Recycling Paper for Nonpaper Uses

Brent W. English
USDA Forest Service, Forest Products Laboratory,
One Gifford Pinchot Drive, Madison, WI 53705

The largest components of the municipal solid waste stream are paper and paper products. Paper comes in many grades and from many sources. A significant portion of wastepaper is readily identifiable and can be easily sorted and collected for recycling into paper products. Old newspapers, office paper, and old corrugated containers are examples of these identifiable paper types. An even greater portion of wastepaper is not easily sorted and collected: this portion includes packaging, plastic-coated paper; and mired paper. In addition, many forms of wastepaper contain contaminants such as adhesives. inks, dyes, metal foils, plastics, or ordinary household wastes. These contaminants must be separated from the wastepaper before the fiber can be recycled into paper products. This is not the case when recycling into wood-based composites. In many uses, wood-based composites are opaque, colored, painted, or overlaid Consequently, wastepaper for recycling into composites does not require extensive cleaning and refinement. Thus, composites provide an unusually favorable option for recycling mixed and contaminated paper and other materials.

The USDA Forest Service, Forest Products Laboratory is currently investigating the uses of these materials in wood-based composite products. This paper discusses possibilities for manufacturing selected Composites from wastepaper and other waste materials. Methods for producing the composites and the resultant product properties and attributes are described. Research and development needs for maximizing the benefits of using recovered waste materials for composite products are discussed.

A comprehensive waste management program relies on the aggregate impact of several courses of action: waste reduction, recycling, waste-to-energy schemes, and landfilling [1]. Of these actions, recycling is the most likely to provide great impact from further research. Increased use of recycled paper fiber will allow the markets for fiber composites to grow without increasing the use of virgin timber. Therefore, forest products industries will benefit from such research because less expensive raw materials will be available for producing high-quality composites. As part of this effort, the USDA, Forest Service, Forest Products Laboratory (FPL) has formed a multidisciplinary team of government, university, and industry specialists to prepare a detailed problem analysis to focus research on composites from recycled materials. Some material in this problem analysis was used in preparing this paper [2].

In the United States, nearly 80 million tons of 6,000 paper and paperboard products are produced each year. More than 70 million tons of this material enters the municipal solid waste stream (MSW). Few paper products are produced solely from fiber and water. Most products consist of a fiber matrix to which some mineral or chemical compound has been added to enhance the utility of the product. When these paper products enter the recycling process. the materials that were formerly pioperty enhancers become contaminants. Whether they are adhesives, inks, dyes, metal foils, plastics, or inorganic materials, contaminants need to be separated from the paper fiber before the fiber can be recycled into other useful paper products. This is generally not the case when wastepaper is used in wood-based composites. In many uses, wood-based composites of varying types are opaque, colored, painted, or overlaid. Consequently. recovered paper fibers used in the production of composites do not require extensive cleaning or refinement.

This report describes the potential for producing selected composites from wastepaper and wastepaper fiber. Using materials that coexist with wastepaper for composite production is also considered, including a variety of plastics and other materials that “contaminate” the wastepaper resource. We first discuss the availability of waste materials from the MSW stream and the desirability of developing ways to recycle these materials into useful, high-performing, value-added composites. We then describe methods for preparing and selecting wastepaper to make selected composites and discuss product properties and attributes. Finally, we outline research and development needs for maximizing the benefits of using recovered waste materials for composite products.

MUNICIPAL SOLID WASTE AS SOURCE OF MATERIALS FOR COMPOSITES

A considerable amount of data are related to the inventory of the U.S. MSW stream (Table 1). In 1990, paper and paperboard, wood, and plastics accounted for approximately 73.3, 12.3, and 16.2 x 10^6 tons of the MSW stream, respectively. These figures are expected to increase to 96.1, 18.4, and 21.1 x 10^6 tons annually by the year 2000 [3]. Of the more than 73 million tons of paper waste, approximately 16% were old newspapers, 20% were old corrugated containers, and 56% were mixed papers. Magazines were just under 2% of the total, and other miscellaneous paper made up the remaining 6%.

