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COST EFFECTIVE ANALYSIS OF RECYCLED PRODUCTS FOR USE IN HIGHWAY CONSTRUCTION

ODOT Project No. 14602 (0)

by

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16. Abstract

Over 4.5 billion of non-hazardous wastes are generated in the United States each year. Out of these waste over 200 million tons of post consumer waste is generated. The disposal of post consumer waste is the responsibility of municipality and society. Four waste materials glass, plastic, rubber tires and paper & paperboard were selected for the detail study.

A questionnaire survey was conducted for obtaining input from all state Department of Transportation (DOT), Recyclers and solid waste management facilities in the state of Ohio. Responses received from state DOT stated that they use various recycled materials in highway construction but do not conduct cost-effectiveness analysis of recycle waste materials.

The cost of disposal of post consumer waste is increasing, which requires an alternate use for these waste materials. One possible use of these post consumer waste materials is in highway construction. An economic analysis is needed for their cost-effectiveness before using these materials in highway construction. Though these recycled waste materials are expensive compared to virgin material, but consideration of the savings in terms of societal cost make these materials become cost-effective and attractive to use in highway construction.

Concepts of marginal costs and marginal benefits are used in developing the cost-effective analysis of recycled materials. The recycled waste material will be competitive with the new material if costs such as disamenity costs of disposal and landfill costs are added to the material. Benefits from recycling are numerous such as the revenue generated from recycling and sale of material, avoidance of disposal costs, and improvement in environmental quality. Revenue from sale of each material is treated as a reduction in costs. Combining all costs together provide a platform to develop a marginal benefit function for recycling. A computer program was developed using Microsoft(T) Access to provide a tool in making an economic decision.

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DISCLAIMER STATEMENT

The contents of this report reflect the views of the author(s) who is responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Ohio Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

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CHAPTER 1

INTRODUCTION

1.1 Waste Problem

One of the major concerns facing the industrialized world is the production of enormous quantities of waste and the problems associated with its disposal and reuse. The handling and disposal of solid waste is an important societal issue because of several reasons. One of the major concerns is that the space available in landfills is being rapidly used up and the cost of land for new landfills is constantly increasing. Another major concern is the increased costs of compliance with new environmental regulations and the depletion of natural resources.

Each year, approximately 4.5 billion tons of non hazardous solid waste is produced in the United States [1]. These solid wastes are broadly classified into four categories: agricultural, domestic, industrial and mineral solid wastes. Table 1.1 provides a summary of the estimated quantities of solid wastes by categories. Generally wastes generated by agricultural and mineral categories do not create a disposal problem. Only the wastes under domestic and industrial category have a disposal problem. Industrial wastes are regulated and industries have to find a solution for their own wastes disposal. Because of the strict regulations and enormous costs of disposal, industries are developing a 'Zero Waste' methods. The generation of domestic waste is approximately 200 million tons annually and poses an enormous disposal problem. Until recently bulk of the domestic waste was transported to landfill for disposal. The domestic waste is also

Table 1.1

Estimated Generated Quantities of Solid Waste Materials by Category in the USA, in 1994.

Category	Annual Quantity (Million tons/ year)	Potential Use in Highway Construction
Agricultural	2100	None
Domestic	200	Yes
Industrial	400	Yes
Mineral	1800	Yes
Total	**4500**	

called a post consumer waste. It mainly consists of paper and paperboard, plastics, yard waste, incinerator ash, scrap tires, compost and used oil. Table 1.2 lists production and uses of domestic wastes by highway agencies [1].

States and Counties dedicate a large percentage of their budget for solid waste management. Increased quantities of waste disposal and its associated costs have forced public agencies to reevaluate the problems associated with disposals. Furthermore, there is a growing concern among people about the environment and the effect of indiscriminate dumping. A strong environmental awareness for preservation of the natural resources has a profound impact in the development of disposal plans.

1.2 Recycling

The environmental awareness and depletion of natural resources have provided a push to the business of recycling, reuse and waste recovery. Also the recycling of waste materials has been recognized as containing the economic value of materials disposed and the concept led to full-grown industry. The added advantages of recycling are reduced volumes that translate to reduced disposal costs, and conservation of natural resources. Since highway agencies use large quantities of material in highway construction, thus usually they are the first in promoting the use of recycled materials. Historically, these agencies have developed programs to recycle and reuse asphalt and concrete in highway construction.

Table 1.2

Generated Materials and Uses of Domestic Wastes in 1993

Waste Type	Amount Generated Annually	Uses (by Highway Agencies)
Incinerator Ash	8.6 million tons	Asphalt paving aggregate Cement stabilized aggregate Vitrified aggregate Masonry block
Sewage Sludge	8 million dry tons	Land application Compost Stabilized dike material
Metals	17.4 million tons	
Scrap Tires	6.2 million tons	Tire-derived fuel Asphalt fine aggregate Asphalt rubber finder Stress-absorbing membranes Rubberized crack sealant Lightweight fill material
Compost	2.5 million tons	Mulching material
Glass and Ceramics	13.7 million tons	Glass cullet Unbound base course Pipe bedding material Asphalt fine aggregate
Plastic Waste	19.3 million tons	Fence and sign stops Plastic lumber Delineators Asphalt-cement modifier Geo-textile manufacture Composite pipe pilings
Used Motor Oil	2 million tons	Recycled as lubricant Fuel in asphalt plants
Paper and Paperboard	77.8 million tons	Recycled paper or cardboard Mulching material
Recycled Refuse from Sanitary Landfills and other waste	49.6 million tons	Core material in medians Embankment construction

Source: **Reference 1**

A recycled waste material in highway construction must meet two criterions. First, the material must meet quality and structural specifications and second, the use of recycled material must be economically justified. The cost of recycled material must be comparable to that of the virgin material.

Besides these considerations, the environmental consequences with respect to recycling and reusing waste materials are important. The use of waste material should not threaten the environment nor it should pose a threat to public safety. Thus, the long-term use of waste materials in highway construction will depend on the cost effectiveness, performance, and environmental considerations of the materials.

A considerable research has been made to investigate the possibility of using waste materials in highway construction. A summary of the uses of waste materials and by products is presented in Appendix A.

It is becoming increasingly expensive to find and get approval of new landfill sites. Also many states have enacted state laws that require the use of certain materials in highway construction. This has been done to increase recycling and thus diverting wastes from landfills. Some of the most common materials used in highway construction are:

- Reclaimed pavements (both asphalt and concrete) are the most commonly used waste materials in highway construction. However, there are environmental concerns about air pollution as a result of asphalt pavement reclamation. Their performance has been satisfactory, though they are still doubts about their cost effectiveness.

- About 242 million rubber tires are generated every year in the U.S. Their storage and disposal has become an environmental concern. Because of their inflammability, and disease causing potential, etc.
- Waste glass is produced in large quantities in the U.S. Glass has been used in asphalt, paint etc.
- Demolition debris has been used as a fill material by many states.
- Waste paper has been identified as a possible fill material and in landscaping.
- Slags have found use in asphalt mixes as fillers.

1.3 Research Objectives

Considerable amount of literature is available regarding the use of waste materials in highway construction. Most of the literature does not discuss the cost effectiveness of these materials. Also most studies did not focus on the accrued benefits to society for keeping the waste out of the landfill. It is necessary to identify and document societal benefits of recycling, so that the recycling of waste materials is cost effective and competitive to new materials.

From an economic standpoint, the cost of incorporating waste materials is higher, in some cases significantly higher than the costs of conventional materials. To justify the use of these materials, these materials need to be cost effective and close to the cost of conventional materials. Also these materials should be suitable for the intended purpose i.e., in terms of the structural and environmental specifications. Thus there is a strong need to list all the waste products that have resulted in performance superior to or at least equal to that of conventional materials. There is also a need for documentation for the possible societal costs, environmental impact costs, and the technical feasibility of the use of such materials.

The specific objectives set for the research project were:

1. To determine what recycled products are successfully being used by state Departments of Transportation.
2. To document the physical properties of recycled materials and to prepare a bibliography of references.
3. To determine what methods are used by state agencies to justify the cost effectiveness for these waste products.
4. To conduct a literature search to document methods used in recyclable waste products.
5. To identify various cost elements (such as salvage value, disposal considerations, storage, processing, etc.) that are associated with each waste product.
6. To select a list of waste products that has potential use in highway construction and conducts a cost-effective analysis.
7. To develop a model incorporating marginal costs (to indicate reduced waste, environmental benefits, future recyclability and disposal concerns, impact on existing industries, etc.) for the use of waste products in highway construction.
8. To develop a look up table of cost effectiveness for each of the waste products (such as rubber tires, plastic, steel, aluminum, glass, paper, fly ash, oil, etc.) with respect to the virgin material and the environmental impact costs.

CHAPTER 2

LITERATURE REVIEW

2.1 Municipal Solid Waste Generation and Problem

Municipal Solid Waste (MSW) is composed of materials that are generated by people in their daily lives at home, at work, and at other sites such as schools, restaurants, retail stores, etc. The MSW does not include construction and demolition debris, industrial wastes or certain other wastes. The increase in population contributes to increased quantity of MSW. However, the growing MSW generation can only be partially explained by the growing population, because MSW generation is growing at a faster rate than the population as it is evident from Figure 2.1. During the last 33 years from 1960 through to 1993, the population increased by 1.08 percent whereas, the generation of MSW grew by 2.66 percent [2]. The USEPA reports that the per capita generation of MSW has increased from 2.66 lb./person/day to 4.39 lb./person/day in 1993. It is projected to level off at 4.32 lb./person/day in the year 2000, due to decrease in yard wastes entering the MSW.

2.1.1 Solid Waste Disposal Options and Costs

In the United States, average household generates about two tons of MSW per year. The disposal costs vary across the country depending on number and availability of waste disposal sites and other local factors. New waste disposal sites are not added in the same proportion to meet the MSW demand. Waste disposal sites has a finite number of years of life. Generally it is in the order of 10 to 20 years. In future, there will be few

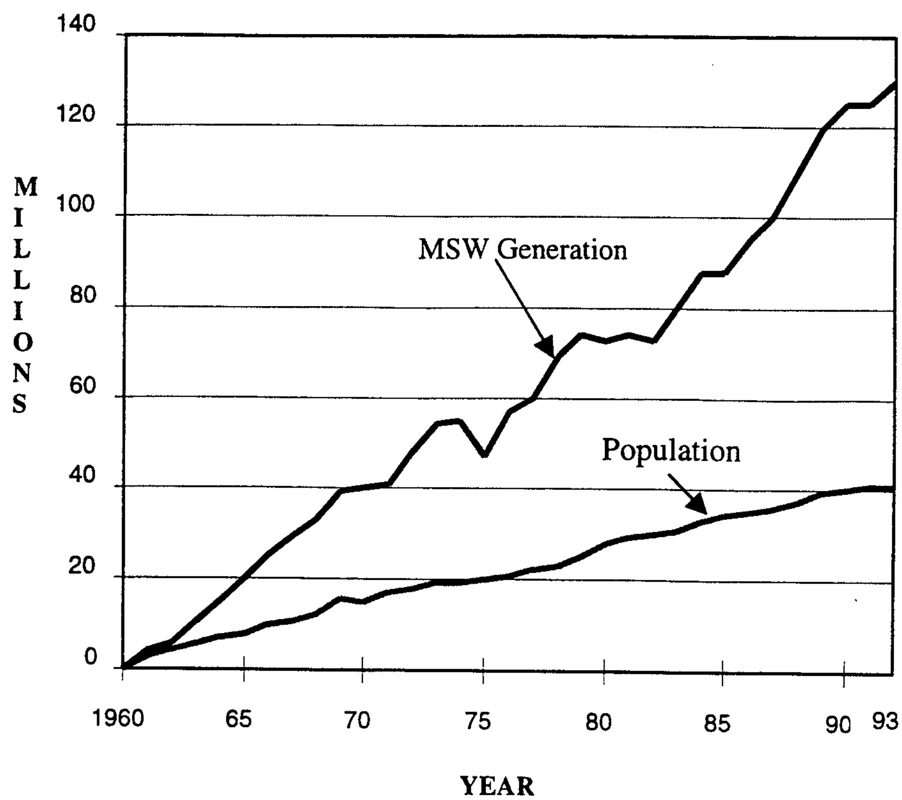


Figure 2.1: **Trend in Population Growth and Municipal Solid Waste Generation in the U.S.A., 1960-1993**

new solid waste disposal sites, as people are not willing to accept a landfill in their neighborhood.

In the United States, waste disposal through landfill is still the dominant method of disposal for MSW. In 1986 about 83 percent of the MSW generated was landfill, while only 10 percent was recycled. By the year 1990, wastes disposal in landfill had been slightly reduced while recycling increased to 13 percent. In the last twenty years, from 1970 to 1990 the number of landfills in New York has dropped from 1600 to 300. During the same period the number of waste disposal sites in Ohio has decreased from 360 to 120. Figure 2.2 shows the decreasing trend in the number of licensed disposal facilities in Ohio.

Solid waste disposal is a $20 billion industry in the United States, and $5 billion of that is spent in the landfill operation [3]. With decrease in the number of landfill sites, the average tipping fee is on increase. The average tipping fee in Ohio has increased from $20 to $30 per ton since 1989 and is shown in Figure 2.3.

2.2 Questionnaire Survey

A questionnaire was developed to receive input on the use of recycle waste in highway construction from various states DOT. To achieve the objectives of the study, a questionnaire was sent to various state department of transportation (DOT) to obtain information on the use recycled material in highway construction. The state DOT's were also questioned for the laws or mandates requiring their use, and their cost effectiveness. Appendix B shows the questionnaire.

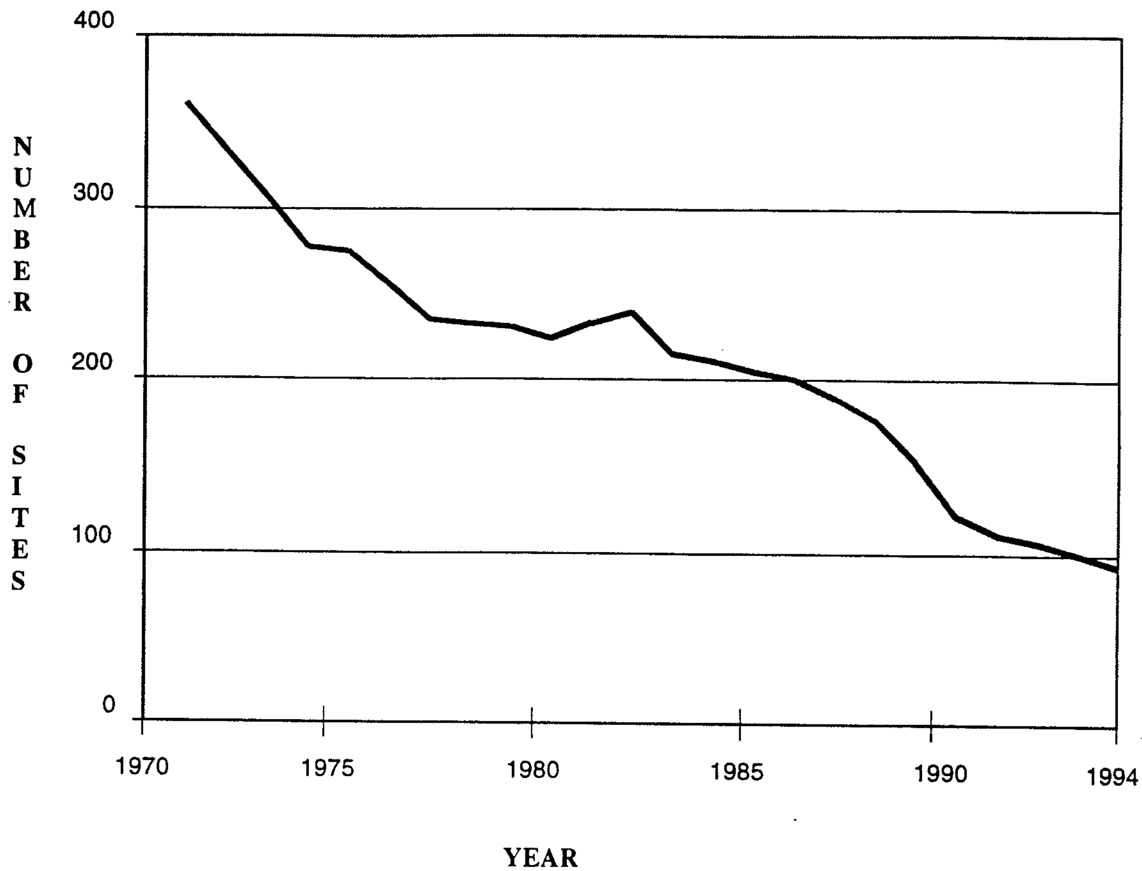


Figure 2.2: Trend in Number of Licensed Disposal Facilities in Ohio.

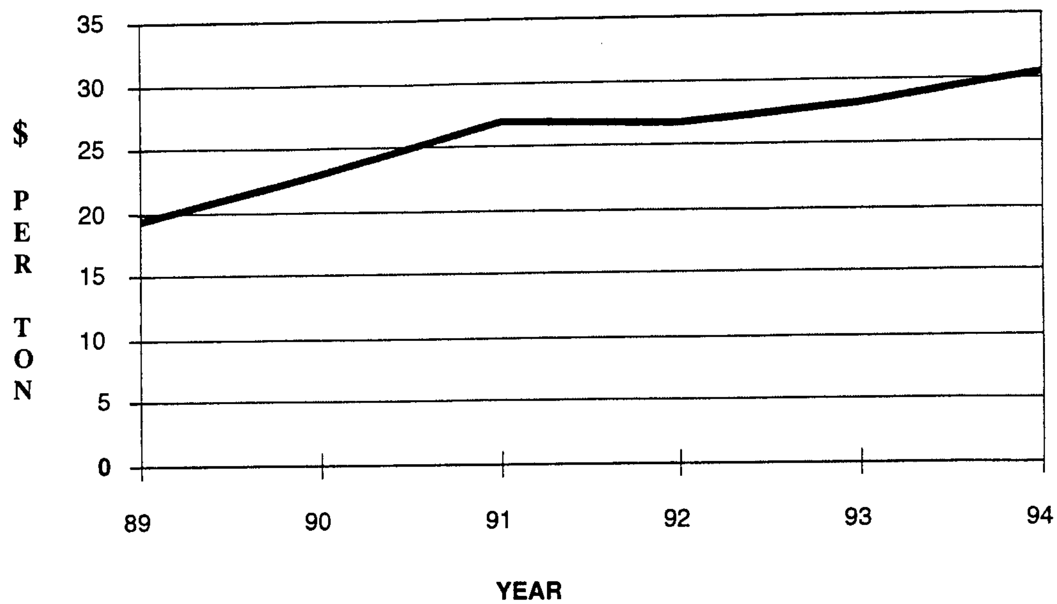


Figure 2.3: Trend in Tipping Fees in Ohio

A total of thirty two states responded to the questionnaires. A summary of usage of waste materials by state Department of Transportation (DOT) is shown in Table 1 in Appendix C. A brief conclusion regarding the usage of waste materials by the state DOT's are given below.

