Technical Report Documentation Page

1. Report No. FHWA/TX-97/1348-2F	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle EVALUATION AND THE USE OF WASTE AND RECLAIMED MATERIALS IN ROADBASE CONSTRUCTION		5. Report Date October 1996
		6. Performing Organization Code
7. Author(s) A. Saeed and W. R. Hudson		8. Performing Organization Report No. Research Report 1348-2F
9. Performing Organization Name and Address Center for Transportation Research, The University of Texas at Austin, 3208 Red River, Suite 200, Austin, Texas 78712-1075		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. Research Study 0-1348
12. Sponsoring Agency Name and Address Texas Department of Transportation, Research and Technology Transfer Office, P.O. Box 5080, Austin, TX 78763-5080		13. Type of Report and Period Covered Final
		14. Sponsoring Agency Code

15. Supplementary Notes

Study conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.
Research study title: "Recycled Materials in Roadbase, Except Glass"

16. Abstract

This report, the second and final report for research project 0-1348, "Waste and Recycled Materials in Roadbase, Except Glass," summarizes the following: (1) Material location and availability survey of commercial sources; (2) the Waste and Reclaimed Materials (WRMs) evaluation system; and (3) the results of the laboratory testing undertaken to develop specifications.

A close examination of the data presented in Report 1348-1, "Location and Availability of Waste and Reclaimed Materials in Texas and Evaluation of Their Utilization Potential in Roadbase," indicated the need for a survey of commercial sources of waste materials in Texas. The survey of commercial sources was considered important, inasmuch as TxDOT has ownership of only two of the reported materials, namely, reclaimed asphalt pavement (RAP) and reclaimed portland cement pavement (RPCP); moreover, TxDOT district personnel could not provide firm estimates of materials available in commercial stockpiles and, hence, recommended a survey of relevant sources.

As to the technology, WRMs cannot match natural aggregate material in technical properties. Technical studies that have been used in the past to evaluate WRMs also fail to take into account the socio-economic and environmental benefits of using these materials, which in our opinion is an oversight. To overcome this problem, a WRM evaluation method was developed that considers the socio-economic and environmental benefits, in addition to the technical and economic aspects. An initial screening method was also incorporated to screen out materials having low or no utilization potential. All the available WRMs were subjected to this evaluation method and, based on objective data, a rational decision was made to select RAP, RPCP, and electric arc furnace slag (EAFS) for detailed laboratory testing (only materials showing high potential were subjected to such extensive technical studies). The detailed laboratory studies are summarized and the resulting specifications are presented in this report.

17. Key Words Recycled construction materials, reclaimed asphalt pavement (RAP), reclaimed portland cement concrete pavement, iron blast slag, steel slag, coal ashes, building rubble, rubber tires	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	203	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EVALUATION AND THE USE OF WASTE AND RECLAIMED MATERIALS IN ROADBASE CONSTRUCTION

by

A. Saeed
W. R. Hudson

Research Report 1348-2F

Project 0-1348

Recycled Materials in Roadbase, Except Glass

conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION
in cooperation with the
U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

by the

CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

October 1996

IMPLEMENTATION RECOMMENDATION

The waste and reclaimed material (WRM) location and availability survey reported herein was conducted to determine the quantities of potential roadbase material available from TxDOT districts, and to classify them by quantity, location, and type. This effort was supplemented by a survey of commercial sources. The report describes the problems associated with available WRMs, and can assist in identifying candidate materials having potential for utilization in roadbase.

The WRM evaluation method described can be used by TxDOT to determine — based on technical, economic, societal, and environmental considerations — the utilization potential of a particular material as a roadbase. Materials having low utilization potential can be discarded on a rational basis using this method (as opposed to being discarded after the expenditure of considerable human and financial resources). The data collected during the technical and economic studies can be used to develop trial specifications for the use of WRMs in roadbase construction, which in turn can be implemented by TxDOT personnel in the field.

Prepared in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration

DISCLAIMERS

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

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

NOT INTENDED FOR CONSTRUCTION, BIDDING, OR PERMIT PURPOSES

W. R. Hudson, P.E. (Texas No. 16821)
Research Supervisor

TABLE OF CONTENTS

SUMMARY

This report, the second and final report for research project 0-1348, "Waste and Recycled Materials in Roadbase, Except Glass," summarizes the following:

- Material location and availability survey of commercial sources
- The Waste and Reclaimed Materials (WRMs) Evaluation System
- The results of the laboratory testing undertaken to develop specifications

A close examination of the data presented in Report 1348-1, "Location and Availability of Waste and Reclaimed Materials in Texas and Evaluation of Their Utilization Potential in Roadbase," indicated the need for a survey of commercial sources of waste materials in Texas. The survey of commercial sources was considered important, inasmuch as TxDOT has ownership of only two of the reported materials, namely, reclaimed asphalt concrete (RAP) and reclaimed portland cement concrete (RPCP); moreover, TxDOT district personnel could not provide firm estimates of materials available in commercial stockpiles and, hence, recommended a survey of relevant sources.

As to the technology, WRMs cannot match natural aggregate material in technical properties. Technical studies that have been used in the past to evaluate WRMs also fail to take into account the socio-economic and environmental benefits of using these materials, which in our opinion is an oversight. To overcome this problem, a WRM evaluation method was developed that considers the socio-economic and environmental benefits, in addition to the technical and economic aspects. An initial screening method was also incorporated to screen out materials having low or no utilization potential. All the available WRMs were subjected to this evaluation method and, based on objective data, a rational decision was made to select RAP, RPCP, and electric arc furnace slag (EAFS) for detailed laboratory testing (only materials showing high potential were subjected to such extensive technical studies). The detailed laboratory studies are summarized and the resulting specifications are presented in this report.

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

Given the large quantities of waste materials generated in the U.S. each year, many individuals and agencies have begun investigating the potential for using these waste materials in state roadway construction. Using waste materials in such applications can reduce the amount of natural aggregate material required and can also reduce the costs associated with the extraction and processing of natural aggregate material [Saeed 95, TGLO 93].

In the technical literature pertaining to the use of waste materials, the term *recycling* is invariably used. Recycling, in essence, is taking an item, after it has been through its useful life, and, instead of discarding it, remaking it into a new, useful product. The term *reusing* on the other hand refers to using an item over and over again in its current form without converting it into something new. *Reclaiming,* as defined by Wood et al., is a process in which a waste material is removed from its original location for use at some other location [Wood 89]. For the purposes of this research, the materials being investigated can be categorized only as waste and reclaimed materials (WRMs) and, consequently, are addressed as such.

According to Kimbell, using WRMs for the environment, as opposed to using them for substance or immediate necessity, is a relatively recent idea [Kimbell 92]. Individuals are now more aware of the fact that our natural resources are limited. The realization of this fact, along with concerns of the population explosion, has led many to conclude that using WRMs is an idea whose time has come. Indeed, utilization of WRMs has recently become so socially desirable that it is now perceived as the "politically correct" thing to do in all facets of daily life [Kimbell 92].

Construction, maintenance, and rehabilitation (M&R) of transportation infrastructure is a costly, time-consuming procedure, one that is often material intensive. Utilization of WRMs in these activities has several advantages over the use of conventional materials and techniques. Prominent among the major benefits are the conservation of energy, natural aggregates and binders, as well as the preservation of the environment and existing highway geometries [NCHRP 80].

WRMs are currently attracting the attention of officials at the federal, state and local levels, including city and county governing bodies responsible for transportation infrastructure; as they see it, such materials can potentially decrease the large quantities of quality natural aggregate material used in transportation infrastructure construction and maintenance and rehabilitation (M&R). Officials are also faced with ever-decreasing funds available for transportation infrastructure needs [Saeed 95]. Together, these problems have prompted officials to optimize the use of available aggregates and binders, subject to financial and other resources for construction and M&R activities.

1.2 PROBLEM STATEMENT

The standard approach to characterizing WRMs has been to evaluate them in laboratory studies and to then compare the findings with standard specifications for naturally occurring materials. This is not, however, an appropriate method, primarily because these materials often do not equal the technical quality natural aggregates, even though they may still have high societal, environmental, and economic value. And because laboratory studies often consider *only* technical material properties, the other benefits of using WRMs are not considered, including the environmental benefits resulting from savings in extraction and processing costs for new materials, and the disposal cost savings realized through use of WRMs. Thus, there is an important need to consider all aspects of WRMs' utilization in transportation infrastructure construction and in M&R activities. This report specifically examines a systematic method for evaluating the use of WRMs.

According to many publications, especially those by Han et al. [Han 95] and Miller et al. [NCHRP 76], there are many reasons for an agency to consider the use of WRMs in transportation infrastructure construction and M&R activities. Among these reasons are local shortages of natural aggregates, the high cost of waste disposal, a commitment to preserving the environment, the availability of natural and waste materials, political pressure, environmental safety, and many others.

Han et al. and Miller et al. also list cost effectiveness, performance, availability, and the prevailing political climate as the four issues fundamental to determining the appropriateness of using waste materials in highway construction [Han 95, NCHRP 76]. These publications evaluate the discussed waste materials with respect to their technical properties, with such evaluations complemented by limited economic analyses, as is the standard practice currently. While societal and environmental factors are deemed necessary, they are not considered in the overall evaluation process.

The feasibility of using a specific WRM depends on a large number of interrelated factors, all of which need to be evaluated objectively in order to make meaningful recommendations. These factors can be categorized as technical, economic, societal, and environmental in nature. What is needed is a simple methodology for evaluating these WRMs for their potential use in transportation infrastructure construction and M&R activities. Based on this evaluation, the overall potential of a particular WRM may be assessed, with only those WRMs having a high potential designated for detailed and expensive studies that will determine the final specifications. In the case of WRMs it must be very clearly understood that technical aspects and economic feasibility are not the only driving factors when the utilization of WRMs is considered. The major considerations related to the utilization of WRMs are environmental factors and societal pressures, both of which must be considered as part of the overall scheme of things. At a minimum, it should be acknowledged that, by utilizing WRMs, public agencies and private enterprises can earn indirect benefits in the form of goodwill and positive public relations campaigns.

1.3 OBJECTIVE

The objective of this research effort is to develop a method for evaluating waste materials for possible use in transportation infrastructure construction and M&R activities, especially pavement bases. This WRM evaluation methodology must consider technical, economic, societal, and environmental aspects of their use, after an initial screening process which should be used to discard WRMs that have low potential for use. The WRM evaluation system developed will then be used to identify waste materials that are most viable in an overall technical, economic, societal, and environmental sense for use in roadbase construction.

A technical evaluation subsystem must be developed that will evaluate WRMs based on the physical, chemical, mechanical, and thermal properties required of a material used for transportation project utilization. Technical properties determined to be of importance will be investigated in laboratory studies to evaluate WRMs on a technical basis.

The economic evaluation subsystem developed will be used to identify waste materials that are most viable in an economic sense. This subsystem should take into account all the costs related to the production of construction aggregate obtained from WRMs, and should compare these costs to those costs incurred in the production of natural aggregate (along with the cost of disposing of the waste material).

Societal and ecological implications most often cannot be measured directly in dollar terms. However, the societal evaluation subsystem described herein will consider the interest or desire expressed by society in general, and by the government and the private sector in particular, when the utilization of WRMs is considered, and will attempt to handle these societal aspects.

The environmental evaluation subsystem will be developed to measure the actual impacts, as opposed to how people feel about them.

Objective data should be an integral part of any WRM evaluation method, and should be used to assess the utilization potential based on the above-mentioned four evaluation subsystems. These objective data should be supplemented with a limited amount of subjective data in cases where objective information does not exist or is difficult to quantify.

As part of this research, the extent of WRMs available in Texas will be determined, and the source of these materials, whether commercial or governmental, will also be established. The current state of the practice of recycling WRMs will also be reported and assessed.

While the initial objective is to develop a WRM evaluation method, the developed methodology will also be used to illustrate the utilization potential of WRMs determined to be available in Texas. A final objective of this research will be to develop trial specifications for the use of these materials in roadbase construction projects, after conducting detailed technical laboratory studies.

1.4 RESEARCH SCOPE

The scope of this research effort is limited to the development of a general WRM evaluation method and to the specific evaluation of some WRMs available in Texas for use in roadbase construction projects. The methodology developed will then be tested by subjecting the top three

WRMs to detailed technical evaluation using laboratory studies. Data from these laboratory tests will be used to prepare trial specifications for the selected three WRMs for use in the field.

As already stated, the scope of this research is limited to the evaluations of available WRMs for use in roadbase construction. However, the overall methodology can be modified for use in other applications of WRMs, with proper reevaluation of objectives and appropriate factors set up for each potential use.

1.5 RESEARCH APPROACH

The research began with a concise literature search and a subsequent report on current practice of WRM utilization in highway construction and M&R projects. Information of interest will be the types and quantities of WRMs available, as well as their performance in engineering applications. An attempt will also be made to gauge public attitudes regarding the use of these materials, the environmental costs and benefits, and the costs of landfilling versus recycling.

The literature search will be followed by the development of the WRM evaluation method based on the systems approach. The systems approach will be used to determine the principle objectives and subobjectives. Determination of appropriate weights, based on their relative importance in the overall evaluation, will be made using the analytic hierarchy process (AHP). The weight assigned will reflect the importance of an objective in an additive model. Candidate WRMs identified by the evaluation methodology will then be further appraised by conducting appropriate detailed laboratory tests on the top three WRMs.

The resulting data will be used to develop trial specifications for the selected three WRMs. These trial specifications, and the verified and improved evaluation method, will be presented in a form ready for field implementation.

1.6 REPORT ORGANIZATION

Chapter 2 of this report documents the results of the literature survey. Information will also be provided on the types and amounts of WRMs available in Texas. Chapter 3 is devoted to the development of the WRM evaluation method, a method based on technical, economic, societal, and environmental aspects of their utilization in roadbase construction projects. The mathematical model developed to assess the utilization potential of available WRMs and the selection of weights of objectives and subobjectives, based on the analytic hierarchy process (AHP), are presented in Chapter 4. An assessment of utilization potential of available WRMs in roadbase will also be made. Chapter 5 describes the laboratory test methods used for characterizing reclaimed asphalt concrete (RAP); Chapter 6 looks at reclaimed portland cement concrete (RPCP); and Chapter 7 discusses electric arc furnace steel slag (EAFS). Chapter 8 discusses the fundamental items necessary in a successful specification; it also outlines the trial specifications for the three tested materials. Chapter 9 describes a case study for a 4.8-km long project in TxDOT's Wichita Falls District, which was set up to demonstrate the applicability of RAP for roadbase construction. Chapter 10 presents the conclusions and recommendations.

CHAPTER 2. STATE OF THE PRACTICE OF WRMs REUSE

2.1 INTRODUCTION

This chapter describes the results of a detailed literature search to identify available information on the use of WRMs in transportation infrastructure construction and M&R activities. The main searching procedure adopted was to use keyword searches through the following data bases:

- Transportation Research and Information System (TRIS)
- National Technical Information Service (NTIS)
- Compendex Plus (on-line form of engineering index)

In the initial search, approximately 200 articles were retrieved related to the use of WRMs in pavements. From these, one-page abstracts of selected articles were obtained. After a review of the obtained information was completed, selected articles were requested from libraries from all over the U.S. The formal literature search was supplemented by recent unpublished reports/findings of research studies, presentations on research updates by professionals at different forums, and by personal meetings with experts. The following sections describe the information obtained from the literature search.

2.2 SOURCES OF WASTE MATERIALS

Waste materials are classified by the recycling industry as being in one of the three major categories: industrial, mineral, or domestic [NCHRP 76]. This classification is particularly helpful in selecting those WRMs having a potential for use in roadbase. These sources are discussed separately in the following sections.

2.2.1 Industrial Waste

The amount of waste generated by American commercial and industrial sources has been estimated to be more than 190 million tons annually [Scanner 71]. The four major sources of industrial wastes are the ceramic, chemical processing, electrical power, and iron and steel industries. The waste materials generated from these industries are listed in Table 2.1.

2.2.2 Mineral Waste

The mineral industries of the United States produce more than 1.6 billion tons of ores and fuel each year. In this process, approximately 1.1 billion tons of solid waste are generated annually. These wastes are deposited in the form of mine wastes, mill tailings, washing plant rejects, processing plant wastes, and smelter slag and rejects [Scanner 71]. Table 2.2 lists these waste materials.

Table 2.1 Waste materials generated though industrial activity

Industry	Waste Materials Generated
Ceramic	Brick plant rejects, ceramic tile waste, clay pipe waste, pottery waste
Chemical Processing	Alumina red and brown mud, phosphate slime, phosphogypsum, sulfate and sulfite sludge
Electrical Power	Fly ash, bottom ash, boiler slag, scrubber sludge
Iron and Steel	Iron blast furnace slag, steel slag, foundry waste products

Table 2.2 Waste materials belonging to mineral wastes category

Waste Type	Waste Materials
Refuse	Anthracite coal refuse, bituminous coal refuse
Chemical Processing	Chrysotile or asbestos tailings, Copper tailings, Feldspar tailings, Iron ore tailings, Lead tailings, Nickel tailings, Taconite tailings, Zinc tailings
Wastes/Spoils	Dredge spoil, Zinc smelter waste, gold mine waste, slate mining waste

2.2.3 Domestic Waste

The total production of various domestic wastes is estimated to be approximately 160 million tons annually. This annual production is growing at a faster rate than the population. More than half of this is dry, organic material. Waste materials belonging to this category include (1) building rubble, (2) plastic waste, (3) reclaimed paving materials, (4) sewage sludge, (5) discarded battery casings, (6) incinerator residue, (7) pyrolysis residue, (8) rubber tires, and (9) waste glass.

2.3 DISPOSAL OF WASTE MATERIALS

There are three techniques for waste material disposal: (1) incineration, (2) burial, and (3) recycling. As indicated by the Environmental Protection Agency (EPA), the bulk of the domestic refuse is either buried or incinerated, with or without the generation of energy [EPA 90]. Both burial and incineration usually involve landfills. Public concern is often expressed about the large quantities of useful materials being discarded or destroyed in landfills. Also, it may be that waste material that is incinerated is being "disposed of" into the atmosphere in the form of exhaust gases, resulting in pollution. For these and other reasons, many states, including Texas, are in the process of developing legislation intended to stimulate recycling efforts [Ahmad 91, Ahmad 92].

2.4 ENGINEERING APPLICATIONS OF WASTE AND RECLAIMED MATERIALS

This section discusses the various uses of reclaimed materials in pavement/roadbase construction in the U.S. Information is provided on the production, use, and performance of various materials of interest to this research. These materials include: (1) reclaimed asphalt concrete pavement (RAP), (2) reclaimed portland cement concrete pavement (RPCP), (3) iron blast furnace slag (IS), (4) coal ashes, fly ash (FA), bottom ash (BA), pond ash (PA), (5) steel slag (SS), (6) building rubble (BR), and (7) rubber tires. Table 2.3 lists the states that have used these WRMs in roadbase construction. It also includes information on the performance of the final product.

Table 2.3 Use of WRMs in roadbase construction by state DOTs

Waste and Reclaimed Material	States
Reclaimed Asphalt Concrete	Kentucky, Nebraska
Reclaimed Portland Cement Concrete	New York, Arizona, California, Connecticut, Georgia, Iowa, Indiana, Kansas, Kentucky, Louisiana, Massachusetts, Maryland, Michigan, Minnesota, Montana, N. Carolina, Nebraska, New Jersey, Ohio, Virginia, Wisconsin, Wyoming
Iron Blast Furnace Slag	New York, California, Michigan, Montana, New Jersey, Ohio
Steel Slag	California, Michigan, Ohio, S. Carolina, Wisconsin
Coal Fly Ash	New York, Florida, Kansas, Kentucky, Louisiana, Michigan, Missouri, Montana, Nebraska, S. Carolina, Virginia, Wyoming
Building Rubble	Connecticut, Missouri
Glass	Alaska, California, Idaho, Minnesota, N. Carolina, New Jersey

2.4.1 Reclaimed Asphalt Concrete Pavement (RAP)

The recycling of asphalt pavements is not a new concept. With the increase in the price of asphalt brought about through the oil crisis of the early 1970s, it became a feasible way of lowering highway construction costs [Ahmad 91, Ahmad 92]. There have been numerous laboratory, field, and synthesis studies on the various aspects of hot mix and cold mix recycling [TRB 78, Ferreira 87, and Wood 89].

Reusing asphalt pavements is an established process and many viable processes exist. It is somewhat cost effective, and has a positive environmental impact. The potential problem of air pollution from asphalt plant operation can be reduced by installing emission control devices to make it environmentally safe. However, there is a need to standardize the design, construction, testing, performance and quality of the evaluation processes [Ahmad 92].

2.4.2 Reclaimed Portland Cement Concrete Pavement (RPCP)

The recycling of PCC pavements has been underway in the U.S. for a number of years [Calvert 77, Marks 84]. For example, a 1991 research project conducted by Purdue University analyzed the experiences of a few state DOTs to determine the feasibility of using PCC pavements [Ahmad 91]. That analysis concluded that it is technically and economically feasible to recycle PCC pavements, and that such recycling also reduces the waste disposal problem. However, further research is needed to address the performance problems of reclaimed PCC pavements, and to refine the mix design and construction procedures.

2.4.3 Iron Blast Furnace Slag (IS)

Iron blast furnace slag (IS), a by-product of the iron industry, has historically been used in the construction of highways. Given its wide availability and scope of uses, it is the waste material of greatest interest to the highway industry.

Iron ore, coke, and limestone are heated in the blast furnace to produce pig iron. A by-product of this process is a material known as blast furnace slag. It is defined as "the non-metallic by-product consisting of silicates and aluminosilicates of lime and other bases," and it leaves the blast furnace resembling molten lava [NCHRP 76]. Four distinct types of blast furnace slag are produced as a result of the selective cooling of the blast furnace slag. These are defined below [Emery 82]:

Air-cooled Blast Furnace Slag: In this manufacturing process, the cooling of the blast furnace slag takes place under ambient air temperature conditions. This type of blast furnace slag is extensively used in conventional aggregate applications. Most of the blast furnace slag produced in the United States falls under this category.

Expanded or Foamed Blast Furnace Slag: In the production of this product, controlled quantities of water are added to the blast furnace slag during the solidification process. Water is sometimes added in the form of steam and, on other occasions, with air. The expanded or foamed blast furnace slag is used mainly as a lightweight aggregate.

Granulated Blast Furnace Slag: Granulated blast furnace slag is manufactured by quenching the molten blast furnace slag to a vitrified state using water. This product is mostly used in the manufacturing process of slag cement.

Palletized Blast Furnace Slag: This type of blast furnace slag is manufactured by quick quenching in a spinning drum using either water or air. This finds application as lightweight aggregate and in the manufacture of slag cement.

Miller et al. [NCHRP 76] reported that, among the waste materials, iron blast furnace slag has a high potential for use in highway construction. Properties of air-cooled blast furnace slag that make it attractive for highway applications include: low compacted bulk density (1200-1450 kg/m^3), high stability (CBR > 100), high friction angle (Ø = 45°), high durability, high resistance to weathering and erosion, free draining and non-frost susceptible, and non-corrosive to steel and concrete [Emery 82].

According to Ahmad et al. [Ahmad 91, Ahmad 92], the current practice indicates that the use of iron blast furnace slag in various highway applications is economical and technically feasible. There are still some doubts about the environmental impacts, such as heavy metal leachates to ground and surface water sources, which need to be investigated further.

2.4.4 Steel Slag

Steel Slag is a by-product of the steel industry. It is formed when lime flux reacts with molten iron ore, scrap metal, or other ingredients charged into the steel furnace at melting temperatures, around 2800°F [Ahmad 92]. During this process, part of the liquid metal becomes entrapped in the slag. It solidifies in the pit area after flowing from the blast furnace, after which it is transferred to cooling ponds. Metallic particles are removed by magnetic separation [NCHRP 76, ISS 85].

Even given the same plant and same manufacturing processes, steel slags have highly variable properties. They have a high bulk density and substantial volume changes (changes up to 10 percent are not uncommon owing to the presence of calcium and magnesium oxides). Steel slags have been used in the highway industry in asphalt mixes, pavement bases and shoulders, fills, and for ice control. However, one study has identified the leachates from this material as an environmental problem [Ahmad 92, Bronson 85, Lawrence 85].

2.4.5 Coal Ash

Coal burned at power plants for the generation of electricity produces a residue of power plant ash known as bottom ash (BA) or fly ash (FA) [FHWA 86, Huang 90, Ahmad 91, Ahmad 92]. These products are described below.

Bottom Ash (BA): This is the slag that builds up on the heat-absorbing surfaces of the furnace and that ultimately falls through the furnace bottom to the ash hopper below. Bottom ash is distinguished as being either *dry bottom ash,* as it is in solid state at the furnace bottom, or *wet bottom ash,* as it is in molten state when it falls into the water. This distinction depends on the type of boiler being used in the power plant. Most of the coal bottom ash produced in the United States is dry bottom ash. Coal bottom ash is non-radioactive and has no effect on underground water sources. It has a low erosion potential but is corrosive by nature.

Fly Ash (FA): This is the finely divided residue that results from the combustion of powdered coal in coal-burning power plants. It is transported from the burning chamber by exhaust gases [Ahmad 92]. In the presence of water, this siliceous material has structural properties comparable to current cementitious materials. These properties are dependent on the coal burning furnace in use. There are three types of coal burning power plants: (1) stoker-fired furnaces, (2) cyclone furnaces, and (3) pulverized coal furnaces. According to Boles, fly ash produced in stoker-fired furnaces is not useful for highway purposes, whereas ash produced in cyclone furnaces is generally not good for use in PCC and also is not as widely available. The best kind of fly ash is produced in furnaces that use pulverized coal and is the most widely available [Boles 86, FHWA 86].

Because most U. S. power plants use powdered coal, coal fly ash constitutes 75 percent of all the ashes produced, with the majority of it buried in landfills. According to Ahmad et al. [Ahmad 92], only 20 percent of all the fly ash produced is reclaimed. Owing to its properties, it is widely used in PCC mixes, but is not recommended for use in bridge decks or in heavily loaded PCC pavements.

State DOTs that have used coal ash in their roadbases report a performance ranging from poor to excellent; overall, however, there is little current use. Although large quantities of coal ash could be consumed in roadbase construction, the implications of its application are unknown, especially its impact on groundwater quality [Ahmad 91].

2.4.6 Building Rubble

Building rubble is defined as any construction material resulting from the demolition of existing structures. Building rubble is generally a heterogeneous mixture of concrete, plaster, wood, steel, brick, piping, asphalt cement, glass, and so forth [Ahmad 92, Paulsen 88]. It has been estimated by Paulsen et al. [Paulsen 88] that roofing waste contains approximately 36 percent asphalt cement, 22 percent hard rock granules, 8 percent filler, and smaller amounts of coarse aggregate and miscellaneous materials [Ahmad 92]. Substantial variation in the composition of building rubble should be expected.

Both research and experience in the use of building rubble indicate that it often has potential for use as subbase and subgrade/embankment material [Paulsen 88], though its technical and environmental feasibility must be determined before use. The economics of using building rubble varies with local conditions and often depends on the structure the rubble was obtained from [Ahmad 92].

2.4.7 Glass

According to several sources, the use of glass in unbound aggregate base is technically feasible [Ahmad 92, Hughes 90]. The only requirements would be that it be crushed to the required gradation and that the level of contaminants is within acceptable limits. The economics of usage depends on local conditions [Ahmad 92].

2.4.8 Rubber Tires

An estimated 240 million waste tires are discarded annually in the United States, the result being large landfill spaces devoted to their disposal. Disposal of large quantities of tires has therefore many economic and environmental implications. Scrap tire piles are a fire hazard, in addition to being an ideal breeding ground for mosquitoes [Ahmad 92]. There is no information available in the current literature regarding the use of tires in roadbase construction, although the following discussion provides some insight into the current use of tires in highway construction as an additive in hot mix asphalt pavements.

