in.) span and the load was placed mid span. Three 4 by 4, one 6 by 6, and one 6 by 8 were tested from each manufacturer. Bending of the 6 by 8 was around the strong axis.

The load deformation results show nonlinear behavior similar to the material tests. Although all three products demonstrated good ductility for structural purposes, they all failed suddenly as reflected by the lack of a descending portion in the load-deformation curves in Fig. 2. The greater ductility of manufacturer B can be attributed to the lack of reinforcement in the product. Table 4 shows the modulus of rupture for the three manufacturers, which illustrates that for recycled plastic, it is a property of the section size as well as the material. This shows the limitations of the current testing procedures and the need to test each section independently as data from one cannot be used to predict the response of another. Furthermore, if an untested section was considered, there would be no means of predicting its response. This is to be expected as noted earlier because of the nonlinear nature of the material.

Analytical versus Test. The bending test results compared with the theoretical curves in Fig. 5 to 7 show that the analytical results agree with the experimental results within 15% for loads less than 80% of the ultimate load for all sections tested. It is suspected that stress concentrations caused by the presence of impurities discussed in material tests cause the deviations, particularly at larger loads. The theoretical curve is derived from the coupon tests, but the member is more able to transfer the stress concentrations to adjacent areas than the coupon due to its larger cross sectional area (i.e., redistribution of stresses).

The material properties reported by the coupon tests may not be entirely representative of the member behavior. The coupon strain was recorded over a 2 in. gage length, and the net effect of specific, localized stress concentrations occurring in this length cannot be determined because there are several parameters that affect how stress concentrations will change the apparent material behavior. Among these are the ratio of coupon size to impurity size, the ratio of coupon size to member size, the density (frequency) of the impurity distribution, and the type of strain gage and gage length. It is not the intent of this research to investigate these effects but rather to develop and investigate a method for the analysis of composite recycled plastic sections.

At larger loads when the material is yielding, the variation between coupon and member behavior will be greater, because for greater loads, the coupon can rely less on the impurity bonds. This suggests that for the theoretical analysis, strength will be affected more than initial stiffness. The fact that the tension strain in the member at failure was greater (typically by

Table 3 Material constants

Manufacturer Coupon	Constant, MPa A	B	C	D
A				
Shell, tension	1.75E + 5	1.68E + 3	8.49E + 3	40
Shell, compression	1.70E + 6	7.24E + 4	–4.33E + 4	1.94E + 3
Core, tension	0	0	0	1
Core, compression	0	0	0	1
B				
Shell, tension	1.16E + 5	2.46E + 3	6.04E + 3	62
Shell, compression	2.55E + 6	–5.39E + 3	–5.19E + 4	3.70E + 3
Core, tension	9.45E + 4	1.47E + 5	1.77E + 4	264
Core, compression	8.62E + 5	7.81E + 4	–1.99E + 5	3.87E + 3
C				
Shell, tension	1.39E + 5	2.98E + 5	1.21E + 4	62
Shell, compression	8.34E + 5	1.16E + 5	–3.99E + 4	1.36E + 3
Core, tension	1.39E + 5	7.28E + 5	1.03E + 4	77
Core, compression	9.58E + 5	8.70E + 4	–4.68E + 4	2.11E + 3

20%) than the maximum coupon strain supports this conclusion. Similarly, the theoretical maximum bending moment (based on maximum coupon tension strain) was less than the maximum moment experienced during testing. Because of this, the flexure program employs a user-defined parameter, the curve fit limit (CFL), to extend the theoretical curves for the purpose of comparison with the tests. The CFL is the maximum coupon tension strain observed before failure, and when the program requires the stress at a strain larger than the CFL, it uses the stress at the CFL. In other words, the test data are extrapolated by assuming pure plastic deformation to take place after the actual observed failure (i.e., no change in stress). This parameter is introduced in an effort to account for the difference in maximum coupon and member tension strain noted in the tests.

Although all of the theoretical curves predict nonlinear behavior, it can be seen that they all anticipate a more linear response than observed in the tests. It can also be seen that all but one predict a higher ultimate load than observed, which is likely due to an artificial strength caused by the plastic CFL assumption noted earlier. The CFL assumption also prohibits determination of the modulus of rupture. While it is possible to model the bending of recycled plastic sections based on the material behavior satisfactorily for low loads, this method seems to deviate more for higher loads. This indicates that the method as applied here is not appropriate for predicting the post yield member response.

