Aggregates from Natural and Recycled Sources

Economic Assessments for Construction Applications—A Materials Flow Analysis

By David R. Wilburn and Thomas G. Goonan

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ABSTRACT

Increased amounts of recycled materials are being used to supplement natural aggregates (derived from crushed stone, sand and gravel) in road construction. An understanding of the economics and factors affecting the level of aggregates recycling is useful in estimating the potential for recycling and in assessing the total supply picture of aggregates. This investigation includes a descriptive analysis of the supply sources, technology, costs, incentives, deterrents, and market relationships associated with the production of aggregates. Results derived from cash flow analyses indicate that under certain conditions aggregates derived from construction and demolition debris or reclaimed asphalt pavement can economically meet the needs of certain markets, but this material can only supplement the use of natural aggregates in construction applications because the available supply is much less than total demand for aggregates. Producers of natural aggregates benefit from their ability to sell a wide, higher valued range of aggregate products and will continue to dominate high-end product applications such as portland cement concrete and top-course asphalt.

Although recycled aggregates can be used in a variety of road construction applications, product variability and strength characteristics usually limit their use to road base, backfill, and asphalt pavement. Quality of the products containing recycled material is often source dependent, and indiscriminant blending may lead to inferior performance. Careful feed monitoring, testing, and marketing can broaden the use of recycled aggregates into other applications.

Aggregates recycling is most likely to be successful where transportation dynamics, disposal and tipping fee structures, resource supply/product markets, and municipal support are favorable. Recycling operations often must overcome risks associated with feed and product availability, pricing, and quality.

Costs for three representative operations of different sizes were modeled in this study. Under study conditions, all were found to be profitable and highly dependent upon local tipping fees and market prices, which can vary significantly by location. Smaller operations were found to have different operational dynamics, often requiring creative marketing or incentives to maintain profitability.

Nationally, consumption of recycled aggregates from crushed concrete increased 170 percent between 1994 and 1996, but constituted less than 0.4 percent of total aggregates consumed in 1995. The supply of construction debris is regional, and is determined by local infrastructure decay and replacement rates. Aggregate recycling rates are greatest in urban areas where replacement of infrastructure is occurring, natural aggregate resources are limited, disposal costs are high, or strict environmental regulations prevent disposal. Consumption is expected to grow as construction contractors recycle as a means of saving on transportation, disposal, and new material costs and natural aggregate producers include recycled material as part of their product mix in order to prolong the life of their reserves and improve product revenues. In some locations, the amount of material available for recycling is insufficient to meet present industry demand. The use of recycled aggregates should be evaluated locally based upon relative cost, quality, and market factors. Policy makers often must weigh the potential benefits of recycling with competing land use, development issues, and economic and societal pressures.

EXECUTIVE SUMMARY

Much of our Nation’s infrastructure (roads, buildings, and bridges) built during the middle twentieth century is in need of repair or replacement. A large volume of cement- and asphalt-concrete aggregates will be required to rebuild this infrastructure and support new construction. Use of construction and demolition debris and reclaimed asphalt pavement as sources of aggregates is increasing. *What are the factors that influence the aggregates recycling industry? How much does it cost to produce recycled aggregates? What are the incentives and deterrents for recycling? Where is the niche for recycled aggregates?* These are some of the questions addressed in this study.

What are the factors that influence the aggregates recycling industry?

Urbanization has generated a high demand for construction aggregates and increased quantities of construction debris that may provide an additional source for aggregates. Recycling is impacted by local and regional conditions and market specifications. Relative transportation distances and costs among construction and demolition sites, recyclers, competing natural aggregate producers, local landfills, and markets influence how much material is available for recycling and set local pricing and fee structures. Plant location, design, and efficiency can have significant impact on economic performance. The quantity, consistency, quality of feed material and a skilled labor force also affect plant efficiency and market options available to the recycler. Costs associated with equipment, labor, and overhead are important to operational economics, but revenues generated by product pricing and tipping fees are even more significant. There will continue to be opportunities for new entrants, but adding new recycling capacity to a market with limited resources impacts the profitability of all participants.

How much does it cost to produce recycled aggregates?

Entry into the aggregates recycling business requires a capital investment of $4 to $8 per metric ton of annual capacity, a cost that is most significant for a small producer because of economies of scale. Processing costs for the aggregates recycler range from about $2.50 to $6 per metric ton. Operating rate and revenues generated from tipping charges and product prices are the most important factors affecting profitability, but can vary considerably by operation and region. Transportation costs associated with feedstock acquisition, while significant to regional dynamics of the industry, were assumed to indirectly affect profitability of a recycler, because such costs are typically incurred by a construction contractor that supplies material rather than the recycler, which processes that material.

Cash flow analyses indicate that all operations except the small recycler could achieve at least a 12 percent rate of return on total investment. Most larger recyclers are more profitable under study conditions because of economies of scale. Recycling operations benefit from tipping fee revenues and relatively low net production costs. Where market forces permit, smaller recyclers can, for example, increase their economic viability by increasing tipping fees or charging higher product prices, or by positioning themselves to gain transportation cost advantages over competitors, acting as subcontractors, operating ad-hoc supplementary businesses, or receiving government subsidies or recycling mandates. Economic benefits for a natural aggregates producer to begin recycling are substantial.

What are the incentives and deterrents for recycling?

The success of aggregates recycling varies by region and municipality. Recycling may reduce the amount of construction debris disposed of in landfills, may reduce the rate of natural resource depletion and environmental disturbance, and has the potential to provide energy and cost savings. Mobile, job-site recycling is becoming common for larger construction projects as a means of avoiding high transportation, disposal, and new material costs. Successful operations must have a favorable transportation and tipping fee structure when compared to alternatives. An abundant local supply and varied markets make it easy and financially attractive for the supplier and construction contractor, and can provide an increase in economic activity to the local community.

A recycling operation may not be the most appropriate alternative in all situations. Without proper site design and layout, equipment and operator efficiency, and creative marketing, many recycling operations could easily fail. An abundant supply of consistent feed material is essential. High capital requirements, inadequate public support, and quality problems or perceptions can also make it difficult for a recycler to compete effectively. Recyclers often have little control over product demand and pricing, which are influenced by the amount of natural aggregates locally available.

Where is the niche for recycled aggregates?

Natural aggregate producers benefit from their ability to sell a wide, higher valued range of aggregate products and will continue to dominate high-end product applications such as portland cement concrete and top-course asphalt. Presently the recycling rate for asphalt pavement is approximately 85 percent. Recycled aggregates are, however, increasingly being used to supplement natural aggregates in road construction in a variety of applications; 44 States allow their use in road base applications, 15 States for backfill, 8 States for portland cement mix, and 7 States for top-course asphalt and selected other applications. Recycled aggregates are commonly used in lower quality product applications such as road base, where recycled aggregates meet or exceed State specifications. This material is presently often not considered acceptable for higher quality product applications such as high-strength concrete because of performance considerations and perception of some decision makers.

Aggregate recycling rates are greatest in urban areas where replacement of infrastructure is occurring, natural aggregate resources are limited, disposal costs are high, or strict environmental regulations prevent disposal. Consumption is expected to grow as construction contractors recycle as a means of saving on transportation, disposal, and new material costs and aggregate producers include recycled material in order to prolong the life of their reserves and improve product mix. In some locations, the amount of material available for recycling is insufficient to meet present industry demand. Although recycled aggregates are a supplement or substitution for natural aggregates in selected road applications, their use should be evaluated locally based upon relative cost, quality, and market factors. Policy makers often must weigh the potential benefits of recycling with competing land use, development issues, and societal pressures.

This study is intended to provide insights for resource decision making and provide a framework for future studies on construction materials, a vital sector in the U.S. economy. Further research is needed to improve quality or expand markets of recycled aggregates, but limits to locally available construction debris could restrict significant growth in the use of recycled aggregates in construction. Additional work is also needed to determine local future supply of such material. Improved technology in combination with expanded education, specification changes, or legislative mandates could make the use of recycled aggregates a more attractive option and broaden product markets.

INTRODUCTION

Since the beginning of the twentieth century, our Nation's infrastructure has grown tremendously. Much of the core infrastructure, including roads, bridges, water systems, and sewers, was put in place during the first half of this century. The Interstate Highway System was constructed during the 1950's, 1960's, and 1970's. Much of this infrastructure has now deteriorated to a point that extensive repair or replacement is required. In areas of rapid population growth, new infrastructure is necessary to meet growing needs.

Construction materials in general, and aggregates in particular, are important components of infrastructure. Development and extraction of natural aggregate resources (primarily crushed stone and sand and gravel) are increasingly being constrained by urbanization, zoning regulations, increased costs, and environmental concerns, while use of recycled materials from roads and buildings is growing as a supplement to natural aggregates in road construction. Recycling represents one way to convert a waste product into a resource. It has the potential to (1) extend the life of natural resources by supplementing resource supply, (2) reduce environmental disturbance around construction sites, and (3) enhance sustainable development of our natural resources.

This study was undertaken to provide an understanding of the options for aggregates supply in construction. Technical and economic information on the aggregates recycling industry is developed in order to analyze the factors influencing aggregates recycling, determine why recycling is occurring, and assess the effects of recycling on the natural aggregates industry. Although data on aggregates recycling are available, no concise data source exists for this important emerging industry. A discussion of the technological, social, and economic factors influencing this industry is intended to provide background information for informed decisions by those interacting with this industry (operators, suppliers, consumers, or regulators), and for those interested in developing sustainable U.S. natural resource and land-use planning and policies.

Related work currently being conducted by the U.S. Geological Survey (USGS) includes the *Aggregates Automation* conference, the *Construction Debris Recycling* conference, *Construction Materials Flow* studies, the *Mid-Atlantic Geology and Infrastructure Case Study*, *Infrastructure* project studies, and the *Front Range Corridor Initiative*. For information on any of these projects access the World Wide Web (WWW) at:

http://minerals.er.usgs.gov/minerals/pubs/commodity/aggregates

or direct inquiries to the Minerals Information Team, 983 National Center, U.S. Geological Survey, Reston, VA 20192; telephone 703-648-6941.

Information for this study was gathered from a variety of published sources, site visits, and personal contacts. Cost data were developed from representative industry data. Appreciation is conveyed to Russel Hawkins of Allied Recycled Aggregates, Larry Horwedel of Excel Recycling & Manufacturing, Inc., William Langer, USGS, and Gregory Norris of Sylvatica Inc. for their contributions of data and technical reviews of this paper.

Specific cost assumptions are documented. Costs and prices for the Denver, Colo., metropolitan area were used in some cases to represent the industry. Although costs and prices in other regions of the country may differ from those assumed in this study, inferences using values different from those used in this study are presented.

STRUCTURE OF THE AGGREGATES INDUSTRY

Aggregates are defined in this study as materials, either natural or manufactured, that are either crushed and combined with a binding agent to form bituminous or cement concrete, or treated alone to form products such as railroad ballast, filter beds, or fluxed material (Langer, 1988). The most common forms of concrete are prepared using portland cement and asphalt as binding agents. About 87 percent of portland cement concrete and about 95 percent of asphaltic concrete are composed of aggregates (Herrick, 1994).

Figure 1 illustrates a generalized version of the flow of aggregate materials in construction. Most natural aggregates are derived from crushed stone and sand and gravel,

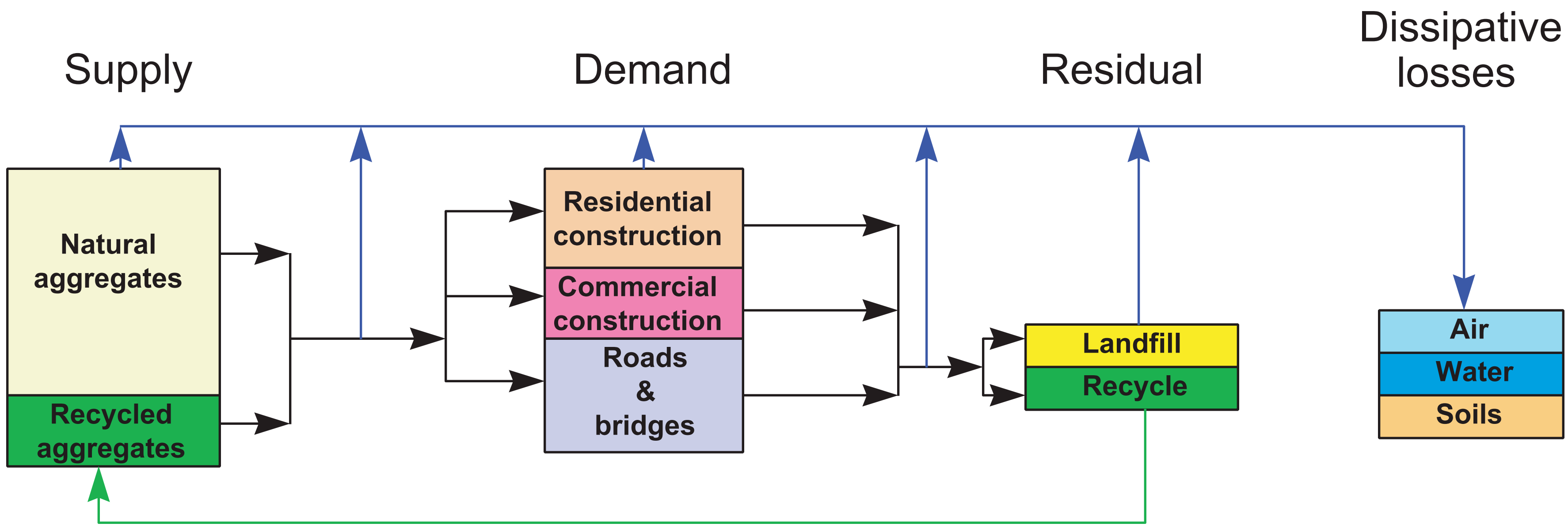
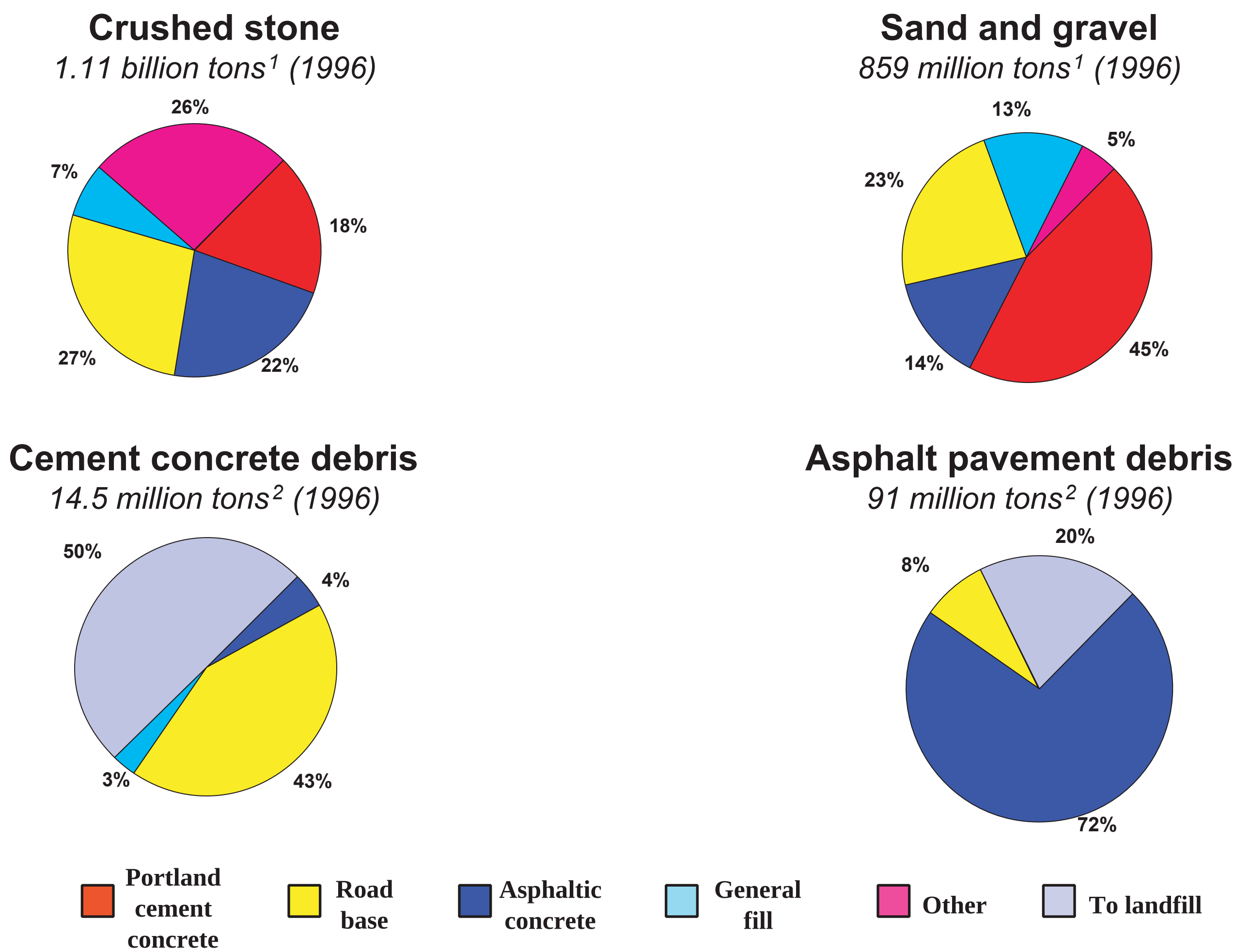