2.2.1 Materials Usage

1. No state uses Phospho-gypsum, Phosphate slimes, or coal refuse.
2. Lime dust and cement dust are used by only one state (Missouri) for soil stabilization
3. In addition to the list of materials sent to the states, some states have indicated that they use other waste materials such as coal ash, silica fume and asphaltic concrete.
4. Only two states have indicated that they use non ferrous slags.

2.2.2 Cost Effectiveness

1. Most states did not provide any information on the economics of using waste materials. Some states such as Illinois have expressed that they aren't concerned whether the material is cost effective or not. It is the contractors' prerogative to use the material if they find it economical.
2. Some states have provided information regarding the cost effectiveness of these materials. States that use rubber tires as CRM found that it is not cost effective. They are using it because it is mandatory. State of New-York reports the use of rubber in sealants is economical.
3. Some states have reported the use of fly ash is economical while others have reported that it is not economical. Also there have been mixed reports on the usage of Recycled Asphalt Pavement (RAP). States such as Nebraska,

Minnesota, New Jersey, Tennessee reported that the RAP is not cost effective, whereas most other states find it cost- effective.

4. Recycled Portland Cement Concrete (RPCC) is reported as being cost effective by almost all states that have used it.

5. Most states have not commented specifically on the cost effectiveness of slag. It is a common understanding that the use of slag is economical. However, Minnesota and Wisconsin find steel slag is not cost effective whereas Indiana reports that blast furnace and steel slag is cost effective.

6. There are mixed reports on the cost effectiveness of mine tailings and silica fume.

Based on these reports, it can be concluded that though the use of waste materials in highway construction is fairly extensive, but no work has been done to investigate on cost effectiveness. The economics of using waste materials have been investigated only on project by project basis, and sometimes not at all.

2.3 Composition of Solid Waste in Ohio

The composition of solid waste varies widely across Ohio depending on intensity of economic activities in the area. In 1993 residential/commercial wastes were 54 percent, whereas industrial waste was 46 percent of the total waste generated in Ohio [4]. The 1993 data shows that the recycling rates vary widely in Ohio from 2 percent for Adams/Clermont solid waste management district (SWMD) to 75 percent for Henry county SWMD. The average statewide recycling rate was 32 percent [4]. The average statewide recycling rates for industrial waste is 67 percent and for residential/commercial waste is 32 percent of the respective category of waste.

2.4 Landfill or Recycle

There is a growing public awareness regarding landfills, waste disposal sites, waste generation, environmental regulations, and its associated costs. Society in general has become environmentally conscious in preserving natural resources. Until recently, it was less expensive to dispose of waste materials in landfills, than to recycle. An improvement in recycling technology has brought recycling costs substantially down. Also there is a growing trend that waste management should be considered as an economic activity. Thus, it warrants that available alternatives for waste disposal should be considered to assess them in monetary terms.

2.5 Methods of Economic Analysis

2.5.1 Life Cycle Costs

The basic premise of this method is to assign some monetary value to every aspect of a project [5]. This would include such aspects as landfill costs, potential legal penalties, degradation of air quality, and so on [6]. Life cycle costs include the initial cost, the maintenance costs over the life, and the salvage value associated with the product at the end of its life. Another approach specified in EPA's Pollution Prevention Benefits Manual is called full cost accounting. This method tries to reconcile some of the weaknesses of life cycle costs.

2.5.2 Benefit Cost Analysis

Benefit cost analysis is the systematic appraisal of all benefits and costs of a contemplated course of action, or of several alternative courses of action [7]. In simple terms it means that a particular course of action is undertaken only if the sum of all its benefits is more than the associated costs with it. A benefit is defined as the value of a good or a service provided to a consumer, and a cost is defined as a foregone benefit [7].

2.6 Societal Waste Disposal Cost

Current production and consumption techniques of firms and households indirectly pass on waste disposal costs to society [7]. The indirect waste disposal cost is not perceived by individuals thus has created present environmental problems. Waste disposal costs may be thought of as a combination of pollution prevention costs and pollution costs. Pollution prevention costs are the costs incurred by firms or the society in controlling or preventing pollution. Pollution costs are the costs incurred by firms and society in cleaning up after pollution has occurred; this also includes the welfare damage due to the pollution. The full welfare costs of pollution damage are impossible to measure accurately because it consists of many intangibles such as health effects and impact on nature. However, waste disposal costs or pollution prevention costs are real opportunity costs because the resources used in this process are diverted from other profitable enterprise. This leads to two interesting observations [7]: First, if the society's goal is a net maximization of goods, then the total waste disposal costs should be minimized; Second, higher pollution avoidance costs are beneficial to the society as long as they reduce the welfare damage dollar for dollar. Certain environmental benefits are easy to conceive and analyze by using the benefit cost approach as they directly affect the production process or consumption. Also the benefit cost analysis is used only for a short term period [8].

2.7 Recycling

The use of recycled material will be attractive if it is economical to replace the use of virgin material with recycled material. In the economic analysis of recycled material, the pollution costs and the benefits of conserving resources (in this case landfill space as well as the new material from natural resource) should be considered. Abelson [9] developed an economic model by incorporating life cycle cost and suggested that for a given level of output, it will be desirable to recycle materials if

$$\sum_{n=1}^{n} \frac{(C_R + P_R - B_R)_n}{(1+i)^n} < \sum_{n=1}^{n} \frac{(C_V + P_V)_n}{(1+i)^n} \tag{1}$$

where,

C_R and P_R : Production and pollution costs of using recycled materials

B_R : Benefit from extending the life of the resource

C_V and P_V : Production and pollution costs of virgin materials

i : Discount rate over a period of 'n' years.

For the minimization of pollution and production costs, industries and business have to consider an optimal level of recycling. Thus, for some materials this may translate an increase in the use of recycled material from current levels and a decrease for some other materials.

2.8 New York City Recycling Project

Literature regarding the economics of recycling and landfill in terms of welfare changes of the society is not available. Kirshner and Stern [10] investigated the economic benefits of recycling and incineration over landfill for the New York city. The rationale behind their work was that keeping waste out of the landfills has a twofold benefit: First, it saves current disposal costs through increasing disposal costs at decreasing rates in the future. Second, by assuming that the future landfill sites will cost more so it will provide savings of resources through extending the landfill life. The formulation or algorithm suggested by them calculates the levellized value of the waste diverted per ton as a function of several variables.

$$C = P + (F - P)[\frac{1}{(1+r)^N}] + N(F - P)[\frac{1}{(1+r)^N}]\ln(1+r) \qquad (2)$$

Where,

F = Levellized future cost per ton of landfill

P = Present cost per ton of landfill

N = Number of years of life left or the time left for depletion of the landfill

r = The real discount rate i.e. the nominal discount rate minus the rate of inflation

C = The levellized value per ton of waste diverted.

2.9 Introduction to Welfare Economics

Natural resources such as forests, clean air, water are invaluable for the human existence. The economic value of a natural resource is defined as the sum of the discounted present values of all the services that constitute that resource. Similarly the damage due to pollution is the reduction in the value of the service that it causes. The basic premise of welfare economics is to increase the welfare or well being of the individual through economic activities. In doing so, the benefits of changes in environmental resources and services with the costs of providing the change in the environmental service should be compared. In general the society will contribute to make the change in the level of the environmental services only if the benefits outweigh the costs i.e. the welfare of the society as a whole is increased.

The value of an environmental resource or service can be defined in terms of an individual's welfare that can be represented by an ordinal utility function. However, this does not deal with the relationship between the utility of two or more persons. Thus the, the concept of Pareto optimality is considered which states that an allocation of goods, resources, and services in an economy is Pareto optimal, if there is no feasible reallocation that can increase one person's utility without decreasing someone else's utility [11]. Therefore, it is meaningful to have a social welfare function rather than an individual's welfare function to account for societal costs.

The first step in building a utility or a welfare function is a method for measuring values of environmental resources. The methods for estimating values are based on two characteristics. The first characteristic is whether the data comes from the observations of people in real-world settings or from people's responses to hypothetical questions of the form "what would you do if...? or "would you be willing to pay...?" The second is whether the method yields monetary values directly or indirectly.

Table 2.1 shows two methods for estimating values for observed and hypothetical behavior. On the basis of these two characteristics, methods for estimating the value of an environmental resource may be divided into four categories - Direct Observed, Indirect Observed, Direct Hypothetical, and Indirect Hypothetical as shown in Table 2.1. One of the most important elements in the methodology of indirect measurement is the model of individual optimizing behavior that relates the individual's choices to the relevant prices

Table 2.1

Methods for Estimating Values

	Observed Behavior	Hypothetical
Direct	**Direct Observed**	**Direct Hypothetical**
	Competitive market price	Bidding games
	Simulated markets	Willingness to pay questions
Indirect	**Indirect observed**	**Indirect hypothetical**
	Travel cost	Contingent Ranking
	Hedonic property values	Contingent activity
	Avoidance expenditures	Contingent referendum
	Referendum voting	

Source: Reference 11

and constraints including the level of an environmental resource [11]. This relationship can be used to derive a marginal rate of substitution between the level of the environmental resource and a choice variable that is a part of the individual's utility function.

2.10 A Model of Environmental and Resource Values

The economic values of an environmental service flow from a system that can be thought of as consisting of three parts [11]. The first is the relationship between the level of the environmental service to the human intervention that affects it. Two kinds of human intervention are existent. One is the unregulated activity of the market economy, namely the exploitation of a natural resource. The second is the government intervention to lessen the adverse impacts of commercial exploitation of the environment.

Let, S = government intervention

q = Quantity of waste produced

$q = q(S)$ Subject to government intervention (3)

Let us consider that government regulates private activities which influence q. Thus, the effect of a change in S on q depends in complex ways on the response of private decision makers to government regulations.

Let, R = private response to government regulations = $R(S)$

$$q = q[S, R(S)] \quad (4)$$

The second part of the relationship involves the human uses of the environmental resource and their dependence on q.

Let, X = Level of some activity involving the use of an environmental resource.

X not only depends on q but also on other factors such as labor, capital, and other resources such as time.

Let, Y = Other factors or inputs.

$$X = X[q, Y(q)] \quad (5)$$

The third part of the relationship gives the economic value of the environment.

Let, V = value of the activities or services that are based on the environmental resource

$$V = V(X) \quad (6)$$

Substituting in equation 6 from equations, 3, 4, and 5, we get

$$V = f\{S, R(S), Y[S, R(S)]\} \quad (7)$$

The marginal value of the change in S can be calculated from the total derivative of equation 7.

Thus,

Benefit B = Change in values ΔV

$$= f\{S^2, R(S^2), Y[S^2, R(S^2)]\} - f\{S^1, R(S^1), Y[S^1, R(S^1)]\} \quad (8)$$

where,

superscript '2' denotes the second level of output

superscript '1' denotes the previous level of output

Figure 2.4 shows the impact of government policy on the use of recycled materials and also depicts the logical sequence of environmental and resource values models.

2.10.1 Models for Indirect Benefit Estimation

Welfare changes have been defined as the area under the appropriate Hicks compensated demand curve for a market good or marginal willingness to pay curve for a non-market good or service [11]. An example of a non-market good is an improvement in environmental service that is provided by an environmental resource. The marginal willingness to pay curve for such non-market goods cannot be estimated from direct observations of transactions in these goods.

This can be explained by assuming 'q' as some level of environmental service or quality provided to society. The problem is to estimate in monetary terms the effect of a change in 'q' on the individual's welfare. This depends on the individual's utility function and the effect of 'q' on it. Generally there are three ways in which 'q' can affect an individual's utility [11].

1. 'q' can be a factor input in the production of a market good thus yielding utility indirectly.
2. 'q' can be an input in the household production of commodities that yield utility.
3. 'q' can be a parameter in an individual's utility function thus yielding utility directly. indirectly.

2.10.2 Environmental Quality as a Factor Input

Most of the economic analysis ignores environmental quality or natural resource as an input factor in production process. Although environmental quality is not described in monetary terms, but in real world, consciously or unconsciously industries do make an economic decision by considering environmental quality. To further understand the

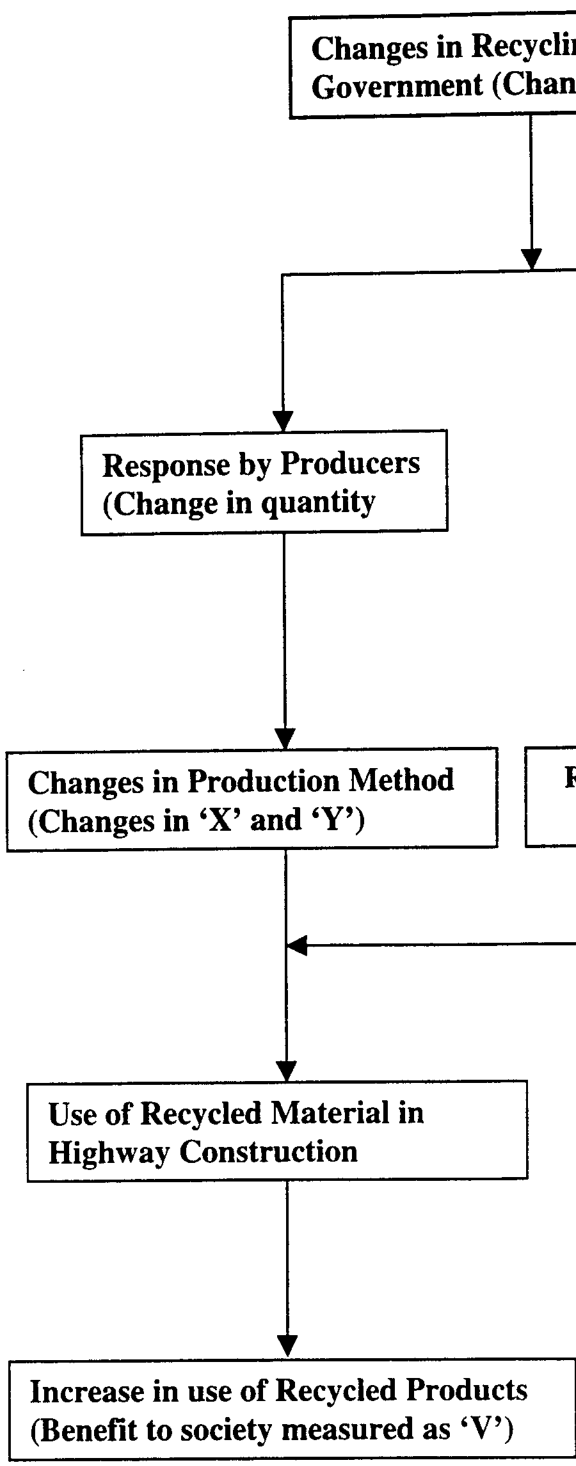


Figure 2.4: Impact of Government Policy on use of Recycled Materials

concept we assume 'q' as a factor input in the production of utility yielding market goods, then a change in the level of 'q' will lead to changes in production costs that affect the price and quantity of output or the returns to other inputs.

If a good 'X' is produced with a production function

$$X = x(k, w, ...q) \quad (9)$$

where,

k = capital,

w = labor (work) and the marginal product of q is positive.

The industries in the production process of 'X' will have a single most objective which is cost minimizing behavior. Thus, the cost function of the process will be:

$$C = C(p_w, p_k, x, q) \quad (10)$$

Since 'q' affects both production and supply of 'X', the effect of changes in 'q' can be measured in terms of changes in variables related to the production of 'X'. Thus a change in 'q' will cause a shift in both cost curves and the factor demand curves. There are two ways through which changes in 'q' can produce benefits [11].

1. Changes in the price of 'X' to the consumer
2. Changes in the returns to the owners of factor inputs used in the production of 'X'.

The benefit to consumers is considered as a societal welfare and is shown in figure 2.5 as a hatched area. It is explained through the following illustrations:

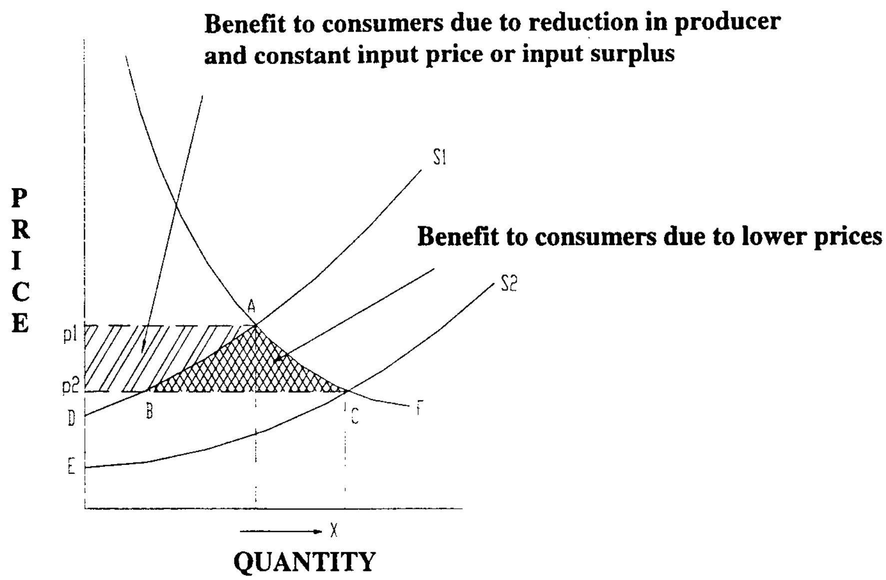
1. If 'x' is produced in a competitive industry at constant cost, then the changes in 'q' affect the cost curves of a large number of producers in the market.
2. If there is only one producer, changes in 'q' will affect only this producer and output price will not be changed. Since the marginal costs of production are changed, the

firm's marginal cost and supply curves are shifted down from S^1 to S^2 as shown in Figure 2.5.

As the supply curve of the industry is shifted down from S^1 to S^2, the price decreases from p_1 to p_2. The benefit to consumers is approximately equal to the change in the consumer's surplus, which is equal to the area 'p1ACp2'. A part of this benefit is due to the reduction in producer cost and factor surpluses and is equal to 'p1ABp2'; so the net gain to the society due to lower prices is equal to the area 'ABC'. Because of the lower supply curve, factor surpluses and quasi rents are now equal to 'p2CE'. The net increase in producers and factors is ' DBCE '. So the total benefits are equal to the area 'DACE'. The estimation of these measures requires knowledge of how 'q' affects the production of 'x'. This becomes fairly simple in two cases.

- q is a perfect substitute for some other input factor. If this relationship is known, the decrease in per unit production cost can be calculated. If the change in total cost does not affect the marginal cost, then the saving is a measure of the benefits of 'q'. However if the change in 'q' affects marginal cost, then the benefits should also include the effect of the lower cost on output and price.
- The second case is when benefits of a change in 'q' will go to the producers. In such a case benefits may be estimated from changes in net income of certain factor inputs.

All measures described so far are for the case where the level of the environmental service is the same for all individuals. In actuality, the level of 'q' can be considered to be a qualitative characteristic of a differentiated market good [11]. Individuals then have the freedom to choose a particular level of this good. A good example is the relationship between environmental quality and housing price as shown in



Welfare Measures when 'q' affects the production of 'x'

Figure 2.5: Welfare Measures

Figure 2.6. The Figure shows that as the environmental quality increases from poor to good the housing price increases exponentially.

