# Recycling of Plastics

    **Recycling** refers to the reprocessing and refabrication of a material that has been used and discarded by a consumer and that otherwise would be destined for disposal as solid waste. This type of recycle is called **postconsumer recycle (PCR)**, as opposed to recycle that is created as a normal part of the scrap from a manufacturing process (generally called **regrind** or **plant recycle**). Regrind that is consumed (reused) within a manufacturing process is not part of the solid waste problem. Regrind that is not used within the plant becomes part of the waste stream and must, therefore, be considered in this discussion.

    The reprocessing and refabrication of recycle materials, both PCR and plant recycle, into useful products requires several steps: collection, handling/sorting, reclamation/cleaning, and end-use fabrication. Each of these steps is costly and so recycling is not as inherently inviting, either economically or from an environmental impact viewpoint, as is source reduction. Still, even with tremendous steps being taken in source reduction, materials will continue to be discarded and recycling will continue to be important as a means of reducing the amount of material in landfills and other waste streams.

    The amounts of all materials being recycled continue to increase. In the United States, 24% of all waste was recycled in 1990, up 10% in just five years and has grown to even more today. Some materials, like aluminum soda cans, have been recycled for many years and a high percentage (over 50%) of the total are recycled. Paper, glass, and plastics, too, are beginning to be recycled more extensively. Reasonable estimates are that between 8% and 17% of plastic products are recycled. Plastics recycling principally involves two products- PET soda bottles and HOPE milk jugs. These two products represent 26% of all waste packaging and (since packaging is 30% of all waste) they are approximately 8% of the total waste stream. Because PET and HOPE bottles are as convenient to recycle as aluminum cans, their recycle percentages of total production, 57% of HOPE bottles and 31% of PET bottles, already approach those of aluminum cans.

    Legislation in some countries, especially in Europe, has mandated near complete recycling of all materials, including plastics. Therefore, significant efforts are underway to accomplish total recycling. For instance, the European Council of Vinyl Manufacturers has set the year 2010 as the date for full recycling of vinyl-containing products.

## 23.3.1. Collection

    The favorable recycling percentages for aluminum cans, HOPE jugs, and PET soda bottles suggest that consumer convenience is an important part of recycling success. These plastics products are easy for the consumer to identify and place in separate recycling bins provided by the waste collector or to save in their own bin and take to a recycling center. In general, voluntary recycling by the consumer has proven to be the most important single factor in improving recycling of all materials.

    An incentive for consumer collection, sorting, and conveyance to a recycling center is the fee paid by aluminum companies when they buy back the cans. This fee is economically justified because of the high cost (especially the high energy requirement) of producing new aluminum (from ore) versus the cost of reprocessing aluminum scrap. For many plastics, the cost of the virgin plastic material is about the same as the costs involved in recycling and so little or no fee can be economically justified for buying scrap plastics. One exception is PET soda bottles. The costs of collecting and bulk bundling PET is estimated to be 7 cents/pound and the cost of reprocessing PET into a clean and usable resin form is about 30 cents/pound, for a total recycling cost of 37 cents/pound. New resin is approximately 55 cents/pound, giving a recycling advantage of 18 cents/pound.

    Municipalities have realized that recycling economics are not as favorable for plastics as for aluminum and so many municipalities have imposed a fee on the consumer (typically about 7¢ in the United States) that can be claimed when the plastic bottle is returned. This fee is intended to give the consumer an incentive to collect and convey PET bottles to recycling centers. The fee can be used to offset some of the costs of recycling. In some locations, machines accept the recycled plastic products (usually bottles) and pay the consumer the fee. Generally, however, consumers do not sort their solid wastes but rather mix all materials together. This means that municipalities must handle and sort the products if recycling is to be done. Some municipalities have mandated that consumers sort their solid wastes by type of material, such as metals, plastics, newspapers, glass, and mixed. These are either picked up on separate collection runs or picked up in separate bins and kept separated in the collection trucks. The costs of separate collections are considerably higher than those of traditional mixed collections.

## 23.3.2. Handling/Sorting

    All recycled materials must be handled. Sometimes the handling involves simply conveying the materials from the pickup point (usually the consumer's house or job location, but occasionally the recycle center) to the reclamation facility. If economical recycling is to be done, some sorting of the materials is also necessary. The maximum economic benefit is obtained when each recycled material is sorted by specific product typealuminum cans, PET soda bottles, HOPE milk jugs, and so on. In some cases, slightly less restrictive separations are also economically viable. Some broader groupings are all aluminum alloys, all PET bottles and other PET waste, and all HOPE waste. Even broader material groupings (such as all metals, all plastics, and so on) usually require further separations in order to be viable. One exception is the case when all plastic parts are grouped. Under certain conditions, these collections of several types of plastics can be recycled. The mixture of several plastic types is called **mixed recycle** or **commingled recycle**.