Figure 1. Construction aggregates flow system.

recovered from widespread, naturally occurring mineral deposits. Vertical arrows represent losses to the environment, which occur throughout the flow system. More than 2 billion metric tons (tons[1]) of crushed stone and sand and gravel were consumed as aggregates in the United States in 1996, much of which was used in road construction and maintenance (Tepordei, 1997a; Bolen, 1997). Recycled material used to produce construction aggregates for concrete comes from two primary sources: (1) road construction and maintenance debris, and (2) structural construction and demolition debris (for example, from demolished buildings, bridges, and airport runways). Virtually all the asphalt for recycling comes from roads and parking lots. Some asphaltic concrete is milled and relaid as base material in place, but most recycled material goes through the process of recovery (demolition, breaking, and collecting), transportation (to a local collection point), processing (crushing, screening, separating, and stockpiling), and marketing (as sized products with multiple uses). Recycled aggregates currently account for less than 1 percent of the total demand for construction aggregates, but the amount recycled is thought to be increasing. Precise consumption statistics for the recycled materials are not available, but estimates for each source and market sector are shown in figure 2. A more detailed analysis of construction aggregates substitution is currently being conducted by the USGS.

[1]For this study, all figures have been reported in metric units in accordance with USGS practice. The term “tons” is used to refer to the metric ton unit of 2,205 pounds.



[1] Data reported in metric tons and derived from Tepordei, 1997a; Bolen, 1997.
[2] Estimates reported in metric tons derived from various USGS and industry sources.

Figure 2. Consumption of aggregates by source and market sector.

As shown in figure 2, most of the demand for aggregates is supplied by sand and gravel or crushed stone producers. Aggregates derived from crushed stone are consumed in portland cement concrete, road base, asphaltic concrete, and other applications, whereas almost half of the aggregates derived from sand and gravel is consumed in portland cement concrete. Currently, more than 50 percent of all cement concrete debris and about 20 percent of all asphalt pavement debris end up in landfills. An estimated 85 percent of all cement concrete debris that is recycled is used as road base, with minor amounts used in asphaltic concrete and fill material. About 90 percent of asphalt pavement debris that is recycled is reused to make asphaltic concrete.

As costs, regulations, land-use policies, and social acceptance of more sustainable natural resource practices have a greater impact on the natural aggregates industry, increased aggregates recycling in urban areas is likely to occur. Producers of natural aggregates and independent entrepreneurs are beginning to consider the recycling of construction and demolition debris as one option for material use, as it has the potential to (1) extend the life of natural resources by supplementing resource supply, (2) reduce environmental disturbance around construction sites, and (3) enhance sustainable development of our natural resources—yet it can be profitable. In some urban areas, recycling of concrete and asphalt has reduced the flow of waste to landfill areas and reduced road construction and maintenance costs. In less urbanized areas, aggregates recycling is expensive or impractical on a large scale. Because of the high transportation cost associated with disposal of construction waste materials and the demand for this material in new construction, the aggregates recycling industry has developed locally or regionally, most often in urban areas. As each region has its own particular needs, a thorough understanding of factors affecting the aggregates industry in a particular area is necessary to determine whether aggregates recycling is advantageous.

Because the aggregates industry is a high-volume, low-unit-value industry, a small variation in operation economics can have a significant impact on the profitability of an operation. Entry into this business often requires significant capital investment, particularly for small operators, and equipment suitable for processing natural aggregates may not be suitable for processing recycled aggregates. The relative distance and associated cost of transporting material between construction, mining, processing, and disposal (landfill) sites influence production site location.

AGGREGATES PROCESSING TECHNOLOGY

The technology required for raw material acquisition and processing of aggregates from both natural and recycled sources is summarized in table 1, which focuses on technical factors that provide both incentives and deterrents to aggregates recycling. A detailed description of processing technology and the technical factors influencing equipment selection are reported in Appendix 2 for the production of aggregates from crushed stone, sand and gravel, recycled aggregates from concrete, and recycled aggregates from reclaimed asphalt pavement.

Table 1. Significant technological aspects of natural and recycled aggregates.

Natural Aggregates	*Recycled Aggregates*
About 2 billion tons of sand and gravel and crushed stone were reported to have been consumed as aggregates in the United States in 1996 (Tepordei, 1997a).	Less than 80 million tons of recycled material were estimated to have been consumed in construction applications in the United States in 1996 (T. D. Kelly, oral commun., 1997).
Aggregates are derived from a variety of source rocks and mined primarily by surface methods.	Aggregates are derived from debris of road and building construction projects.
Mining requires environmental monitoring and reclamation. Costs for exploration, permitting, overburden removal, site preparation, and both ongoing and final site reclamation must be considered.	Recycling requires limited monitoring and reclamation. Costs for exploration, mining, or stripping are not incurred, but costs for ongoing reclamation, site cleanup, and dust and noise reduction may be incurred.
Quality depends primarily upon the physical and chemical properties of the source deposit.	Quality varies significantly due to large variation in type and impurities of debris sources.
Must conform to Federal, State, or local technical specifications for each product application.	Must conform to Federal, State, or local technical specifications for each product application.
Currently used in road base, concrete, and asphalt applications in all States (see Appendix 1).	Forty-four States allow its use as road base, other permissible applications vary by State (see Appendix 1).
Processing primarily consists of crushing, sizing, and blending.	Processing similar to natural aggregates, but increased wear of equipment may result because of variable size and angularity of feed and the presence of deleterious material.
Location dependent upon resource. Equipment selection depends upon numerous technical, economic, and market factors. Transportation distances and costs among resources, processing facilities, and markets affect end uses.	Location determined by feed sources and markets. Location, equipment selection, and plant layout affect operational economics. Transportation distances and costs affect both feed supply and markets.
Mine and plant layout in part determines the efficiency of an operation.	Recycler must be able to adjust material feed and output to meet changing product requirements.
Processing generally occurs at mine site, often outside city limits. Resource suitable for multiple products.	Processing often at centrally located site in urban area using mobile equipment. Product mix often limited.
Mobile, on-site plants may be used for large projects; time required for takedown, transport, and setup.	Mobile plants commonly relocate 4 to 20 times each year, affecting productivity; time required for takedown, transport, and setup.
Products marketed locally or regionally, mostly in urban areas. Higher valued products may have larger marketing area.	Products marketed locally in urban areas. Lower valued product mix may constrain markets.

Figure 3 illustrates the typical steps required to process recycled material. Technology primarily involves crushing, sizing, and blending to provide aggregates suitable for a variety of applications. Concrete and asphalt recycling plants can be used to process natural sand and gravel, but sand and gravel plants usually won't process recycled material efficiently. Construction concrete often contains metal and waste materials that must be detected and removed at the start of processing by manual picking or magnetic separation. Feed for recycling is not uniform in size or composition, so equipment must be capable of handling variations in feed materials.

The "Urban Deposit"

One of the significant differences between generating aggregate products from natural and recyclable sources is the nature of the deposits from which each is derived. For the former, operators are dependent on naturally occurring deposits. Such deposits have to be located, explored, proved economic, developed, financed, permitted, and bonded prior to production. In many cases, reaching production status can take many years. When in production, costs for overburden removal, blasting, and on-site transportation may be incurred prior to crushing.

Recycled materials originate from the "urban deposit," which is made up of construction and demolition debris including widely dispersed material from buildings, roads, bridges, sidewalks, driveways, parking lots, runways, among others. Aside from catastrophes such as wars[1] and earthquakes,[2] these stocks generate material for recycling at rates determined by physical decay (for example, asphalt roads wear out in about 30 years) and loss of economic utility (for example, replacement of warehouses with a new sports complex).

Regional recyclers compete among themselves and with nearby landfills for the material that is being made available at variable rates from multiple and often dispersed sources. The percentage of the total available material in the "urban deposit" that can be obtained by a particular recycler is dependent upon three elements: the relative costs and charges at the recycling facilities; the relative distances from the "urban deposit" sources to the competing facilities; and the quantity of material that the recycler is able to supply.

Because the supply of material that is available for recycling at any given time is constrained, the only way to increase the recycling of concrete (almost all asphalt is recycled or reused) is to make concrete recycling a more attractive option for contractors, aggregates producers, and potential recyclers without sacrificing product quality. This can be done by providing markets for recycled products through education, specification changes that allow the use of comparable quality recycled materials in road building applications, improved market information flow, or legislative mandates (for example, requiring the use of recycled materials in government-funded projects) and increasing fees at landfills[3] to make them a less attractive option for disposal than recycling.

[1]The Europeans took the lead in developing construction debris recycling techniques at the end of World War II, when massive amounts of war-ravaged infrastructure required replacement (DePauw and Vyncke, 1996).
[2]Recent earthquake events in California have caused the State, with assistance from the Federal Emergency Management Agency, to become a leader in recycling techniques and supportive legislation (Construction Monthly, 1996).
[3]Bogardus (1997) reported on fees at landfills in southern California. It seems that landfills, even those run by municipalities, need a minimum inflow of wastes to cover costs, so they charge landfill disposal fees, commonly called tipping fees, based upon regional waste flow dynamics. Fees can vary widely across the United States.

TECHNICAL FACTORS AFFECTING AGGREGATES RECYCLING

Based upon data from reference documents, personal communications, and site visits, the following technical factors were determined to affect the profitability of an aggregates recycling operation. All factors don't always apply, but they have been found to apply in many cases.

Product Sizes: Screen product-size distributions determine the amount of each product available for sale. Regional supply and demand considerations often dictate local prices for various size products. Because different products have different values in any given market, the operation that is able to market high-value size distributions is likely to improve its cash flow position. Screen configuration can be adjustable to reflect changing market conditions for different size products. Experienced operators have the ability to maximize production of high-value products and to respond to changes in product requirements.

Operational Design: In order to maximize efficiency and profitability, careful consideration must be given to operational layout and design, production capacity, and equipment sizing. Although economy-of-scale efficiencies benefit larger operations, the higher capital cost of equipment and the limited availability of feed material may limit the size of an operation. Equipment configuration also affects product mix (what products are produced; mixes of products) and plant efficiency. Equipment selection is influenced by the decision on whether to be a fixed or mobile recycler. Mobile plants must meet roadway restrictions to be allowed to move from site to site. Fixed site equipment can be somewhat larger and perhaps more durable, thereby trading off lower unit production costs with reduced transportation costs for the mobile unit. Busse (1993, p. 52) explained, "The smaller processing plants are a great concept. They work well for asphalt recycling. But for concrete, the preparation cost is enormous when using small crushers because the material needs to be broken down tremendously. If only flat work or roadwork is being processed, perhaps it can be done. If bridges, parapets, demolition debris, or building columns are being processed, the small plants won't work. The wear cost is too high."

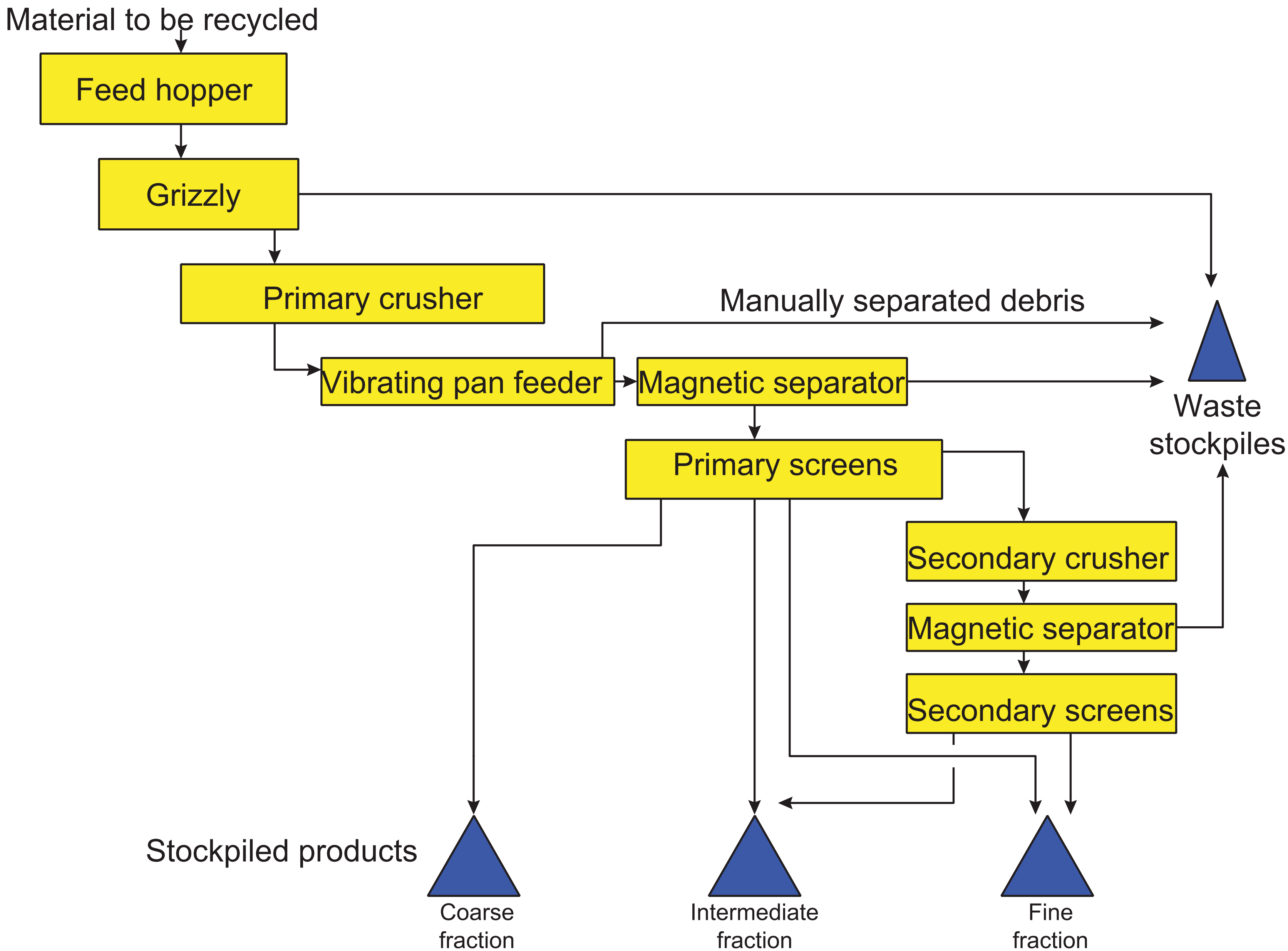


Figure 3. Generalized flow diagram for an aggregates recycling operation.

Labor: Labor requirements are low for recycling operations. A typical operation would require fewer than 10 personnel, whether it is a small size operation or the largest operation. For a stationary concrete recycling facility, labor accounts for about 20–30 percent of the total operating cost. For a mobile operation, labor costs can be higher due to takedown and setup requirements from frequent relocation of equipment.