The price differentials for the similar type of house but at different levels of environmental quality are implicit price levels of the public goods. For Example if 'Y' is any product and 'Q' represents a series of characteristics of 'Y', thus Q is a vector of (q_1, q_2, q_3...q_n).

A general model for any product Yi can be represented as:

$$Y_i = Y_i(q_{i1}, q_{i2}, q_{i3},....q_{in}). \qquad (11)$$

The hedonic price function for Y gives the price of any model as a function of its characteristics.

$$p_{yi} = p_y(q_{i1}, q_{i2}, q_{i3},....q_{in}) \qquad (12)$$

Where,

p_{yi} can be estimated from observations of the prices and characteristics of different models.

Consider that a person purchases a product Y (a house) at a particular time. The product 'Y' has 'Q' characteristics and the individual is limited by his budgetary constraint M. Let the individual's consumption be represented by 'X'.

The individual's utility function

$$u = u(X, Q) \text{ for product Y} \qquad (13)$$

The individual maximizes his/her utility of product 'Y' subject to constrained by his/her budget.

Thus,

$$u = u(M - P_{yi}, q_{i1},....q_{in}) \qquad (14)$$

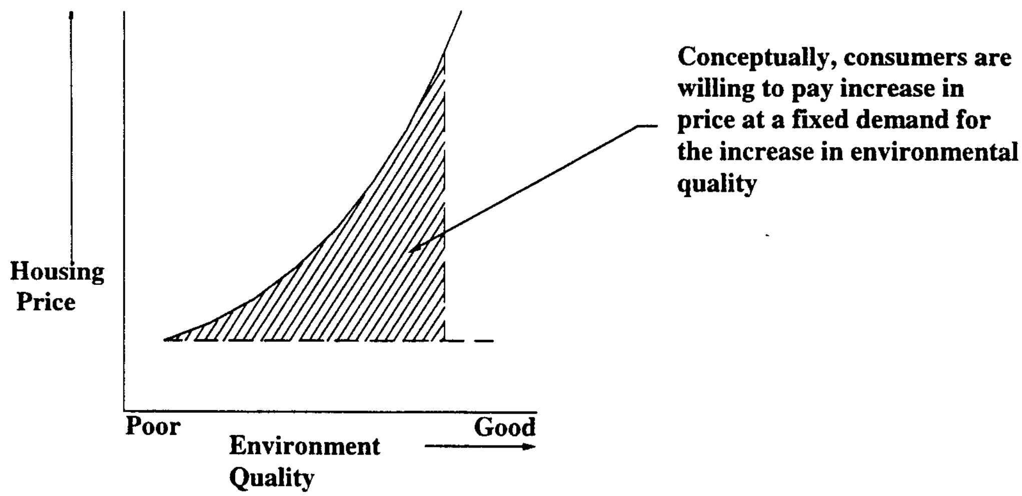


Figure 2.6: Housing price versus Good Environmental Quality

subject to constraints:

$$M - P_y - X = 0 \qquad (15)$$

The individual must choose levels of each characteristic such that

$$\frac{\partial u / \partial q_j}{\partial u / \partial X} = \partial p_y / \partial q_j \qquad (16)$$

Inverting Equation 13 and holding all but the characteristic 'j' constant, we get a bid curve or indifference curve that gives the maximum an individual would pay to obtain the model as a function of q_j holding other things constant [11].

$$B_j = B_j(q_j, Q^*, u^*) \qquad (17)$$

where,

B_j is indifference curve for characteristic j

u^* is the solution to the constrained utility problem and

Q^* represents the vector of the optimal quantities of the other characteristics

For the supply side of the market, similar to an individual's bid function, there exists an offer function that is obtained by inverting the firm's profit function. The offer curve is of the form:

$$C_j = C_j(q_j, Q^*, \Pi^*) \qquad (18)$$

Where,

Π^* is the maximum attainable profit.

For all firms and individuals to be in equilibrium, all of the bid and offer curves must be tangent to the hedonic price function. Thus the hedonic price function is a double envelope of the two families of bid curves and offer curves.

The marginal implicit price of a characteristic is found by differentiating the hedonic price function Equation 12 with respect to the characteristic.

$$\partial p_y / \partial q_j = p_{q_j}(q_{i1}, \dots q_{ij}, \dots, q_{in}) \tag{19}$$

This equation provides the increase in expenditure incurred to obtain a product with one more unit of the characteristic 'j'. If equation 12 is linear, then the implicit prices are constant for individuals, but if equation 12 is non-linear, then the implicit prices depend on the quantity of the characteristic being purchased.

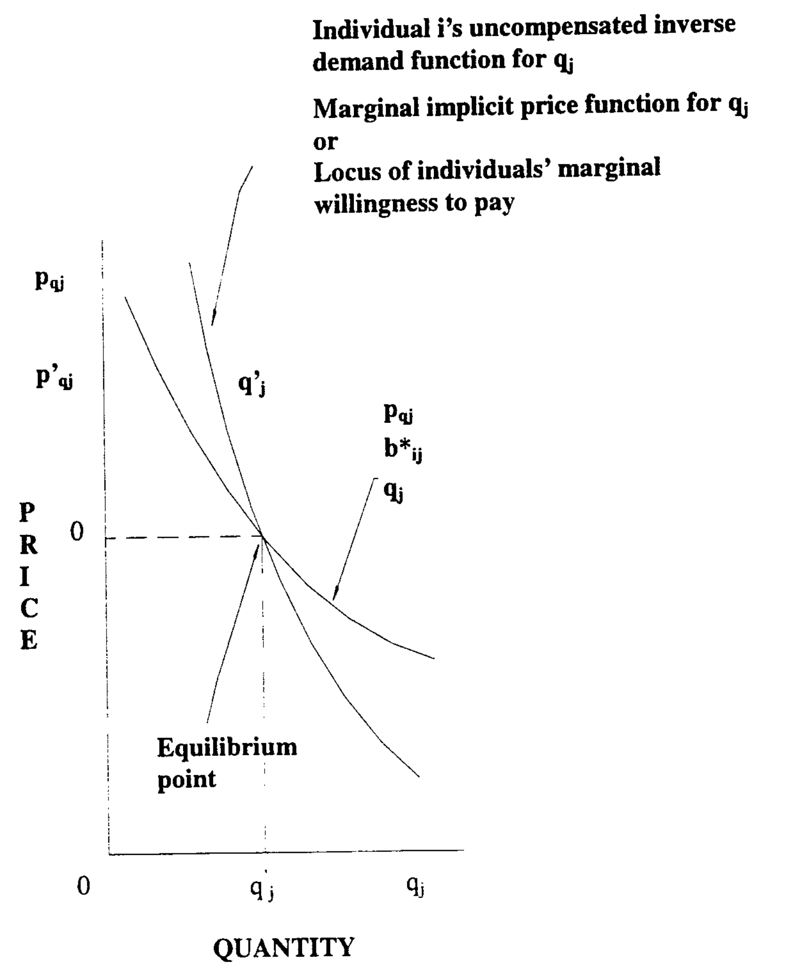
Figure 2.7 illustrates another way to look at the market equilibrium. Given the individual's inverse demand function, and the marginal implicit price function of 'j', the point (q_j, p_{qj}) is the utility maximizing equilibrium point. Individuals move along p_{qj} as long as their willingness to pay (inverse demand curve) is more than the marginal implicit price.

After defining the individual's marginal willingness to pay and inverse demand functions, the next step is to identify marginal implicit prices from these observations.

One of the difficulties with this method is that data from a single hedonic market is insufficient to identify how the same individuals would respond to different implicit prices and incomes.

2.10.3 Hypothetical Methods for Direct and Indirect Valuation

There is no direct method to estimate the value of environmental resources based on individual choices. In many cases, value measures cannot be directly inferred from individuals' choices. Hypothetical methods have been devised to evaluate how the level



Marginal Implicit Price and Inverse Demand Curves for q

Figure 2.7: Marginal Implicit price and Inverse Demand Curves for q

of the environmental resource affects individuals' utility and their willingness to pay. In the hypothetical methods a series of questions of the following forms are developed:

What would you do if......?

Would you pay......?

There are four major types of hypothetical questions that are generally asked to assess the value of environmental resources.

1. **Contingent Value Method (CVM):** People are asked what value they place on a certain change in the environmental resource or what amount would they be willing to pay to have it happen. This method estimates the consumer surplus (CS).

2. **Referendum Questions**: This method asks yes or no questions of the form "Would you be willing to pay $X for....?" The responses obtained give an upper bound for individual willingness to pay. Discrete choice methods are used to estimate willingness to pay functions or utility functions based on individual responses.

3. **Contingent Ranking**: Respondents are given a set of alternatives and are asked to rank them in order of preference. This will provide a Marginal Rate of Substitution (MRS) between a characteristic and the level of the environmental amenity. If the characteristic has a monetary price, it is possible to compute the respondents' willingness to pay.

4. **Contingent Activity**: Individuals are asked how they would change the level of environmental amenity. If the change in the level of the activity can be interpreted in monetary terms, then the willingness to pay for that individual can be obtained

from these questions.

A problem of reliability of data lies with hypothetical methods of evaluation. Freeman[12] identifies two types of concerns with hypothetical data.

1. The existence of an incentive for respondents to provide biased replies.
2. The absence of an incentive for respondents to provide accurate responses when asked about purely hypothetical situations.

2.10.3.1 A Model for Reliability of Data:

Freeman [12] hypothesized a model for reliability of data as:

$$W_{ti} = W_{ti}(\Delta q, M_i, S_i) \qquad (20)$$

Where,

W_{ti} = the true willingness to pay of the individual i

W_{ri} = Revealed willingness to pay of the individual i

True willingness (W_{ti}) to pay can be estimated by considering three parameters

Δq as the environmental change

M_i as Individual income, and

S_i as Individual socio-economic variables.

He differentiated between the true willingness to pay and the revealed willingness to pay is due to three reasons:

1. Random error $f_1(X, \alpha)$ where X is a vector of variables and α is a vector of parameters for this process.
2. Systematic process error affecting W_{ri}, $f_2(W_{ti}, Y, \beta)$ where Y and β represent another set of variables and parameters.

3. Probabilistic error that W_{ri} is actually observed, $f_3(W_{ti}, Z, \gamma)$ where Z and γ represent another set of variables and parameters.

Generally, $f_2(W_{ti}, Y, \beta)$ and $f_3(W_{ti}, Z, \gamma)$ are eliminated and validity can be increased by eliminating $f_1(X, \alpha)$ usually by increasing the sample size.

2.10.3.2 Validity of Hypothetical Methods

There are two methods available to assess the validity of responses to hypothetical questions. The first method is a careful analysis to see if all sources of error and bias have been removed. The other method is the empirical analysis of responses to see if they conform to results obtained from other methods or from basic economic theory.

CHAPTER 3

POST CONSUMER WASTE

3.1 Introduction

The quantities and composition of waste produced in a society during any time period depend on the prevailing culture. Earlier farming communities left practically no waste at all. With the industrialization and rapid urbanization, the quantity and composition of waste began to change, and by the middle of the twentieth century, the composition of waste began to undergo a drastic change. The amount of paper and food waste began to increase and reflected the prevalent trends of society. By mid eighties, an increase in the amount of plastic waste became noticeable.

Present trend to replace paper products with plastic seems to be increasing. At the end of the eighties, the percentage of plastics in Municipal Solid Waste (MSW) had reached 8.5 percent by weight [13]. Though plastics are replacing some of the paper products, but it does not mean that the use of paper is reducing. In fact the percentage of waste paper and paperboard is also increasing. The amount of paper in landfills in 1990 was between 40 percent to 50 percent while the amount of plastics was around 5 percent by weight [14]. Due to an increased emphasis on packaging, the amount of paperboard and plastic wastes generation are on increase.

3.2 Solid Waste Growth

The solid waste stream in the U.S. has been steadily increasing for the past 30 years from approximately 88 million tons in 1960 to 206 million tons in 1988 [2]. The quantity and composition of the solid waste stream has a direct impact on the technologies selected for management and disposal. Table 3.1 [2] shows selected waste materials in the U.S. for the past 30 years and the projection for the year 2010. It also

Table 3.1

Selected Post Consumer Waste Materials in the US, by Weight and Percentage, 1960 - 2010.

Million of Tons (By Year)								
Materials	1960	1970	1980	1990	1991	1992	1993	2010
Paper and Paperboard	29.91	44.180	54.730	72.860	71.100	74.310	77.840	121.2
Glass	6.680	12.680	14.950	13.180	12.740	13.140	13.670	9.5
Plastics	.400	3.060	7.870	16.820	17.230	18.520	19.300	25.7
Rubber and Leather	2.030	3.260	4.290	5.930	5.800	6.030	6.220	8.100
Percent of Total Generation								
Paper and Paperboard	34.1%	36.2%	36.1%	36.7%	36.1%	36.6%	37.6%	48.4%
Glass	7.6%	10.4%	9.9%	6.7%	6.5%	6.5%	6.6%	3.8%
Plastics	0.5%	2.5%	5.2%	8.5%	8.8%	9.1%	9.3%	10.3%
Rubber and Leather	2.3%	2.7%	2.8%	3.0%	2.9%	3.0%	3.0%	4.0%

NOTE : **Reference [2]**

shows that the selected post consumer wastes have increased considerably from 1960 to 1990. An extrapolation to year 2010, indicates that the amount of post consumer wastes will increase in future.

According to the USEPA [2], in 1994 approximately 206.9 million tons of waste was produced. Of this amount, approximately 62.4 percent was landfill, 21.7 percent was recycled, and 15.9 percent was disposed off through incinerators. The U.S. trend in waste material discards and recovery for selected years from 1960 - 1993 is shown in Figure 3.1. It shows the increasing trend in landfill and recovery of waste materials.

3.3 Composition of Solid Waste

Table 3.2 provides the typical solid waste generation rates per day in the US by type of facility. These rates are considered as a guideline for estimation of post consumer waste generated for any community.

3.3.1 Solid Waste in Ohio

The 1995 Ohio solid waste facility data report shows that Ohio residents generated more than 21 million tons of MSW. Table 3.3 shows the solid disposal methods and quantities disposed of in Ohio. It shows that 78.30 percent of total waste was disposed through landfill and 14.30 percent was transferred to other states.

A tipping fee study was conducted to determine rates for disposal of solid waste through landfill. It indicates that an average tipping fees over the years for the Northwest region of Ohio has increased from $19.42 in 1989 to $30.50 per ton in 1994. Table 3.4 shows the trend in tipping fees in Ohio. The increase in landfill tipping fees is related to

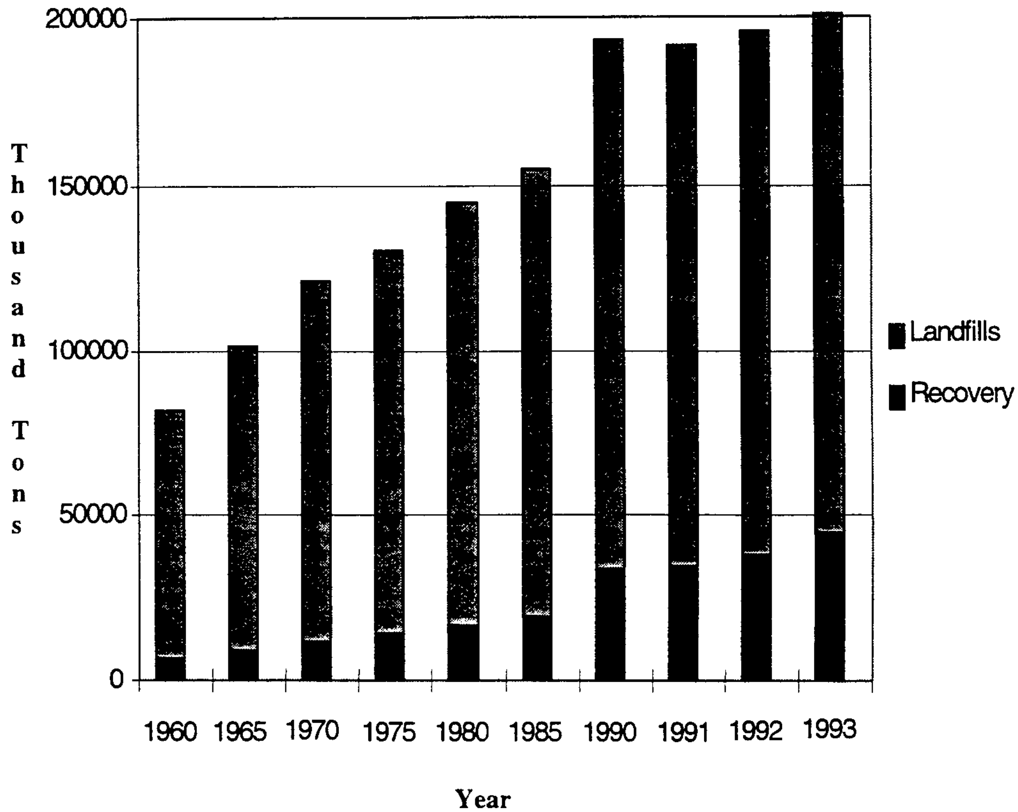


Figure 3.1: U.S. Trends in Material Recovery and Discard

Table 3.2

Typical Daily Solid Waste Generation Rate by Building Type

Building Type	Estimated Waste
Private Homes	5 lb. basic + 1 lb. per bedroom/day
Apartments	4 lb. per sleeping room /day
Warehouses	2 lb. per 100 sq ft / day
Office Buildings	1.5 lb. per 100 sq ft/day
Department Stores	4 lb. per 100 sq ft / day
Restaurants	2 lb. per meal / day
Grade Schools	10 lb. per room + 0.25 lb. per student / day
High Schools	8 lb. per room + 0.25 lb. per student / day
Hospitals	15 to 18 lb. per bed / day
Nursing Homes	3 lb. per person / day
Hotels, Class I	3 lb. per room + 2 lb. per meal / day
Hotels, medium	1.5 lb. per room + 1 lb. per meal / day
Motels	2 lb. per room / day
Trailer Camps	6 to 10 lb. per trailer / day

Source: Reference [15]

Table 3.3

Disposal Quantities of MSW through Various Management Methods in Ohio, 1994.

Method	Quantity (tons)	Percentage
Landfill	16,595,043	78.30
Transferred	3,039,219	14.30
Incinerated w/ Energy Recovery	688,129	3.30
Incinerated e/o Energy Recovery	499,486	2.36
Ash Disposed	369,820	1.74
Total	21,191,697	100.00

Source: **1995 Ohio Solid Waste Facility Data Report**

Table 3.4

Trend in Tipping Fees in Ohio

Year	Tipping fee $/ton
1989	19.42
1990	22.98
1991	27
1992	26.8
1993	28.15
1994	30.5

Source: **1995 Ohio Solid Waste Facility Data Report**

the remaining landfill capacity in Ohio. Table 3.5 shows the remaining landfill capacity in years by region in Ohio. It shows that in 1995, the Central region of Ohio has only 2.8 years of landfill capacity. The landfill capacity varies from low of 2.8 years for Central region to a high of 19.1 years in Northwest region.