Recycling not only extends the life of landfills by removing materials from the MSW stream but also makes available large volumes of valuable raw materials for use by industry in place of virgin resources. Many problems are associated with the use of waste materials, including problems with collection, analysis, separation, clean up, uniformity, form, and costs. If these problems can be overcome on a cost-effective basis, some resultant reclaimed materials should be very useful. Industrial use of waste materials reduces both costs for raw materials and energy required to make a finished product [4]. Industry use requires that the recycled ingredients meet the quality and quantity requirements of the consuming production operation.

COMPOSITES FROM WASTEPAPER. WOOD FIBER, PLASTICS. AND INORGANIC MATERIALS

Wastepaper, wood, plastics, gypsum, and other materials can be reclaimed from industrial and MSW streams and used for several composite products: wood fiber-plastic composites, air-laid wood-fiber-based composites, inorganic-bonded wood composites, and composites that combine wood and paper fibers with other lignocellulosics like agricultural fibers.

The following sections are not intended to be a comprehensive review of recent research on alternative paper recycling. Instead, we describe the effects of some important composition and processing variables in the composite processes, most notably, material preparation.

Melt-Blended Thermoformable Composites

A typical composition for a melt-blended composite is about 40 to 50 weight percent wood flour or paper fiber with a powdered or pelletized thermoplastic such as polypropylene or polyethylene. In the melt blending process, the paper fiber or wood flour is blended with the melted thermoplastic matrix by shearing or kneading. Currently, the primary commercial processes employ extruders for melting and mixing. The mixture is extruded as sheets, pellets, or profiles. Limits on the melt viscosity of the mixture restrict the amount of paper fiber or wood flour that can be used.

Recycled paper fiber prepared for use in a twin screw extruder is typically mechanically reduced to fibers by hammermilling. Proper feeding of the paper fiber into the extruder is a key factor to the economic potential of melt-blended paper fiber/plastic composites [5]. The low bulk density of paper fiber necessitates the use of special feeders and can result in somewhat lower throughput rates than when plastic is used alone. Pelletizing paper fiber may improve feeding. Research needs to be conducted to determine if pellets can be made of sufficient strength to be handled efficiently, yet weak enough to break up and disperse during the extrusion process.

In a technological alternative to extrusion for the production of melt-blended composites being used at FPL, a high shear thermo kinetic mixer (K-mixer) is used to melt blend the paper fiber and plastic. Recycled paper prepared for use in a K-mixer is typically mechanically reduced to fragments of 5 to 100 mm^2 by hammermilling or chopping. Because paper fragments have a higher bulk density than do paper fibers, feeding problems are somewhat reduced when paper fragments are used. The high shear forces encountered in K-mixing effectively reduce the paper fragments into individual fibers or small fiber bundles. These high shear forces also tend to break the paper fibers, to some extent limiting their useful length.

Publications are beginning to appear on the effect of added recycled materials on the behavior of melt-blended lignocellulosic-polyolefin composites. Selke et al. [6] showed that composites from aspen fiber and once-recycled blow-molding high-density polyethylene (HDPE) from milk bottles possessed essentially equivalent strength and high-density polyethylene composites made from virgin HDPE; however, impact energy was reduced with the former [7]. Woodhams et al. [8] found that composites made from polypropylene and pulp fibers or fiberized old newspaper possessed strength and impact properties generally superior to those of composites made from wood flour-polypropylene systems. In research at the FPL, the properties of wood flour-polypropylene and wood flour-HDPE systems were compared with properties of a fiberized old newspaper-

HDPE composite. The differences between wood flour-polypropylene and wood flour-HDPE systems were qualitatively consistent with expectations based on the lower strength and greater flexibility of HDPE relative to polypropylene. Also, strength was improved by substituting fiberized old newspaper for wood flour [9].