Crumb rubber additive (CRA) is the generic term for the product obtained from scrap tires used in asphalt products. The manufacture of CRA can be divided into the following two processes: (1) the wet process blends CRA with hot asphalt cement and allows the rubber and asphalt to fully react in mixing tanks to produce an asphalt-rubber binder; and (2) the dry process mixes CRA with hot aggregate at the hot mix asphalt (HMA) facility before adding the asphalt cement to produce a rubber-modified HMA mixture. The four general categories of asphalt paving products that use CRA include crack/joint sealant, surface/interlayer treatments, HMA mixtures with asphalt-rubber binder, and rubber-modified HMA mixtures [Ahmad 91, Ahmad 92].

Two techniques for incorporating waste tires in subgrade/embankment include (1) using shredded tires as a lightweight fill material and (2) using whole tires or their sidewalls for soil reinforcement in embankment construction. The concept of using tires in embankments has also been extended as a way of enhancing the stability of steep slopes along highways, for temporary protection of slopes, for retaining of forest roads, and for the protection of coastal roads from erosion [Keller 90, Read 90].

2.5 SUMMARY OF LITERATURE SURVEY

The literature search provided insight into the use of WRMs in pavement construction. An extensive effort to use WRMs in highway construction has been made by researchers for a long time, and many reports and findings have been produced. Surprisingly, most of the research so far has been directed towards incorporating these WRMs in the wearing course in AC pavements and in the slab for PCC pavements. Very little effort has been directed to the reuse of WRMs in roadbase or subbase layers, which are generally the most aggregate intensive. Figure 2.1 shows the number of states that have used WRMs in roadbase construction. The performance of the constructed roadbases is also indicated. The WRMs used had DOT sources as well as non-DOT sources. These materials ranged from old pavements, to slag from the metal industry, and to mining wastes from mining operations.

Another point to note is that all the WRMs were evaluated using technical laboratory studies. The effective use of WRMs in pavements is dependent on a number of other factors, including economic, societal, and environmental considerations. Early research did not take into account the environmental and societal factors, and it is felt that this was a serious omission. WRMs are not as good as natural aggregate materials when judged solely on technical grounds. Research has also demonstrated that these materials often do not possess favorable economic properties. The impetus to use these materials comes from societal and environmental considerations — specifically when it can be shown that the societal and environmental benefits outweigh the technical and economic disadvantages. Even within a profit-oriented environment, large indirect (and therefore difficult to quantify) economic benefits can accrue to DOTs and private enterprises that use WRMs. These indirect benefits include favorable image enhancement.

Recent literature, especially Han et al., contends that, while economic, societal, and environmental aspects are important, the technical aspects should determine the final decision [Han 95]. Another problem has been that, although findings from these studies were followed up by limited field experiments, most of the field experiments have not been continued to evaluate long-term performance.

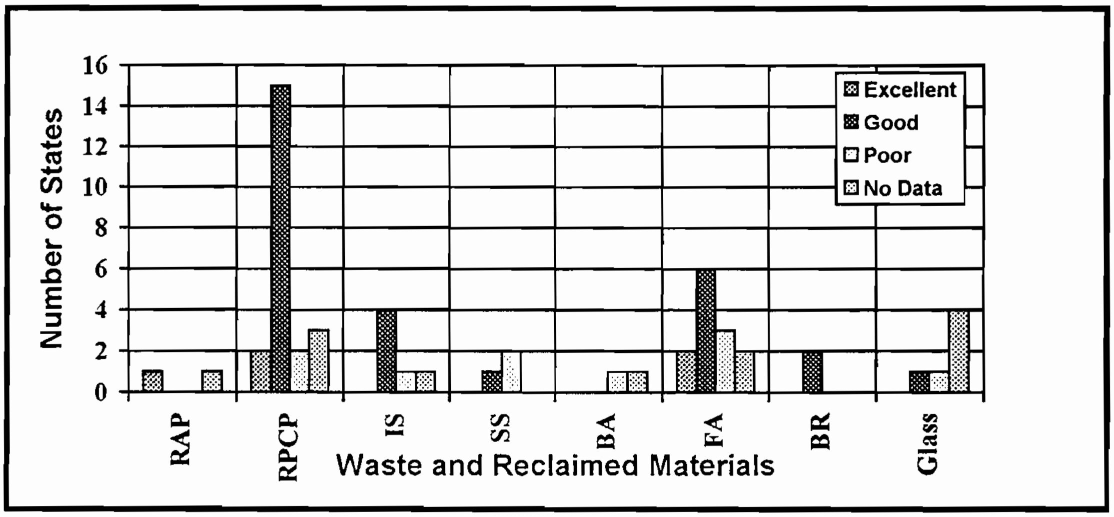

Figure 2.1 Number of states using various WRMs for roadbase construction and the resulting observed field performance

2.6 WASTE AND RECLAIMED MATERIAL AVAILABILITY AND LOCATION SURVEY

Before state and local governments in Texas can make maximum use of WRMs in roadbase construction and maintenance, they must know, among other things, the types, properties, quantities, and sources of available materials. To promote increased utilization of WRMs in road construction, the Texas legislature enacted enabling statutes, including Senate Bills 352 and 1340, whose focus is on RAP. Among other provisions, these laws require TxDOT to maximize the use of RAP when feasible, and to keep a public record of the amount of RAP owned by TxDOT.

The objectives of the location and availability survey were consistent with the requirements of these statutes. Specifically, the survey was conducted to determine the quantities of potential roadbase materials available in TxDOT districts, and to classify them by quantity, location, and type. This survey is described in detail in Center for Transportation Research Report 1348-1 [Saeed, Hudson, and Anaejionu 95]. A very brief discussion is also presented here.

2.6.1 Research Methodology

Data collection methods for this segment of the research included (1) mail questionnaires sent to TxDOT district office engineers, (2) telephone interviews of individuals with personal knowledge of potential material sources, and (3) limited site visits designed to enable the research team to verify the existence of WRMs and to collect samples.

The original design for the survey in this project called for using the chain referral sampling method at two levels. At the primary level were the 25 TxDOT district offices. Several respondents from TxDOT recommended individuals for the second-level survey. The results presented in Report 1348-1 are limited to responses from TxDOT district offices.

At the first level of sampling, 84 percent (21) of the 25 districts responded to the research questionnaire. Questions were designed to obtain information regarding such issues as: types of WRMs available for roadbase construction; locations where materials are stockpiled; approximate amounts of stockpiled materials; shipment facilities available; locations where materials have been used; performance of these WRMs where used; availability of scientific/engineering test results; and the supply of sample materials for additional testing.

2.6.2 Results of the Survey

A detailed discussion of the results of the WRM availability and location survey is documented in Report 1348-1. A brief discussion is presented here.

A total of 21 out of 25 TxDOT districts responded to the survey. Of these, 19 districts reported having stockpiles of RAP, while 9 districts reported having stockpiles of RPCP. RAP was estimated to be present in excess of 355,000 tons, followed by about 19,000 tons of RPCP. Only four TxDOT districts reported having any stockpiles of coal combustion by-products. RAP stockpiles were distributed all over the state, whereas RPCP stockpiles were located in seven counties only. Figure 2.2 summarizes the response to the question regarding the type of various WRMs available. Estimated quantities of other WRMs are shown in Figure 2.3.

The data from the WRM location and availability survey suggest that there is room for expanded utilization of WRMs (other than RAP and RPCP) in roadbase construction. Private ownership of operations that produce most of the potential base materials may limit the availability of suitable materials, or at least control the cost of such materials. WRMs from commercial operators included blast furnace slag, steel slag, fly ash, bottom ash, power plant pond ash, spent foundry sand, tire chips and other rubber products, cement kiln dust, rice husks, and ceramic products.

Problems associated with widespread utilization of these materials include limited knowledge about their availability, environmental regulations, costs for transporting materials to project sites, and gaps in scientific and engineering knowledge about the behavior of these materials in roadbase applications. Dealing effectively with these problems requires collaborative research and project implementation efforts by TxDOT, other government agencies, private companies, academic institutions, and other business organizations.

2.7 FINAL OBSERVATIONS

A close examination of the data presented in CTR Report 1348-1 [Saeed, Hudson, and Anaejionu 95] indicates a need to survey commercial sources of WRMs in Texas. Because they possess only two of the reported materials, namely RAP and RPCP, TxDOT districts were able to give estimates of the amounts of these two materials available in stockpiles. Yet the districts could not give firm estimates of the materials available in commercial stockpiles. District engineers suggested that we obtain these estimates from relevant sources. Second, during the first survey we learned from TxDOT that there is room for expanded utilization of WRMs other than RAP and RPCP in roadbase.

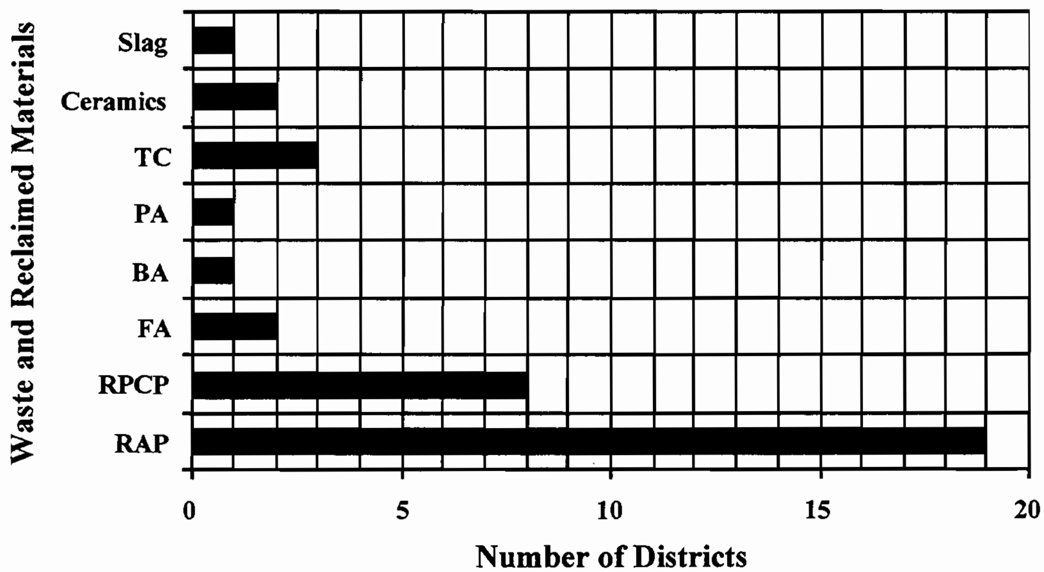

Figure 2.2 Number of districts reporting stockpiles of various WRMs

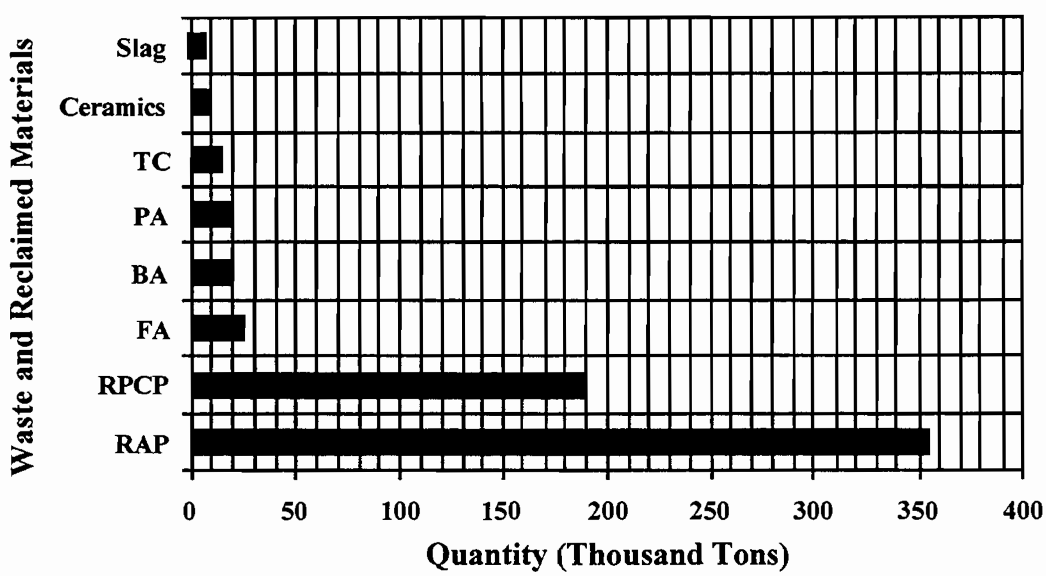

Figure 2.3 Estimated quantities of WRMs owned by TxDOT

Whether the reclaimed material is RAP, ceramic waste, or fly ash, several questions remain: How much of the material is produced? How much natural aggregate would it save? Where is it produced? What are the alternate uses for the material? These and other questions suggested the need for more research regarding WRMs available from commercial operations. The results of the commercial survey are presented in Appendix I of this document.

On the technical front, there is a need to test the suitability of these materials for roadbase construction. Also needed is a consideration not only of the technical, economic, and environmental aspects, but also of the relevant societal factors. These and other questions suggested the need to develop a WRM evaluation system, as stated previously in Chapter 1. The next chapter discusses the development of such a WRM evaluation system.

CHAPTER 3. WASTE AND RECLAIMED MATERIALS EVALUATION METHOD

3.1 INTRODUCTION

In most cases, WRMs are technically inferior to conventional, time-tested construction materials. One must, however, guard against judging them based on the claims of researchers who have investigated the material *only* in technical laboratory studies. The viability of a specific WRM depends on many interrelated factors other than technical properties. In order to make meaningful recommendations, all factors need to be evaluated objectively.

Agencies, whether they are federal or state, responsible for transportation infrastructure construction and M&R are faced with a number of problems, some of which are listed below [NCHRP 80]:

1. There has been a reduction in available funds for transportation infrastructure construction and M&R owing to various reasons. These reasons range from decline in the tax base to fiscal demands of other competing projects.
2. There may be material supply problems near the point of use owing to a depletion of sources. The unavailability may also be due to zoning laws; increased haul distances and associated transportation costs; strict environmental codes limiting production in certain areas; and use of natural aggregate materials for other construction projects. The environmental codes may result in major expenditures for air and water quality, noise control, and pit and quarry restoration.
3. There may be an urgent need to reduce the amount of energy required for the production of natural aggregate (for quarrying, size reduction, etc.), and the availability of various fuels, and their cost.

Because of these and other problems, the use of WRMs for construction and M&R of transportation infrastructure is an attractive alternative. The use of WRMs in transportation projects has several advantages over the use of natural aggregate materials. These advantages are economical, environmental, and societal in nature and it is these advantages against which the WRMs' inferior, but still basically sound, technical qualities must be balanced.

The WRM evaluation system developed through this research and described in this chapter therefore considers four aspects of utilization of WRMs. These are: (1) technical, (2) economic, (3) societal, and (4) environmental (an initial screening process is also included). A WRM must possess certain minimum fundamental physical, chemical, mechanical, and thermal properties for it to be suitable technically for utilization in roadbase construction projects. At the same time, it must be able to compete economically with natural aggregate materials, and must have societal and environmental benefits to offset any technical and economic disadvantages, if such disadvantages exist. The initial screening process and the four evaluation subsystems are discussed below. Each WRM which has potential for use in roadbase construction is evaluated separately. Figure 3.1 shows the WRM evaluation system.

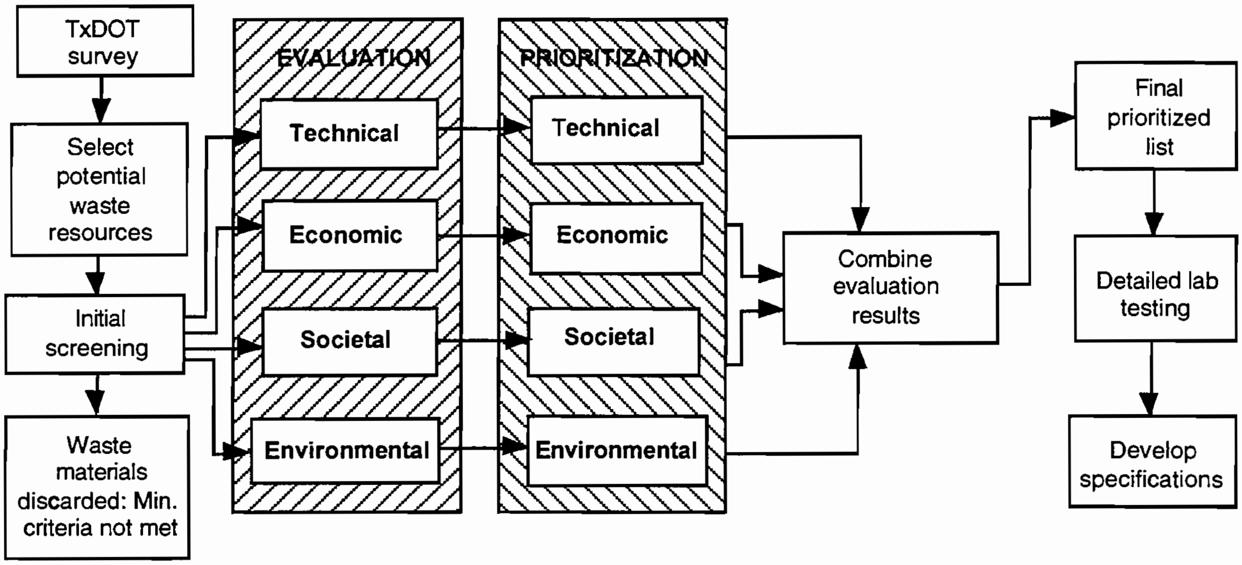

Figure 3.1 WRM evaluation system

A quantitative rating system, based on objective data, was developed in order to examine the relevant properties. An additive model approach was then adopted to estimate the overall utilization potential of WRMs in question. The advantage of this approach is that it makes it possible to examine all properties. Furthermore, the relative importance of these properties is also considered. Each candidate waste material will be ranked on a scale of zero to five, where zero is the poorest and five is the best, for the selected properties. A total score for each evaluation subsystem is obtained by combining the scores of all the considered properties; finally, an overall utilization potential is estimated for each WRM individually.

3.2 INITIAL SCREENING

Initial screening is utilized to eliminate WRMs having low potential for roadbase construction so that no additional time and resources are wasted evaluating them using other criteria. The factors which serve to determine the minimum acceptability of WRMs belong to technical, economic, and environmental aspects. These factors are: 1) accumulated or annually produced quantity, 2) material location, 3) material toxicity, 4) water solubility, and 5) material durability. Societal factors are not included in the initial screening process, as it is assumed that it is always societally acceptable to reduce the amount of waste material being generated and discarded into landfills.

WRMs are not considered for further evaluation if they do not meet the initial screening requirements. If all the requirements of the initial screening are met, then the WRM is subjected to separate technical, economic, societal, and environmental evaluations. The initial screening criteria are discussed in the following paragraphs.

3.2.1 Accumulated or Annually Produced Quantity

Miller et al. [NCHRP 76] recommend that an annual production quantity of 50,000 tons or an accumulated quantity of at least 0.5 million tons be considered the minimum material amounts capable of fulfilling a reasonable portion of the aggregate requirements for a road project. These recommended values are used to eliminate WRMs based on accumulated or annually produced quantity.

3.2.2 Material Location

The location of a WRM with respect to the site where it is to be potentially used has an impact on its being used and depends on the available mode of transportation and the distances involved. The WRM must be located within a reasonable distance from the place of potential use; otherwise, the transportation costs will be very high and may ultimately make its use prohibitive. Distances of 80 km for truck transport, 160 km for rail transport, and 480 km for barge transport are suggested as maximum economic haul distances by Miller et al. [NCHRP 76]. It must, however, be noted that transportation costs will vary with the region of the state, so judgment must be used when making use of these recommended distances.

3.2.3 Material Toxicity

Processing WRMs to produce aggregate for roadbase construction must not make them toxic to the flora and fauna, and the permitted level of suspended solids and leachates must not be above the permitted limits set by the Environmental Protection Agency (EPA) for such purposes. It must also be noted whether the material was toxic to begin with. If so, did processing for use increase toxicity or reduce it or it remained unchanged?

3.2.4 Water Solubility

The base material is the primary load carrying element of an AC pavement in the case of thin-surfaced pavements, and provides a stable support structure when used under PCC pavements. When some base materials come in contact with water, they lose their ability to carry load owing to their solubility in water and to other reasons. This criterion eliminates WRMs based on their inability to carry applied loads in the presence of water.

3.2.5 Material Durability

As outlined by American Society for Testing and Materials (ASTM) specification ASTM D2940 - 92 [ASTM 92], roadbase aggregate material must be durable and capable of withstanding the effects of handling, spreading, and compacting without degradation productive of deleterious fines. Roadbase aggregate produced from WRM sources must be able to withstand these construction and M&R-related activities.

3.3 TECHNICAL EVALUATION SUBSYSTEM

WRMs must possess adequate physical, chemical, mechanical, and thermal properties required of a material for use in roadbase construction projects. The material properties listed in

Table 3.1 must be considered when evaluating materials technically. Properties such as particle shape and hardness, resistance to load, and/or temperature-induced degradation are evaluated.

The National Stone Association recommends that aggregate properties be determined by the material's end-use application [NSA 91]. Aggregates intended for base course application have required levels of some of the properties that differ from those used in asphalt concrete, and vice versa. Properties usually required of a base course include high stiffness, resistance to permanent deformation, and high permeability or drainability. For best performance, the base should be well-graded, consist of 100 percent crushed, angular particles, and be compacted to 100 percent of AASHTO T-180 density [NSA 91]. The following section summarizes the testing methods for determining the technical score.

Table 3.1 Aggregate properties considered for roadbase use

Classification	Properties
General Properties	Uniformity, Previous Performance
Physical Properties	Presence of Deleterious Substances, Gradation, Particle Size, Maximum Particle Size, Porosity and Pore Structure, Particle Specific Texture, Specific Gravity.
Mechanical Properties	Particle Hardness and Soundness, Particle Strength, Mix Permeability, Mass Stability
Chemical Properties	Solubility, Resistance to Chemical Attack, Resistance to Volume Changes due to Wetting and Drying, Resistance to Degradation from Freeze-Thaw Cycling, Oxidation and Hydration Reactivity, Slaking.

3.3.1 Particle Size Analysis and Distribution

The aggregate grading, including percent fines, markedly affects stability, drainage, and frost susceptibility; hence, grading is an important variable in determining performance. Dry mechanical sieving, the most common method used for this purpose, consists of passing a known quantity of dry aggregate particles through a set of sieves.

A round sieve having a diameter of 20 cm is customarily used for fine aggregates, whereas coarse aggregate is normally sieved in a larger rectangular sieve about 38 x 58 cm in size. These sieves have rectangular openings formed by wire cloth, with the wire diameter increasing as the size of the sieve opening increases. Sieves are stacked upon each other in order of decreasing sieve opening size from top to bottom. A pan is placed at the bottom to catch any particles passing the smallest sieve size. A mechanical sieve shaker is used that imparts either a vertical or vertical and horizontal motion to the particles. Determination of the grading of a sample of aggregate by passing dried material through a series of standard sieves is described in AASHTO T-27, ASTM C 136 - 93 [NSA 91, ASTM 93].

The slope of the grain size distribution curve, which is expressed as the *coefficient of uniformity* C_u, is an important property that can be related to permeability and mass stability of the base course. The coefficient of uniformity used in the technical evaluation is defined in Equation 3.1.

$$C_u = \frac{D_{60}}{D_{10}} \qquad \text{Eq 3.1}$$

where:

C_u = Coefficient of uniformity,

D_{60} = Sieve opening size (mm) through which 60% of the aggregate passes, and

D_{10} = Sieve opening size (mm) through which 10% of the aggregate passes.

A value of C_u greater than 6 indicates a dense-graded (i.e., well-graded) material composed of a considerable range of particle sizes. A C_u value less than 4 indicates a uniformly graded (i.e., open-graded) material having a narrow range of particle sizes. Dense-graded aggregate is desirable for maximum stability [NSA 91]. The C_u value obtained from sieve analysis is used to determine the gradation score on a scale of zero to five, where zero corresponds to a C_u of zero and 5 corresponds to a C_u value of 10.

3.3.2 Los Angeles Degradation Test

Degradation of the aggregate material can occur as a result of physical and chemical actions during storage, transportation, construction, and service life. For dense-graded bases in which the fines just fill the voids between aggregate particles, this can result in the presence of excessive amounts of fines (thus reducing performance). The WRMs need to be evaluated to determine their resistance to degradation that can result in the production of fines.

The quality of material known as toughness is the ability of a material to resist fracture under impact. The Los Angeles Degradation Test (also known as LA Abrasion Test), AASHTO T-96, ASTM C 131 - 89 [ASTM 89], is the most widely specified test for evaluation of the resistance of a coarse aggregate to degradation by abrasion and impact. It is often described erroneously as a hardness test. Wear or loss in the LA Degradation test is the result of impact and surface abrasion in the drum. During the early portion of the test, impact is the cause of production of fines, as no or few fines are available to cushion the impact forces. Hard materials are more susceptible to fracture than softer materials, as they are better in absorbing the impact forces. Soft materials, logically, are more susceptible to fine production owing to the wearing of the surface [Huang 90].

A sample of material having a specified grading is placed in a steel drum along with 6 to 12 steel balls, each weighing about 420 gms. The drum is rotated for 500 revolutions, and the resulting tumbling action imparts impact to the material that causes the more brittle particles to shatter, with surface wear and abrasion occurring as the particles rub against one another and against the steel balls [NSA 91].

Following the completion of the specified number of revolutions, the sample is removed from the steel drum and the amount of material passing the No. 12 sieve is determined. This number represented as a percent of the total material is termed as the percent loss or wear and is used to determine the load degradation score on a scale of zero to five, where a score of zero corresponds to a load degradation of 50 percent or more and a score of five corresponds to a load degradation of 0 percent or no fine production at all.

3.3.3 Particle Shape and Texture

Particle shape and surface texture are important in providing a stable base course. Angular, nearly equidimensional particles having a rough surface texture are preferred over round, smooth particles. Angularity contributes to aggregate interlock, and a rough surface texture inhibits movement of one particle relative to another. Thin, elongated aggregate particles have reduced strength when load is applied to the flat side and are also prone to size segregation under handling and to breakdown during compaction. In cases where it is desirable to have high base stability, round aggregate should not be used, as it has a tendency to move under the applied traffic load [NSA 91].

ASTM D 3398 provides an index of particle shape and texture by compacting each size fraction with a standard tamping rod into a 17.78 cm high mold having an internal diameter of 15.24 cm. Two different compactive efforts are used and the Particle index is computed using the following formula:

$$I_a = 1.25\, V_{10} - 0.25\, V_{50} - 32.0$$

where:

I_a = Particle Index for a given size fraction,

V_{10} = Voids in the aggregate when compacted using 10 blows per layer, and

V_{50} = Voids in the aggregate when compacted using 50 blows per layer.

Particle index, I_a, values range between a maximum of 20 and a minimum of zero [ASTM D 3398]. Using the results from this test, the best aggregate material, consisting of rough, angular particles ($I_a = 20$), is assigned a score of five and the worst a score of zero ($I_a = 0$). Intermediate values are assigned a score linearly between zero and five.

3.3.4 WRM Hardness

The resistance to scratching or abrasion offered by a smooth surface is known as hardness and is a measure of the strength of the bonding forces holding the constituents together in a structure. Materials, such as talc, are so soft that they can be easily scratched or abraded by rubbing between the fingers. Diamond, at the other extreme, is so strong that it can be scratched only with another diamond.