A broad conclusion can be drawn that solid waste generation is increasing along with increased disposal costs. However, the amount of space available in landfills is rapidly decreasing. The waste disposal problem in Ohio is not so severe as compared to New York and the Northeast states, but if remedial measures are not taken now, Ohio could soon be facing the same waste disposal problems as New York state.

3.4 Choice of Materials for Study

One of the objectives of the research study was to select four post consumer waste materials for a detailed cost-effective analysis. The researcher with the help of the Ohio Department of Transportation (ODOT) and the Ohio Department of Natural Resources (ODNR) personnel identified the following four waste materials for the detail study:

- Glass,
- Plastic,
- Rubber tires and
- Paper & Paperboard.

3.4.1 Glass

Each year approximately 13 million tons of glass is disposed of in the United States. The glass waste contributes about 7 percent of the Municipal Solid Waste

Table 3.5

Remaining Landfill Capacity in Years by Region in Ohio

Region	Remaining Capacity in years
Northeast	11.2
Northwest	19.1
Central	2.8
Southeast	11.3
Southwest	7.3

Source: 1995 Ohio Solid Waste Facility Data Report

(MSW). Out of the total glass waste generation, only 12 percent of glass waste is recycled, and the rest is disposed of in landfills [13]. The waste generation and recovery rates for glass are illustrated in Figure 3.2. It shows that the recovery of glass is in small quantity as compared to generation and only in early eighties the recovery of glass has began.

The recycled glass is mainly used in bricks and paving mixtures. Glass is also used as an additive to asphalt and the mix is known as Glass-phalt. Also recycled glass is used in reflective paint and as a base course in pavement. The potential user for crushed recycled glass is the glass manufacturing companies. They use crushed glass to reduce the energy and emissions involved in glass making. The glass manufactures require that glass should be sorted by colors as commingled glass is of no use to them. Color sorted recycled crushed glass has a good market with the demand for it being constantly high.

- **Problems Associated with Glass Recycling**

The only problem associated with crushed glass is commingled glass, i.e. glass of different colors and varieties. The glass industries cannot use commingled glass in glass manufacturing. Therefore, separation of glass containers by color is necessary before crushing and sale to glass industries. The processing involves separating the glass according to color, crushing, and removal of foreign matter. The glass recycle industries sell crushed clean glass to glass industries.

3.4.2 Plastic

The production and recovery rates for plastics from 1960 to 1993 are illustrated in Figure

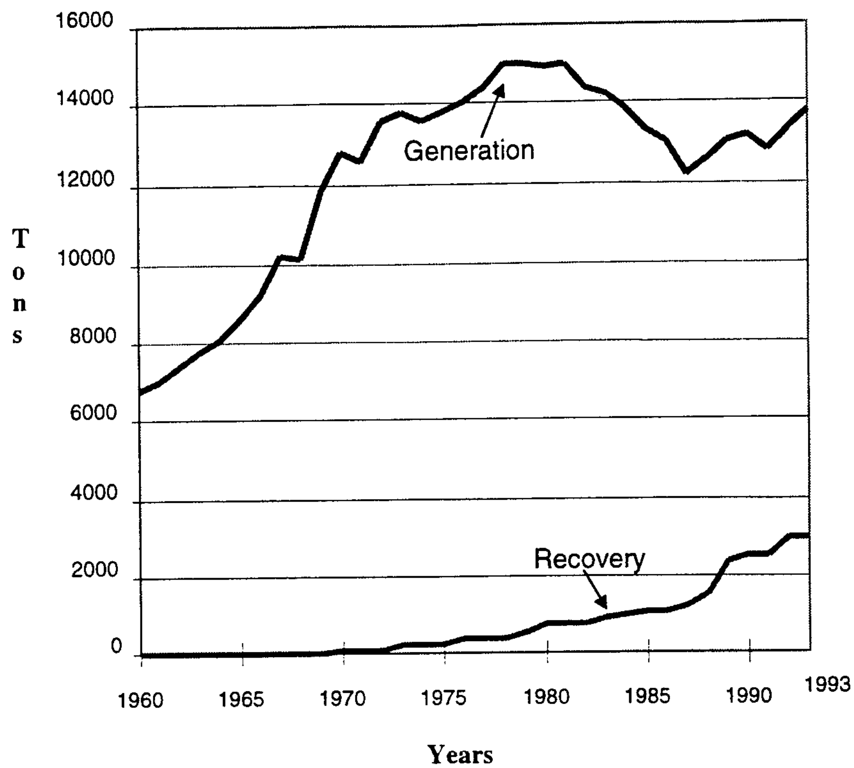


Figure 3.2: Glass Generation and Recovery from 1960 to 1993

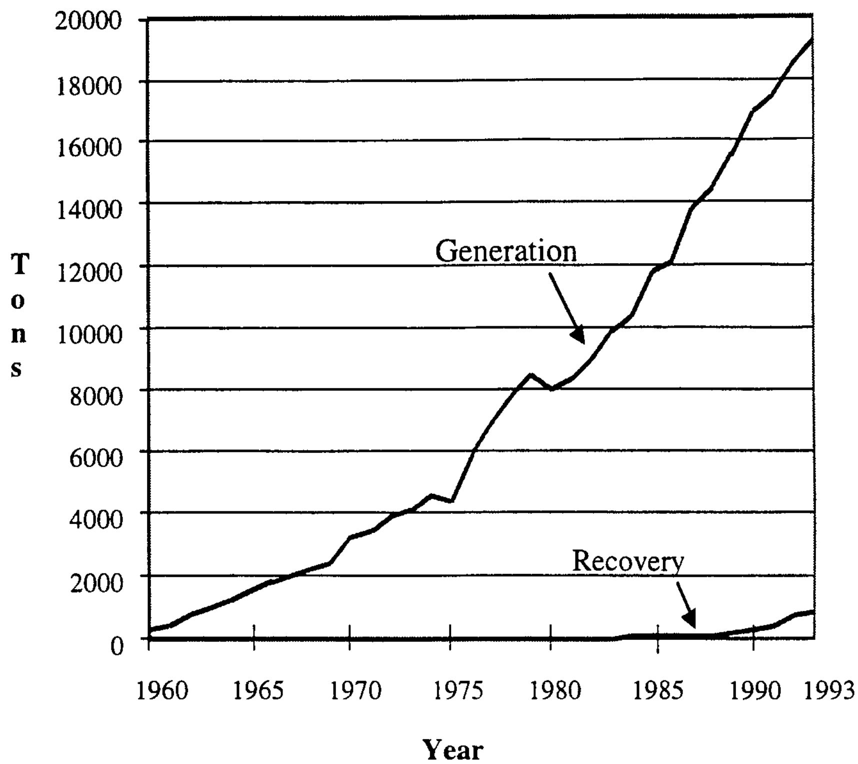


Figure 3.3: Plastic Generation and Recovery, 1960 to 1993.

3.3. It shows the plastic waste generation is increasing at a high rate and it reached to 20,000 tons in 1993 from less than 100 tons in 1960. The rate of plastic wastes recovery for recycle is only 900 tons in 1993 that is less than 5 percent of the generation rate.

Plastics are strong, lightweight, waterproof and more durable than glass. They generate toxic emissions when burned and generally are non biodegradable when buried in landfills. In addition, plastics kill marine life when disposed of in water. The manufacturing of plastics involves toxic chemicals and non-renewable resources such as petroleum. For these and other reasons, recycling of plastics is necessary to reduce plastic disposal problem.

- **Problems Associated with Plastic Recycling**

Manufacturing of plastic is a complex method and involves combination of different molecules in various proportions. Each combination produces a certain type of plastic. Therefore, plastic containers are coded by special alphanumeric code to signify its processing mechanism and to utilize resins in the manufacturing process. There are hundreds of different types of plastics and each one of them requires a different way of processing before it is reused. This is why plastic "products" are coded so that they can be easily separated and recycled. Sometimes manufacturers do not indicate the type of plastic on their products. This creates a myriad of problems in the sorting process.

- **Uses**

The amount of plastic used in packaging has increased tremendously over the years, but the recycling of plastic remains just 1.2 percent of total generation. Presently most of the plastic recycled is soft drink plastic bottles made of Polyethylene Terepthalate (PETE). With increase use of plastic and constant recycling level, the Environment Protection Agency (EPA) estimates that the amount of plastics in MSW will reach to 10 percent by the end of the century [16].

3.4.3 Rubber Tires

More than 242 million tires are disposed off annually in the USA. This amounts to approximately 1 tire per person per year. It is estimated that 75 percent of the total tires is either stockpiled or dumped illegally. Scrap tires are considered a non-hazardous waste, but fires in large tire stockpiles are cause for concern. In addition, there is a danger of disease from mosquitoes and rodents that are normally associated with these stockpiles.

Whole scrap tires find a variety of uses including artificial reefs, breakwaters etc. Many of the highway agencies use scrap tires in highway construction as asphalt mixes. Tires are processed into crumb rubber before being used as additives in asphalt mixes. The scrap tire rubber has been used in binders since the sixties. The economics of tire disposal depend on the disposal regulations associated with state. Some states have disposal charges, while some do not. This factor plays an important role in deciding the market for scrap tire rubber.

3.4.4 Paper and Paperboard

In the eighties the paper output of the world increased by 30 percent [17]. The production and recovery rates for paper are illustrated in Figure 3.4. It shows that the paper production increased from 30 million tons in 1960 to 78 million tons in 1993.

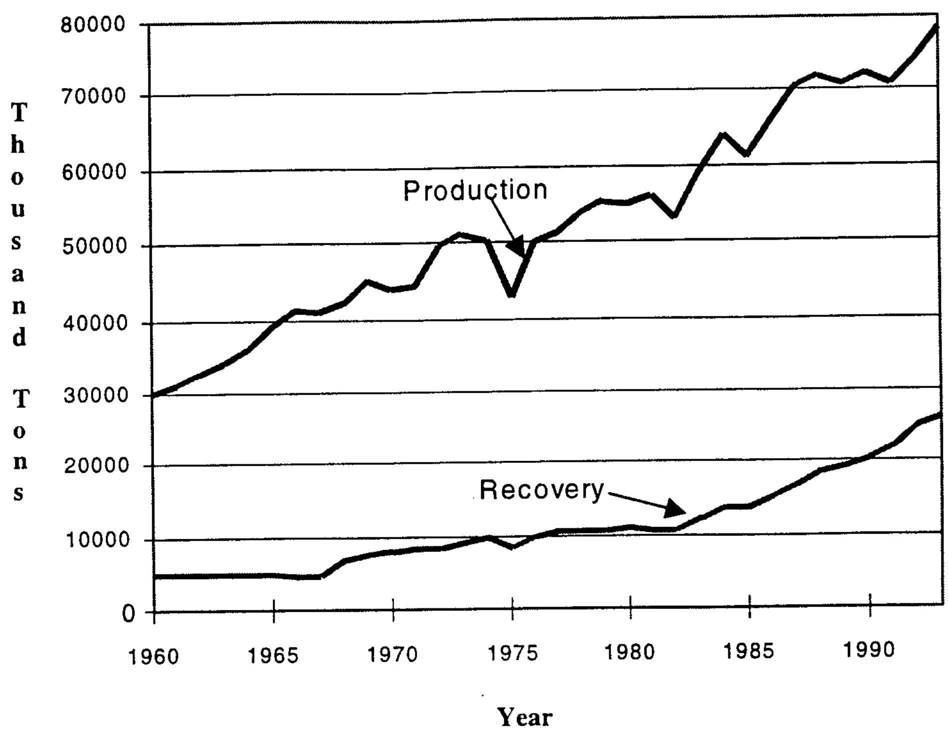


Figure 3.4: Paper Generation and Recovery from 1960 to 1993

The rate of paper and paperboard waste recovery from waste stream has also increased from less than 5 million tons to 27 million tons during the same period. The rate of recovery has increased since 1982.

Paper mills are the largest consumers of paper and paperboard waste. The paper mills use waste papers to make paper as it saves energy, water, emissions, and chemicals required for processing. The use of waste paper in highway construction is minimum and limited to mulch and lightweight fill.

The waste paper market is very volatile. In some areas, the municipal waste paper has no value and requires disposal charges to be paid and in some areas, it has a positive monetary value. The most effective way to create a waste paper market is to attract a pulp and paper mill industry to the area. The economics of paper recycling are complex and depend on a large number of factors including location and available supply of waste paper.

3.5 Alternate Use of Selected Post Consumer Waste in Highway Construction

These selected four products show a potential for use in highway construction. A list of potential uses of these waste products is developed from the 1997 ODOT Specification [18]. Table 3.6 lists alternate uses for these selected waste materials. The Table lists post consumer waste material, specification number and description. The post consumer waste materials can replace the virgin material that is listed under description.

Table 3.6

Potential Use of Post Consumer Waste in Highway Construction

Material	Specification	Description
Glass	203	Embankment: Fine aggregate in subbase
	301, 302, 304	703.04: Aggregate for Bituminous aggregate base (301, 302), Aggregate base (304)
	310	Fine aggregate material for sub-base
	401.03	Fine aggregate in asphalt - 703.05
	402, 403, 404, 412	Fine aggregate for asphalt concrete
	411	Fine aggregate in Stabilized Crushed Aggregate
	603.02	Pipe bedding
Paper & Paperboard	659.06	Mulching material
Plastic	517.04	Steel and Iron railings
	517.05	Aluminum Railings
	518.05	Drainage pipe 707.19
	521	Commingled plastic along with steel used to make piles
	603.02	Corrugated polyethylene drainage tubing 707.15, Corrugated polyethylene drainage pipe 707.16, Plastic pipe 707.19
	710.14, 710.15, 710.16	Pressure treated guardrail posts and spacer blocks 710.14, Steel guardrail posts 710.15, and guard posts 710.16

Table 3.6 Contd:

	607.02	Fence materials: Fence posts 710.11
	620	Delineator Posts 720.03
	625.05	Light Poles & Towers
	630	Traffic signs and supports Steel :U channel posts 730.015, Square Posts 730.016, Tube and Pipe 730.01, Poles and arms 730.03 Aluminum Tube and pipe 730.13
	632	Traffic signal Equipment Steel Poles, supports, arms, appurtenances and anchor bases 730.02. 730.03, 730.04, 730.05, 730.06, 730.07, 732.11, 732.12. Wood Poles 732.13
	638	Water mains and Service Branches PVC pipe, joints and fittings 748.02, Polyethylene PE service branches and fittings 748.03, Plybutylene PB service branch and fittings 748.04
	605.02	Underdrains: Perforated vitrified clay pipe 706.08, Perforated corrugated Polyethylene Drainage tubing 707.15, Polyvinyl Chloride Plastic pipe 707.17
Scrap Tire Rubber	301.03	Bituminous material 702.01
	401.03	Plant mix pavements: Bituminous material 702.01, 702.02, 702.03, 702.04
	405.02	Bituminous cold mix: Bituminous material 702

Table 3.6 Contd:

	407	Tack coat: Bituminous material
	408	Prime coat: Bituminous material
	409	Seal coat: Bituminous material
	413	Asphalt Concrete Pavement Joint sealant 705.04
	451.13	Joint Sealants 705.04 or 705.11
	512.02	Waterproofing: Asphalt primer 702.02 RC-70, RC-250, 702.05, Emulsified Asphalt primer 702.04, MS-2, SS-1, Asphalt for waterproofing 702.06
	603.02	Pipe Culverts, Sewers and Drains: Pipe joint filler 706.10 or 706.14
	609.06	Asphalt Concrete curb: Bituminous material 407.02 sprayed on surface course
	615.05	Temporary roads and pavement: Flexible Pavement - Asphalt concrete 404, Asphalt concrete 402, Bituminous aggregate base 301

CHAPTER 4

LIFE CYCLE COST

During the past decades a number of new criteria have emerged for design and fabrication. These are environmental sustainability, operational staff effectiveness (re-engineering), total quality management (TQM), value engineering (VE), and life cycle costing (LCC). The life cycle costing analysis assists designers in assessing the economic consequences of continued use of an existing building, system, or component, in comparison with the expense of substituting some alternative which may offer better performance.

The life cycle costing is defined as an economic assessment of competing design alternatives considering all significant costs of ownership over the economic life of each alternative, expressed in equivalent dollars. In 1972, the U.S. Department of Health, Education, and Welfare summarized life cycle analysis as the systematic consideration of cost, time and quality [19].

4.1 Historical Development of LCC

One of the first government references to the LCC was published in 1933 by the Comptroller General of the United States [20]. With regard to tractor acquisitions, the General Accounting Office (GAO) supported acceptance of bids predicated on the total cost to the government after 8000 hours of operation. Maintenance costs were included in the bid price. More than 25 additional rulings in the following years mandated the for procurement of all types of equipment. The GAO for the Department of Defense [20] published the final report on the LCC in 1973. During the decade from 1940 to 1950, the origin of the concept of Value Engineering (VE) took place. As conceived, VE was much broader than life cycle cost analysis as it incorporates the study of functions along with a total cost concept. The earliest proponent of VE for the construction industry was Alphonse J. Dell' Isola [20] who published an application guide in 1972 that pointed out graphically how initial planning and design choices have maximum effect on life cycle costs.

4.2 Definitions

A significant key to the LCC is an economic assessment using equivalent dollars. If different assets are spread across different points in time, then it is difficult to determine which asset is most valuable. The technique used in this case is to establish a baseline time reference. All monies are then brought back to the baseline, using proper economic procedures to develop equivalent costs. To conduct a life cycle cost analysis, cost information is required: such as the facility's expected life, the anticipated return on investment, and their financing costs, as well as non monetary requirements. From project to project, this information varies greatly. Initial costs include the owner's costs associated with initial development of a facility, such as project costs (fees, real estate, site, and so on) and construction costs. Financing costs include the cost of any debt associated with the facility's capital costs. Operation costs keep track of costs of items such as salaries, fuel, and so on. Maintenance costs include costs of periodic maintenance as well as the wages paid to maintenance personnel. Alteration costs are those costs involved in improvement or changing the function of the facility. A replacement cost would be a one-time cost to be incurred in the future to maintain the original function of the facility. Other costs associated with a facility are taxes, credits, and depreciation. Another important concept is salvage value, which is the value associated with the facility at the end of its life.

Using the LCC to make a decision is a process of several steps. The first step is to reduce the time and complexity of the analysis. Facility elements that are same in any of the alternatives under consideration are identified and removed from further considerations during the comparative analysis. Next, the decision making team isolates the significant costs associated with each alternative. The costs isolated for each alternative must be grouped by year over a number of years equal to the economic life of the facility. The probable replacement costs and salvage value must also be considered. All costs are converted to base year dollars by present worth techniques using a reasonable discount factor (7 percent is used by federal agencies) [20]. Finally, the team adds up the discounted costs and identifies the lowest-cost alternative. It may be necessary to make a sensitivity analysis of each of the assumptions to see if a reasonable modification in any of the cost assumptions would change conclusions.