    The handling and sorting steps in the recycling process can be relatively simple or relatively difficult and costly, depending on the degree of consumer participation and the level of sorting required. If consumers carefully sort the recyclables by specific product type (aluminum cans, PET bottles, HOPE milk jugs, newspapers, and so on) and convey them to the recycling center, then the handling consists simply of bundling the products into some convenient shipping form (such as crushing the bottles and pressing them together into a bale) and then conveying the materials to the reclamation location. However, if the materials must be separated from a general waste stream as would be the case if consumers did no sorting, considerable labor is required to pick out the recyclables by hand. Even if consumers have separated the materials into general material groups (such as metals, plastics, and paper products), some additional sorting at the collection point is usually required. For the highest economic benefit, the aluminum must be separated from the iron and steel, the HOPE and PET and other recyclable plastics must be separated from the plastics that are not to be recycled, and so on.

    In the case of metals, some separation by metal family can be done by machine because iron and steel are magnetic. Aluminum cannot readily be separated from other metals such as zinc and brass, but generally at this stage, aluminum cans simply are separated by sight and the rest of the metal is sent to a metal reclaimer. Some sorting of plastics can also be done by machine. These machines rely on inherent characteristics of the various plastic resins that distinguish one resin from the others. For instance, the light absorption of a resin (at some frequency band) can be used because each resin type has a different absorption pattern. A machine has been developed that shines light (IR, visible, UV, and so on) through the plastics and detects the pattern of light absorbed (or transmitted). This detection then triggers a separation mechanism to route the plastic part in a particular direction along the conveying system according to the detected pattern. This process has been demonstrated in test runs but is not as yet widely used.

    The most widely used method of sorting plastics is by sight. Some plastic products, such as PET soda bottles and HOPE jugs, are easy to identify. Others, however, are much more difficult to distinguish, especially when they are not easily identified by shape. To assist both consumers and sorters at the collection facility, a system was developed by the Society for the Plastic Industry (SPI) for identifying the resin type or family. A number and a recycling symbol have been assigned to each of the major resin types and that number is molded onto each plastic product (usually on the bottom). The major resin types and their numbers are given in Table 23.1. For instance, PET soda bottles and other PET waste is abbreviated PETE and given the number 1. HOPE is number 2, and polyvinyl chloride is number 3 (V). (PETE's used instead of PET and Vis used instead of PVC because of possible trademark infringements if the more common abbreviations were used.)

    Even with the several special categories for the most common plastics, many plastic types are assigned to the "other” category (7). These "other" products present special processing problems and must be handled as commingled recycle. Plastics That are unknown or that have several different types of plastic in them are classed as "other." The large number of plastics that fall into this "other" category is a problem in the economics of recycling.

    The many coextruded plastics and multilayered plastics are all "other." Sometimes these multilayered materials are needed for proper product performance. For instance, small lunch box drink boxes are made of six layers, each with a particular purpose. The outer layer is polyethylene, which serves as a water-resistant coating to keep the package dry and structurally sound. The second layer is paper, which provides stiffness, strength, and shape. The third layer is polyethylene, which bonds the second and fourth layers together. The fourth layer is aluminum foil, which forms a barrier against light and oxygen and prevents spoilage or taste change. The fifth layer is another polyethylene adhesive. The sixth layer is a polyethylene film, which provides an inert food contact surface that prevents spoilage, contamination, or leakage.

    We can see, therefore, that some plastics are easy to sort by shape, number, or physical characteristic and can be re-formed into the original application, just as is done with aluminum cans. The relatively pure (one type of plastic resin) materials can also be used to make products that are not the same as the original but are nevertheless quite valuable.

**Table 23.1 Numbering System for Plastics Recycling**

    For instance, PET soda bottles can be recycled into fibers, strapping, and reinforcement for concrete; HDPE milk bottles can be recycled into flower pots, pipe, toys, trash cans, soft­ drink-bottle carriers, pails, and drums; and vinyl can be recycled into drainpipe, vinyl floor tile, outdoor furniture, and truck bed liners.