The hardness of a given material is determined by the ease of scratching one of its smooth surfaces with the sharp edge of a mineral of known hardness using Moh's scale of hardness, as proposed by Friedrich Moh, an Austrian mineralogist, in 1812. It uses ten relatively common minerals as a scale, which in the order of increasing relative hardness are: talc, 1; gypsum, 2; calcite, 3; fluorite, 4; apatite, 5; orthoclase, 6; quartz, 7; topaz, 8; corundum, 9; diamond, 10. A material can be scratched with a mineral having a similar or higher hardness. Some convenient test materials include finger nail hardness, 2.5; copper coin, 3; steel knife blade, 5.5; and steel file, 7. The hardness of a material may also vary, depending on the direction of the scratch with respect to the orientation of the constituents [Berry 83].

This simple test is used to assign scores from zero to five, where the highest score of five is assigned to a material as hard as diamond, and zero is assigned to a material as soft as talc. The Moh's relative hardness value for a particular WRM may thus simply be divided by two to obtain the score for this attribute.

3.3.5 Summary of Technical Evaluation Subsystem

The technical evaluation subsystem assesses the technical utilization potential of WRMs based on the coefficient of uniformity, C_u; the particle index, I_a; Moh's hardness, M_h; and percent material loss, $M_{l\%}$. The technical evaluation scores for the attributes are based directly on the C_u, I_a, M_h, and $M_{l\%}$ values estimated by conducting the appropriate laboratory tests as discussed in the preceding sections. Table 3.2 shows the estimation of technical evaluation scores.

Table 3.2 Estimation of technical evaluation scores using laboratory test

Evaluation Attribute	Test Designation	Technical Attribute Score					
		0	1	2	3	4	5
Gradation	Tex-110-E - 95 Coefficient of Uniformity	0	2	4	6	8	10
Particle Shape & Texture	ASTM D 3397 - 93 Particle Index	0	4	8	12	16	20
Moh's Hardness	Moh's Hardness Scale	0	2	4	6	8	10
Resistance to Applied Load	ASTM C 131 - 89 % Material Loss	50	40	30	20	10	0

3.4 ECONOMIC EVALUATION SUBSYSTEM

The main purpose of an economic evaluation is to identify WRM resources that are most feasible for utilization as aggregate in roadbase construction in terms of economics. The same five-point scale evaluation process is utilized as described earlier in the technical evaluation section. The five attributes evaluated on a five point scale for economic evaluation are:

- Disposal costs
- Processing costs of reuse
- Transportation costs
- Accumulated or annually produced quantity
- Cost of modifiers/stabilizers or additional material

A well-thought-out economic analysis is an essential tool for highway planning, but widespread use of this technique still has to overcome the problem of assessing the costs and the benefits for hard-to-quantify social factors. It must be noted that approximate costs for the above-listed attributes can be used to make an economic analysis only within broad terms. In local, competitive, real-life situations, an extensive marketing study, supported by exact current costs, should be conducted in order to determine more precise costs [NCHRP 76].

3.4.1 Disposal Costs

The disposal cost of waste material is an important input in determining its economic feasibility for use in roadbase. Landfills usually accept material for disposal in terms of the volume it will occupy and quote a rate in terms of cubic yards. Two rates are usually quoted, one each for compacted and uncompacted material. The WRMs considered in this study fall under the compact material category. Quoted rates ranged from $1.2–4.5 per ton, excluding transportation costs to the landfill. Disposal cost is the dollar savings that will be realized if the material is used; this cost is termed a benefit as far as this evaluation method is concerned. The higher the disposal cost, the more we should be try to use the material and, hence, the higher the score. A disposal cost of $5.0 per ton is assigned a score of five and a score of zero is assigned when no savings can be realized.

3.4.2 Processing Costs of Use

The cost of processing and converting a WRM into a useful aggregate product is probably the most important and sometimes most costly factor in determining economic feasibility. Processing costs for WRMs are meaningful only when compared with the cost of conventional aggregate material, which varies from location to location for obvious reasons. Cost per ton is based on tons per hour of production, manpower costs, and equipment costs required in order to achieve the tons per hour of production. If the production rate is 250 tons per hour, the processing costs per ton of processed material can be calculated as shown in Table 3.3.

The costs estimated in Table 3.3 should be revised to reflect location conditions. For example, if one assumes a production of only 125 tons per hour with breaking and hauling costs remaining constant, then all other costs should be doubled, and costs per ton would be $2.50. The values were estimated after detailed discussion with leading recycling plant manufacturers [Svedala 95, Universal 91].

A processing cost of $2.50 results in an evaluation score of 0 to indicate our preference for those materials which have a minimum processing cost; $0.00 processing cost is assigned the highest possible evaluation score of five.

Table 3.3 Determination of maximum processing costs for WRMs

Item	Cost $ per Ton
(1) Plant Superintendent @ $30.00 per hour loaded labor cost	0.12
(1) Laborer @ $19.00 per hour loaded labor cost (LLC)	0.08
(1) Rubber tire loader operator @ $ 30.00 per (LLC)	0.12
(1) Rubber tire loader @ $6,000.00 per month	0.11
Plant Depreciation	0.21
Plant maintenance	0.11
Breaking and hauling cost	0.90
Cost for per ton of minus 1.00" material produced	0.75
Total Cost	**1.75**

3.4.3 Transportation Costs

Several alternatives are available for transporting WRMs. The most feasible of these are truck, rail, and barge, as discussed earlier.

Cost figures of transporting WRMs are subject to wide variations for various reasons. The Texas Sand and Gravel Carriers Association uses a published rates list to quote prices for transporting WRMs a certain number of miles on a per-ton basis. These costs range from a high of $20.00 per ton for transporting material a distance of 320 km, to a minimum of $1.00 per ton for transporting WRMs within 16 km [TSGCA 95].

The lower the transportation cost, the higher we should score it, as it will be much cheaper to use. Keeping this in mind, a transportation cost of zero dollars is assigned the highest score of five and the maximum of $10.00 per ton or higher is assigned a score of zero. After a distance of about 80-96 km for truck transport, transportation costs start to overshadow other related costs in the economic evaluation subsystem. Intermediate values are assigned scores using linear interpolation between the maximum and the minimum possible values.

3.4.4 Accumulated or Annually Produced Quantity

This factor takes into account the quantity of WRM available or produced annually. Obviously, the larger the available quantity of a particular WRM, the higher the assigned score. A survey of TxDOT districts, described in CTR Report 1348-1 [Saeed, Hudson, and Anaejionu 95], was conducted to determine the types and quantities of WRMs owned by TxDOT. The maximum available quantity, 355,000 tons of RAP, was assigned the maximum possible score of five, whereas the minimum available quantity was assigned a score of zero. WRMs having intermediate quantities are assigned scores linearly between the two extremes.

3.4.5 Cost of Stabilizers/Modifiers or Additional Material

There may be certain WRMs that require the addition of natural aggregate or some stabilization agent to use them in roadbase construction. This cost is the dollar amount spent to produce a ton of the final mix. Currently, natural aggregate is available at a cost of $4.00 per ton.

For the purpose of the WRM evaluation method, the more the cost for additional material, the less the assigned score. A WRM which requires no additional additive/stabilizer or natural aggregate material is assigned a score of five, and a WRM which requires about $6.00 per ton of the final produced mix is assigned a score of zero, to indicate our preference for a material which requires no additive at all.

3.4.6 Summary of Economic Evaluation Subsystem

The economic evaluation subsystem assesses the economic utilization potential of WRMs based on the disposal cost, processing cost of use, transportation cost, cost of stabilizers/modifiers or additional material required, and the accumulated or annually produced quantity. Actual dollar values are used to estimate the economic evaluation scores.

Landfill operators in the Austin and San Antonio areas were contacted to determine the WRM disposal costs. Transportation costs for WRMs were obtained courtesy of the Texas Sand and Gravel Carriers Association [TSGCA 96]. In order to identify processing costs, manufacturers of recycling plants and equipment were contacted [Svedala 95, Universal 91]. Table 3.4 shows the estimation of economic evaluation scores based on objective data.

Table 3.4 Estimation of economic evaluation scores using actual $ values

Evaluation	Economic Attribute Score					
Attribute	0	1	2	3	4	5
Accumulated or Annually Produced Quantity (10^3 tons)	0	71	142	213	284	355
Disposal Cost ($/ton)	0.00	1.00	2.00	3.00	4.00	5.00
Processing Cost of Use ($/ton)	2.50	2.00	1.50	1.00	0.50	0.00
Transportation Cost ($/ton)	10.0	8.00	6.00	4.00	2.00	0.00
Cost of Stabilizers/Modifiers or Additional Material ($/ton)	6.00	4.80	3.60	2.40	1.20	0.00

3.5 SOCIETAL EVALUATION SUBSYSTEM

Many WRMs, owing to their volume, location, or associated disposal problems, present a threat to the environment; consequently, they have been the focus of interest groups involved in environmental issues. There is societal as well as political pressure to find a means to stabilize, remove, or use these wastes. The impetus to use WRMs, hence, comes from both society and the government. It is difficult, if not impossible, to measure societal and environmental implications in actual dollar terms; nevertheless, the societal evaluation subsystem evaluates the following three societal attributes on a scale of zero to five:

- Storage site aesthetics
- Safety / health hazard
- Government / special group interest

3.5.1 Storage Site Aesthetics

WRMs that are visible can promote, within a community, a desire to use them. Conversely, a material that is hidden by thick vegetation or is otherwise invisible will not generate public interest. A highly visible material is assigned a score of five, to indicate our preference for its use, while a hidden material is assigned a score of zero. A material storage site partially hidden is assigned a score between one and two; a landscaped site, between two and three. A site visible in the distance is assigned a score between three and four. Figures 3.2 to 3.6 show the storage site aesthetics in real-life situations.

3.5.2 Health/Safety Risk

This factor takes into consideration the potential of WRMs, *in their current condition*, to impair the health of the general public. A WRM which possesses no risk at all must be rated at the low end of the scale, as there is minimum incentive for its use. On the other hand, a WRM which posses the highest damage/health risk to the general public is assigned the highest possible score. Fire hazard, the maximum damage that can be passed on to the general public, is assigned a score between four and five. This is followed by disease risk, which is assigned a score between three and four. One might argue that toxic leachates polluting the ground and surface water supplies pose the greatest risk and contribute towards long-term health problems. Actually, there is a slim chance that such toxic material will be stockpiled in the open or without some filter layer in a landfill; consequently, these can be assigned a score between three and four based on their disease-causing potential. If there is risk only to workers handling the waste material, it is assigned a score between one and three, based on the precautions necessary.

Figure 3.2 WRM stockpiles highly visible, next to highway (Score = 5.0)

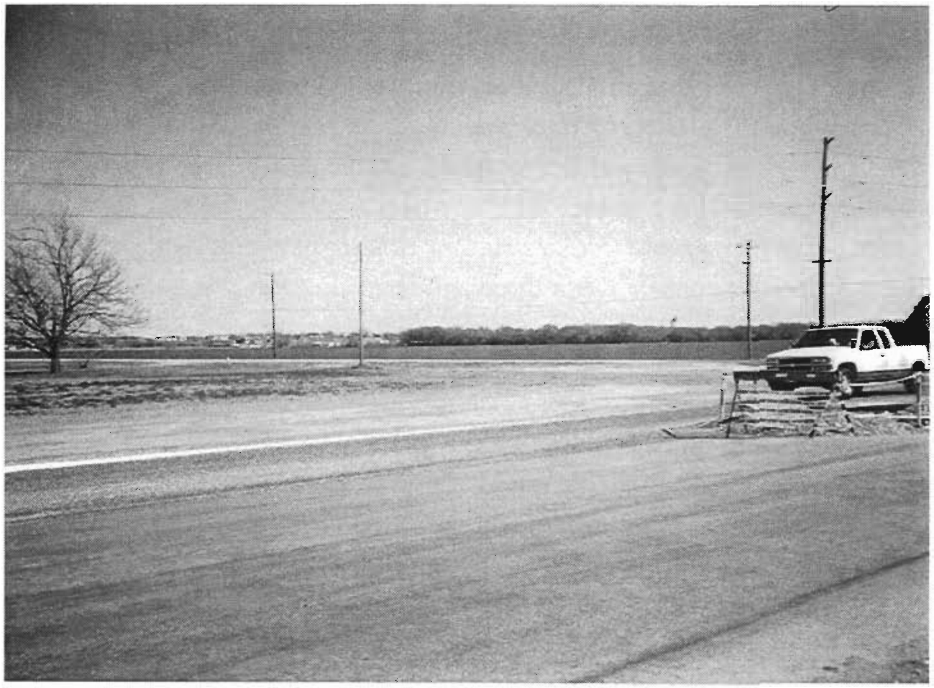

Figure 3.3 WRM stockpiles visible in distance (Score = 3.0 - 4.0)

Figure 3.4 Landscaped area before WRM stockpiles (Score = 2.0 - 3.0)

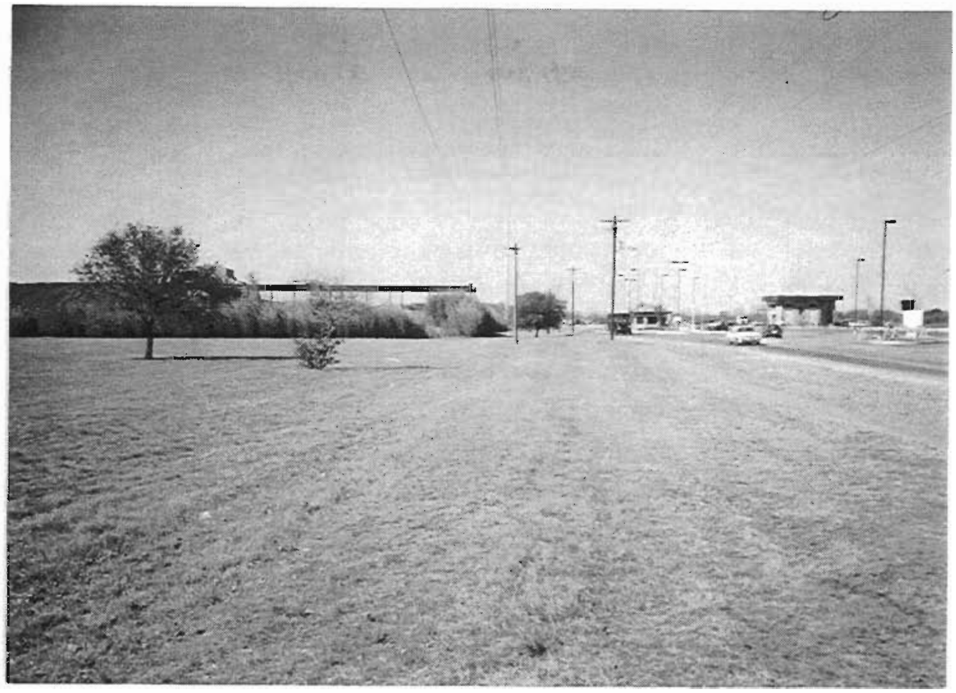

Figure 3.5 WRM partially hidden from sight (Score = 1.0 - 2.0)

Figure 3.6 WRM completely hidden from sight (Score = 0.0)

3.5.3 Government/Special Group Interest

The general public's interest in using WRMs is often supplemented by the presence of environmental or preservation groups, which generate much political pressure. The legislature can propose and pass laws to control these environmental and ecological problems. The proposed evaluation scale considers this logical propagation of actions and assigns scores accordingly. The highest score of five is assigned to WRMs which have some legislation making their use mandatory. RAP is one such material. Texas Senate Bills 352 and 1340 requires TxDOT to keep track of all state-owned RAP and to maximize its use. If there is no legislative action, then a material is assigned a score between zero and one. If some legislation is being prepared, it qualifies for a score between one and two, and a score between two and three if it is being considered. A score between three and four is assigned to those WRMs which have some legislation seeking to maximize their use but would come into effect at some later date. It is further assumed that any WRM for which legislation exists banning its use would not be a candidate and would have been rejected in the initial screening process.

3.5.4 Summary of Societal Evaluation Subsystem

Table 3.5 illustrates the estimation of societal attribute scores based on storage site aesthetics, safety/health hazard, and government/special group interest. By defining each attribute properly, care has been taken to be as objective as possible during the estimation of these scores.

Table 3.5 Estimation of societal evaluation scores

Societal Evaluation Attribute	**Societal Attribute Score**					
	0	**1**	**2**	**3**	**4**	**5**
Storage Site Aesthetics	Hidden	Partially Hidden		Visible in Distance		Highly Visible
			Landscaped			
Safety/Health Hazard	Risk to Handling Personnel (Protective Gear Required)				Fire Hazard	
	None	Gloves	Masks	Full		
				Disease Risk		
Government/Special Group Interest	Legislation					
	None	Being Prepared		Future Implementation		In Effect
			Being Considered			

3.6 ENVIRONMENTAL EVALUATION SUBSYSTEM

The general public, departments of transportation, legislatures, lawyers, and academia have all expressed a great deal of concern about the environmental issues relating to the utilization of WRMs in highways. From a technical point of view, the potential environmental impact of a WRM should be evaluated before actual field use. Some factors included in the environmental evaluation are directly or indirectly related to technical, economic, and social evaluations. The environmental effects associated with the processing and use of WRMs in roadbase are considered in the following three ways:

- Benefits of using WRMs
- Effects of processing WRMs
- Effect on environment of WRM use in roadbase construction

3.6.1 Benefits of Using Waste Materials

This factor attempts to quantify the benefits that might derive from altering the present method of waste material disposal or from removing existing stockpiles by using them in roadbase. Conservation of natural aggregate is an important benefit related to the use of WRMs. If we are able to conserve natural aggregate by using a particular WRM, it should be assigned a high score. On the other hand if a WRM requires a lot of natural aggregate to make its use possible, then it should be scored at the lower end. A 100-percent conservation of the natural aggregate qualifies for a score of five and a 0-percent conservation of natural aggregate results in a score of zero.

3.6.2 Effects of Processing Waste Materials

This factor takes into account the effects of processing a specific waste resource as part of the recycling system. Noise and dust pollution from the recycling facility are a major concern within populated areas. The amount of noise and dust generated usually tends to have less effect the farther away one is from the processing plant. Noise can be heard for long distances, depending on wind direction and other factors, whereas most of the dust usually settles within a distance of 1.6 km on a normal day (i.e, moderate wind).

A material which produces a high noise level when processed must be rated low as compared with a material which produces next to no noise. A noise level of 150 dB, which is painfully loud, is assigned a score of zero, whereas a noise level of 120 dB, the maximum vocal effort, is assigned a score of one. A noise level of 90 dB, very annoying, is assessed a score of three; 60 dB, roughly the loudness of an air-conditioning unit 9 m away, yields a score of two; and 30 dB, very quite, yields a score of four. No noise at all, such as would occur in the case of a WRM that requires no processing at all, is assigned a score of five [NSA 91].

Dust in the air is a function of distance from the plant; most will settle about 1.5 km from the point of origin [NSA 91]. The best possible score of five is assigned in the case where there is no dust produced at all or where populated areas are about 1.61 km away from the processing plant. A score of zero is assigned when, hypothetically, atmosphere dust measurements are taken at a plant in full production and with no dust or noise control in operation.

3.6.3 Effects on Environment of Waste Material Use in Roadbase

It is the responsibility of the academic and scientific communities to establish, based on scientific techniques, what is hazardous and what is not, irrespective of what the general public or the society at large believes. There are several well-known laboratory test procedures used for determining the toxicity (and thereafter the leaching characteristics) of waste materials. These tests include specifications from EPA and ASTM, among many others.

The hazard potential of a particular WRM can be accounted for if one considers the effect of using it on ground and surface water. This translates to the amount of metal leachates possible from a WRM. If a particular WRM permits substantial amounts of metals to leach out during its service life when used in roadbase construction, then it would be very unwise to use that particular WRM. On the other hand, a WRM having a low leaching potential is recommended for use in roadbase construction, since even if it contains undesirable materials, this will not affect the surroundings. Based on this, a WRM having significant leaching potential is rated low, while a material having next to no leaching potential is rated high in the evaluation system, when determining its utilization potential.

As stated earlier, there are a number of tests that can be used for determining impacts on ground and surface water. The Extraction Procedure (EP) Toxicity Test and the BioAssay Test are particularly well-adapted for use in the evaluation procedure and are described in detail. The EP Toxicity Test is used in the evaluation process, as the BioAssay Test is still being assessed by the environmental group at Purdue University [Bhat 96, Alleman 96].

The EP toxicity Test is performed in accordance with EPA test method 1310. This test method is specified in EPA specification EPA/SW-846: "Test Methods for Evaluating Solid Wastes, Physical/Chemical Methods," 3rd edition. In this test, a sample of 100 grams of WRM is added to 1600 grams of deionized water, with the mixture then agitated in a Plexiglas container. All the coarse sample particles are broken down so that no material is retained on the 0.95-cm (3/8-in.) sieve. Extraction is performed using acetic acid; the pH of the mixture is maintained at 5.0 ±0.2 throughout the extraction procedure. At the end of the extraction period, the solids and the extraction liquid are separated by filtering the mixture through a 0.45 micrometer nominal pore size filtering membrane. The liquid thus obtained is called the EP extract, and is analyzed for eight trace metals, namely, arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver, using EPA test specifications as described in EPA/SW-846.

The EP toxicity test models the behavior of waste materials in co-disposal situations in municipal landfills; it is considered a "worse case" scenario by the EPA. The industry is opposed to this test inasmuch as it reflects the maximum leaching effects that could result from the mismanagement of wastes, rather than suggest that most of wastes are disposed of in well engineered landfills [Huang 90, EPRI 87, EPA 85].

Another recent technique, well-suited for this evaluation system, is the commercial bacterial BioAssay test, Microtox, used to determine the effect of WRMs on the environment. Recently this method was used by Bhat et al. to determine the effect of spent foundry sands on the environment [Bhat 96].

In this test, leachate generated from the waste material is exposed to a photoluminescence (light-emitting) bacteria called *photobacterium phosphorium*. The light emitted by these marine organisms can be measured before and after exposure to a leachate. When exposed to a toxicant, the light output decreases, which can be quantified. Using this procedure, the toxicity of various WRMs can be quantified and compared [Bhat 96].

For generating leachate, a 20-gram sample is placed in a flask and 80 milliliters of 20 percent sodium chloride (NaCl) solution is added. This NaCl (salt) solution is used because the microorganisms, being marine, require a medium that is similar to their original environment. This WRM suspension is shaken for 18 hours, and then the solids are separated from the liquid portion using a filtration, and finally a centrifugation, operation. The original light output is measured, and then a small quantity of leachate is added. After adding the leachate, light output is measured after 5 and 15 minutes and is compared with the control [Allemen 96].

3.6.4 Summary of Environmental Evaluation Subsystem

Table 3.6 shows the estimates of environmental attribute scores. Although the results from the EP toxicity test were used in this evaluation process, the BioAssay test would be a better choice, once it is fully developed; these results are also shown.

3.7 FINAL ESTIMATION OF WRM UTILIZATION POTENTIAL

Once a particular WRM has been subjected to the four evaluation subsystems, the individual scores from each attribute within each evaluation subsystem must be combined to determine the final utilization potential. An additive model is used for this purpose, and the final score, expressed on a scale from zero to five, is called the WRM Potential Index (WRMPI), as shown in Equation 3.2. On this scale, five represents the maximum utilization potential of a particular WRM in roadbase construction, whereas a WRMPI of zero indicates the least utilization potential, or no potential at all for utilization in roadbase. The WRMPI expressed as a percent is termed the *WRM Utilization Potential* (WRMUP).

Table 3.6 Estimation of environmental evaluation scores

Evaluation Attribute	**Environmental Attribute Score**					
	0	**1**	**2**	**3**	**4**	**5**
Benefits of Recycling WRMs (Conser. of Natural Material, %)	0	20	40	60	80	100
Noise Pollution (dB)	150	120	90	60	30	0
Dust Pollution (Distance to population, km)	0	0.32	0.64	0.96	1.28	1.60
TCLP (EPA Limits)	Above		At		Below	
Microtox Bioassey Test (% Reduction in light output)	10	8	6	4	2	0

$$WRMPI_i = W_T \sum_{J=1}^{n} w_{T,J} S_{T,J} + W_E \sum_{J=1}^{n} w_{E,J} S_{E,J} + W_S \sum_{J=1}^{n} w_{S,J} S_{S,J} + W_{En} \sum_{J=1}^{n} w_{En,J} S_{En,J} \qquad \text{Eq 3.2}$$

where:

$WRMPI_i$ = WRM Potential Index for WRM_i,

$W_{T, E, S, En}$ = Weight for technical, economic, societal, environmental evaluation subsystems,

$w_{J; T, E, S, En}$ = Weight for technical, economic, societal, and environmental attributes, and

$S_{J; T, E, S, En}$ = Score for technical, economic, societal, and environmental attributes.

The selection of weights for attributes and evaluation subsystems is based on their importance in the overall scheme of things and may vary from location to location according to the prevailing local conditions (especially political and societal). Given that the selection of weights is an important part of the WRM evaluation system, Chapter 4 first describes a method useful in developing these weights and then makes initial estimates. The developed weights, however, are meant to serve only as a reference, and the user is strongly encouraged to develop weights that reflect the prevailing local conditions more accurately.

3.8 OVERALL RANK OF THE EVALUATED WASTE MATERIALS

Although a WRMPI may now be calculated for any candidate material, a simple scale for characterizing materials is desirable for quick reference to their overall potential. Four categories are thus proposed below.

3.8.1 Category I WRMs

Category I contains those WRMs that have the highest potential for roadbase use. These WRMs require no processing prior to use and hence are cheaper to produce. These WRMs are characterized by having technical properties comparable to natural raw aggregate. Also, these WRMs are present in large quantities, there is more public awareness of their existence, and they are environmentally safe.

3.8.2 Category II WRMs

Category II contains those waste materials which require more processing and/or whose physical properties are not considered to be as sound as those in Category I. These WRMs most probably require the addition of natural raw material or some modifier to make their use feasible; for this reason they are expensive to use. These WRMs are also not as abundant as Category I materials.

3.8.3 Category III WRMs

Category III contains those waste materials which show less promise than those in class I or class II for a number of reasons. They may require a lot of processing or may have an undesirable physical property. In general, it could be said that these materials can be used in local, isolated cases.

3.8.4 Category IV WRMs

Category IV contains those waste materials that show little or no potential for roadbase use. At best they might be used in small quantities as a filler or in very specialized applications. When used as a filler material, they would require a maximum amount of natural raw material and, hence, would be very expensive. Also, these WRMs lack desirable technical properties.

3.9 SPECIFICATIONS DEVELOPMENT

The WRM evaluation system described in previous sections formed the first step in the development of trial WRM specifications. It was used to select WRMs for detailed laboratory testing. Only those WRMs which passed the WRM evaluation system and were feasible on an overall technical, economic, societal, and environmental basis were forwarded to the next step. This approach saved both financial and human resources.

Chapter 4 applies the developed method to WRMs determined to be available to TxDOT during the WRM availability and location survey, as described in Chapter 2. Once the method had recommended WRMs for detailed laboratory testing, they were tested using standard TxDOT tests. In instances where TxDOT tests were unavailable, ASTM and AASHTO specifications were looked at and adopted.

CHAPTER 4. EVALUATION OF AVAILABLE WASTE AND RECLAIMED MATERIALS

4.1 INTRODUCTION

In today's complex world, no amount of information seems adequate for making objective decisions on such multifaceted and controversial problems as the utilization of WRMs in roadbase construction. Individuals and even public and private enterprises often make decisions based on subjective and limited objective knowledge, rather than on a thorough and complete logical study of the issues. The proposed WRM evaluation method, as described in the previous chapter, logically resolves issues and thus provides for the rational selection of WRMs for use in roadbase. Through this method, a complex problem is divided into smaller units as a way of reducing subjectivity, and a number of factors are taken into account that might otherwise be overlooked.