Feed Source Material Characteristics: The quality of the feed material to be processed affects product mix, production efficiency, and labor requirements. Recycling operations generally receive a variety of materials from numerous sources, so have only limited control over material quality. Because of the variability of source material, recycled aggregates may not be suitable in product applications where a high degree of particle uniformity is required (for example, top course of cement concrete). Broken or fine material increases the production rate, while clean concrete with only limited fines decreases the production rate. Concrete from building construction and demolition debris can contain nonmagnetic debris such as wood, aluminum, or plastic which must be hand picked, adding to labor costs.

Energy: Energy, primarily electricity and diesel fuel, is required for powering the processing and transportation equipment of both natural and recycled aggregates. Based on a 1996 energy audit of a Denver, Colo., area recycling facility which processes both portland cement concrete and recycled asphalt pavement, an estimated 34 million joules[2] per ton is required to process demolished portland cement concrete and 16.5 million joules per ton is required for recycled asphalt pavement. The Portland Cement Association reported 1993 energy requirements for natural aggregate materials of 5.8 million joules per ton for sand and gravel material and approximately 54 million joules per ton for crushed stone (Portland Cement Association, 1993); however, update and corroboration of this information were not possible. These values do not include the energy required to demolish construction debris or transport this material for processing. Transportation energy requirements are estimated to be 2,700 joules/kilogram-kilometer for sand and gravel, 3,800 joules/kilogram-kilometer for crushed stone, and 3,800 joules/kilogram-kilometer for recycled aggregates. The difference in unit energy consumption is a result of being able to carry a greater tonnage of fine materials (sand) in a given volume.

Infrastructure Life: The useful life of infrastructure affects both supply and demand for recycled aggregate products. Road and building design determines how long such structures will last, and the amount of maintenance required. Aggregate characteristics, economic utility choices, weather conditions, and intensity of use also impact infrastructure life. A large segment of Interstate 70 in Colorado, which had been designed to last 40–50 years, had to be replaced after only 25 years of service because of deterioration of the original concrete due to an alkali-silica reaction, making the concrete more susceptible to local freeze-thaw cycling. After a substantial testing period, the original concrete was replaced with a mix in which 10 percent of the subbase aggregates layer and 75 percent of the asphalt overlay were derived from recycled material. Testing indicated that the mix containing the recycled material should prove to be more durable than other mixes tested (Wachal, 1994).

Asphalt roads can have markedly different lives depending on original design, climate, traffic load, and the schedule and type of maintenance. For example, U.S. Highway 34 through Big Thompson Canyon in Colorado has demonstrated a life of more than 20 years while Interstate 25 through the Denver metropolitan area has demonstrated a life of only 6 years (S. Shuler, oral commun., 1997).

Recycled Product Specifications: Many States set technical specifications for selected recycled aggregate product applications. These specifications define product characteristics that must be met for all construction projects within the State. Virtually all States allow recycling of reclaimed asphalt pavement.

Hawkins (1996) listed the following advantages for using recycled concrete products as road subbase aggregates:

- Recycled concrete is nonexpansive and will not grow or expand with moisture.
- Recycled concrete has an optimum moisture of approximately 13 percent—about twice that of natural road base, due to its particle size distribution. It may absorb twice the water before becoming saturated.
- Recycled concrete is 10–15 percent lighter in weight, resulting in reduced transportation costs.
- Recycled concrete compacts faster—up to two to three times as fast as nonstabilized natural road base.

Recycled concrete aggregates can also have disadvantages:

- They are often composed of material with highly variable properties.
- The strength values are often lower than those of natural aggregates, resulting in product application limitations.
- Use of recycled material must be evaluated on a project by project basis in order to determine suitability. Customers are often not used to matching material characteristics with project quality requirements.

Because aggregates derived from natural and recycled sources can have different properties, blending of different aggregates must be carefully monitored in order to prevent quality problems. Construction contractors that use blended mixes must recognize these property differences and practice application techniques to accommodate such differences.

[2]Energy from both electricity and fuels. For perspective, a barrel of oil contains about 6.12×10^{12} joules.

TRANSPORTATION FACTORS

Transportation distances and costs are a significant part of the dynamics that define the use of construction aggregates within a region, but they normally do not directly affect operational profitability of the recycler, because costs for transportation are typically incurred by the contractor of a construction project (who supplies feed for recycling), rather than the recycler. The contractor is, however, concerned with the cost associated with transportation. The amount of material that the contractor makes available to the recycler is based in part on a calculation that compares the relative costs of delivering and paying a tipping fee to the recycler, the costs of transporting construction debris to competitors, or the cost of disposing of this material in a landfill. Although site location dynamics are similar in all areas of the United States, local conditions will vary as material sources and markets change.

Construction aggregates are primarily used in bulk quantities that are transported to a point of use by truck, rail, or water carrier. On a national average, approximately 85 percent of all aggregates are delivered by truck, 6 percent by rail, 3 percent by water carrier, and the remainder is consumed on-site (Socolow, 1995). The average 1995 cost of trucking aggregates 1 kilometer is reported to be approximately $0.13 per ton. The distance that aggregates can be hauled economically varies regionally; however, each kilometer that a ton of aggregate is hauled can add $0.13 to its cost, if trucks return empty to get more aggregates. Backhauling of material from the delivery site can reduce delivery cost by as much as 50 percent (R. Hawkins, oral commun., 1997).

Table 2 illustrates the importance of transportation costs on a typical highway construction project in New England (Socolow, 1995). For an assumed 56-kilometer transportation distance, the cost of transporting the lower layers of road base exceeds the estimated purchase price of the product. Therefore, the proximity between construction project and aggregates source, particularly for lower value products such as road base material, is critical. A recycler must be able to position operations such that it is more cost effective for the construction contractor to send construction debris to the recycler rather than transport it to a landfill.

Although transportation costs are considered important in terms of plant location and competitiveness, feed supply transport costs were not included in the cash flow analysis of this study because the cost of transporting feed material to the recycling facility is commonly incurred by the supplier. Movement on-site by heavy equipment is included as a cost to the operation. Products were assumed to be sold free on board (f.o.b.) plant; cost of product transportation would be incurred by the purchaser.

Layer thickness of typical 1.6-km length of 4-lane highway	*Amount of material per kilometer of construction (tons)*[1]	*Average f.o.b.*[2] *price ($/ton)*	*Total material cost ($)*	*Transportation cost (56 km; $0.13/ton/km)*	*Total cost ($/ton)*	*Percent of total cost related to transportation*
12.7 cm asphalt	8,700	$28.66	$249,000	$63,000	$312,000	20%
130 cm crushed gravel	14,400	$7.72	$111,000	$105,000	$216,000	49%
30 cm gravel	14,900	$5.51	$82,000	$108,000	$190,000	57%
15-61 cm sand	27,900	$5.51	$154,000	$203,000	$357,000	57%
Base course (borrow)	≤6,900	NA[3]	NA	NA	NA	NA
TOTAL	72,700	NA	$596,000	$479,000	$1,075,000	45%

[1] The term "tons" refers to the metric ton unit of 2,205 pounds.
[2] f.o.b., Free on board, processing plant.
[3] NA, Not available.
Adapted from Socolow, 1995.

LOCATING AN AGGREGATES RECYCLING FACILITY

Minimization of the distances between a recycler and its suppliers and markets is critical to the economic success of an aggregates recycling facility. The primary source of recyclable concrete is obsolete infrastructure. Areas of urban renewal or suburban growth offer the greatest opportunity as markets for recycled concrete aggregates. Figure 4 illustrates the factors that need to be considered when locating a recycling facility.

A recycler will normally not be located within a growth area because of zoning restrictions or community resistance, unless it is a mobile plant temporarily located at a large construction site. Because a landfill may represent an alternative to recycling construction debris, distances to local landfills also need to be considered. A construction contractor often must choose whether to dispose of debris at a landfill or send it to a recycling facility. Relative transportation costs and distances, and associated tipping fees (charges by either a landfill or recycler to process material at that facility) most often influence this decision.

In the simplified case illustrated in figure 4, where relative transportation distances serve as a proxy for relative transportation costs and fees, a construction contractor demolishing obsolete infrastructure at the center of the metropolitan area would most likely choose to deliver first to the recycling facility located at C, then B, then A because transportation costs would be less, all other things being equal.

A recycler would set its tipping fee at a level low enough to attract sufficient feed material to meet the demand of its local markets but high enough to cover its expenses. Recycler C may be able to charge higher tipping fees than B or A, because of its location closer to the source of construction debris. With proper fee management, recycler C would probably receive sufficient construction debris to supply its local growth area; but recyclers B or A may not receive sufficient material to satisfy the need of their larger growth areas, unless tipping fees are lowered or other operational factors make them attractive to construction contrators.

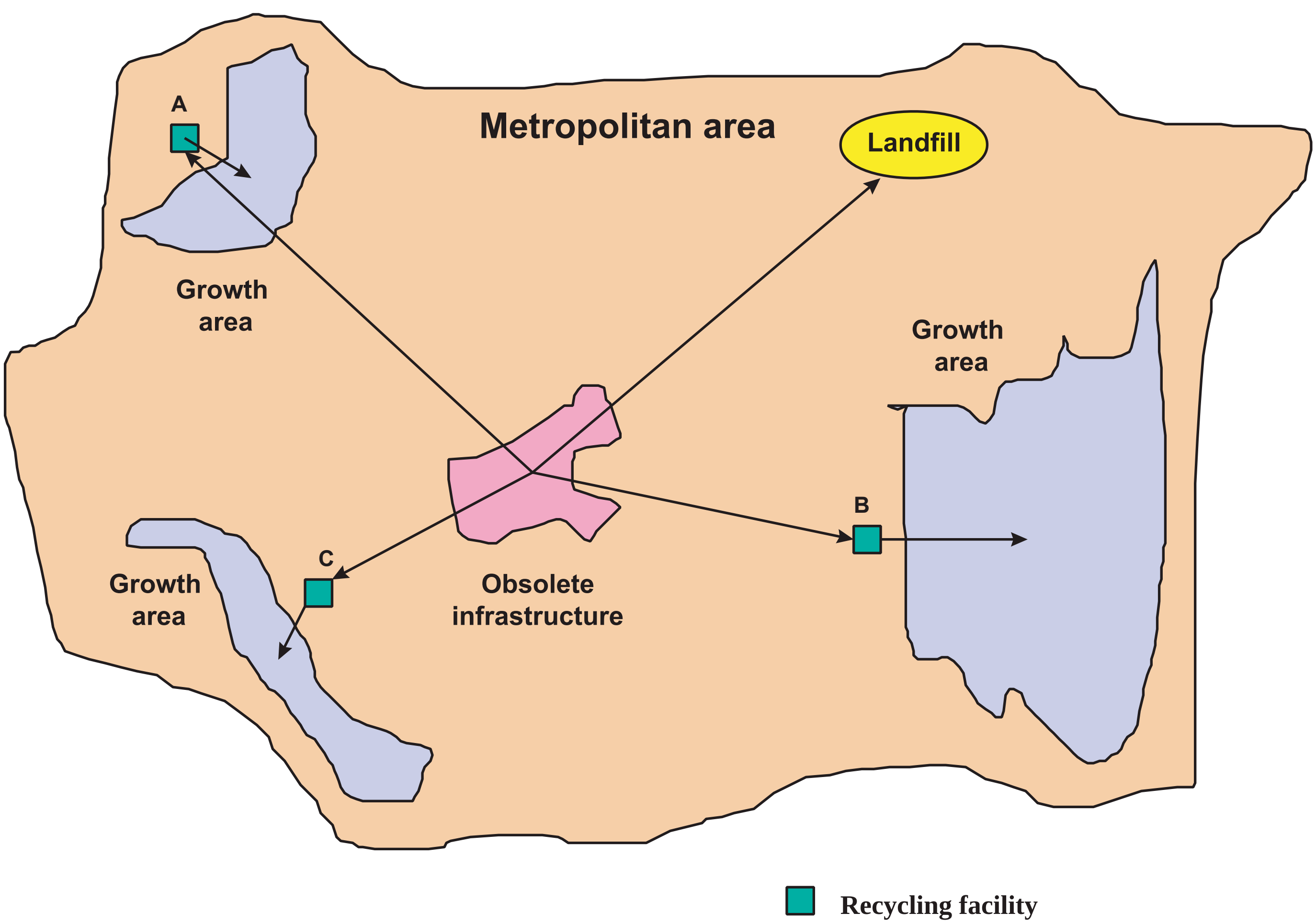


Figure 4. Locating a concrete recycling facility.

In the case where the distance from the infrastructure to A is about equal to the distance to the landfill, and recyclers B and C are not accepting material for whatever reason, then tipping fee differences between the landfill and recycler A will most likely determine where the construction debris is sent. Further discussion of tipping fees is given in the cost section of this report.

COSTS OF PRODUCING RECYCLED AGGREGATES

Of the costs associated with the production of recycled aggregates, product price and tipping fee were found to have the greatest effect on operational economics; variations of these parameters were analyzed. A method of economic evaluation presented here can be used for making informed planning and policy decisions related to aggregate production from recycled sources.

METHODOLOGY

Costs for producing recycled aggregates were developed based on data from the Denver, Colo., area. Costs in other regions of the United States may differ due to raw material supply, operational, competition, or demand variations. The methodology used in this study allows for variation in costs and revenues to be evaluated and analyzed.

Production cost information for three representative fixed-site recycling operations is presented. Costs used in this evaluation were developed from data collected from published literature, personal contacts, and site visits. Based on these data, cost models were built to represent small (110,000 tons/year), medium (253,000 tons/year), and large (312,000 tons/year) capacity aggregates recycling operations. The recycling models represent facilities processing a 60:40 percent mix (tonnage basis) of recovered asphalt pavement to cement concrete debris. Assumptions for the recycling models are shown in table 3.

For each size model, capital expenditures for the processing plant and associated equipment, as well as all necessary reinvestments, were estimated. Investments include mobile and stationary equipment, construction, engineering, infrastructure, and working capital. Infrastructure includes the cost for construction and installation of access and haulage roads, water facilities, power supply, and personnel accommodations. Working capital was estimated at 15 percent of the variable operating cost.

Land requirements for recycling operations are typically small (generally 2–6 hectares). Consequently, many operations lease land rather than purchase it. In this study, land was assumed to be leased. Based upon reported lease fees[3] for comparable industrial land in the Denver area, an average annual cost of land of about $97,000 per hectare was assumed. Lease rates in the Denver metropolitan area ranged from 8 to 10 percent of the property value; a value of 9 percent was assumed for this study. Based upon these data, a leased land charge of approximately $19,000 was assumed for the small operation, $43,000 for the medium operation, and $53,000 for the large operation. These charges were included in the fixed operating costs.

Operating costs are a combination of variable and fixed costs. Variable operating costs include production and maintenance labor, operating supplies, and utilities. Fixed operating costs include technical and clerical labor, payroll overhead, land lease costs, administrative costs, facilities maintenance and supplies, advertising, and sales. Taxes, insurance, depreciation, permitting costs, and other local fees are also included in this analysis.

A range of different size products is typically produced by recycling operations to meet the varying needs of local markets. Prices for each product can vary regionally due to demand and market considerations. An average price of $5.23 per ton was assumed for this study, based upon an assumed throughput ratio of asphalt to cement concrete of 60:40 and a weighted average of reported 1996 prices for known products in the Denver area. Products containing different proportions of cement/asphalt concrete would generate different prices depending upon the prices of these products for the area of the United States in question. Recovery of byproducts such as rebar from recycling operations was not considered in the evaluations.

After production parameters and cost estimates were determined for each model, the production data were entered into PCMINSIM, a software package developed by the former U.S. Bureau of Mines to perform discounted-cash-flow rate of return (DCFROR) analyses of mineral properties (Fraser, 1990). The DCFROR is commonly defined as the rate of return that makes the present worth of cash flow from an investment equal to the present worth of all after-tax investments (refer to Davidoff, 1980). For this study, a 12 percent rate of return was considered the necessary rate of return for operations to cover the opportunity cost of capital plus risk.

