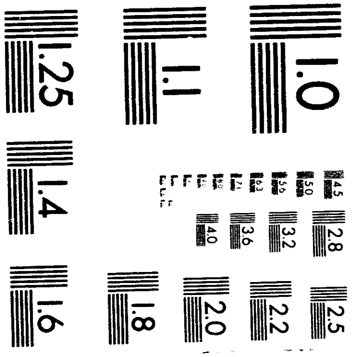
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Proceedings of Waste Stream Minimization and Utilization Innovative Concepts - An Experimental Technology Exchange

Volume 1 - Industrial Solid Waste Processing Municipal Waste Reduction/Recycling

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Abstract

This two-volume proceedings summarizes the results of fifteen innovations that were funded through the U.S. Department of Energy's Innovative Concept Program. The fifteen innovations were presented at the sixth Innovative Concepts Fair, held in Austin, Texas, on April 22-23, 1993.

The concepts in this year's fair address innovations that can substantially reduce or use waste streams. Each paper describes the need for the proposed concept, the concept being proposed, and the concept's economics and market potential, key experimental results, and future development needs. The papers are divided into two volumes: Volume 1 addresses innovations for industrial solid waste processing and municipal waste reduction/recycling, and Volume 2 addresses industrial liquid waste processing and industrial gaseous waste processing.

Summary

In 1983 the Office of Energy Utilization Research within the U.S. Department of Energy (DOE) initiated the Innovative Concepts Program (InnCon). The program is now a part of DOE's Inventions and Innovation Division. The continuing objective of this program is to identify immature concepts having the potential for saving substantial amounts of energy and to provide seed money for a preliminary investigation of their technical and economic feasibility. This report provides information on the fifteen waste stream minimization and utilization concepts selected for further examination during the sixth cycle of the InnCon Program.

The approach used in this project assumes that 1) good concepts come from experienced, knowledgeable innovators; 2) innovators frequently generate more good ideas than can be used within their own organizations; and 3) ideas are frequently generated in an organization unable to realize the benefits of further development. Therefore, other industrial organizations or federal agencies could be interested in providing financial support for further development of such concepts.

This project is an experiment in a continuing program to harvest creative, novel approaches to saving energy. This year's fair sought innovative concepts and inventions that could reduce or use waste streams. As with the last cycle of the program, conducted in April 1991, several agencies with interests in this topic are co-sponsoring the fair. Within DOE, the following are sponsors: Inventions and Innovation Division, Office of Technology Utilization, Office of Industrial Technologies, Office of Fossil Energy, and the Office of Environmental Restoration and Waste Management. Another sponsor of this year's cycle is the Office of Advanced Technology within the State of Texas's Department of Commerce.

Over 130 innovative proposals were received by the InnCon Program in response to the formal call for concepts. Fifteen were selected to receive seed money and nonfinancial assistance. The highlights of each paper are presented in two volumes: Volume 1 addresses innovations for industrial solid waste processing and municipal waste reduction/recycling, and Volume 2 addresses industrial liquid waste processing and industrial gaseous waste processing.

This volume, Volume 1, contains papers on the seven concepts dealing with industrial solid waste processing and municipal waste reduction and recycling. Those papers are briefly summarized below. The abstracts contained in each paper provide more highlights of each concept.

Concrete Application for Magnetic Sand Waste From Steel Foundries

Magnetic sand waste is being investigated for use as fine aggregate in concrete. The magnetic sand is the product of a recently completed and related process in which the magnetic sand waste is reclaimed. Using magnetic sand waste can minimize solid waste from foundries, save landfill capacity, use sand sources more efficiently, and create more profits for both foundry and concrete operators.

Using Fungi and Bacteria to Extract Pollutants From Solid Wastes

This concept proposes using fungi and bacteria to remove and concentrate undesirable trace contaminants; removing phosphorus from iron ore is the initial focus. The advantage of the proposed concept is that the mechanical, chemical, energy, and labor overhead of the process is far smaller than that of more conventional techniques. The concept's advantage results from the fungi's and bacteria's ability to specifically apply their metabolic energy to the materials being removed rather than the entire mass of solids, most of which does not need to participate in the reaction.

Substituting Nonrecyclable Waste Paper for Virgin Paper in Industrial and Commercial Packaging

American Paper Converters is modifying existing processes and developing new processes to manufacture converted paper products from papers that formerly could not be repulped en masse because they contain large quantities of chemicals or coatings that interfere with the repulping process. Prototype machines have been developed and are producing the paper products for market testing.

Hydrocyclone Classifiers for Microsorting Mixed Thermoplastics From Consumer Waste

Two new processes using hydrocyclones are being developed to further separate unsorted, chipped plastics. In one process, lighter-than-water constituents are being fractionated by a novel light-medium separation using a suspension of glass microbubbles in water to achieve an effective density between the fractions of interest. In the second process, resins that have no significant density difference are also being fractionated based on differences in either size or shape.

A Method and Apparatus for Making Continuous-Reinforced Thermoplastic/Cellulose Composites From Recycled Materials

A new process compresses and heats a simple ambient-temperature dry mixture of expanded thermoplastic and cellulose by forcing the mixture through a heated tube. The resulting material is a homogeneous wood substitute with superior dimensional stability that can be molded and easily recycled.

Sound Barrier Wall Containing Recycled Rubber and Plastic

Scrap tire waste is being used with a structural element to create an aesthetic, functional, and long-lasting sound barrier wall. A design has been developed that uses a fiberglass-reinforced composite structural panel encasing a recycled rubber core, which provides the mass needed for appropriate sound blockage. The panel is a pultruded shape that is durable, color compounded, and high strength.

Pulverization Process for Recovering Commingled Plastic Waste

A novel pulverization process known as solid-state shear extrusion is being investigated for recycling commingled, unsorted, post-consumer plastic waste. The process uses a specially designed twin-screw extruder with integrated heating and cooling. Polyolefins such as high-density polyethylene, low-density polyethylene, and polypropylene were selected for the initial pulverization study because they are widely used in packaging and are found in significant quantities in the post-consumer waste stream.

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Introduction

The initiation of invention/innovation needs to be accelerated in the United States to speed up the entire process of technology transfer. During the past several years, business leaders, engineers, scientists, and politicians have recognized that our industrial competitiveness has been deteriorating while our excellence in research continues. This trend has produced a growing consensus that we must improve our ability to bridge the gap between research and the marketplace in the United States. We can no longer afford the patterns of the past where innovative technology trickled out into the marketplace in a serial process that took as long as 25 years. International competitors are bringing technology into the marketplace in months instead of years.

Many solutions are being proposed to accelerate technology into the marketplace. Acceleration of the latter stages of this process is already occurring. State and federal programs help fund and develop new technologies having well demonstrated technical and economic feasibility. However, concepts that have not been given that initial chance provided by a preliminary evaluation of the technical and economic potential are very unlikely to get further assistance. Very few programs are specifically designed to assist in the very beginning of the process of defining the technical and economic feasibility of brand new ideas.

The U.S. Department of Energy (DOE) established the Innovative Concepts Program (InnCon) in the Office of Energy Utilization Research in 1983 after two years of planning. The ICP objective is to develop and demonstrate methods for identifying and encouraging the growth of immature concepts having the potential to save energy and increase productivity through innovative approaches fundamentally different from current practices. The InnCon is encouraging the first steps of the invention/innovation (technology transfer) process.

Pacific Northwest Laboratory (PNL)[a] operates InnCon for DOE to provide a bridge between fundamental scientific progress and technology areas of energy utilization research and to identify large energy-saving improvements to eliminate energy-intensive activities. The program is designed to accomplish these tasks by the following activities:

- identify a focus area (for example, waste stream minimization and use) for a cycle of innovation
- solicit concepts in this focus area and select a limited number for further investigation
- provide modest funding to innovators for investigating the concepts' technical and economic potential
- personally visit each inventor to provide encouragement and concrete suggestions for making the most efficient use of the limited funding
- develop a one-sheet description ("tech brief") of the concept and provide editing of the proceedings
- introduce the selected concepts to potential sponsors at a fair.

(a) Pacific Northwest Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

Innovators who originated these concepts received approximately $20K to perform a preliminary investigation of the technical and economic potential of a concept. A preliminary investigation sometimes proves that a concept should be developed further. This document and the tech briefs are provided to assist potential sponsors in their search for worthwhile products or programs for reducing or using waste streams.

This is the sixth funding cycle sponsored by the ICP. The previous 5 cycles were as follows:

- Buildings Innovative Concepts in May of 1984 funded 12 concepts.
- Industrial Innovative Concepts in November of 1985 funded 10 concepts.
- Industrial Separations Concepts in May of 1988 funded 10 concepts.
- Building Retrofit Innovative Concepts in October of 1989 funded 8 concepts.
- Waste Stream Prevention/Utilization Innovative Concepts in April of 1991 funded 15 concepts.

The original goal of InnCon was to have 10% of the funded concepts receive follow-on funding by other programs or organizations. Of the 55 concepts funded in the first five cycles, 26 or 47% have received substantial follow-on funding totaling more than $12.5 million to date; 2 companies have been started; 20 patents have been issued; 13 patents are pending; and many master theses and more than 80 journal articles have been written on these concepts.

1.0 Concrete Application for Magnetic Sand Waste from Steel Foundries

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Abstract

About 9 million tons of waste foundry sand are generated annually in the United States. While disposing of the sand is a common problem confronting many foundry operations, fine aggregate sand is needed in concrete mixes. However, used or waste foundry sands cannot meet the quality requirements of fine aggregates because the residual binders used in foundry operation exist as organic or inorganic impurities on the used foundry sands' surfaces.

Commercial systems are available to reclaim part of the foundry sand for foundry use (mold backing and facing). Current processes include thermally treating or mechanically scrubbing the used sand. The fines and magnetic portion generated during reclamation are removed and discarded, and the reclaimed sand is returned to the foundry.

The goal of this concept is to use the magnetic sand waste as fine aggregate in concrete applications. Using magnetic sand waste can minimize solid waste from foundries, save landfill capacity, use sand sources more efficiently, and create more profits for both foundry and concrete operators.

A reclamation process has recently been developed that can either partially or completely reclaim, from steel foundries, the used foundry sands containing silica and chromite sand. Partial reclamation uses only magnetic separation to obtain nonmagnetic sand for reuse; the magnetic silica sand is discarded. Complete reclamation applies sizing and tabling after magnetic separation in order to separate chromite from magnetic silica sand. In this case, both the chromite and magnetic sands can be reused.

Any foundries using chemical binders, chromite, and silica sands in their operation are potential customers for the reclamation process. Foundries that use 3 to 6 wt% or more chromite sand in their operations will greatly benefit from using this reclamation process. Preliminary indications show that the reclamation and separation technology can also be applied to foundries that want to separate zircon, olivine, or iron oxide from silica.

Preliminary experimental results conclude that the separation process produces magnetic sand that satisfies the physical and chemical composition ASTM[a] specifications for use as fine aggregate and can be used to produce concrete that has acceptable workability and strength properties. Mixing magnetic sand, which has low fineness modules, with a commercially produced fine aggregate that has high fineness modules can increase both the fineness modules of the mixture and the resulting compressive strength of the concrete. The percentage of magnetic sand used to replace fine aggregate in concrete can vary from 100% to 50%, depending on the specific requirements.

Before the magnetic sands can be used large scale in concrete, additional ASTM tests are recommended to study the effect of magnetic sands on concrete properties. Water reducer should be added in the mix that uses magnetic sand as fine aggregate in order to reduce the water-to-cement ratio to 0.500 (same as the control mix) and to maintain designed slump and air content. Compressive strength tests should be performed on the samples using water reducer, and the results should be compared with the control mix. The results of all of these tests will provide more information on the effect of the small amount of chromite sand in magnetic sand on properties of concrete.

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[a] American Society for Testing and Materials.

1.1 Introduction

About 9 million tons of waste foundry sand are generated annually in the United States (Baillod et al. 1991). While disposing of the sand is a common problem confronting many foundry operations, fine aggregate sand is needed in concrete mixes. Only a limited amount of research has studied the feasibility of substituting used foundry sand for fine aggregates in concrete (Twarog and Burnley 1992; Baillod et al. 1991).

Quality and grading are two basic requirements for fine aggregates in concrete applications. To meet quality requirements, fine aggregate should consist of clean, hard, durable, uncoated particles of sand that are free from organic impurities and clay lumps [ASTM C 33; Michigan Department of Transportation (MDOT) 1990]. Used foundry sands cannot meet these requirements because organic resins or clays are used as binders in foundry operations to form molds, and the residual binders exist as organic or inorganic impurities on the used foundry sand surfaces.

For example, waste green sand cannot be used as fine aggregate because it contains clay binder, and the clay will react with water, reducing the fresh concrete workability, disrupting the entrained air void system, and therefore decreasing the freeze-thaw resistance of the concrete [American Foundry Society (AFS) 1992]. Because foundries use different organic binders and different dosages, varying levels of residual binder are used in foundry sands, making concrete quality control very difficult and limiting the application of used foundry sand in concrete. Grading requirements for fine aggregate in concrete will be discussed later.

Two types of sand sometimes are used in some foundry operations. For example, in a steel foundry, silica sand is used as the mold backing material and chromite sand is used at the face of the mold next to the metal. Before either can be reused in the foundry, the silica must be separated from chromite sand. Commercial systems are available to reclaim part of the foundry sand. Current processes include thermally treating or mechanically scrubbing the used sand. The fines and magnetic portion generated during reclamation are removed and discarded, and the reclaimed sand is returned to the foundry.

1.2 Concept Description

The goal of this concept is to use the magnetic sand waste as fine aggregate in concrete applications. Using magnetic sand waste can minimize solid waste from foundries, save landfill capacity, use sand sources more efficiently, and create more profits for both foundry and concrete operators.

Magnetic sand is a mixture of magnetic silica sand[a] (95 wt%) and chromite sand (5 wt%), which has not been suitable for reuse in foundry operations and would be discarded in current foundry practice. In a recently completed and related project, a sand reclamation and separation process for a steel foundry was developed at the Institute of Materials Processing, Michigan Technological University (Hwang et al. 1992b).

The new reclamation process incorporates 1) thermal treatment to remove residual organic binder from sand particles, 2) magnetic separation to obtain reusable nonmagnetic silica sand and 3) a wet gravity separation (tabling) to separate magnetic silica sand from chromite sand to obtain reusable chromite sand (Hwang et al. 1992a,b.)[b,c]

Figure 1.1 shows the sand reclamation and separation process, which can be applied in two different ways: partial reclamation or complete reclamation. Partial reclamation uses only magnetic separation to obtain and reuse nonmagnetic silica sand; the magnetic mixture is discarded. Complete reclamation applies sizing and tabling after magnetic separation in order to separate chromite from magnetic silica sand. A dry separation

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(a) Here, magnetic silica sand means that the silica sand can be attracted by a rare earth magnetic separator.

(b) Hwang, J. Y., X. Liu, B. Kesling, U. S. Ghose, and S. L. Holman. 1993 (draft). "Sand Reclamation for a Steel Foundry." 1991 American Steel Foundry Society Annual Meeting, Chicago, Illinois, submitted to *AFS Transactions*.

(c) Liu, X., J. Y. Hwang, T. J. Hozeska, A. M. Hein, and R. I. Kramer. 1993 (draft). "Generation of Magnetic Sand During Thermal Treatment of Silica Sand." Submitted to *AFS Transactions*.

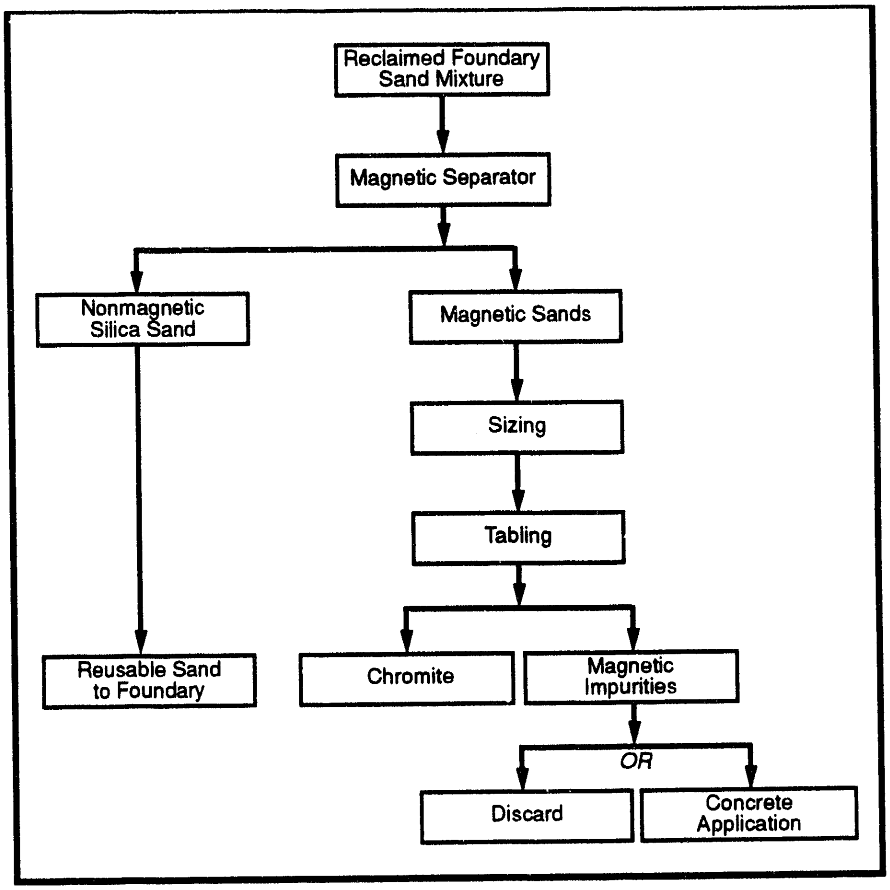

Figure 1.1. Reclamation and Separation Flowsheet for Sand Reclamation and Reuse

process, such as air tabling, could be used instead of wet concentration tabling, depending on the purity requirement of chromite obtained as the concentrate product. With the proposed concept, both the chromite and magnetic sand would be reused.

1.3 Economics and Market Potential

If sand reclamation is performed in steel foundries that use more than 3 wt% chromite sand as facing material, separating chromite from silica will result in [illegible]gnetic sand. An example of the savings' potential from the new process would be a moderate-sized foundry that uses 80 tons of sand per day, or 20,000 tons of sand per year (assuming 250 operating days per year), 87.5 wt% of which is silica sand and 12.5 wt% of which is chromite sand. Table 1.1 shows the estimated annual costs of reclamation options. As the table shows, completely reclaiming the sand can save almost $500,000/year for a moderate-sized foundry. The estimated costs of reclaimed sand are listed in Table 1.2.

Figure 1.2 is the material distribution flowsheet of sand reclamation for a steel foundry. By implementing a sand reclamation system, the foundry only needs to dispose of 6,000 tons (30% of 20,000 tons) of solid waste/year, 4,200 tons (70%) of which are magnetic sands. If the magnetic sand can successfully be used in concrete, only 1,800 tons of solid waste (cyclone fines and baghouse fines) would be discarded per year. The disposal cost for landfilling waste foundry sand varies from $7 to $50 per ton, depending on the landfill tipping fees, handling methods, and transportation distance. If this 4,200 tons of magnetic sand waste can be used in concrete applications, the foundry will save an extra $29,400/year (assuming $7/ton) or $210,000/year (assuming $50/ton). Additional savings would result because the foundry pays $6/ton for shipping

Table 1.1. Estimated Annual Costs ($)

	No Reclamation	Complete Reclamation	Partial Reclamation
Annual Depreciation	0	104,853	91,020
Operating Costs	0	148,350	142,400
Sand Purchase-Silica	262,500	79,431	79,431
Sand Purchase-Chromite	500,000	82,846	500,000
Sand Disposal	251,114	73,163	90,235
Annual Cost	1,013,614	488,643	903,086
Capital Costs	0	783,550	698,550

Table 1.2. Estimated Costs of Reclaimed Sand

	No Reclamation	Complete Reclamation	Partial Reclamation
Cost/Ton Silica	28	22	22
Cost/Ton Chromite	208	44	208
Cost/Day for Total Sand Requirements[a]	4,040	1,959	3,620

(a) Based on 80 tons of sand needed per day; 87.5% of which is silica sand and 12.5% of which is chromite sand.

waste sand to a concrete manufacturer but receives no compensation for the sand; by reusing the 4,200 tons of magnetic sand, another $25,200 in shipping savings would result.

Any foundries using chemical binders, chromite, and silica sands in their operation are potential customers for the reclamation process. Foundries that use 3 to 6 wt% or more chromite sand in their operations will greatly benefit from using this reclamation process. Preliminary indications show that the reclamation and separation technology can also be applied to foundries that want to separate zircon, olivine, or iron oxide from silica.

1.4 Key Experimental Results

To determine whether the magnetic sand obtained in the reclamation process is suitable in concrete application, several experiments were conducted. An ASTM (C 150) Type I portland cement was used for this study. A commercially available ASTM C 260 air-entraining admixture was used in the concrete mix. The coarse aggregate was a commercially produced ASTM C 33, 6A/6AA natural gravel from Hancock, Michigan. This aggregate is typically used in ready-mixed concrete in Upper Michigan. Three sands were used as fine aggregate in this study:

1. The standard fine aggregate used in the control mix for comparison was commercially produced ASTM C 33, 2NS natural sand from Hancock, Michigan, which is typically used in ready-mixed concrete in Upper Michigan.

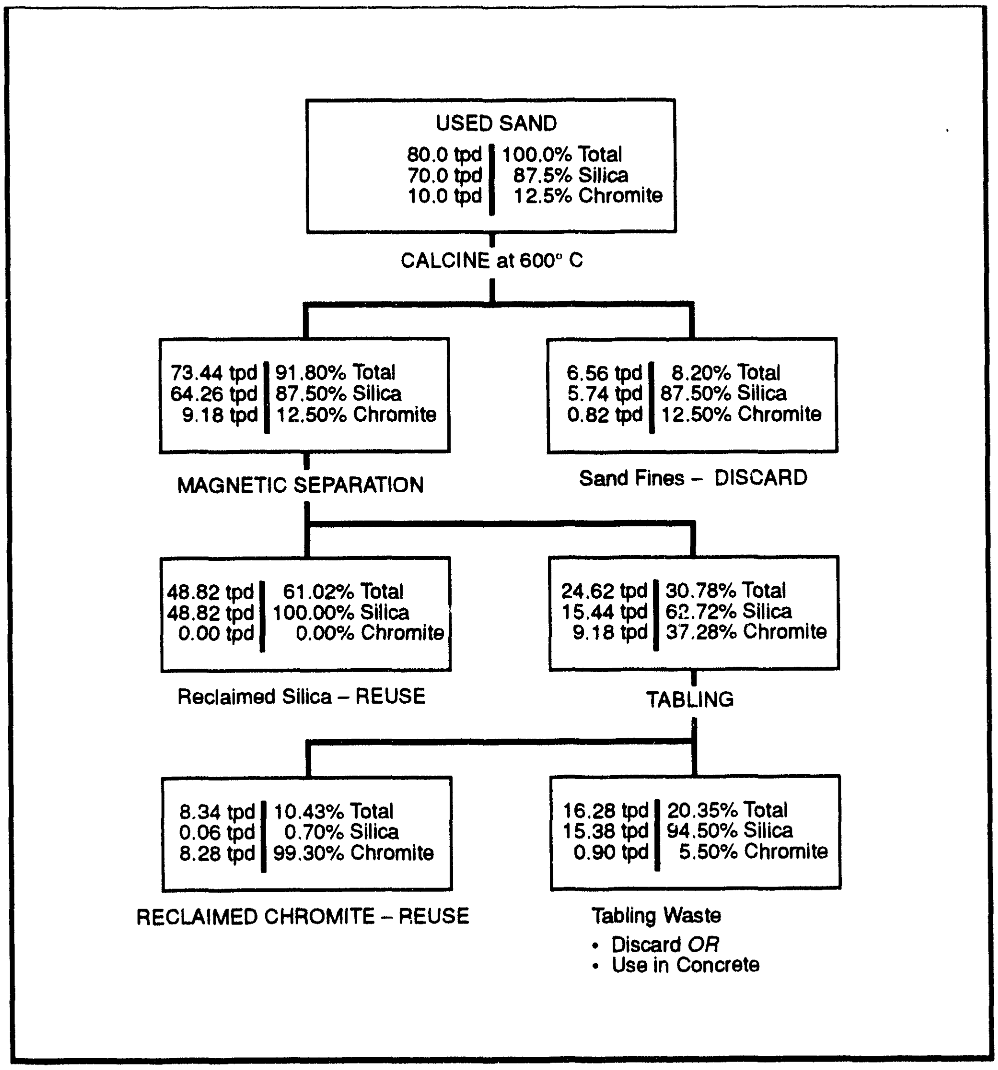

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Figure 1.2. Material Distribution Sheet of Sand Reclamation for a Steel Foundry

2. The fine aggregate used was magnetic sands generated during a pilot-plant-scale study of reclamation and separation of used foundry sand from Bay Cast, Inc., in Bay City, Michigan.