Input data for the facility generally consists of initial cost, useful life, maintenance and operation costs, and site data such as climatic and environmental conditions. Development of alternatives depends on the quality and quantity of input data. Next the life cycle cost is predicted for each alternatives. The predictions may be modified by non-economic comparisons before a final recommendation is made. For input data requirement, the specific project information and site data are most easily available. But it is very difficult to obtain or collect useful data regarding facility life, facility maintenance, operational costs, environmental and societal costs.

The definition of life cycle cost analysis (LCCA) suggests that the following six questions should be asked:

1. What analysis approach is to be used?
2. What is a realistic discount rate to that can be used in the analysis?
3. How are the effects of inflation and increases in individual costs are considered into account?
4. Over what specific period of time total costs of ownership is determined?
5. When is the time period to begin?
6. What types of costs are included in the analysis, and what costs are ignored?

4.3 Life Cycle Cost

In a Life cycle cost analysis it is important to consider technical, performance and economic life of the product under consideration. The economic life is most important from the viewpoint of cost minimization; however the technological and the useful lives must also be considered when its economic life is determined.

- The technological life of an item is the estimated number of years until the item becomes obsolete.
- The useful life of the item is the estimated number of years during which it will perform its function according to an established performance standard.
- The economic life of an item is the estimated number of years until that item no longer represents the least expensive method of performing its function.

During its economic life, an item is subject to purchase, use, repair, maintenance, perhaps modification, and finally disposal. These processes constitute the life cycle of the item and the costs of these processes make up the life cycle costs or total cost of ownership. In most cases the economic life of an item is not known and is not easily determinable. To overcome this difficulty, the analyst usually compares results using several reasonable estimates of economic life.

Discount Rate

The discount rate or the interest rate is the time value of money. It is normally the prerogative of the owner to select the discount rate, as there is no universally accepted method or resulting rate used by various organizations. For analysis purposes, federal rate or prime rate can be used.

Analysis Period

The analysis period is the number of years over which the total cost of ownership will be determined for the various design alternatives. Some of the commonly used criteria for establishing the analysis period are

- Component life: If the alternatives being considered have the same economic life, then this period of life or a multiple of it may be used as the analysis period.
- Common multiple of component lives: If the alternatives have different economic lives, then a common multiple of these lives can be chosen as the analysis period.

- Facility life: In some situations, the analysis period may be based on the technological or useful life of the facility as a whole.
- Investment or mission life: The analysis period is sometimes established by limiting it to some investment or mission life for the facility. This is the expected number of years until the owner's objective is fulfilled.
- Arbitrary life: At times a somewhat arbitrary analysis period is selected even though there is a good reason to maintain the facility for an indefinite period of time. The analysis period may be established by an organizational policy or as the limit of a planning horizon.

CHAPTER 5

ECONOMIC ANALYSIS FOR RECYCLING

5.1 Introduction

To find and develop appropriate sites for waste landfill is more difficult due to the negative public health effects of air and ground pollution. This creates an impact on considerable increase in disposal costs. The increased cost of landfill and environmental awareness has lead to a demand for materials recycling. In fundamental economic terms, the solid waste problem is a negative externality problem. The market economy does not force waste producers and consumers to pay all the costs of production, or consumption. Some costs are passed on to others, and these are called negative externalities. Typical externalities include downstream air pollution due to an incinerator, or the groundwater contamination due to landfills. It is possible to pass such externalities costs to the society because the system of prices generated in the present market economy does not understate the value of natural resources. In principle, a series of prices can be generated that covers the true cost of solid waste disposal. Such a system of prices would change the production and consumption patterns from disposal and dumping to more recycling and reuse.

5.2 Economics of Recycling

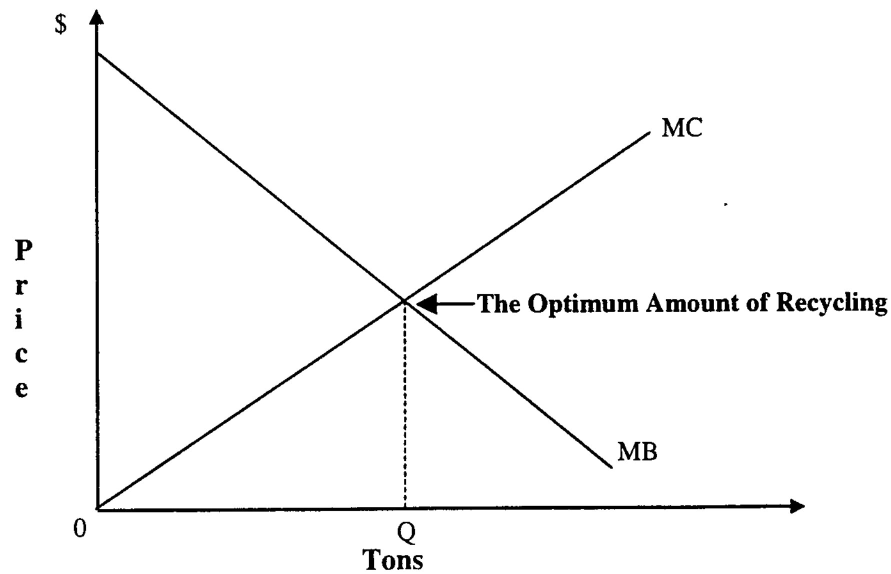
Due to the public perception of health and environmental consequences of unrestricted disposal of waste materials lead to the restriction of new disposal sites. In availability of land for solid waste disposal has become scarcer in an economic sense. As a result, disposal costs are rising towards their true social costs and hence the price of disposal has risen. This can be explained by the fact that the increased concern for the environment has caused an increase in waste disposal costs by increasing the number of unacceptable areas.

Figure 5.1 represents the concept of marginal costs and marginal benefits to recycling. It shows that as the quantity of waste recycled, the marginal cost of recycling increases, whereas the marginal benefit represents a declining incremental satisfaction from increased recycling.

Any production processes such as the production of recycled goods are generally subject to increasing incremental costs due to the law of diminishing returns. Figure 5.1 shows the rising value of Marginal Costs to depict the production process costs for recycled goods. The point Q is an intersection of MC and MB curves and represents the optimum amount for recycling. At recycling levels less than Q tons, the recycling value is not fully captured (since MB > MC); if recycling exceeds Q, the marginal costs MC exceed marginal benefits MB and it would not be beneficial. At point Q tons of waste recycled would provide the maximum value possible from recycling.

5.3 Components of Recycling

Price of materials that are manufactured from waste materials depends on the processing, transportation and availability of waste. The price of each recycled good is based on the specific material being recycled, there is a wide variation among them. Mills and Graves (1986) [21] have suggested that any waste material should be reused if



Quantity of Material Recycled

Figure 5.1: **The Concept of Marginal Cost and Marginal Benefits to Waste Recycling.**

the sum of costs of new material, disposal costs and landfill costs is greater than the cost of processing recycling wastes. The recycled waste material will be competitive with the new material if costs such as disamenity costs of disposal and landfill costs are added to the material. This concept is demonstrated in the following form:

$$P_m + D + L > S + C, \qquad [1]$$

Where,

P_m = Price of the new material/ton,

D = dis-amenity cost of disposal/ton,

L = landfill costs/ton,

C = processing costs/ton of separated material, and

S = recovery cost of waste material from waste stream or separation cost.

P_m, D, and L refer to the purchase of the new material, and the related disposal cost when it becomes solid waste. S and C are the costs of recycling. The extent to which the left side of the equation exceeds the right side may be thought of as the maximum price of recycling. Approach suggested by Mills and Graves is modified for the application to the municipal recycling program.

1. Transportation costs are often a very significant cost element of waste disposal. This is particularly true with the trend toward regional landfill or incineration facilities. Also transportation costs of waste materials to waste processing plants are significant. These costs do vary from location to location for multi-disposal facilities or processing plants. Thus, transportation costs must therefore be included explicitly on both sides of the inequality.

2. The equation suggested by Mills and Graves assumes that the recycled material is available free of costs, once it is separated and processed. In their model they only consider the price of new material but not the price of the recycled material. In fact, the authors assume that the recycled materials are never in the form that they can be reused as is basis. Generally without proper processing recycled material is not a perfect substitute for new materials. Thus, the price of recycled material should include processing costs.

3. Separation costs for certain type of materials such as plastics and glass etc. to recycling industries is significant. The separation costs of waste materials will depend on the extent the society is willing to participate in the generation of wastes separation program.

4. A regional waste disposal facility imposes the disamenity cost of landfilling to the adjoining area where the regional facility is located. It is important to consider compensation charge to the society in terms of landfill disposal fee. The question needs to be addressed that whether the society has been properly compensated for the disamenity costs.

5. Regardless of whether waste is hauled to a regional landfill or to a regional incinerator, the transport costs are based on volume. Thus for maximizing profit there will always be some justification for increasing the density of the material by compaction. To incorporate transport costs, a waste processing term on the waste generation side of the expression as well as on the recycling side should be considered.

To incorporate above points it is proposed to modify Mills and Graves cost of recycling algorithm. The suggested equation will be of the following form:

$$SC(i) + PCR(i) + TCR(i) - PR(i) < PCW(i) + TCW(i) + FW(i) \quad [2]$$

Where,

SC(i) = separation costs for recycling of waste material i,

PCR(i) = processing costs for recycling of waste material i,

TCR(i) = transport costs for recycling of waste material i,

PR(i) = price of recycled material i,

PCW(i) = processing costs for waste material i for landfill,

TCW(i) = transport costs for waste material i for landfill, and

FW(i) = landfill disposal fee for waste material i

The SC will be minimized to the extent that households are willing to participate in the separation of wastes in such a way that the waste materials are not contaminated. This will reduce the negative component on the left side of the equation. Even with a strong public acceptance of recycling, some labor cost for monitoring will likely be necessary. Households must separate some items because the cost of separation becomes very high once they reach the waste stream. An example of such a material is paper and paper products. On the other hand, there are certain materials like scrap metal that require considerable knowledge to separate into appropriate categories. The recycling of glass represents an intermediate stage where initial separation can be done in houses and attendants do disposal in separate bins according to color.

Processing of waste materials for recycling directly affects the marketability. For paper products and plastics, appropriate processing is crucial for cost effectiveness. .Transportation cost for recycled products are related to the degree of processing of the waste material. Certain products are expensive to transport so they are compacted to make transportation cost effective. On the other hand, aluminum cans are easy to separate and high in value then the transportation costs thus do not affect in recycling costs.

Both landfill disposal costs and transportation costs need to be expressed in dollars per ton, as there is always a significant gain that can be realized from compaction of wastes. Considering the fact that cost of large scale compaction is relatively low, it is reasonable to assume that compaction of wastes always has a positive processing cost (PCW > 0). The overall concern for landfill is the availability of landfill space (volume) in future. This concern is reflected in the volume based landfill charges.

Wastes have to be transported for disposal. A transportation costs (TCW > 0) is always imposed and a tipping fee will invariably exist (FW > 0) as wastes after sorting of items for recycling must be transported for landfill disposal.

The above cost benefit approach is helpful to understand related costs and benefits to recycling. This concept does not consider the costs of incremental changes that often occur in both costs and benefits as the amount of recycling changes. By using the tool of economics, the incremental costs can be shown for a number of different items in the waste stream.

5.4 Microeconomics of Recycling

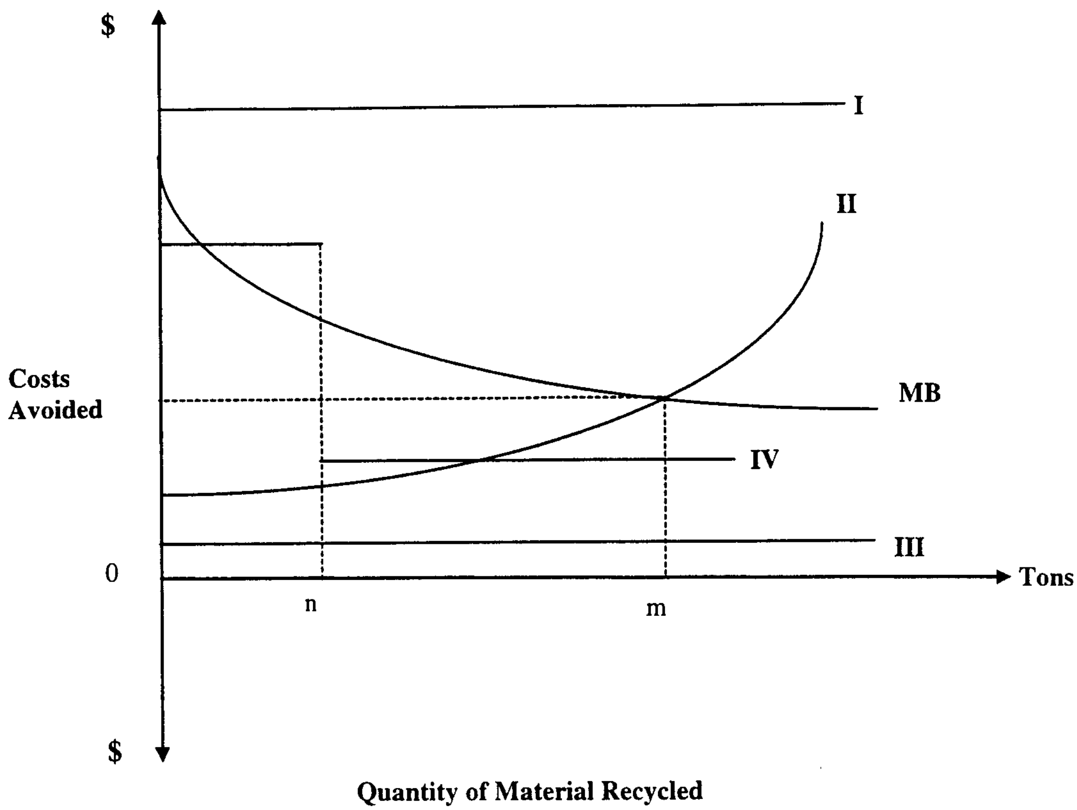
The condition suggested by Mills and Graves for recycling waste materials is very helpful as it suggests item by item analysis to determine the payoff from recycling. Generally materials in the waste stream consists of numerous materials. Each material differs in market price, processing costs, and disposal costs. These and other factors point out that each waste material has to be evaluated separately. Figure 5.2 shows the marginal cost and benefit concepts as derived from Figure 5.1 and applied to different materials.

5.4.1 Marginal Benefits

Benefits from recycling are numerous such as the revenue generated from recycling and sale of material, avoidance of disposal costs, and improvement in environmental quality. Revenue from sale of each material is treated as a reduction in costs. Combining all costs together provide a platform to develop a marginal benefit function for recycling. It could also be thought of as a community demand curve. As shown in Figure 5.2 the marginal benefits (MB) curve declines, but would approach to a constant value at par for the dollar value of disposal avoidance costs. Surveys were conducted to determine the value people place on environmental quality.

5.4.2 Marginal Costs

The marginal cost of recycling tends to be material specific because the marginal cost is dependent on market prices and processing requirements. There are four scenarios of cost patterns for recycling. An example would be the sale of the junk furniture. The first scenario could be cost of disassembly that is so high that no amount of recycling is



Curve I :	MB<MC
Curve II:	MB>MC at low rates
	but MB<MC at high rate
Curve III:	MB>MC at all points
Curve IV:	MB>MC at high volume

Figure 5.2: Concepts of Marginal Benefits and Marginal Costs from Recycling (Four Cases)

worth (MB < MC) at all points. A second type is initially low marginal costs that justify recycling up to a point (i.e., MB > MC at low rates but MC > MB at high rates). An example of such behavior is the recycling of plastics. At the low recycling cost end, there is a fairly easily recyclable HDPE and PET; but at higher recycling it is difficult to recycle mixed resin containers and plastics. A third distinct type is a material like aluminum cans with a high market value that overcomes separation and processing cost at all recycling amounts (MB > MC at all points). Lastly there is the case where recycling is justified only at large volumes or weights. An example would be cardboard recycling. These four cost patterns for recycling are numbered I to IV respectively in Figure 5.2.

5.4.3 Public and Private Benefits from Recycling

The benefits shown in Figure 5.2 are community benefits since municipal waste disposal is considered as part of tax revenue. Individuals can dispose off waste by paying small amount and it is considered as a personal cost to individuals. In this case an avoidance cost is very small. The marginal benefit curves in Figures 5.1 and 5.2 depict community benefits as opposed to individual benefits. The distinction between the community and individual benefits and how each relates to mandatory recycling is shown in Figure 5.3.

Figure 5.3 represents the same concepts as in Figure 5.1, except that an individual or private benefit curve is added and labeled MB_p, and the community curve is relabeled as MB_s to represent the society's marginal benefit. The point Q represents the optimum amounts of recycling whereas the point Q' represents voluntary recycling since

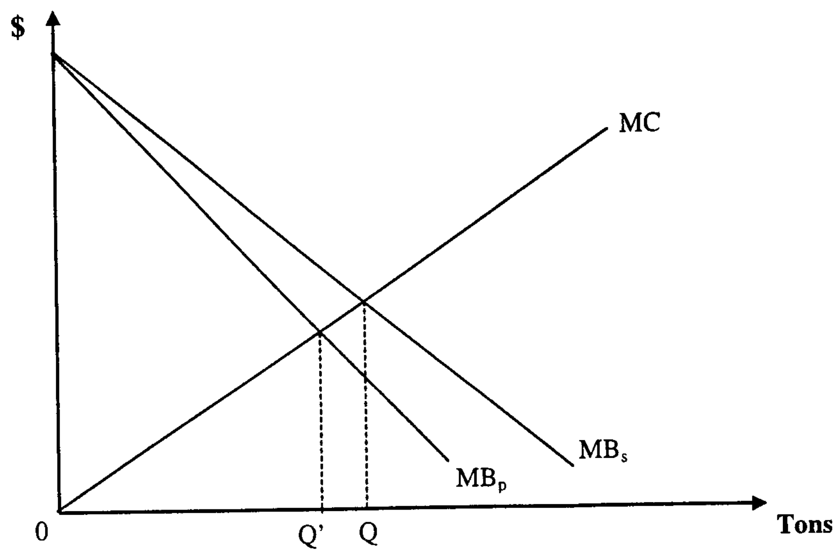


Figure 5.3: Individual and Social Benefits from Recycling

individuals would have lesser incentive to consider the costs avoidance benefits. It suggests that recycling needs to be mandated in order to achieve the optimal amount Q. An alternative way to look at recycling is to consider it as public goods with the classic free rider problem. This means that a person 'A' gains the most if everyone else recycles but 'A' does not. In this case, 'A' would be the free rider. Of course, if everyone thinks the same way, then no recycling would get done. This again is a valid argument for mandatory recycling.

One of the advantages when a waste producer has to pay fees to dispose off its waste then the marginal benefit can be measured explicitly, because the cost avoidance gain from recycling is explicit. A ton removed from the waste stream will have a cost avoidance gain of 'X' dollars per ton. If a town or municipality owns a landfill or incinerator, the cost avoidance gain would not be so easy to calculate. The technique used in this case is to estimate the gains in present value terms.