Although old newspapers appear to be the paper fiber of choice for many melt-blended composites, other options exist. Mixed office wastepaper should perform as well as old newspapers, as long as coated papers are avoided. Glossy magazines can be used but magazines contain large quantities of inorganic fillers [10]. When compared on a weight basis to other wastepaper, the high filler content of glossy magazines results in reduced amount of fiber; mechanical properties suffer as a consequence. Old corrugated containers may also be an option for composite production, but little research has been conducted on this fiber source in the area of melt blending.

Currently, the primary application of melt-blended thermoformed composites is interior door panels and trunk liners in automobiles. Some producers of plastic lumber are adding wastepaper fiber to their product to increase stiffness and reduce creep. Additional large-volume, low-to-moderate cost applications are expected in areas such as packaging (trays, cartons, pallets), interior building panels, and door skins.

Nonwoven Mat Composites

In contrast to melt-blended composites, nonwoven mat technology involves room temperature mixing of lignocellulosic fibers or fiber bundles with other long fibrous materials (usually synthetic fibers). Nonwoven processes allow and tolerate a wide range of wastepaper types dependent on application. With this technology, the amount of paper fiber can be greater than 90 weight percent. After the fibers are mixed, they are air laid into a continuous, loosely consolidated mat. The mat then passes through a secondary operation in which the fibers are mechanically entangled or otherwise bonded together. This low-density mat may be a product in itself, or the mat may be shaped and densified by a thermoforming step. The remainder of the discussion in this section will be on low- and high-density products.

Low-Density. Low-density nonwoven mats are composites made using the aforementioned nonwoven mat process without significant modification by post processing. These mats have a bulk density of 50 to 250 kg/m^3. Nonwoven technology is particularly well known in the consumer products industry. where this technology is used to make a variety of absorbent personal care products, wipes, and other disposable items These products use high-quality pulps in conjunction with additives to increase absorptive properties. Other applications, described next, can use dirty wastepaper reduced to fragments by hammermilling, chopping, or shredding.

One interesting application for low-density nonwoven mats is for mulch around newly planted seedlings. The mats provide the benefits of natural mulch; in addition, controlled-release fertilizers, repellents, insecticides, and herbicides can be added to the mats as needed. Research results on the combination of mulch and pesticides in agronomic crops have been promising [11]. The addition of such chemicals can be based on silvicultural prescriptions to ensure seedling survival and early development on planting sites where severe nutritional deficiencies, animal damage, insect attack, and weed problems are anticipated. The Forest Service is conducting preliminary research on using wastepaper fiber and other low-density mats to improve the survival rate of loblolly pine seedlings in southern Louisiana.

Low-density nonwoven mats can also be used to replace dirt or sod for grass seeding around new home sites or along highway embankments. The grass seed can be incorporated directly into the mat. These mats promote seed germination and moisture retention. Low-density mats can also be used for filters. The density of the mats can be varied, depending on the material being filtered and on the volume of material that passes through the mat per unit time. The FPL is conducting preliminary work on developing nonwoven mats for filters. All these applications for low-density nonwoven mats provide excellent and attractive outlets for recycled paper fiber.

High-Density. High-density fiber mats are composites made using the aforementioned nonwoven mat process, but these composites are post formed into rigid shapes by heat and pressure. To ensure good bonding, the paper fiber can be precoated with a thermal setting resin (for example, phenol-formaldehyde), or the paper fiber can be blended with synthetic fibers, thermal plastic granules, or any combination of these. Plastic-coated paper is an especially interesting material to work with, because the plastic coating can serve as a binder.

High-density fiber mats typically have a specific gravity of 0.60 to 1.40. After thermoforming, the products possess good temperature resistance. Because longer fibers are used, nonwoven products can achieve better mechanical properties than those obtained with the melt blending process. However, high paper fiber content leads to increased moisture sensitivity.

Like low-density nonwoven composites, high-density nonwoven composites allow and tolerate a wide variety of wastepaper types and forms. Depending on application, the paper may be reduced through hammer-milling. chopping, shredding. or pulping. Generally, the wastepaper for high-density composites needs no deinking or other significant cleaning, but like other composite processes, when surface area of the waste-paper is increased through size reduction, adhesive and binder considerations change.