3. The third sand was a Lake Michigan silica sand (or Lake sand), a widely used foundry sand in Michigan with a fineness modulus similar to magnetic sand but containing no chromite sand. The Lake sand was as-received from the sand manufacturer; that is, the sand was new or unused.

The bulk compositions of these three sand samples were determined using direct current plasma-atomic emission spectrometry. Table 1.3 summarizes the sand compositions. The composition of the magnetic sand is very close to that of 2NS sand. The major composition difference between magnetic sand and 2NS sand is because magnetic sand contains approximately 5 wt% chromite sand.

As discussed earlier, the quality of the sand used for fine aggregate is an important requirement. Loss on ignition (LOI) tests were performed on the sand samples to evaluate the level of residue

Table 1.3. Composition of Sands (wt%) Used

Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	Cr_2O_3
Magnetic Sand	75.6	10.5	4.2	1.1	1.2	2.2	3.3	2.0
Lake Sand	93.2	3.1	0.4	0.3	0.1	0.6	1.2	0.0
ASTM C 33 Sand (2NS)	75.0	7.8	4.5	4.1	2.1	1.6	1.9	0.0

organic binder on the reclaimed sand surface. LOI is the weight loss that occurs when sand is ignited in a muffle furnace at 750°C. Carbon and residual organic impurities on sand surfaces are the dominant source of LOI. The LOI values determined for magnetic sand during previous work were below 0.3 wt%, which is much lower than the LOI value for 2NS sand (1.85 wt%).

The LOI tests indicated that during thermal reclamation almost all the residual organics were eliminated from the magnetic sand surfaces. Tests described in ASTM C 40, "Organic Impurities in Fine Aggregates for Concrete," were performed to evaluate the sands' level of organic impurities that might degrade the quality of the fine aggregate. All three sands passed the tests. The consistency between LOI test and the ASTM C 40 test shows that magnetic sand satisfies the requirement for low levels of organic impurities on fine aggregates. Composition analysis revealed about 5.5 wt% alkali in the magnetic sands. Potential reactivity of the aggregates was investigated using ASTM C 289 and showed that both magnetic sand and as-received silica sand passed the test--or could be considered innocuous.

Limiting the amount of clay in fine aggregate is very important because clay in fresh concrete reduces the concrete workability, disrupts the entrained air void system, and therefore decreases the freeze-thaw resistance of the concrete (AFS 1992). Because the particle sizes of both magnetic sand and as-received foundry sand are finer than 20 mesh, the AFS clay test was performed on sand samples. The test results showed that the clay contents for both magnetic sand (0.4%) and Lake sand (0.2%) are lower than that of 2NS sand (0.7%).

Table 1.4 summarizes the results of the LOI, organic content, potential reactivity, and clay content tests. The table also lists the specific gravity and absorption of the three sands. As Tables 1.3 and 1.4 show, the magnetic sand satisfies the composition (or quality) requirements for fine aggregates; the presence of small amounts of chromite does not affect the magnetic sands' use as fine aggregate.

The grading or particle size distribution is another important parameter for fine aggregate. Table 1.5 summarizes the ASTM C 33 requirement for fine aggregate grading. From the ASTM standard, fine aggregate should be uniformly graded from coarse (No. 8) to fine (No. 100) and meet the grading requirement--including fineness modules--and the maximum amount of fine particles that can pass a 200 mesh sieve. However, the particles for both magnetic sand and as-received silica sand are primarily (over 90 wt%) distributed from the No. 30 to No. 100 sieve, resulting in a fineness modulus lower than 1.40. The fine aggregate that satisfies ASTM C 33--2NS sand, with a fineness modulus of 2.76--was mixed with magnetic sand and Lake sand, respectively, to obtain sand mixtures with larger fineness modulus. The effect of the fineness modulus of fine aggregate on concrete was investigated by mixing 50 wt% 2NS sand with 50 wt% of either magnetic sand or as-received Lake sand, respectively. The properties of the individual sands and the 50:50 mixtures are summarized in Table 1.6.

The concrete mixtures were designed to be similar to Grade 35S, one of the most commonly used concrete mixes in Michigan. Grade 35S concrete is designated by MDOT, which has a moderate

Table 1.4. Properties of Sands Used

Properties	ASTM C 33 Sand (2NS)	Magnetic Sand (MS)	Lake Sand (LS)
Specific Gravity	2.66	2.62	2.60
Absorption (%)	0.9	0.50	0.20
Dry Loose Unit Weight (PCF)	114.0	96.0	94.7
LOI (wt%)	1.85	0.30	0.14
Organic Impurities ASTM C 40[a]	Pass	Pass	Pass
Potential Reactivity ASTM C 289[b]	Innocuous	Innocuous	Innocuous
AFS Clay Content (wt%)	0.7	0.4	0.2

(a) ASTM C 40, "Test Method for Organic Impurities in Fine Aggregates for Concrete."
(b) ASTM C 289, "Test Method for Potential Reactivity of Aggregates, Chemical Method."

Table 1.5. Summary of Fine-Aggregate Grading Limits and Magnetic Sand Grading

Sieve Size	ASTM C 33 Requirement wt% Passing	2NS Sand (MDOT Requirement) wt% Passing	Magnetic Sands wt% Passing	Lake Sand wt% Passing
3/8" (9.5 mm)	100	100	100	100
No. 4 (4.74 mm)	95-100	95-100	100	100
No. 8 (2.36 mm)	80-100	65-95	100	100
No. 16 (1.18 mm)	50-85	35-75	100	100
No. 30 (0.6 mm)	25-60	20-55	99.5	99.5
No. 50 (0.3 mm)	10-30	10-30	61.9	60.1
No. 100 (0.15 mm)	2-10	0-10	8.9	1.1
No. 200 (0.075 mm)	<3	<3	0.6	0.3
Fineness Modulus	2.3-3.1	2.50-3.35	1.30	1.39

Table 1.6. Properties of Aggregates Used

Coarse Aggregate						
	Gradation (wt% passing the sieve indicated)			Bulk Specific Gravity (SSD) (g/cm^3)	Absorption (%)	
	1 in. 96	0.5 in. 50	No. 4 7	2.70	1.60	
Fine Aggregates						
Sieve Size and Property	ASTM C 33 Sand (2NS)	Magnetic Sand (MS)	Lake Sand (LS)	Mix. of 2NS/M S 50:50	Mix. of 2NS/LS 50:50	ASTM C 33 Limit
No. 4	99.0	100	100	99.4	99.3	95-100
No. 8	83.5	100	100	91.5	91.5	80-100
No. 16	63.7	100	100	81.6	82.6	50-85
No. 30	46.2	99.5	99.5	72.8	75.0	25-60
No. 50	22.1	61.9	60.1	41.7	47.0	10-30
No. 100	9.2	8.9	1.1	15.7	6.1	2-10
Fineness Modules	2.76	1.30	1.39	1.97	1.99	2.3-3.1

(design) compressive strength of 3500 psi at 28 days (MDOT 1990). The mix design is a performance-based approach following the Absolute Volume Method as detailed by Portland Cement Association (Kosmatka and Panarese 1990). All concrete mixes were prepared in the laboratory using a portable concrete mixer with a batch capacity of 2.5 cubic feet and following the procedures outlined in ASTM C 192-90A, "Test Method of Making and Curing Concrete Test Specimens in the Laboratory."

For comparison, the 2NS fine aggregate was used to make Grade 35S concrete as a standard, or control mix. Magnetic and Lake sands were used to replace 2NS sand in the concrete mixture. Additionally, sand mixtures containing 50 wt% 2NS and either 50 wt% magnetic sands or 50 wt% Lake sand were used as fine aggregate in the concrete mixtures. For each type of fine aggregate used in the study, several trial mixes with different water-to-cement ratios were fabricated to obtain design slump and air content, that is, 3 ± 1 inch for slump and 7 ± 1 vol% for air content. The mix proportions, fresh concrete parameters, and compressive strength test results are summarized in Tables 1.7 and 1.8.

The results of 28-day compressive strength tests show that, in the three sands used, concrete with 2NS sand as fine aggregate (the control mix) has the highest strength. The magnetic sand had the lowest strength but was still within the strength requirements. One reason for magnetic sands' lower strength is its finer particle size distribution of the magnetic sands. Mixing 2NS sand with magnetic sand can improve the properties of the concrete by increasing the fineness modulus of the mixture and will increase the strength of the concrete mix.

Table 1.7. Concrete Mix (lb per cubic yard) and Test Data

Fine Aggregates	2NS (Control Mix)	Magnetic Sand (MS)	Lake Sand (LS)	Mixture of 2NS and MS (50:50)	Mixture of 2NS and LS (50:50)
Specified Design Strength (psi)	3500	3500	3500	3500	3500
Cement (lb)	564	564	564	564	564
Water (lb)	292.9	301.7	295.1	293.9	290.7
W/C ratio	0.500	0.520	0.510	0.505	0.500
Sand (MC<0.5%)	1094	1046	1052	1078	1080
6A Coarse Aggregate (MC<1.0%)	1904	1904	1904	1904	1904
Air-Entraining Agent[a] (oz.)	9.8	9.9	9.8	9.8	9.8
Slump (inch)	3.6	3.7	2.6	3.9	3.7
Air Content (%)	7.0	8.0	7.0	6.4	6.4
Fresh Unit Weight (pcf)	146.1	141.0	144.0	146.3	146.1
28 Days Compressive Strength (psi) 1	4555	3693	4470	3981	4788
2	4721	3543	4484	4060	4777
3	4640	3428	4643	3979	4862
Average	4639	3552	4532	3981	4834

(a) Grace Daravair air-entraining agent was used.

According to Kosmatka and Panarese (1990), the most desirable fine aggregate grading depends on the type of work to be done, the richness of mix, and the maximum size of coarse aggregate. In general, if the water-to-cement ratio is kept constant and the ratio of fine-to-coarse aggregate is chosen correctly, a wide range in grading can be used without strength being measurably affected. Therefore, mixing a portion of 2NS sand with magnetic sand to increase the fineness modulus of the mixture and to ensure the compressive strength is the best way to use magnetic sand in concrete. The percentage of magnetic sand used as fine aggregate can be varied from 100% to 50%, depending on the specific requirements.

As Table 1.7 shows, concrete mix using magnetic sand as fine aggregate needed a higher water-to-cement ratio (0.520) than the control mix (0.500) to achieve the same slump and air content. The higher water-to-cement ratio is one of the factors that lowers the compressive strength for the concrete using magnetic sand as fine aggregate. Table 1.8 shows the effect of water-to-cement ratio on properties of concrete using magnetic sand as fine aggregate. As the water-to-cement ratio decreased from 0.520 to 0.510, the slump of the concrete mixture decreased from 3.7 in. to 1.5 in. In addition, the compressive strength increased from 3,552 psi to 3,862 psi, which was very close to 3,981 psi, the strength of the concrete mixture using 50% magnetic sand and 50% 2NS sand as fine aggregates.

As mentioned previously, the compressive strength of the concrete mixture using 50-50 2NS/magnetic sand mixture as fine aggregate was 3981 psi, which was 82% of the strength of the concrete mixture using 50-50 2NS/Lake sand mixture as fine aggregate. The slump and air content

Table 1.8. Effect of Water-to-Cement Ratio on Properties of Concrete Using Magnetic Sand as Fine Aggregate (lb per cubic yard)

W/C Ratio		0.530	0.520	0.510
Specified Design Strength (psi)		3500	3500	3500
Cement (lb)		564	564	564
Water (lb)		307.3	301.7	296.9
Sand (MC<0.5%)		1031	1046	1066
6A Coarse Aggregate (MC<1.0%)		1904	1904	1904
Air-Entraining Agent[(a)] (oz.)		9.9	9.9	9.9
Slump (in.)		6.5	3.7	1.5
Air Content (%)		11.0	8.0	7.4
Fresh Unit Weight (pcf)		139.0	141.0	141.5
28 Days Compressive Strength (psi)	1	2933	3693	3763
	2	2968	3543	4046
	3	2844	3428	3866
	Average	2915	3552	3862

(a) Grace Daravair air-entraining agent was used.

for the two concrete mixtures are very close, as Table 1.7 shows. No apparent differences exist in the particle grading for the two sand mixtures (2NS/MS and 2NS/LS), as shown in Table 1.6. The major difference between these two sand mixtures is 2 to 3 wt% chromite sand in the 50-50 2NS/MS sand mixture. The major component of chromite sand is FeO*Cr_2O_3 (or MgO*Cr_2O_3). During thermal reclamation processes, iron rich phases, such as FeO, will migrate to or from the surfaces of chromite sand and create a rough surface on the sand particle (Hwang et al. 1992b; Scheffer 1975; Sontz 1972). The rough surfaces on the chromite sand will increase the surface area of the sand, requiring that more water be added to achieve the same workability. This results in an increased water-to-cement ratio, which possibly explains the concrete's decreased strength. Fortunately, the surface area change did not affect the potential reactivity of the magnetic sand, and the strength of the concrete made from using magnetic sand as fine aggregate met the compressive strength specifications.

The effect of magnetic sands' brown color on the overall appearance of the concrete also was examined but did not noticeably darken or stain concrete.

From these preliminary experimental results, the following can be concluded:

1. Magnetic sands obtained from the reclamation and separation process satisfy the requirements that fine aggregate in concrete be free from organic impurities and clay lumps. Magnetic sand also passed ASTM's "Test Method for Potential Reactivity of Aggregates" (ASTM C 289). Magnetic sand satisfies the physical and chemical composition requirements for use as fine aggregates in concrete.

2. Magnetic sands can be used to replace fine aggregate in concrete. The concrete mix using magnetic sands as fine aggregate requires a higher water-to-cement ratio to obtain the same slump and air content as the control mix. The strength of the concrete using magnetic sand as fine aggregate is lower than the control mix, but still meets compressive strength specifications. Mixing magnetic sand, which has a low fineness modules, with a commercially produced fine aggregate that has a high fineness modules can increase both the fineness modules of the mixture and the resulting compressive strength of the concrete. The percentage of magnetic sand used to replace fine aggregate in concrete can vary from 100% to 50%, depending on the specific requirements.

3. The brown color of the magnetic sands will not noticeably decrease the concrete's overall appearance. Applying magnetic sands in concrete did not darken or stain concrete.

1.5 Further Development Needs

This project has shown that magnetic sands can be used to produce concrete within acceptance workability and strength properties. Before the magnetic sands can be used large scale in concrete, additional ASTM tests are recommended to study the effect of magnetic sands on concrete properties. These tests include ASTM C 457, "Practice for Microscopical Determination of Air-Void Content and Parameters of the Air-Void System Analysis of Hardened Concrete"; ASTM C 856, "Practice for Petrographic Examination of Hardened Concrete"; ASTM C 666, "Test Method for Resistance of Concrete to Rapid Freezing and Thawing"; and ASTM C 469, "Test Method for Static Modulus of Elasticity and Poission's Ratio."

Water reducer should be added in the mix that uses magnetic sand as fine aggregate in order to reduce the water-to-cement ratio to 0.500 (same as the control mix) and to maintain designed slump and air content. Compressive strength tests should be performed on the samples using water reducer, and the results should be compared with the control mix. The results of all of these tests will provide more information on the effect of the small amount of chromite sand in magnetic sand on properties of concrete.

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Acknowledgments

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2.0 Using Fungi and Bacteria to Extract Pollutants from Solid Wastes

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Abstract

Removing small amounts of troublesome contaminants from solids is an extremely common problem that is very expensive to address because of the large volumes of material that must be handled. Conventional technologies treat the entire mass of solids rather than just the materials being removed.

This concept proposes using fungi and bacteria to remove and concentrate undesirable trace contaminants. The mechanical, chemical, energy, and labor overhead of the process is far smaller than that of more conventional techniques. The concept's advantage results from the fungi's and bacteria's ability to specifically apply their metabolic energy to the materials being removed rather than to the entire mass of solids, most of which do not need to participate in the reaction.

This concept is currently focused on removing phosphorus from iron ore. Phosphorus causes serious problems in steelmaking, and its removal currently is very expensive. The high-phosphorus slags produced in the steel mill when the phosphorus is removed also present a significant waste problem. Because U.S. iron ores tend to be high in phosphorus, the desirability of the ore is reduced, hindering the competitiveness of the U.S. steel industry.

As the concept is developed, many other trace impurities could be dissolved and reconcentrated from solid wastes, such as mercury, arsenic, selenium, and other heavy metals.

A number of different fungi and bacteria are being cultured and used for this concept. Tests to date indicate that these fungi can dissolve phosphorus even at high pH, where the most important phosphorus compounds are normally completely insoluble. Because most processes should be conducted at a near-neutral pH, the preliminary results are very promising.

Although they are effective, the fungi examined all have a rather slow growth rate. Therefore, the bacteria *Bacillus subtilis* is also being cultivated because bacteria grow significantly faster than most fungi. Because it is also a very common soil organism, it will be easily grown in an industrial-scale process where it will be competing with other, wild organisms.

This bacteria is expected also to be effective for dissolving apatite with secretions of both organic acids and phosphorus-complexing agents. Following the trials with pure apatite, further experiments must be conducted with the actual ore to be processed. The biotechnology of fungi and bacteria, once developed for removing phosphorus impurities in iron ore, will be applied to a host of related problems, particularly removing hazardous heavy metals from solid wastes.

2.1 Introduction

A common industrial problem is solids, either wastes or feedstocks, which contain small amounts of contaminants that will cause serious environmental and processing problems if they are not removed. For example, ore tailings contain heavy metals that gradually leach into ground and surface waters. Also, when the iron ore is smelted and purified, elements such as phosphorus and sulfur produce large amounts of toxic gases and waste slags, thereby reducing the quality of the finished product.

Iron ore deposits in the United States are a sizable portion of the world's iron resources. However, these deposits often contain enough phosphorus to be troublesome. If the phosphorus is not removed, it seriously degrades the quality of the steel produced. To successfully compete with foreign steel producers and to maximize the use of present iron reserves, phosphorus must be removed from the iron ore.

Current practice is to remove phosphorus from the molten metal with special slags, but this practice is expensive and produces a great deal of phosphorus-rich slag as a waste product. Phosphorus, when released into lake waters, will provoke unchecked growth of algae, which in turn produces rotting vegetation and destroys the quality of the lake for water supplies and recreational use.

Attempts to separate the phosphorus-bearing minerals from the iron ore before melting, such as by froth flotation, have been unsuccessful because of the fine dissemination of these minerals in the ore. Conventional chemical leaching also has not been successful because it consumes far too much reagent as a result of the great bulk of material being processed.

In general, conventional extraction methods are not suitable for removing small amounts of noxious impurities from solids because the energy and reagent costs of existing removal technologies are prohibitive. As a result, when a solid waste contains a small amount of a toxic material, such as mercury, the entire mass of solid waste must be treated as a hazardous material and must be disposed of in expensive, low-permeability hazardous waste sites. Similarly, when an industrial feedstock contains a troublesome substance such as sulfur or phosphorus, a great deal of energy and chemical additives must be used to purify it to meet quality standards.

In part because of current technological limits for purifying this country's iron ore sufficiently to meet modern quality standards, last year the U.S. auto industry imported high-quality steel from Japan rather than from domestic suppliers.

A promising method that has recently attracted great interest is using fungi and bacteria to remove phosphorus from iron ore. Fungi are known to produce acids that have been found by other investigators to dissolve minerals containing iron, aluminum, silicon, and magnesium (Silverman and Munoz 1970). Fungi have also been found to leach phosphorus out of minerals and then incorporate the phosphorus into their biomass (Harley and McCready 1981), although no attempt has been made to use these phenomena industrially.

A strain of fungus, *Paxillus involutus 1*, has been found to dissolve phosphorus minerals in the lab (Lapeyrie et al. 1991). Another fungal strain, a species of *Penicillium*, has dissolved 18% of ore phosphorus (Parks et al. 1990), as shown in Table 2.1. The acids secreted by the fungi (oxalic and itaconic acids) can, in their pure form, remove over 50% of the phosphorus, which shows the ultimate effectiveness that can be expected from the fungi under proper conditions. This degree of phosphorus removal is enough to make a currently unmarketable ore into a marketable one. However, this leaching is occurring at pH values less than 3, which is sufficiently acidic to be environmentally troublesome. Also, iron ore processing is normally conducted in neutral or alkaline pH, so attempting to dissolve the phosphorus at a higher pH is very desirable.

Table 2.1. Solubilizing Ore Phosphorus by Spent Culture Medium and Its Organic Acid Constituents[(a)]

Acid	Acid Conc. (mg/10 mL)	pH	% Phosphorous in Treated Ore
None	--	7.0	0.059
Fungal broth	32	2.8	0.049
Oxalic/itaconic acids	32	2.1	0.028

(a) The action of the spent broth shows the effectiveness of the organisms, while the action of the synthetic oxalic/itaconic acid mixture shows the level of phosphorus removal that can be expected from fully adapted organisms.

Other fungal and bacterial strains also are expected to increase the solubility of phosphorus. Because phosphorus is a vital nutrient, many organisms have evolved particularly effective methods for obtaining and storing it. Therefore, it is only a question of isolating the organisms that are most effective.

Bacteria of the genus *Micrococcus* have been found to accumulate phosphorus from solution and then to release it when glucose is added (Nakamura et al. 1991). This process can be refined to a method for concentrating low levels of phosphorus at reasonable cost, potentially concentrating phosphorus to a high enough level to be a saleable material.

A combination of these bacterial and fungal strains should be an effective means of removing phosphorus impurities from iron ore in a low-cost, environmentally benign process.