Table 4 Modulus of rupture versus section size

	Modulus of rupture, MPa		
Manufacturer	**4 by 4**	**6 by 6**	**6 by 8**
A	16,500	8,300	10,300
B	21,400	19,300	11,000
C	9,600	11,000	9,600

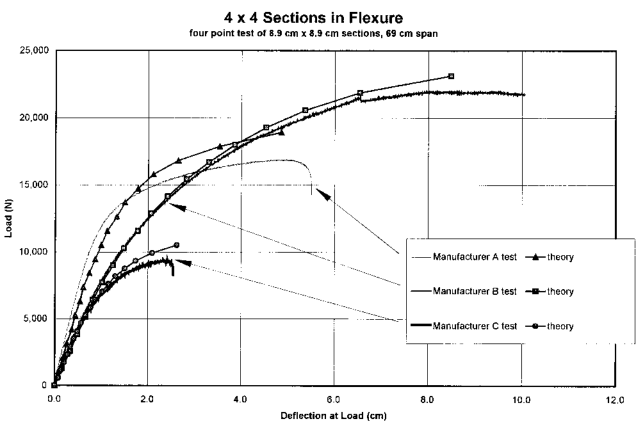

Fig. 6 Bending test results for 4 by 4 sections

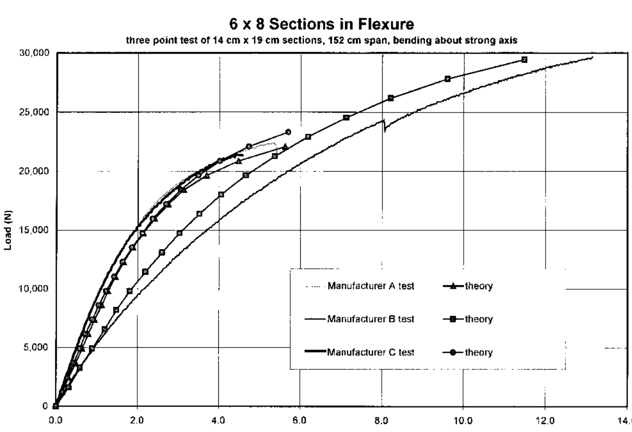

Fig. 8 Bending test results for 6 by 8 sections

4.2 *Axial Compression*

Axial compression tests were performed on entire 4 by 4 sections with an initial height of 11.4 cm. Four samples from each manufacturer were used, and testing proceeded following ASTM D 198, "Static Tests of Timbers in Structural Sizes."

The axial compression results showed that samples from all manufacturers exhibited similar behavior. Near the ultimate load for the section, the stiffness dropped considerably, and the shell began to buckle away from the core. The ultimate compressive strength of the member, thus, is affected by not only the height of the section, but also the bond strength between core and shell materials, particularly for short columns. After visual failure, all samples sustained large plastic deformations

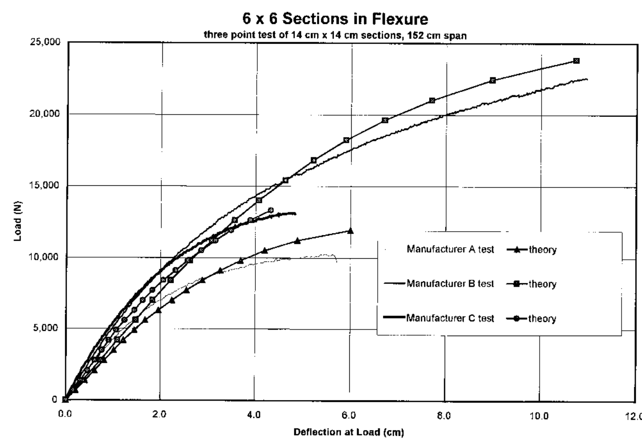

Fig. 7 Bending test results for 6 by 6 sections

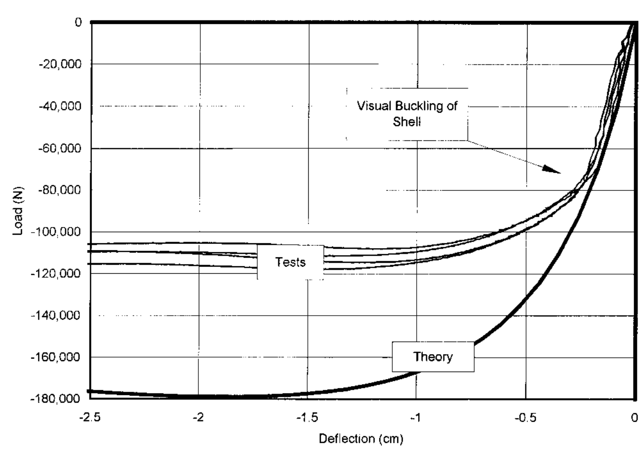

Fig. 9 Axial compression test results of 4 by 4 for manufacturer A

suggesting that these materials might be well suited for one-time, large energy absorbing mechanisms such as crash cushions.