Researchers at FPL use nonwoven techniques to produce a multitude of high-density composite products using wastepaper and other materials. including waste wood, agricultural fibers, and plastics. These composite products may be flat sheets or molded shapes. As flat sheets. these materials can be used as sheathing, underlayment, or paneling substrates. However, to fully exploit the benefits of nonwoven technology, the mats should be molded into shapes. These shapes include automotive interior substrates. packaging, and engi-neered building system components.

Paper-Fiber-Based Composites

For the purpose of this paper. paper-fiber-based composites are defined as composite materials consisting mostly of recycled paper fiber. These composites can be wet laid or air laid. The main difference between paper-Fiber-based composites and nonwoven composites is fiber length. Generally, nonwovens use and require much longer synthetic fibers (1 to 20 cm) and larger paper fiber or wood fiber bundles compared with paper-fiber-based composites, which require individual fibers or small fiber bundles.

Wet-Laid Paper Fiber Composites. Commercial paper-fiber-based composites are made in a process not dissimilar to paper making. In this process, wastepaper is first hydropulped to produce a paper fiber slurry. The slurry is used to distribute and randomize the recycled paper fibers into thick mats. The fibers are interfelted in a reconstitution process and are characterized by hydrogen bonds produced by the interfelting. Like conventional wastepaper recycling, the process discussed here generates sludge and effluents that must be treated or disposed of.

Wet-laid composites are frequently classified as fibrous-felted board products. At certain densities under controlled conditions of hot pressing. rebonding of the lignin effects another bond in the resultant panel product. Binding agents and other materials may be added during manufacture to increase strength or resistance to fire, moisture, or decay. These materials include rosin, alum, asphalt, paraffin, synthetic and natural resins, preserva-tive and fire-resistant chemicals, and drying oils. Wax sizing is commonly added to improve water resistance.

There are great opportunities to produce fiber-based composites of varying densities from recycled paper fibers. One family of products, called Homasote, was first produced in 1916 and is made from old newspapers and other groundwood paper [12]. Other fiberboard-type products now on the market also use all or partly re-cycled wood fiber as the raw material base stock. These products include insulating acoustical board; carpet board; wall, ceiling, and floor acoustical insulation panels; nail baseboard; and floor and roof insulation boards. We anticipate that many other uses for paper-fiber-based products will be developed as collection. separation, and clean-up processes are further refined and developed.

Wet-Laid Paper Fiber/Polyethylene Composites. Research is ongoing at FPL to determine the feasibility of using a wet laying method for producing paper fiber/ polyethylene composites. The advantages of the wet laying process when compared to either the melt blend-ing method and the air-laid process are (1) wet laying maintains the length of the individual wood fibers (melt blending shortens the fibers) and (2) wet laying should result in good interfiber hydrogen bonding, a phenomena that occurs primarily in paper and paperboard manufac-ture but to a very little extent in dry processes.

Wet-laid mats of various blends of nondeinked recycled paper pulp and granulated polyethylene are formed on a screen. The mats are typically about 25-mm thick and have good dispersion. Several additives, including a debonding agent and a nonionic polymeric surfactant, are being tested for their ability to compatabilize the cellulose/polyethylene system. These additives have been noted to have an immediate effect as surfactants, resulting in reduced foaming and increased dispersion during the mixing process. Research continues on this study. Various ratios of paper fiber to polyethylene are being examined, as is varying the amount of additives.

Air-Laid Paper Fiber Composites. Air-laid composites differ from wet-laid composites in that air is used to distribute and randomize the fibers rather than water. As such, little or no hydrogen bonding takes place and other means are necessary to bind the fibers together. Fiber bonding is usually accomplished with a thermal setting resin. One FPL research project recently completed in this area was the investigation of air-laid, dry-process hardboards made using old newspapers [13]. In preparation for the study, old newspapers were hammermilled using a 25-mm screen. The paper fragments were then hydropulped and mechanically dewatered. These processes left the paper fiber in a tightly compacted wet mass. To ensure even drying, the fibers were opened up using the hammermill again, this time with a 6-mm screen. After drying the fibers were ready for the rest of the study.