2.2 Concept Description

Using the fungi's ability to dissolve and then to concentrate phosphorus into biomass, the Michigan Tech Metallurgical and Materials Engineering Department is studying the possible methods for using fungi and bacteria to develop a general class of processes that can remove objectionable trace impurities from solid wastes and feedstocks and then reconcentrate these impurities into an easier-to-handle form. These microorganisms produce acids that dissolve the trace contaminants. Once the contaminants are in solution, the fungi and bacteria concentrate and reprecipitate the contaminants in their biomass. Figure 2.1 shows a schematic of the basic process.

The initial application being investigated is using fungi and bacteria to dissolve phosphorus impurities in ore and to reprecipitate the impurities into fungal and bacterial biomass. This application was chosen because of the interest expressed in phosphorus impurity removal by American Iron and Steel Institute and the Cleveland Cliffs Iron Company.

Biologically concentrating the impurities will not only simplify the disposal of the contaminants but will ultimately be a useful method for concentrating the impurities to a marketable level, removing the need for disposal altogether.

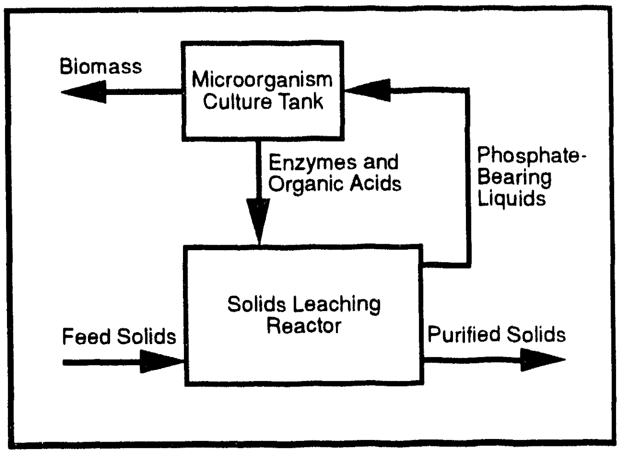

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Figure 2.1. Basic Process for Removing Phosphorus from a Solid Material Such as Iron Ore

2.3 Economics and Market Potential

The advantage of using fungi and bacteria to remove traces of a noxious material from a solid is that the organisms will provide pinpoint application of metabolic energy and chemicals to the impurities being removed, leaving the vast bulk of the material unaffected and therefore reducing costs. The organisms used will be able to obtain their energy from low-cost biological sources such as decomposing plant matter, thereby reducing operating costs still further.

Most solid hazardous wastes that are currently being produced consist mainly of large amounts of inert, harmless materials, with only a small amount of noxious impurities. If the troublesome materials can be removed and concentrated, then the bulk of hazardous wastes will be drastically reduced. Normally, the noxious impurities are not removed because of the great cost of concentrating trace elements by conventional methods. By using a low-cost biological method to dissolve and reconcentrate the trace materials, the waste volume can be greatly reduced. Ultimately, the traces of objectionable materials will be concentrated enough to allow them to be used themselves, so waste volumes can be reduced to nearly zero.

The initial application being studied, removing phosphorus from iron ore, will be useful to most of the U.S. steel industry because many domestic iron ores contain enough phosphorus to be a serious problem. As the technique is developed, many other trace impurities will be able to be dissolved and reconcentrated from solid wastes, such as mercury, arsenic, selenium, and other heavy metals. If phosphorus is removed from the ore, then less waste is produced during steelmaking. The quality of the steel product produced from this purified ore would reduce the need to further develop and exploit low-phosphorus iron resources, thereby preventing further ecological disruption caused by more exploration for new iron-ore reserves.

Ultimately, this process will be useful for virtually all toxic ore tailings, many industrial wastes, and a number of currently unusable industrial feedstocks. It will also simplify recycling by providing a simple, low-cost method for separating mixed wastes into readily usable stocks. The potential for the widespread use of this basic procedure must therefore be regarded as excellent. Dr. Kawatra was invited to speak on this topic at the American Iron and Steel Institute's meeting in 1992, and the industry is seriously interested in this technology.

2.4 Key Experimental Results

Three fungal strains were cultured on agar plates: 1) *Paxillus involutus*, 2) *Laccaria bicolor*, and 3) *Herbeloma crustiforme*. To determine optimal growth conditions, the growth of each fungal strain was carefully monitored for periods from two to six weeks. After the fungal colonies on the agar had grown to their maximum size, the agar was liquefied and filtered to extract the cell secretions. These secretions were then used in the leaching experiments.

The cell secretions from the *Laccaria bicolor* were used to leach pure apatite [$Ca5(PO4)3$]. Excellent results were obtained, even at high pH. Apatite is normally insoluble at pH=6 (Krauskopf 1967), but the filtrate from the *Laccaria bicolor* was nevertheless able to dissolve 4% of the apatite at pH=6 in only 24 hours. Further work with *Laccaria bicolor* showed that up to 76% of the apatite could be dissolved in 76 hours. Such a result has never been reported in the literature, indicating that the fungi are producing a very effective complexing agent for phosphorus, which greatly enhances the solubility of apatite, even when the amount of acid produced is low. These results are extremely encouraging for removing phosphorus from iron ore because iron ore concentrating operations are normally carried out at pH=6 or higher.

2.5 Future Development Needs

Although they are effective, the fungi examined all have a rather slow growth rate. Therefore, the bacteria *Bacillus subtilis* is also being cultivated because bacteria grow significantly faster than most fungi. Because it is also a very common soil organism, it will be easily able to grow in an industrial-scale process where it will be competing with other wild organisms. This bacteria is expected also to be effective for dissolving apatite with secretions of both organic acids and phosphorus-complexing agents.

Following the trials with pure apatite, further experiments must be conducted with the actual ore to be processed. Also to be studied are the advantages of culturing the fungi and bacteria in liquid media and of adding the material to be solubilized directly to the active culture rather than separating out the secretions.

The biotechnology of fungi and bacteria, once developed for removing phosphorus impurities in iron ore, will be applied to a host of related problems, particularly removing hazardous heavy metals from solid wastes. Solids that are made useless or toxic by small amounts of impurities are very common, including many potential ores, ore tailings, industrial wastes, and municipal wastes.

The extraction and concentration of trace materils have been major problems for living organisms for billions of years, which they have had to either solve, or die trying. So, our best course for accomplishing the same thing ourselves is to make as much use of existing organisms as possible, rather than trying to "re-invent the wheel."

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3.0 Substituting Nonrecyclable Waste Paper for Virgin Paper in Industrial and Commercial Packaging

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Abstract

Each year, the average American is responsible for 1,500 pounds of solid waste that must be landfilled. This 1,500 pounds of waste converts to 2.5 cubic yards of space per person, or 625 million cubic yards of landfill space used each year in the United States. Of this waste, 75 million ton--or 42% of all solid waste--is paper or paper products. Currently, the United States recycles only about 22% of its waste paper.

Many current manufacturing processes are designed to manufacture end products from made-to-order paper rolls, not from waste paper. The purpose of this concept is to determine the feasibility of substituting waste paper for made-to-order paper to manufacture certain paper products. American Paper Converters is modifying existing processes and developing new processes to manufacture converted paper products from papers that cannot be repulped because they contain large quantities of chemicals or coatings that interfere with the repulping process.

American Paper Converters will use the waste paper to manufacture three of its current products: auto floor mats, chick pads, and brick packs. A prototype machine has been developed and is currently manufacturing approximately 10 tons of chick pads per week and 2 tons of brick packs that are being test marketed. A prototype machine is producing auto floor mats; the longevity and speed of that system are being tested.

Each time a ton of waste paper can be substituted for a made-to-order ton of packaging paper, a vast amount of resources is saved, including 17 trees, 5,777 kWh of electricity, 10,000 gallons of water, and 3.3 cubic yards of landfill space. If American Paper Converters could substitute waste products for just 50% of its manufacturing needs, this company alone would save 1,190 trees, 405,000 kWh of electricity, 700,000 gallons of water, and 231 cubic yards of landfill space each week.

3.1 Introduction

Today we live in a high-tech society that seeks high-tech approaches to solve any problem. This high-tech approach has been successful in many areas; for example, the United States currently is able to recycle 22% to 25% of its waste paper. However, 75%--or over 50 million tons--of waste paper are not recycled but are shipped to landfills.

Among the many reasons why this paper is not being recycled is that current technology cannot repulp many types of paper:

1. *Photo paper in roll form*, such as the paper on which glossy photographs are printed, contains chemicals.
2. *Latex-impregnated paper*, such as that used to produce wallpaper, contains latex.
3. *Wet-strength kraft, linerboard, and medium*, such as are used in the corrugated container industry for containers subjected to wet or damp conditions, contain a chemical that makes these papers resistant to water but then difficult or impossible to repulp.
4. *Beater-dyed wet papers and boards* contain a dye that cannot be extracted in the repulping process.
5. *Absorbing papers* such as those used in manufacturing tape or formica cannot be repulped because of their chemical content.

While these papers are being landfilled, American Paper Converters and its affiliates each week require 135 tons of made-to-order paper to manufacture several of its products--25 tons of auto floor mats, 100 tons of chick pads, and 10 tons of brick packs. Current production equipment requires that these products be manufactured from specific-type and specific-size paper, thus requiring the made-to-order paper. American Paper Converters' plan is to take each of these waste papers and use them to manufacture auto floor mats, chick pads, and brick packs:

1. *Auto floor mats* are the disposable type of protective, embossed mat used by dealerships, car washes, repair shops, tire stores, and quick-oil-change shops. A mechanic places the mat on the floor of the car to avoid getting dirt and oil on the customer's carpet. This product is used throughout the country and is purchased in small and multi-million quantities.

2. *Chick pads* are indented paper products used to line the bottom of chick boxes when baby chicks are being transported from the hatchery to the chicken farm. The pads must be cut to size (17 in. by 22 in.) and slotted to fit the chick box. They also must be indented so that the baby chick will not become splay legged from sliding on slick material.

3. *Brick packs* are a type of paper cut to approximately 8-1/2" x 25" to interlock layers of brick to prevent breakage when bricks are shipped on pallets.

3.2 Concept Description

American Paper Converters has developed processes and equipment (see Figure 3.1) to manufacture auto floor mats, chick pads, and brick packs, from nonrecyclable waste papers. Auto floor mats are being made from jumbo rolls of defective photographic paper that is printed with special water-based inks, and a unique drying process that keeps the print flexible for the indentation process. A prototype machine has successfully manufactured chick pads from dyed paper and medium that contain significant quantities of wet strength. Brick packs are being manufactured from beater-dyed papers and photo paper that required a new indenting and folding process to accommodate the slippery surface of the materials.

One requirement for manufacturing auto floor mats, chick pads, and brick packs was that they prevent slippage. If the disposable auto floor mat is too stiff or too slick, it can create a hazard for the customer or the mechanic entering or exiting the vehicle. Slick chick pads would tend to cause the baby chick's legs to be broken when they slide to the side during shipment; when that occurs, the

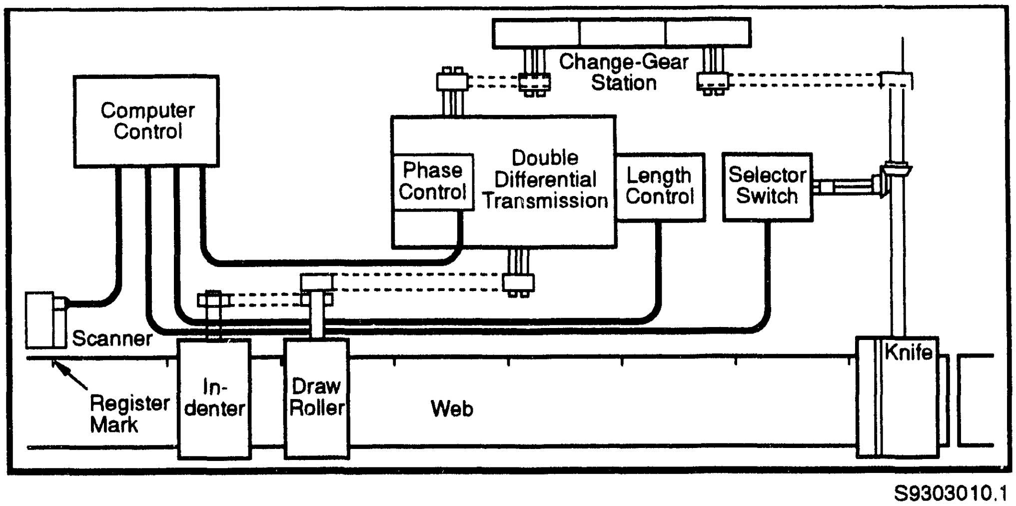

Figure 3.1. Prototype Equipment for Manufacturing Auto Floor Mats, Chick Pads, and Brick Packs

chick must be disposed of. Brick packs need a nonslip surface or bricks will be broken during shipment.

All of the waste products intended for use would promote slippage instead of preventing it. To obtain a slip-resistant product, American Paper Converters passed the waste materials through matched steel-indenting rollers, thereby imparting a waffle pattern of indentation to the substrate and reducing slippage. Indentation permits the product to conform to the shape of the floor and to stay in place.

Before the process for producing auto floor mats from waste paper was investigated, problems were anticipated and encountered with in-register cutting because waste paper's inconsistency causes it to be rejected in the base case. While registration appears to be the simple process of a rotary knife cutting a continuous preprinted web into separate sheets, two registration errors found in preprinted indented webs had to be corrected independently.

The first registration error is a random phase error, which is created by acceleration errors, machine backlash, inconsistent thickness of the substrate, inconsistent indentation, and other inconsistencies that cause papers to be rejected. A momentary speed adjustment of the indent rollers and draw rollers relative to the rotating knife will correct phase error.

The second registration error is a constant length error, which represents the difference between the actual repeat length of the preprinted web and the length of the finished product after indentation and cutting. Because this error is constant, it will accumulate as the web is processed. To eliminate this error, a permanent correction to the draw roller speed and to the indent rollers must be made. By adjusting the draw roller speed, the actual repeat length of the web and the circumferential travel of the draw rollers are matched.

We resolved the registration errors by developing a system that corrected both the random and the constant errors found in the preprinted indented web. In this system, as the preprinted web is fed through the machine, a scanner detects a printed registration mark and then sends a signal to a programmable controller. At that same moment, a selector switch attached to the shaft of the rotating knife generates a signal, indicating the knife's cut position. With this information, the controller determines if the knife will cut the web in the register position. If it is so determined, no adjustments are made. If the controller determines that the knife will make its cut in a retard position (after it should have cut), the controller will send a signal to advance the draw rollers. If the controller determines that a cut will be made before the register condition, then a signal will be sent to retard the draw rollers. Because the draw rollers drive the indent rollers in this operation, the indent rollers are also adjusted.

In addition, the controller counts corrections; once four consecutive corrections in one direction have been made, a signal is sent to the transmission, either increasing or decreasing the repeat length. The transmission corrects both the constant length and phase errors by regulating the speed of the draw rollers relative to the knife.

The corrections are made by the transmission's two miter-gear differentials. The first differential is controlled by the variable-speed-drive portion of the transmission. The variable-speed unit makes permanent speed corrections to the output shaft. This constant correction is necessary to eliminate any length error found in the preprinted web. The second miter-gear differential is controlled by the controller and the correction motor. Based on signals received, corrections are made to momentarily increase or decrease the output, correcting the random phase error.

3.3 Economics and Market Potential

Each time a ton of waste paper can be substituted for a made-to-order ton of packaging paper, a vast amount of resources is saved, including 17 trees, 5,777 kWh of electricity, 10,000 gallons of water, and 3.3 cubic yards of landfill space. If American Paper Converters substitute waste products for just 50% of its manufacturing needs, this company alone would save 1,190 trees, 405,000 kWh of electricity, 700,000 gallons of water, and 231 cubic yards of landfill space each week.

Table 3.1 shows the nonrepulpables that American Paper Converters is using, the virgin paper they replace, and the useful item that is being produced. American Paper Converters and its affiliates produce as much as 90% of the chick pads in the southeastern United States, or approximately 100 tons of chick pads each week. Currently, these pads are being produced on equipment designed by American Paper Converters to use cut-to-size medium or kraft. However, up to 50 tons of chick pads could be made from nonrepulpables. Most of this material could be replaced by wet-strength materials and beater-dyed materials.

Currently, American Paper Converters manufactures 10 tons of brick pack each week from virgin liner board, medium, or kraft. Beater-dyed board or photographic paper can be substituted for the virgin paper, but would require in-line folding of the material while it is being converted to overcome the slick surface. American Paper Converters is aware of a current market for this product of 25 tons per week. The substitute materials should be able to capture 50% of the existing market in the southeastern United States, thus using 100 tons of nonrepulpables weekly. This alone would save 1700 trees, 577,700 kWh of electricity, 1 million gallons of water and 330 cubic yards of landfill.[a]

Table 3.1. Substituting Nonrepulpables for Virgin Paper

Nonrepulpable	Material Replaced	Item Produced
Photo Paper	Bleached Kraft	Disposable Auto Mat Brick Pack
Photo Paper (trim)	Virgin Liner Board	Brick Pack
Latex Impregnated Paper	Bleached Kraft	Disposable Auto Mat
Beater-Dyed Board	Bleached Kraft	Disposable Auto Mat
Beater-Dyed Board	Medium or Kraft	Chick Pad Brick Pack
Wet-Strength Papers and Board	Medium and Kraft	Chick Pad Brick Pack

Various manufacturers use nearly 50 tons of bleached virgin craft for auto floor mats each week. The nonrepulpable photo paper makes a better product than the virgin matter when American Paper Converters' printing and indenting process is used. The new type of mat is more durable, better looking, and more pliable to conform to the floor of the auto. This product can be manufactured more economically because the waste material sells for approximately one-third of the price of the virgin material.

Many mill managers and secondary waste brokers, after hearing of American Paper Converters' success with substituting nonwoven material for virgin kraft, have contacted us with offers of other such nonrepulpable paper products. Almost every day American Paper Converters receives offers to buy multiple truckload (45,000 pounds) quantities of such products.

3.4 Key Experimental Results

American Paper Converters began building a prototype machine to produce brick packs and chick pads by placing a set of waffle-pattern, matched steel-indenting rolls driven in line with a 36-in.-wide Beck sheeter. After attempting to indent the waste materials, some materials gained length in the machine direction, causing wrinkles and bagging between the indenters and the draw rollers of the sheeter; other materials shrank upon indentation, causing web breaks between the indenters and the draw rollers. This problem was eliminated by placing a PIV-type[b] transmission driven by the sheeter that was able to be adjusted to drive the indenters at the same surface speed as the draw rollers of the sheeter.

These additions created problems. The gear-change assembly of the sheeter that determines the cut length of the sheet was not built to withstand the added drag of the PIV and the indenters. Gear failure became a daily problem. This problem was solved by replacing the gear-change assembly with

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(a) Keiffer Paper Mills, Brownstown, Indiana.

(b) PIV-positive infinite variable.

another PIV-type transmission designed to carry the added torque. This appears to have worked and solved the drive problems.

After driving the machine consistently for several weeks time, it became apparent that the waste products were more abrasive than the products previously indented and were causing excessive wear on the indenters. The indenters were removed from the frame and sent to a local machine shop where they were ground true and chrome plated. This seems to have eliminated the wear problems. This prototype machine is currently manufacturing approximately 10 tons of chick pads and 2 tons of brick pack each week.

Producing auto floor mats created different problems. The project was begun by taking a 60-in.-wide and 50-in.-diameter roll of photo paper and converting it into three 20-in.-wide rolls because the finished floor mats are 20 to 21 in. wide and 17 in. long. The rolls then were taken to our four-color, flexographic-type printing press.

Attempting to print the photo paper caused many problems. First, the lack of absorptive capacity of the paper's coating did not allow the ink to dry. The first attempt to solve this problem was with the help of the ink manufacturer. Special additives were put in the ink to increase its drying capacity. This helped and permitted printing, but at a slow speed. To increase the speed, the heating capacity of the dryer oven was increased, and forced air was added. The speed increased threefold, but not to full press speed.

Another problem was encountered in the printing process. The slick nature of the substrate makes the rewind roll tend to "telescope" while being printed. Changing the gearing of the rewind shaft to increase torque has helped but did not eliminate the problem.

The registration system using the double differential transmission and the scanners appears to be working. The only question remaining is its life span. The system appears to be constantly making adjustments and is running at a temperature higher than expected.

Slide angle tests indicate that both the auto floor mats and brick pack made from nonrepulpables, when properly indented, provide a surface that is less likely to cause slippage than unindented made-to-order materials.

3.5 Future Development Needs

The chick pads and brick packs produced from the waste paper are being test marketed. A prototype machine is producing auto floor mats and its longevity and speed are being tested.

4.0 Hydrocyclone Classifiers for Microsorting Mixed Thermoplastics from Consumer Waste

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Abstract

In 1990, the United States was putting more than 7 billion pounds of plastic in the post-consumer waste stream each year. At an average heating value of 20,000 Btu/lb, this waste represents an energy resource of 140 trillion Btu/year. Proposed legislation in the United States could require 50% of consumer plastic waste to be recycled by the year 2000. Auto-part recycling (especially plastic components) has also been identified recently as a top priority for industry. Of the more than 5 billion pounds of automobile shredder residue (ASR) produced annually in the United States, almost 50% is waste plastic. Currently, this material is disposed of in landfills.

The objective of this project is to determine the feasibility of using hydrocyclones to sort granulated thermoplastic chips into relatively pure resin streams, based on differences in density, size, and shape. At Michigan State University (MSU), two new approaches have recently been identified that could provide a practical method to further separate light and heavy fractions of commingled (unsorted) chipped plastics. The new microsorting processes are expected to have applications both in sorting post-consumer containers and in developing value-added streams from automobile shredder residue.

In one of MSU's processes, lighter-than-water constituents are being fractionated in a hydrocyclone by a novel light-medium separation using a suspension of glass microbubbles in water to achieve an effective density between the fractions of interest. This technique has separated high-density polyethylene from polypropylene in our laboratory. In a second process, resins that have no significant density difference can also be fractionated in hydrocyclones based on differences in either size or shape. Significant differences in shape between polyethylene terephthalate and polyvinyl chloride have been obtained by unique processing conditions in a small-scale laboratory grinder at 0°C. Preliminary separation tests are incomplete.

MSU is presently forming a cooperative university/industry/government research consortium to further develop and commercialize hydrocyclone processes for recovering thermoplastic resins from consumer and industrial waste streams.

4.1 Introduction

As waste disposal facilities continue to decrease in availability and increase in cost, recycling becomes an attractive option. Many local, state, and federal legislative initiatives are seeking to establish goals and requirements for diverting waste and for using recycled materials, especially for packaging.

In 1990, the United States was putting more than 7 billion pounds of plastic in the post-consumer waste stream each year. At an average heating value of 20,000 Btu/lb, this waste represents an energy resource of 140 trillion Btu/year. Proposed legislation in the United States could require 50% of consumer plastic waste to be recycled by the year 2000. By 1995, Germany will recycle 80% of plastic packaging material (Protzman 1992).

Auto-part recycling (especially plastic components) has also been identified recently as a top priority for industry (Leaversuch 1992). Of the more than 5 billion pounds of automobile shredder residue (ASR) produced annually in the United States, almost 50% is waste plastic. Currently, this material is disposed of in landfills. In 1981 about 65% of automotive plastic scrap was acrylonitrile-butadiene-styrene (ABS), polyurethane (PUR), polypropylene (PP), and polyvinyl chloride (PVC)

(Hegberg et al. 1991). However, with the introduction of new advanced thermoplastic materials such as alloys, blends, and composites, this distribution is rapidly changing.