This chapter describes the estimation of weights for each evaluation subsystem, and provides the corresponding attributes, based on the analytic hierarchy process (AHP). In addition, WRMs are also evaluated using the developed evaluation system to determine their utilization potential (WRMUP) and to select WRMs for the kind of detailed laboratory testing that can lead to trial specifications.

4.2 MATHEMATICAL MODELS

The objective of this chapter is to estimate the WRM utilization potential (WRMUP) for each potential WRM, prioritize them for further laboratory testing, and, finally, to develop trial specifications for top-ranked WRMs. A simple additive model, as discussed in Chapter 3, can be used to estimate the WRM potential index (WRMPI) based on the assessed score for each attribute and a weight assigned based on the importance of that attribute in the evaluation subsystem. WRMUP is simply WRMPI represented as a percentage.

The selection of the weights of different factors in the overall scheme inevitability introduces subjectivity into the WRM evaluation method. This, however, is reduced to some extent by using the analytic hierarchy process to select these weights.

4.3 THE ANALYTIC HIERARCHY PROCESS

One must first understand complexity before one is able to deal with it. Complex system problems can challenge and tax our capability to logically understand their causes and the consequences of any action we may take to resolve them. The use of WRMs in roadbase is one such problem in which a number of factors interact. AHP integrates all available information — technical, economic, societal, political, etc. — that has a bearing on the WRM use problem in order to make a decision.

Yet the proper assessment of the importance of these factors, as well as the development of a system of weights based on priorities, poses a major problem. AHP resolves this by using qualitative descriptions to define a problem and to represent the interaction of its parts. It also uses qualitative judgments to assess the strengths of these interactions to assign weights based on relative importance [Saaty 82a, Saaty 82b]. By using AHP, concerns about non-quantitative factors can be presented in a systematic manner. AHP resolves the argument of subjective weights that has traditionally been assigned by researchers using intuitive judgment [Guo 93].

By dividing the problem into levels, the decisionmaker can focus on smaller sets of decisions. The AHP incorporates judgments and personal values in a logical way. Structuring the hierarchy depends on knowledge, understanding, and experiences. Saaty summarizes the advantages of using AHP as follows [Saaty 82a]:

1. AHP provides a single, easily understood, flexible model for a wide range of problems.
2. AHP enables people to refine their definitions of a problem and to improve their judgment and understanding through repetition.
3. AHP reflects the natural tendency of the mind to sort elements of a system into different levels and to group like elements into each level.
4. AHP can deal with the interdependence of elements in a system and does not require linear thinking.
5. AHP integrates deductive and systems approaches in solving complex problems.
6. AHP does not insist on consensus but synthesizes a representative outcome from diverse judgments.
7. AHP tracks the logical consistency of judgment used in determining importance.

When several factors need to be weighted, individuals intuitively select one factor as the base of a certain weight, then compare the factors with this base. This approach can lead to judgmental errors which AHP avoids by making $n(n-1)/2$ comparisons, where n is the number of factors under consideration. Moreover, AHP is the only decision method that considers consistency.

Suppose that we need to compare a set of n factors or objectives in pairs according to their relative weights. The factors or objectives are denoted by $A_1, A_2, \ldots\ldots, A_n$ and their weights as $w_1, w_2, \ldots\ldots, w_n$. Saaty represented the pair-wise comparisons by a matrix of underlying ratios (assumed to exist) as matrix A, which is a reciprocal matrix because it has positive entries in all the cells and the reciprocal property $a_{ji} = 1/a_{ij}$ is satisfied [Saaty 82b]. If the matrix is multiplied by the column vector $(w_1, w_2, \ldots\ldots, w_n)$ we obtain the vector nw; that is, Aw = nw. The solution w of this problem is any column of matrix A. Although these solutions differ by a multiplicative constant, it is often desirable to normalize a solution so that its components sum to unity. This results in a unique solution no matter which column is used.

Matrix A	A_1	A_2	...	A_n
A_1	w_1/w_1	w_1/w_2	...	w_1/w_n
A_2	w_2/w_1	w_2/w_2	...	w_2/w_n
...	...	...	...	...
A_n	w_n/w_1	w_n/w_2	...	w_n/w_n

The judgments elicited from individuals to estimate w_i / w_j are taken qualitatively, and numerical values are assigned to them until the participants learn to select the numbers themselves. According to Saaty [Saaty 82a, Saaty 82b], personal feelings do not conform to an exact formula and are not expected to be consistent because we are trying to model their sometimes erratic behavior. However, to improve consistency, whatever value a_{ij} is assigned in comparing the *ith* activity with the *jth* one, the reciprocal value is assigned to a_{ji}. Thus, it can be said that $a_{ji} = 1/a_{ij}$. Usually, a value representing dominance greater than unity is recorded first. Roughly speaking, if an activity is judged to be α times stronger than another, then we record the latter as only $1/\alpha$ times as strong as the former. Table 4.1 shows an absolute intensity of importance scale. The basic procedure involved in AHP can be summarized as:

1. Develop a hierarchical structure of factors and subfactors contributing to the final objective or goal (described in previous chapters).
2. Rank these factors in order and place them as headings of both rows and columns in the comparison matrix. The comparison matrix will have the value 1 at all the diagonal cells.
3. Compare the factors relatively on a scale of 1 to 9, and fill in the upper diagonal half of the comparison matrix. The scale 1 to 9 represents a ratio comparison of the two factors as described in Table 4.1.
4. Put the reciprocal of each cell to the symmetric cell of the lower half of the matrix.
5. Calculate $\sum_{i=1}^{n} \frac{cell\ value_i}{column\ sum_i}$ to reach a combined weight of each factor.
6. Normalize the combined weight to generate a priority vector. The coefficient of the priority vector implies the weight of each factor.

4.3.1 Assessment of Weights

In order to assess the weights of the four evaluation subsystems and their subfactors, a presentation was made to graduate research assistants at the Center for Transportation Research of The University of Texas at Austin. This was done to familiarize those attending with the WRM evaluation system and AHP.

Table 4.1 Intensity of importance scale (after Saaty et al. [Saaty 82b])

Intensity of Importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Weak importance of one over the other	Experience and judgment slightly favor one activity
5	Essential or Strong	Experience and judgment importance strongly favor one activity over another
7	Demonstrated importance	The evidence favoring one activity over another is of the highest possible order
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed

In order to keep matters simple, the factors were compared relatively on a scale of 1 to 5, and the upper half of the comparison matrix was filled. Saaty suggested a scale of 1 to 9, which was revised as follows for easier comparison. The 1-to-5 scale represents a ratio comparison of two factors with respect to,

1 : two factors contribute equally,
2 : one factor is slightly favorable over the other,
3 : one factor is moderately favorable over the other,
4 : one factor is strongly favorable over the other, and
5 : one factor dominates the other.

The following working example illustrates the procedure for estimating the weights of the four main evaluations based on the responses at the presentation, as shown in Matrix B.

Matrix B	**Technical**	**Economic**	**Societal**	**Environmental**
Technical	1.00	2.00	4.00	4.00
Economic		1.00	4.00	2.00
Societal			1.00	0.50
Environmental				1.00

Once the comparison matrix was decided upon, the lower half of the matrix was filled and column sums calculated as shown in Matrix C.

Matrix C	**Technical**	**Economic**	**Societal**	**Environmental**
Technical	1.00	2.00	4.00	4.00
Economic	0.50	1.00	4.00	2.00
Societal	0.25	0.25	1.00	0.50
Environmental	0.25	0.50	2.00	1.00
Column Sum	**2.00**	**3.75**	**11.00**	**7.50**

Then the row sum was calculated using $\sum_{i=1}^{n} \frac{cell\ value_i}{column\,sum_i}$, as shown in Matrix D.

Matrix D	**Technical**	**Economic**	**Societal**	**Environmental**	**Row Sum**
Technical	1.00	2.00	4.00	4.00	**1.93**
Economic	0.50	1.00	4.00	2.00	**1.15**
Societal	0.25	0.25	1.00	0.50	**0.35**
Environmental	0.25	0.50	2.00	1.00	**0.57**
Column Sum	**2.00**	**3.75**	**11.00**	**7.50**	**4.00**

Finally, utilizing the row sum vector from Matrix D, the normalized weights were obtained as shown in Matrix E.

Matrix E	**Row Sum**	**Weight**	
Technical	**1.93**	0.4826	48.26
Economic	**1.15**	0.2867	28.67
Societal	**0.35**	0.0873	8.73
Environmental	**0.57**	0.1434	14.34
Total	**4.00**	**1.000**	**100.00**

4.3.2 Consistency Check

One of the advantages of AHP is its ability to check for consistency. Individuals tend to be inconsistent when comparing a number of factors using pair-wise comparisons. Each column of the Matrix C, as stated earlier, can be used to estimate the weights of different factors, and the estimated weights should be consistent no matter which column is used. The comparison scale used is of no value if the inconsistency is high enough to ruin the comparison logic. This is to say that if factor A is more important than factor B, which is more important another factor C, then factor A is more important than factor C, both logically and quantitatively.

To check for the consistency of the comparison scales, Saaty proposed an Eigenvalue method (Saaty 82b). A matrix is said to exhibit perfect consistency if the weights estimated using each column of the matrix are identical. In this case, the maximum Eigenvalue, $\lambda_{max.}$, will be equal to the size of the matrix. Because people are unlikely to be totally consistent while making several pair-wise comparisons, then for a reciprocal and positive matrix, the value $\lambda_{max.}$ will always be greater than N, the size of the matrix. So, $\lambda_{max.}$ - N provides a measure of the degree of the inconsistency. This measure is normalized by using the size of the matrix and is termed the comparison index, CI, as shown in Equation 4.1.

$$CI = (\lambda_{max.} - N) / (N-1) \qquad \text{Eq 4.1}$$

Saaty used 500 differently sized random matrices to derive average random consistencies, RC, to compare with CI. If we divide CI by RC for the same size matrix, we obtain the consistency ratio, CR. This CR value should be less than 10 percent to be acceptable. The random consistencies for differently sized matrices are shown in Table 4.2.

The illustrated working example is used again now to demonstrate the consistency check procedure. First of all, the comparison matrix is multiplied by the weight or the priority vector, as shown below:

$$\begin{vmatrix} 1.00 & 2.00 & 4.00 & 4.00 \\ 0.50 & 1.00 & 4.00 & 2.00 \\ 0.25 & 0.25 & 1.00 & 0.50 \\ 0.25 & 0.50 & 2.00 & 1.00 \end{vmatrix} x \begin{vmatrix} 0.4826 \\ 0.2867 \\ 0.0873 \\ 0.1434 \end{vmatrix} = \begin{vmatrix} 1.9788 \\ 1.1640 \\ 0.3513 \\ 0.5820 \end{vmatrix}$$

Table 4.2 Random consistencies for different-order matrices (after Saaty 82a)

Size of Matrix	Random Consistency
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

The consistency vector is obtained by dividing the above result by the priority vector.

$$\begin{vmatrix} 1.9788 \\ 1.1640 \\ 0.3513 \\ 0.5820 \end{vmatrix} / \begin{vmatrix} 0.4826 \\ 0.2867 \\ 0.0873 \\ 0.1434 \end{vmatrix} = \begin{vmatrix} 4.1005 \\ 4.0594 \\ 4.0239 \\ 4.0594 \end{vmatrix}$$

By averaging the values of the consistency vector, we obtain the $\lambda_{max.}$, the maximum Eigenvalue, as shown below:

$$\lambda_{max.} = (4.1005 + 4.0594 + 4.0239 + 4.0594) / 4 = 4.0608$$

The comparison index is calculated as:

$$CI = (\lambda_{max.} - N) / (N - 1) = (4.0608 - 4) / (4 - 1) = 0.0203$$

Table 4.2 indicates that the random consistency (RC) for a matrix of size 4 is 0.90. Dividing the CI by the RC gives the comparison ratio (CR), which should be less than 10 percent to be acceptable, as described by Saaty [Saaty 82a].

$$CR = CI / RC = 0.0203 / 0.90 \times 100 = 2.25 \% \quad (<10\%, \text{OK})$$

4.3.3 Combined Model

After going through the mathematical procedure described above, the WRM potential index (WRMPI), as described earlier, was developed to indicate the overall utilization potential of a particular WRM in roadbase construction. Equation 4.2 shows the WRMPI. Equations 4.3 through 4.6 show the technical, economic, societal, and environmental score models. The coefficients (weights) were obtained from the sample group.

WRMPI = 0.4826 * Technical Score + 0.2867 * Economic Score
+ 0.0873 * Societal Score + 0.1434 * Environmental Score Eq 4.2

Technical Score = 0.2646 * Gradation Score + 0.0784 * Shape & Texture Score + 0.1356 * Hardness Score + 0.5214 * Applied Load Resist. Score Eq 4.3

Economic Score = 0.4587 * Quantity Score + 0.1471 * Transp. Cost Score + 0.2482 * Disposal Cost Score + 0.0580 * Stabilizer Cost Score + 0.0880 Processing Cost Score Eq 4.4

Societal Score = 0.2311 * Gov./Sp. Grp. Interest Score + 0.6655 * Health/Safety Risk Score + 0.1037 * Site Aesthetics. Score Eq 4.5

Environmental Score = 0.2854 * Recycling Benefits Score + 0.0882 * (Noise Pollution + Dust Pollution) Score + 0.5382 * Leaching Potential Score Eq 4.6

Table 4.3 tabulates these values. It should be remembered that these estimated weights are for reference purposes only, and the reader is advised to develop weights keeping local conditions in view. Although the previous discussion addresses the estimation of the weights for the final combined model, the same procedure was used to determine the weights for evaluation attributes for each of the four evaluation subsystems.

Table 4.3. Estimated weights for the evaluation factors based on AHP

Factor	Mean Weight
Technical Evaluation	**0.4826**
Gradation	0.2646
Particle Shape and Texture	0.0784
Hardness	0.1356
Resistance to Applied Load	0.5214
Economic Evaluation	**0.2867**
Quantity	0.4587
Transportation Cost	0.1471
Disposal Cost	0.2482
Stab./Mod. or Add. material Cost	0.0580
Processing Cost of Reuse	0.0880
Societal Evaluation	**0.0873**
Govt./Sp. Group Interest	0.2311
Health/Safety Risk	0.6652
Storage Site Aesthetics	0.1037
Environmental Evaluation	**0.1434**
Benefits of Recycling	0.2854
Noise Pollution	0.0882
Dust Pollution	0.0882
Leaching Potential	0.5382

4.4 ESTIMATING UTILIZATION POTENTIAL: A WORKING EXAMPLE

Chapter 2 lists eight WRMs available at various locations in TxDOT. These WRMs include RAP, RPCP; FA, BA, and PA from power plant operations; ceramics, BF and SS from steel and iron industry, and TCs. These materials were evaluated using the WRM evaluation system to determine the utilization potential (WRMPI) for each material. Before presenting these results, it will be useful to illustrate the evaluation system using an example. For this purpose, we use the WRMUP for RAP, the most abundant material, to demonstrate the WRM evaluation procedure.

4.4.1 Initial Screening of Reclaimed Asphalt Concrete

As stated earlier, the initial screening process is based on five factors that encompass the economic, technical, and the environmental aspects of WRM utilization. These factors include accumulated or annually produced quantity, material location, material toxicity, water solubility, and material durability. RAP fulfills all these requirements easily, as is explained.

It was estimated during the WRM availability and location survey that TxDOT owns at least 355,000 tons of RAP material. This material is located at various locations in all the TxDOT districts and was readily accessible for use. Figure 4.1 shows the location of RAP stockpiles, by county, in various TxDOT districts. Such stockpiles easily fulfill the available quantity and location criteria. The material is also durable, as it originates from TxDOT projects. Moreover, it is non-toxic and has been used under conditions where it has been exposed to moisture. RAP, therefore, met all the initial screening requirements and was forwarded to the next phase of the evaluation process.

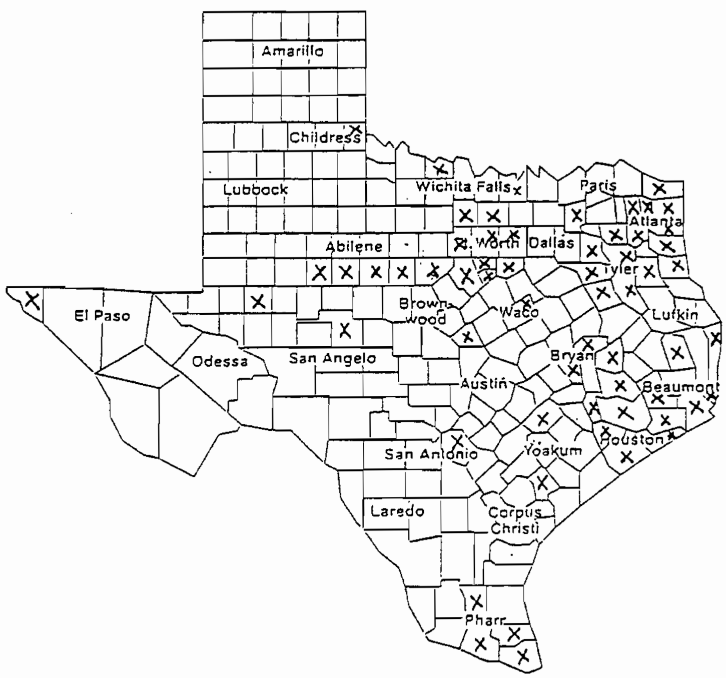

Figure 4.1 Location of RAP in various districts of TxDOT, by county

4.4.2 Technical Evaluation of Reclaimed Asphalt Concrete

The technical evaluation is based on the four attributes described earlier, namely, gradation, degradation due to load, hardness, and particle shape and texture. (Particle shape and texture are considered a single attribute.) For the technical evaluation portion, RAP samples were obtained from three sites:

- FM 2818 and US 192 in the Bryan District
- US 183 and Springdale Road in the Austin District
- FM 39 S in North Zulch in the Bryan District

All these sites had material stockpiled over a large area. In order to ensure that a representative sample was obtained, the sites were visited to determine if there were any large variations in the stockpiled material.

Particle size and distribution analysis of RAP samples was conducted using the ASTM C 136 - 93 test procedure [ASTM C 136]. Figure 4.2 shows the gradation curve. The coefficient of uniformity, C_u, and coefficient of curvature, C_c; provide good characterization of aggregate particles. C_u expresses the ratio of the diameter of the particle at 60 percent passing to the diameter of the particles at 10 percent passing on the grain size distribution curve, and is a measure of the particle size range. C_u values of ≥ 4.0 are generally considered to be good. C_u was calculated using the formula given in section 3.3.1.

The shape of the particle size distribution curve is represented by Cc, whose value should range between 1 and 3, for a material to be considered well graded. C_c, though not used directly in the evaluation process, can be expressed in equation form as indicated in Equation 4.7.

$$C_c = \frac{(D_{30})^2}{(D_{10})(D_{60})} \qquad \text{Eq 4.7}$$

where:

C_c = Coefficient of curvature,

D_{60} = Sieve opening size (mm) through which 60% of the aggregate passes,

D_{10} = Sieve opening size (mm) through which 10% of the aggregate passes, and

D_{30} = Sieve opening size (mm) through which 30% of the aggregate passes.

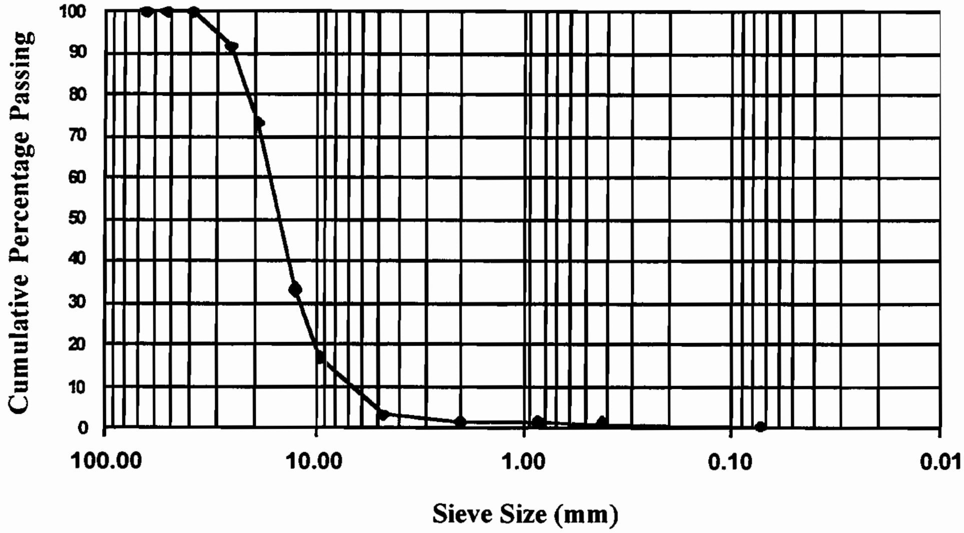

Figure 4.2 Shape of the particle distribution curve for RAP obtained from the Austin District

C_u for RAP samples obtained from US 183 in the Austin District was determined to be 2.5, which gave it a gradation score of 1.5. C_c was determined to be 1.3, well between the prescribed values of $1 \leq C_c \leq 3$.

RAP particles generally have a shape that can be characterized as angular and flaky. ASTM D 3398 was used to determine the shape and texture of RAP particles [ASTM D 3398]. The particle index was determined to be 14.20, which on the proposed scale was linearly interpolated to a score of 3.55. The hardness of RAP particles, using Moh's hardness scale, was determined to be about 7, yielding a score of 3.5 for this attribute.

The LA degradation test, ASTM C 131, was run at the TxDOT Austin District facilities. The material was prepared as shown in Table 4.4, according to Grading A of the test protocol. The recommended charge for grading A is 12 steel spheres with a combined weight of 5000 ± 25 grams. The total sample weight was 5010.0 grams, and the material loss was determined to be 1289.9 grams after sieving through the #12 U.S. standard sieve. The material loss was estimated to be 25.75 percent, earning a score of 2.6 for this attribute on the proposed scale. The technical evaluation score was estimated to be 2.40, using Equation 4.8, as shown below.

Table 4.4 Grading of test samples for Los Angeles Degradation Test

Sieve Size (Square Openings, mm)		Weight of Indicated Sizes (g)
Passing	**Retained On**	**ASTM C 131 Grading A**
37.5	25.0	1250 ± 25
25.0	19.0	1250 ± 25
19.0	12.5	1250 ± 10
12.5	9.5	1250 ± 10
Total		**5000 ± 10**

Technical Score = 0.2646 * Gradation Score + 0.0784 * Shape & Texture Score
+ 0.1356 * Hardness Score 0.5214 * Applied Load Resist. Score

Eq 4.8

Technical Score = 0.2646 * 1.5 + 0.0784 * 3.55 + 0.1356 * 3.5 +
0.5214 * 2.4 = 2.40

4.4.3 Economic Evaluation of Reclaimed Asphalt Concrete

The material availability and location survey reported by Saeed et al. [Saeed, Hudson, Anaejionu 95] determined RAP to be the most abundant material owned by TxDOT (approximately 355,000 tons). This quantity was assigned the highest possible score of 5.0. Disposal cost savings, in terms of landfill cost per ton of material disposed, were estimated to be considerable; hence a score of 5.0 was assigned. On average, given the location of stockpiles as indicated in Figure 4.1, one might expect a stockpile to be located within 50-65 km from a project, earning it a score of 3.50. But in many cases, RAP is used where it is reclaimed, resulting in a very high score. Overall, RAP might be expected to score at least 4.0 for transportation costs.

It was estimated that RAP would require the addition of about 30 percent natural raw material to compensate for the lack of fines. This amounts to an expenditure of about $1.05 for each ton of flexible base material produced, if the cost of natural material is considered to be $3.50 per ton. This expenditure was scored at 4.125. The economic evaluation score is calculated using Equation 4.9, as shown:

Economic Score = 0.4587 * Quantity Score + 0.1471 * Trans. Cost Score +
0.2482 * Disposal Cost Score + 0.0580 * Stabilizer Cost Score+
0.0880 Processing Cost Score Eq 4.9

Economic Score = 0.4587 * 5.0 + 0.1471 * 4.0 + 0.2482 * 5.0 + 0.0580 *
4.1 + 0.0880 * 5.0 = 4.8

4.4.4 Societal Evaluation of Reclaimed Asphalt Concrete

Most of the RAP storage sites visited were located next to major highways and in direct view of the traveling public. This fact, as discussed in Chapter 3, gives maximum visibility to the storage site and, hence, a score of 5.0 was assigned. The state of Texas has statutes in effect that require TxDOT to inventory all department-owned RAP. A score of 5.0 was once again assigned for the factor, "Government/Special Group Interest." There are no known health risks associated with RAP pertaining to the general population. While there have been concerns expressed regarding the safety of the workers involved in the hot recycling of this material, the health risks have not been verified. Nonetheless, recognizing that there *could* be health risks involved, a score of 1.50 was therefore assigned. The economic evaluation score is calculated using Equation 4.10, as shown.

Societal Score = 0.2311 * Gov./Sp. Grp. Interest Score +
0.6655 * Health/Safety Risk Score + 0.1037 * Site Aesthetics Score Eq 4.10

Societal Score = 0.2311 * 5.0 + 0.6655 * 1.5 + 0.1037 * 5.0 = 2.67

4.4.5 Environmental Evaluation of Reclaimed Asphalt Concrete

RAP requires no plant processing as it is being site-mixed and, hence, the noise and dust produced at the plant are also eliminated. RAP was therefore assigned a score of 5.0 for noise pollution as well as for dust pollution. As RAP requires the addition of 30 percent natural material, 70 percent savings in natural raw material are realized. This qualified for a score of 3.5. In addition, no significant leachate potential is exhibited by this material, so there is no degratory effect on surface or ground water supplies. As no leaching potential is expected, a maximum score of 5.0 was assigned. The environmental evaluation score was calculated using Equation 4.11, as shown:

Environmental Score = 0.2854 * Recycling Benefits Score + 0.0882 *
(Noise Pollution + Dust Pollution) Score + 0.5382 * Leaching Potential Score Eq 4.11

Environmental Score = 0.2854 * 3.50 + 0.0882 * (5.0 + 5.0) +
0.5382 * 5.0 = 4.5719

4.4.6 Combined Evaluation of Reclaimed Asphalt Concrete

Using the four evaluation subsystem scores, as calculated in previous sections, the total utilization potential for RAP was estimated using Equation 4.2.

WRMPI = 0.4826 * Technical Score + 0.2867 * Economic Score + 0.0873 *
Societal Score + 0.1434 * Environmental Score Eq 4.12

WRMPI = 0.4826 * 2.40 + 0.2867 * 4.80 + 0.0873 * 2.67 +
0.1434 * 4.57 = 3.43

Out of a possible score of 5.00, RAP has an estimated score of 3.43. This value, when expressed as a percentage, is termed the utilization potential; based on the discussion so far, RAP has a WRM utilization potential (WRMUP) of 68.60 percent.

4.5 UTILIZATION POTENTIAL OF SELECTED WASTE AND RECLAIMED MATERIALS

Having evaluated RAP as an example, this section undertakes to evaluate and estimate the WRMUP of the remaining WRMs.

4.5.1 Utilization Potential of Reclaimed Portland Cement Concrete

RPCP is the second most abundant material owned by TxDOT and is available at various locations, as documented by Saeed et al. [Saeed, Hudson, Anaejionu 95]. During the material and location survey, only Pharr, Houston, San Antonio, Odessa, and Wichita Walls Districts of TxDOT reported stockpiles of RPCP. RPCP samples were obtained from stockpiles located near SH 48 West of the Shrimp Harbor at the Port of Brownsville in the Pharr District.