Dry-process hardboards are generally made from softwood fiber and a thermal setting resin. Krzysik et al. [13] thought these hardboards represented a favorable option for recycling old newspaper fibers. The objective of the research was to determine the effects of various wood fiber to old newspaper ratios (100:0, 50:50, and 0: 100) on the mechanical and physical properties of hardboards made from these fibers. Resin was applied at the 3% and 7% levels. Boards made with either 100% old newspapers or 100% wood fiber processed easily. However, the 50:50 boards were much more difficult to process. Differences in bulk density (old newspaper was much lighter) made blending the materials difficult. In the final method, resin was applied separately to the old newspapers and wood fiber. The two materials were then blended together in a tumbler and ran through a single disc atmospheric refiner with a wide gap setting to break up clumps and disperse resin.

Boards were tested for static bending, tensile strength, dimensional stability, and water resistance. As expected, increasing the resin level generally improved all measured properties. Increasing the amount of old newspapers caused a corresponding deterioration in both mechanical and physical properties. Even with the reduction of properties caused by the addition of old newspapers, hardboards made from a 50:50 ratio containing 7% resin equalled or exceeded all American National Standard Institute-American Hardboard Association standards. Based on Krzysik et al. [13] it is apparent that at least part of the normal hardboard furnish could be supplemented with old newspapers.

Another FPL research project was prompted by a recent landmark conference on paper recycling [14] where three types of paper were identified as the hardest to reuse for paper products. These were unsorted mixed office paper, colored paper (the type used for newspaper ads), and magazine paper. This very preliminary FPL research [15] explored the properties of fiberboards made from the mentioned wastepapers. For the study, the various wastepapers were hammermilled into small fragments and a thermal setting resin was applied. The resulting blend was pressed into fiberboard panels for testing. The results of this research showed no significant differences between boards made at equivalent levels of adhesive. Although no comparisons were made to existing products, the study did show that interesting and attractive composites could be made using wastepapers identified as hardest to reuse.

Structural Paper Products

Researchers at the FPL have developed a structural fiber concept called FPL Spaceboard [16]. In the process of making Spaceboard, various wastepapers such as old newspapers, old corrugated containers, or mixed office waste are prepared by conventional paper pulping means. The paper fiber is not usually deinked.

The production of Spaceboard is generally a wet forming process not dissimilar to paper making. To make the three-dimensional structural board, wood or paper fibers are suspended in a wet slurry, water is removed via vacuum, and the fibers are press dried against rubber molds with wafflelike configurations to produce two symmetrical halves. An adhesive is then used to bond the two halves, creating numerous small shaped cells in the center of the board.

With this technique, Spaceboard can be made as a laminate or a sandwich; it can be thin enough for strong light-weight corrugated containers or thick enough for wall sections. The result is a fiber composite structural material that is strong in every direction.

Laboratory tests showed that Spaceboard is between 30% and 200% stronger than conventional corrugated fiberboard. This strength is due to the special configuration of the core and the superior strength imparted by the press dry method that molds the core and facing together

With further refinement, Spaceboard can provide the wet strength and dimensional stability necessary to build highly engineered structures, as well as significantly improved fiberboard containers. The superior performance parameters of Spaceboard are improved strength and weight characteristics of press-dried fiber facings, unequaled versatility in mechanical design variables, sheet size, cell size, sandwich thickness, core density, and adaptability to a wide range of raw materials.

Spaceboard is a concept in structural fiber construction and, as such, its full potential for application and its economic payoff are just now being determined. Spaceboard is currently licensed for packaging and structural applications. Spaceboard is an excellent outlet for recycled paper fiber, and as for other composites mentioned in this paper, the paper fiber requires little or no cleaning and deinking.