Of all major packaging materials, plastics' recycling lags well behind glass, paper, steel, and aluminum. A major obstacle to increasing plastics recycling is the need to separate plastics by resin type. Most existing sorting operations are performed by hand, which is very expensive and is generally limited to a few easily identifiable container types. Automated sorting systems are being developed, but they work effectively only on whole containers. Unfortunately, the cost of recovering valuable thermoplastics from consumer waste streams exceeds the cost of manufacturing virgin resins. However, if a certain percentage of plastics must be recycled by law, then the economics of specific recycle collection and separation technologies could influence the cost of certain plastics. Therefore, alternative recycling approaches must be compared at an early stage of development to identify cost-effective options.

One of the most costly factors facing plastics recycling is the large volume-to-mass ratio of plastic containers, making curbside collection expensive as currently practiced. If the containers could be chipped either at the collection site or at a nearby facility, transportation costs could be significantly reduced. Although truck-mounted grinders are currently available for this chipping, they are limited to operations that either collect only one type of plastic or use the collected plastics in low-value commingled applications such as plastic lumber. Therefore, an important factor in improving the economics of plastics recycling is to develop sorting methods that can accommodate early and significant densification of the plastic material.

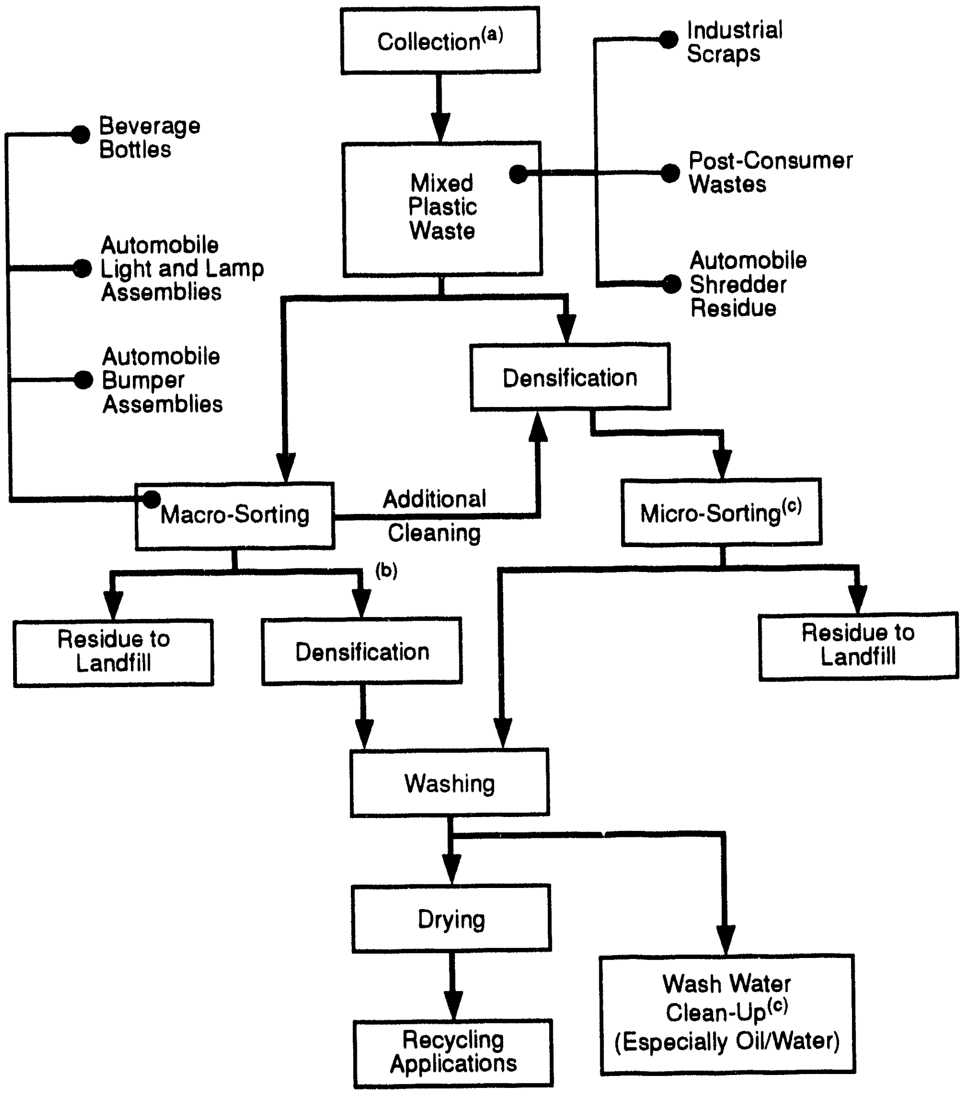
At present, the most widely used process for reducing the volume-to-mass ratio is baling, but this interferes with automated macro-sorting techniques and does not offer as much volume reduction as shredding or grinding. On the other hand, micro-sorting techniques can significantly improve collection efficiency and therefore the economics of recycling (Dinger 1992). Figure 4.1 illustrates the macro- and micro-sorting options for recovering plastic resins for recycling.

Current plastic recycling technology uses macro-sorting of mixed plastic waste streams to produce a relatively clean product. The purities of recycled plastic chips from existing commercial separating systems range from 70% to 99.9%. However, because different thermoplastics do not blend well to give products with good properties, reprocessors can require recycled plastic streams with <1,000 wppm contaminants in order to produce high-valued products.

Current recycling costs range from \$0.40/lb to \$0.80/lb, which are comparable to the costs for new commodity resins, but are lower than the costs of new specialty or composite resins. Therefore, the major issues of viable commercial systems for plastic and composite materials are the cost of the recycling process and the purity of the recycled stream.

Solvent dissolution methods for recovering pure resin constituents from a mixed plastic waste are being developed by Nauman and Lynch (1992) and by Hegberg et al. (1991). [Also see Battle et al. (1992)]. Flotation cells are also being evaluated for separating thermoplastic resins having different surface properties. Size and shape differences between resins in shredded plastic waste can also be exploited by screens, spirals, and other inertial type classifiers. Because ASR is currently being landfilled, industry has a strong interest in exploring the feasibility of applying recovery methods as a way not only to reduce waste, but also to recover material having a relatively high energy value.

Although the concentration of PP (bottle caps) in consumer waste is not as high as high-density polyethylene (HDPE) (bottle base cup), these two constituents should be separated because PP adversely affects the material properties of HDPE. Also, because small amounts of PVC in polyethylene terephthalate (PET) can seriously degrade end-product properties, micro-sorting technologies that can recover clean PET are needed. Further motivation to recycle clean PET stems from ongoing



(a) Most costly portion of recycling process.
(b) 99.5% purity of resin material can only be achieved for a few special examples such as PVC.
(c) Opportunities for improvement based on hydrocyclone technology.

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Figure 4.1. Some Options for Reclaiming Plastic Resins From Mixed Plastic Waste Streams

research to chemically convert PET into raw material for unsaturated polyester resins and polyols for producing polyurethane resins (Smoluk 1988).

Hydrocyclones can be used as a pretreatment operation to separate the "light" (density less than water) plastic fraction from the "heavy" (density greater than water) plastic fraction. Different two-phase media, salt solutions, and supercritical fluids are all being evaluated for float/sink operations. A mixed thermoplastic waste stream can be sorted into a "light" fraction containing PP and HDPE and a "heavy" fraction containing ABS, poly (methyl methacrylate [PMMA]), PVC, and PET by using conventional hydrocyclone technology. Hydrocyclones are presently being used to make this type of separation on some post-consumer waste streams such as beverage bottles. However, no commercial technology is currently available to further separate either the "light" or the "heavy" fractions, although several approaches are presently being investigated (see Hegberg et al. 1991).

Hydrocyclone technology has a well-established technical and scientific base. Because the United States has an extensive manufacturing infrastructure that serves many sectors, a practical microsorting process for recycled thermoplastics based on hydrocyclone washers and classifiers will have an immediate impact on recycling facilities. The hydrocyclone is an important unit operation in the chemical, food, and mineral industries. As an inertial separator, it is especially noteworthy because it is simple and has many diverse applications. Often the hydrocyclone plays an important secondary role in a process by reducing the load on other, more expensive types of separation equipment or by protecting high-speed machinery from abrasive solids.

Depending on their specific use, the diameter of a hydrocyclone can be as small as 10 mm (wet corn milling) or as large as 5 ft (phosphate ore beneficiation). Hydrocyclones used for coal washing and mineral classification in grinding circuits are typically 18" in diameter. Three-inch-diameter hydrocyclones have been used for preparing fine coal (particle size <500 microns). Hydrocyclones have also been developed to remove light-weight plastic material from aqueous pulp suspensions and from water (Sjogren and Larsson 1988; Colman and Thew 1983; and Bliss 1980). Figure 4.2 illustrates the typical frustoconical shape of a hydrocyclone.

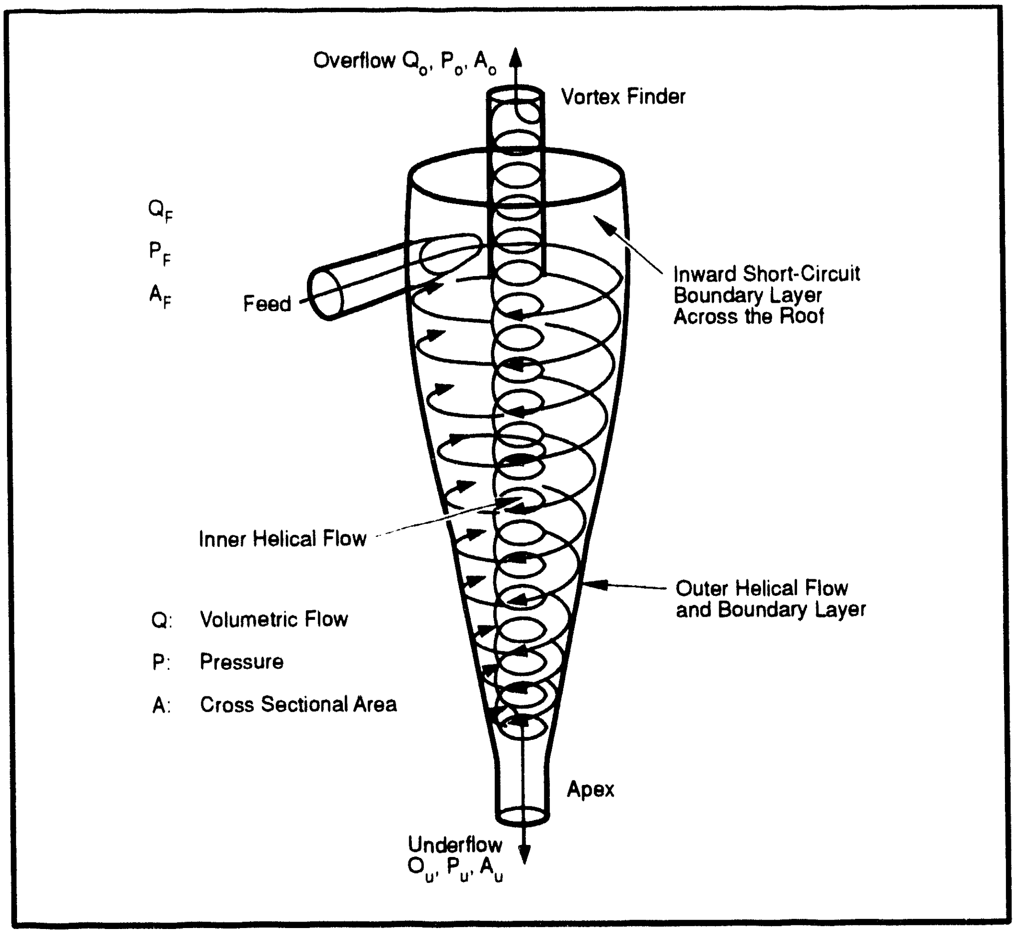

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Figure 4.2. Conventional Design of Reverse Flow Hydrocyclone

Extensive literature on hydrocyclones is available (Svarovsky and Thew 1992; Wood 1987; Pickford 1984; Svarovsky 1984; Priestley and Stephens 1980; and Bradley 1965). Although the relationship between the geometric scales of a hydrocyclone and its performance has been studied extensively, new applications currently being developed require a better understanding of how the secondary flow patterns within hydrocyclones affect the cut-size and sharpness-of-separation parameters.

4.2 Concept Description

The objective of this project is to determine the feasibility of using hydrocyclones to sort granulated thermoplastic chips into relatively pure resin streams, based on differences in density, size, and shape. At Michigan State University (MSU), two new approaches using hydrocyclones have recently been identified that could provide a practical method to further separate light and heavy fractions of commingled (unsorted) chipped plastics. The new microsorting processes are expected to have applications both in sorting post-consumer containers and in developing value-added streams from ASR.

In one of MSU's processes using a hydrocyclone, lighter-than-water constituents are being fractionated by a novel light-medium separation using a suspension of glass microbubbles in water to achieve an effective density between the fractions of interest. This technique has separated HDPE from PP in our laboratory.

In a second process using a hydrocyclone, resins that have no significant density difference can also be fractionated based on differences in either size or shape. Significant differences in shape between PET and PVC have been obtained by unique processing conditions in a small-scale laboratory grinder at 0°C. Preliminary separation tests are incomplete.

Many economic incentives exist to seek new designs and operating strategies for recovering fine coal, for separating oil and water, and for classifying recycled plastic materials (this concept). The swirling flow within a hydrocyclone causes suspended particles "lighter" than the suspending media to migrate toward the axis of a reverse flow vortex. Particles "heavier" than the suspending media migrate toward the outer region of the vortex. The intense shear field and turbulent fluctuations reduce agglomeration of dissimilar particles. Therefore, "light" and "heavy" particles can be classified by removing the core fluid and the outer fluid as two separate streams. The "sharpness-of-separation" depends critically on the internal flow structures induced by the shape of the hydrocyclone and the operating conditions. Figure 4.3 illustrates that the density of separation as well as the sharpness of separation of a hydrocyclone washer can be manipulated by changing the flow-split ratio.

Coal and shale both have densities greater than water. However, these two materials can be sharply separated in hydrocyclone washers by using a "heavy" medium such as a fine suspension of magnetite in water (Bradley 1965). The basic idea is to adjust the concentration of the dispersed magnetite so the effective density of the magnetite/water suspension falls between the densities of coal and shale. Although heavy-medium cyclones were developed for coal cleaning more than fifty years ago, their counterpart for "light" constituents (such as PP and HDPE resins) has not been developed.

Technical and marketing information supports our suggestion that a fine suspension of either glass or ceramic microbubbles can be used as a "light" medium for separating PP and HDPE in hydrocyclones (Barber 1991; Sutker 1989; Ward 1987; and McMurrer 1985). The relative simplicity of recovering an effective medium comprised of immiscible constituents (such as glass microbubbles and water) rather than miscible constituents (such as alcohol and water) makes the proposed light-medium cyclone separation of PP and HDPE an attractive alternative.

Figure 4.4 illustrates the separation concept proposed for development. Because the microbubbles are spherical, the effective rheological properties of a microbubble/water suspension would support the various unit operations needed to sort PP and HDPE. Figure 4.5 is a concept flowsheet presently

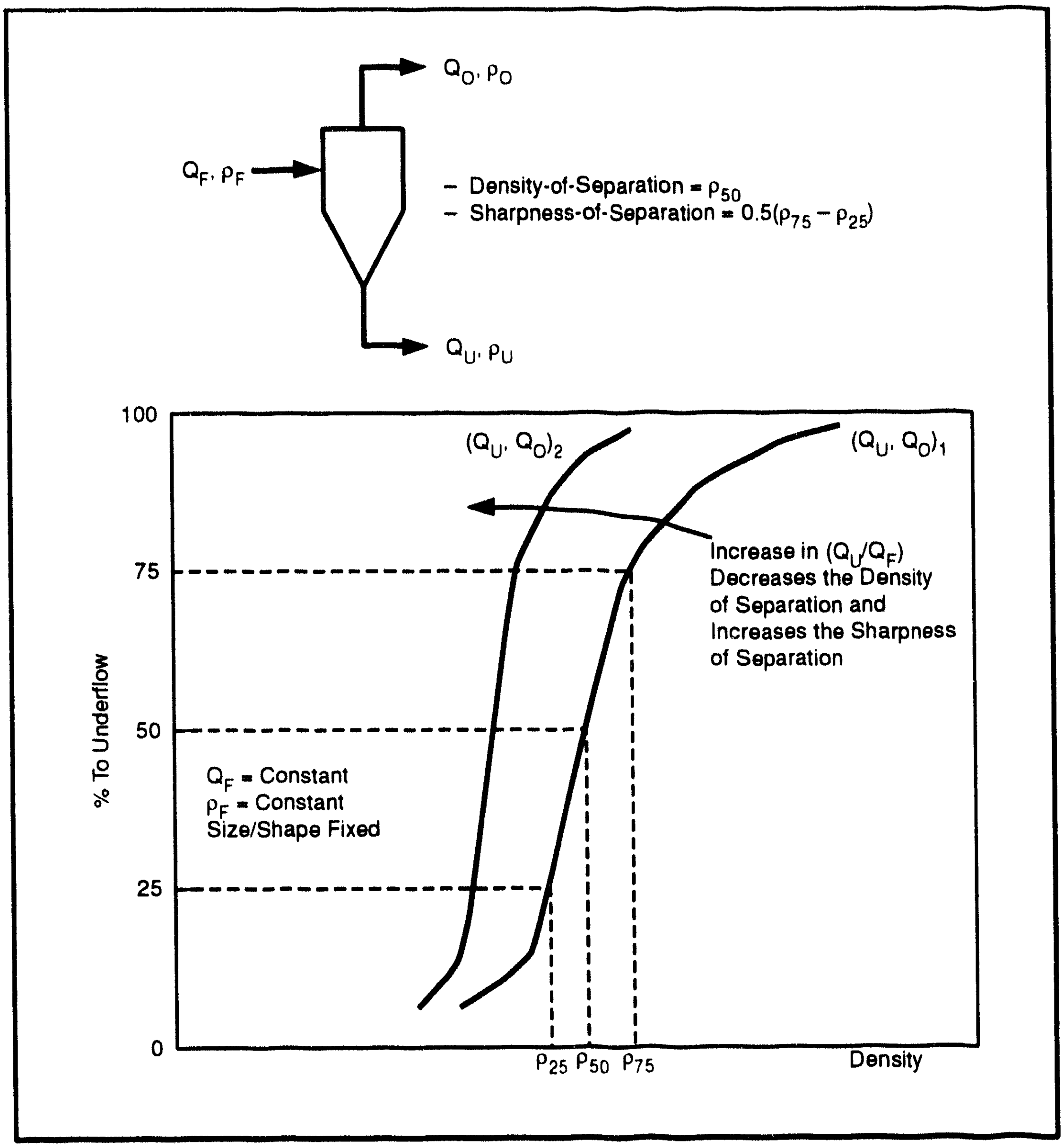

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Figure 4.3. Typical Separation Performance of a Hydrocyclone Washer (Svarovsky 1984; Bradley 1965)

being evaluated at MSU. To sharpen the cut between PP and HDPE, reclassification using a parallel/series arrangement of hydrocyclones could be used. Because current manufacturing techniques can produce different particle size distributions (PSD) of microbubbles, the PSD will be selected to obtain the following three features:

1. a "stable" medium for sorting PP and HDPE in a cyclone
2. a medium that can be easily removed from the product by drain and rinse screens
3. a medium that can be easily recovered by a hydrocyclone (or float/sink) thickener.

Glass microbubbles are presently available that have a density of 300 kg/m^3. Therefore, a 10 vol% (3.23 wt%) suspension of microbubbles in water would give an effective medium density of

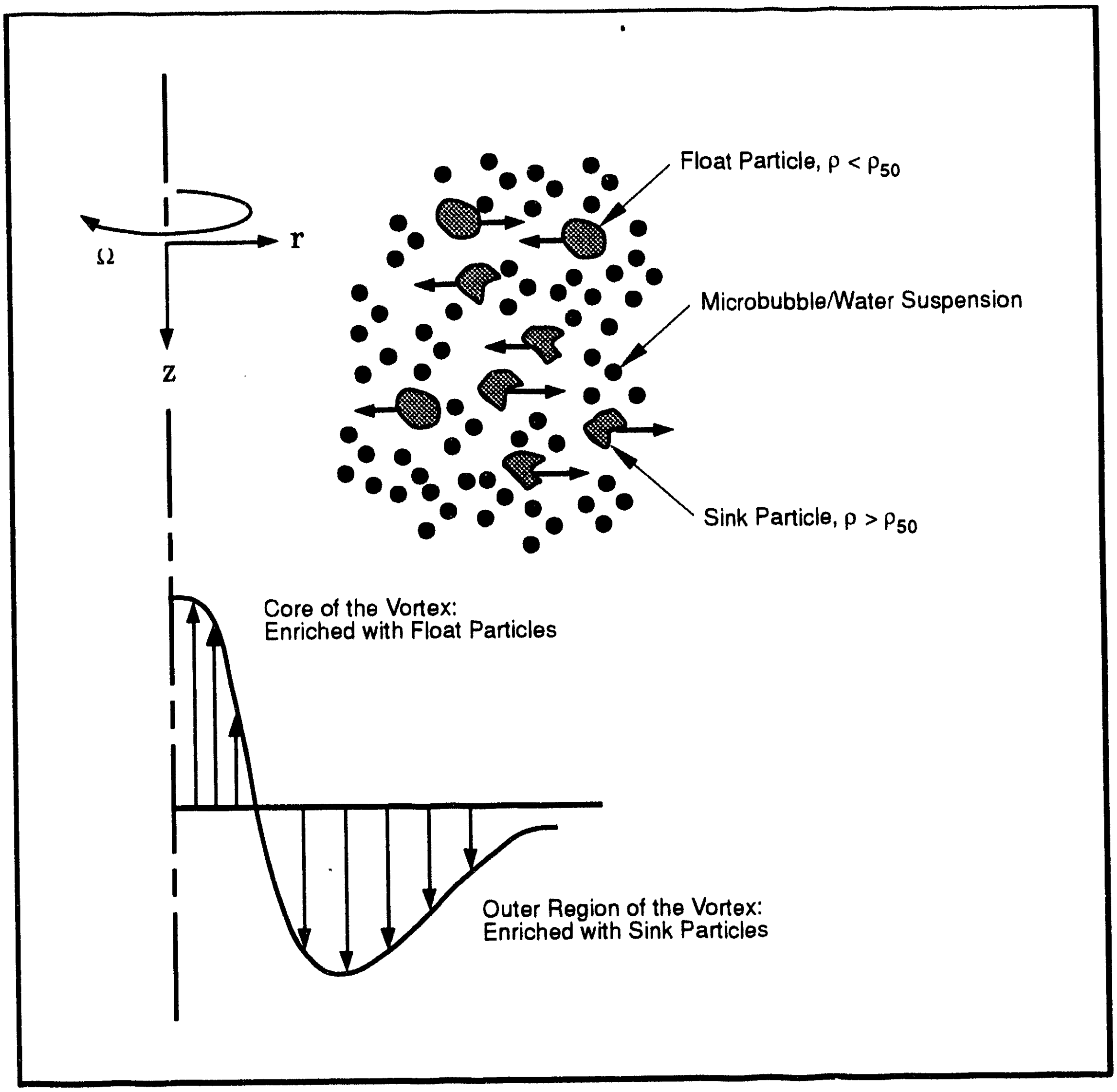

Figure 4.4. Float/Sink Separation Concept in a Hydrocyclone Washer

930 kg/m^3. With this light medium, a sorting operation based on hydrocyclone principles could be used to separate PP and HDPE.