Analytical versus Test. Figures 9 to 11 show the theoretical curves plotted with the axial member compression test results. The curves closely follow the behavior of the member before buckling of the shell occurs for all three manufacturers. The test obviously deviates from theory at this point because the possibility of shell buckling is not considered in the computer program. Note that Fig. 8 suggests that manufacturer A exhibits a local buckling failure of the shell while manufacturer C seems to have a more general buckling failure. The agreement between the test and theory before visual failure occurs indicates that it is possible to predict axial member behavior with reasonable accuracy in this range, but the model gives no prediction of when the shell buckling might occur. The good prebuckling test and theory agreement suggests that the flexural analysis is flawed by the shift in the location of the neutral axis, which causes an inelastic unloading and stress reversal.

5. Conclusions

Experimental and analytical studies have shown that recycled plastic is a viable material that could have structural applications. Key findings of this study are:

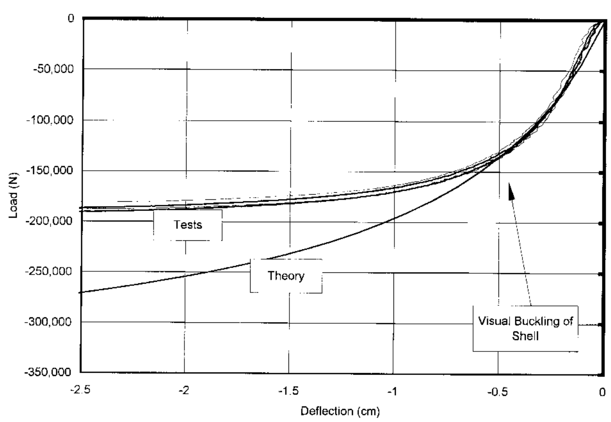

Fig. 10 Axial compression test results of 4 by 4 for manufacturer B

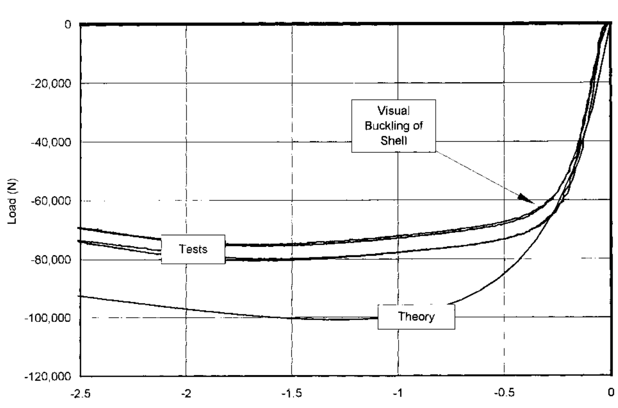

Fig. 11 Axial compression test results of 4 by 4 for manufacturer C

- Recycled plastic has a highly nonlinear stress-strain behavior.
- Stress-strain behavior is different in tension and compression as well as shell and core materials.
- Stiffness ranges from 350 to 2070 MPa, and strength ranges from 3.1 to 16.8 MPa. Thus structural applications are possible.
- Creep is a significant problem, and applications involving large sustained loads should be avoided.
- Freeze/thaw appears to be a problem for recycled plastics with wood fibers.
- The proposed constitutive model can simulate member results with good accuracy for service loads and gives a fair estimate of ultimate strength.

Because the analysis procedure is based on simpler, less expensive coupon tests and does not necessitate separate tests of the entire member for each specific cross section considered, it is anticipated that it will prove useful for recycled plastic analysis. Future work should include validation with products from different manufacturers as well as different member sizes. Additionally, effort should be made to more accurately predict the postyield member response. This can possibly be achieved by obtaining more representative material data. It is thought that the material testing methods could be improved by setting standards more appropriate for recycled plastics as noted earlier. Additionally, manufacturers have taken major steps in improving quality and initiating efforts to develop design standards that can be used by structural engineers.

Acknowledgments

This research and development study was sponsored by the New Jersey Department of Transportation (NJDOT) and the Federal Highway Administration (FHWA). It was coordinated by the Quality Assurance, Improvements, and Research office of NJDOT. The results and conclusions are those of the authors and do not necessarily reflect the views of the sponsors.

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