Inorganic-Bonded Wood Composites

Wood particles or paper fibers held together with an inorganic matrix, such as portland cement or gypsum, form a composite that can be used in a variety of structural and industrial applications [17]. These composites have a unique advantage compared with some conventional building materials because they combine the characteristics of both the wood fiber and mineral matrix. Some of these composites are water resistant and can withstand the rigors of outdoor applications, and almost all are either fireproof or highly fire-resistant and are very resistant to attack by decay fungi.

A unique feature of inorganic-bonded composites is that they are adaptable to either end of the cost and technology spectra for building materials. In the Philippines, cement board is fabricated using mostly manual labor and is used in low cost housing. In Japan, cement board fabrication is automated and cement board is used in very expensive modular housing.

Inorganic-bonded wood composites, which provide another major recycling opportunity for wastepaper and wastepaper fiber, are made by blending proportionate amounts of the wastes with inorganic materials. The most apparent and widely used inorganic material is cement. Portland cement. when combined with water, immediately begins to react in a process called hydration to eventually solidify into a solid stone-like mass. The second most used inorganic binder is gypsum. The gypsum can be mined from natural supplies or derived from flue gas. Gypsum is commonly used in the manufacture of drywall.

Cement Board. Generally, cement board is a 50/50 mixture of cement and wood or other lignocellulosic fiber. Cement board is surprisingly lightweight, is easy to nail and saw, and has excellent insulation properties. In addition, cement board is very resistant to moisture, rot, and insect and vermin attack.

Cement board should be of great interest to individuals in the wastepaper pulping industry. One large solid waste material problem for that industry is sludge. Sludge consists of short paper fibers, fiber fragments, inorganic fillers, inks, water, and other waste materials. Generally, this sludge is either landfilled, used as a one-time soil conditioner, or burned. Burning may not be the best option because of the high moisture content and low fuel value of sludge. Scientists at the FPL believe that sludge can be used in cement board and that the high moisture content will be advantageous.

The sludge could be utilized in two ways. The first is to make a conventional cement-bonded composite and substitute a portion of the lignocellulosic content with sludge. A second strategy involves the production of a three-layer board. The center layer would be a low-density composite with quite large wood elements. The outer layers, or faces, would be high-density mixtures of sludge and cement that would be smooth and ready to take paint or other finishes.

Some advantages of using sludge in cement board are paper mills could find an outlet for their sludge, the landfilling or burning of sludge could be eliminated, and making cement board from sludge and other recycled wood products could extend the forest resource.

Although interest in this technology is growing in Europe, the Philippines, and Japan, the United States is just starting to utilize the excellent properties of cement board. Several companies have started to manufacture roof shingles, shakes, and slates made from cement and paper fiber. Some composite slates have 60-year warranties [18].

Gypsum-Bonded Composites. Another inorganic material that can be used to make composites is gypsum. Gypsum can either be derived by mining from natural sources or can be obtained as flue gas gypsum. Flue gas gypsum, now being produced in very large quantities because of Clean Air Act regulations, is the result of introducing lime into the combustion process to reduce sulphur dioxide emissions. By 1995, more than 100 power plants throughout the United States will be producing gypsum. Flue gas gypsum can replace mined gypsum.

Gypsum-bonded wood and paper fiber panels can replace standard gypsum wallboard. Old newspapers are reduced to fibers by hammermilling and are mixed into the slurry that forms the panel. The fibers make up 15 to 30 weight percent of the finished panel. The gypsum/paper fiber panels have strong nail- and screw-holding properties, good moisture and fire resistance, and improved impact, mold, and mildew resistance [19]. Other reported advantages of these panels include improved anti-sag properties (for ceiling boards), better sound insulation, and easy installation (joints do not require taping). Gypsum boards with wastepaper content are now being marketed by Louisiana Pacific, Highland American Corporation, and Schenck Industries [18].