Particles having the same density can also be classified in hydrocyclones based on differences in size and shape. Table 4.1 shows that polystyrene spheres (0.36-mm dia.) and discs (3-mm dia. and 0.03-mm thick) of about equal gravitational settling velocities can be separated cleanly in wide-angle hydrocyclones (Bradley 1965; Dreissen and Fontein 1963; Fontein et al. 1962; and Fontein 1961). The size/shape effect in wide-angle hydrocyclones is the result of differences in acceleration of particles and their capture by different internal flow structures. This important result suggests that using hydrocyclones to classify mixed thermoplastics can be improved significantly by managing the size and shape distributions of the waste stream at the particle scale associated with microsorting.

Materials having similar densities can also be selectively separated in froth flotation cells because of differences in surface properties. However, unlike hydrocyclones, relatively quiescent (nonhydrodynamic) conditions are used in flotation cells to

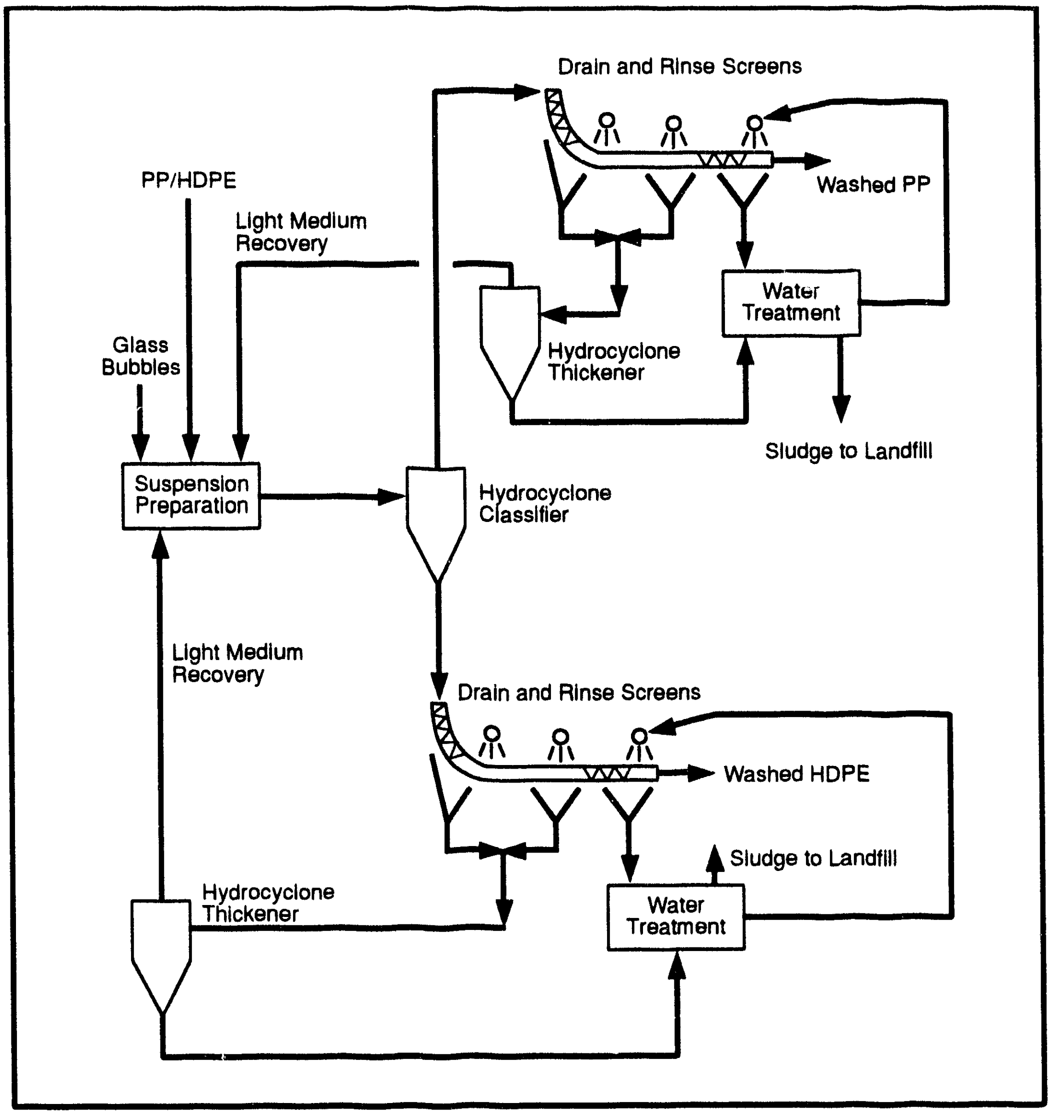

Figure 4.5. Light-Medium Cyclone Flowsheet for Sorting PP and HDPE

Table 4.1. Results of Tests with Spheres and Disks (Dreissen and Fontein 1963)

60 mm-Diameter Cyclone	Test 1	Test 2	Test 3
Cone Angle	10°	45°	60°
Capacity of Underflow (% capacity of feed)	15.1	10.0	9.3
Catch Spheres in Underflow (%)	99.3	95.2	90.4
Catch Disks in Underflow (%)	45.5	2.8	0.5

exploit the effect of gravity in a sink/float operation. As a result, the drift velocities of particles within flotation devices are low, and this unit operation requires more space than compact hydrocyclones. More significantly, however, the flotation cells cannot exploit acceleration effects accentuated by size and shape differences of particles. Therefore, the hydrocyclone could potentially replace less convenient unit operations such as flotation cells currently being used to separate PET and PVC.

4.3 Economics and Market Potential

The proposed micro-sorting strategy for recovering high-purity thermoplastic resins from ASR has significant energy-savings' potential because current practice simply landfills this waste plastic stream. As previously noted, at the current rate of ASR production, energy savings would total more than 5 trillion Btu/year. One of the key performance parameters for operating either a light-medium or a heavy-medium hydrocyclone circuit is the loss of the medium. Current dense media cyclones that use magnetic suspensions show losses as low as 0.005 lb medium per pound of dry feed processed.

One of the objectives of our current research is to estimate expected losses of microbubbles from washing and from breakage. An estimate is being developed to determine energy savings from recovering specific groups of thermoplastic resins associated with automobile light assemblies and automobile bumpers. Although automobile dismantlers currently do not target specific plastic parts for shredding, this could change if an economic means of micro-sorting the mixed plastic waste were available. Therefore, the results of this technology development project could impact the infrastructure related to how automobiles are dismantled in the United States. The proposed process concepts offers the potential to divert the plastic fraction of ASR from landfills, thereby providing a significant, long-term economic impact. However, a realistic engineering analysis of this conclusion requires information presently being developed and analyzed.

Conventional hydrocyclone techniques are being used in several facilities to separate dissimilar resins by specific gravity using centrifugal force. However, because PET and PVC have similar densities, conventional hydrocyclone strategies for separating these two materials are difficult, if not impossible. This problem is important in mixed thermoplastic waste streams because small amounts of PVC in PET can seriously degrade end-product properties. Motivation to recycle clean PET stems from ongoing research to chemically convert PET into raw material for unsaturated polyester resins and polyols for producing polyurethane resins. The innovative separation strategy proposed in this development project, if successful, would have a significant economic impact on PET recovery.

Because of the increased use of PP caps in the bottle beverage industry, the concentration of PP in the waste stream is increasing above a critical level for reprocessing HDPE. Therefore, another unresolved separation problem for recycled mixed waste is separating PP and HDPE. Because this concept seeks to solve this problem by exploiting the unique hydrodynamic feature of hydrocyclones, one focused goal of this effort is to also develop practical solutions for separating PP and HDPE by using hydrocyclone technology. The formation of a university/industry/government research consortium will provide a way to identify solutions that have commercial potential.

4.4 Key Experimental Results

Although size reduction of thermoplastic resins is difficult (see Perry and Chilton 1973, Chapter 8), shape alterations in high-speed impact grinding could provide enough difference between PVC and PET to exploit the large acceleration effects of hydrocyclone classifiers. Recent preliminary experiments in our laboratory support the hypothesis that the size and shape of PVC and PET chips (10 mm x 10 mm x 1 mm) can be altered significantly if subjected to a cold (0°C), high-speed, impact grinding operation. Under these conditions, the PVC apparently encountered a brittle fracture mechanism, whereas the PET resin seemed to undergo a crystalline phase change before delamination.

Earlier, Garcia (1980) used cryogenic grinding to separate laminated plastic film structures. The films were ground to a fine powder and then separated by density. HDPE showed a high degree of plastic deformation rather than brittle fracture. This operation produced a fluffy, fibrous HDPE powder.

Differences in particle size distribution and particle shape could provide the physical basis for a classification operation of thermoplastic resins commonly encountered with recycled plastic bottles or ASR. Controlled grinding of mixed thermoplastics could provide a way to "engineer" the size and shape of particles. Differences in particle morphology after grinding can be caused by 1) differences in the failure mechanisms for amorphous and crystalline materials, and 2) differences in failure mechanisms induced by different grinding operations.

Materials with the same glass transition temperature can exhibit different fracture morphologies. Although PVC and PET have qualitatively different Izod impact strength coefficients at room temperature, the grinding results at MSU are opposite of what was expected based on the standard ASTM impact test. Apparently, the high-speed grinder, together with the reduced temperature, promote different failure mechanisms of PVC and PET.

Clearly, a fundamental understanding of failure mechanisms under different grinding environments is needed to achieve selective size/shape modification of thermoplastic chips. Ongoing basic research at MSU on thermoplastic grinding supports this applied research and development initiative.

Exploratory experiments with a commercial hydrocyclone have indicated that HDPE and PP can be separated by using a "light" medium of glass microbubbles and water. The data summarized by Table 4.2 shows that the purity and the recovery of HDPE in the underflow stream can be influenced

Table 4.2. Separation Results for HDPE and PP

1. **Test Hydrocyclone**

$DH = 4"$
$D_o/D_H = 3/16$
$D_F/D_H \sim 1/5$
12" Cone Angle
$\Delta P \sim 5$ psi (air core)
$Q_F \sim 15$ gpm
$S = Q_U/Q_O, (S_1 > S_2)$

2. **Microbubble/Water**

Density of Suspension: <0.95 g/cm3
Mean Particle Size:
- Suspension "A" < Suspension "B"
< 100 microns

3. **Thermoplastic Constituents**

Feed Concentration of HDPE: <300 ppm
Feed Concentration of PP: <300 ppm
HDPE and PP Flakes:
- Maximum Length Scale: ~ 2.5 mm (both)
-Nominal Aspect Ratio: ~5 (both)

4. **Experimental Results**

Split Ratio		Suspending Medium		
		Water	"A"	"B"
S_1	% Purity	--	--	>90%
	% Yield	--	--	30%
S_2	% Purity	100%	98%	100%
	% Yield	<2%	18%	<5%

5. **Definitions**

$$\text{Purity} = \frac{C_{F,PP} - C_{U,PP}}{C_{F,PP}} \times 100$$

$$\text{Yield} = \frac{Q_U C_{U,HDPE}}{Q_F C_{F,HDPE}} \times 100$$

where $C_{F,PP}$ and $C_{U,PP}$ = concentration of PP in the feed and underflow, respectively.
$C_{F,HDPE}$ and $C_{U,HDPE}$ = concentration of HDPE in the feed and underflow, respectively.
Q_F and Q_U = volumetric flow rate of the feed and underflow, respectively.

by adjusting suspension properties ("A" and "B") and by changing the hydraulic split ratio $S = Q_u/Q_o$. These specific results clearly illustrate the potential of this separation strategy for recovering a relatively clean high-density polyethylene resin from a mixed thermoplastic waste stream.

4.5 Future Development Needs

The light-medium hydrocyclone concept for separating HDPE and PP is presently being tested in a prototype vortex chamber. The effects of various operating conditions and hydrocyclone configurations on the purity and yield of the HDPE are being studied, and a preliminary economic evaluation is being conducted. Obviously, this limited exploratory project permitted only a partial evaluation of the economical and technical merits of using hydrocyclones to separate mixed plastic streams. Therefore, efforts are under way to establish a university/industry/government consortium to continue developing this technology.

This activity will parallel the very successful consortium established at MSU to develop hydrocyclone technology for oil-water separation. A Multiphase Flow Facility, constructed at MSU to test hydrocyclones of various designs, is available to support this initiative. Extruders and plastic characterization equipment are also available within MSU's Department of Chemical Engineering, the School of Packaging, and the Composite Materials and Structures Center. During the proof-of-concept stage of the consortium project, the following applications of hydrocyclones will be evaluated:

- to provide a "sharp" separation between the light and heavy constituents of ASR and recycled beverage bottles
- to achieve a sharp separation between PP and HDPE, by using a "stable" light medium, such as finely dispersed glass or ceramic microbubbles in water
- to achieve a sharp separation between ABS and polyoxymethylene by using a "stable" heavy medium, such as finely dispersed glass or ceramic microbubbles in water
- to sort PVC and PET based on different shapes induced by a controlled-grinding process.

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5.0 A Method and Apparatus for Making Continuous-Reinforced Thermoplastic/Cellulose Composites from Recycled Materials

William R. Reetz
Engineered Composites

Abstract

Consumers and government are becoming more aware of the need to find new uses for waste material as the effect of decade-old environmental legislation reduces landfill space and increases the cost of waste disposal. Almost half of the waste that ends up in landfills is paper and plastic, but currently, only 25% of paper and 2.5% of plastic is recycled. A host of technical and economic issues preclude these percentages from improving unless alternative, competitive nontraditional uses are found.

The concept of bonding cellulose with thermoplastic resin has been in existence since the 1950s. The primary obstacle to combining these materials is the high-viscosity thermoplastic "glue" that makes effective coating and bonding of the cellulose filler difficult. Because the densities of thermoplastic resins are almost three times that of cellulose, the high filler-to-plastic ratios needed for a competitive product are hard to achieve.

A patented process has been developed that solves this problem. The process involves a simple, ambient-temperature dry mixture of expanded thermoplastic and cellulose that is compressed and heated by forcing the mixture through a heated tube. The resulting material is a homogeneous wood substitute with superior dimensional stability that can be molded and easily recycled. A method has also been devised to allow continuous-fiberglass-strand reinforcement to be introduced into the mixture to create a material with highly predictable strength characteristics that equal those of high-grade Douglas fir.

This continuous process allows the composite to be extruded, roll formed, or stamped into various shapes. It can be coated and textured, and have surface laminates applied to it. These composites are projected to cost from \$345 to \$1400/1000 bd ft (\$5.90 to \$23.94/ft^3), depending on the types of plastics and fillers used and the presence of reinforcement.

These composites could be considered for many applications in which wood is currently used. The early market success of companies using considerably less versatile processes indicates that the marketplace is ready to accept these materials. Engineered Composites has many patents granted or pending on this process, the formulation, and the machinery. An engineering prototype production line is currently operating. An immediate need is to be aligned with a group of individuals or an organization that has the financial, technical, and marketing resources to develop a full-scale prototype production line, to determine an entry market for the materials, and to begin test marketing.

5.1 Introduction

Environmental and endangered species legislation is restricting the timber industry's access to raw material and consequently is increasing prices of finished lumber. This trend is expected to accelerate as the country moves out of the recession and the new pro-environmental administration begins to exercise power. The combination of these factors holds the potential of sufficiently eroding the competitive position of wood to allow alternate materials to emerge in the marketplace.

Paper, wood, and plastic waste currently constitute 47% of the waste stream (National Solid Waste Management Association 1989). However, only ~25% of paper and 2.5% of plastic are recycled. In spite of poor economics and difficult technical issues, these volumes are steadily increasing because of consumer pressure and environmental legislation decreasing the availability of landfill space (*Modern Plastics* 1992c). The major recycling effort has been to force these materials into market niches that their virgin counterparts have successfully penetrated. Because the nature of recycled plastic and paper is much different from virgin material, their success in these markets has been mixed. Unless alternative competitive nontraditional uses are found, the negatives of recycling paper and plastic will hamper further waste stream reduction.

Products made from reconstituted wood fiber have long been a staple of the construction industry. These products include particle board, flake board, orientated strand board, insulation board, fiberboard, hardboard, and laminated paperboard. These products use the wood fiber primarily as an inexpensive filler material that enhances the flexibility and impact resistance of the more brittle and expensive binders or glues. Depending on the type of adhesive used and the form of the reconstituted wood fiber, these composite materials can approach or even exceed the strength of common lumber (U.S. Department of Agriculture 1987).

Thermoplastics have many attributes that make them ideal for structural applications, including a relatively high strength (*Modern Plastics* 1992b), extremely high durability, a chemical structure that makes them homogenous and predictable in all loading directions, an ability to be molded into efficient structural shapes, and an ability to be combined with other materials to meet specific structural criteria.

Wood is highly competitive compared with manmade alternatives. To effectively compete with this subsidized resource, a material must be found that has a very low raw material cost, a highly efficient manufacturing process, equal or superior structural properties, and some unique properties or advantages that differentiate it from the competition.

The concept of bonding cellulose with thermoplastic resin has been around since the early 1950s (Gramelspacher 1953). The primary obstacle to combining these materials is that the high viscosity of the thermoplastic "glue" hinders effective coating and bonding of the filler material. Because the densities of thermoplastic resins are almost three times that of cellulose, the high filler-to-plastic ratios necessary for a competitive product are hard to achieve because the filler constitutes such a large volume of the mixture. Most attempts to solve this coating problem involve compressing and heating thin layers of cellulose and thermoplastic (Krzysik and Youngquist 1991; Van Smith 1975; and Gramelspacher 1953), mechanically mixing the thermoplastic and finely ground cellulose in the presence of heat (Nippon Paper 1975), or reducing the viscosity of a specific thermoplastic with chemicals. All of these complicated and expensive solutions exhibit modest filler-to-plastic ratios.

To compete with existing wood processing efficiencies, we determined that a material made in a continuous process would be the most versatile and cost effective. Existing continuous-plastic-processing technologies rely mainly on screw extruders to melt, mix, and pressurize the plastic so that it can be formed. Because the tolerances in these machines prevent them from accepting relatively large filler fragments, adapting this technology to large-particle composites with continuous reinforcement is difficult and expensive.

The most common method of inserting continuous-stranded material, such as fiberglass, into a thermoplastic matrix is the pultrusion manufacturing process (Schwartz 1984). This process relies on using a screw extruder to make a plastic form over which stranded thermoset-impregnated material is laid under tension, cured, and then covered with more thermoplastic resin ejected from a screw extruder. These fiberglass continuous strands improve the tension strength of the structural member. Again, because the pultrusion process requires a screw extruder, its adaptability to a thermoplastic/cellulose composite is limited.

Zoning different types or strengths of materials in a single structural member is another technique to enhance the strength-to-cost ratio of a beam. The ratio is enhanced by placing lower strength (and thus less costly) material in the areas of the beam that are subjected to lower stress levels. This technique is also used in the common glue-laminated wood beam. In this application, the beam's outer layers, which are subjected to high tension and compression stresses, are made of clear, very high-strength wood; and the center of the beam, which experiences lower stress, is made of wood with more knots and other defects. In plastic processing, the common way of placing materials of different properties in a single piece is to use a co-extrusion process in which different plastics are melted in separate screw extruders and then combined by merging the ejected plastics in a common extrusion die. Unfortunately, requiring screw extruders in the co-extrusion process limits its use in forming a zoned thermoplastic/cellulose composite.

5.2 Concept Description

A patented process has been developed to solve the problem of effectively coating and binding the cellulose filler in order to bond cellulose with thermoplastic resin. In its basic form, this proven concept involves a simple, ambient-temperature dry mixture of expanded thermoplastic and cellulose that is compressed and heated by forcing the mixture through a heated tube. The only "glue" used to bind the cellulose together is the thermoplastic.

The key element of this process is that the expanded thermoplastic effectively suspends the cellulose in the mixture and thereby allows the filler to be completely coated during the compression/heating step (Reetz 1992). This suspension occurs because the density of the expanded thermoplastic is about one-third that of the cellulose.

The process, shown in Figure 5.1, involves dry mixing the cellulose and expanded thermoplastic by tumbling and transferring the loose mixture into a compression chamber, where a ram forces it through heated tubes that melt the plastic and bond it with the cellulose. Rapid melting at the surface creates a liquid interface between the unmelted mixture and the containment tube surfaces, drastically reducing friction and allowing the ram extruder to operate in a pressure range of 1600 to 6000 psi.

After leaving the heated tubes, the mixture is run through an oven to complete bonding. At the oven exit, it is either roll-formed into a shape or transferred to a second ram extruder that further densifies and shapes it. At this stage, several options are possible. The material can be formed in various shapes, including sheet material. It can also be coated with other types of plastic--such as polyvinyl chloride (PVC), which has very good ultraviolet resistance--and embossed with a wood grain pattern to create a thick inexpensive siding material that requires no painting. The sheet material can also be placed in a heated compression press and formed into a nestable pallet or other stamped or molded-type product.

As Figure 5.1 shows, vertical heat vanes are placed in the heated tube to evenly heat the large volume of material necessary to make the sections required (typically 4 in. by 12 in. or greater). These vanes serve two purposes. While their most important purpose is to distribute the heat evenly throughout the mixture, the vanes' thickness and added surface area also compress the mixture simply by reducing the cross-sectional area and increasing the frictional resistance. Obviously, the layout of the vanes in the heated tube and its length can change depending on the thermal characteristics of the mixture and the pressure available from the ram.

Figure 5.2 is a top view of a modified hopper shown on the machine in Figure 5.1. By placing partitions in the hopper and introducing different mixtures into each of the compartments created by the partitions, a zoned composite can be formed because no mixing (other than some turbulence in the heated tubes) occurs once the material is placed in the compression chamber (see Figure 5.1).