COSTS

Cost models for the three size operations are given in table 4 and shown in figures 5, 6, and 7. Capital costs, operating costs, and revenues are represented for each model.

From these data, the costs associated with equipment (such as equipment capital, equipment maintenance, and recovery of capital) clearly are a significant contributor to total production costs for a recycling operation, particularly

[3]Based upon data provided by Fuller and Company, Denver, Colo., August 31, 1997.

Table 3. Assumptions used in this evaluation.

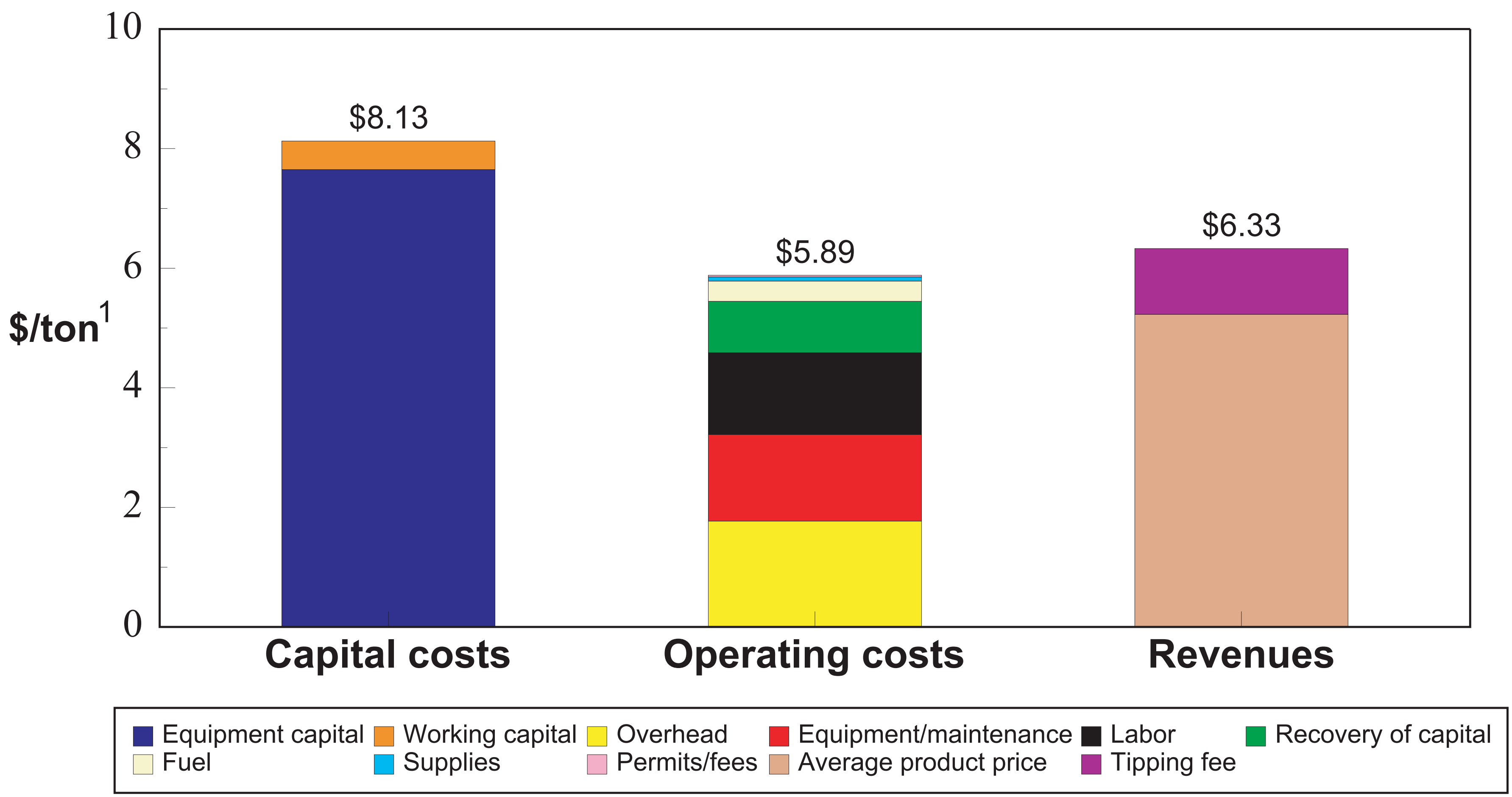
Category	*Value*	*Basis*
Operational capacity	Small-110,000 tons[1] per year Medium-253,000 tons per year Large-312,000 tons per year	Selection based upon known producer capacities and available cost data.
Land requirement	2 hectares for small operation; 4 hectares for medium operation; 6 hectares for large operation	Selected as representative of industry.
Land lease rate	9 percent of land value	Average rate for Denver, Colo., area.
Cash flow period	11 years	Chosen to permit sufficient time to recover capital.
Rate of return	12 percent per year	Selected as representative of industry.
Inflation rate	3 percent per year	Chosen to reflect recent trends.
Depreciation period	7 years (straight line method)	Reflects industry standard for crushing equipment.
Federal tax rate	34 percent	Federal tax rate.
State tax rate	5 percent	Colorado tax rate.
Debt:Equity Ratio	0.9	A rate of 90 percent debt financing assumed based on industry practice.
Loan interest rate	10 percent	Reflects typical industrial rate.
Average tipping fee[2]	$1.10 per ton	Reflects average for Denver area.
Average product price	$5.23 per ton	Reflects average price in Denver area for recycled aggregate derived from 60:40 mix of asphalt and concrete.
Average production rate (percent of design capacity)	88 percent	Based on site visits and contacts.
Production schedule	1-8 hour shift per day, 5 days per week	Based on site visits and contacts.

[1] In accordance with USGS standards, all figures have been reported in metric units.
[2] Tipping fees are often charged to process construction debris; fees vary locally depending upon the characteristics and quality of the waste, the general level of competition for feed material, and local landfill charges.

Table 4. Estimated 1996 costs for recycled aggregate operations.

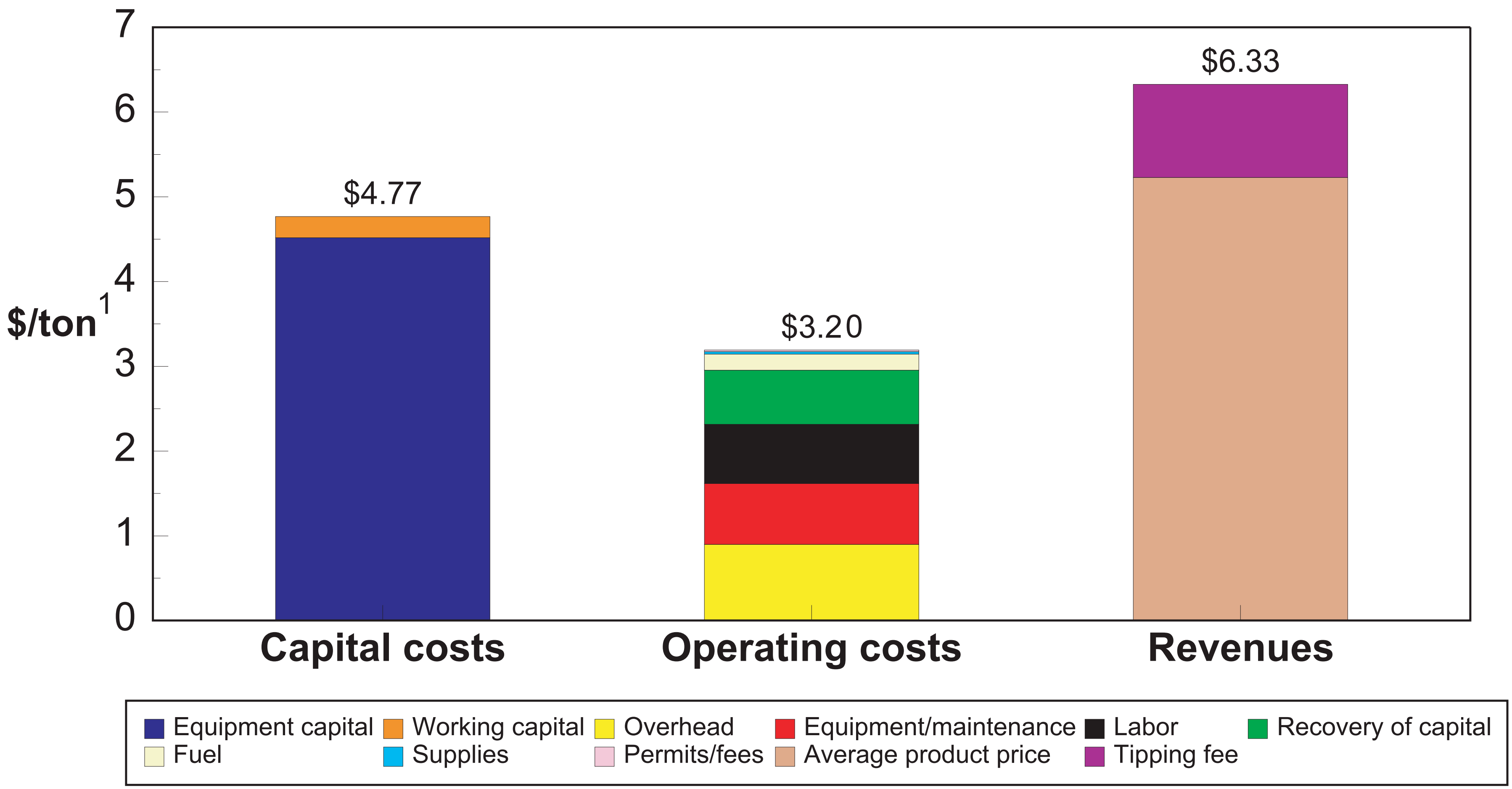
	Small recycler	*Medium recycler*	*Large recycler*
Operation Capacity (tons/year)	110,000	253,000	312,000
Capital Costs[1]	$842,000 ($7.65/ton)	$1,143,000 ($4.52/ton)	$1,363,000 ($4.37/ton)
Working Capital[2] (15% of variable operating cost)	$53,000 ($0.48/ton)	$64,000 ($0.25/ton)	$72,000 ($0.23/ton)
Total Capital Costs	$895,000 ($8.13/ton)	$1,207,000 ($4.77/ton)	$1,435,000 ($4.60/ton)
Variable Operating Costs[3] ($/ton)			
Equipment Maintenance	$1.45 (24%)[4]	$0.72 (22%)	$0.72 (24%)
Labor	$1.37 (23%)	$0.70 (22%)	$0.57 (20%)
Fuel	$0.34 (6%)	$0.19 (6%)	$0.20 (7%)
Supplies	$0.07 (1%)	$0.03 (1%)	$0.02 (1%)
Permits and Fees	$0.03 (1%)	$0.02 (1%)	$0.02 (1%)
Net Operating Costs ($/ton)	$3.26	$1.66	$1.53
Recovery of Capital (Straight line depreciation over 7 year period)	$0.86 (15%)	$0.64 (20%)	$0.63 (21%)
Fixed Costs (Overhead)	$1.77 (30%)	$0.90 (28%)	$0.76 (26%)
Total Operating Costs ($/ton)	$5.89	$3.20	$2.92
Tipping Fee Credit ($/ton)	($1.10)	($1.10)	($1.10)
Average Market Price ($/ton)	($5.23)[5]	($5.23)[5]	($5.23)[5]
Net Present Value[6] (At 12% DCFROR, reported tipping fee and market price of assumed product mix)	-$72,000	$631,000	$901,000

[1] Assumes equipment is purchased new. Excludes cost for purchased land; includes cost for reclamation bond.
[2] Includes cost for ongoing environmental remediation.
[3] Reported for 1996 (assumed initial year of model production).
[4] Values in parentheses reflect percent of total unit operating cost.
[5] Reflects composite 1996 price in Denver, Colo., area for recycled aggregate derived from 60:40 mix of asphalt and concrete.
[6] Net Present Value refers to the present value of all revenues less the present value of all costs, including initial capital costs.



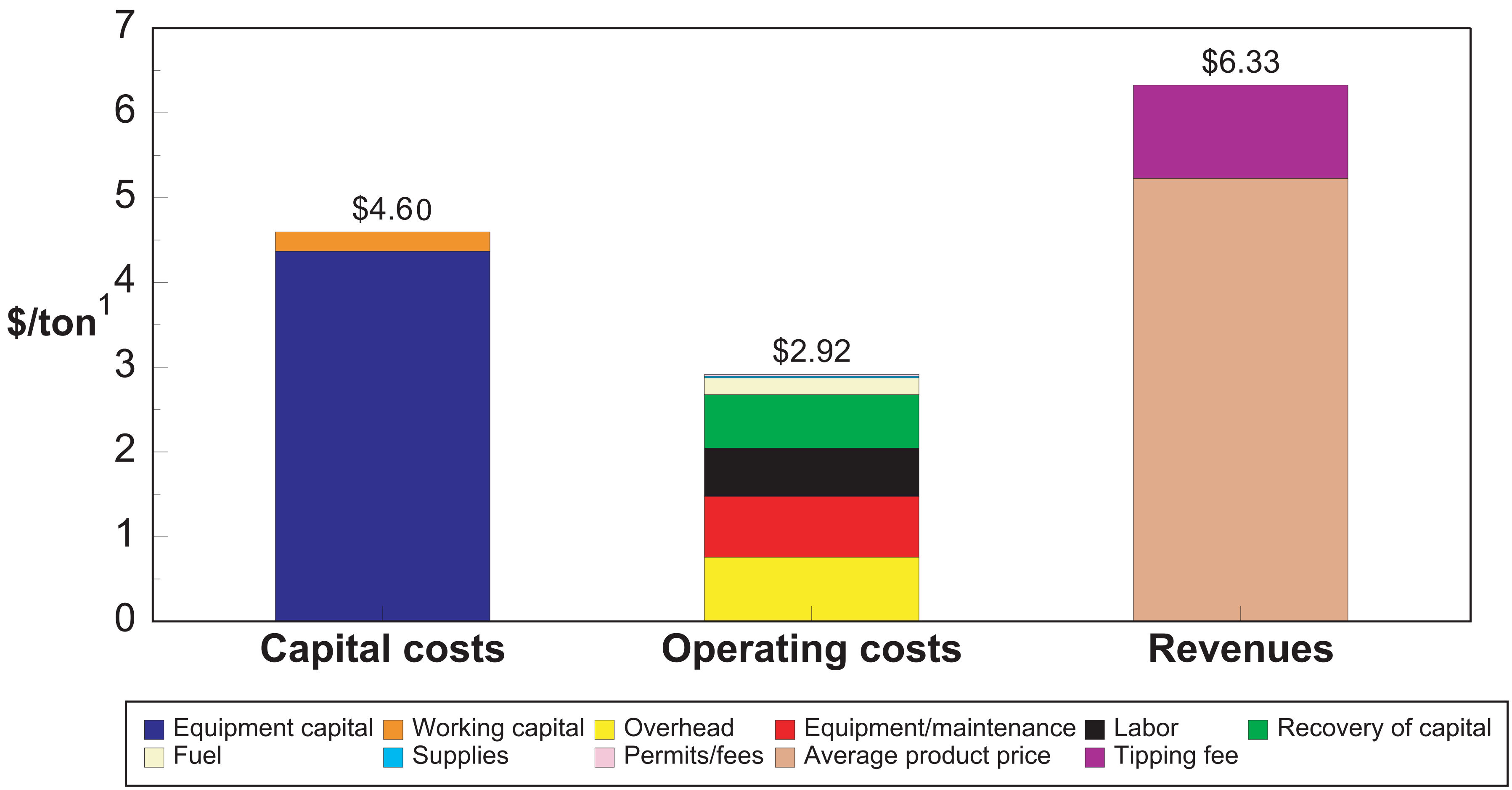
[1] All costs are expressed in terms of U.S. dollars per ton (2,205 pounds).

Figure 5. Estimated 1996 costs for a 110,000 t/yr recycled aggregates operation.



[1] All costs are expressed in terms of U.S. dollars per ton (2,205 pounds).

Figure 6. Estimated 1996 costs for a 253,000 t/yr recycled aggregates operation.