Particle size analysis and distribution of RPCP from the Pharr District samples were conducted using ASTM C 136 - 93 test procedure [ASTM C 136]. Figure 4.3 shows the gradation curve for RPCP. The C_u for RPCP samples from SH 48 in the Pharr District was determined to be 4.68, which gave it a gradation score of 2.34. C_c was determined to be 1.02, which was just within the prescribed values of $1 \leq Cc \leq 3$.

RPCP particles are round and encased in a Poland cement film. The particle index value using the ASTM D 3398 test was determined to be 13.0, which translates to a score of 3.25 for this attribute. The hardness of RPCP particles, using Moh's hardness scale, was determined to be about 7, resulting in a score of 3.5 for this attribute.

The LA degradation test, ASTM C 131, was run at the TxDOT facilities in the Austin District. The total sample weight was 5000.5 grams, and the material loss was determined to be 1523.2 grams after sieving through the #12 U.S. standard sieve. The material loss was estimated to be 30.46 percent, earning a score of 1.95 for this attribute on the proposed scale.

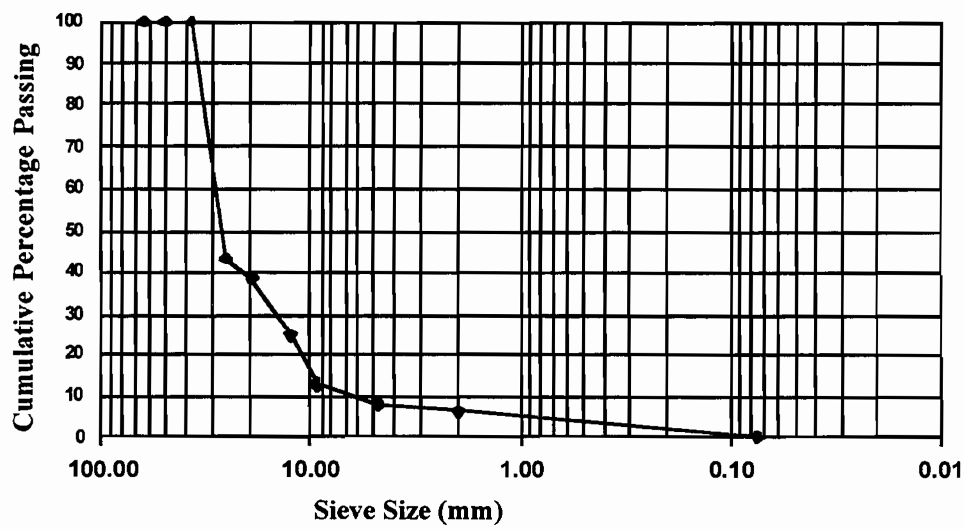

Figure 4.3 Shape of the particle distribution curve for RPCP obtained from the Pharr District

Because RPCP is the second most abundant material owned by TxDOT , a score of 0.2676 was assigned based on available quantity. During the material availability and location survey only six TxDOT districts reported RPCP stockpiles (located in six counties). The stockpiles are located far apart from each other, and the distances involved are in excess of 96 km, as shown in Figure

4.4. Overall, RPCP might be expected to score at least 1.5 for transportation costs. Furthermore, the sampled material was low in fines, and about 50 percent of natural aggregate material had to be added in at a cost of $3.00 per ton of the final produced roadbase mix. The WRMUP of RPCP was estimated to be 50.20 percent, as shown in Table A.1 in Appendix A.

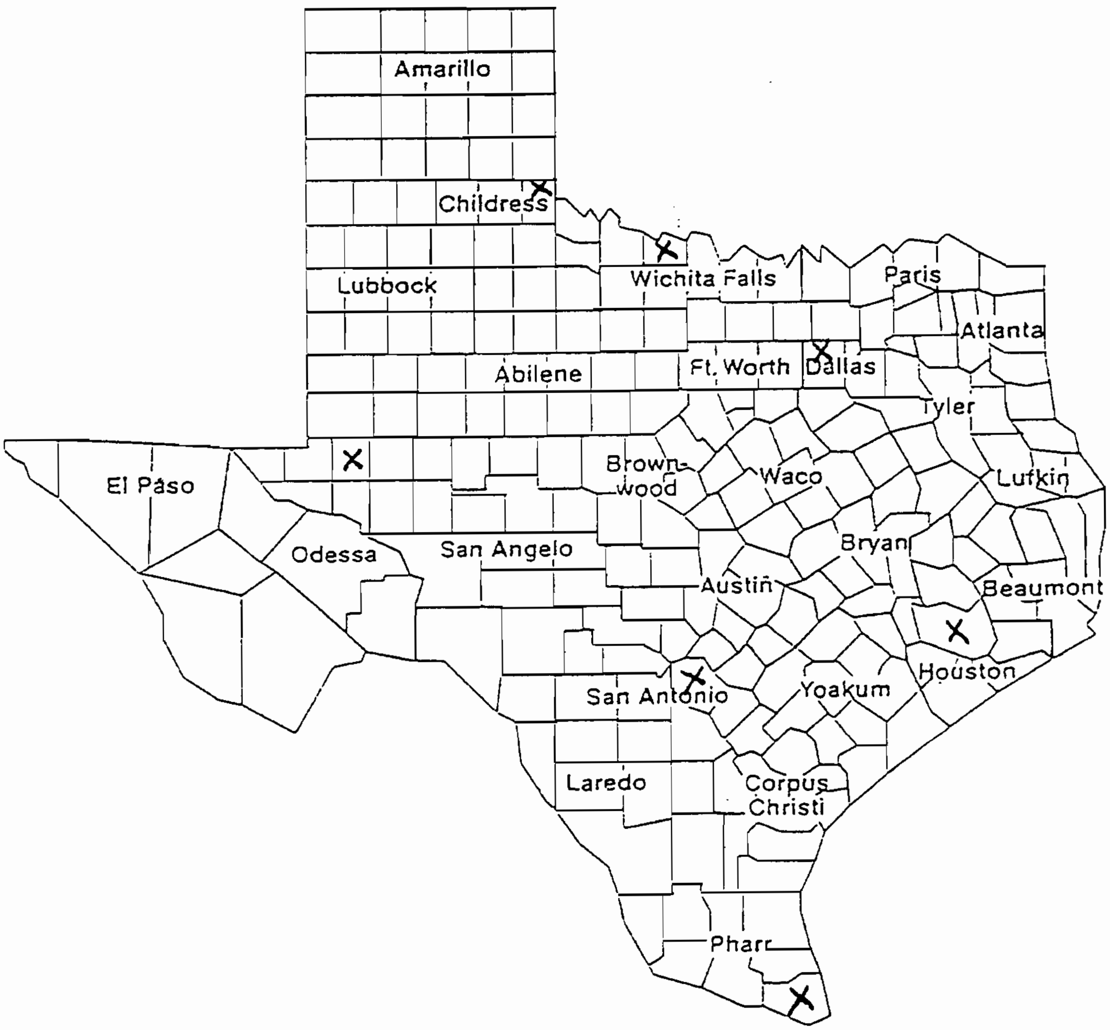

Figure 4.4 Location of RPCP in various districts of TxDOT, by county

4.5.2 Utilization Potential of Fly Ash

Fly ash (FA) is the third most abundant material owned by TxDOT and available at various locations. FA belongs to the coal ash family and its composition varies depending on the source of the coal, the power plant type, and the plant's operational characteristics [FHWA 86]. During the material location and availability survey, only the San Antonio District reported the presence of FA stockpiles in various counties. The Atlanta District reported some material in one of the counties in its jurisdiction.

FA samples were obtained from Monex Resources, Inc., from units 1 and 2 of their Fayette plant. The obtained FA sample was grayish white in color and was odorless. FA particles are generally spherical and have the consistency of a very fine powder, normally varying in size from 1 micron to 100 microns [FHWA 86]. FA is a health hazard because overexposure can cause irritation of eyes, skin, and mucous membranes. Furthermore, prolonged exposure can lead to fibrotic diseases and to cancer [Monex 89a]. Workers handling fly ash are required to wear special masks to minimize inhalation of this product.

Owing to its cementitious properties, fly ash is used as a stabilizer in roadbase construction, but with no saving of the natural aggregate material since it is provided in powder form. This is to say that to utilize FA in roadbase construction one would have to add 100 percent of natural aggregate material to it at a cost of about $5.00 per ton of the final produced material.

As this evaluation system considers the final product utilizing the WRM, the properties of natural aggregate used are evaluated for the technical evaluation subsystem. Natural aggregate material was obtained from two producers: Vulcan Materials and Redline Stone. Three samples were tested using the same technical laboratory tests as described in the technical evaluation subsystem for WRMs. For sake of simplicity, the results are shown in Table 4.5.

Table 4.5 Technical evaluation of standard TxDOT roadbase material

Factor	**Material Producer**			**Average**	**Score**
	Vulcan	**Redland Stone**			
	Helotes Pit	Beckman Pit	IH 10		
Gradation	10.00	10.00	10.00	10.00	5.00
Shape & Texture	15.80	15.75	15.40	15.65	3.91
Hardness	6.00	6.00	6.00	6.00	3.00
Resistance to Applied Load	32.00	34.00	31.00	32.33	3.23

Because the material can be produced in the desired gradation, it is assigned the highest possible gradation score of 5.00. Table A.2 tabulates the estimation of the utilization potential of FA, which is estimated to be 45.20 percent.

4.5.3 Utilization Potential of Bottom Ash

TxDOT owns approximately 2,000 tons of bottom ash (BA), which are stockpiled at various locations. BA also belongs to the coal ash family and is also known by its various trade names, including LWA and Lite Sand. BA was sampled from the unit 3 of the Fayette plant of Monex Resources, Inc.

As is the case with FA, BA contains respirable particles that can lead to diseases of the lungs and to cancer. Special dust masks are recommended for workers handling this material; specific precautions are contained in the material fact sheet [Monex 89b] that, by law, must accompany each shipment.

The material's properties are similar to those of FA, except for the method in which it is produced. As was the case with FA, natural aggregate needs to be added to BA. Table A.3 tabulates the estimation of BA utilization potential, which is estimated to be 45.20 percent.

4.5.4 Utilization Potential of Pond Ash

TxDOT owns approximately 2,000 tons of pond ash (PA). PA is very similar to FA and BA in all aspects except the way it is produced. FA is the component of ash which is carried by the flue gases in a coal-fired power plant, whereas the heavier component that falls to the bottom is the bottom ash. Table A.4 estimates the utilization potential of PA. Only the Atlanta and Wichita Falls Districts of TxDOT reported having stockpiles of PA and BA.

4.5.5 Utilization Potential of Tire Chips

Shredded tires or tire chips (TCs) have been used as a lightweight fill material in many experimental projects [Han 95, MPCA 90]. These research projects report that these roads are working well as long as no moisture is allowed to enter the TCs layer. According to a Minnesota Pollution Control Agency study [MPCA 90], it is necessary to limit the use of TCs in unsaturated pavement layers and roadway surfaces; ditches therefore need to be incorporated in the final design so as to carry the surface water away from the pavement to limit water infiltration.

Laboratory TCLP studies have indicated that metallic constituents have a tendency to leach out and contaminate the surrounding water in concentrations higher than those determined to be safe by the EPA [MPCA 90].

TxDOT does not own sufficient quantities of tire chips to pass the initial screening test prior to the WRM evaluation system. Also, a number of recent studies have indicated that in pavement layers where they might be exposed to water, their toxicity may be a problem, though they seem to perform well in layers where water cannot reach them. One important point to be noted is that the TCLP tests subject the material to conditions similar to those that would be encountered if the WRM was disposed of in a municipal landfill. This condition would not occur for tire chips utilized in roadbase. The Texas Natural Resource Conservation Commission (TNRCC) owns tire chips in substantial quantities to warrant their detailed study and to subject them to some appropriate environmental test, such as the commercial bacterial BioAssay test, Microtox™ to study their toxicity. Nevertheless, for the purposes of this research, tire chips did not qualify for additional evaluation based on the results of the initial screening.

4.5.6 Utilization Potential of Iron and Steel Slag

TxDOT owns approximately 130,000 tons of steel and blast furnace slag stockpiled at various locations. Steel slag (SS) samples were obtained courtesy of Structural Metals, Inc. (SMI) of Seguin, Texas, which is the largest supplier of reinforcing bars to TxDOT. Although SS contains many metallic constituents, various laboratory studies have indicated that their leaching potential is very low. According to SMI personnel given the task of marketing SS, EPA is considering lowering the hazard classification of SS. (SS was one of the waste materials selected for detailed study; more details are presented in Chapter 6 on various aspects of the material.)

Particle size analysis and distribution of SS samples from SMI were conducted using ASTM C 136 - 93 test procedure [ASTM C 136]. Figure 4.5 shows the gradation curve. The C_u for SS samples from SMI from Seguin in the Austin District was determined to be 6.82, which gave it a gradation score of 3.41. The C_c was determined to be 1.7, which was within the prescribed values of $1 \leq C_c \leq 3$. Figure 4.5 shows the gradation curve for SS from which the C_c and C_u values were estimated.

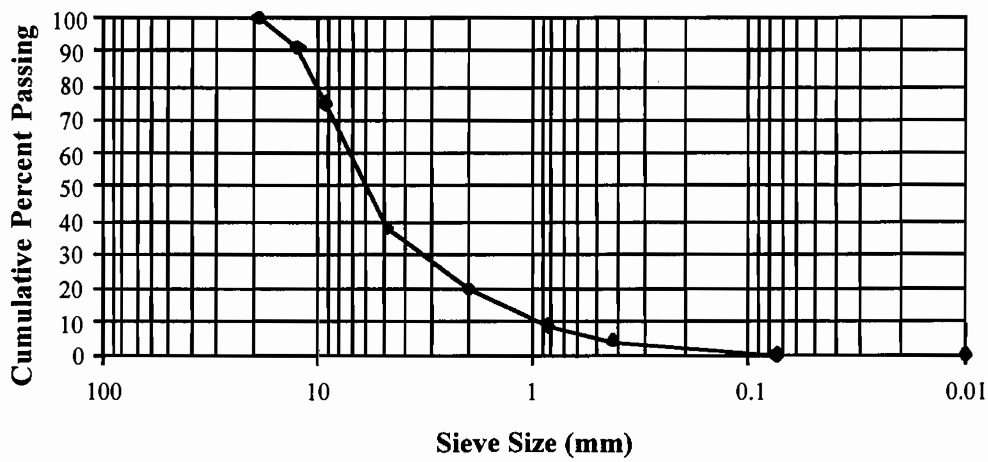

Figure 4.5 Shape of the particle distribution curve for steel slag (SMI, Seguin)

The angularity and roughness of SS particles ensure good interlock. The particle index value using the ASTM D 3398 test was determined to be 15.0, which translates into a score of 3.75 for this attribute. The hardness of SS particles, using Moh's hardness scale, was determined to be about 8, resulting in a score of 4.0 for this attribute.

The LA degradation test, ASTM C 131, was run to determine the loss owing to impact and degradation. The total sample weight was 5010.50 grams, and the material loss was determined to be 1102.0 grams after sieving through the #12 U.S. standard sieve. The material loss was estimated to be 22.00 percent, earning a score of 2.8 for this attribute on the proposed scale. The WRMUP is estimated as shown in Table A.5.

4.5.6 Utilization Potential of Waste Ceramic Products

During the Material Location and Availability survey, only two TxDOT districts, Waco and San Antonio, reported having large quantities of waste ceramic product. The San Antonio District has experimented with utilizing crushed toilet fixtures in roadbase. In 1995, ceramic toilet fixtures were crushed and added to the standard roadbase material at the rate of 5 percent.

Cercon, Inc., of Hillsboro, Texas, produces waste ceramic shells as part of its manufacturing process. The company has been collaborating with TxDOT's Waco District to incorporate this material in roadbase construction. At the time of this writing, no material had been received from Cercon, Inc., for evaluation.

According to an article by Larry Flynn in *Roads in Bridges* [R&B 93], a number of states have experimented with using ceramic wastes in their highway construction aggregate and in many instances was even mixed with varying quantities of RAP, or RPCP, as well as a combination of the two. While the material holds promise for utilization in roadbase, a continuous supply must be assured.

4.6 CATEGORIZATION OF WASTE AND RECLAIMED MATERIALS

The estimation of utilization potential of various WRMs is incomplete unless we are able to compare them with a base line case, that of the standard natural aggregate (SNA). Table A.6 shows estimates of the utilization potential of SNA consisting of crushed limestone. Table 4.5 shows the sources from which the tested material was obtained, and the average values for conducted laboratory tests for technical evaluation subsystem. SNA obviously passes all the requirements of the initial screening process associated with the WRM evaluation system.

It must be noted that SNA gets a WRMUP of about 60 percent, which is not surprising when looked at more closely. As expected, SNA scores high on the technical attributes and gets a score of 2.96 out of a possible of 5.00 for the technical evaluation subsystem. This score is second only to that of steel slag (SS). The only reason for this is that SS performed extremely well on hardness, degradation due to applied load, and particle shape and texture. The strength of SS is unquestionable, as it contains metallics from the iron and steelmaking processes, hence performs better than SNA. Also, the surface of SS particles is very rough and textured. This imparts a good interlock between individual SS particles when they are compacted to determine the particle index.

SNA also loses a lot of points owing to its inability to perform well on attributes that were designed to check the acceptability of WRMs in roadbase construction. Based on the results of the four sub-evaluations, SNA is always going to score less for the economic, societal, and environmental evaluation subsystems, when compared with WRMs. It was the third-ranked material in economic evaluation subsystem, last on the societal evaluation subsystem, and third in the environmental evaluation subsystem.

All those WRMs that were estimated to have a WRMUP equal to or near the estimated SNA WRMUP of 60 percent are eligible to be used considering the technical, economic, societal, and environmental aspects of their utilization in roadbase construction. All those having a WRMUP of significantly less than this value are not eligible for use owing to a number of reasons that may be economic, technical, societal, or environmental or a combination of these. This value can also be used to distinguish between category I, II, III, and IV materials, as defined in Chapter 3. Category I materials have the best utilization potential, followed by category II and III materials. Category IV materials are generally unacceptable for use. Category III materials can be used in rare circumstances where local conditions dictate their use.

Table 4.6 lists all the evaluated WRMs and classifies them according to described categories. Keeping in view the results of the evaluation method, the top three materials, reclaimed asphalt concrete (RAP), steel slag (SS), and reclaimed portland cement concrete (RPCP), were subjected to detailed testing to develop trial specifications for their reuse in roadbase construction.

Table 4.6 Categorization of WRMs as roadbase construction aggregate

Waste and Reclaimed Materials	**WRMUP**	**Category**	**Remarks**
Reclaimed Asphalt Concrete	68.60 %	I	Best materials
Electric Arc Furnace Steel Slag	60.40 %	II	2nd best
Standard crushed limestone roadbase	58.85 %	**For comparison only**	
Reclaimed Portland cement concrete	50.20 %	III	Marginal
Fly ash	45.20 %	IV	Unsuitable as agg-
Bottom ash	45.20 %	IV	regate in roadbase
Pond ash	45.0 %	IV	construction

CHAPTER 5. LABORATORY TESTING OF RECLAIMED ASPHALT PAVEMENTS FOR USE AS ROADBASE

5.1 INTRODUCTION

Aggregates used in pavement construction must be strong in their natural state (or when held together by a binding agent) and must have properties that will withstand the stresses in a loaded pavement structure. A base layer resists these stresses by particle interlock in the absence or presence of cementitious binders. Additionally, aggregates must have a particular particle size distribution and shape selected for the type of construction. The aggregates must not have flakes, slivers, or unnecessarily thin and elongated pieces; finally, they must be hydrophobic in nature and have low porosity [Lum 92].

RAP used in pavement surfaces, a topic that has been discussed by many authors, must possess certain properties to make such use possible. The RAP being dealt with in this study is contaminated with underlying paving material or the asphalt binder has become too soft and hence unsuitable for such use. On the other hand, it may be used in underlying layers, as the material requirements are not that stringent. The WRM evaluation method identified RAP as the highest ranked material for such an application. Therefore, in order to establish its usefulness conclusively, it was necessary to conduct detailed laboratory tests. This chapter reports results of the conducted laboratory test and guidelines for using RAP in roadbase.

5.2 LABORATORY EVALUATION OF RECLAIMED ASPHALT CONCRETE

When using RAP for road construction great care must be exercised, as the asphalt binder is often very hard and brittle. By the addition of asphalt modifiers or stabilizers, mixtures which match conventional asphalt-bound materials can be produced. A visual evaluation of the RAP stockpiles was made before sampling to ensure material uniformity [NCHRP 80].

The laboratory testing of RAP is divided into three parts. The first part deals with testing RAP for general properties, such as specific gravity and particle size distribution. The second part deals with testing RAP for strength when used as a flexible base material without any additional stabilization; the third part describes the strength testing of RAP after asphalt stabilization.

5.3 GENERAL PROPERTIES OF RAP

This section describes the laboratory tests conducted to establish general properties of collected RAP samples. Tests were conducted to determine the specific gravity, grain size distribution, the Los Angeles (LA) degradation, and the original asphalt content.

5.3.1 Obtaining RAP Samples from Stockpile

RAP samples were obtained in accordance with Test Method Tex-100-E, "Surveying and Sampling Soils for Highways" [Tex-100-E 95], and were prepared according to Test Method Tex-101-E, "Preparation of Soil and Flexible Base Materials for Testing" [Tex-101-E 95]. When sampling RAP stockpiles, the outer 15-cm thick layer was removed and material was collected from the underlying material. This was done to discard material which may have become hardened and/or crusty due to age. RAP samples were obtained from sources listed in Table 5.1. RAP samples from US 287 in the Wichita Falls District and from US 183 in the Austin District were subjected to detailed testing (the Wichita Falls material was selected because it was actually going to be used in a roadbase construction project; the Austin sample was selected owing to its proximity to Austin).

Table 5.1 Sources of reclaimed asphalt concrete samples

Material	Source / Location
RAP 1	Stockpile on US 287, Wichita Falls District
RAP 2	FM 2818 & US 192, Bryan District
RAP 3	US 183 & Springdale Road, Austin District
RAP 4	FM 39 S in North Zulch, Bryan District

5.3.2 Grain Size Distribution of RAP Samples

The gradation of RAP samples was determined using Test Method Tex-200-F (a modification of ASTM Designation C 136), which is designed for aggregates [Tex-200-F 95]. The dry sieve analysis was carried out using a Gilson Sieve Shaker using square sieves. All sieves were TxDOT standard sieves conforming to Test Method Tex-907-K specifications [Tex-907-K 95]. Figure 5.1 shows the gradation curves for the collected RAP samples.

5.3.3 Specific Gravity of RAP Samples

Specific gravity of RAP samples was determined using Test Method Tex-201-F, "Bulk Specific Gravity and Water Absorption of Aggregate" [Tex-201-F 95], which is a modification of ASTM designation ASTM C 128-93, designed to test specific gravity and absorption of aggregates. This test method determines the bulk specific gravity after 24 hours of soaking. The RAP specific gravity was determined to be 2.20, which is consistent with that documented by various researchers [ARRA 95, Hicks 95].

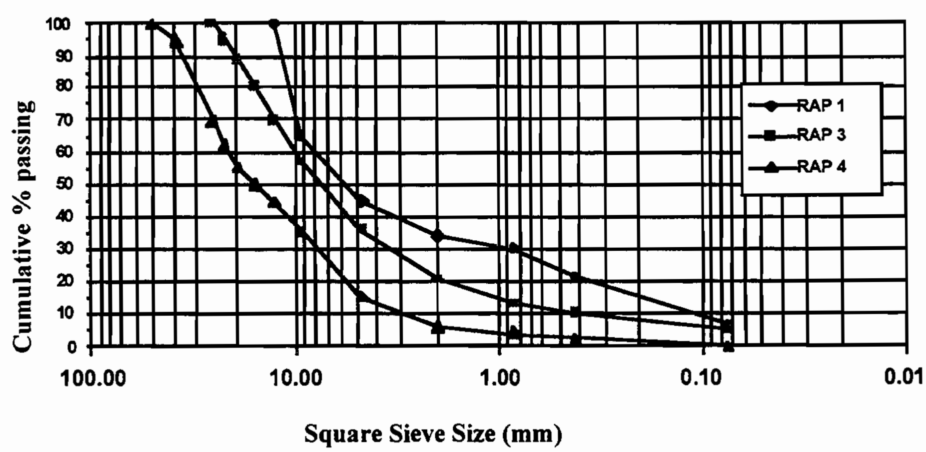

Figure 5.1 Cumulative percentage passing of RAP on various square mesh sieves

5.3.4 Los Angeles Degradation Test

The LA degradation test, ASTM C 131, was run at the TxDOT facilities in the Austin District. Details of the test have already been given in Chapter 4. The material loss was estimated to be 25.75 percent.

5.3.5 Estimation of Asphalt in RAP Samples

Estimation of bitumen present in RAP is vital when designing for the optimum binder content of the final mix. Test Method Tex-210-F, "Determination of Asphalt Content of Bituminous Mixtures by Extraction" [Tex-210-F 95], was used to estimate the quantity of binder present in RAP samples. The solvent used in this procedure was 1, 1, 1 Trichloroethylene. Two samples from the Wichita Falls District and one sample from the Austin District were tested. The results are presented in Table 5.2.

Table 5.2 Estimated asphalt content in selected RAP samples

Location	Sample 1	Sample 2	Mean
Stockpile on US 287, Wichita Falls Dist.	4.3 %	4.5 %	4.4 %
US 183 & Spring Dale Rd., Austin Dist.	4.1 %	—	4.1 %

5.3.6 Extracted Asphalt Penetration

Item 345, "Asphalt Stabilized Base (Plant Mix)," of TxDOT Standard Specifications for Construction of Highways, Streets, and Bridges [TxDOT 95] recommends that the extracted asphalt be tested for penetration at 77°F. Samples of recovered asphalt must show a minimum penetration of 30 and a maximum penetration of 55 when tested in accordance with Test Methods Tex-211-F, "Recovery of Asphalt from Bituminous Mixtures by the Abson Process" [Tex-211-F 95], and Tex-502-C, "Test for Penetration of Bituminous Materials" [Tex-502-C 95], which is based on AASHTO Specification T49. The RAP samples were tested for penetration at 77°F using a weight of 100 grams for 5 seconds; the obtained penetrations are listed in Table 5.3.

5.4 STRENGTH TEST WITHOUT STABILIZATION

There exist a number of test procedures that can be used to characterize roadbase material. Some of these tests are empirical in nature and exact procedures must always be followed to obtain reproducible results. The 1995 version of *TxDOT Standard Specifications for Construction of Highways, Streets, and Bridges* [TxDOT 95] recommends a number of tests to be carried out for evaluating roadbase materials. Although these tests do not address waste materials directly, they do offer guidance on possible tests for RAP base.

Table 5.3 Penetration test results of selected RAP sources

Location of Stockpiles	Penetration			
	Sample 1	Sample 2	Sample 3	Mean
US 287, Wichita Falls	31	30	29	30
US 183, Austin	29	28	30	29

5.4.1 Selection of the Test Method

The Texas Triaxial Test (TTT), Tex-117-E 95, which is used to determine the shear strength of an aggregate-soil mixture under lateral pressure, is considered the most important of the recommended tests. TxDOT specifications for base materials permit more leeway in gradation and other requirements than shear strength measured using the TTT, since strength requirements many times override other requirements. The apparatus for this test consists of a hollow stainless-steel cylinder with a rubber membrane inside the cylinder. The test procedure requires that a cylindrical test specimen, 20.32 cm high with a 15.24 cm diameter, be prepared by compacting in a standard mold. After compaction, the specimen is extracted from the mold and subjected to capillary wetting for a period of 10 days, after which it is tested in compression. For cohesionless materials, the strength requirements are waived because they cannot be tested using the TTT, and the base material is labeled as Grade 3 material. Most of the WRMs are cohesionless in nature, and the TTT test specimens could not be prepared without the addition of some binding agent [TxDOT 95]. This is demonstrated in Chapter 6, which discusses electric arc furnace slag (EAFS), by trying and failing to prepare test specimens, even after using the modified compaction method.