An excellent opportunity is available to introduce continuous-reinforcement strands into the cross section because the mixture is very loosely packed when it is placed into the compression chamber. The strands must be placed in the compression chamber and covered by a protective sheath. The loose mixture is then forced around the

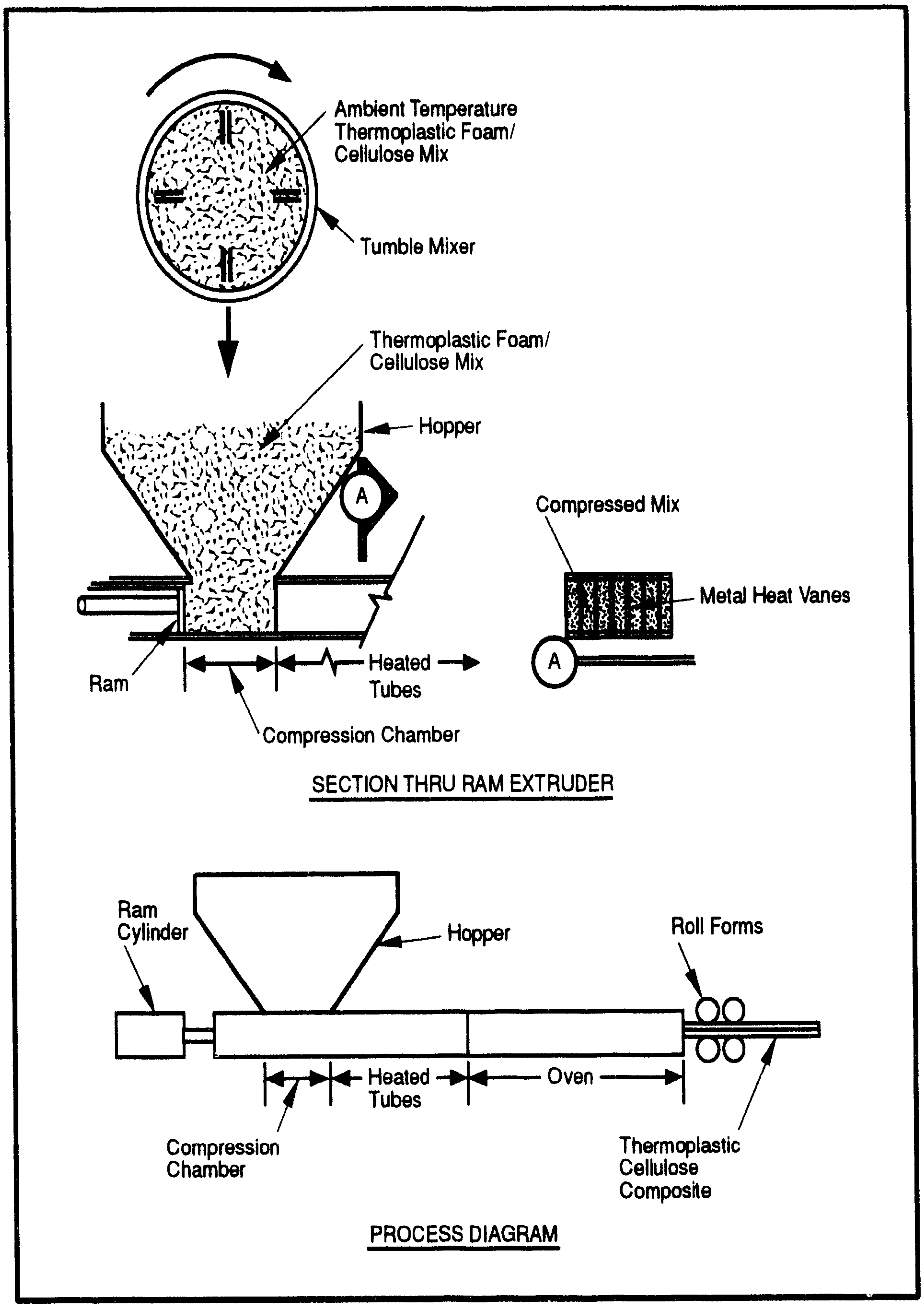

Figure 5.1. Thermoplastic/Cellulose Composite Manufacturing Process

sheath. The ram then moves over the sheath and presses the mixture around the exposed strands at the beginning of the heated tube. The strands are dispensed from a creel reel located at the back of the machine.

To initially feed the strands through the heat chamber (which is filled with solid composite material at any given time), the ends of the strands are attached to wedge-shaped blocks placed in a hole in the mixture made at the front of the heat chamber. Then, each time the ram cycles, it forces material behind these blocks and therefore moves them and the attached strands through the tube. When the cooled composite, strands, and blocks are ejected from the machine, the blocks are cut out.

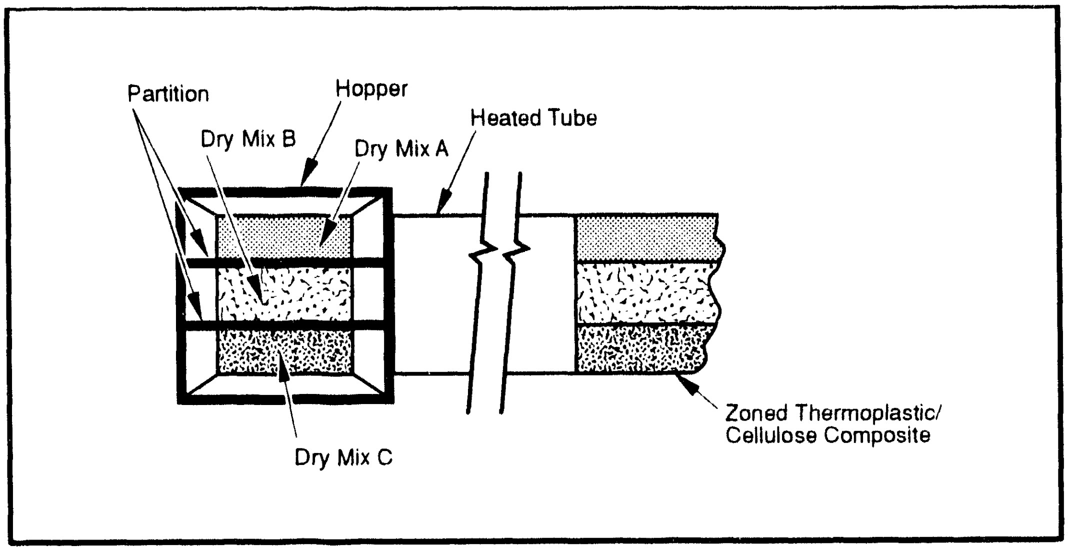

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Figure 5.2. Hopper for Zone Composites

The strands remain locked in the composite. They can then be placed in tension by the creel reels, and the process continues with the pretensioned strands placed in the critical stress area of the thermoplastic cellulose composite. Figure 5.3 details some of the more important elements of the mechanism and process.

5.3 Economics and Market Potential

Price is a major factor in determining the market viability of thermoplastic/cellulose composites. The cost of raw material, particularly the thermoplastic, has the most influence on price. For example, if a 60% wood, 25% polystyrene (PS), and 15% polyethylene (PE) thermoplastic composite is made with virgin thermoplastic, the raw material cost is as follows (*Modern Plastics* 1992a):

$\text{Wood} = (.60)(25\ \text{lb/ft}^3)(\$0.015/\text{lb}) = \$\ 0.22/\text{ft}^3$
$\text{PS} = (.25)(71\ \text{lb/ft}^3)(\$0.520/\text{lb}) = \$\ 9.23/\text{ft}^3$
$\text{PE} = (.15)(59\ \text{lb/ft}^3)(\$0.360/\text{lb}) = \underline{\$\ 3.19/\text{ft}^3}$
$\text{Total} = \$12.64/\text{ft}^3$

On the other hand, using recycled thermoplastic results in the following costs:

$\text{Wood} = (.60)(25\ \text{lb/ft}^3)(\$0.015/\text{lb}) = \$0.22/\text{ft}^3$
$\text{PS} = (.25)(71\ \text{lb/ft}^3)(\$0.190/\text{lb}) = \$3.37/\text{ft}^3$
$\text{PE} = (.15)(59\ \text{lb/ft}^3)(\$0.150/\text{lb}) = \underline{\$1.33/\text{ft}^3}$
$\text{Total} = \$4.92/\text{ft}^3$

This translates into a raw material price per 1000 bd ft of ($\$4.92/\text{ft}^3$)($\text{ft}^3$/17.1 bd ft of finished lumber)(1000 bd ft) = \$288/1000 bd ft.

Increasing the wood content to 70% and reducing the recycled PS content to 20% and the recycled PE to 10% result in the following:

$\text{Wood} = (.70)(25\ \text{lb/ft}^3)(\$0.015/\text{lb}) = \$0.26/\text{ft}^3$
$\text{PS} = (.20)(71\ \text{lb/ft}^3)(\$0.190/\text{lb}) = \$2.70/\text{ft}^3$
$\text{PE} = (.10)(59\ \text{lb/ft}^3)(\$0.150/\text{lb}) = \underline{\$0.88/\text{ft}^3}$
$\text{Total} = \$3.84/\text{ft}^3$

The raw material price per 1000 bd ft is ($\$3.84/\text{ft}^3$)($\text{ft}^3$/17.1 bd ft of finished lumber)(1000 bd ft) = \$224/1000 bd ft.

The prices for recycled thermoplastics used in these examples are their cost when purchased from a scrap dealer and reflect the scrap dealer's overheads and profit margin. Eliminating this middleman by working directly with a recycling program would significantly reduce the thermoplastic cost.

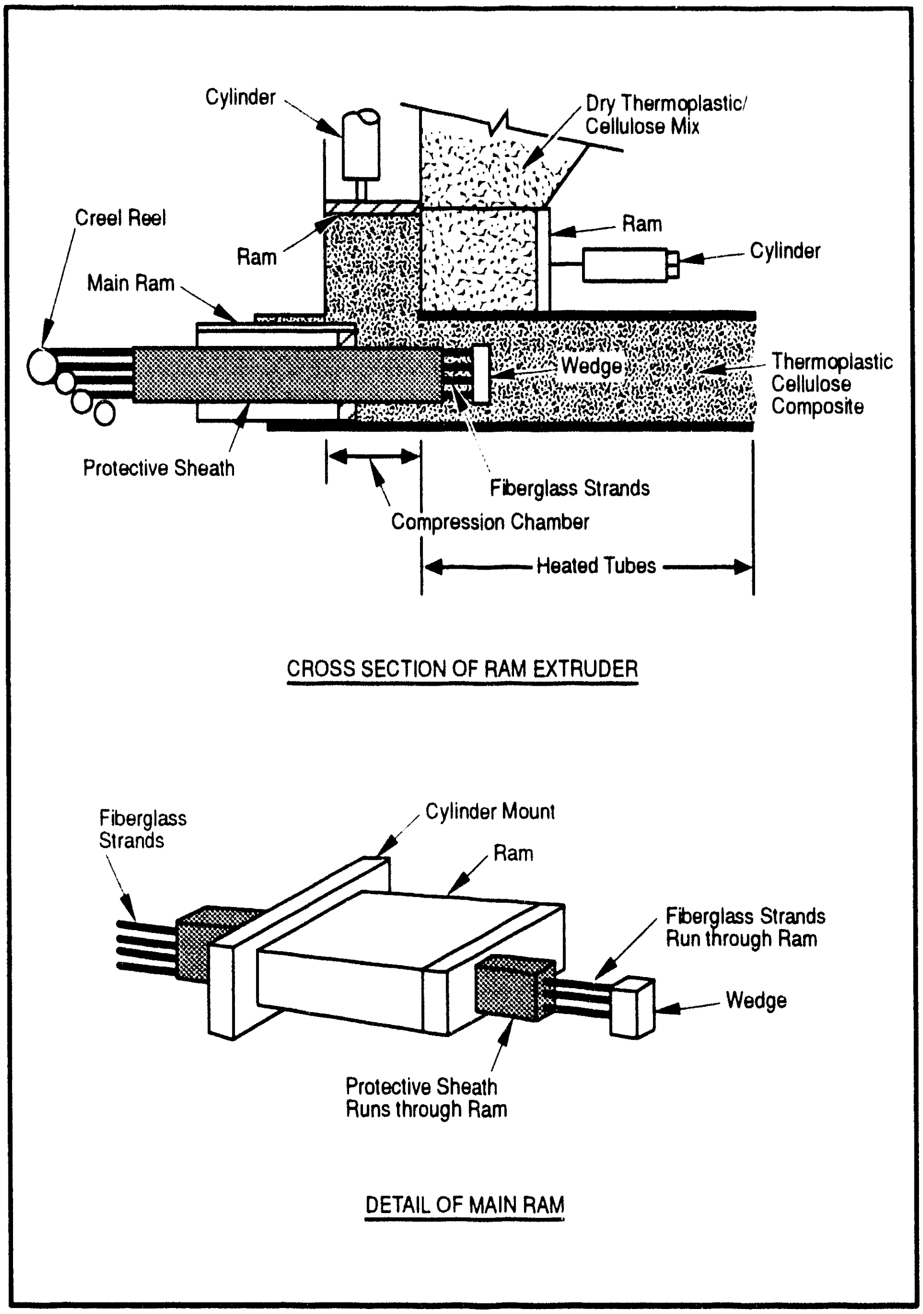

Figure 5.3. Details of Strand Reinforcement Mechanism

Another issue affecting the cost of the thermoplastic is freight. Because this process must use expanded thermoplastic to suspend the filler particles, manufacturing the expanded thermoplastic onsite and avoiding the high cost of shipping basically by air to the facility would require either 1) locating the manufacturing facility near a source of expanded thermoplastic, or 2) installing a blowing line. The second option has several advantages for the manufacturer. One advantage is that it allows the size, density, and type of the expanded thermoplastic and the type of blowing agent to be controlled. Also, it is easier to get a much wider array of recycled thermoplastic in pelletized solid form, and it allows much more flexibility in siting the manufacturing facility.

Table 5.1 compares the price of dimensional lumber, engineered wood products, finished lumber products, "plastic lumber," and some of these thermoplastic/cellulose composites. The table is based on the following simplistic assumptions: 1) recycled thermoplastic is used; 2) expanded thermoplastic is made in-house; 3) the recycled thermoplastic is purchased from scrap dealers on the open market; 4) the manufacturing facility is fully amortized; 5) the cost of manufacturing is 15% of the raw material cost (the entire production line can be automated); 6) freight cost is zero; and 7) the wholesale selling price is based on the product of the raw material cost multiplied by 1.15 to account for manufacturing; this number is then divided by 0.75 to cover overhead, marketing, and profit margin.

Initial estimates of the capital necessary to build a production facility that can produce 70,000 bd ft/day is ~$750,000, based on 1991 quotes for a designed, full-scale production machine that can produce a continuous 4-in.-by-12-in. section and our estimate (based on experience with an engineering prototype machine) of production rates. This capital estimate does not include the cost of a blowing line to expand and grind the thermoplastic nor the infeed and outfeed sections of the production line.

One potential concern is the availability of sufficient thermoplastic material for large-scale commercial development. About 10 million tons of thermoplastic material are landfilled every year (National Solid Waste Management Association 1989). Of that, only ~250,000 tons, or 2.5%, is being recycled because of formidable economic and technical issues (*Modern Plastics* 1992c).[a] Two of the great difficulties in recycling post-consumer thermoplastic are the intolerance of current plastic processes and products to impurities and contaminants. These impurities can involve such things as incorrect color or traces of incompatible plastics. The contaminants can be anything from a piece of paper to traces of contents residue in the reclaimed resin.

The new process can solve these problems by creating market-defined durable products that are not as sensitive to impurities and contaminants. Thermoplastic/cellulose composites created by this method essentially use the thermoplastic as a binder or glue. "Contaminants" are not only tolerated, they constitute most of the material. Color variation is not important to the final product because it can be coated if the application requires it. Also, the process can use any thermoplastic in the waste stream if it is matched with the correct filler material. This flexibility means that the vast majority of waste thermoplastics, rather than just the more popular and easy to handle ones, are potential material sources. If only 10% of the available waste material was used to make thermoplastic/cellulose composites, about 2.5 billion bd ft of composite lumber could be produced each year. This represents the annual production of the largest U.S. lumber producer, or about 3.5% of the annual softwood/hardwood lumber production in the United States and Canada in 1991 (*Forest Industries* 1992).

Table 5.1 indicates that thermoplastic/cellulose composites (#'s 4, 7, and 13) made from cleaned, reground, post-consumer, and post-industrial recycled thermoplastics are very competitive if this concept is used. The physical properties of these composites indicate the potential to perform as well as the materials that bracket them in Table 5.1.

Thermoplastic/cellulose composites represent a family of materials, rather than a specific product. The process can formulate any thermoplastic and any filler material into a reasonably high filler-to-thermoplastic ratio composite material. By using structural devices such as shape, zoning, and strand reinforcement, the process can tailor the material for a specific set of market-defined structural and price constraints. The ability to create a composite for the application means that the opportunity to penetrate several market niches is high. For example, at low plastic-to-wood ratios, such as #4 in Table 5.1, the materials have the characteristics and stiffness of particle board. The materials do, however, have the added benefits of excellent dimensional stability and much improved weatherability because the wood particles are totally encapsulated in plastic and have a random orientation.

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[a] Figures for 1990 were compiled by the Society of Plastics Industry, Council for Solid Waste Solutions. The 1990 figure was double the 1989 figure.

Table 5.1. Material Cost/Volume Comparison

#	Material	\$/ft^{3}[b]	\$/mbf[c]
1	1/2" Particle Board (western)[a]	3.72	
2	1/2"Oriented Strand Board/Waferboard[a]	4.27	
3	2 x 4 STD & BTR (kd eastern SPF)[a]	4.41	258
4	Thermoplastic Composite - 70% Wood Chips; 20% Regrind PS; 10% Regrind PE[d]	5.86	343
5	2 x 6 Western Red Cedar #2 & BTR[a]	5.90	345
6	2 x 12 SP Pressure Treated - 16' length[a]	6.92	405
7	Thermoplastic Composite - 60% Wood Chips; 25% Regrind PS; 15% Regrind PE[d,e]	7.56	442
8	PSL 300® Oriented Strand Lumber[f]	11.75	687
9	Mobil Oil Timbrex Thermoplastic Composite; 50% Wood Chips; 50% PE[g]	13.68	800
10	5/4 White Fir and Molding & BTR[a]	13.94	815
11	MICRO=LAM® Laminated Veneer Lumber[f]	13.97	817
12	1 x 8 Prime Trim Fascia (G.P.)[i]	14.96	875
13	Thermoplastic Composite - 60% Wood Chips; 25% Regrind PS; 10% Regrind High-Density PE 5% E Glass Strands[d,h]	16.63	972
14	1 x 8 Clear Redwood Fascia[a]	19.07	1155
15	5/4 Ponderosa Pine Rough Molding and BTR[a]	20.86	1220
16	Parallam® - Parallel Strand Lumber[f]	21.37	1250
17	Durawood® -- Regrind HDPE "Plastic Wood"[j]	29.07	1700
18	Recyclmaid® -- Regrind HDPE "Plastic Wood"[k]	34.51	2018

(a) Prices are FOB mill - based on pricing in *Random Lengths* (1991).
(b) In cases where $/1000 bd ft and \$/ft^{3} are given, 1000 bd ft is taken to equal 58.5 ft^{3} of *finished* lumber.
(c) In cases where $/1000 bd ft are given, prices are $/1000 bd ft.
(d) Wood chip prices based on one-half truckload of material purchased from HOFF Building Products, Boise, Idaho ($0.015/lb).
(e) Based on quoted regrind prices from Rainier Plastics, Yakima, Washington, on July 15, 1992 ($0.17/lb HDPE; $0.19/lb PS). Assumes EPS manufactured onsite. Material prices increased 15% for manufacturing and marked up 25% to estimate FOB mill price.
(f) Register trademark of TJ/MacMillan, Boise, Idaho. Prices estimated by Ron Taylor, formally of TJ/MacMillan.
(g) Based on prices published quoted in *Modern Plastics* (1993).
(h) Glass price from prices published in *Modern Plastics* (1992a) ($0.80/lb). Based on quoted regrind prices from Rainier Plastics, Yakima, Washington, on July 15, 1992 ($0.17/lb HDPE; $0.19/lb PS). Assumes EPS manufactured onsite. Material prices increased 15% for manufacturing and marked up 25% to estimate FOB mill price.
(i) Prices from BMC West, Boise, Idaho.
(j) Registered trademark of Eaglebrook Products, Chicago, Illinois. Price quoted on phone in October 1991.
(k) Registered trademark of Recycled Plastics Industries, Inc., Green Bay, Wisconsin. Price based on July 29, 1991, price sheet.

As a result, this particular composite could easily be used in applications where a wood-like substrate material is required or where wood sheathing is currently used.

The thermoplastic composite represented by #7 in Table 5.1 could be considered for applications such as window frames, door frames, and molding. In fact, a company in Rogers, Arkansas, AERT, has successfully marketed a composite material made from cellulose and reground post-industrial PE for these applications the last couple of years. The material's ability to be extruded or roll-formed into various shapes and clad with ultraviolet protective or decorative coatings allows it to be formed into such things as molding or clapboards with little or no waste in a continuous process. This material can also be used to form nestable pallets or agricultural bins. The material has advantages over existing technologies in this area because it uses a competitive material that can be totally recycled in a process that requires no assembly.

Other markets that have been identified for thermoplastic/cellulose composites or solid recycled plastic materials are industrial flooring, highway guard rails, railroad ties, docks, decking, landscape timbers, fence posts, and rails. Several companies are successfully marketing "solid" plastic wood in these areas. This material, which is reground 100% high-density polyethylene material or 100% mixed thermoplastic (#17 and #18), is made by about 9 U.S. manufacturers (*Garbage* 1991). These companies have found a market niche in exterior and marine applications, even though their material is four times the price of wood or the thermoplastic/cellulose composites presented in this paper.

Mobil Oil has recently formed a composite product division that is placing its wood chip/PE composite in industrial flooring and offset block guard rail applications. Their current production of 5000 tons per year (~4.3 million bd ft/yr) is expected to double in 1993 (*Modern Plastics* 1993).

A composite, such as #7 in Table 5.1, could be used for wall studs in the construction industry. The material appears to have very consistent and reasonably high compression values. However, it would probably have to be restricted to applications that allowed it to be completely sheathed by fire-retardant materials, such as drywall, to satisfy building codes. Because thermoplastic resins act much like a wax when they are heated, creep at elevated temperatures becomes a major concern when these materials are considered for structural applications.[a]

At normal working temperatures, a competitive thermoplastic/cellulose composite (#13 in Table 5.1) can be created that has bending strength properties equal to that of glue-laminated timber or engineered wood products used as main structural members. The toxicity of combustion materials of this thermoplastic/cellulose composite appears to be about the same as wood (Stacy 1988; Albert 1969), and the thermoplastic's fire resistance can be improved with additives. If the material's stiffness can be improved considerably with little additional cost and if the concerns about creep at elevated temperatures can be addressed, these materials can be considered in structural building applications.

Years of experience in dealing with building code agencies leads the author to believe that widespread use of thermoplastic composites as structural bending members will not occur unless the cost of competing materials drastically increases. Thermoplastic/cellulose composites will be more easily accepted as nonstructural members or fire-protected compression members. Products made from these composites that could be accepted by the code agencies in the near term are studs and fascia boards (Stacy 1988; Albert 1969). Fascia boards alone represent a 234-million bd-ft market valued at ~$190 million/yr.[b] It should be noted that thermoplastic PVC siding has already been accepted and widely used by the industry. The

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[a] Conclusions are based on a very lengthy discussion with several senior structural engineers at TJ/MacMillan Inc., Boise, Idaho, in August 1990.

[b] Assume 1.1 million housing starts/yr and the average house having 160 lineal feet of 2 x 8 fascia board (1.33 bd ft/lin. ft). Therefore, board feet = (1.1 x 10^6 houses) (1.6 x 10^2 ft/house) (1.33 bd ft/ft) = 2.34 x 10^8 bd ft = 234 x 10^6 bd ft. Assume 2 x 8 fascia costs $800/1000 bd ft; then (2.34 x 10^8 bd ft) ($800/$10^3$ bd ft) = $1872 x 10^5 = $187 x 10^6/yr.

market for studs and clapboard siding are each several billion dollars per year.