[1] All costs are expressed in terms of U.S. dollars per ton (2,205 pounds).

Figure 7. Estimated 1996 costs for a 312,000 t/yr recycled aggregates operation.

a smaller size facility. Recycling requires initial capital expenditures of approximately $4 per ton of production capacity for the large recycling operation to about $8 per ton for the small operation. In general, larger operations are not as capital intensive as smaller operations. Costs reflect the purchase of new equipment; used equipment may be an option in some cases. Capital recovery of equipment (depreciation) constitutes an additional 14–20 percent of total operating cost, and is highest for the larger operation. During the period of capital recovery, equipment maintenance constitutes about 22–24 percent of the total unit operating cost.

The largest component of operating cost for a recycling facility is fixed overhead, including major expense items such as management and clerical salaries, building and land rental costs, advertising expense, and property and real estate taxes. Overhead ranged from 26 percent of total unit operating cost for the large operation to 30 percent for the small operation. Land lease costs represent a significant portion of operational overhead.

Labor costs contribute about 20–23 percent to total unit operating cost. For the capacities assessed in this study, labor requirements vary little on a percentage of total cost basis, but vary significantly on a unit cost basis. Most recycling plants require pickers to ensure that feed material is as free as possible from deleterious material. Large-sized recycling plants require only one or two additional equipment operators to handle a significant capacity increase. Consequently, the large plant, with a capacity of about three times the small plant, incurs a labor cost per unit of product that is 42 percent of the small operation. A unit cost savings is achieved. Productivity of the large plant is also higher. At full capacity, productivity estimates for this study range from 52,000 tons per person for the large operation to 22,000 tons per person for the small operation.

Fuel costs average 6–7 percent of total unit operating cost, mainly for diesel fuel and electricity used to provide power for mobile and stationary equipment. Energy, supplies, and permitting fees generally constitute less than 10 percent of the total unit operating cost.

Figure 8 relates the costs reported in this study with reported U.S. costs, prices, and tipping fees (Deal, 1997). The wide variation in product price is a result of the variable nature of recycled aggregate products and regional markets. Highly specialized products such as sprayed landscape rock may sell for as much as $15 per ton, while poor quality fill material might sell for less than $1 per ton. The price spread for road base, the principal market for recycled aggregates, is much narrower; the reported Denver price of $5.23 per ton fits well with reported U.S. sale prices for road base which range from $2.76 to $6.61 per ton.

The reported range in U.S. tipping fees for recycling operations is likewise quite broad. The assumed Denver tipping fee of $1.10 per ton falls on the low end of this range. Aggregates from both natural and recycled sources are readily available in the Denver market, and local landfill charges for construction debris are relatively low. A low fee would be expected where source material is readily available and costs of alternatives are low.

Operating costs for the three model operations fit well within the U.S. range reported by Deal (1997). Cost variation across the United States is much smaller than variation in either product price or tipping fee.

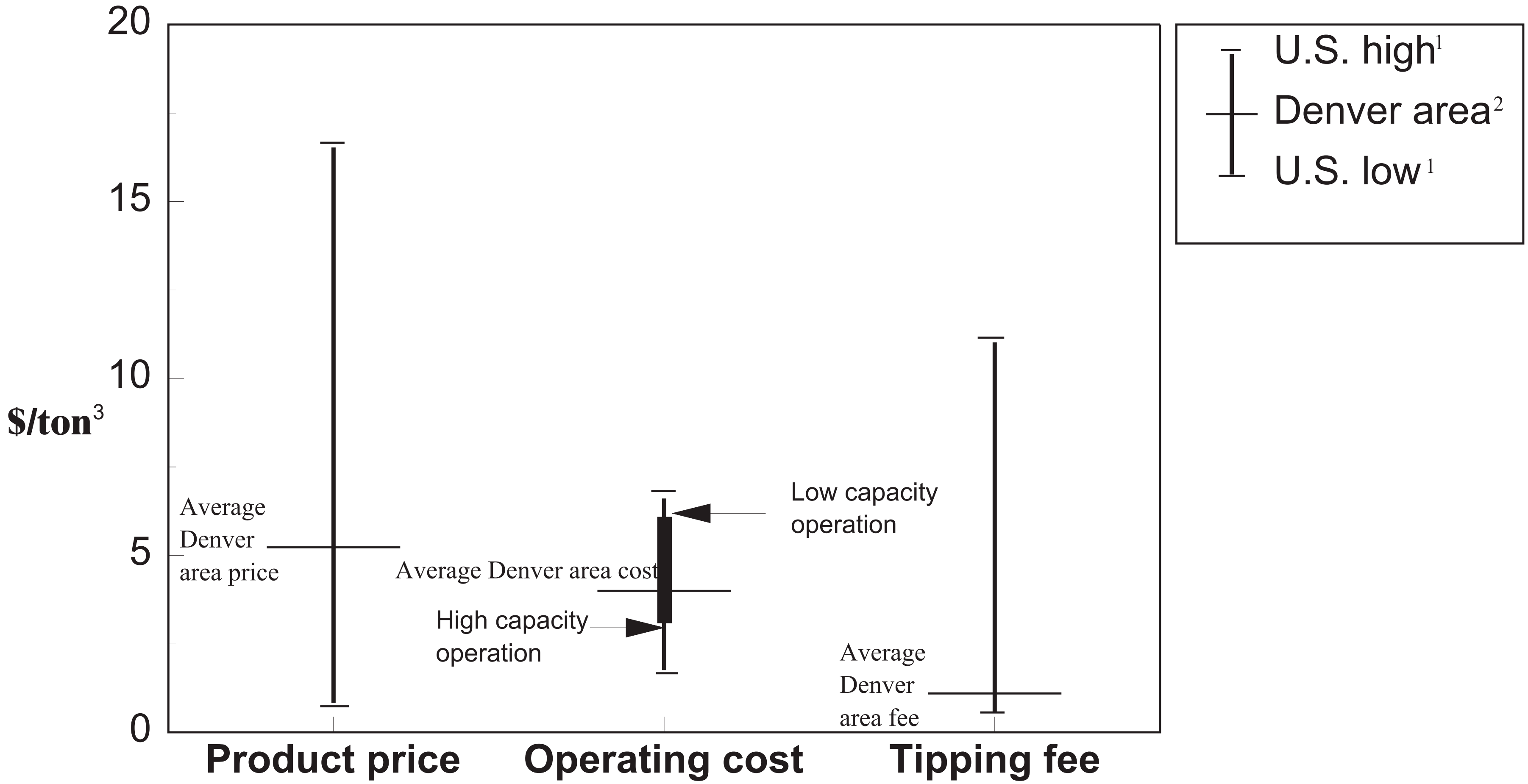
SENSITIVITY ANALYSIS

Figure 8 suggests that whereas operating costs are influenced by such parameters as production rate, product prices and tipping fees are the principal factors affecting the economics of the operation. Production capacity determines equipment and labor requirements, and such requirements are not greatly influenced by regional variations. Once an operation's capacity has been determined and equipment selected, an operator is limited in what it can do to significantly change equipment and labor costs. Fixed operating costs also offer limited flexibility. However, a recycling operation is affected by regional variations in product prices and local tipping fees. Sensitivity analyses were performed to point out the effect of variations of both of these parameters on the relative economics of recycling operations.

Both product price and tipping fees vary significantly from region to region, as each region has different market conditions, specifications, and aggregate sources. Because crushed stone and sand and gravel contribute a far greater volume of source material to the aggregates market than recycled material in most regions, the price of available crushed stone or sand and gravel often determines the local market price for recycled aggregates. In a similar manner, local tipping fees are set based upon the volume of waste material, the availability of disposal sites, local demand for aggregates, relative transportation distances and costs, and legislation.

In order to evaluate the effect of product price and tipping fee on profitability, a series of cash flow analyses were performed at different tipping fee levels, each calculating the product price that would have to be realized in order to produce a discounted cash flow net present value (NPV) equal to zero. NPV is commonly defined as the present value of all revenues less the present value of all costs, including initial capital costs (Stermole, 1980). A NPV is associated with a discounted rate of return (assumed to be 12 percent). Output from these calculations is presented as a set of product price and tipping fee pairs, each yielding $NPV_{12}=0$ (at a 12 percent DCFROR).

Figures 9, 10, and 11 are line graphs of product price versus tipping fee generated based on the cash flow analyses of the three models. The solid line on the graph represents combinations of product price and tipping fee yielding a zero NPV (break even point) with a 12 percent discount rate. The area above this line represents recycling operations which



[1] Adapted from Deal (1997).

[2] Estimated from this study.

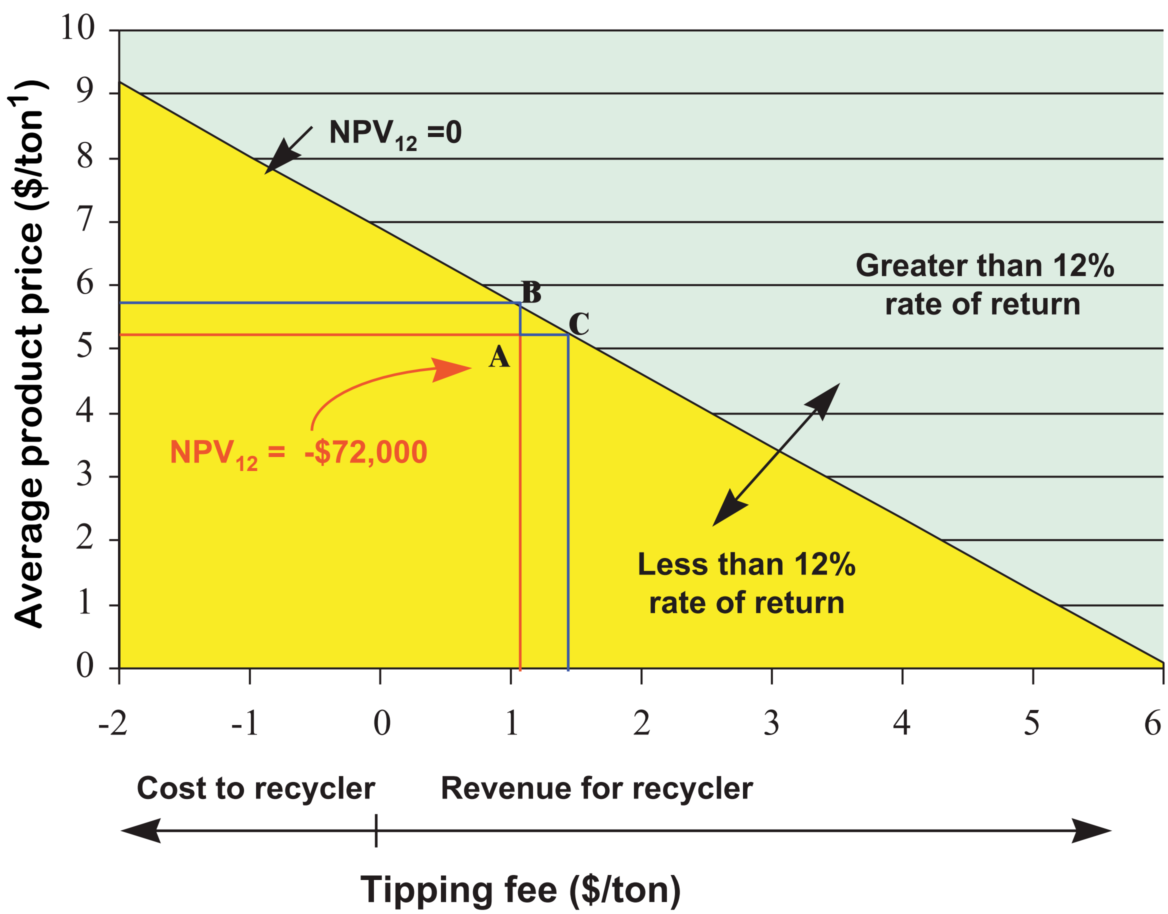
[3] All costs are expressed in terms of U.S. dollars per ton (2,205 pounds).

Figure 8. Estimated costs and revenues of recycled aggregates.

earn a rate of return greater than 12 percent. Below the line, in the yellow shaded area, all combinations of product price and tipping fee yield a negative NPV, indicating operations that earn less than a 12 percent rate of return.

In each figure, the horizontal axis reports a range of tipping fee values. Positive tipping fee values reflect the most common situation for recyclers where a fee is paid to the recycler by the supplier to receive and process construction debris. Such fees represent revenue to the recycler. A negative value reflects the situation where the recycler may pay for construction debris; usually this would occur only when the recycler is in short supply of feed material and thus must pay for additional material in order to meet the demand for established contracts. This represents a cost to the recycler somewhat analogous to mining costs incurred by natural aggregate producers.

For each of the three graphs, the NPV representing base case conditions (product price of $5.23 per ton, tipping fee of $1.10 per ton) is plotted as point A. The distance that the plotted point is above/(below) the NPV_{12} = 0 line represents the degree of profitability or loss for the assumed rate of return of 12 percent. For a small (110,000 tons per year) recycling operation, figure 9 shows that such an operation earns less than a 12 percent rate of return, and has an estimated negative NPV_{12} of -$72,000 (the point falls below the NPV_{12}=0 line). Such an operation would require an average market price of $5.77 per ton of product (point B), or an increase in tipping fee from the assumed $1.10 per ton value



[1]All costs are expressed in terms of U.S. dollars per ton (2,205 pounds).

Figure 9. Profitability of a 110,000 t/yr recycled aggregates operation. (Represented by combinations of product price and tipping fee which result in a NPV12=0.)

to about $1.71 per ton (point C), or a combination of these to achieve a rate of return of 12 percent.

The medium size (253,000 tons per year) base case operation model, however, plots above the NPV_{12}=0 line (NPV_{12}= $631,000), showing a level of profit above the assigned 12 percent rate of return. Figure 10 indicates that for this model, the average product price could fall to $2.69 per ton (point B), and the operation would still achieve a rate of return of 12 percent (assuming a charge of $1.10 per ton tipping fee). Alternatively, the tipping fee could be eliminated (at a product price of $5.23 per ton) and the recycler could pay up to $1.38 per ton of material (point C) and still achieve a rate of return of 12 percent. A combination of these would also result in achieving a rate of return of 12 percent.

Figure 11 indicates that under the base conditions, the large (312,000 tons per year) operation model would be more profitable, with an estimated NPV_{12}= $901,000. For the large operation, the average product price could fall to $2.31 per ton (point B) before the operation would no longer achieve a rate of return greater than 12 percent (at $1.10 per ton tipping fee). Alternatively, the tipping fee could be eliminated (at a product price of $5.23 per ton) and the recycler could pay up to $1.69 per ton of material (point C) and still achieve a rate of return of 12 percent. A combination of these would also result in achieving a rate of return of 12 percent. Therefore, larger sized operations have more leeway than the smaller sized operations to absorb product price decreases and (or) tipping fee decreases before becoming unprofitable.