## 23.3.3. Reclamation/Cleaning

    After the recycle materials have been sorted, they must be chopped or shredded so that they can be further processed. The plastic materials are usually chopped into small flakes about the size of a fingernail. These flakes are then treated with solvents and washed to remove any residual contaminants (such as the original contents and paper labels). The mixed or commingled recycle materials are usually sent to the fabricators as cleaned flakes. The carefully sorted recycle materials are often extruded into pellets so that the refabricator will be able to use the traditional processing equipment for making the finished parts.

    quipment for making the finished parts. A final separation step is sometimes done with well-sorted flakes. After the flakes have been cleaned, they are introduced into a water bath. The flakes that have a density lower than water (chiefly polyolefins) float, whereas the heavier plastics sink. This method is used to separate PET bottles from the HDPE bottom caps used by some molders to give the soda bottles a stronger and more stable bottom. The HDPE has a specific gravity of about 0.96 and so it floats after agitation. The PET has a specific gravity of about 1.2 and so it sinks.

## 23.3.4. End Uses–Sorted PCR

    The ideal use for recycled material is the same as the original use or some other high-value application. For many plastics that have been carefully sorted, reuse in the original application is perfectly acceptable. Examples include recycled LDPE for new bags and films, recycled PS in insulation and delicate instrument packaging, PP in auto parts and industrial fibers, and vinyl in detergent bottles and pipe. These examples are just a few of the hundreds of products that are and will be made from recycled materials that are re-formed into their original uses. Because thermoplastic materials can generally be reheated and re­processed many times without significant degradation, reusing these materials in almost any application is possible.

    For most plastic resins, however, some minor changes in resin properties are to be expected after the plastic has been reprocessed. A typical change is a reduction in molecular weight with an accompanying drop in resin melt viscosity and an increase in the melt index. However, these changes are minor and probably reflect random molecular scission rather than a widespread phenomenon throughout the melt. This conclusion arises from the apparent retention of many physical and mechanical properties, such as yield strength and elongation.

    Some fabricators of products made from postconsumer recycled have noted that the small changes in molecular weight and other properties cause processing difficulties. Finely tuned injection molding operations find that the optimum cycles are altered and sometimes the filling of the mold is much more difficult. Rotational molders also have found that post-consumer recycled can alter their cycles and cause disruption in the uniformity of their products. Blow molders have generally found fewer problems in their processing but have found some limitations on the use of PCR. These molders are able to use PCR by blending it with virgin material. Blend ratios of 20% PCR are typical, although some have found that up to 50% PCR can be used without significant change in processing or product performance.

    However, recyclers and molder of PCR plastics are reluctant to reuse the recycled materials in medical and food-contacting applications because of the danger of contamination and disease. Therefore, PET from soda bottles typically is not reused in bottles but is made into non-food-contacting applications such as carpets, textile fibers, and fiberfill for sleeping bags and winter coats. HOPE from milk jugs is reused in nonfood applications such as motor oil bottles, recycling bins, trash carts, and laundry soap packages. A perhaps unexpected benefit of recycling plastics was recently encountered when the cotton harvest in India was severely and adversely affected by a drought. The yields of the cotton were so low that the textile mills in India were not able to buy enough fiber to meet their orders. The mills were contemplating closing prematurely because of the lack of raw material. This would have been devastating to the economies of the regions where the mills were located, not only for the mill employees who were laid off but also the many people in downstream jobs in clothing manufacturing plants and in support companies. The mills investigated converting over to using blended fiber, that is, part cotton and part synthetic (probably polyester) but the price of the polyester (PET) was too high. However, after some investigation and trials, it was found that recycled soda bottles could be reprocessed into polyester fibers that had adequate strength and other properties for blending with the cot­ ton. Hence, the Indian fabric mills began to buy recycled soda bottles and convert them into fibers. The plan worked very well, although it should be mentioned that after many of the mills began to buy the recycled soda bottles, the price of the recycle increased and the benefit of using recycled PET resin rather than virgin gradually diminished. This shortage probably reflected the poor system for recycling that currently exists in the world.

## 23.3.5. End Uses–Commingled PCR

    This category of materials includes all of the plastic materials that are normally included in the "other" category in the recycling separation system. These "other" plastics include several types that should be considered separately: thermoplastic materials that cannot be separated into a single resin type or family, thermoset materials, and composite materials. The commingled category also includes mixtures of plastics that cannot be economically separated.

    Thermoplastic materials are the most abundant of the three "other" types. There has been some success in recycling these materials, but they cannot be recycled back into their original products because they usually come from many different products. Moreover, they cannot be processed as a single material because a single batch of commingled materials likely contains materials with varying melting points and processing characteristics. Therefore, different processing methods are needed for commingled materials. New products are also required.

    The value of products made with commingled recycle will undoubtedly be less than the value of the original products made with virgin materials. The economic focus should therefore shift to a comparison with products made from nonplastic sources. The objective should be to find applications and value where products made of generic plastics materials have inherent advantages over other materials. Several of these types of products have been identified.