5.4 Key Experimental Results

A preliminary investigation of the structural and environmental properties of many of the more common thermoplastic/cellulose composite materials is being conducted at our facility and is expected to continue throughout 1993. Our initial focus has been on two commonly available expanded thermoplastics (PS and PE) combined with wood chips, newspaper, or straw. Table 5.2 presents the standard tests that were performed on each formulation, and Tables 5.3 and 5.4 summarize the test results. All of the percentages shown in the formulation column represent weight percentages. Typically, 10 samples were tested for each test/formulation. The numbers in Tables 5.3 and 5.4 are the mean of the samples tested. The sample size is too small to give a meaningful COV of the data.

The wood chips used in the various formulations were spruce/pine/fir planer shavings from a local molding processor. The wood was very dry, ~5% to 7% moisture content. The chips were sieved through 1/4-in.-square mesh to remove most of the sawdust. Removing the dust produces a stronger, more consistent board that exhibits better moisture swell characteristics because it reduces the number of internal bonds required and allows the remaining cellulose particles to be more thoroughly coated.

The formulations tested consisted of PS and PE thermoplastic binders. While availability played a part in their selection, we found that PS is a particularly good adhesive that bonds well with wood and other incompatible thermoplastics. The PE was chosen because it tends to reduce the brittleness of the composite, and it serves as a good lubricant for the formulation as it passes through the heated tubes of the ram extruder. All of the thermoplastic used in these tests was clean regrind foam thermoplastic (0.5 to 3 pcf) recycled from post industrial waste.

The paper used in some of the formulations was shredded newspaper (with ink) and a particle size of ~1/4 in. to 3/8 in. square. Although the formulations using paper as a filler material required the largest number of internal bonds, the porosity of the newspaper allowed the plastic to soak through it during the compression/heating step. As a result, a consistent, well-bonded material was produced. The straw was typical bailed straw used for animal bedding and was cut into ~1-in.-long pieces. Its moisture content was not determined, but appeared to be from 15% to 25%. This moisture produced some steam in the ram extruder during processing, but the material still bonded well.

All of the material for the test samples was produced in a continuous piece with a 1-3/4 in. by 7-3/4 in. cross section on a ram extruder similar to the one depicted in Figure 5.1. The test samples were either stamped into the proper size, shape, and thickness in a compression hot press while the material was still hot, or they were machined once the composite had cooled. The fiberglass-reinforced samples were formulated in the ram extruder and

Table 5.2. Tests for Evaluating Thermoplastic/Cellulose Composites

Test Reference	Test Type	Test Reference	Test Type
ASTM D1037	Edgewise Shear	ASTM D143	Tension ⊥ to Flow
ASTM D1037	Tension	ASTM D648	Defl. Temp. under Flexural Load
ASTM D1037	Compression	ASTM D635	Fire Resistance
ASTM D3043	Bending	ASTM D1037	Thickness Swell
ASTM D3043	Stiffness	ASTM D1761	Nail Withdrawal

Table 5.3. Mechanical Characteristics of Thermoplastic/Cellulose Composites

Formulation	Density	Edgewise Shear	Tension[a]	Compression	Bending	Stiffness
50% Wood, 25% PS, 25% PE	54 pcf	699 psi	1560 psi	3390 psi	2216 psi	260,000 psi
60% Wood, 25% PS, 15% PE	39 pcf	587 psi	853 psi	2318 psi	1185 psi	148,000 psi
66% Wood, 17% PS, 17% PE	36 pcf	496 psi	438 psi	1705 psi	585 psi	88,000 psi
60% Wood, 40% PE	36 pcf	535 psi	689 psi	2015 psi	985 psi	139,000 psi
50% Wood, 25% PS, 20% PE, 5% E-glass/Polyester Resin	46 pcf				6772 psi[b]	685,000 psi
50% paper, 25% PS, 25% PE	57 pcf	522 psi	342 psi	2189 psi	475 psi	77,000 psi
50% Straw, 35% PS, 15% PE	48 pcf	539 psi	452 psi	1472 psi	637 psi	92,000 psi

(a) Parallel to flow.
(b) Compression failure mode.

Table 5.4. Mechanical and Environmental Characteristics of Thermoplastic/Cellulose Composites

Formulation	Tension ⊥ to Flow	Nail Withdrawal[a]		Fire Resistance[b]	Deflection Temperature Under Load 264 psi	Thickness Swell[c]
		80°F	175°F			
50% Wood, 25% PS, 25% PE	437 psi	159 #/in.	39#/in.	0.55 in./min.	265°F	0.5%
60% Wood, 25% PS, 15% PE	365 psi					
66% Wood, 17% PS, 17% PE	246 psi	112 #/in.				1.3%
60% Wood, 40% PE	325 psi	139 #/in.			254°F	
50% Wood, 25% PS, 20% PE, 5% E-glass/Polyester Resin						
50% paper, 25% PS, 25% PE	231 psi	91 #/in.	42 #/in.	0.51 in./min.		1.3%
Fire Retardant Paper, 50% Paper, 25% PS, 25% PE				0.27 in./min.		
50% Straw, 35% PS, 15% PE	238 psi	108 #/in.		0.24 in./min.		1.2%

(a) 6d nail.
(b) 0.5 in. by 0.5 in. cross section.
(c) Sanded 1 in. diameter disk, 24-hour soak.

then were laid up and bonded in a compression hot press because the continuous-strand-reinforcement feature shown in Figure 5.3 was not installed on the engineering prototype ram extruder.

Generally, all of the materials tested exhibited structural characteristics that make them reasonable alternatives to current container and structural materials. Their primary difference from some of these common cellulose materials is that they are sensitive to elevated temperatures. This is not necessarily a negative because this characteristic allows the composites to be formed into virtually any shape and allows recycling by simply grinding the material up, adding some additional thermoplastic, and reprocessing the mix. The thermoplastic adhesive in these thermoplastic/

cellulose composites is successfully used in its pure state in many of the applications where these materials could be considered.

Table 5.4 indicates that as the wood content increased, the strength properties tended to decrease because of a lack of control of the expanded thermoplastic's size and density. This also points out the need for more thorough dry mixing of the thermoplastic and cellulose. These materials have many characteristics that are similar to particle board. It is commonly known that the mechanical properties of particle board are highly dependent on manufacturing variables (Bodig 1982). As our process controls become more refined and we examine the effects of secondary extrusion and hot compression pressing on the material, we expect all of these structural numbers to increase.

The samples tested in bending with 5% by weight fiberglass placed on the extreme tension fiber is a rather interesting result. This composite acted exactly like a steel-reinforced concrete beam. The composite was basically in compression, and the glass carried the tension stress. These members failed in compression.

None of the materials tested were formulated with a fire-retardant plastic additive. Consequently, the numbers shown in Table 5.4 represent the worst performance possible. A special, hot-air medium-heat deflection test apparatus that meets the requirements of ASTM D648 was constructed to test larger and thicker samples than those typically evaluated. A thermocouple was bonded in the center of some of the 1-in.-thick samples to determine the heat transfer/time relationship and its effect on deflection performance. These tests indicate that while the materials are heat sensitive, considerable time is required to bring a thick sample up to a uniform temperature. Because most fire tests for structural assemblies are ended when the structural support member reaches a temperature that is much lower than the numbers indicated in Table 5.4, it appears that these materials could be considered for structural applications if they are used in properly designed fire-rated assemblies.

At normal temperatures, these materials performed as well as wood in all categories except stiffness. The importance of stiffness is that it directly relates to deflection performance. Materials that have lower stiffness commonly are manufactured in deeper sections, combined with stiffer materials (stressed skin panels), or they are formed in shapes, such as an I-beam or a waffle pattern, to provide competitive deflection performance.

In one area, tension perpendicular to flow, these materials performed much better than soft woods. Wood is a nonhomogeneous material that exhibits different strength properties depending on how it is loaded. In one particular direction--tension across the grain--wood is extremely weak. Many, if not all, connection and other structural wood failures can be attributed to excessive stresses applied in this direction. All of the composites tested, even those bonded with brittle polystyrene, took nails without splitting because of the high content and uniform distribution of the cellulose filler. Consequently, Table 5.4 and direct observation seems to indicate that mechanical connections, such as nails or bolts, will be much more predictable and reliable than their wood counterparts.

Table 5.4 indicates that as the plastic content increases the moisture swell is not as noticeable. Processing parameters also affect this performance. Informal tests indicated that if these composites are subjected to low heat and pressure for a considerable time, the wood cell can be completely saturated with plastic, thus creating true "plastic wood." This material feels and looks like plastic even though it is over 50% wood fiber; it has excellent moisture swell and durability properties.

Work by others on similar composites has found that fiber encapsulation by the thermoplastic "keeps the [material] ultraviolet stable, moisture resistant, and colorable. The small percentage of fibers exposed at the surface imparts paint adhesion, traction, and wood-like feel and esthetics." Unlike the expansion and contraction of timber which loosens nails, "the composite's fibers, cocooned in polymer, impart a strong grip on nails" (*Modern Plastics* 1993).

We have also found that formability increases and surface finish improves as plastic content increases. From the author's perspective, the durability and the formability of these composite materials are their most desirable features.

5.5 Future Development Needs

Engineered Composites is a partnership that was formed in 1991 to develop the materials and processes described in this paper. Since that time we have received a U.S. patent on the process and have two additional patents pending on the mixture formulation and machinery. We've also developed an engineering prototype production line to prove the process, provide material for testing, and project manufacturing efficiencies.

With this protection and capability, we are now poised to undertake the development of a full-scale prototype production line, identify an entry market for the materials, and begin preliminary test marketing. We also need to continue to examine the effects of process refinements on the mechanical properties of the materials, and to have an independent test agency verify the test results presented and complete other tests, such as accelerated aging (ASTM D1037), natural decay resistance (ASTM D2017), and any tests required for a specific product application.

Our most pressing need is to form an alliance with a group of individuals or an organization with the necessary financial, technical, and marketing resources to move the process and these new materials to this next stage of development.

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6.0 Sound Barrier Wall Containing Recycled Rubber and Plastic

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Abstract

Each year the United States discards ~285 million tires. About 100 million tires are productively reused or recycled. The remaining 185 million tires are added to stock piles, landfills, or illegal dumps across the country. Those waste tires could be recycled for use in sound barrier walls. With the expansion of freeways in urban America, the public is demanding sound barrier walls to abate highway noise. To date, over 700 miles of sound barrier walls have been built in the United States and the number of miles constructed each year is increasing.

The objective of this concept is to determine the feasibility of using scrap tire waste in combination with a structural element to create an aesthetic, functional, and long-lasting barrier wall. A design has been developed that uses a fiberglass-reinforced composite structural panel encasing a recycled rubber core. The panel is a pultruded shape that is durable, color compounded, and high strength. The recycled rubber core provides the mass needed for appropriate sound blockage.

The Carsonite sound barrier wall can use ~250,000 lb of tire rubber per mile and can be constructed for an estimated \$15 to \$17/ft^2. The Carsonite price compares to a 1989 national average cost for construction of noise barrier walls of \$15/ft^2. The national cost figure includes all kinds of walls, including earth mounds, which are relatively inexpensive. Considering adjustment for inflation, the Carsonite sound barrier wall can compete with other walls of similar construction and projected life.

A first-generation prototype of the noise barrier wall has been constructed at the plant, showing that the wall is feasible and effective as a noise barrier. The design is being refined and includes new architectural treatments and revised structural details. In addition, tests indicate that the components of the Carsonite wall meet all regulatory requirements relative to toxic material specifications, safety, and sound barrier effectiveness.

Further experimentation needs to be done to demonstrate the best techniques for formulating and producing the recycled rubber core. Research also needs to be conducted on assembly-line techniques to facilitate final assembly of the modular panels. A second-generation prototype needs to be constructed to refine construction and erection details. Sources of scrap rubber and potential nation-wide licensed contractors for fabrication and erection need to be determined.

6.1 Introduction

Studies indicate that about one used tire is generated annually for every U.S. citizen. As a result, ~285 million tires need to be disposed of every year. Discarded tires are a major contributor to the waste stream and create a problem of appropriate disposal procedures because of their bulk and enormous quantities generated annually. To reduce their bulk, tires are ground or chipped before they are landfilled. This grinding process is an enormous waste of energy because this material is not productively used.

Of the 285 million tires discarded every year, about 33 million tires are retreaded and 22 million tires are reused or resold. Another 42 million are diverted to various other uses. The remaining 188 million tires are added to stock piles, landfills, or illegal dumps across the country. The U.S. Environmental Protection Agency (EPA) (1991) estimates that the present size of the scrap tire problem is 2 to 3 billion tires.

Most of the markets using the 97 million recycled tires cannot support additional expansion. The supply of retread, reused, and processed rubber products meets or exceeds the existing demand. These saturated markets represent 70% of the present demand for scrap tires. Compared with the annual number of tires discarded, this 65 to 70 million tires used by the saturated markets only absorb 20% of the tire waste stream.

Of the available expanding markets for scrap tires, only two have shown potential to use a significant number of scrap tires: fuel for combustion and crumb rubber modifier for asphalt paving. Combustion already plays a major role, consuming 26 million tires annually. Crumb rubber modifier, which currently consumes 1 to 2 million tires per year, can incorporate the rubber from 2 to 6 tires into a metric ton of hot mix asphalt paving material. To recycle 10 million scrap tires annually as crumb rubber modifier, 2 to 5 million metric tons of hot mix asphalt material would need to be modified (Federal Highway Administration 1992).

As a result of Congressional concern about the scrap tire problem, Section 1038 of the Intermodal Surface Transportation Efficiency Act of 1991 was passed in 1992. Section 1038 of this Act requires that all states use crumb rubber modifier in constructing asphalt pavements. This section mandates that all states increase their use of crumb rubber modifier in asphalt pavements as a percentage of the total tons of asphalt laid from 5% in 1994 to 20% in 1997 and each year thereafter. The use of crumb rubber modifier in asphalt pavements is still experimental in many states. Crumb rubber modifier is expensive, and its improvement in asphalt performance has been questioned. Congress recognized these concerns and required the Federal Highway Administration and EPA to study the environmental effect, performance, and other aspects of combining crumb rubber modifier with asphalt pavements (U.S. Congress 1991).

Alternative highway uses exist for scrap tires. The Transportation Research Board (TRB) initiated a study in 1989 to document these alternative uses. Several highway agencies have examined the potential use of scrap tires or rubber processed from scrap tires for lightweight embankments, retaining walls, safety hardware, and pavement sub-base. Details of these uses will be published in a TRB synthesis in the future (Federal Highway Administration 1992).

State and national legislation has been initiated as a result of environmental risks linked to the presence of scrap tire stock piles and a number of recent, well-publicized tire stock pile fires. By the beginning of 1991, 44 states had drafted, introduced, regulated, or enacted laws to control the scrap tire problem. Typical provisions of the states legislation include regulations to control the processing, hauling, and storage of scrap tires; restrictions on scrap tires and landfills; provisions for funding, normally a tire disposal fee; and in a number of states, incentives for developing new alternative use markets (Federal Highway Administration 1992).

A number of states are concerned that they will become importers of scarp tires if regulations and control are not established. They also realize that markets must be developed locally for recycling scrap tires because tires cannot be disposed of in landfills or exported to other states. It is evident that new products and new technology for the use of scrap tires must be developed. The research and development of the Carsonite sound barrier wall address these issues, and the sound barrier wall has potential for use in every state.

6.2 Concept Description

The objective of this concept is to determine the feasibility of using scrap tire waste in combination with a structural element to create an aesthetic, functional, and long-lasting barrier wall. The recycled scrap tire core consists of a mixture of several crumb rubber sizes and a phenolic binder. A ten-foot-high, one-mile-long wall would consume ~250,000 lb of scrap tire rubber.

The structural element, shaped into a tongue-and-groove building plank, is a fiberglass-reinforced plastic composite that has consistent and predictable mechanical properties with an expected life cycle of 50 years. The glass-reinforced plastic contains flame retardant, is self-extinguishing, and is protected by ultraviolet inhibitors to prevent solar degradation. The tongue-and-groove structural element is manufactured by a continuous process that ensures high quality and structural soundness to meet the load-bearing requirements of the sound wall.

Carsonite has used this process in developing and manufacturing over 100 million linear feet of similar, structural-reinforced composite elements. These elements are used by many agencies, including highway departments, public works departments, utility companies, major pipeline companies, the U.S. Forest Service, and the Bureau of Land Management.

Figure 6.1 depicts the structural shape and dimensions of the structural channel. Figure 6.2 depicts the configuration of a section of an assembled wall using the structural channel with its recycled rubber core. The wall is lightweight and modular and can be easily erected with small erection equipment. Similarly, the wall can be removed, repaired, or moved to a new location without large construction equipment. The wall can be manufactured in virtually any color or with variable shading.

Current sound barrier walls are constructed of many materials, most commonly masonry, wood, or steel. The raw material usually is selected based on their regional availability.

The Carsonite sound barrier wall will provide another option for local and state agencies to select an appropriate sound barrier wall. The new sound barrier wall will increase competition and will provide an incentive for agencies to reduce the problems encountered with the scrap tire waste stream.

6.3 Economics and Market Potential

With the expansion of freeways through urban America, the public is demanding sound walls to

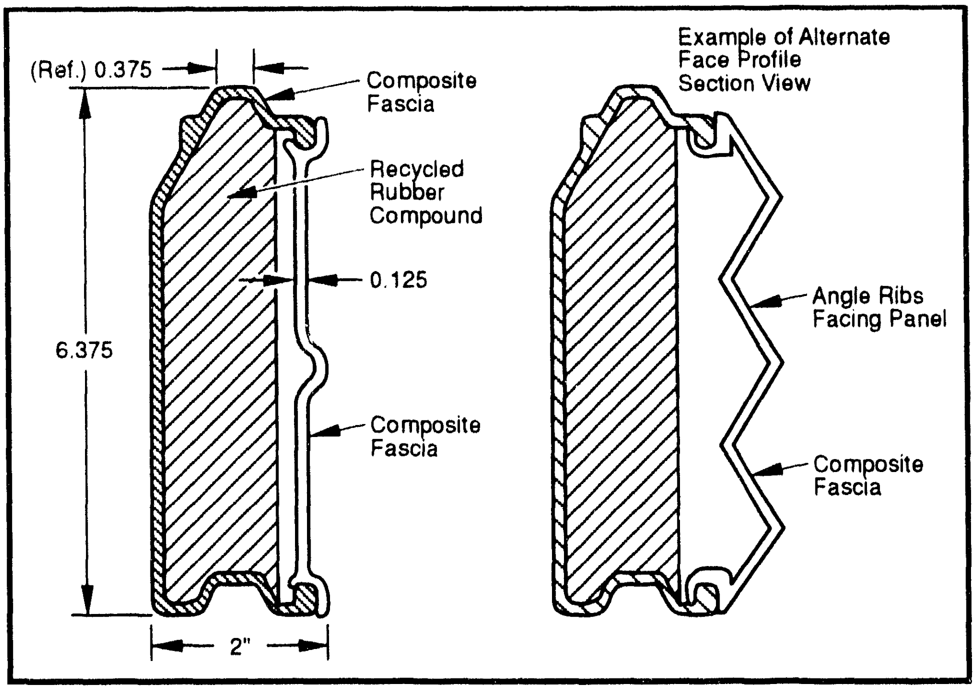

Figure 6.1. Configuration of a Section of an Assembled Wall Using the Structural Channel with Its Recycled Rubber Core

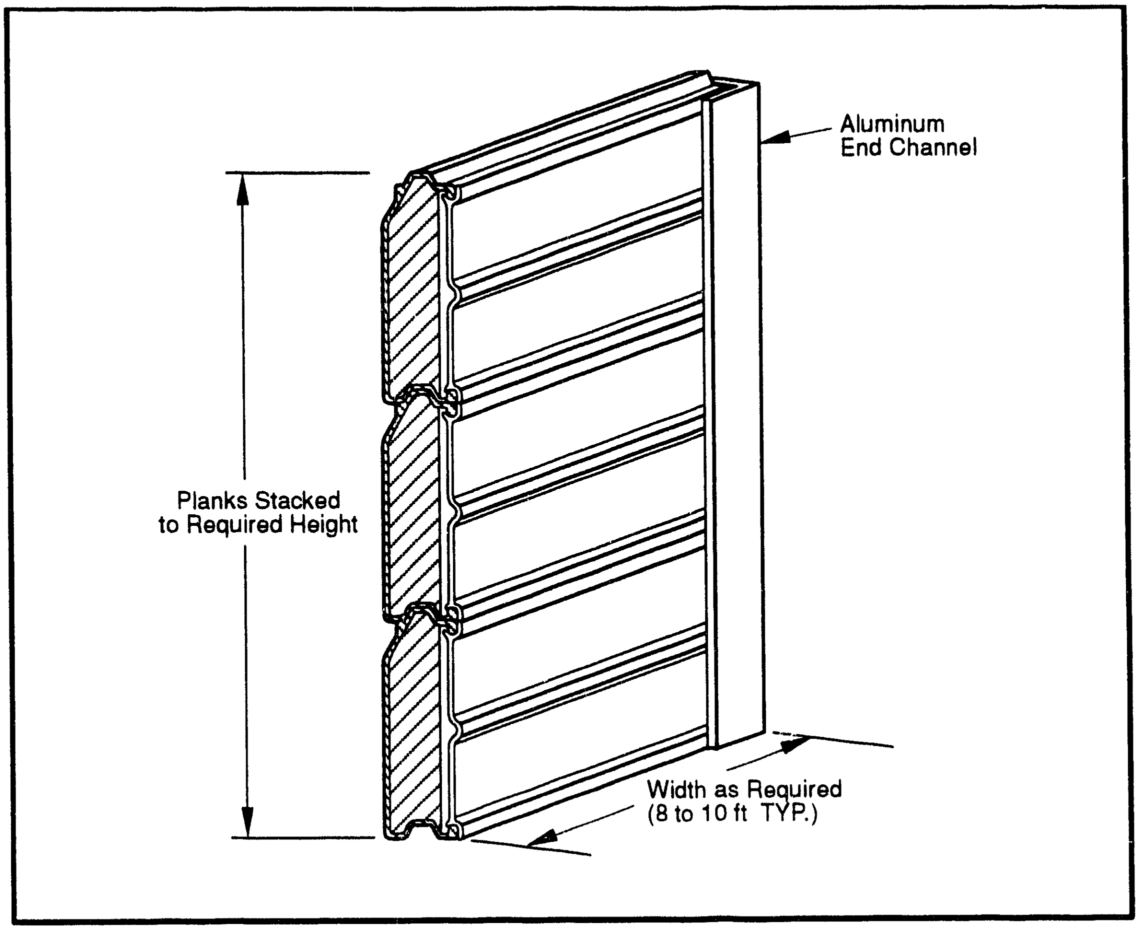

Figure 6.2. Structural Shape and Dimensions of the Structural Channel

abate highway traffic noise. To date, over 700 miles have been constructed in the United States, and the number of miles constructed is increasing every year (Federal Highway Administration 1991). Sound walls, as proposed, have potential for use in every state. As traffic increases, sound abatement and noise pollution reduction are required. As traffic increases, the number of used tires in that region automatically increases. Therefore, using recycled tires for noise abatement is especially appropriate.

The sound barrier wall concept using the scrap tire rubber is especially desirable because it can be used anywhere. The scrap tire filler for the core can be manufactured locally in any area of the country, and the modular panels can also be assembled at that site and as a simple cold process that is environmentally sound. The Carsonite wall can use ~250,000 lb of tire rubber per mile. With the increasing need for noise barrier walls, the proposed wall is expected to be an effective user of a substantial amount of scrap tire.