This analysis indicated that under the base case scenario, with a product price of $5.23 per ton and a $1.10 per ton tipping fee, both the medium and large recycling operation models do not need a tipping fee to achieve a rate of return of 12 percent. For the 253,000 ton-per-year operation, the operating cost could increase by $2.55 per ton, and the

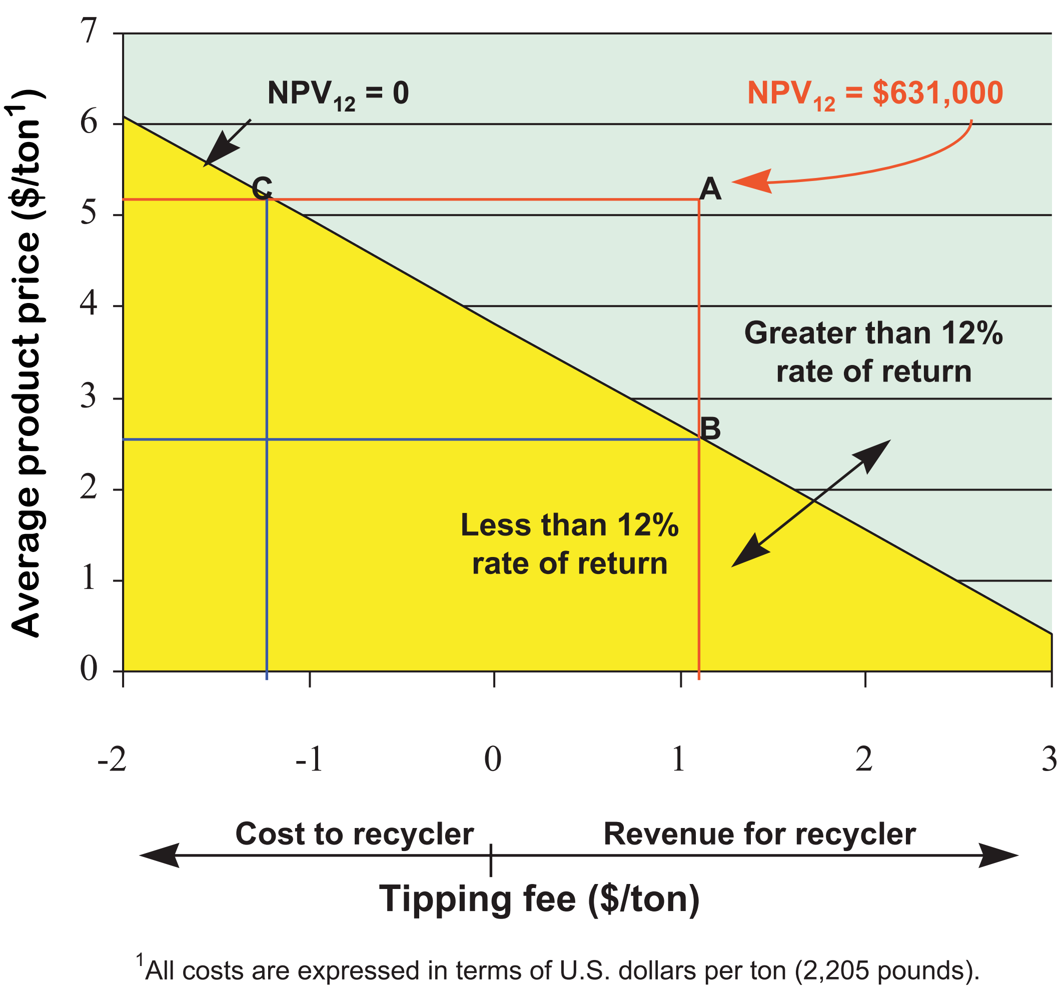


Figure 10. Profitability of a 253,000 t/yr recycled aggregates operation. (Represented by combinations of product price and tipping fee which result in a NPV_{12}=0.)

operation would still achieve a 12 percent rate of return. For the 312,000 ton-per-year operation, the operating cost could increase by $2.92 per ton under the stated conditions and still achieve a 12 percent rate of return.

Figures 9, 10, and 11 were developed based on Denver area costs, product prices, and tipping fees. These figures, however, can be used to represent the product price/tipping fee combinations reported in other areas of the United States to provide an indication of profitability of a recycling operation. Once an appropriate size model is chosen, a particular combination of price and tipping fee can be located on the graph representing that model. For a recycling operation, a positive tipping fee would normally be selected. The intersection point of these two factors would indicate a relative level of profitability one could expect from that operation, depending on whether the point fell to above or below the NPV_{12} = 0 line and the proximity of that point to the line. If the point fell below the NPV_{12} = 0 line, the modeled operation would likely not be profitable, whereas a point falling above the line would indicate the likelihood of earning at least a 12 percent rate of return.

Note that these graphs are based on an assumption that the facility would operate at 88 percent of maximum capacity. Typically, recycling operations seldom operate at a sustained full capacity level, because of periodic shutdowns to remove deleterious material or (if using a mobile plant) to relocate the plant to a new site. Consequently, the level of reported profitability reported by figures 9 through 11 may vary if productivity differs significantly from the assumed rate of 88 percent. In order to determine the relative impact of productivity variation on operational economics, reduced capacity runs for the large-size operation were generated. These showed that a large operation running at about 72 percent of capacity produced the same NPV_{12} = $587,000 value

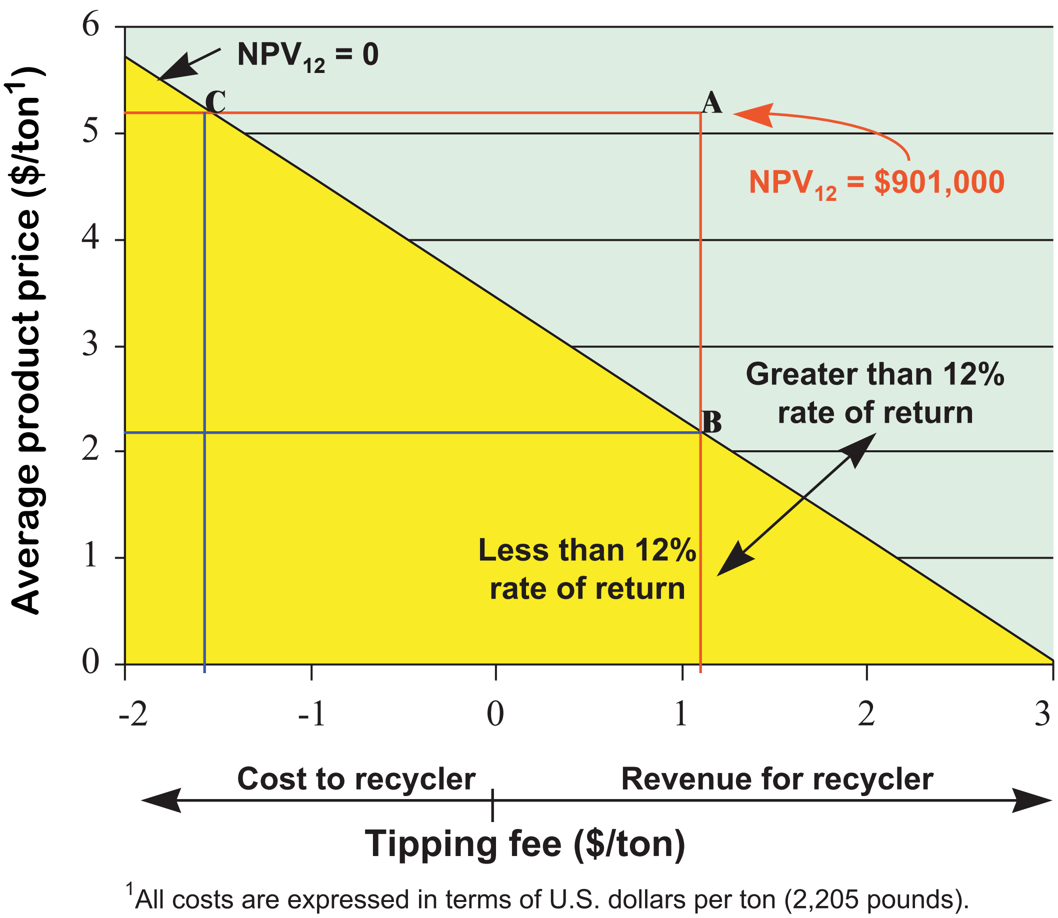


Figure 11. Profitability of a 312,000 t/yr recycled aggregates operation. (Represented by combinations of product price and tipping fee which result in a NPV_{12}=0.)

as a mid-size operation operating at 88 percent of capacity. The closer to its rated production capacity a recycled aggregate facility operates, the higher rate of return it could earn, all other things being equal.

Consequently, one factor affecting the viability of an aggregates recycler is the availability of feed material. If construction debris or other sources of feed are not consistently available, or if there is some seasonality to the availability of local feed material that limits the ability of the recycler to operate at or near capacity, this would reduce the profitability of an operation. The amount of material available for recycling is limited by the size and changing conditions of the "urban deposit." Often recycle supply fails to meet demand for aggregates, so natural aggregates production continues to be the primary source of aggregates in road construction in applications where they can substitute. At best, the contribution of recycled material will grow gradually until all of the available supply is consumed.

Product pricing is often controlled by factors outside the direct control of the recycler. The amount of material presently available from natural aggregate deposits often substantially overshadows the amount of material available from recycling. In the Denver area, for example, recycled aggregates only account for about 1–2 percent of the aggregates market and about 20 percent of the road base market; consequently, prices for road base or asphaltic concrete, the principal end uses of recycled aggregates, are often largely a function of the amount of natural aggregates locally available.

Product quality and uniformity can also pose a risk to the potential recycler. Natural aggregate producers continue to supply the bulk of the material for building and road construction because they are able to supply sufficient high-quality material for a wide variety of higher valued product applications. Unless the recycler has established long-term contracts for consistent, high-quality feed material, it may be difficult for the recycler to maintain a predictable revenue stream because of uncertainty related to future feed availability and quality or market price fluctuations.

The analysis suggests that a small operation (operating at or below a level of 110,000 tons per year) might have difficulty operating profitably as a fixed-site operation (NPV_{12} = -$72,000 under market conditions of product price = $5.23 per ton and tipping fee = $1.10 per ton). Smaller operations appear to be more constrained by negative changes in productivity or market conditions, so must adjust their methods of operation to increase their chances of success. The following examples illustrate methods recyclers have used to do this:

1. They can increase tipping fees or charge higher product prices to increase the amount of revenue generated in markets that can absorb these higher amounts.
2. They can geographically reposition themselves to gain a transportation cost advantage over their fixed-site competitors.
3. They can act as subcontractors to the principal contractor on a job site, operating on land that does not require payment for use. This reduces the operating cost for the recycler and reduces the disposal cost for the principal contractor, thus allowing the contractor to pay a higher fee for recycling. The job-site recycler may then be able to offset the additional costs of relocation and setup.
4. While operating on the site of the prime contractor, the small operator could take on supplementary business on an ad hoc basis, which would spread the costs over a larger output, improve efficiency, and increase revenue to the recycler.
5. When recycling is mandated by States or municipalities (as in California after recent earthquakes) the guaranteed market for the recycler's product removes some of the risk of doing business. In this situation, a contractor must use a specified proportion of recycled material. This may result in higher prices for recycled aggregates than would otherwise be the case.

Increasingly, recyclers are developing creative cooperative agreements with municipalities to ensure a stable supply of material or establish long term markets. Examples of such agreements follow.

PUBLIC POLICY

A complete picture of the aggregates recycling industry cannot be presented without considering the effect of Government policy on this sector. Societal concern for the environment has in recent years resulted in increased emphasis on promoting a more sustainable use of our natural resources. Recycling is considered by many to be one program contributing to such a goal. Local, State, and Federal officials have implemented different methods to promote recycling efforts, contributing to the development of a new and expanding industry. The Texas Department of Transportation (TxDOT) has developed an extensive database recording State recycling activities and incentive programs (Texas Department of Transportation, 1996). Although policies and regulations vary across the United States, all affect the industry by shaping new markets and helping to determine costs. Specific areas of government activity are covered in the following discussion.

Federal Legislation: Several pieces of Federal legislation enacted in recent years have affected the aggregates recycling industry. Such legislation has in effect provided mandates to recycle. The effect of such mandates has been to create new businesses and markets, reduce the risk of uncertainty for the growing industry, and increase competition for existing recyclers.

DeGroot and others (1995) listed examples of Federal legislation that has contributed to the emergence of the aggregates recycling industry:

1. The Solid Waste Disposal Act (1965), as amended by the Resource Conservation and Recovery Act (RCRA, 1970) called for the Federal procurement of products with recycled material content. As a result, most Federally funded construction projects require incorporation of a set percentage of recycled material.
2. The Resource Conservation and Recovery Act (1976): RCRA explicitly recognized that dumping of recoverable materials is a national problem and acknowledged the importance of recycling as part of the Nation's solid waste management efforts. Specifications for secondary materials (such as recycled concrete and asphalt) and revision of existing specifications to include such materials were called for under the Act.
3. The Strategic Highway Research Program (1987): The Strategic Highway Research Program (SHRP) is part of the Surface Transportation and Urban Relocation Assistance Act of 1987. SHRP is a project-oriented program that is targeted to produce performance-based specifications, improved equipment, advanced-technologies test procedures, and training aids that highway agencies can use in the short term to improve the performance of pavements and enhance highway construction and maintenance. The program sponsored efforts to develop technologies to enhance recycling of asphalt and concrete pavement.
4. Intermodal Surface Transportation Efficiency Act (ISTEA) (1991): The U.S. Congress explicitly dealt with the use of recycled materials in transportation through Section 1038 of the ISTEA, which was passed in 1991. This Act is mainly concerned with issues related to asphalt.

State and Local Incentives: In some areas, States and local municipalities are encouraging recycling activities in a variety of ways, while receiving financial benefits. The following summarizes four agreements that serve as recycling incentives.

In 1995, the city of Sunnyvale, Calif., entered into a 5-year contract with Raisch Products to recycle construction debris. The nearest landfill is 43 kilometers from town and charges a tipping fee of $46 per ton. Raisch charges a fee of $11 per ton to process this material (includes materials other than concrete), and produces a product suitable for road base, which is used on municipal road contracts. Under this arrangement, the company has an assured source of feed material while the city receives $120,000 per year plus a percentage of revenue over a certain threshold. The city also benefits from a cost savings of $35 per ton in transportation and disposal charges. Sunnyvale residents are able to dispose of waste driveway concrete free of charge under this agreement (Mark Bowers, City Manager, Sunnyvale, Calif., oral commun., 1997).

The town of Epping, N.H., established a contract with the Environmental Resource Return Corporation (ERRCO) in 1997 under which the town's public works department and local residents supply ERRCO with construction refuse free of charge and purchase end products at discounted prices. The town receives a fee beginning at $0.55 per ton of product, which should generate revenues of about $87,000 per year when the facility reaches full production (Prokopy, 1996).

The State of Iowa, in an effort to increase recycling to 50 percent, awarded a $500,000 grant to a concrete/asphalt recycling operation to demonstrate that it could significantly reduce the amount of construction and demolition debris sent to State landfills. Previously, economics for such an operation were questionable because of the area's relatively low tipping fee of $33 per ton charged by the landfill. Today the landfill diverts 50 percent of its incoming waste to recycling, providing a 32.5 percent reduction in the amount of material that is disposed of at the site. Recycled aggregates are sold for about $1.10 per ton less than locally available natural aggregates (Turley, 1997b).

Flexible contracts have also been used to provide an economic incentive for aggregates recycling. An agreement was reached between a recycler and a contractor in California to supply recycled road base at approximately $1.96 per cubic meter below market price. In return, the recycler was allowed to set up a mobile recycling plant on the contractor's land for free. The contractor was able to obtain aggregates at a discounted rate and could place orders on an as-needed basis, while the recycler was able to set up operations close to ready markets while incurring no land costs. As a result of this agreement, the contractor was able to exceed the 25 percent minimum California recycling mandate.

Local Tax Revenues: The amount of local tax revenue available for infrastructure renewal and local transportation improvement can impact the quantity and extent of aggregates production from both natural and recycled sources. Such revenues and their distribution determine whether there will be enough money to support rebuilding of roads and (or) construction of additional infrastructure, or whether only spot repairs are possible. Spot repair jobs, being small, generally do not meet the job-size requirements to support a recycling operation.

Permits and Fees: Regulatory costs affect the cost of doing business and the competitiveness of recycled aggregates with natural aggregates. Such costs apply to both sectors in different ways, perhaps with less of an effect for the recycling industry.

Federal Highway Budgets: The amount of Federal funding available to supplement local infrastructure budgets and provide funding for research impacting the recycling industry (for example, to create specifications for recycled aggregate products) appears to be increasingly scarce as money and priorities shift. The current trend is to shift responsibility for road construction and maintenance to the States. It is up to State highway departments (with or without Federal grants) to promulgate standards and specifications for the industry.

CONCLUSIONS

The trend towards urbanization in the United States has provided, and probably will continue to provide, a strong demand for high-volume, low-cost aggregates material for repair and development of additional infrastructure. The total demand for aggregates, driven by demographics, urbanization, and the economy, is expected to remain strong in the short term (Tepordei, 1997b).