The combination of paper fibers with inorganic binders provides a unique opportunity to utilize wastepaper fiber. Research has clearly indicated that inorganic-bonded composites can meet structural and industrial needs.

RESEARCH AND DEVELOPMENT NEEDS

The USDA Forest Service, by virtue of its role as steward of the National Forests and its research mission coupled with its expertise in wood-based composites and recycling research at the FPL, is actively engaged in a high-priority research program on alternative uses for recovered materials from the MSW stream. The FPL recycling research program is focusing on developing value-added composites from waste materials, including wood and paper fiber/plastic composites, air-laid wood- and paper-fiber-based composites, and composites fabricated with inorganic binders. For each program area, the FPL is

1. developing methods for converting recovered fibers into forms suitable for subsequent processing into alternative end-use applications,
2. optimizing laboratory methods For making prototype products,
3. developing a performance data base, including determining mechanical and physical properties of wood-based products and conducting analytical tests,
4. determining the potential for recycling composites with minimal loss of properties, and
5. studying product applications and economic viability of alternative end-use applications.

In each research area, economic and laboratory studies are being conducted on a continual basis to set research priorities and guide process development. The research will focus on the components of successful recycling systems through determining the supply and availability of waste wood and paper fiber, analyzing the economic efficiency of processing concepts, and studying the market potential for products made from recovered fiber. Studies will examine the effect of new technologies on the environment, such as the projected impact on the landfill burden and on the quality of the air, forests, soil, and water. Studies will also examine the broader economic impact of these technologies on timber markets and trade.

CONCLUDING REMARKS

Recycling is a critical element in the long-term management of renewable resources. Recycling paper fiber into composite products enhances resource conservation. The USDA Forest Service, Forest Products Laboratory, is uniquely capable of a wide range of composites research. This research is transferable to industry through technology transfer activities. The industrial sector has the technical knowledge and equipment to separate and process solid waste and to make useful, economically viable products from waste materials. Partnerships in recycling research will benefit resource conservation and promote economic activity.

LITERATURE CITED

1. Kovacs, W.L., Ecology Law Quarterly 15(4): 537–625 (1988).
2. Rowell, R.M., R.A. Arola, H. Spelter, P. Davis, T. Friberg, R.W. Hemingway, T. Rials, D. Luneke, R. Narayan, J. Simonsen, and D. White, Forest Prod. J. 43(1): 55–63 (1992).

3. EPA. Characterization of municipal solid waste in the United States: 1990 update. Report EPA/530–SW–90–042. U.S. Environmental Protection Agency,Washington, DC (1990).

4. New York Legislation Commission on Solid Waste Management, "The economics of recycling municipal waste", (1986).

5. Myers, G.E. and C.M. Clemons, Final Report for "Solid Waste Reduction Demonstration Grant Program": Project No. 91-5, Wisconsin Department of Natural Resources (1993).

6. Selke, S.E., K.L. Yam, B. Gogoi, and C.C. Lai, "Compounding wood fibers and recycled high density polyethylene using a twin-screw extruder", Abstract, Cellulose, Paper, and Textile Div., ACS Meeting, June (1988).

7. Yam, K., S. Kalyankai, S. Selke, and C.C. Lai, "Mechanical properties of wood fiber/recycled HDPE composites", ANTEC 1988. (1988).

8. Woodhams, R.T., S. Law, and J.J. Balatinecz, "Properties and possible applications of wood fiber-polypropylene composites", Proc., Symp. on wood adhesives, Madison, WI, May 16–18 (1990).

9. Myers, G.E., I.S. Chahyadi, C. Gonzalez, C.A. Coberly, and D.S. Ermer, Intern. J. Poly. Mater. 15: 171–186 (1991).

10. Clemons, C.M. and G.E. Myers, "Properties of melt-blended composites from post-consumer polypropylenes and wastepapers", Soc. of Plastic Eng. Conf. Proc., 3: 3213–3215 (1993).