5.4.4 Waste Materials that need special Recycling

Certain materials are separated out of the waste stream, not primarily because they can be reused (though they may be), but because they cannot be landfilled or incinerated. An example of such a waste material is scrap tires. The benefits of recycling these materials include environmental improvements, which generates marginal benefits (MB) for such materials higher than other materials. Individuals bringing such materials have to pay a nominal fee enough to cover all or most of the external disposal fee, and provide incentives to prevent illegal dumping.

5.5 Monetary Impact of Recycling

To project the costs and benefits from recycling, it is necessary to know the characteristics of the waste stream, and resources required to separate and process. Thus actual labor and capital costs and market prices of recycled materials will yield the financial data that is needed to determine the costs and benefits of recycling. There are two significant monetary benefits from recycling: first the revenue from the sale of recycled materials, and the gain due to the avoidance cost. Every time a ton of material is removed from the waste stream, the fee for disposing off that ton of waste is saved. These savings are called 'avoidance costs'. In recycling programs, consideration of avoidance costs is the benefit that makes the program cost-effective. Second is the saving in the stockpile of natural resources.

5.5.1 Components of Avoidance Costs

Each ton of waste material removed from the waste stream of a town, institution, or firm reduces solid waste disposal costs by the amount it takes to process, transport, and dispose off that ton as a landfill waste. The gains from avoidance costs often have to be estimated for disposal process of each waste material. There are four general types of costs associated with disposal of waste: these are costs of collection, processing, transportation, and disposal. Generally, there is only one flat fee is imposed to the waste generator. A waste management contractor collects this flat fee to haul waste from the generation premise. This flat fee includes other costs that are associated with waste disposal. In some other situations, all four costs have to be addressed.

Collection Costs

A major factor in the collection costs is to account for the cost from waste production points to central locations where it is loaded to be taken to a disposal site. The cost of waste collection should fall with the implementation of a recycling program simply because there will be lesser waste to collect. It should be noted that the collection cost is referred to the reduced waste collection costs and it does not consider the added collection costs due to recycling.

Processing Costs

MSW normally does not represent a weight problem and it is usually compacted before hauling. With a reduction in the amount of waste disposed of due to the recycling program, cost reductions are possible in the processing of waste for disposal.

Transportation Costs

There are two types of transportation costs: the cost of transportation of the separated materials, and the cost of transporting the waste to the disposal site. The cost saving due to the lower waste volumes due to recycling should be considered for credit to the recycling program. The increase in transportation costs of the separated materials should be added to the costs of recycling.

Disposal Fees

Waste disposal fee is based on the weight of waste disposed, thus makes it easy to calculate the tipping fee avoidance cost. The calculation of landfill disposal costs avoided is more complicated if the town or county has its landfill. Recycling programs help in extending the life of a landfill. The gain due to avoidance costs should be considered in accounting the monetary benefits of extending the life of the landfill. For example if it is assumed that the recycling program will extend the life of a landfill by four years from four years to eight years, then gain due to the avoidance cost would be:

1. The value in today's dollars is putting off the expense of a new landfill for four more years.
2. The value in today's dollars is to start hauling waste materials to a distant site eight years from now instead of four years from now.
3. The value in today's dollars is putting off the substantial closing costs of the landfill for four years.

5.5.2 Revenue from Sale

The second type of monetary gain from recycling comes from the sale of recycled materials. The market value of separated materials exhibits wide variation. The market prices at any time vary widely depending on the material, the region, current supply and demand, and the degree of processing the material.

5.5.3 Monetary Costs of Recycling

The cost per ton for each stage of recycling needs to be accurately established to estimate total costs. The costs of recycling are similar to the costs of waste disposal with three exceptions. First, the separation cost of recycle waste materials, second is the cost of recycling, and the third is the difference in transportation cost. The specialized trucking for carrying processed recyclables makes it more efficient for buyers to pick up materials at a recycling center or at a processing facility. The price is often quoted at the seller's dock, so transportation costs are included. On the other hand, when waste is hauled to a disposal site, transportation is often an explicitly quoted price. The transportation of waste therefore shows as a positive in the avoidance costs as part of the benefit to recycling, while the transportation cost of processed recycle materials shows up as negative because the seller's price is less than it would be without the transportation.

5.6 Stages of Recycling

The stages of recycling can be categorized as diversion, separation or extraction, and delivery for processing; accumulation, storage, and transportation to buyer. From the perspective of those operating recycling centers, it is convenient when households, firms, or institutions bring already separated materials to central collection facilities. In this case, the cost of bringing the materials from the collection center to the processing facility is zero. This may be more costly or complicated if the materials must be picked up and separated at curbside or at workstations. As with waste collection, there can be delivery charges internal to the process, such as moving the material from collection facilities to the processing centers.

The marketability of many separated materials is highly dependent on proper processing. Processing include industrial balers for cardboard, newspaper and magazines, and plastics; granulators for plastics; and crushers to reduce the volume of glass. Marketability is also enhanced by on-site storage capabilities. A simple covered roof structure as a warehouse is sufficient for plastics and glass; even for paper. Provision must also be made for accumulation before processing. A good recycling program will require a forklift for materials handling as much as it requires a baler for processing. Another important concept in materials handling is the need to prevent contamination of the separated recyclables.

5.7 Estimation of Gains from Recycling

A mathematical algorithm is developed to estimate gains from recycling. The algorithm considers material types, revenue generated from the sale of waste materials, cost incurred in recycling and waste disposal costs as avoidance costs. The model has the following form:

$$G^m = R^m - C^m + D^m$$

Where,

G^m = Net gains per ton from recycling by waste material type m

R^m = Revenue received per ton from sale of waste material type m

C^m = Costs of collection and processing per ton of waste material type m

D^m = Landfill disposal costs per ton of waste material type m

The above model should be considered as a general model to calculate the gain or loss of recycling a particular material.

Two concepts that are important in the recycling business are present value, and capital cost. Since some benefits and costs occur in the present and some benefits will be realized in the future, a comparison of values has to be based on a common base year. For example, if a recycling program extends the life of a landfill for a certain number of years, then a comparison need to be made between a future dollar amount and a current dollar amount. This is achieved by discounting the future amount, since the gains are not going to be realized until some time in the future. Capital costs are generally those for the plant and equipment. Since plant and equipment provide service for several years, normal accounting practice allows spreading the cost over a number of years.

5.8 Economic Decision to Use Recycle Materials

It is important that an economic decision should be made before state DOT's use recyclable waste materials in highway construction. The economic decision to use waste materials is only carried out after the performance of these materials in highway construction is acceptable.

A computer program was developed using Microsoft(T) Access to provide a tool in making an economic decision. Appendix D shows the window based Microsoft(T) Access program. The program considers all 50 states in the USA according to ten regions of the USEPA. Table D.1 labeled as "Microsoft Access Tables for Various Recycle Waste Materials" is developed as an input table to enter various cost elements for material type, State and USEPA region. By selecting and opening the listed waste materials an appropriate cost information can be entered through this table that subsequently will lead to output in terms of three forms.

The Microsoft(T) Access program considers the following input to estimate the net cost or savings for the use of recycle wastes in highway construction.

- Material type
- State and USEPA region
- Cost of collection of waste materials
- Cost of sorting of waste materials
- Initial cost of processing of waste materials
- Environmental cost
- Economies of scale cost
- Processing and technical cost
- Market value of process material
- Transportation cost

Appendix Table D.2 lists various forms by material type. It also shows "Recycle Cost Form" and "Societal Cost Form". The "Recycle Cost Form" provides the cost of each recycle material by state considering the above inputs. The "Societal Cost form" is designed to consider societal benefits for using the recycle waste materials. The estimation of societal benefits considers the following three main inputs:

- Savings in landfill cost
- Savings in property value cost
- Savings in environmental cost

The savings in landfill cost and property value cost can be estimated with some precision. The savings in environmental cost are considered intangible goods and a best hypothetical estimate can be made. It could be correlated to the question such as how many consumers consider waste materials valuable to recycle? For example several states have instituted a deposit for the return of aluminum soda cans and plastic bottles. Assume that if the deposit for each can is only one cent, then consumer may not be willing to participate in the recycle program to receive their deposit back. If the deposit per can is ten cents, then it may be possible that majority of consumer will participate in the recycle program. There seems to be a relationship between the deposit amount and the amount of recycling.

The "Societal Cost Form" displays the output for the societal cost by type of waste materials and state. The form is linked to "Recycle Cost Form" and to another form "Decision Form" to arrive a decision with regard to cost effectiveness. The "Decision Form" is the final decision form for making decision to use the recycled waste or not to use the waste material. It displays the net cost savings and the cost for the use of recycled waste in highway construction. It displays cost by material type and state. This form is linked to "Recycled Cost Form" and "Societal Cost Form".

Appendix Table D.3 shows output in-terms of various input cost elements by material type. The Table is designed to show the cost elements by state through clicking to various buttons.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Over 4.5 billion of non-hazardous wastes are generated in the United States each year. Out of these waste over 200 million tons of post consumer waste is generated. The disposal of post consumer waste is the responsibility of municipality and society, where as other generated waste are the responsibility of the generator. The cost of disposal of post consumer waste is increasing, which requires an alternate use for these waste materials. One possible use of these post consumer waste materials is in highway construction. An economic analysis is needed for their cost-effectiveness before using these materials in highway construction. Though these recycled waste materials are expensive compared to virgin material, but if the savings in terms of societal cost are considered, then these materials become cost-effective and attractive to use in highway construction.

A questionnaire survey was conducted for obtaining input from all state Department of Transportation (DOT), recyclers and solid waste management facilities in the state of Ohio. Responses received from state DOT stated that they use various recycled materials in highway construction. None of the state responded on the question of cost-effectiveness of recycle waste materials. There was poor response from solid waste management district officers and recyclers. Most of the solid waste management district officers replied that the information on cost-effectiveness is proprietary and decline to furnish.

Some of the broad conclusions that are drawn from the research project are:

1. Post consumer waste materials can replace conventional material. Savings are recognized by not having to landfill or incinerate the waste.
2. The waste materials require proper process, which is expensive. It can only be cost-effective if there is a continuous supply of waste materials available to process and there is willingness of society to use these materials. Incentives at the federal, state and local levels can overcome the initial high cost of processing.

6.2 Recommendations

The growing trend in the generation of waste, decrease in the number of waste disposal sites, increase in tipping fees and increasing societal costs warrant the use of waste materials in highway construction. The following general recommendations are made based on results of the survey, literature reviews, visit and discussion with the MSWD management officer:

1. Before substituting recycle waste material for existing virgin material in highway construction, the recycle waste materials should be evaluated for its performance.
2. Conduct a cost-effective analysis of the post consumer waste material for use in highway construction project. Most of the waste material is cost effective by incorporating societal costs in terms of savings in land cost, environmental cost, collection and transportation cost and savings in natural resources.
3. Table 3.6 shows the possible use post consumer waste materials in highway construction. Investigate the performance of the waste materials for the possible use as suggested in the Table 3.6.

4. Develop new construction methods, new quality control procedures and develop a database of cost information related to the use of waste materials in highway construction.

5. Collaborate with post-consumer waste recycle industries to develop materials that replace the existing materials. Collaboration with recycle industry will provide a better understanding on the cost effectiveness of the waste materials.

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APPENDIX - A

APPENDIX A

This literature review investigates the possible uses of waste materials in highway construction and the economic measures that can be used to evaluate the cost effectiveness.

Broken Concrete

This is a product resulting from the manufacture of various pre-cast concrete products such as manholes, pads, pipes, cubes, blocks, culverts, beams, etc. Possible use for this material could be as ditch checks and slide repair [1]. The state of Minnesota has used crushed concrete successfully in concrete mix aggregate and base aggregate [2]

Construction and Demolition (C & D) Debris

It is estimated that annually approximately 20 to 30 million tons of C & D debris are produced in the U.S. The C&D debris consists largely of wood and plaster but also includes concrete, glass, metal, brick, shingles and asphalt [3]. Materials such as concrete, bricks, glass and old asphalt are reclaimed and processed into aggregates. Crushed concrete when separated from reinforcing steel can be used as an aggregate in foundation sub grades, road construction and other applications [4]. Coastal areas have used concrete rubble to construct artificial reefs. Wood chips can be used as fuel, lightweight fill or as landscaping material. C & D debris can be utilized advantageously in mechanical stabilization [5]. Possible contaminants that could be included in C & D debris are sewage sludge that causes odors and asbestos which is hazardous [6]. Collins and Ciesielski [3] list the possible use of rubble as a highway construction material, as an embankment borrow source, as an unbound base course aggregate and as an aggregate in asphalt paving.

Cement and Lime Kiln Dusts

An estimated total of 20 million tons of cement kiln dust is collected annually, and approximately 60% are recycled in cement plants. The remaining 8 million tons of cement dust per year needs landfill or alternate use in some way [7]. Physical characteristics include a material that is grayish buff colored and a gradation having 100% passing the No. 80 sieve with about 90 to 99% passing No. 200 sieve [2]. Cement kiln dusts have been used in stabilized base course mixtures and as mineral filler in asphalt. Lime kiln dusts is physically similar in characteristics to cement kiln dusts but differ chemically. A possible use of kiln dusts and clinker would be as embankment fill material. There has only been a limited use of this material in highway construction.

Lime Waste

One of the waste products generated in the manufacture of acetylene is carbide lime. The lime waste is either in the form of sludge or powder depending on whether the process is carried out with or without water. Carbide lime is similar physically and chemically to commercial hydrated lime [3]. Carbide lime has some potential for use in soil stabilization or as mineral filler in asphalt paving mixes [8]. Collins and Ciesielski [3] report that lime waste is evaluated by two states (Kentucky and Missouri) as a soil stabilization reagent and by Ohio as a mulching material. Al-Sayed et. [9] studied the potential of using de-watered carbide lime sludge as mineral filler in asphalt paving mixtures. They showed that the lime waste was effective in improving the viscosity and temperature susceptibility of the mix and satisfied all other criteria such as stability, flow etc. It is reported [3] that no field use of lime waste has been made by the various highway agencies, nor is any research being planned.

Mining Wastes

These are broadly divided into the following categories.

a. Coal Refuse

b. Mine Tailings

c. Phosphate Slimes

d. Phosphogypsum

e. Waste Rock

Coal Refuse

It is estimated that approximately 120 million tons of coal refuse is produced annually in the U.S.A. [3]. The total accumulations of coal refuse are in the range of 3 to 4 billion tons [10]. The material is classified as either fine or coarse and approximately 70 to 80 percent of coal refuse are coarse. It largely consists of slate and shale with some sandstone or clay [3]. The physical characteristics of coarse refuse include a material that is generally gray in color and a gradation having a top size of about 6 inches with about 10 percent minus No. 200 sieve material [2]. If placed in large piles, this material may ignite by spontaneous combustion due to the heat generated from within. There is also concern regarding its potential for acidic leaching into ground water. Though this material is subject to weathering, its properties are stable when compacted to its maximum dry density. This material becomes slick when wet and tends to have a cementing action. Fine refuse results from coal washing operations. It is dull black in color and is generally considered chemically inert although some sulfur may be present [2]. Both coarse and the fine refuse can be used as embankment fill material. Rose [11] has studied the use of sintered coal refuse as aggregate for use in bituminous concrete mixes and structural lightweight Portland cement concrete. Literature review reveals that embankments have been built out of coal refuse in four states: Illinois, Maryland, Ohio and Pennsylvania. West Virginia has used coarse coal refuse as stabilized subbase material.

Mine Tailings

It is estimated that approximately 500 million tons of milling waste is generated per year in the U.S.A. [3]. The largest amount of mine tailings is generated from the concentration of copper, iron and taconite, lead, zinc and uranium ores [3]. The gradation of these tailings varies greatly depending on the ore processing methods. The Missouri Highway and Transportation Department [2], has identified various uses for mine tailings such as an embankment fill material, as a subbase material, as snow and ice abrasive material or as aggregate in bituminous mixtures. Iron mine tailings have also found use as aggregate in Portland cement and asphaltic concrete. Rose [11] reported that copper mill tailings have excellent potential for use as compacted fill in embankments, compacted foundation and subgrade material, cement treated base, emulsion treated base, and stabilized material for lining canals, ponds and reservoirs. A research [3] is underway to demonstrate the use of tailings as concrete aggregate, as riprap aggregate, or as a chip seal aggregate.

Phosphate Slimes

These mineral wastes are by- products of the phosphate industry. Annually in excess of 100 million wet tons of slimes need disposal by the phosphate industry, mainly in central Florida, but also in North Carolina and Tennessee [10]. There has been no attempt to use this material in highway construction.

Phosphogypsum

Phosphogypsum is a calcium sulfate hydrate produced when phosphoric acid is produced from phosphate rock by wet process. The current method of its disposal is to dewater it in ponds and then dispose the dry material in stacks. Total accumulations of Phosphogypsum stacks are probably in excess of 700 million tons [12]. This material has been recovered and utilized in stabilized road base mixes. In 1989, the EPA issued a ban on its use because of the possible health effects due to radiation from Phosphogypsum stacks. The ban by the EPA includes both research studies as well as the use of the material. As a result, there is no current use of this material nor is there any research into its possible uses. Before the ban, researchers at Texas A&M and at the University of Miami have laid experimental sections of road having a cement stabilized Phosphogypsum road base.

Waste Rock

The largest amounts of waste rock are produced from surface mining operations, such as open-pit copper, phosphate, uranium, iron ore, and taconite mines [10]. The major problem associated with the use of waste rock is that most mines are located in remote areas and it is not economically feasible to transport the waste to construction sites. Although waste rocks are 12 inches in top size, there is considerable variation in the degree of size uniformity from pile to pile. Possible uses of the waste rock would be as a base fill, embankment fill, shoulder material, and in gabions [2]. There has been widespread use of waste rock at various levels from the state highway agencies to local road agencies. Collins and Ciesielski [3] report that New York is the only state now using waste rock as a highway material. It's performance as stone fill for banks and as riprap for bank and channel protection has been described as very good.

Quarry Waste

Quarry waste consists mainly of fine material and some wet silt clay left over from the processing at quarries. It is estimated that at least 175 million tons of quarry waste is generated per year and as much as 4 billion tons of waste has accumulated over the years [3]. The properties of the waste both physical and chemical and the mineralogy of the waste vary from place to place and depends on the quarry where the waste is produced. Quarry waste fines are used as fill or borrow material, as filler in concrete and flowable fills, in base or subbase stabilization, or as cement-stabilized base material for low-volume roads [13]. Gaspar [5] states that quarry waste can be utilized advantageously in mechanical stabilization. The National Stone Association has studied and recommended use of quarry waste as flowable fill and as cement treated subbase. Other uses are as mineral filler in asphalt or as slurry seal aggregate [14]. Quarry wastes have been used in Arkansas, Florida, Georgia, Illinois, Missouri, and Vermont [3].

Reclaimed Pavement Materials

These are broadly divided in two categories: 1. Reclaimed Asphalt Pavement, and 2. Reclaimed Concrete Pavement.