Recycling of construction materials has grown along with demand for aggregates. Recycled aggregates compete favorably with natural aggregates in many local markets as road base material. Recycling has the potential to reduce the amount of waste disposed of in landfills, preserve natural resources, and provide energy and cost savings while limiting environmental disturbance. Potential sources for recycled material grow as maintenance or replacement of the Nation's infrastructure continues. Because of the finite life of such infrastructure, this "urban deposit" may be considered a renewable resource. The relative costs and charges (tipping fees) of recyclers, their competitors, and landfills determine the amount of material ultimately available for recycling. At approximately $0.13/ton/kilometer, the cost of transportation has a significant impact on the economics of construction operations. It is not surprising that mobile, job-site recycling is becoming common for larger construction projects, as a means of avoiding high transportation, disposal, and new material costs. Even so, the amount of material available overall for recycling is insufficient to meet present industry demand. On a national basis, it is unlikely that recycling will ever completely replace natural aggregates as road base in road construction.

Transportation costs are part of the dynamics that define the market for recycled material, but they most often do not directly affect the profitability of the recycling operation. The supplier of material from the "urban deposit" to the recycler is aware of transportation costs. The amount of material that the supplier will make available to the recycler is based on a calculation that compares delivering and paying a tipping fee to the recycler, to any competitor of the recycler, or to the landfill. Transportation distance and costs are very significant factors in determining the optimum location of a recycler when assessed alongside sources of material, competitors, and customers. General site location dynamics are similar in all areas of the United States, but specific local conditions must be assessed by a potential recycler when developing a business plan.

Based upon economic considerations alone, aggregate recycling should continue. Product pricing and tipping fees are the most significant factors influencing the competitiveness of a recycling operation. Under the conditions specified in this analysis, both medium and large recycling operations can operate profitably because of the tipping fee and lower overall costs. Even so, a combination of economic, social, and legislative factors tend to restrict the use of recycled material to lower valued product applications in road construction.

Slight variations in revenues generated by product prices or tipping fees can affect operational profitability significantly. Equipment capital, operating, and maintenance costs, coupled with plant layout and efficiency, also have significant impact on economic performance. Operator experience in crushing technology, material handling, and efficient plant design are important to success. Although land requirements are typically small for recycling operations, land costs can have a significant impact on economics, particularly for smaller operations.

Aggregate recycling operations often must overcome risks associated with feed and product availability, pricing, and quality. A facility that is able to maintain a high level of sustained production and secure consistent, long-term sources of feed material has a greater chance of success. Similarly, a facility that produces consistent, quality products suitable for diverse markets has a greater opportunity for success.

Recycling operations that would normally not be profitable as fixed-site operations must use creative methods to establish a market niche for themselves. Examples of successful approaches that are being used include (1) operating as a mobile, job-site operation; (2) geographic repositioning to gain competitive advantage; (3) job-site subcontracting; (4) establishing supplemental businesses; (5) State or municipal contracting; and (6) mutually beneficial or flexible pricing contracts. Such entrepreneurial operations appear to be growing in number.

Natural aggregate producers, however, continue to supply the bulk of material for building and road construction, because they are able to supply sufficient high-quality material for a wide variety of higher valued product applications in established markets. Commonly, recycled material does not meet specifications for high-quality applications such as portland cement concrete and top-course pavement, and natural aggregates will continue to dominate these markets. The revenue (tipping fee) that is received for processing construction waste material does, however, enhance the competitive position of the recycler, often allowing new recyclers to successfully enter selected markets such as road base. Recycling operations will not be able to effectively compete as suppliers of these higher quality products unless recycling is made a more attractive option for contractors, either through improved education and awareness, specification changes, or legislative mandates.

The economic benefit for a producer of natural aggregates, which generally relies on its own resource, has a deeper market penetration, and has demonstrated the ability to produce quality products, to begin recycling is substantial. The producer is already supplying a large portion of the road aggregates market. It has the necessary processing equipment and expertise in place to process recycled material (perhaps with minor modifications). Recycled material can supplement natural sources and prolong the life of natural aggregate deposits, thus sustaining the life of the operation. Recycling appears to be profitable and in most cases can meet demand requirements of lower value product applications such as road base, thereby freeing up higher quality material for higher value applications.

Opportunities for new entrants will continue to emerge, but adding new recycling capacity to a market with a limited level of feed material impacts the profitability of all competitors in a given area as downward pressures on product prices and tipping fees are created. A given location has a finite amount of material on which to draw for recycling at one time, and as costs or local regulations limit the distance this material can be transported, recyclers compete for this material, thereby drawing prices and tipping fees down. A new operation coming on line in the same territory might reduce its tipping fee to generate feed supply. If demand is fixed, prices would be expected to remain stable until the total level of local production reached the maximum amount of feed material available, at which time prices would be expected to decline and the less competitive operation would begin to lose market share.

In today's urban setting, a policy maker often must weigh the potential benefits of recycling with competing land-use and development issues. The economic climate for recycling can be improved by making waste disposal in landfills less attractive (imposing higher tipping fees), increasing markets for recycled materials, educating the public as to the benefits of recycling, increasing research and development to improve recycled aggregates quality or show consumers where recycled products are competitive with natural materials, expanding specifications to accept more recycled material where it has demonstrated its ability to compete technically, and facilitating the flow of market information.

Data gaps still remain in assessing aggregates recycling. Reliable data on how much recyclable material is available and how much recycling is actually occurring by industry are needed to quantify future market potential and industry impact. Further quantitative studies of the flow of construction materials such as aggregates are also needed in order to anticipate future economic activity and commodity use.

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APPENDIX 1. STATE CONCRETE RECYCLING ACTIVITY

The following table shows the applications where recycled concrete is used by State.

State	Road base	Portland cement	Rip rap	Asphalt	Drainage aggregates	Backfill	Mandates	Tax credits	Information exchange	Landfill restricted	Loans
AL	Y										
AK	NR										
AZ	E										
AR	E					Y					
CA	Y	Y				Y	X	X	X		X
CO	E		Yb	Yb						X	
CT	Y	Y			Y	Y					
DE	Y					Y					
FL	Y										
GA	Y										
HI	NU										
ID	Y										
IL	Y	Y		Y							
IN	Y										
IA	Y				Y	Y					
KS	Y		E			Y					
KY	Yb										
LA	Y	Y		Y		Y					
ME	NU										
MD	E					Y					
MA	Y										
MI	Y	Y		Y	Y						
MN	Y	Y		Y		Y					
MS	Y										
MO	Y		Yb								
MT	Y	Yb				Y					
NE	Y			Y							
NV	E										
NH	E	Y									
NJ	Y					Y					
NM	NU										
NY	Y										
NC	Y					Y					

E = Experimenting with recycled concrete in this application [TxDOT (1996) and DeGroot (1995)].
NR = no response to TxDOT survey.
NU = No use of recycled concrete in this application [TxDOT (1996)].
X = Information from Moore (1993).
Y = Uses recycled concrete for this application, and has specifications in place [TxDOT (1996) and DeGroot (1995)].
Yb = Uses recycled concrete in this application, but has no specifications in place [TxDOT (1996) and DeGroot (1995)].

State	Road base	Portland cement	Rip rap	Asphalt	Drainage aggregates	Backfill	Mandates	Tax credits	Information exchange	Landfill restricted	Loans
ND	Y										
OH	E										
OK	E										
OR	Yb					Y					
PA	Y										
RI	Y					Y					
SC	Yb										
SD	NU										
TN	NR										
TX	E										
UT	NU										
VT	NU										
VA	Y										
WA	Y				Y	Y					
WV	NU										
WI	Yb										
WY	E			Yb							

E = Experimenting with recycled concrete in this application [TxDOT (1996) and DeGroot (1995)].
NR = no response to TxDOT survey.
NU = No use of recycled concrete in this application [TxDOT (1996)].
X = Information from Moore (1993).
Y = Uses recycled concrete for this application, and has specifications in place [TxDOT (1996) and DeGroot (1995)].
Yb = Uses recycled concrete in this application, but has no specifications in place [TxDOT (1996) and DeGroot (1995)].

APPENDIX 2. AGGREGATES PRODUCTION TECHNOLOGY

PRODUCTION PROCESSES

Natural aggregates are produced principally from crushed stone or sand and gravel deposits similar to the one pictured here.

Figure 12. Typical natural aggregates operation.
(Courtesy of Rocky Mountain Construction, Inc.)

CRUSHED STONE

USE

More than 80 percent of the 1.33 billion tons of crushed stone consumed in 1996 was used as construction aggregates, mostly for highway construction and road maintenance (Tepordei, 1997a). Crushed stone is also used in the manufacture of concrete for road, building, and bridge construction, and nonconstruction applications. Approximately 72 percent of the crushed stone produced came from limestone, about 15 percent from granite, 7 percent from basalt, and the remainder from a variety of other rock types (Tepordei, 1997a).

Construction aggregates are hard materials suitable for forming concrete when a cementing or binding material is added, or used alone in other applications. Aggregates derived from sand and gravel, crushed stone, or recycled sources generally make up the bulk of the volume of the concrete being produced. Although deposits from which crushed stone can be produced are widespread in the United States, they are not available everywhere. Factors such as market availability, transportation distances, local environmental impact, and permitting factors must be considered in site selection. Deposits suitable for concrete aggregates production must meet strict technical specifications related to quality and quantity.

Specifications for crushed stone are developed by organizations such as:

The American Society for Testing and Materials (ASTM)

http://www.astm.org

American Association of State Highway and Transportation Officials (AASHTO)

http://www.aashto.org

U.S. Department of Transportation, Federal Highway Administration (FHWA)

http://www.fhwa.dot.gov

U.S. Army Corps of Engineers

http://www.usace.army.mil

and the various State departments of transportation (DOTs). Product specifications are often mandated for all State or Federal construction projects. Local transportation districts may select specifications suitable for their needs, generally based on State guidelines. Crushed stone specifications may be modified regionally to reflect local climatic conditions and availability of materials.

TECHNOLOGY

Stone suitable for producing a crushed stone product is most often recovered by standard quarrying techniques. Underground operations are occasionally used where suitable and in areas where community resistance to surface mining is high. For most surface operations, once a suitable deposit is selected and acquired, the stone is often recovered by removing any overburden, loosening of the rock by blasting, crushing the rock to the desired size, separation of deleterious material, stockpiling of marketable material of various sizes and grades, and transporting products to market. Depending upon nature of the deposit and rock type, not all of these steps may be required. The capacity of a crushed stone operation in the United States ranges from less than 25 thousand tons to over 5 million tons per year.

The relative layout of the primary and secondary crushers, screening plant, stockpiles, and ancillary equipment determines how efficiently materials can move throughout the operation. Because transportation among resource, processing plant, and markets is one of the most important factors in site profitability, efficient site location and design are critical.

Most crushed stone operations employ surface mining methods to recover the resource. Trucks and shovels are commonly used at larger operations or where material must be moved longer distances or over public roads. Front-end loaders or scrapers are used at smaller operations or where shorter haulage distances are necessary. Draglines may be used where material to be moved is under water and hydraulic shovels may be used where the rock surface is irregular.

The nature and geometry of the deposit determine the drilling and blasting requirements. Operation size may determine whether company or contract drilling is used. Environmental, regulatory, and social considerations also affect type of drilling and scheduling of blasting, particularly if the site is located in or near an urban area.

Crushed stone plants are generally classified as either wet or dry plants, depending upon stone classification, the types of contaminants present, availability of water and land area, zoning, and environmental considerations. In the wet process, clay and contaminants are removed by washing and waste water is sent to settling ponds. Wet plants do not have the dust problems often associated with dry plants, but require a larger site area in order to accommodate the space required for settling ponds. Dry plants often require dust collectors or other dust suppression systems to reduce the amount of dust generated in processing.

Both permanent and portable plants or a combination of the two types may be used, depending upon such things as plant capacity, deposit life, product mix, equipment and space availability, and time constraints. Portable plants are often used to supply stone for specific construction projects, and may be sited at the project rather than at the resource location. Such plants are designed to travel on public roads and are generally used for large projects or where no permanent operations exist. A portable plant may not be as efficient as a comparable permanent plant. A permanent plant is generally preferred when a wide range of products is desired.

Crusher selection depends on a number of factors including rock characteristics, products desired, the quantity and type of deleterious material, screening capacity, and economic factors. Impact and compression crushers are used to reduce the size of stone particles. Impact-type crushers have greater capacity-to-cost ratios than do compression-type crushers, but abrasive stones may cause increased wear on impact crushers.

After crushing, the stone is separated to desired specifications by means of screening, classifying, and washing circuits. Factors considered in designing the circuits include the number and types of products required, the nature of the processed material, amount of wet or sticky material, particle shape, amount of oversize or fine material, the relative densities of each material, and economic factors.

Construction aggregates can be used with or without a binder, such as asphalt. Road base, macadam surfacing material, riprap, and railroad ballast are construction applications that do not require binders. Aggregates for cement and bituminous concrete in highway construction and repair, and residential and commercial construction applications require binder material. The binding agent is generally added at the concrete plant or construction site.

Products of crushed stone operations are often stockpiled prior to sale. Automated stockpile systems require less labor and less equipment for handling the stone, but are higher cost and generally not used at smaller operations. Other factors to consider include the amount of available storage space, transport requirements, plant capacity, and storage time.

Transportation is a major factor in the delivered price of crushed stone. The method of transportation is generally determined by cost and availability. Although trains and barges are used, truck haulage is the most common mode of transportation. Because of the high cost of transportation and the large quantities of material hauled, haulage distances seldom exceed 160 kilometers. Crushed stone is usually marketed locally, although increasing land values, land-use decisions, and environmental concerns are moving crushed-stone quarries farther from end-use locations.

Crushed stone operations are subject to Occupational Safety and Health Administration (OSHA) and Mine Safety and Health Administration (MSHA) regulations and must conform to established environmental regulations pertaining to air, water, noise, and safety. The type of control program selected depends upon the amount and type of dust generated; available water and pond space; local zoning, and environmental regulations; the type of processing utilized, and economic considerations. Special regulations are imposed on siliceous dust, due to potential health risks if inhaled. Regulatory limits vary depending upon location, site design, and the enforcing agency.

SAND AND GRAVEL

USE

Most of the 914 million tons of construction sand and gravel produced in 1996 in the United States was used in construction applications (Bolen, 1997), principally portland cement concrete, road base, asphaltic concrete, and as general fill. Of the material consumed in 1996 with a specified use, about 43 percent was used for concrete aggregates; 23 percent for road base, coverings, and stabilization; 13 percent as asphalt concrete aggregates and other bituminous mixtures; and 12 percent as construction fill. In the United States, sand and gravel production ranks second in the nonfuel minerals industry behind crushed stone and is the only mineral product recovered in all 50 States. The quality of aggregates depends not upon rock type, but rather on physical and chemical properties and subsequent changes related to weathering, tectonic history, or chemical alteration. Suitable material is often found in unconsolidated beach, stream, alluvial, and glacial sedimentary deposits.

The construction industry uses sand and gravel chiefly in concrete aggregates, asphalt, or road base. Concrete mixes commonly contain 15–20 percent water, 7–14 percent cement, and 66–78 percent aggregates (Goldman, 1994). The physical properties of sand and gravel most significant for concrete use include abundance and nature of fractures and pores, particle shape and surface texture, and volume changes resulting from weathering, freezing, or thawing. Nonreactive mineral and rock particles that are strong and capable of resisting weathering without decomposition are suitable candidates for concrete. Asphalt concrete mixtures predominantly used for paving consist of sand, gravel, and mineral fines coated with asphalt derived from the refining of petroleum. Crushing is generally required in high-quality asphalt applications to provide freshly fractured faces that provide maximum adherence for the asphalt binder.

Concrete aggregates have to meet physical and chemical requirements and specifications similar to those for crushed stone. Materials used in construction and transportation applications must conform to appropriate Federal and State specifications related to characteristics of abrasion, soundness, specific gravity, size and grading, reactivity, absorption, durability, and sand equivalent. Sand and gravel specifications may be modified to reflect local climatic conditions.