11. Crutchfield, D.A., G.A. Wicks, and O.C. Burnside, Wood Sci. 34(1): 110–114 (1985).

12. Post, H., Wood Based Panels Intern. 10(7): 23 (1990).

13. Krzysik, A.M., J.A. Youngquist, J.M. Muehl, R.M. Rowell, P. Chow, and S.R. Schook, "Dry process hardboards from recycled newsprint paper fibers", Mat. Res. Soc. Symp. Proc. 266: 73–79 (1992).

14. Focus '95. "Landmark paper recycling symposium", Atlanta, GA, March 19–21(1991).

15. Rowell, R.M. and S. Harrison, "Fiber based composites from recycled mixed paper and magazine stock", Mat. Res. Soc. Symp. Proc. 266: 65–72 (1992).

16. Setterholm, V.C., Tappi J. 66(6): 40–42 (1985).

17. Moslemi, A.A., "Mineral bonded wood composites: Emerging technologies", Proc. IUFRO 19th World Congress, Montreal, Canada (1990).

18. Loken, S., W. Spurling, and C. Price, Guide to Resource Efficient Building Elements, Center for Resourceful Building Technology, Missoula, MT (1991).

19. Donnell, R., Panel World 31(6): 5 –11 (1990).

20. EPA. Characterization of municipal solid waste in the United States: 1992 update. Report EPA/530–S–92-019. U.S. Environmental Protection Agency, Washington, DC (1992).

Table 1. Estimated distribution of materials generated in municipal solid waste (MSW) stream in 1990[a]

Source	Amount in MSW stream (%)	Weight ($\times 10^6$ t)
Paper and paperboard	37.5	73.3
Yard waste	17.9	35.0
Metals	8.3	16.2
Food waste	6.7	13.2
Glass	6.7	13.2
Plastics	8.3	16.2
Textiles	2.9	5.6
Wood	6.3	12.3
Rubber–leather	2.3	4.6
Miscellaneous inorganics	1.5	2.9
Other	1.6	3.2
(Total)	(100.0)	(195.7)

[a]Adapted from EPA [20].

Advances in Forest Products Environmental and Process Engineering: The 1993 Forest Products Symposium

Elmer L. Gaden, Jr., Series Editor

Christopher L. Verrill, Volume Editor

Andrew J. Baker, Thomas J. McDonough, Kenneth M. Nichols

Scott A. Sinquefield and Vic Uloth, Volume Co-editors

M. Bachelani
Ranier Backman
L. Boonsongsup
E. Calvin Clark, Jr
Victor C. Dallons
H.J. Empie
Brent English
W.J. Frederick
Wolfgang J. Glaser
L.A. Hiner
Mikko Hupa
P. Hyöty
K. Janka
J.K. Jokiniemi
Jerry K. Kaczur
E.I. Kaupinnen
M. Kymäläinen
Linda M. Lamb
K. Lisa
M. Mäkinen
P. Mikkanen
Kenneth M. Nichols
Max R. Peterson
Raili Puumalainen
Bandaru V. Ramarao
John C. Rickard
Cortie J. Rolison, III
K. Salmenoja
S.A. Sinquefield
Hans Theliander
L.M. Thompson
Chi Tien
Pia Tiljander
Marjo Törönen
Christopher L. Verrill
H.A. Wells, Jr.
Kevin Whitty
Kenneth E. Woodard, Jr

AIChE Staff

Maura N. Mullen, Managing Editor; Rachel Buckley, Editorial Assistant
Cover Design: Joseph A, Roseti

Inquiries regarding the publication of Symposium Series Volumes should be directed to:
Dr. Elmer L. Gaden, Jr., Series Editor
University of Virginia, Department of Chemical Engineering
Thornton Hall, Charlottesville, VA 22903-2442. FAX (804) 924-6270

No. 302 — AIChE Symposium Series — Volume 90

1994

Published by
American Institute of Chemical Engineers

***AIChE** will not be responsible for statements or opinions advanced in papers or presented in its publications.*

ISBN 0-8169-0663-7