The Carsonite sound barrier wall can be constructed, including posts and foundations, for an estimated \$15 to \$17/ft^2. In 1989, the national average cost for construction of noise barrier walls was \$15/ft^2. The national cost figure includes all kinds of walls, including earth mounds, which are relatively inexpensive. Considering adjustment for inflation, the Carsonite sound barrier wall can compete with other walls of similar construction and projected life.

6.4 Key Experimental Results

A first-generation prototype of the noise barrier wall has been constructed at the plant, showing that the wall is feasible and effective as a noise barrier. The design is being refined and includes new architectural treatments and revised structural details. A second-generation prototype will be built in the near future.

The following tests have been performed that reflect barrier's effectiveness and acceptability under environmental requirements:

- Noise Attenuation--A minimum sound transmission class of 25 is required, whereas the Carsonite sound barrier wall has a sound transmission of 36. The sound barrier has a noise reduction coefficient (measure of sound absorption) of 0.15, compared with 0.01 and 0.10 for concrete and wood, respectively.

- Flame Spread--The wall shows a flame spread of 20 in meeting the requirements of ASTM E-84 and a smoke density of 275. The wall is classified as a Class I Building Material suitable for indoor construction.

- Toxic Characteristic Leach Procedure (TCLP)

  - TCLP metals: All components of the wall meet regulatory requirements for presence of arsenic, barium, cadmium, chromium, lead, mercury, silver, and selenium.

  - TCLP volatiles: All components of the wall meet regulation requirements for benzene, carbon tetra chloride, chlorobenzene, chloroform, 1,2-dichloroethane, 1,1-dichloroethylene, tetrachloroethylene, trichloroethylene, vinyl chloride, and methyl ethyl ketone.

  - TCLP semi-volatiles: All components of the wall meet regulation requirements for presence of O-cresol, M-cresol, P-cresol, 1,4-dichlorobenzene, 2,4-dinitrotoluene, hexachlorobenzene, nitrobenzene, pentachlorophenol, 2,4,5-trichlorophenol, 2,4,6-trichlorophenol, hexachlorobutadiene, hexachloroethane, and pyridine.

- Reactivity, Corrosivity, and Ignitability--The wall components meet regulatory requirements.

All of these tests indicate that the components of the Carsonite sound barrier wall meet all regulatory requirements relative to EPA toxic material specifications, safety, and sound barrier effectiveness.

6.5 Future Development Needs

A first-generation prototype of the Carsonite wall has been constructed and demonstrates that the concept is feasible and practical. To refine and facilitate construction, the following activities need further research, development, and funding:

1. identify source and availability of mixing equipment for core material

2. conduct engineering analysis of different facial treatments

3. develop assembly-line techniques for mass production of wall sections

4. identify contractors throughout the United States who can act as subcontractors for preparing core material and assembling wall sections.

5. identify various combinations of scrap crumb rubber and scrap polyvinyl chloride that will function as a suitable core.

6. investigate other post and foundations designs.

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7.0 Novel Pulverization Process for Recovering Commingled Plastic Waste

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Abstract

A novel pulverization process known as solid-state shear extrusion is being investigated for recycling commingled, unsorted, post-consumer plastic waste. Polyolefins such as high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polypropylene (PP) were selected for the initial pulverization study because they are widely used in packaging and are found in significant quantities in the post-consumer waste stream. A specially designed twin-screw extruder with integrated heating and cooling is used to process commingled plastic waste.

This continuous process converts post-consumer HDPE, LDPE, and PP in chopped or shredded form to fine powders and fluff (<500 microns). The powder's particle size is controlled by changes in the screw design and process conditions. The particle shape and surface roughness are also important characteristics and are being studied with scanning electron microscopy. The powders and fluff are formed in the solid state by shear deformation under pressure, coupled with a rapid temperature change, which ruptures the chemical bonds. Because of the fine powder size, the number of broken bonds is expected to be high, and the powders consequently will be reactive. The reactivity of the powders is being studied with electron spin resonance.

This novel pulverization process should offer new opportunities for developing high value-added products from commingled plastic waste. Examples of such products include compatibilized polymer blends from traditionally incompatible polymers, block and graft copolymers, and reinforced thermosets.

7.1 Introduction

Plastics account for approximately 20% (by volume) of the municipal waste stream. Decreasing landfill space and rapidly rising disposal costs have forced many municipalities to begin curbside recycling of post-consumer waste. Because of the low quality and relatively high cost of recycled post-consumer plastics, the ability to collect and recover plastic waste has exceeded current market demands.

Most existing processes for recycling plastic waste result in products that are less valuable than the original plastic. Generally, the physical properties of recycled commingled (unsorted) plastics are inferior to the virgin materials because of chemical incompatibilities and varied colors in collected waste. The presence of fillers and other additives makes recycling mixed plastics even more difficult and more expensive. Clearly, the long-term success of recycling depends on developing innovative technology to reduce the cost and improve the quality of recycled plastics (Ehrig 1992).

7.2 Concept Description

A nonconventional pulverization process known as solid-state shear extrusion[a] is being further developed for recycling commingled post-consumer plastic waste without sortation. This work is being pursued in cooperation with Hermann Berstorff Maschinenbau GmbH.

The products of this process are plastic powders and fluff. Powdered materials are advantageous in plastics processing because they can be blended easily with other materials and additives if needed and can be used for other important applications

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(a) This process also has been investigated by Enikolopyan et al. 1988; Danielyan et al. 1987; and Akopyan et al. 1987.

such as powder coating and blow molding. Laboratory work to date has indicated that the plastic powders formed in the solid-state shear-extrusion process are somewhat reactive. This reactivity should facilitate the in-situ formation of novel compatible polymer blends (Casale and Porter 1978). This recycling technology shows potential as an alternative to current practice and could increase the use of plastic waste.

A specially designed co-rotating, twin-screw extruder with integrated heating and cooling is being used to process commingled plastic waste. This unit is shown schematically in Figure 7.1. This continuous process converts post-consumer high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polypropylene (PP) in chopped or shredded form to a controlled particle size powder or fluff, which may include fine powders (<500 microns).

The process is not limited to the plastics discussed here, but should be able to handle any plastic or mixture of plastics. This process differs from traditional extrusion in that the product is in particle form, rather than large extruded shapes or granules. These powders can be further processed by standard processing equipment.

This process should be much more energy efficient than conventional repetitive grinding because the pulverization occurs in one step. The powders are formed in the solid state by shear deformation under pressure, coupled with a rapid temperature change. When the process conditions are optimal, a spontaneous fragmentation occurs, producing particles that are smaller than any of the clearances in the extruder. This particle formation mechanism is dramatically different than the mechanisms of grinding (Enikolopyan et al. 1988; Akopyan et al. 1987).

The particle size of the produced powder and fluff is controlled by changes in the screw design and by the consideration of screw elements as well as process parameters. The formation of powder involves the rupture of chemical bonds. Because of the fine powder size, we expect that the number of broken bonds will be high, and the powders will consequently be reactive (Casale and Porter 1978). This reactivity is being investigated and could allow new polymer blends to be produced from normally incompatible plastics in the post-consumer waste stream.

7.3 Economics and Market Potential

The high cost of sorting is one of the reasons for the low success of recycled plastics in the marketplace. Collected and sorted post-consumer plastics are usually more expensive than virgin materials. The nonconventional pulverization technology

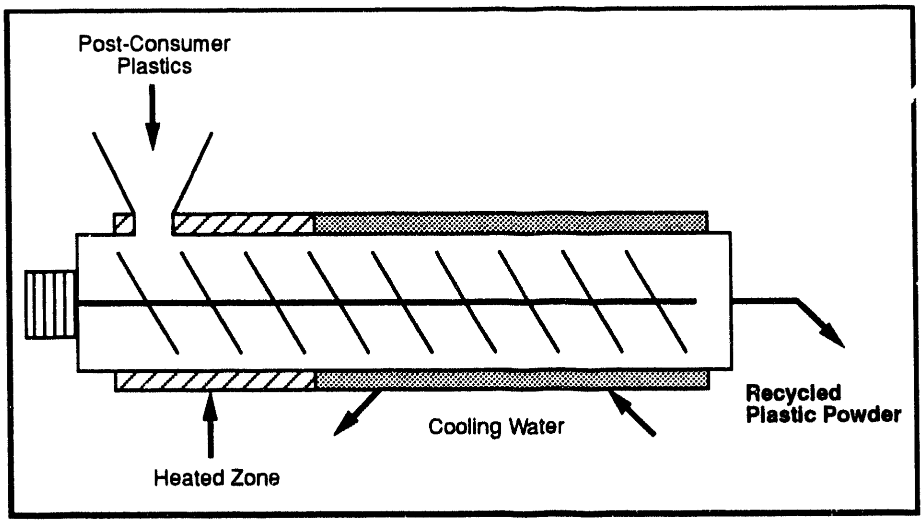

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Figure 7.1. Schematic Diagram of the Pulverization Equipment

described here has the potential to process commingled, unsorted, plastic waste, which offers a significant cost advantage over conventional technologies.

The novel pulverization process described here should offer new opportunities for developing high value-added products from commingled plastic waste. Examples of such products include compatibilized polymer blends from traditionally incompatible polymers, block and graft copolymers, and reinforced thermosets. Novel products such as these are expected to stimulate interest in recovering post-consumer waste, leading to new markets and applications.

7.4 Key Experimental Results

Initial experimental work has included pulverizing post-consumer plastics in pilot plant equipment, preparing injection-molded test specimens from the pulverized plastics and measuring key physical properties, observing the pulverized materials with optical and electron microscopy, and conducting electron spin resonance studies of reactive sites in the processed materials.

Post-consumer, mixed-color LDPE, HDPE, and PP obtained from various recyclers was processed in a pilot-plant-scale, 40-mm twin-screw extruder. Plastics were fed as individual components and as dry blends at various ratios. The final products are strongly affected by the cooling available for the extruder and by the intensity of shearing during the process. The products range from flakes (2 to 3 mm) and fluff (1 to 2 mm) to various particle-size powders.

The post-consumer plastics include various colors, but the products from this process have homogeneous, unusually light colors that are not the conventional dark shades of gray or brown seen in recycled commingled plastic products such as plastic lumber (Ehrig 1992). The homogeneous pastel color of the pulverized material demonstrates one advantage of this process as a step in plastics recycling. Products of a single, uniform color could be formed from this material, and the color could probably be adjusted by adding additional pigments if needed.

Optical microscopy using a Bausch and Lomb microscope at 7x magnification revealed that differently shaped particles are formed during the pulverization process. These particles range from fine powders to fluff of various sizes. Flakes of recycled resins (as received) have sharp, angular surfaces that result from blade-grinding processes. All pulverized materials have smooth surfaces that are suggestive of flow or solid-shearing processes. The fluff consists of fibrous, easily peeled, laminated particles. Electron microscopy is providing further information.

The melt index of polyolefins in a flake form (as received from recyclers) and pulverized materials in powdered (fluff) form were determined using an automatic Kayeness Melt Index apparatus in accordance with ASTM D1238. Procedural conditions were 150°C and 2.16 kg for LDPE and HDPE, and 230°C and 2.16 kg for PP.

LDPE (both flake and pulverized samples) were soft, indicating low-viscosity material. PP samples (both flake and pulverized samples) extruded into very thin strands. The pulverized sample of HDPE had some inclusions (probably a higher melting temperature polymer) that blocked the capillary orifice of the instrument, preventing extrusion of this sample. Flakes of HDPE had even larger inclusions of unmelted particles, which also blocked the capillary. Results for as-received post-consumer plastic flakes and for pulverized material are shown in Table 7.1.

Test specimens were prepared from mixed-color, post-consumer plastic flakes as-received from recyclers, and from pulverized post-consumer material, by injection molding. A 4-cavity MUD(a) family mold was used with a 1-ounce Battenfeld injection-molding machine. Specimens had the standard ASTM "dog bone" shape, about 5 in. long and 0.125 in. thick.

Izod bars (2.5 in. long, 0.5 in. wide, 0.125 in. thick) and 5-in. heat distortion temperature bars were also molded. Plastics used for injection molding are listed in Table 7.2, along with the results of key mechanical property measurements.

(a) MUD = Master Unit Die.

Table 7.1. Melt Index of Recycled Plastics Before and After Pulverization

Material	Melt Flow (grams/ 10 min)	Condition
Low-density polyethylene (LDPE)		
LDPE flake (as received)	55.2	150°C/2.16 kg
Pulverized LDPE	57.3	150°C/2.16 kg
Polypropylene (PP)		
PP flake, as received	28.0	230°C/2.16 kg
Pulverized PP	26.4	230°C/2.16 kg

The color of specimens prepared from the as-received flakes displayed the marble effect, with light and dark swirl patterns. In all cases, the molded specimens prepared from pulverized material had an extremely uniform color that was slightly darker than those prepared from the post-consumer flakes. The surfaces of all injection-molded samples were very smooth and shiny. It is important to note that even though the polyolefins studied here are mutually incompatible, the three-component HDPE/LDPE/PP blends and mixtures were successfully injection-molded, and that they did not show delamination upon breaking.

The injection-molded specimens were used in the indicated ASTM tests of tensile strength and elongation (D638), notched Izod impact strength (D256) and Shore D hardness (D2240). Heat distortion temperature measurements (D648) are in progress. Tensile strengths are reported at yield, or break before yield. Tensile strengths were measured with an Instron tester (crosshead speed = 2 in./min, gauge length = 2.25 in., strain rate = 0.9 in./in.-min). Elongations are reported at the breaking point. Results are shown in Tables 7.2 and 7.3.

During tensile tests, the cross-sectional failure surfaces of tested specimens had visible impurities that probably caused the specimens to fail prematurely. That explains the high standard deviation of elongation measurements on specimens made from PP in flake (value of 157) and from LDPE in flake and pulverized form (values of 29 and 39, respectively). PP samples also had a "skin" effect that was exhibited during tensile testing as a core pulling out of a thin surface skin.

Table 7.2. Tensile Strength and Elongation of Post-Consumer Plastics

Material	Tensile Strength (psi)	Standard Deviation	Elongation (%)	Standard Deviation
HDPE flake, as received	3240	166	12	3
HDPE-pulverized	2870	110	7.5	0.9
LDPE flake, as received	1980	129	33	29
LDPE-pulverized	2060	23	60	39
PP flake, as received	4840	92	330	157
PP-pulverized	4730	17	100	41
HDPE/LDPE/PP 60/30/10 dry blend of as-received flake	2680	57	9	0.8
HDPE/LDPE/PP pulverized 60/30/10 blend	2970	152	9	1.7

Table 7.3. Impact Strength and Hardness of Post-Consumer Plastics

Material	Notched Izod Impact Strength (ft-lbs/in.)	Standard Deviation	Hardness (Shore D)
HDPE flake, as received	1.0	0.04	63
HDPE-pulverized	1.0	0.03	63
HDPE flake, as received	1.3	0.06	56
LDPE-pulverized	1.3	0.10	57
PP flake, as received	1.3	0.05	72
PP-pulverized	1.3	0.09	72
HDPE/LDPE/PP 60/30/10 dry blend of as-received flake	0.9	0.04	62
HDPE/LDPE/PP pulverized 60/30/10 blend	0.9	0.03	64

Electron spin resonance (ESR) is a good technique for studying broken chemical bonds (radicals) (Klopffer 1984; Schnabel 1981). However, because the radicals are very reactive, samples for ESR study must be handled carefully to prevent the radicals from reacting with each other, with oxygen, or with atmospheric moisture. We used a special technique to obtain samples from the pulverization process for ESR study.

To facilitate reactivity studies of the as-produced pulverized material, small samples (2 to 3 grams) of the powder exiting the screw were collected in a pan filled with 2 to 3 cm of liquid nitrogen. The hot powder was rapidly cooled by the liquid nitrogen, preventing reactions with oxygen and suppressing reactions between polymer radicals. The powder was transferred to a 2 ml cryogenic vial while still immersed in liquid nitrogen. Samples were kept at liquid nitrogen temperature for storage and transport in a liquid nitrogen vapor shipper (Minnesota Valley Engineering SC4/2V). The cryogenic hardware is standard equipment for storing and shipping biological materials.

Samples were loaded into quartz tubes under liquid nitrogen for ESR measurements. ESR spectra were acquired at liquid nitrogen temperature (-196°C) on a custom-modified continuous wave spectrometer operating in the X-band (microwave frequency near 9 GHz).

Our initial studies of pulverized LDPE prove that reactive sites (ruptured bonds) are formed during processing. Figure 7.2 shows ESR spectra for samples of LDPE before and after pulverization. The "before" sample was acquired so that its spectrum is enlarged 3.2 times relative to the spectrum of the "after" sample. The appearance of a large, well-defined signal demonstrates that the process described here produces plastic powder by rupturing polymer molecules.

The data shown in Figure 7.3 demonstrate that the reactive sites formed by polymer bond rupture are slowly lost during exposure to ambient conditions. The top spectrum represents LDPE powder immediately after pulverization, and the bottom spectrum (enlarged 25 times) represents the same sample after three days of air exposure at room temperature. The ESR signal, although still observable, is nearly zero after this ambient exposure, indicating that the maximum lifetime we can expect for these reactive sites is one or two days. Note that these spectra represent the total number of broken bonds in the samples and should be

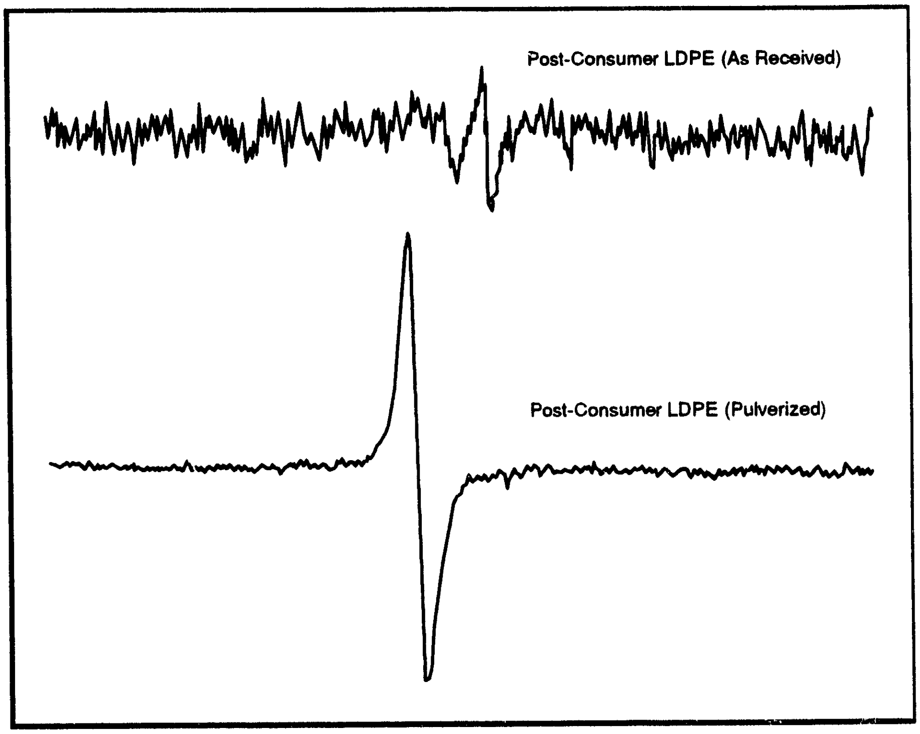

Figure 7.2. ESR Spectra of Post-Consumer LDPE Before (top) and After (bottom) Pulverization

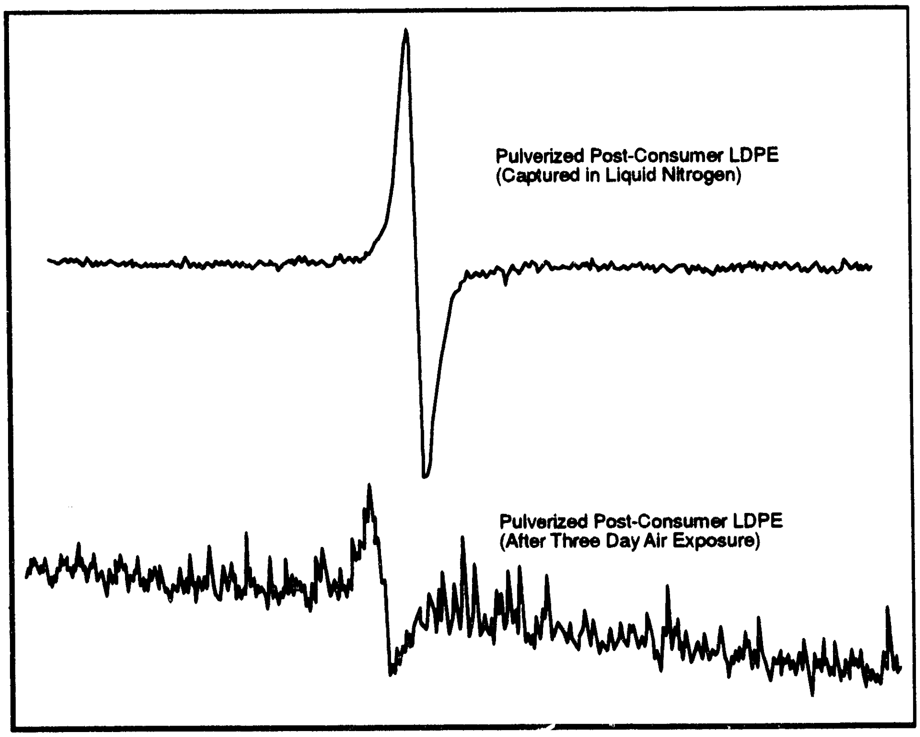

Figure 7.3. ESR Spectra of Samples of Pulverized, Post-Consumer LDPE Before (top) and After (bottom) Exposure to Ambient Air for Three Days

normalized by the sample mass to obtain truly quantitative information.

These preliminary results provide good support for developing polymer blends by in-situ compatibilization of dissimilar plastics. Reactive sites are formed during processing, and the sites have lifetimes that can be conservatively estimated as several hours at ambient conditions.

7.5 Future Development Needs

Further development of the pulverization process is proceeding simultaneously on manufacturing and bench-scales. Additional bench-scale experiments are needed to determine parameters for optimizing process design and operation. Pulverization trials currently are being performed at the equipment manufacturer's site (Berstorff Corporation, Charlotte, NC). Additional manufacturing-scale work would be facilitated by acquiring an extruder for our laboratory. Because the physical structure and composition of the powders/fluff produced in this process are unique, applying the powders in conventional and novel plastics processing operations also needs to be studied.

The current version of the pilot-scale pulverization extruder is based on a commercially available co-rotating, twin-screw extruder with integrated heating and cooling that has been redesigned for this process. Further development of the concept is expected to lead to the design of equipment that is optimized for this process, which would facilitate recycling.

Better understanding of the relationships among the processing parameters of the pulverization process, the particle size of the resultant powders, and the degree of reactivity of the powders will guide further development of this concept. Because the chemistry of the commingled plastics pulverization process is not yet understood, further reactivity studies need to be conducted. The work should also be extended to consider other plastics used for packaging such as polyethylene terephthalate, polystyrene, and polyvinylchloride.

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