This is believed to be inadequate; instead of labeling WRMs as being Grade 3 materials because they could not be tested using the TTT, they must be tested for strength using some method, even if that method provides a relative measure of their strength. Two other tests were studied in this regard.

A test used for material characterization is the resilient modulus (M_R) test. M_R is a dynamic test in which the response is defined as the ratio of the repeated axial deviator stress, σ_d, to the recoverable axial strain, ε_a. This test requires the preparation of a test specimen which is normally 10.16 cm in diameter and 20.32 cm high. The prepared test specimen is then tested in a triaxial device equipped for repetitive load application. The same problem of preparing test specimens from cohesionless materials is encountered. Though it might be possible to find a highly sophisticated procedure to prepare the test samples where they are held together using some induced confining pressure during compaction and removal from the compaction mold, this approach was not considered to be feasible for the research project owing to financial, equipment and time constraints. A highly sophisticated test was also beyond the scope of this research.

Instead of trying to come up with a new, highly-sophisticated strength test for WRMs, an existing test for the relative strength of pavements was selected, namely, the California Bearing

Ratio (CBR) test. The CBR test is a penetration test in which a standard circular piston is made to penetrate a compacted sample in a round steel mold at a controlled rate. The ratio of the unit load at 2.54 mm penetration with a standard load, which indicates the bearing capacity relative to the standard material, is defined as the CBR. This empirical test is advantageous inasmuch as it does not require the test specimen to be extracted from the mold in which it is compacted. Hence, the problem of cohesionless materials not forming a free-standing test specimen is not encountered. This test was run on all the WRM specimens, whether cohesive or cohesionless, in order to keep the results consistent across the tested WRMs and to provide a comparison between their relative strengths.

5.4.2 Adjustment of RAP Gradation

ASTM specifications D 2940 - 92, "Standard Specifications for Graded Aggregate Material for Bases and Subbases for Highways and Airports," covers quality-controlled graded aggregates that when hauled to and properly spread and compacted on a prepared grade to appropriate density standards may be expected to provide adequate stability and load support for use as highway or airport bases. According to the specification, the gradation of the final composite material, consisting of durable particles of crushed stone, gravel or *slag*, shall conform to the approved job-mix formula, within the design range as prescribed in Table 5.4, subject to the appropriate tolerances as shown.

Figure 5.2 shows the gradation envelop formed by the above specifications. If the gradation of the material falls within this envelop, then the material can be expected to provide adequate stability and load support in roadbase application. As we do not know the proper gradation for RAP that will perform well, this specification provides a good starting point for WRMs. Figure 5.2 also shows the particle size distribution for RAP obtained from US 183 in the Austin District. The distribution of RAP did not fall within the prescribed limits and had to be adjusted. This was done to ensure a proper gradation for flexible base, as the waste material was to be used without any stabilization to enhance the strength properties. Also shown is the adjusted gradation of RAP which can be expected to provide adequate stability and support. Although it is expected to provide good load support after gradation adjustment, the CBR test, as detailed earlier, was performed to determine its strength characteristics.

Table 5.4 Grading requirements for final mixture (after ASTM D 2940-85)

Square Sieve Size (mm)	Percentage Passing by Weight		Job Mix Tolerances	
	Bases	Subbases	Bases	Subbases
50.00	100	100	- 2	- 3
37.50	95 - 100	90 - 100	± 5	+ 5
19.00	70 - 92	70 - 92	± 8	± 8
9.50	50 - 70	50 - 70	± 8	± 8
4.75	35 - 55	30 - 60	± 8	± 10
0.60	12 - 25	12 - 25	± 5	± 5
0.075	0 - 8	0 - 12	± 3	± 5

5.4.3 CBR Testing of RAP

In CBR testing, the first step is the determination of the optimum moisture content (OMC). Test method ASTM D 698, "Test Method for Laboratory Compaction Characteristics of Soils Using Standard Effort" [ASTM D 698], determines the relationship between water content and the dry unit mass (density) for base materials. The base material, RAP in this case, was compacted in a mold with a rammer dropped from a set height. The OMC of gradation adjusted RAP was estimated to be 10.25 percent using this procedure, as shown in Figure 5.3

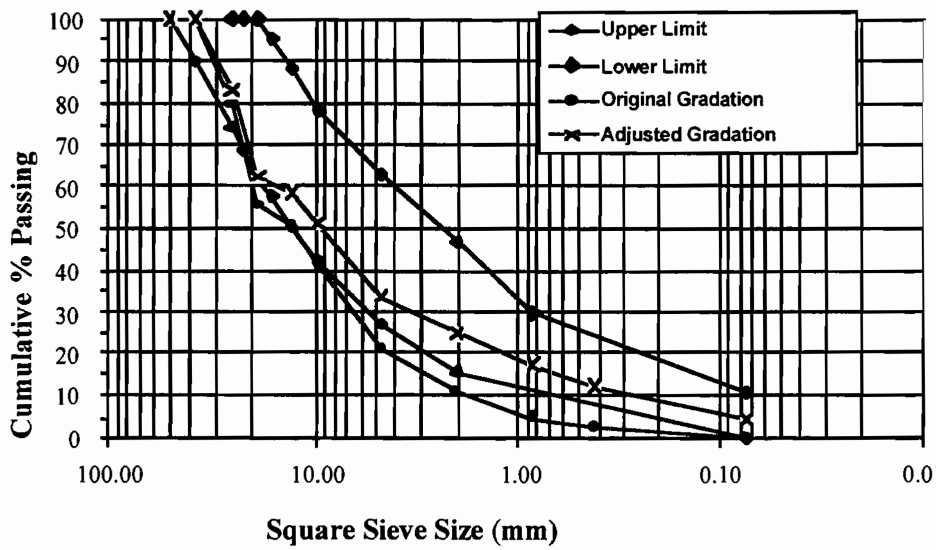

Figure 5.2 Cumulative percentage passing on various square mesh sieves

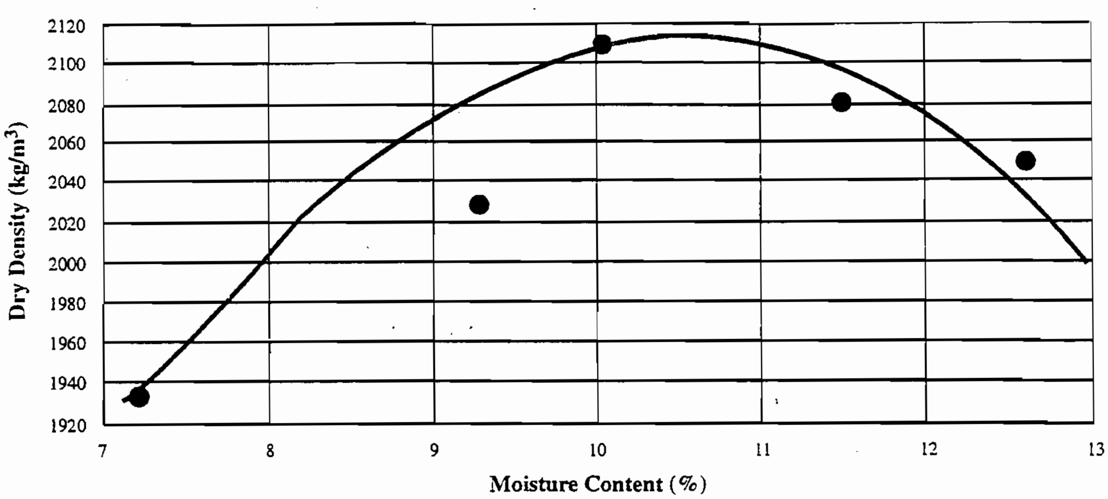

Figure 5.3 Estimation of the optimum moisture content for adjusted RAP

After the OMC had been determined, three test specimens were prepared according to Test Method ASTM D 698, "Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort," and ASTM D 1883, "Standard Test Method for CBR (California Bearing Ratio) of Laboratory Compacted Soils" [ASTM D 698, ASTM D 1883 - 94]. Test Method ASTM D 1883 recommends that a total of three test specimens be prepared by compacting in a standard mold at the OMC, using three different compacting efforts of 10, 25, and 55 blows per layer. The prepared test specimens were 11.43 cm high and 15.24 cm in diameter (approximately). Immediately after compacting the specimens, a surcharge weight of 4.45 kg was placed on the compacted material while soaking and also during compression testing. The prepared test specimens were tested in compression using the Baldwin Compression Testing System and were subjected to penetration by a cylindrical piston for a depth of 12.7 mm. Results of the stress versus penetration depth for each compactive effort are tabulated in Appendix B. Also shown is the CBR at 2.54 mm and 5.08 mm penetration for each specimen. The CBR at 2.54 mm penetration was greater than the CBR at 5.08 mm penetration for the three specimens, validating the test results. Results of stress (load) versus penetration depth were plotted to determine the CBR for each specimen, as shown in Figure 5.4. Figure 5.5 shows the graph of CBR versus dry density (DD), which can be used to determine CBR at the specified dry unit weight. The plotted curves for all the compactive efforts were concaved downward, except for that of 10 blows/layer compaction; thus no correction was required. The stress penetration curve for 10 blows/layer compaction was adjusted for 2.54 mm penetration.

The estimated CBR of 97.05 percent at the maximum compactive effort indicates that RAP is a good candidate material for use as a roadbase in place of conventional materials, if the gradation has been adjusted to conform to the requirements of ASTM D 2940. The material is also characterized by a low swelling potential.

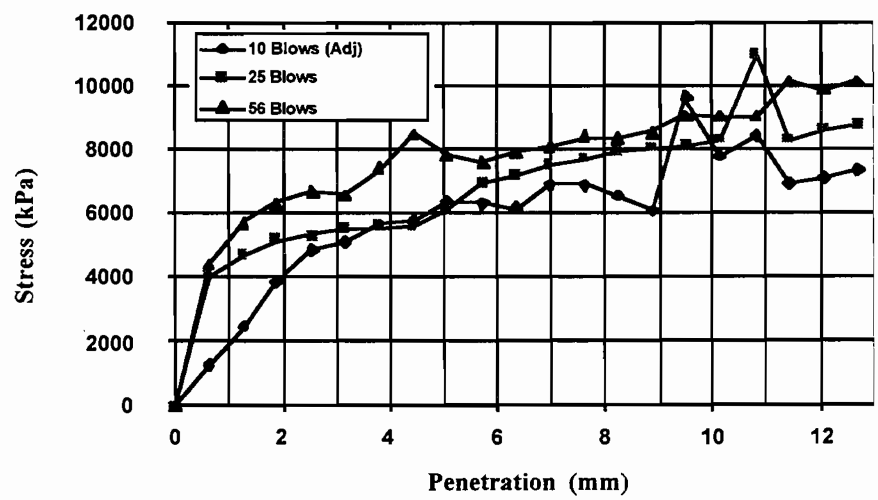

Figure 5.4 Stress-penetration curves for RAP

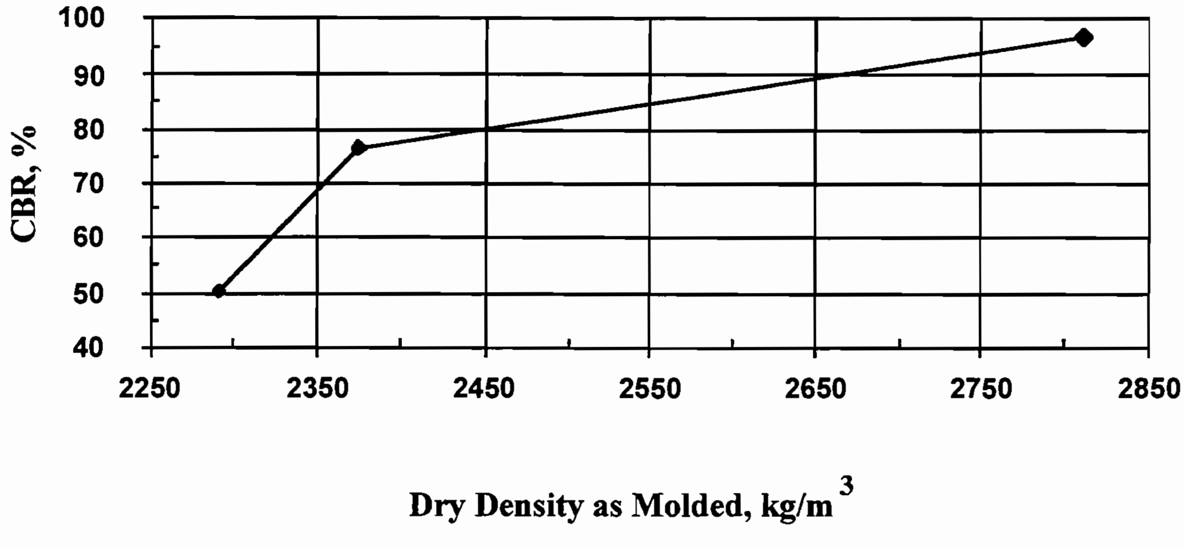

Figure 5.5 California bearing ratio vs. dry density for RAP

5.5 STRENGTH CHARACTERISTICS OF ASPHALT STABILIZED RAP

Once RAP had been tested as a flexible base, another alternative was to use RAP as a stabilized base. The Hveem method of mix design was chosen for this purpose because it determines the optimum asphalt content based on two properties of the compacted specimen. These properties are cohesion and friction. The stability of the prepared specimens, which depends upon these properties, is measured with a Stabilometer, which is a triaxial testing device. In the Hveem Stabilometer, vertical loads are applied to the specimen at a controlled rate and the horizontal pressures are measured [AI 91].

The procedure used by TxDOT is designation Tex-208-F, "Test for Stabilometer Value of Bituminous Mixtures." This test method is a modification of ASTM designation ASTM D 1560, which describes a method for determining the Hveem stability value for an asphalt concrete mixture using a Hveem Stabilometer. The RAP material was batched, as shown in Table 5.5.

The tested RAP had an original asphalt cement (AC) content of 4.1 percent determined by vacuum extraction, as described in Section 5.3.5. The additional AC percentage ranged from a low of 1.0 percent by weight of the RAP mix to a maximum of 5.0 percent. Samples were prepared for additional AC content up to 4.0 percent, as the prepared samples obviously became too wet (this proved to be the correct approach, as samples with additional AC content more than 3.00 percent were too soft to test). The AE used was obtained from Koch Materials, Inc., and was of the type designated CMS-2S. This AE had to have a residual AC content of approximately 65 percent, and the actual AC content was estimated to be 68 percent. The aggregate mass weight was a constant value of 950.0 grams. Three samples of each batch were produced for testing.

Table 5.5 Batch weights of US 183 RAP samples

Batch Number	Additional AC Percentage	AC Weight (grams)	AE Weight (grams)
1	1.0	9.5	14.0
2	1.5	14.3	21.0
3	2.0	19.0	27.9
4	2.5	23.8	35.0
5	3.0	28.5	41.9
6	3.5	33.3	49.0
7	4.0	38.0	55.9

Original AC Content by Vacuum Extraction: 4.10%
Constant Batch Mass: 950.00 grams
(7/8" - 1/2" : 558.50 grams,
1/2" - 3/8" : 191.14 grams
3/8" - pan : 200.17 grams)
CMS-2S Emulsion used at 68% residual AC content

5.5.1 Curing and Compaction of Mixed Material

The basic idea was to develop specifications for cold mixed RAP base course, as TxDOT already has specifications for plant mixed AC stabilized base (Item 345) [TxDOT 95]. Two samples were used to determine the curing method for prepared specimens before compaction. One of these samples was cured for a period of 2 hours in an oven at 100°F and compacted. The other sample was allowed to cure at room temperature for a period of 24 hours, and then compacted. The density of both the compacted samples was then determined, but no significant difference was observed. To expedite the testing, we decided to cure the mixed material for two hours in an oven at 100°F before compaction.

Test samples were compacted using Test Method Tex-206-F, "Method of Compacting Test Specimens of Bituminous Mixtures," using the Texas gyratory compactor. The compacted test samples were allowed to cure for a period of 24 hours at room temperature to simulate the field conditions.

5.5.2 Stability Testing of Test Samples

The test specimens were placed in an oven at 100°F for an hour before testing for Hveem stability. Density and bulk specific gravity calculations were also made. The results of Hveem testing are shown in Table 5.6.

The highest Hveem stability was estimated to be 27.2 percent at an additional AC content of 2.0 percent. This was selected as the optimum additional AC content. According to the Asphalt Institute (AI), Hveem stability is not as good a measure of how a roadbase is going to perform as it is indicative of the rutting potential of the surface layer. Using the data collected during the Stabilometer testing, a *Resistance R-Value* can also be calculated. The Resistance R-Value is used to measure the stability or bearing capacity of roadbase mixtures. The minimum allowable limit is 70.00 [AI 90]. Table 5.6 lists these values as well, and all were above the minimum allowable.

Using the Hveem stability method, the optimum additional asphalt content was determined to be 2.00 percent. Figures 5.6, 5.7, and 5.8 plot the variation of Stability, Resistance *R-Value*, and density versus additional asphalt content for the Austin District RAP.

Table 5.6 Test results for stability testing of RAP

Add. AC Content, %	Density (gm/cc)	Bulk Spec. Gravity	Corrected Stability	Resistance R-Value
1.00			*Not Proper Mixing*	
1.50	2.30	2.436	26.3	84.7
2.00	2.30	2.410	27.2	84.4
2.50	2.37	2.433	16.3	76.4
3.00	2.36	2.417	12.7	72.1
3.50			*Too Low to Calculate*	
4.00			*Too Low to Calculate*	

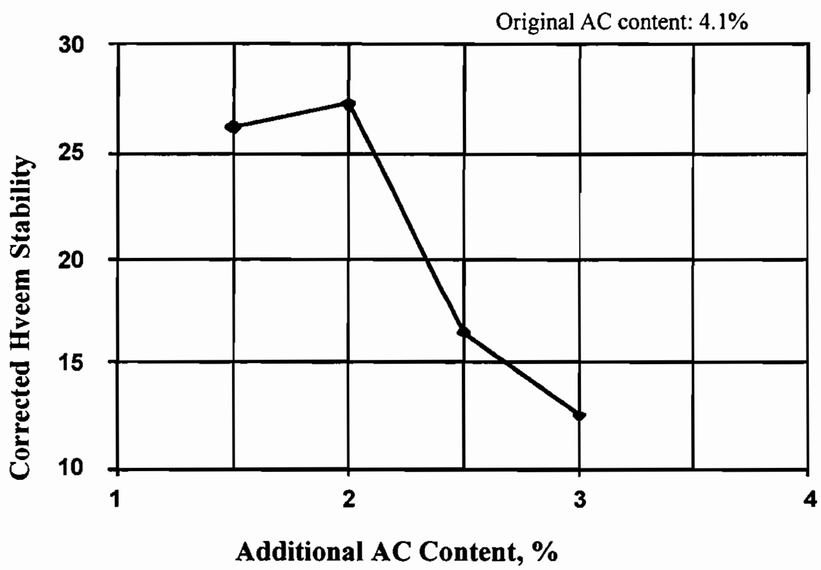

Figure 5.6 Estimation of additional optimum AC content using Hveem Stability

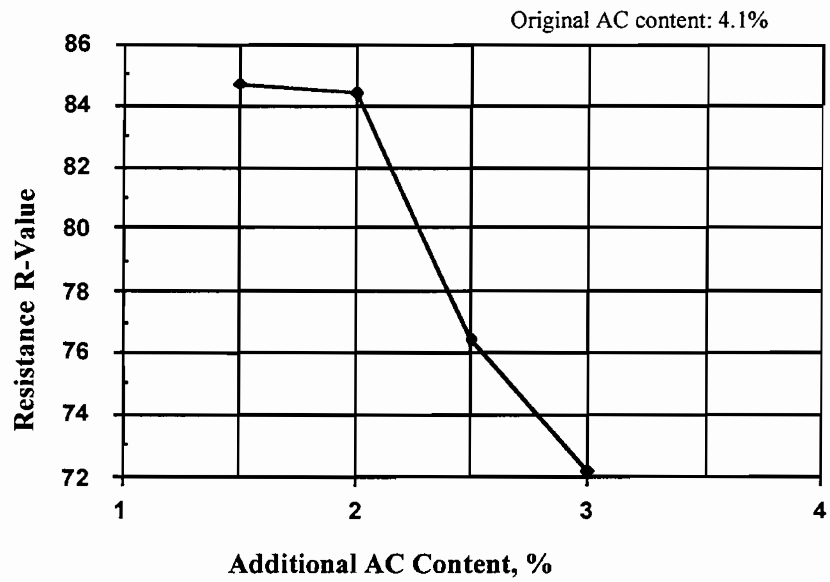

Figure 5.7 Variation of resistance R-Value and additional AC

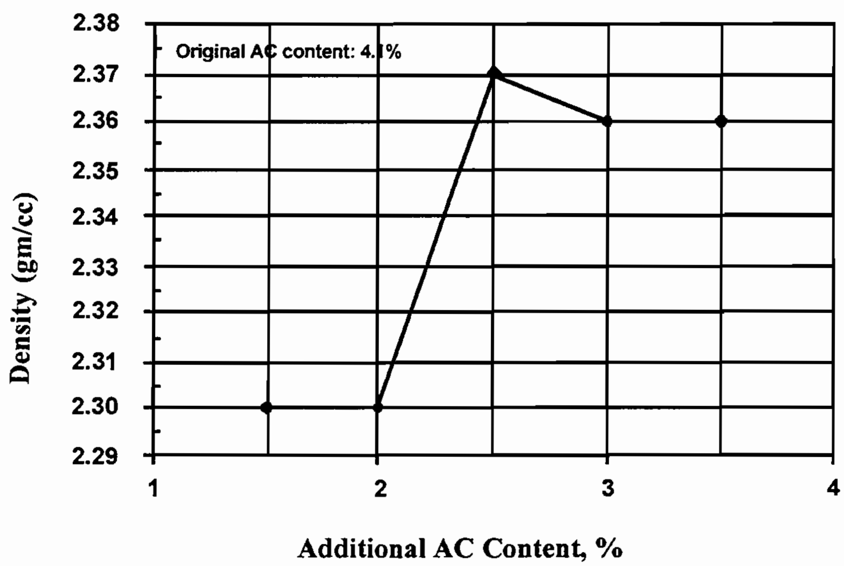

Figure 5.8 Variation of density with change in additional AC content

5.10 SUMMARY OF RAP LABORATORY TESTING

A number of RAP samples were available for testing. Material from Bryan/College Station was collected, as well as RAP samples from the Wichita Falls and Austin Districts. Only samples from the latter two sources were subjected to detailed laboratory testing for reasons stated earlier.

The test results indicated that there is much variability in RAP samples obtained from various sources. RAP properties depend a lot on the properties of the original AC layer and the reclaiming process used. Care must be exercised when characterizing RAP, which should be tested on a project-to-project basis owing to its variability. The conducted laboratory tests also demonstrate the possibility of using of 100 percent RAP in roadbase construction projects when stabilized with asphalt or as flexible base at proper gradation. For use as flexible base, RAP gradation had to be adjusted using additional natural material. The adjusted RAP had a CBR of 97, which identifies it as a good base material. However, care must be taken to estimate the trade offs between the two types and to select the most economical choice for the design life. Owing to the high cost of AE, it is expected that stabilized RAP would be justifiable only in those circumstances where layer thickness are restricted by highway and associated structure geometrics. Nonetheless, whichever type of base is selected, the use of RAP is a viable solution from a technical point of view, though its economic feasibility will have to be determined on a project-to-project basis.

CHAPTER 6. LABORATORY TESTING OF ELECTRIC ARC FURNACE SLAG FOR USE AS ROADBASE

6.1 INTRODUCTION

Another material that passed the initial screening of the WRM evaluation method — and that ranked the second best for use in roadbase — was electric arc furnace slag (EAFS). This chapter describes the laboratory testing performed to determine the feasibility of using EAFS in roadbase.

Almost all steel-making processes yield slag phases that remain in contact with the steel, refractories, and furnace atmosphere. Slags are formed through the addition of mixtures of oxides and fluxes or by other unavoidable, but often necessary, chemical reactions. Chemical properties of EAFS, together with its particle size, shape, and gradation, depend on the composition of the raw material used, the melting process, and on the slag reduction process in which slag is quenched using water [ISS 85]. In light of this considerable variability, it is important that a detailed evaluation of slag from a particular steel mill be carried out before it can be recommended for use. Nonetheless, in order to arrive at some consensus, this chapter describes the evaluation of EAFS obtained from a typical steel mill.

6.2 LABORATORY TESTING PROGRAM

As was the case with RAP, the first part of the laboratory testing program investigated EAFS by examining its physical properties for classification as an aggregate in roadbase. The second part of the laboratory testing investigated the strength characteristics of EAFS when used as a flexible base, using the CBR test. The final part investigated the strength of cement-stabilized EAFS roadbase. Item 247, "Flexible Base" of "TxDOT Standard Specifications for Construction of Highways, Streets and Bridges," recommends that the Texas Triaxial Test (TTT) be used to classify base materials with respect to the five triaxial classes. Most of the WRMs are cohesionless materials and do not hold together when extracted out of the mold, even after modified compaction. This fact is demonstrated in Figures 6.1 and 6.2, which show that some material remains on the base plate when the mold is removed after compaction, and that the test specimen collapses as soon as it is extracted from the mold.

6.3 PHYSICAL CHARACTERISTICS OF EAFS

6.3.1 Collection of EAFS Samples

EAFS samples were collected from the Alexendar Mills Service (AMS) crusher site located on the Structural Metals, Inc., (SMI) plant premises in Seguin, Texas. Due care was exercised in order to collect representative samples according to TxDOT specifications Tex-100-E, "Surveying and Sampling Soils for Highways" [Tex-100-E-95]. A bucket of a shovel loader was placed directly underneath the discharge of the conveyor belt. When sufficient material had accumulated, the bucket was lowered and all the material was transferred to sample bags. Figure 6.3 shows the shovel loader collecting EAFS from the conveyor belt.