As with crushed stone, sand and gravel are a high-volume, low-unit-value commodity with an industry characterized by thousands of operations serving local and regional markets. Resources are widespread but shortages exist locally, either because the resource doesn't exist in an area, or because of land-use conflicts and environmental concerns associated with rapid urbanization. Deposits are recovered by standard surface mining techniques. Ideally a commercial deposit would contain about 60 percent gravel-sized particles and 40 percent sand-sized particles, where the gravel would be used for road base or bituminous aggregates and the sand would be used for making concrete. This ratio can vary significantly, however, depending upon deposit makeup.

TECHNOLOGY

Sand and gravel deposits are mined with power shovels, draglines, front-end loaders, or dredges. The choice of excavating equipment depends upon operation size, resource type, economic considerations, and whether the resource is mined by wet or dry methods. In a dry operation, shovels, loaders, or draglines load the sand and gravel into trucks or onto conveyor belts for transfer to the processing plant. Because the material is unconsolidated, drilling and blasting are generally not required. A wet operation recovers sand and gravel from deposits below the water table. The material is excavated by a land-based dragline, floating dredge, or hydraulic mining operation. Conveyors or pipelines transport the slurry to adjacent processing plants.

Commercial processing plants are most often located at the resource, where blending can be performed to produce a variety of products. As with crushed stone, processing consists of crushing, screening, and washing. Sized material is then stockpiled based on product requirements prior to transport to market. Plant capacities range from less than 23,000 tons for small, intermittent operations to more than 4.5 million tons per year. Most operations are small, turning out one product or a limited range of products, but the bulk of total U.S. production comes from large operations.

Most plants are designed to produce different products. There is usually a dry side, where material is crushed and screened for use as road base or bituminous aggregate, and a wet side, where sand and gravel are washed and screened for use as concrete aggregate. A jaw crusher is commonly used for primary size reduction. Gyratory, roll, or impact crushers further reduce the size of the gravel. Rod mills are used to manufacture sand to supplement natural sand that is deficient in fine sizes.

The sand fraction is ordinarily washed and classified in spiral classifiers. Cyclones may be used to recover fine sand from classifier overflow. Settling tanks may be used to separate sand into various sizes. The desired blend of sand is then drawn off and dewatered in a second series of spiral classifiers. Plants processing clay-rich material may use scrubbers or log washers to remove the clay. Mechanical vibrating screens separate the gravel into appropriate sizes. Heavy media separators are used where soft porous particles such as shale are present. Jigs may also be used in selected applications.

For large construction projects or in remote areas where no permanent operations exist, a semi-mobile plant may be set up, which will remain at the construction site until completion of a specific project, then relocated to the next project. In urban areas, however, most production is done from permanent facilities. It is common for asphalt concrete and ready-mix concrete plants to be located at the sand and gravel production site.

Because transportation makes up a significant portion of the overall cost of sand and gravel operations, most construction sand and gravel continue to be marketed locally. Truck haulage is the main form of transportation; approximately 79 percent of sand and gravel products is transported by truck. Only a small percentage is transported by either rail or barge. Approximately 16 percent of construction sand and gravel is not transported, but used at the production site (Socolow, 1995).

Sand and gravel operations are also governed by OSHA and MSHA regulations. As with crushed stone, regulatory requirements vary depending upon location and the enforcing agency.

RECYCLED AGGREGATES FROM CONCRETE

USE

As recycling of construction materials increases, aggregate producers, building contractors, and road paving contractors are recycling a greater amount of material each year. In 1996, a total of 1.2 million tons of cement concrete was reported to be recycled by 43 aggregate producers in 16 States (Tepordei, 1997a). These figures do not include the numerous recyclers not associated with natural aggregates production. It is estimated that about 7.3 million tons of scrap concrete was recycled in 1996, principally as road base (T. D. Kelly, oral commun., 1997). Recycled aggregates presently represent a small fraction of the total amount of aggregates consumed, but recycling potential increases as the amount of material available from traditional sources is increasingly affected by regulation and land-use issues.

Recycled concrete has many applications in road construction. It is commonly used as road base; 44 States allow recycled concrete in road base applications (TxDOT, 1996). Growth in the use of recycled concrete for retaining wall backfill, portland cement concrete mix, landscaping rock, drainage aggregates, and erosion control is also occurring.

Sources and the nature of recycled material can vary over time from project to project: the “resource” is the material being recycled. Each construction project requires material that meets specific specifications; therefore, the recycler must be able to adjust material feed to meet those specifications. As with crushed stone and sand and gravel operations, specifications are developed by a variety of Federal and State agencies, and often vary considerably by location and climatic conditions.

TECHNOLOGY

Processing of recycled material is a relatively simple process, but one that can require expensive, heavy-duty equipment, capable of handling a variety of materials. Technology basically involves crushing, sizing, and blending to meet the required product mix. Concrete and asphalt recycling plants can be used to process natural sand and gravel, but sand and gravel plants cannot process recyclable materials efficiently in most cases. Much construction concrete contains metal and waste materials that must be detected and removed at the start of processing by manual picking or magnetic separation. Feed for recycling may be non-uniform in size or composition, so equipment must be capable of handling variation in feed materials. Equipment must be versatile yet efficient for a variety of materials. Figure 13 pictures a typical construction site recycling operation.

Location, equipment selection, and plant layout are in many cases critical to the efficiency of a recycling operation. Equipment size and type impact project performance. Items that need to be considered for both stationary and portable plants include the amount of space the plant requires, potential for fines bypass, crusher discharge area considerations, magnetic separation requirements and effectiveness, debris removal, and dust control. Portable plants need to consider the ability to set up and relocate the plant easily and quickly and must be small enough to fit on existing roads and under overpasses.

Most recycling occurs in urban areas with access to adequate transportation routes and infrastructure. Whether a mobile or a fixed plant is used, the site of the recycling

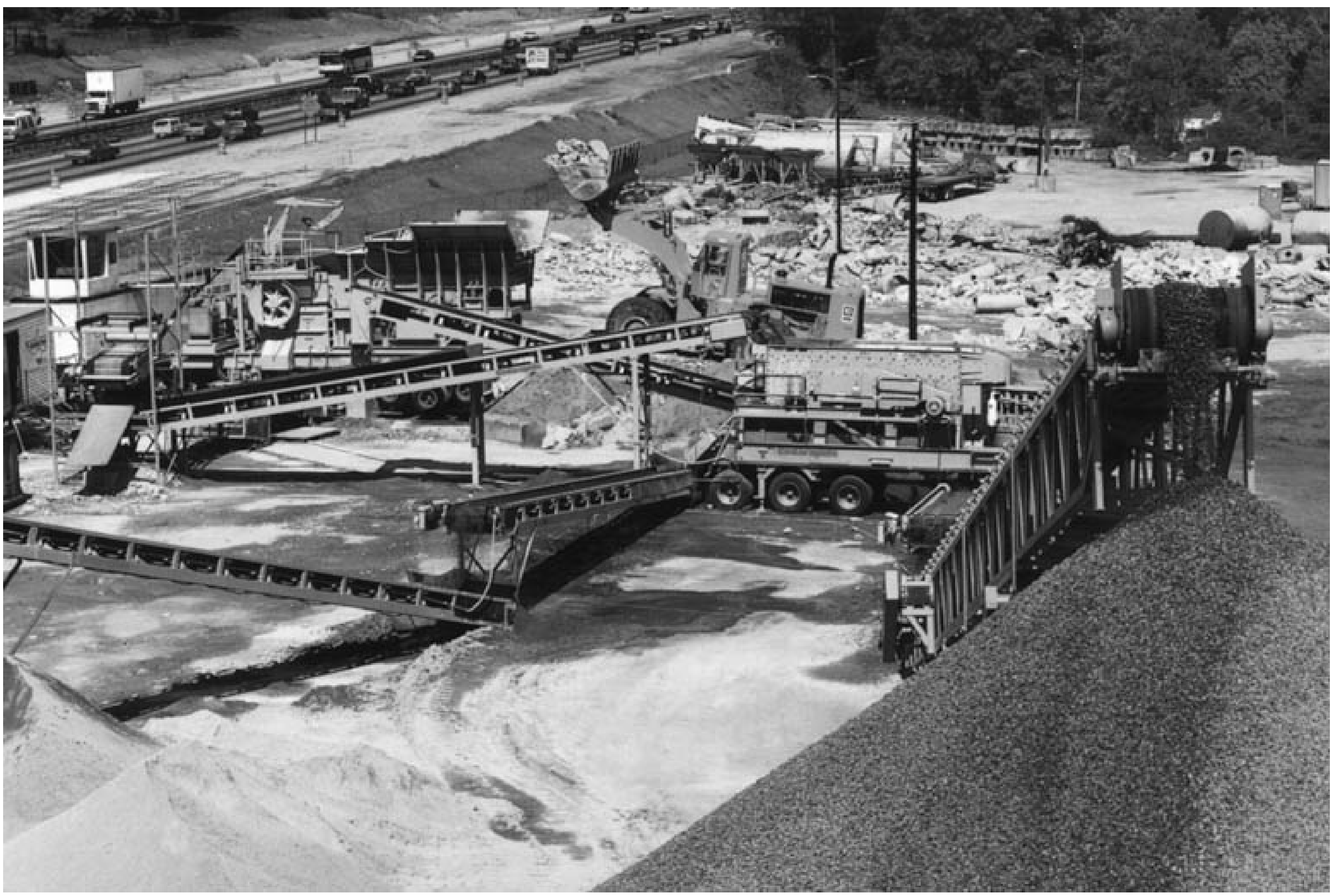

Figure 13. Typical recycled aggregates operation. (Courtesy of Cedarapids.)

operation must be located close to sources of raw materials and product destinations. Permanent plant sites tend to be small in area, usually between 2 and 4 hectares. Even with mobile sites, a small quantity of land is usually required for resource and equipment storage.

Moving and setup for portable plant affect profitability. Such operations frequently move 4–20 times a year, and time taken for transport and setup results in lost production. A shorter transportation and setup time minimizes the impact on cash flow.

Recycled concrete can result in more wear on equipment than some forms of natural aggregates, depending upon the rock type from which it was derived. For example, a crushed stone producer may get a 10-year life out of a conveyor belt, whereas a recycler may only get a 6-month life out of a similar belt because of the physical characteristics (coarseness, angularity) of the processed material and the presence of deleterious material (such as rebar or wire). Recycling also requires more labor than natural stone production on a per unit basis, as pickers are required to extract debris from the concrete being reprocessed.

The principal step in processing recycled concrete is the crushing of the material, generally conducted in two stages. Several types of crushers are used in recycling; each type has advantages that must be considered. Table 5 outlines some combinations and considerations for this equipment.

A two-stage crushing system is generally preferred unless the operator is doing multiple small projects. For small asphalt projects or where concrete does not contain rebar or other debris, a portable single trailer operation may be suitable. Feed material must be free from debris and the feed must be fairly uniform in composition.

Material to be recycled can be dumped directly into the primary crusher; however, a grizzly can be placed ahead of the crusher to increase production and reduce crusher wear. Dirt and fines generated from the grizzly may be separated by the loader operator prior to crushing, and stockpiled as waste, eliminating the necessity to process this material further. Spacing between the grizzly feeder and the crusher must be sufficient to allow long slabs of concrete to dip into the crusher. Careful inspection of feed for deleterious material by the loader and crusher operators can prevent work stoppages and prolong crusher life.

A crusher discharges onto an underlying belt conveyor. Clearance between the two pieces of equipment should be at least 122 centimeters; larger distances allow long pieces of

Table 5. Crusher combinations commonly used in concrete and asphalt recycling.

Category	*Jaw/cone combination*	*Horizontal-shaft impactor*	*Jaw/roll combination*
Capacity	180 - 360 tons per hour.	<90 - 360 tons per hour.	220 - 320 tons per hour.
Versatility	Jaw crusher can handle rebar and wire mesh; cone crusher cannot; wood a problem for both.	Accommodates wide variety of feed material.	Accommodates rebar and wire mesh.
Wear on equipment	Amount of wear on equipment is low.	Wear higher than jaw/cone combination.	Wear low for jaw crusher; wear for roll high if aggregates are abrasive.
Primary feed	Accommodates concrete; less suitable for soft asphalt concrete.	Mainly suitable for asphalt.	Accommodates both asphalt and concrete materials.
Dust control	Easy to control	More difficult to control	Easy to control.
Capital investment	High	About half of jaw/cone	High.
Labor requirement	Semi-skilled	Skilled	Semi-skilled.
Other	Maintenance critical on cone crusher.	Wide variation in crusher design.	Not applicable.

Adapted from Justice, 1993.

rebar to fall free of the crusher without jamming the machine. A smaller clearance height may be necessary on portable plants to allow for transport and bridge clearance. Material is often hand picked at this point to remove waste material.

Magnets are an important piece of equipment when recycling concrete, as they aid in the removal of rebar and wire mesh commonly found in concrete demolition debris. Separator design and layout are important; separators commonly used in other mining applications often have features (pulley design, metal belt, for example) that are costly in recycling (Busse, 1993). For optimum efficiency, the conveyor beneath the magnetic separator should be running at the same speed as the separator belt.

Once the material has undergone primary crushing, it generally is screened to separate usable sizes of material from waste. Screens that maximize open area are generally the most efficient but wear out rapidly in recycling operations. Screened material is either sent to a secondary crusher, conveyed to stockpiles, or sent directly to the construction project as feed.

Debris removal at a recycling facility can be minimized but not eliminated. Operators at permanent plants can be selective in the materials accepted, but portable operations accept most of what is available for reprocessing on-site. For both plant types, manual picking stations located both prior to crushing and during screening separate out rags, paper, wood, and other debris. At sites that process various materials, the loader and crusher operators can also serve to sort, blend, and keep the feeder properly filled, improving the productivity of the operation.

Because recycling operations are often located near construction sites in urban areas, the need for good dust control becomes increasingly important. An engineered water spray system with a wetting agent can meet most regulatory agency requirements for dust control. For dusty crushers, a baghouse may be used. Small baghouses designed for portable crushers and smaller stationary operations have been shown to meet regulatory requirements.

RECYCLED AGGREGATES FROM RECLAIMED ASPHALT PAVEMENT

USE

In 1995, a total of 1.6 million tons of asphalt concrete was reported as being recycled by 62 companies in 26 States (Tepordei, 1996c). Although only a small fraction of the total material available is reported to be recycled, it represented a 92 percent increase over the amount recycled in 1994. An estimated 45.4 million tons of scrap asphalt pavement was recycled in 1996 (T.D. Kelly, oral commun., 1997). Asphalt plants allow up to 45 percent of the product to contain recycled material from reclaimed asphalt pavement; recycled material typically makes up 20–25 percent of the asphalt concrete mix in most U.S. locations. Parking lots may utilize up to 100 percent of recycled asphalt material in selected hot-mix applications.

Applications for recycled asphalt concrete in road construction include pavement hot-mixes, road base, parking lot and residential driveway surfacing, and road shoulder work. Technical specifications for recycling asphalt concrete are similar to those of primary asphalt concrete; local or State specifications must be met for each construction project. Often, specifications are different depending upon location or application.

TECHNOLOGY

Site location and equipment selection criteria are similar to those reported for recycled concrete operations. Much of the equipment has been adapted from rock crushing applications, with modifications for efficiently handling the oil-based asphalt mixture. As with concrete recycling, technology basically involves crushing, sizing, and blending to meet the required product mix. Crusher types used for asphalt concrete recycling are reported in table 5. As with concrete recycling, much feed material is not uniform in characteristic and composition, so the equipment must be able to treat a wide variety of materials and remove nonrecyclable debris. Although smaller jaw crushers have been used at some operations, it is generally agreed that unless the operation is a portable one, the bigger units provide better wear and productivity than smaller units (R. Hawkins, oral commun., 1996). For portable operations, the size of the unit should generally be as large as local movement restrictions allow.

When recycling asphalt concrete, operators make provisions for removing dirt from the feed material. A grizzly feeder located prior to the crusher can accomplish this task. Dirt removal can also reduce the moisture content of the asphalt concrete and reduce the amount of asphalt that adheres to the machinery.

Asphalt is often cleaner and easier to separate than cement concrete debris. In many operations, loads of asphalt are processed separately from loads of cement concrete debris, using the same equipment.