    The most common product made from commingled PCR is plastic wood. Plastic wood has its highest value in applications where natural wood rapidly decays or rots. Such uses are high maintenance and would, therefore, justify a higher price for plastic if the maintenance were eliminated. Another advantage of plastic wood is that it doesn't need to be treated with the highly toxic antifungal and anti-rot additives that must be pressurized into natural wood to allow it to be used in the high rot- and degradation-sensitive applications. Wood docks and pilings are submerged in seawater and have high maintenance problems, so they are prime target markets for plastic wood. Other applications include park benches and tables, signposts, playground equipment, and landscape timbers when weathering is a problem, especially when access is difficult. Some manufacturers have had success in making home fences of plastic wood simply because of the consumer's desire for low maintenance. Plastic wood splinters less than natural wood and is therefore valuable as a decking material and has shown promise in playground equipment and reusable pallets.

    Plastic wood is generally produced by pressing commingled flakes together at a temperature sufficient to melt the majority of the flakes. These flakes then bind the nonmelted flakes together. Color additives mask the multicolored appearance of most commingled PCR. The process can be designed like ram extrusion, which is inexpensive and well suited to making single parts that do not have to be melted together (as would be the case if they were extruded). Alternatively, an adiabatic (low thermal input and high mechanical heating) extruder with little filtration and a very wide die orifice can be used to melt most of the plastic and form it into wood-shaped pieces.

    Plastic wood is not without its problems, however. The dissimilar hygroscopic characteristics of some components (for instance, nylon versus PE) cause differential water absorption and dimensional changes. This problem can be reduced by controlling the source streams and ensuring that highly hygroscopic materials are not mixed with hydrophobic materials. Plastic lumber falls short as a structural material compared to natural wood. This can be designed around by using thicker and heavier plastic wood beams or by placing some natural wood in critical load-bearing locations.

    The most important drawback to plastic wood is its higher cost (about 20%) compared to untreated lumber. Therefore, its major uses continue to be in applications where treated lumber would be used, especially those in which an additional cost for maintenance would be high. Some researchers have demonstrated that a woodlice product can be created by combining commingled PCR with waste wood fibers. The materials are mixed in a twin-screw extruder (wide clearance) and then formed by a die. Another technique for avoiding the processing problems with commingled PCR is to shear chopped commingled plastics in very-high-intensity mixers. Processors have found that the resulting heated mass can then be compression molded into a wide variety of products.

    Mixed recycle material has also been used for applications where the principal value is the lighter weight of the plastic versus a traditional product. One example is parking stops, which typically are made of concrete. These products are used simply to take up space and so almost any material that can withstand the environment will work. These applications are the lowest valued and should be pursued only to use excess capacity in the recycling operations.

    Thermoset materials can also be part of the "other" category in the plastics recycling system. Most people consider thermosets to be nonrecyclable because they cannot be remelted and therefore cannot be re-formed into their original product. However, as already discussed, many materials are recycled into products other than their original ones; moreover, some are recycled without ever being melted. The possibility exists, therefore, for recycling thermoset plastics.

    This type of recycling has been demonstrated using several different types of thermoset materials. The thermosets are ground into powders and then used as fillers in other products. For instance, ground rubber tires are used successfully in polyolefin blends and crosslinked PE is used with virgin HOPE to make tote bins, wheels for carts, trays, and pallets. The mechanical properties of the products with thermoset fillers are only slightly less than or superior to the properties of virgin materials. These results indicate that the thermoset particles bond with the virgins to create a stronger material than would have been created if nonplastic fillers had been used. Alternatively, in some cases the filler adds toughness or some other beneficial property to the virgin material.

    Composite materials can also be recycled even though composites are often made from a thermoset resin and have the added complication of a reinforcing material. However, parts made from sheet molding compound (SMC) and bulk molding compound (BMC), which a made of thermoset polyester with glass reinforcement and inorganic fillers, have been recycled by grinding the parts and then using the resultant granules as fillers in other SMC/BMC mixes or in polyolefin molding compounds. The presence of the reinforcement does not seem to present any special problems, except that the grinding of the cured material is somewhat more difficult than would be the case with nonreinforced thermosets.

    The properties of the filled parts are generally the same as the conventional molding compound, provided the amount of recycle is 20% or less. Problems that have not as yet been fully resolved include processing materials with paint or adhesive contaminants, control of moisture in the granular material, segregation of various SMC/BMC formulations to provide material consistency, and development of viable SMC/BMC collection and recycled product marketing scenarios.

    Other composite products, such as advanced composites and nonpolyester glass­ reinforced plastics, are recycled by grinding the composites and then using the granules in molding compounds. These molding compounds are processed by compression molding and by injection molding.

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