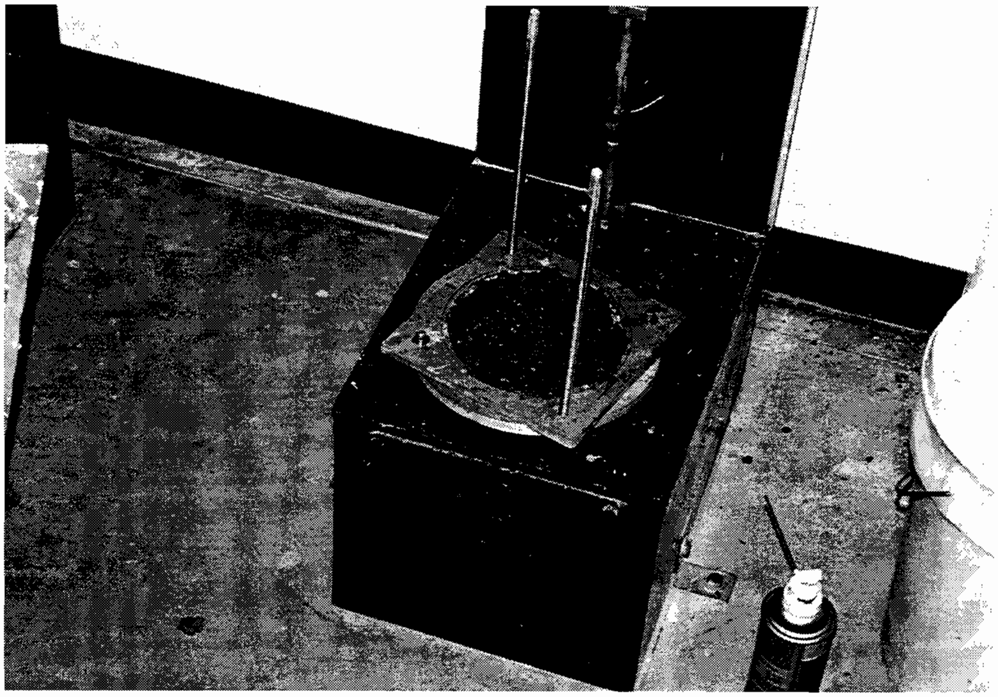

Figure 6.1 Material left on the base plate after mold removal

Figure 6.2 Collapsed specimen after extraction from the compaction mold

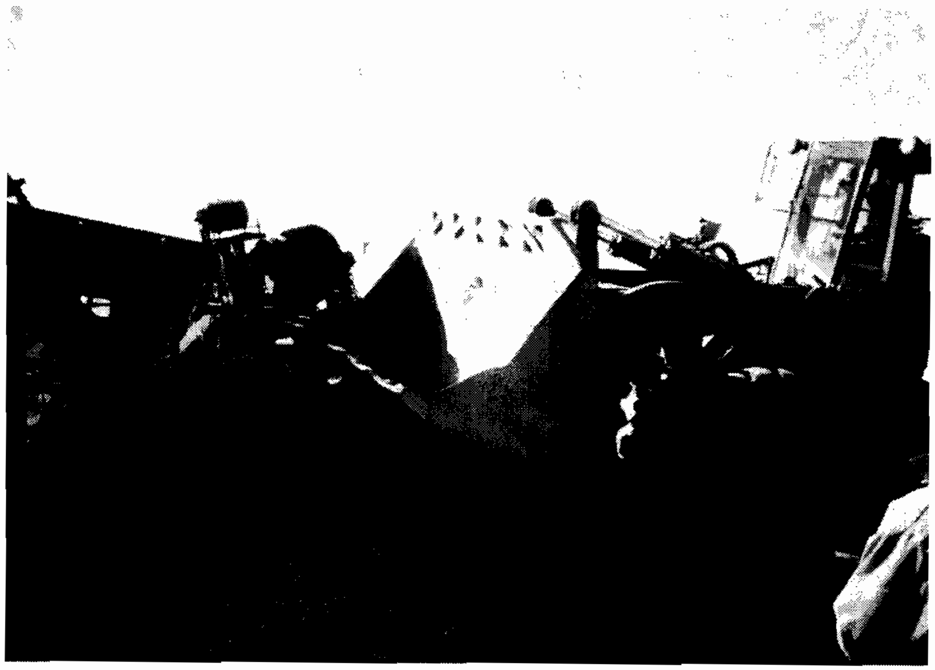

Figure 6.3 Shovel loader collecting crushed EAFS from the conveyor

6.3.2. Particle Size Analysis

Particle size analysis and distribution of EAFS samples were conducted using ASTM C 136-93 test procedure [ASTM C 136]. TxDOT also specifies the same procedure with TxDOT designation Tex-200-F [Tex-200-F 95]. Dry sieve analysis was carried out using a Gilson sieve shaker with square sieves. Figure 6.4 shows the gradation curve. The shape of the particle size distribution curve indicated the suitability of this material for roadbase construction. No additional material was required and all the TxDOT specifications were met without adding any additional natural aggregate material. As discussed in Chapter 4, this material actually has a better particle index than natural crushed limestone aggregate.

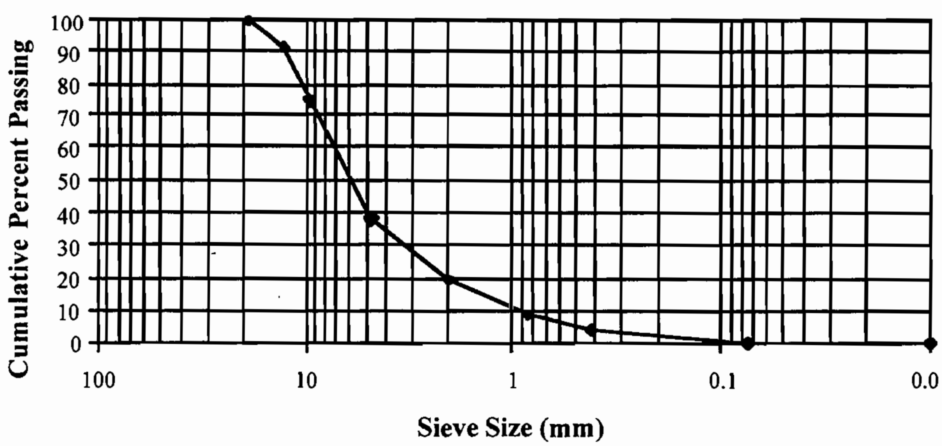

Figure 6.4. Shape of the particle distribution curve for steel slag (SMI, Seguin)

6.3.3. Estimation of Specific Gravity of EAFS

The specific gravity of EAFS samples was determined using Test Method Tex-201-F, "Bulk Specific Gravity and Water Absorption of Aggregate" [Tex-201-F 95]. The average EAFS specific gravity was determined to be 3.40, which is higher than that of natural crushed limestone aggregate. This unusually high value can be explained by the presence of metallic components left over from the steel making process. Lum et al. also found the specific gravity of EAFS to be higher than that of natural aggregate materials [Lum 92].

6.3.4. Los Angeles Degradation Test

The LA degradation test, ASTM C 131, was run to determine the loss due to impact and degradation. Facilities at the TxDOT district laboratories in the Austin District were used for this purpose. The material was prepared as shown in Table 4.5 and the material loss was estimated to be 22.00 percent.

6.4 CBR DETERMINATION OF UNSTABILIZED EAFS

Figure 6.5 shows the upper and lower bounds of the ASTM D 2940 gradation envelope. The gradation of EAFS closely followed that envelope and, thus, there was no need to modify it by adding any natural material. The same gradation was also used for batching purposes when CBR test specimens were prepared.

6.4.1 OMC Determination for EAFS

Once it was established that the EAFS gradation did not require any adjustment, the next step was to determine the OMC so that the CBR test specimens could be compacted at that moisture content. The OMC was determined using test method ASTM D 687. Tables B.4 and B.5 in Appendix B present the data collected to determine the OMC and the corresponding dry densities (DD). As shown in the compaction curve, Figure 6.6, the OMC for EAFS was estimated to be 5.5 percent.

6.4.2 Determination of California Bearing Ratio

Once the OMC had been determined, three specimens were prepared according to test procedure ASTM D 1883. The specimens were prepared using three different compactive efforts — 10, 25, and 56 blows per layer — so as to have a range of dry densities over which the CBR can be estimated. The prepared specimens were soaked in water for a period of 96 hours before testing. Each specimen was subjected to penetration by a cylindrical rod to a depth of 12.70 mm.

The results of the stress versus penetration depth for each compactive effort are tabulated in Table B.6 in Appendix B. Also shown is the CBR at 2.54 and 5.08 mm penetration for each specimen. The CBR at 2.54 mm penetration was greater than the CBR at 5.08 mm penetration for the three specimens, hence validating the test results. The results of stress (load) versus penetration depth were plotted to determine the CBR for each specimen, as shown in Figure 6.7. Figure 6.8 shows the graph of CBR versus DD plot which can be used to determine CBR at the specified dry unit weight. The plotted curves for the three compactive efforts were concaved downward; hence, no correction was required.

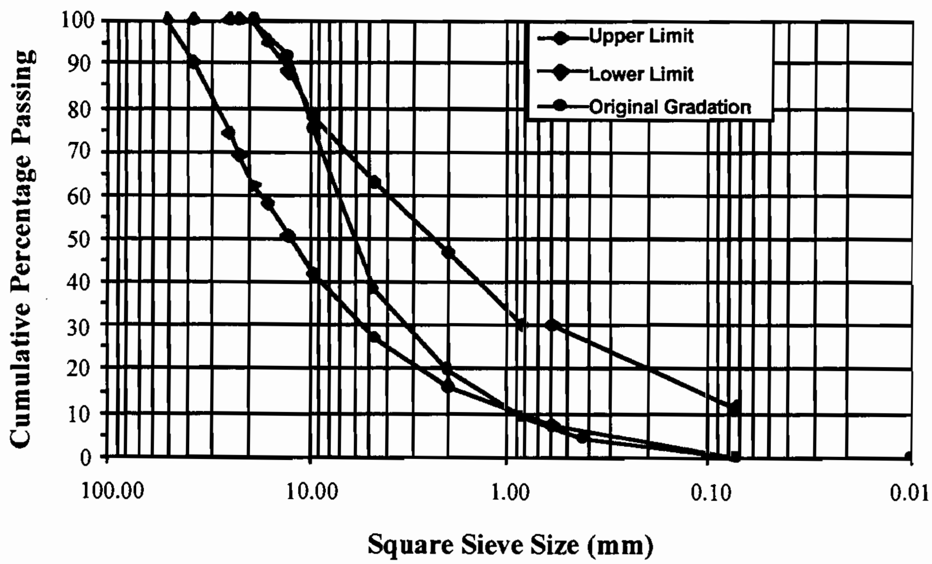

Figure 6.5 Conformity of EAFS gradation to ASTM D 2940

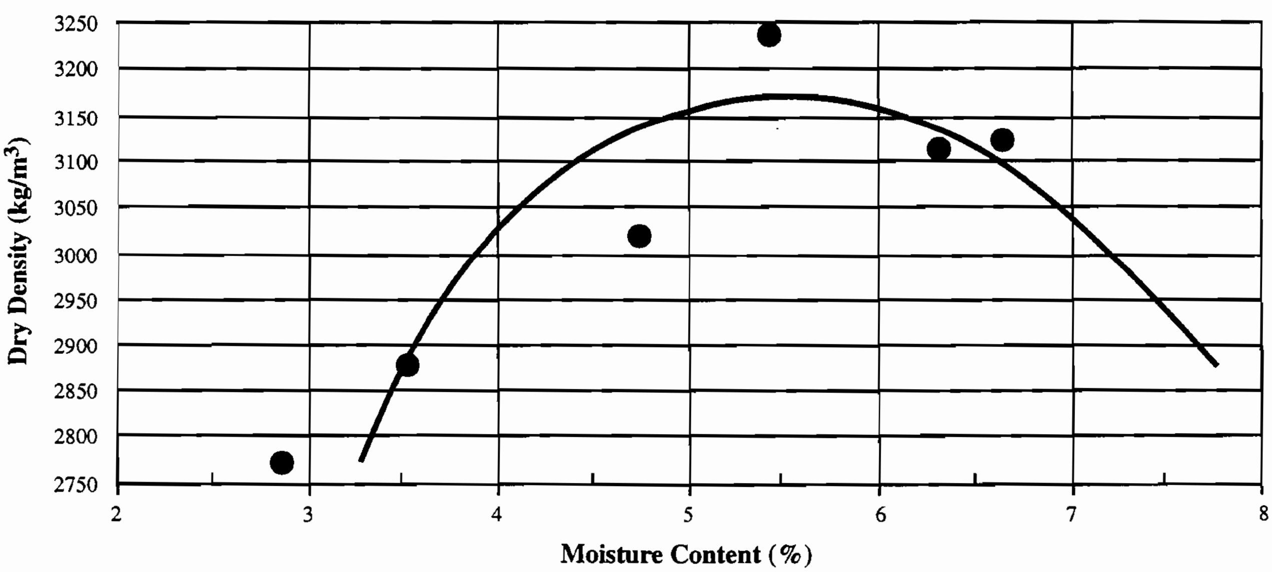

Figure 6.6 Compaction curve of EAFS

The estimated CBR of 135 percent at the maximum compactive effort indicates that EAFS is a good candidate material for use as a roadbase in place of conventional materials. The material is also characterized by a low swelling potential.

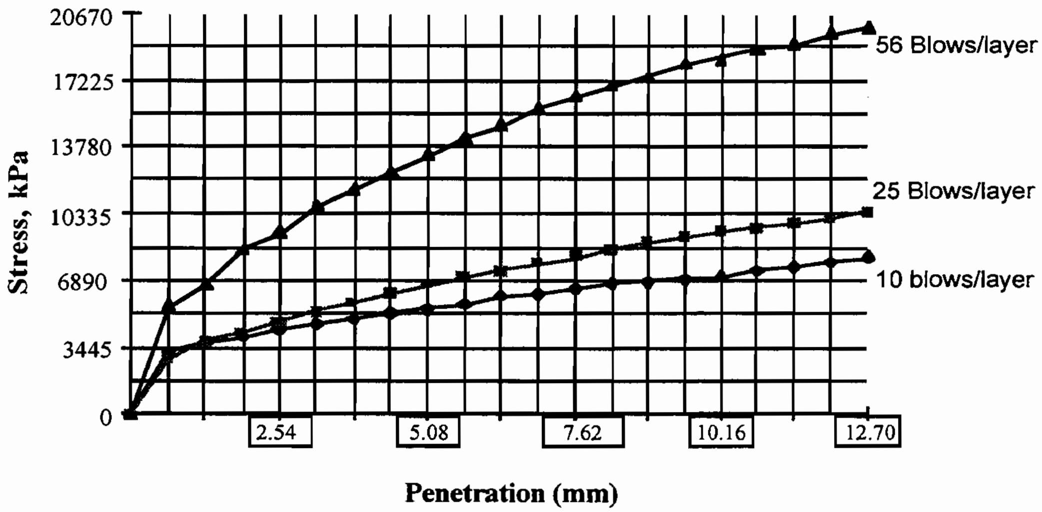

Figure 6.7 Stress-penetration curves for EAFS

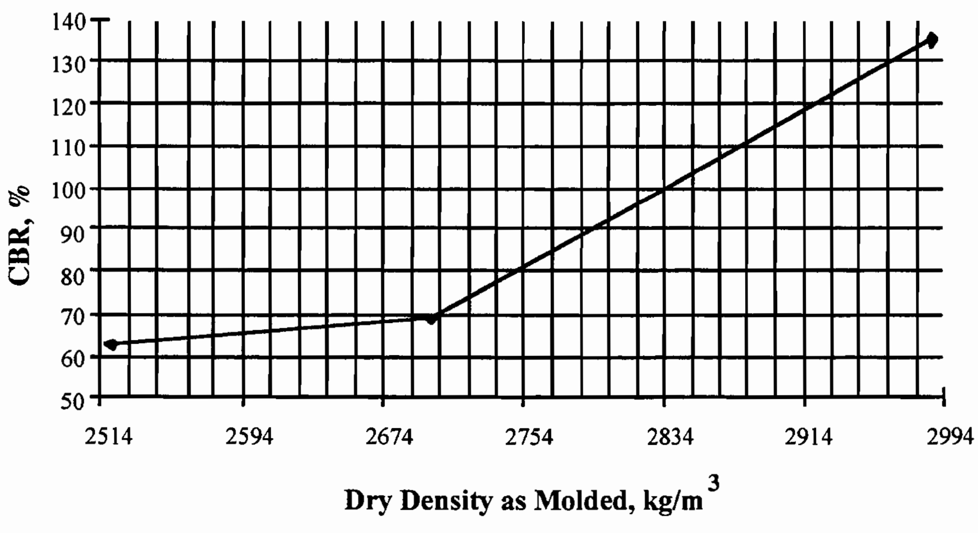

Figure 6.8 California bearing ratio vs. dry density for EAFS

6.5 STRENGTH CHARACTERISTICS OF CEMENT STABILIZED EAFS

The second alternative for use of EAFS in roadbase is with cement stabilization. The approach is definitely expensive but the resulting base is also relatively strong. Nevertheless, the choice should be based on a complete life-cycle cost analysis

Item 275, "Portland Cement Treated Materials (Road Mix)," of "TxDOT Standard Specifications for Construction of Highways, Streets, and Bridges" [TxDOT 95] recommends that cement-treated material be tested with Test Method Tex-120-E, "Soil Cement Compressive Strength Test Methods," to determine the optimum portland cement content of the stabilized base mix. The first step in this method is to determine the OMC and the maximum density for a aggregate cement mixture containing 6 percent cement using test method Tex-113-E, "Laboratory Compaction Characteristics and Moisture Density Relationship of Base Materials and Cohesionless Soils" [Tex-113-E 95]. The OMC so determined for EAFS cement mixture containing 6 percent cement is used to estimate the OMCs for mixtures containing 4 percent, 8 percent, and 10 percent cement by dry weight of the EAFS, using Equation 6.1. These OMCs were then used to prepare three test specimens for each cement content.

$$\% \text{ Molding Moisture} = \% \text{ Molding Moisture}_{6\% \text{ Cement}} \pm 0.25 \ (\% \text{ cement change}) \qquad \text{Eq 6.1}$$

6.5.1 Determination of Optimum Moisture Content

Tables B.7 and B.8 in Appendix B tabulate the data collected to determine the OMC of EAFS and 6 percent cement mixture using Test Method Tex-113-E. Using these values, the graph shown in Figure 6.9 was plotted to determine the water content corresponding to the maximum dry density, which is the required OMC.

From the graph plotted in Figure 6.9, the OMC for EAFS with 6 percent cement was determined to be approximately 8.00 percent. Equation 6.1 was then used to determine the OMCs or the moisture content for each of the EAFS batches containing 4 percent, 8 percent, and 10 percent cement by weight of the EAFS, as shown in Table 6.1.

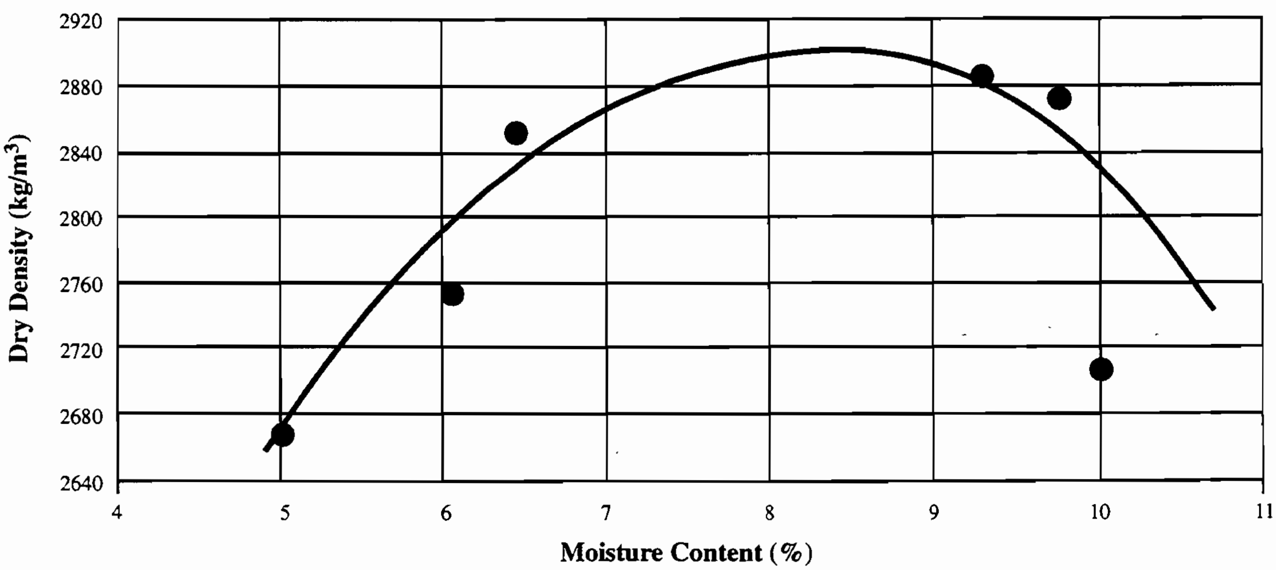

Figure 6.9 Estimation of the optimum moisture content for EAFS and 6 percent cement

Table 6.1 Estimation of molding water content for various cement contents

% Cement	Cement Increase %	Additional Water %	Total Water Content %
4.00	- 2.00	- 0.50	7.50
6.00	0.00	0.00	8.00
8.00	+ 2.00	+ 0.50	8.50
10.00	+ 4.00	+ 1.00	9.00

6.5.2 Preparation and Compression Testing of Test Specimens

Three specimens were prepared for each of the four cement contents using representative samples. Using the particle shape distribution curve, Figure 6.2, we used the batch fractions tabulated in Table 6.2. It was also estimated that about 27.24 kg of EAFS material would be required to produce three test cylinders for testing. The total batch mass was fixed at 27.24 kg; individual weights for each fraction are also listed in Table 6.2. Table 6.3 lists the weights of individual components for a batch to prepare three test cylinders.

Table 6.2 Batch fractions and the corresponding weights in aggregate mix

Sieve Size		% of Total Mix	Weight in Mix
Passing	Retained		(kg)
4.45 cm	1.27 cm	25.00	6.80
1.27 cm	0.95 cm	11.67	3.18
0.95 cm	# 4	33.33	9.08
# 4	# 10	15.00	4.09
# 10	Pan	15.00	4.09

Table 6.3 Estimation of cement and water weights for each batch

Batch No.	EAFS	Water		Cement	
	(kg)	(%)	(kg)	(%)	(kg)
1	27.24	7.50	2.04	4.00	1.09
2	27.24	8.00	2.18	6.00	1.63
3	27.24	8.50	2.32	8.00	2.18
4	27.24	9.00	2.45	10.00	2.72

The prepared cylinders were 15.24 cm in diameter and 20.23 cm in height to accommodate the larger EAFS aggregate. Mixed material for each batch was compacted in three layers, giving each layer 25 blows with the specified tamping rod. The test cylinders were allowed to cure at room temperature for about two hours. The prepared specimens were then placed in the moisture room for a period of seven days for curing, as specified by test methods Tex-120-E and ASTM D 1633 [Tex-120-E 95, ASTM D1633].

The test specimens were allowed to cure for a period of seven days, after which they were removed from the moisture room to measure the dimensions and the weight of each cylinder, in the wet condition. They were then allowed to dry overnight and weighed again. Before testing, the cylinders were immersed in water for a period of four hours, as required by testing procedures ASTM 1633 and Tex-120-E. The saturated EAFS cylinders were tested using the Baldwin compression testing system. The load rate was fixed at 137.80 kPa/min, which translated to a load rate of approximately 2447.5 N per minute. Tables B.9 and B.10 in Appendix B present the relevant laboratory data.

Figure 6.10 shows the increase of unconfined compressive strength with an increase in the amount of cement by weight. The slope keeps on increasing, however, though it is expected that it would level off at higher cement contents where an increase in cement content will not result in an increase in the unconfined compressive strength.

Item 275, "Portland Cement Treated Materials (Road Mixed)," requires a compressive strength of 5167 kPa with an allowable cement content of 4-9 percent by weight for Grade 1 material [TxDOT 95]. From the graph plotted in Figure 6.10, it can be estimated that this value is achieved at a cement content of about 5 percent; hence the unconfined compressive strength specifications were satisfied.

The failure pattern exhibited by the test cylinders is also of importance. The test cylinders failed completely at the lower cement contents, while at the higher cement content, visible cracks appeared in the cylinder. After the appearance of cracks these were still carrying load owing to particle interlock. The low cement content cylinders simply disintegrated. This could be attributed to the low amount of cement present, which was not enough to hold the particles together.

6.10 SUMMARY OF EAFS LABORATORY TESTING

The laboratory testing of EAFS supports the results of the WRM evaluation method, in which the material was found to be better than natural aggregate material from a technical point of view. The material is well-graded and does not require the addition of any natural aggregate to make its use possible. The material is also very hard owing to the presence of steel and other metallic components introduced by the steel-making process. This aspect was very evident during the LA abrasion testing of the material, where the material loss was determined to be only 22 percent. As a comparison, natural crushed limestone aggregate had a material loss of about 32 percent when tested. The surface of the particles was also very rough; its characteristic pitting gave it additional advantage of having a high degree of particle interlock.

The material had a soaked CBR of 135 percent, which qualifies it as a good flexible base material. The results of testing undertaken to determine the unconfined compressive strengths after cement stabilization, especially at the more than 5 percent cement content, were comparable to those of cement-stabilized natural aggregate. A complete life-cycle cost analysis is essential when deciding which type of roadbase to select.

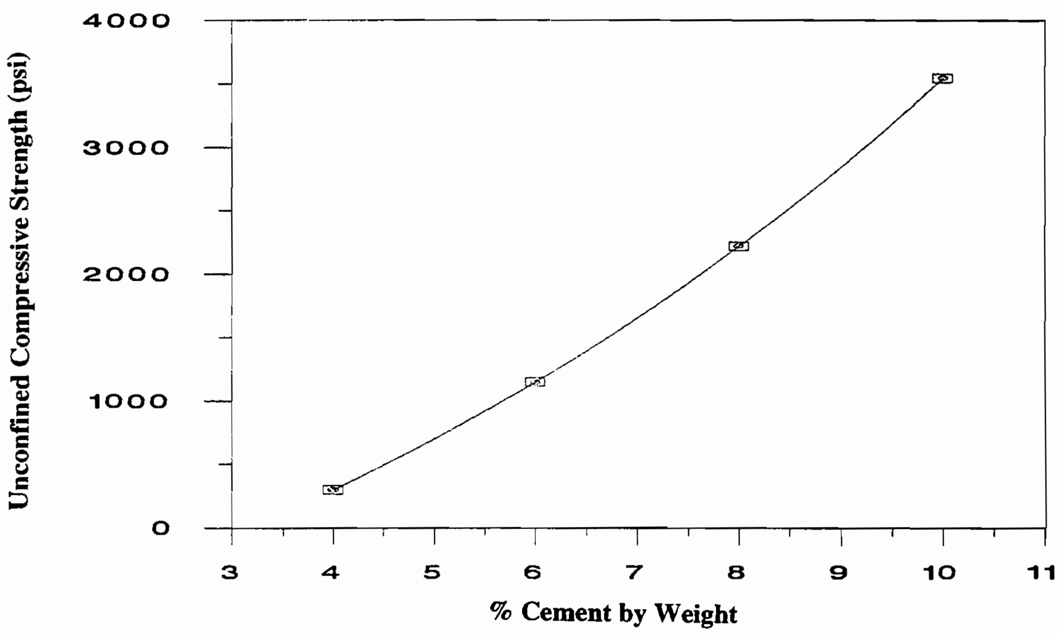

Figure 6.10 Compressive strength vs. percent cement for EAFS, SMI, Seguin (1 psi=6.89 kPa)

CHAPTER 7. LABORATORY TESTING OF RECLAIMED PORTLAND CEMENT CONCRETE FOR USE AS ROADBASE

7.1 INTRODUCTION

The third WRM recommended for detailed laboratory testing by the WRM evaluation system was reclaimed portland cement concrete (RPCP). This chapter describes the results of the laboratory testing undertaken to determine the possible implementation of RPCP in roadbase construction. As was the case with RAP, the use of RPCP is a viable approach, but only when the new roadbase containing RPCP possesses characteristics needed in order for it to perform in the environment and under the service conditions it is subjected to.

RPCP evaluated during the laboratory testing program originated from a TxDOT project in TxDOT's Pharr District and met the gradation requirements as given in Table 7.1 [TxDOT PO 94].

Table 7.1 Gradation requirements of crushed portland cement concrete rubble

Retained on Square Sieve	Percent Retained
5.08 cm	0.00
1.27 cm	20 - 60
# 4	40 - 75
# 40	75 - 85

7.2 LABORATORY TESTING PROGRAM

As was the case with RAP and EAFS, the suitability of using RPCP in roadbase was evaluated using standard ASTM, AASHTO, or TxDOT methods. The first part of the laboratory testing program investigated RPCP by examining its physical properties for classification as an aggregate in roadbase. The second part involved testing RPCP as aggregate in a flexible roadbase; the final part of laboratory testing estimated the strength characteristics of a cement-stabilized RPCP roadbase.