Reclaimed Asphalt pavement (RAP)

RAP is generated by removal of an existing bituminous surface. It is estimated that approximately 50 million tons of asphalt paving materials is being milled annually [3]. RAP can be recycled into hot mixes, cold mixes, or in-place mixes, and can also be used in unbound aggregate base and subbase, stabilized base course, shoulder aggregate, and open-graded drainage courses [3]. Some of the recycling processes are discussed below. The process of Cold in-place recycling (CIR) consists of partial milling of the pavement, processing the material to a suitable size, treating with an emulsion, and placing the recycled cold mix using conventional methods of paving and compaction [15]. Since 1986, the Kansas Department of Transportation has used CIR with an additive of emulsified asphalt as a cost-effective option for rehabilitating thermally cracked low-volume pavement [16]. Hot in-place surface recycling (HIR) techniques offer in-place surface recycling with rejuvenation and hot mix overlay [17]. In addition, there are the processes of plant cold recycling and hot mix plant recycling. It is estimated that only about 20-50 percent of all the milled asphalt material is being recycled into hot-mix asphalt paving mixtures because it has not been possible to maintain satisfactory mix temperatures with higher percentages [18]. A microwave process that can recycle up to 100 percent of RAP into hot-mix asphalt is under development [19]. Collins and Ciesielski [3] report that virtually every state in the U.S. uses RAP in some way or the other. It further lists that at least 16 states use it as unbound base or subbase aggregates, two states have used asphalt millings as aggregate in stabilized base courses, and one state has used RAP as concrete aggregate.

Concrete

It is estimated that about 2.9 million tons of reclaimed Portland cement concrete (RPCC) is being recycled annually in the U.S. [3]. Existing Portland cement concrete (PCC) pavements represent a readily available source of aggregate that can be used for various purposes. Yjarson [19] identifies various uses for RPCC such as aggregate for new PCC pavements, econocrete (lean concrete) bases for highways and airports, shoulder concrete, porous granular fill, unstabilized base courses, and open graded drainage courses under new PCC pavements. The findings of a number of studies conducted on RPCC are summarized in the report. It was found that the RPCC coarse aggregate had better properties as compared to mineral aggregates. The use of coarse RPCC aggregates had no effect on the mix proportions or on the workability of concrete. When RPCC was used as fine aggregate, the mix was found to be less workable and required more cement. Research has also shown an increase in freeze-thaw resistance and durability of concrete containing RPCC aggregate. The RPCC aggregate was found to be not detrimental to the compressive strength of the mixture and the use of water-reducing admixtures was effective in increasing its strength. Air entraining admixtures and fly ash were found to be useful in providing durability and improving the workability of the concrete mix. RPCC has also found use in cement treated base, as an asphalt paving aggregate, and as rip rap [3]. Recycling concrete pavements has become more economical over the years with the developments of new methods and equipment for breaking concrete pavement, for removing reinforcement, and crushing slabs with reinforcement. Eight states use it as an aggregate in new concrete; five states use it as a subbase material; four states use it in asphalt paving mixtures, and one state uses it in stabilized base courses [3].

Sewage Sludge

In U.S. annually an estimated 8 million tons of dry solids of sewage sludge is produced [20]. Sewage sludge consists mainly of organic material like nitrogen and phosphorous, but may also contain other contaminant [3]. Stabilized sewage sludge has potential for use as a soil amendment or nutrient on highway rights of way and also as an embankment material. Sludge incinerators produce 0.5 to 1 million tons of sludge ash annually [21]. It can be used in asphalt mix as filler, and also used in brick manufacturing in California [3]. The use of sintered sludge ash pellets as coarse aggregate in concrete was investigated by the University of Minnesota and it was found that the resulting concrete cubes had 15 percent more '28 day strength' than conventional mixes [22]. The sewage sludge has been used as asphalt filler in Minnesota and New Jersey and as a topsoil amendment in New York [3]. The environmental concerns resulting from the use of sewage sludge and its effect on the health of workers has yet to be studied and is a major factor affecting its acceptance.

Slag

These are broadly classified into iron and steel slag, and non-ferrous slag. Blast furnace slag is derived from iron production of iron in a blast furnace. It consists of silicates and alumino-silicates of lime. There are three types of blast furnace slag commonly produced; air cooled, granulated, and expanded [3]. Air-cooled slag is commonly used in concrete, asphalt pavement, and road bases, and as a fill material.

Granulated slag is ground and used as slag cement. Expanded slag is used as aggregate in lightweight concrete [3].

Steel slag is a by-product of steel production consists of a fused mixture of oxides and silicates of calcium, magnesium, and iron. There are steel slag processing locations in 26 states in the U.S. [23]. Steel slag is heavier than ordinary aggregate and is very hard and abrasion resistant; hence, it has been used in asphalt pavement, as a fill material, as railroad ballast, and for snow and ice control. Aging of steel slag with water is recommended when it is used for purposes other than asphalt pavement. Gupta, Kneller and etc.[24], report that slag leachate clogs under pavement drains.

Collins and Ciesielski [3] report that at least 22 states have used air-cooled blast furnace slag, mostly as an aggregate in asphalt or cement concrete, but also as aggregate base and subbase. Granulated blast furnace slag has been used as a cementitious material in at least two states, steel slag is used as aggregates in asphalt pavement in at least 11 states and steel slag has been used as a subbase or embankment material in at least two other states [3].

Non-ferrous Slag

In the US approximately 10 million tons of non-ferrous slag is produced annually from thermal processing of copper, lead, zinc, nickel, and phosphorous ores [3]. Non ferrous slag are either in a air cooled or in a granulated form and all contain some proportion of metals in the ores from which they were produced [25]. Copper, lead and zinc slags are ferrous silicates while phosphate and nickel slags are calcium or magnesium silicates. Some of the slag has been used in asphalt and concrete mixtures, as road base materials and as railroad ballast. The Oklahoma State University tested zinc smelter for possible use in stabilized base mixtures, asphalt paving, and Portland cement concrete and found that it provided satisfactory results as aggregate in asphalt and stabilized base mixtures but proved unsatisfactory for use in concrete [26]. The state of

California has made limited use of a copper oxide blasting slag in asphalt mixes. Florida and Tennessee states have used phosphate slag as aggregate in asphalt paving. Texas State has used aluminum slag as aggregate in asphalt paving but its performance was unsatisfactory. Michigan state has approved the use of copper reverbatory slag for all aggregate uses, except as a fine aggregate in Portland cement concrete [3, 27].

Post Consumer Waste

The amount solid wastes in the U.S. has been steadily increasing for the past 30 years from about 88 million tons in 1960 to about 180 tons in 1988 [28]. The quantity and composition of the solid waste has a direct impact on the technologies selected for management and disposal. The literature review examines some possible uses of these materials in highway construction.

Glass

In 1998, approximately, 12.5 million tons of glass was discarded in the U.S. [28]. Most of the recycled glass is uses as cullet in glass manufacturing. The possible uses of waste glass in highway construction are as a fine aggregate in unbound base courses, embankment material, pipe bedding, or in asphalt mixes (Glasphalt). In addition to these uses, waste glass beads may also be used in reflective paint on road [3]. Loss of adhesion between glass and asphalt occurs when the samples are immersed in water. Glasphalt offers adequate skid resistance but on the other hand increases wear and tear on the tire. Glasphalt pavements have been laid on low volume and low speed roads for various purposes: research, aesthetic reasons, symbolic recycling gesture, and to save landfill space. There is no application of Glasphalt on roads of higher speed [29]. Glasphalt on the pavement surface may not be acceptable in residential areas. The cost of laying Glasphalt is generally higher than a conventional asphalt pavement due to the use of anti-stripping additives like hydrated lime, and the cost of transportation of the glass to the site. Potential savings in landfill cost could offset the added costs. For these reasons, FHWA and the Asphalt Institute urge caution in using Glasphalt. The state of New Jersey intends to continue using Glasphalt as a competitive alternative to all asphalt construction projects. The New Jersey Department of Transportation also reports that the use of the anti-stripping agent can be eliminated as little benefit was derived from its use [30]. The angularity of crushed glass particles is detrimental to the stability of the concrete mix when glass is used as aggregate and hence it is not recommended for this purpose [3]. The use of glass in embankments has been found to be a viable alternative to its use in pavements by Connecticut DOT [29]. The state of California is evaluating the use of waste glass in a cement stabilized base, state of Maine is investigating the use of crushed glass beads in reflective paint, and the state of New Hampshire is investigating its use in an unbound base course [3].

Plastic

It is estimated that about 14.4 million tons of plastic found its way into the municipal solid waste stream in 1991 [31]. Recyclable plastics are coded into seven major categories by the Society of the Plastics Industry, based on the polymer they contain. They are:

1. PET (polyethylene terepthalate)
2. HDPE (high density polyethylene)
3. V (polyvinyl chloride)
4. LDPE (low density polyethylene)
5. PP (polypropylene)
6. PS (polystyrene)
7. Other

The above code, as a number surrounded by a triangle is molded into a rigid container. Each of these products has different uses. It is estimated that about 30 percent of PET and 7 percent of HDPE are being recycled [32]. The following table lists products used in the construction industry which contain recycled plastic [33].

Uses of Plastics in Highway Construction:

Drainage Pipe	Culverts
Sign Blanks	Lumber
Traffic Barricades	Traffic Cones
Traffic Drums	Geo-textiles
Conduit	Sign Posts
Delineator Posts	Guide Rail Posts
Concrete Construction Reinforcement Supports	Glare Screens
Plastic Sheeting	Parking Stops
Construction Stakes	Safety Fence
Fence Posts	Manhole Steps
Curbing	

Plastic lumber, sign and delineator posts are made from reclaimed HDPE and commingled products while LDPE has been recycled into pellets for use as an asphalt modifier. Geo-textiles have been made out of recycled PET [34] and PET has also been used in polymer concrete [35]. Composite piles have been made from steel pipe and commingled plastic [36]. It is reported [3] that Colorado, Nevada and New York states have placed pavements with recycled LDPE pellets as an asphalt cement modifier. Florida and North Carolina states have used commingled plastic to manufacture fence and sign post. North Carolina and Kansas states are using recycle plastic to fabricate delineators. In Elgin, Illinois a Portland cement concrete bridge was built containing 30 percent granulated plastic as partial replacement for sand to reduce dead weight at comparable compressive strength [35].

Rubber Tires

It is estimated that about 243 million scrap tires (2.4 million tons) are generated each year in the U.S. [37]. The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, Section 1038 requires states to use a minimum amount of asphalt pavement containing scrap tire rubber, beginning with 5 percent in 1994 and increasing uniformly to a total of 20 percent by 1997 [38]. Since mid 1960's the use of scrap tire in asphalt mixtures has been in vogue in the U.S. Crumb rubber modifier (CRM) is a type of asphalt modifier that contains rubber from scrap tires. Asphalt paving products can be made from crumb rubber by various processes including a wet process and a dry process [37]. These modifiers can be used as joint or crack sealers or as binders in asphalt mixtures. The use of asphalt rubber as a crack sealer is more widespread than its use as a joint sealer [37]. Laboratory tests indicate that asphalt rubber mixtures are more resistant to deterioration than conventional asphalt mixture [39]. There is a limited data available currently on the performance or cost of asphalt rubber joint and crack sealers, except that their effectiveness seems to be relatively high and a substantial quantity of asphalt rubber is used [37]. Asphalt rubber binders are also, used as chip seals, the use of which was pioneered by McDonald [40] in Phoenix. Chopped, shredded, and whole tires have been used for a number of other transportation related uses such as in fills and embankments, erosion control, (shoulder reinforcement and channel protection), retaining walls, membranes, revetments for slope protection, railroad crossings etc. [37]. The results of the use of tires in fills and embankments has been encouraging but there are environmental concerns such as disease causing potential from stockpiles.

Paper and Paper board

Waste paper makes up a major part of the domestic solid waste stream (up to 40 percent) [41]. It is estimated that it takes about seventeen trees to make a ton of paper.

When paper is made from waste paper, it is not only saves trees, but also saves energy, water, reduces emissions, and saves landfill space and its associated costs. The major use of waste paper is in paper manufacturing. The only recognized use of waste paper in highway construction is as mulch material. It has been reported that eight states (Georgia, Illinois, Kansas, Missouri, New Hampshire, Oregon, Pennsylvania, and Wisconsin) are using or have used waste paper as mulch [3]. Missouri has had success with hydraulic mulch over-sprays using slick paper, and has recommended it for adoption as a standard option for asphalt emulsion [42].

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APPENDIX - B

APPENDIX B

Questionnaire

1. Does your state's DOT use waste materials or recycled products (refer attached lists) as construction materials ? If yes, please provide the following information.

Waste Material	Type of Highway use
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2. Has a study been made into the cost effectiveness of these materials? ☐ YES ☐ NO
If YES please provide the following information

Waste Material	Cost Effective YES	Cost Effective NO
----------------------------	☐	☐
----------------------------	☐	☐
----------------------------	☐	☐
----------------------------	☐	☐

3. Are you aware of your state's DOT performing research into potential uses of waste material or by-product in highway construction ? ☐ YES ☐ NO

If YES please provide the following information

Waste Material	Prospective use
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Please attach copies of reports if possible.

4. Is there any state law(s) or legislative mandate(s) which require your state's DOT to investigate or use a particular waste material(s) in highway construction? ☐ YES ☐ NO

If YES please provide the following information

Material	State law or Mandate	Use
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5. Is there an EPA mandate regarding the use of a particular waste material in highway construction?

☐ YES ☐ NO

If YES please provide the following information

Material	EPA Mandate	Use
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Thank you for taking the time and the effort to respond to this questionnaire. Please indicate your name, address and telephone number in case any follow-up information is required. Any other comments you wish to make would be welcomed. Please include a separate letter attached to this questionnaire if you wish to make additional comments.

Name: ____

Address: ____

____

Phone: ____________________Fax:____________________

APPENDIX - C

Appendix C

Table 1: Usage of Waste Materials by Different States

Name Of State	Broken Concrete	Demolition Debris	Lime Dust	Cement Dust	Coal Refuse	Mine Tailings
Alabama						
Alaska						
Arizona						
Arkansas						
California						
Colorado						
Connecticut		Embankment fill				
Delaware						
Florida						
Georgia						
Hawaii						
Idaho						
Illinois						
Indiana		Roofing shingles proposed in asphalt mixtures				
Iowa						
Kansas						Asphalt pavements-general aggregate
Kentucky						
Louisiana						
Maine						
Maryland						
Massachusetts						
Michigan						Hot mix, aggregate base
Minnesota						
Mississippi						
Missouri	Rip rap, erosion control	Fill	Soil Stabilization	Soil stabilization		Bituminous mixture aggregate
Montana						Construction fills

Name Of State	Broken Concrete	Demolition Debris	Lime Dust	Cement Dust	Coal Refuse	Mine Tailings
Nebraska						
Nevada						
New Hampshire						
New Jersey						
New Mexico						
New York	Embankments					
North Carolina	Pavement Base Course					
North Dakota						
Ohio						
Oklahoma						
Oregon		Wood chips-lightweight fill				
Pennsylvania						
Rhode Island	Reinforcement removed and processed into granular fill or subbase	Bricks-Granular fill or subbase				
South Carolina						
South Dakota						
Tennessee						
Texas						
Utah						
Vermont						
Virginia						
Washington		Wood fiber waste used in lightweight fills				
West Virginia						
Wisconsin						
Wyoming						Granular base, asphalt pavement

Name Of State	Phosphate Slimes	Phosphogypsum	Waste Rock	Quarry Waste	Sewage Sludge	RAP
Alabama						Pavement Structure buildup
Alaska						
Arizona						
Arkansas						Stabilized base
California						Subbase, aggregate base
Colorado						
Connecticut						Bit. surface, base, subbase, granular fill, pervious backfill, free draining material
Delaware						
Florida						Asphalt mixtures
Georgia				Borrow material, berms		Asphalt pavement construction and resurfacing
Hawaii						Recycled into hot mixes
Idaho						
Illinois						Recycled asphalt mixtures
Indiana						Upto 20% in any bituminous mix except mainline surface
Iowa						20% of new asphalt concrete pavement
Kansas						Asphalt pavements-subgrade modifier
Kentucky						

Name Of State	Phosphate Slimes	Phosphogypsum	Waste Rock	Quarry Waste	Sewage Sludge	RAP
Louisiana				Fines replacement in HMAC		Upto 30% replacement in asphalt concrete mixtures except wearing course
Maine						
Maryland						
Massachusetts						
Michigan			Embankment, aggregate base, concrete, asphalt aggregate			Aggregate base, HMA
Minnesota						Hot recycled mix, CIR, Aggregate base
Mississippi						
Missouri			Fill	Fill		Recycled asphalt mixtures
Montana						Recycled asphalt pavements, stabilized base
Nebraska						
Nevada						
New Hampshire						
New Jersey						Dense graded base and hot mix
New Mexico						
New York						HMA, embankments
North Carolina					Soil Amendment	Asphalt Pavement Additive
North Dakota						
Ohio						
Oklahoma						

Name Of State	Phosphate Slimes	Phosphogypsum	Waste Rock	Quarry Waste	Sewage Sludge	RAP
Oregon						Hot mix, base material, low standard road surface, shoulder aggregate
Pennsylvania						Hot mix recycling
Rhode Island				Deep embankment fill-fines mixed with granular particles		In asphalt concrete mixes, in cold recycled base courses
South Carolina						Asphalt concrete
South Dakota						
Tennessee						Used in HMA
Texas						Hot mix and cold mix
Utah						
Vermont			Fill, slope protection			Hot mix, shoulders, base course
Virginia						
Washington					Soil amendment	Hot, cold, and in-place mixes
West Virginia						
Wisconsin						Asphalt concrete mixes
Wyoming						Asphalt pavement

Name Of State	RPCC	Rubber Tires	Blast Furnace Slag	Metallurgical Slag	Steel Mill Slag	Coal Ash
Alabama					Pavement structure buildup	
Alaska						
Arizona						
Arkansas		Asphalt modifier, surfacing				
California	Subbase, aggregate base	Asphalt rubber binder, rubberized asphalt concrete			Imported borrow, aggregate subbase, class 2 aggregate base, asphalt concrete	
Colorado		Embankments, retaining wall backfill, rockfall barriers				
Connecticut	In PCC, base, subbase, granular fill, pervious backfill, draining material					
Delaware						Concrete pozzolan
Florida						
Georgia	Rip rap		Admixture in PCC			In PCC
Hawaii	Aggregate in asphalt concrete mixtures, base aggregate, PCC aggregate	Modifier for asphalt cement	Concrete pozzolan			
Idaho						

Name Of State	RPCC	Rubber Tires	Blast Furnace Slag	Metallurgical Slag	Steel Mill Slag	Coal Ash
Illinois	Base, subbase, additive to wearing and subbase courses	Additive to crack sealers	Wearing, base and subbase courses, landscaping, in PCC		Wearing course, landscaping	Additive to wearing and subbase course and as a wearing course
Indiana	Aggregate base course		Bituminous, PCC and unbound aggregate		Bituminous, PCC and unbound aggregate	
Iowa	Base under new PCC, aggregate for PCC	CRM in asphalt concrete pavement			Asphalt concrete pavement	Cementitious material for PCC
Kansas		Crack repair, Asphalt pavement				Cold recycled asphalt pavement- subgrade modifier
Kentucky						
Louisiana	Limited application	Limited experimental use in HMA				PCC replacement
Maine						
Maryland						
Massachusetts						
Michigan	Aggregate base, concrete /asphalt aggregate	Joint sealers, HMA	Aggregate base, concrete/ asphalt aggregate		Aggregate base, concrete/ asphalt aggregate	
Minnesota	Concrete mix, aggregate base, PCC aggregate				Hot mix	
Mississippi						
Missouri	Base, riprap etc.	Bituminous mixtures	Bituminous mixture aggregate		Bituminous mixture aggregate	Concrete, grout, underseal, fill
Montana	Pavements, subgrade stabilization, fill material	Asphalt modifier (wet and dry processes)				

Name Of State	RPCC	Rubber Tires	Blast Furnace Slag	Metallurgical Slag	Steel Mill Slag	Coal Ash
Nebraska	Base course, rip rap					PCC, flowable fill, soil stabilization
Nevada						
New Hampshire						
New Jersey	Dense graded base	Hot mix base and surface course				
New Mexico						
New York		HMA, hot poured sealant	Embankments, lightweight fill			20% cement substitute in high performance concrete
North Carolina		Embankment, backfill, asphalt additive, retaining wall				Asphalt additive
North Dakota						
Ohio						
Oklahoma						
Oregon	Used with base material	Asphalt cement				
Pennsylvania	Subbase aggregate		PCC		Subbase aggregate, bituminous pavement	
Rhode Island						In PCC
South Carolina			In PCC	Chrome slag used in asphalt concrete for low volume roads		In PCC and flowable fills
South Dakota						
Tennessee						
Texas		Hot mix, seal coat				
Utah						

Name Of State	RPCC	Rubber Tires	Blast Furnace Slag	Metallurgical Slag	Steel Mill Slag	Coal Ash
Vermont		Lightweight fill, underdrain backfill				
Virginia						
Washington	Unbound base course aggregate	Asphalt concrete pavement and lightweight fills				Replacement for cement in PCC
West Virginia		Bituminous concrete pavement	Aggregate	Aggregate	Aggregate	
Wisconsin	PCC base course		Base course, friction course		Base course, friction course	In PCC
Wyoming	Concrete pavement	Lightweight fill and asphalt friction course				Cement replacement in concrete

Name Of State	Silica Fume	Rubberized or Asphaltic Concrete	Glass	Plastic	Metals	Paper & Paperboard
Alabama		Pavement structure buildup				
Alaska						
Arizona						
Arkansas						
California			Subbase, aggregate base, thermoplastic traffic striping, painted plastic striping			

Name Of State	Silica Fume	Rubberized or Asphaltic Concrete	Glass	Plastic	Metals	Paper & Paperboard
Colorado			Underdrain aggregate, flowfill aggregate			
Connecticut						
Delaware						
Florida			Aggregate in asphalt mix	Fence posts, guardrail blockouts, flexible delineator posts		
Georgia			Thermoplastic striping			
Hawaii			Asphalt concrete pavements and aggregate base			
Idaho						
Illinois						Landscaping
Indiana						
Iowa						
Kansas						
Kentucky						
Louisiana						
Maine						
Maryland						
Massachusetts						
Michigan						
Minnesota						
Mississippi						
Missouri						Mulch
Montana				Asphalt pavement modifier (Novophalt)		
Nebraska	PCC	Base course, erosion control				
Nevada						

Name Of State	Silica Fume	Rubberized or Asphaltic Concrete	Glass	Plastic	Metals	Paper & Paperboard
New Hampshire						
New Jersey			Hot mix base course			
New Mexico						
New York			HMA paving		Aluminum, panel signs, rail steel sign supports	
North Carolina	Embankment fill	Reuse as base course	Paint & pavement markings, backfill	Pipes, fencing, delineator barricades	X	X
North Dakota						
Ohio						
Oklahoma						
Oregon						
Pennsylvania						
Rhode Island						
South Carolina						
South Dakota						
Tennessee						
Texas						
Utah						
Vermont						
Virginia						
Washington			Additive to aggregates upto a max of 15%			
West Virginia		Bituminous concrete pavement				
Wisconsin				Non structural applications		
Wyoming						

Table 1 Respondents to Questionnaires Sent on 3 July, 95.

Name Of State	Received on	Enclosures	Contact Person	Address
Alabama	17 July 95	Questionnaire- UT	F. L. Holman Ph: 334 206 2203 Fax: 334 264 2042	Bureau of Research & Development, Montgomery, AL 36130-3050
Alaska				
Arizona				
Arkansas	17 July 95	Questionnaire- UT	Billy Connor Ph: 907 474 2479 Fax: 907 474 2411	2301 Peger Rd., Fairbanks, AK 99709-5399
California	23 August 95	Questionnaire- UT California state energy plan	Raymond D. Tsztoo Ph: 916 653 5507 Fax: 916 653 2124	Caltrans 1120 N. St., Room 2300, Sacramento, CA 95814
Colorado	17 July 95	Questionnaire- UT	John B. Gilmore Ph: 303 757 9275 Fax: 303 757 9242	4340, E. Louisiana, Denver CO 80222
Connecticut	17 July 95	Questionnaire- UT; 9 project reports.	Charles E. Dougan Ph: 203 258 0372 Fax: 203 529 0323	280 West Street, Rocky Hill, CT 06067
Delaware				
Florida	23 August 95	Questionnaire- UT	Lawrence L. Smith Ph: 904 372 5304 Fax: 904 334 1648	State Materials Office, 2006 N.E. Waldo Rd., Gainesville Florida 32609
Georgia	1 August 95	Questionnaire- UT; 2 project reports	Lamar Caylor Ph: 404 363 7569 Fax: 404 363 7684	Research & Development Branch, 15 Kennedy Dr., Forest Park, GA 30050
Hawaii	17 July 95	Questionnaire- UT	Garret Okada Ph: 808 832 3570 Fax: 808 832 3407	2530 Likelike Hwy., Honolulu, HI 96819
Idaho				
Illinois	17 July 95	Questionnaires- UT, NCHRP, Purdue	Eric Harm Ph: 217 782 7200 Fax: 217 782 2572	126 East Ash, Springfield IL 62704
Indiana	23 August 95	Questionnaire- UT 2 project reports	Rebecca S. McDaniel Ph: 314 463 1521 Fax: 314 497 1665	P.O. Box 2279, West Lafayette, IN 47906

Name Of State	Received on	Enclosures	Contact Person	Address
Iowa	9 August 95	Questionnaire- UT; 7 project reports	Vernon J. Marks Ph: 515 239 1447 Fax: 515 239 1092	800 Lincolnway, Ames, IA 50010
Kansas	1 August 95	Questionnaire- UT; 2 project reports	Rodney A. Montrey Ph: 913 296 2231 Fax: 913 296 2526	2300 Van Buren, Topeka, KS 66611
Kentucky				
Louisiana	25 July 95	Questionnaire- UT; R&D implementation data sheet, 1 project report	Chris Abadie Ph: 504 767 9110 Fax: 504 767 9108	4101, Gourrier, Baton Rouge, LA 70808
Maine				
Maryland				
Massachusetts				
Michigan	17 July 95	Questionnaire- UT	Jon Reincke Ph: 517 322 1632 Fax: 517 322 5664	P.O Box 30049, Lansing, MI 48909
Minnesota	25 July 95	Questionnaire- UT	Roger Olson Ph: 612 779 5517 Fax: 612 779 5616	Materials Lab, 1400 Gervais Ave., Maplewood, MN 55109
Mississippi				
Missouri	12 July 95	Questionnaires- NCHRP, Purdue; 1 project report, 1 law	Bill Trimm Ph: 314 751 2551 Fax: 314 751 6555	Capitol Ave. at Jefferson St., P.O. Box 270. Jefferson City, MO 65102
Montana	17 July 95	Questionnaire- UT	Robert A. Garber Ph: 406 444 6269 Fax: 406 444 6204	2701 Prospect Ave., P.O Box 201001, Helena MT 59620-1001
Nebraska	17 July 95	Questionnaire- UT	Dalyce Ronnau Ph: 402 479 4544 Fax: 402 470 3918	P.O Box 94759, Lincoln, NE 68509
Nevada				
New Hampshire				
New Jersey	25 July 95	Questionnaire- UT; 3 project reports, 1 paper	Robert F. Baker Ph: 609 530 5957 Fax: 609 530 5972	1035 Parkway Ave., Trenton, NJ 08625
New Mexico				
New York	1 August 95	Questionnaire- UT; 1 project report	Jill Baker Ph: 518 457 4582 Fax: 518 457 8171	Materials Bureau, Bldg. 7A 1220 Washington Ave., Albany, NY 12232

Name Of State	Received on	Enclosures	Contact Person	Address
North Carolina	12 July 95	Questionnaires- UT, NCHRP; 2 project reports, one summary, 1 law.	Marie L. Casey Ph: 919 250 4128 Fax: 919 250 4119	Design Services Unit, P.O. Box 25201, Raleigh, NC 27611
North Dakota				
Ohio				
Oklahoma		Returned to sender		
Oregon	23 August 95	Questionnaire- UT	Elizabeth Hunt Ph: 503 986 2848 Fax: 503 986 2844	ODOT Research Unit, 2950 State St., Salem, OR 97310
Pennsylvania	1 August 95	Questionnaire- UT + references on the questionnaire	Paul Ingram Ph: 717 787 3580	Bureau of Construction & Materials, 1118 State St Hbg, PA 17120
Rhode Island	23 August 95	Questionnaire- UT	Michael Sherrin Ph: 401 277 3030 ext 4115 Fax: 401 277 6038	Rm 013, 2 Capitol Hill Providence Rhode-Island 02905
South Carolina	23 August 95	Questionnaire- UT 3 project reports	Richard L. Stewart Ph: 803 737 6681 Fax: 803 737 6649	P.O. Box 191, Columbia, South Carolina 29202
South Dakota				
Tennessee	1 August 95	Questionnaire- UT	Floyd E. Petty Ph: 615 350 4100 Fax: 615 350 4128	6601 Centennial Blvd., Nashville, TN 37243-0360
Texas	9 August 95	Questionnaire- UT	Maghsoud Tahmoressi Ph: 512 465 7603 Fax: 512 302 2288	Materials & Tests Division, 125 E 11th, Austin, TX 78701
Utah				
Vermont	23 August 95	Questionnaire- UT 2 research updates, 1 project report	Milan W. Lawson Ph: 802 828 2587 Fax: 802 828 2848	133 State St., Montpelier Vermont 05633
Virginia		Returned to sender		
Washington	1 August 95	Questionnaire UT; 5 project reports	Keith W. Anderson Ph: 360 586 8959 Fax: 360 586 4611	Materials Laboratory, P.O. Box 47365, Olympia, WA 98504-7365
West Virginia	23 August 95	Questionnaire- UT	Gary L. Robson Ph: 304 558 5999 Fax: 304 558 0253	MCS&T Division, 312 Michigan Ave., Charleston, WV 25311

Name Of State	Received on	Enclosures	Contact Person	Address
Wisconsin	23 August 95	Questionnaire- UT	Robert B Schmiedlin Ph: 608 246 7950 Fax: 608 246 4669	Office of Construction, 350 C Kinsman Blvd., Madison, WI 53704
Wyoming	25 July 95	Questionnaire- UT	Rick Harvey Ph: 307 777 4070 Fax: 307 777 4481	P.O. Box 1708, Cheyenne, WYO 82003

APPENDIX - D

Table D.1: Microsoft Access Tables for Various Recycle Waste Materials

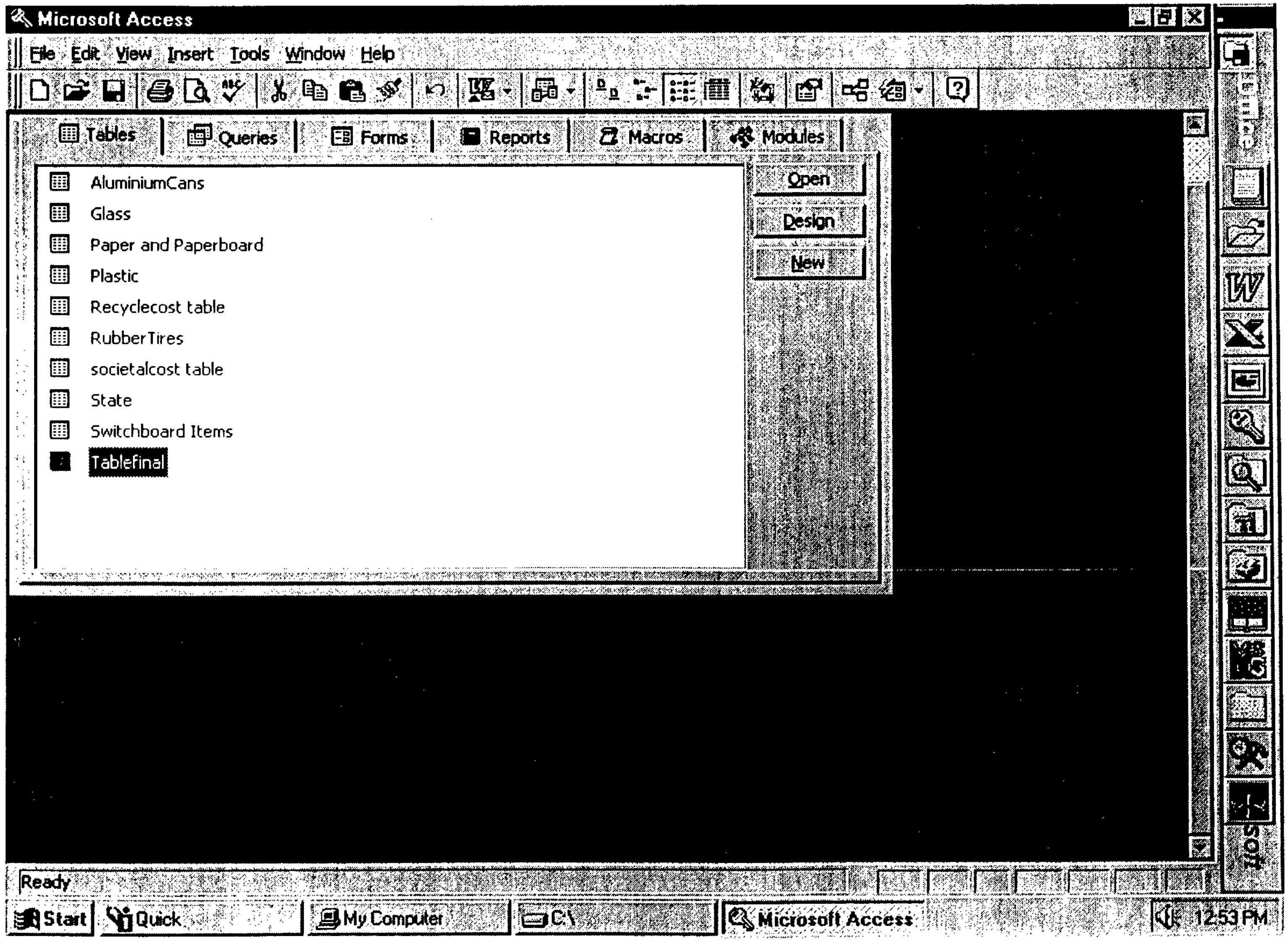

Table D.2: Microsoft Access Material Forms

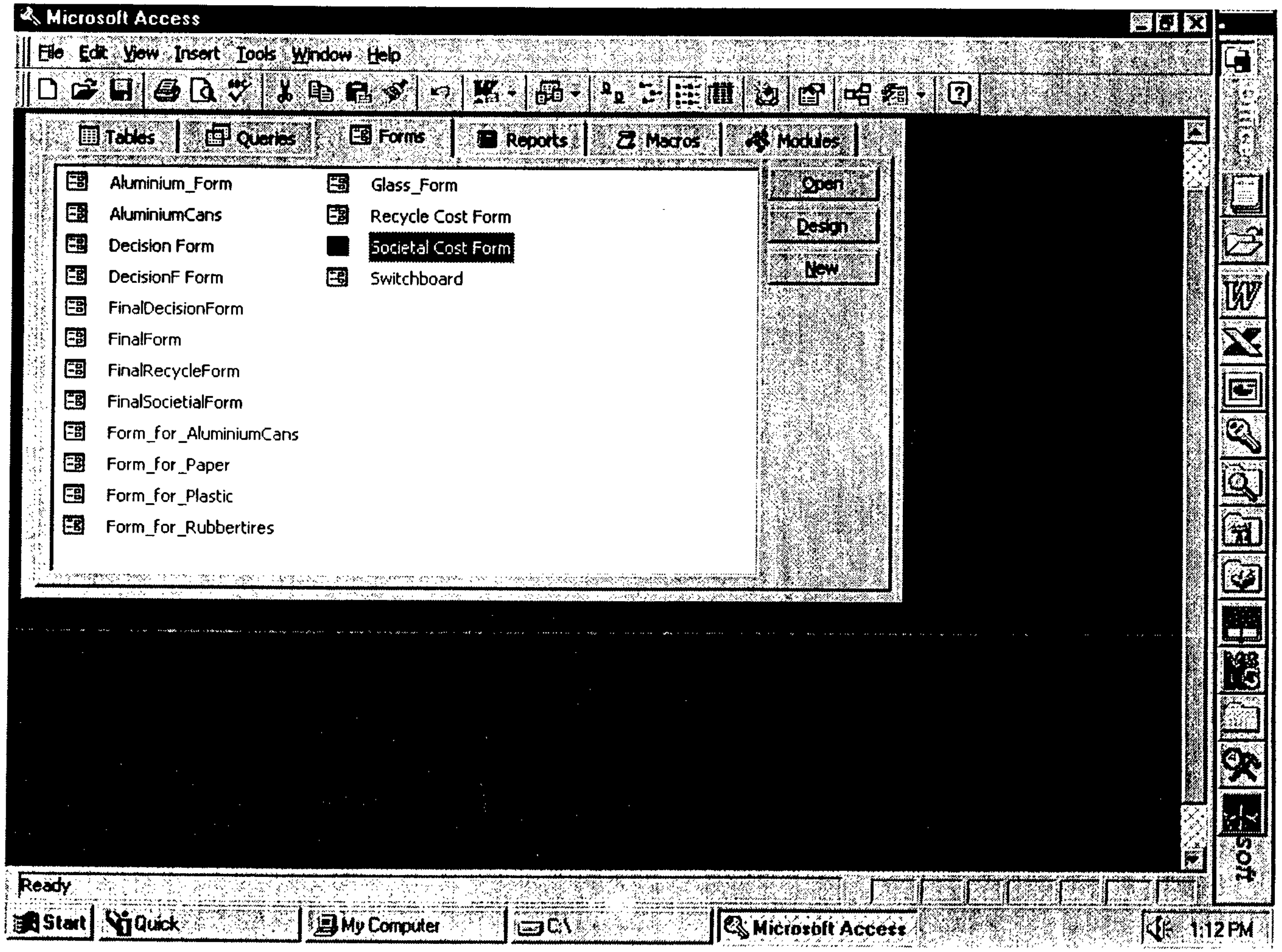

Table D.3: Display of Various Cost Component by Material Type and State