7.3 PHYSICAL CHARACTERISTICS OF RPCP

7.3.1 Particle Size Analysis

Particle size analysis and distribution of the RPCP samples were conducted using ASTM C 136 - 93 test procedure [ASTM C 136], which is similar to TxDOT designation Tex-200-F [Tex-200-F 95]. Dry sieve analysis was carried out using a Gilson sieve shaker using square sieves, as explained in Chapter 4. Figure 7.1 shows the particle size distribution curve for collected RPCP samples.

7.3.2 Estimation of Specific Gravity of RPCP

The specific gravity of RPCP samples was determined using Test Method Tex-201-F, "Bulk Specific Gravity and Water Absorption of Aggregate" [Tex-201-F 95]. Details about the test are provided in Chapter 5. The average RPCP specific gravity was determined to be 2.36, which is lower than that of natural crushed limestone aggregate. This low value is in agreement with those findings reported by Burke and Bergren [Burke 92, Bergren 77].

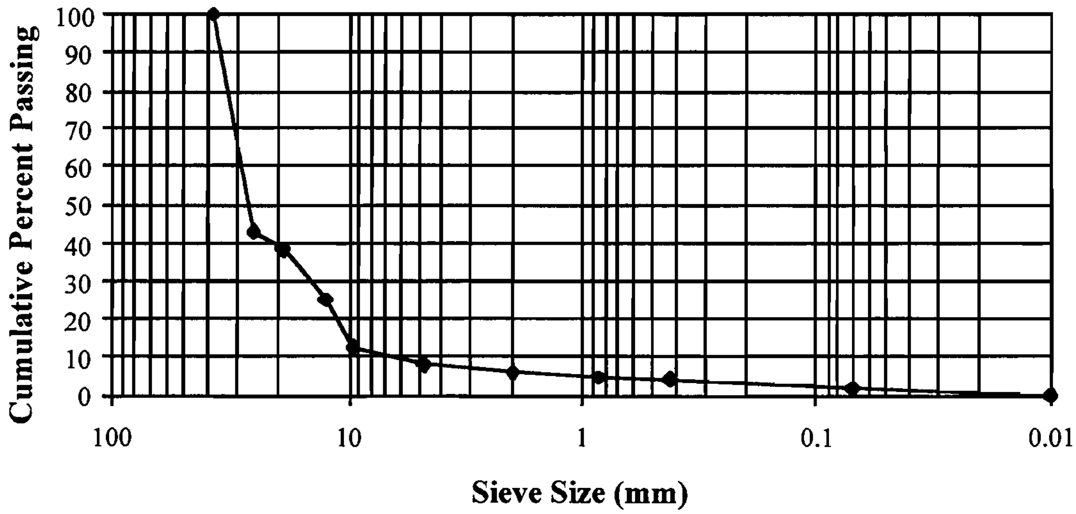

Figure 7.1 Shape of the particle distribution curve for RPCP from the Pharr District

7.3.3 Los Angeles Degradation Test

The LA degradation test, ASTM C 131, was run to determine the loss resulting from impact and degradation. After sieving through the #12 U.S. standard sieve, the material loss was estimated to be 30.46 percent. This loss of material is slightly less than that of crushed limestone aggregate. The slightly better performance can be attributed to the loosened cement paste, which started to cushion the impacts in the later stages of the test.

7.4 STRENGTH TEST WITHOUT STABILIZATION

As was the case with RAP and EAFS, RPCP was also checked for conformity to ASTM D 2940 gradation specifications before performing the CBR test. Figure 7.2 shows the gradation envelop formed by the ASTM specifications. The distribution of RPCP did not meet the prescribed limits and had to be adjusted as shown. This was done to ensure a proper gradation for flexible base, as the waste material was to be used without any stabilization to enhance the strength properties.

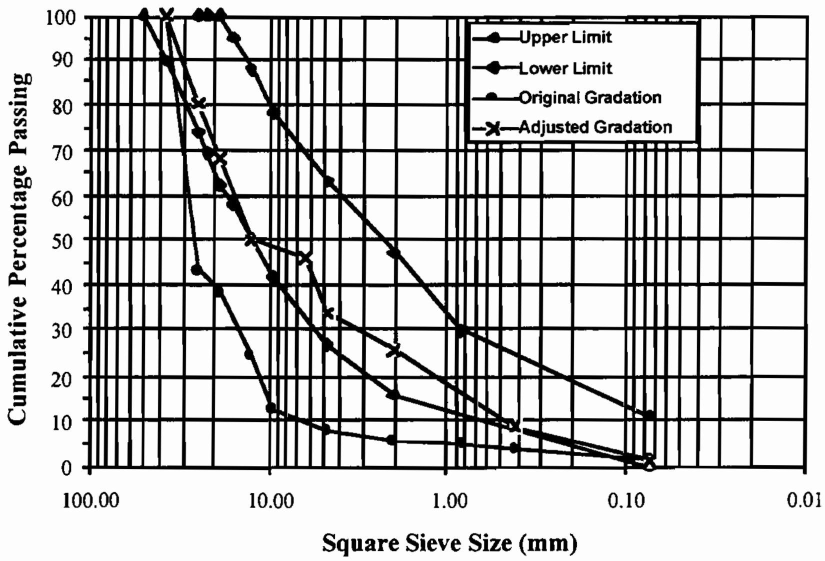

Figure 7.2 Cumulative percentage passing on various square mesh sieves

The OMC of adjusted RPCP was determined using test method ASTM D 687. Tables B.11 and B.12 in Appendix B present the data collected to determine the OMC and the corresponding dry densities (DD). As shown in the compaction curve, Figure 7.3, the OMC for RPCP was estimated to be 11.50 percent.

The CBR of RPCP was determined using the same procedure as described in Chapters 5 and 6. The CBR at 2.54 mm penetration was greater than the CBR at 5.08 mm penetration for the three specimens, hence validating the test results.

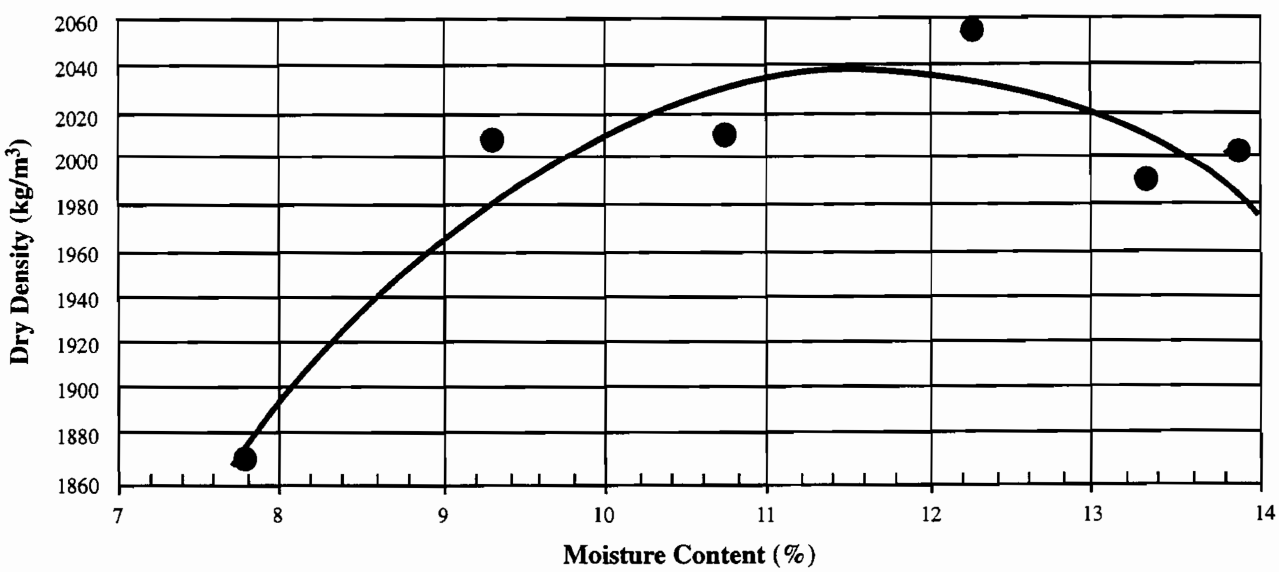

Figure 7.3 Compaction curve of gradation adjusted RPCP

Results of stress (load) versus penetration depth were plotted to determine the CBR for each specimen, as shown in Figure 7.4. Figure 7.5 shows the graph of CBR versus dry density, which can be used to determine CBR at the specified dry unit weight. The plotted curves for the three compactive efforts were concaved downward; hence no correction was required.

The estimated CBR of 90 percent at the maximum compactive effort indicates that RPCP is a good material for use as a roadbase. The stress penetration curve for the lowest compactive effort is not a smooth one. This erratic behavior may be due to the fact that the material did not obtain the maximum possible density during the compaction procedure.

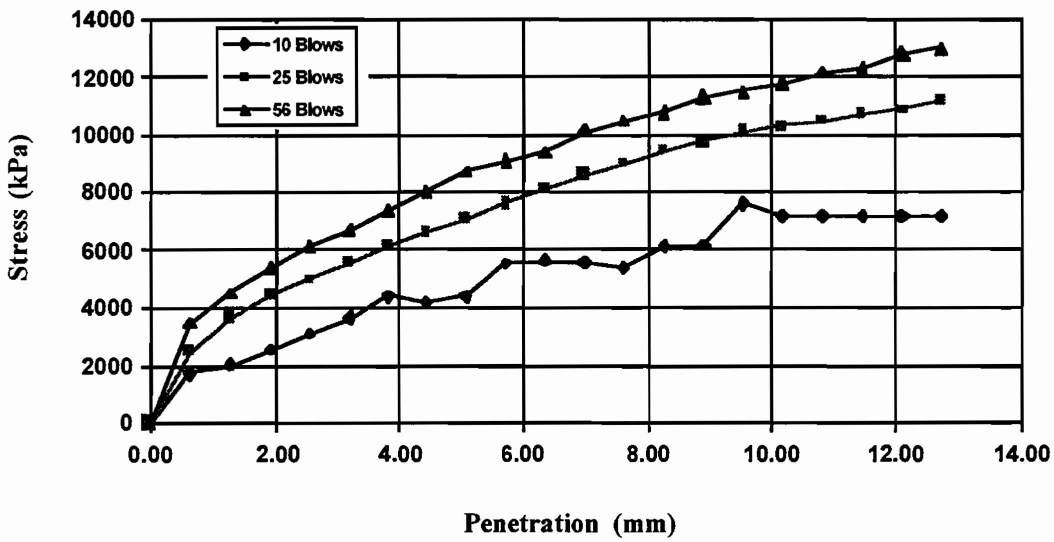

Figure 7.4 Stress-penetration curves for RPCP

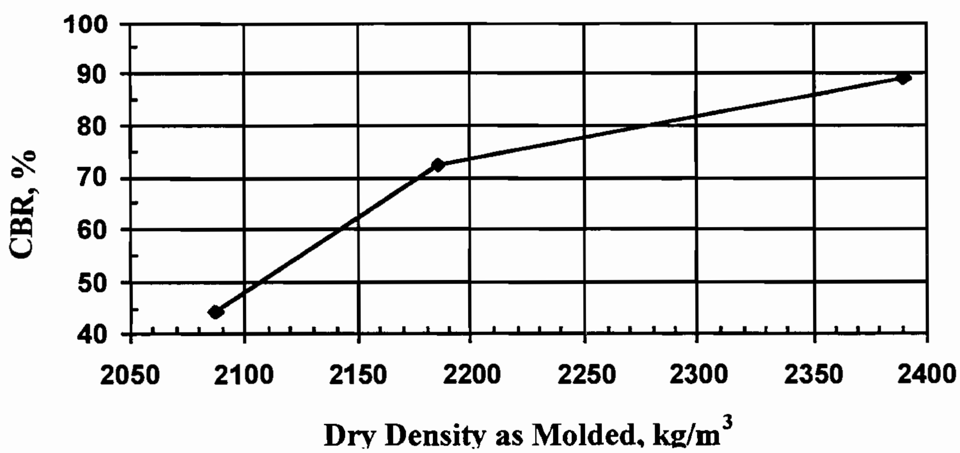

Figure 7.5 California bearing ratio vs. dry density for EAFS

7.5 STRENGTH CHARACTERISTICS OF CEMENT-STABILIZED RPCP

As was the case with EAFS, Test method Tex-120-E, "Soil Cement Compressive Strength Test Methods" [Tex-120-E 95], was used to determine the unconfined compressive strength of compacted soil cement specimens after seven days of curing. The method is described in detail in section 6.5.

The first step was to determine the OMC and the maximum density for a RPCP cement mixture containing 6 percent cement using test method Tex-113-E. The OMC for RPCP cement mixture was determined to be 11.50 percent, as shown in Figure 7.6. Equation 6.1 was then used to determine the OMCs for each of the RPCP batches containing 4 percent, 8 percent, and 10 percent cement by weight of the RPCP, as shown in Table 7.2.

The next step was to prepare three specimens for each of four cement contents using the batch fractions shown in Table 7.3. It was estimated that about 27.24 kg of RPCP material would be required to produce three test cylinders for testing. Thus, the total batch mass was fixed at 27.24 kg; individual weights for each fraction are listed in Table 7.3. Table 7.4 lists the weights of individual components for a batch to prepare three test cylinders.

The prepared specimens were placed in the moisture room for a period of seven days for curing, as specified by test methods Tex-120-E and ASTM D 1633 [Tex-120-E 95, ASTM D1633]. Before placing in the moisture room for seven days, the test cylinders were allowed to cure at room temperature for about two hours.

Finally, the RPCP cylinders were tested using the Baldwin compression testing system following the procedure outlined in section 6.5.2. Table B.17, in Appendix B, tabulates the calculation of the unconfined compressive strengths. Figure 7.7 shows that the unconfined compressive strength increases with an increase in cement content, but only up to 8 percent cement content, after which point it reduces sharply.

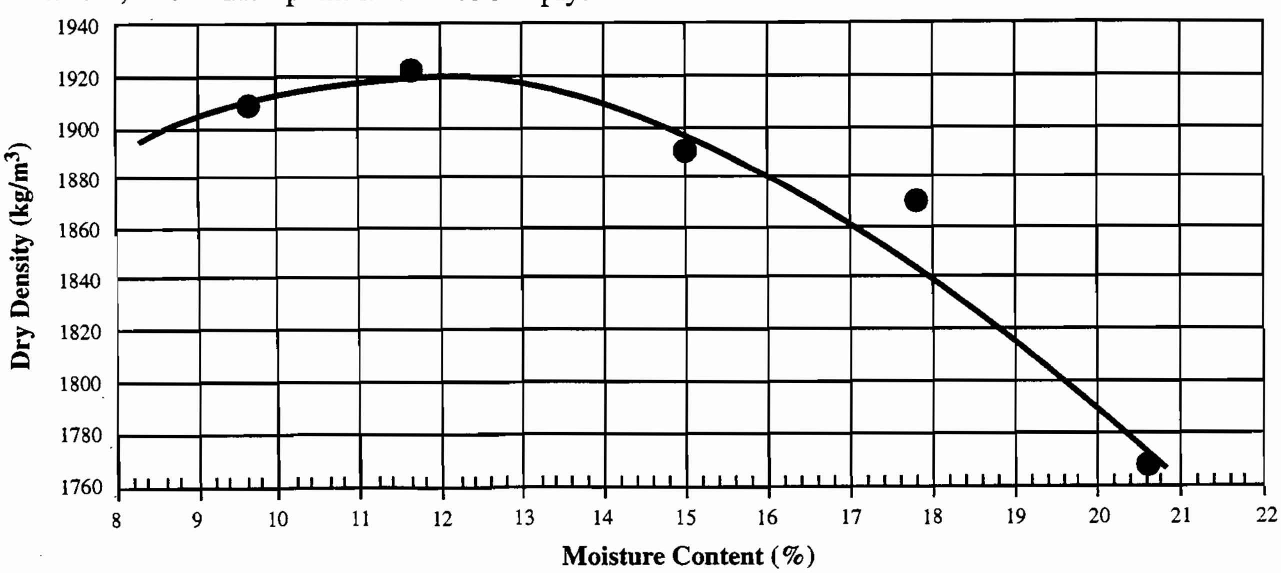

Figure 7.6 Estimation of the optimum moisture content for RPCP

Table 7.2 Estimation of molding water content for various cement contents

% Cement	Cement Increase %	Additional Water %	Total Water Content, %
4.00	- 2.00	- 0.50	12.25
6.00	0.00	0.00	12.50
8.00	+ 2.00	+ 0.50	12.75
10.00	+ 4.00	+ 1.00	13.00

Item 275, "Portland Cement Treated Materials (Road Mixed)," suggests a compressive strength of 5.17 MPa at the higher end, with an allowable cement content of 4-9 percent by weight [TxDOT 95]. From the graph plotted in Figure 7.7, it can be estimated that this value is achieved at a cement content of about 6.25 percent; hence the unconfined compressive strength specifications were satisfied.

Table 7.3 Batch fractions and the corresponding weights in aggregate mix

Sieve Size		% of Total Mix	Weight in Mix
Passing	Retained		(kg)
44.45 mm	12.70 mm	33.33	9.08
12.70 mm	# 4	33.33	9.08
# 4	Pan	33.33	9.08

Table 7.4 Estimation of cement and water weights for each batch

Batch No.	RPCP	Water		Cement	
	(kg)	(%)	(kg)	(%)	(kg)
1	27.24	12.25	3.34	4.00	1.09
2	27.24	12.50	3.41	6.00	1.63
3	27.24	12.75	3.47	8.00	2.18
4	27.24	13.00	3.54	10.00	2.72

7.6 SUMMARY OF RPCP LABORATORY TESTING

Laboratory testing of RPCP strengthened the results of WRM evaluation method in which the material was found to be marginal from a technical point of view. The material is gap graded and requires 50 percent natural aggregate to be added to make its use possible. This material could not be used in the form existing in the field, as it was deficient in fines. The material exhibited the properties of the natural aggregate used to make the original. This aspect also became evident during the LA abrasion testing of the material, where the material loss was determined to be about 30 percent. As a comparison, natural crushed limestone aggregate has a material loss of about 32 percent when tested. The material did not lose as much as natural aggregate because the cement paste which came off the RPCP particles started to cushion the impact.

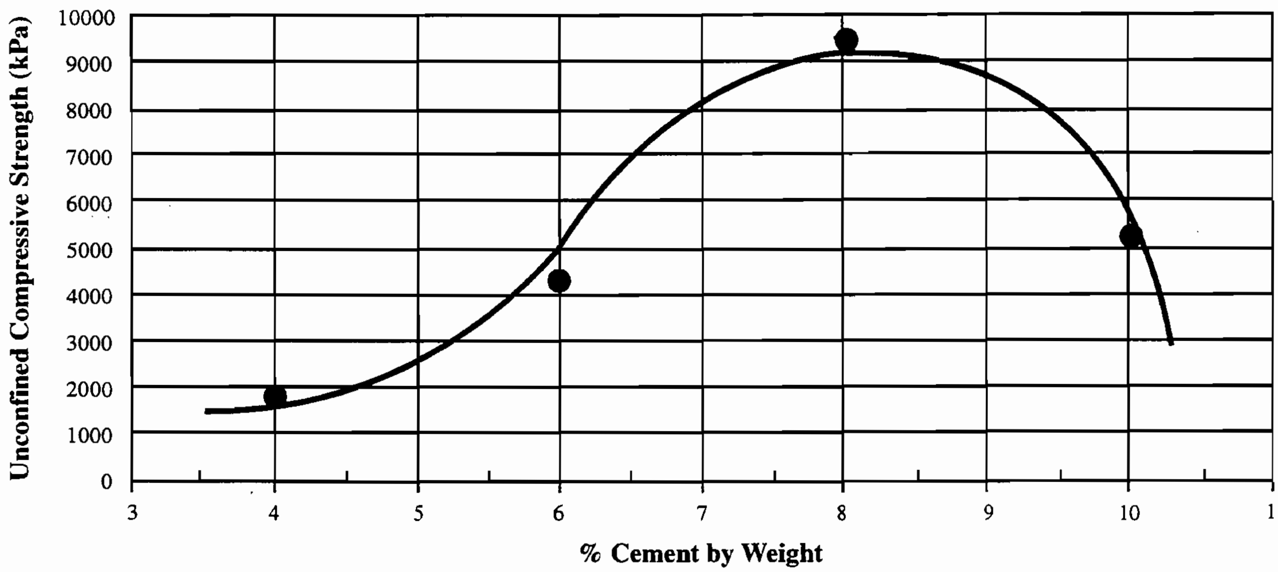

Figure 7.7 Unconfined compressive strength vs. percent cement for RPCP

CBR testing performed characterized RPCP as good base material, with a CBR of 90. With respect to cement-stabilized bases consisting of RPCP, at a 8.0 percent cement content it is an expensive approach and, consequently, should be avoided. An economic analysis made on a project-by-project basis could assist in determining which type of roadbase would be appropriate for a particular situation.

CHAPTER 8. TRIAL SPECIFICATIONS FOR TESTED WASTE AND RECLAIMED MATERIALS

8.1 INTRODUCTION

This chapter describes trial specifications and quality control procedures for using RAP, RPCP, and EAFS as roadbase. As an example, "TxDOT Standard Specifications for Construction of Highways, Streets, and Bridges" [TxDOT 95], which address a number of issues, were used. The discussed items ranged from an overall description of work, to the method in which the payment is calculated. TxDOT specifications do not address WRMs specifically, except RAP. Also, National Cooperative Highway Research Program (NCHRP) Report 160 [NCHRP 90], which describes guidelines for cold in-place recycling, was looked at for guidance. Such specifications contain elements of method and end-result specifications and rely on the experience of the public agency, contractors, material suppliers, and equipment manufacturers to obtain the desired end product at a reasonable cost [NCHRP 90]. Specifications for WRMs must contain the following items to describe all aspects of their use as roadbase:

- Description of work
- Materials
- Equipment and construction methodology
- Quality control inspection, sampling, and testing
- Payment basis

8.2 COMPONENTS OF WRM TRIAL SPECIFICATIONS

The primary trial specifications for WRMs deal with aggregate gradation, asphalt and portland cement binder content, water content, and density requirements. These are described in the following sections.

8.2.1 Maximum Aggregate Size

Most specifications for WRMs base the acceptability of aggregate produced from WRMs on the maximum particle size. Some agencies require that all the material should pass the 25.0 mm (1 in.) sieve (0 percent retained on 25.0 mm sieve). This in our opinion is overly restrictive and leads to a slowing down of the recycling process if a continuos chain of equipment is used. According to Scherocman [Scherocman 83], the maximum size of materials reclaimed from existing pavement structures is a function of:

1. Condition of existing pavement
2. Maximum size of the original aggregate mix used
3. Speed of milling process (higher speeds produce larger sizes)

4. Depth of cut (thicker cuts tend to produce large chunks of material)

Laboratory testing done for this research study, including that undertaken in many documented sources, has indicated that a small percentage of material retained on 38.1 mm (1.50 in.) is not harmful. It is the preferred alternative to allow some oversized material to be present in the recycled mix by specifying a maximum percentage for the nominal maximum size, instead of placing restrictions on the maximum size. For example, 97 percent passing the 38.1 mm (1.50 in.) sieve with chunks no larger than 7.5 cm or with the remaining 3 percent not so large as "to affect adversely the stability and structural integrity of the mixture nor to hamper the shaping operation" [Scherocman 83, ARRA 86, NCHRP 90] has been permitted.

8.2.2 Aggregate Gradation

As these are trial specifications, and given that we are not sure what works for WRMs, ASTM specifications D 2940 provide a good starting point. According to these specifications, when a graded aggregate meeting the requirements given in Table 5.5 is properly spread and compacted to the appropriate density, it can be expected to provide adequate stability and load support for highway and airport bases [ASTM D 2940]. So, a WRM whose gradation falls within this envelop can be expected to perform well as a base. As material gradation is one aspect of its future performance, the decision to use a WRM must not be based solely on this attribute, but must be followed up with some strength test.

8.2.3 Binder Specifications and Content

One should try to use WRMs in their existing conditions as flexible base. Sometimes, however, some sort of binder or other additive would need to be added to make them suitable for roadbase construction. The specified binder or additive should conform to the appropriate AASHTO, ASTM, AI, ACI, or state DOT specifications for such binder and additive. The binder and additive specifications to be followed must be clearly stated in the specifications for use of WRMs as roadbase.

The equipment for adding the binder and additive should be capable of an accurate application rate such that the total binder content of the recycled mix is equal to the job-mix formula amount within a specified tolerance, typically ± 0.50 percent. Care should also be taken for the accurate application of the required pre-mix water as specified by the job-mix formula [NCHRP 90].

8.2.4 Job-Mix Formula

The responsibility for establishing the job-mix formula and required sampling procedures, test methods, and design criteria for the mix design needs to be clearly outlined in the job specifications. The specifications for WRMs must clearly indicate the amount of waste material allowed in the job mix. Conditions for which these values can be relaxed must be defined clearly. The mix design process can be used to determine if any new aggregate is needed to improve the quality of the final product.

8.2.5 Raw Natural Aggregate

It order to adjust the WRM gradation so that it conforms to that specified by ASTM D 2940, it may sometimes be necessary to add raw natural aggregate. All the required tests, based on state DOT requirements, should be carried out before the natural aggregate is allowed in the job-mix.

8.2.6 Construction Equipment

It is the responsibility of the specifying agency to assure quality equipment for all phases of the construction. Factors such as contractor and equipment availability, economics, and the desired quality of work should be considered by the agency when specifying equipment for a particular project.

8.2.7 Density

The required density of the compacted mix is a major component of the job specifications. It can be specified as a percentage of theoretical maximum density, a percentage of laboratory density, or as a percentage of field density [NCHRP 90].

Some agencies recommend using the percentage of theoretical maximum density instead of percentage of laboratory density. Agencies citing the problem with variation in the original pavement suggest that a target density combined with a rolling pattern that can be changed may be the most realistic type of density specification [R & B 85]. The extent of agency experience with using waste materials in construction and environmental factors will probably determine which type of density specification is appropriate [NCHRP 90].

8.3 TRIAL SPECIFICATIONS FOR WASTE AND RECLAIMED MATERIALS

8.3.1 Trial Specifications for Flexible Base Using RAP

These trial specifications deal with using RAP as a flexible base material. Though these are based on the test results conducted on RAP from two different sources, it is expected that by following the gradation requirements, variability in the finished product can be reduced. These specification describe the construction method as well as the payment method, both of which are based on standard TxDOT procedures. Another important fact is that provision for using both stockpiled RAP as well as pulverizing the existing pavement and using it in-place are also provided. Appendix C provides the complete trial specifications.

8.3.2 Trial Specifications for Asphalt Stabilized Base Using RAP

These specifications describe the construction of a base course using either previously reclaimed and stockpiled asphalt concrete or pulverizing the existing asphalt concrete pavement, mixing it with asphalt and compacting. Since a binder is being added, no gradations requirements are enforced, except those needed to control the maximum aggregate size. As RAP is being used in the base course, the quality requirements were made less stringent. Appendix D provides detailed trial specifications.

8.3.3 Trial Specifications for Flexible Base Using RPCP

These trial specifications deal with using RPCP as a flexible base course. As reclamation of RPCP is difficult and generally results in large-sized aggregate particles, compliance to ASTM D 2940 specifications is made an important part. Additionally, a considerable amount of natural unused aggregate material would be required to make them work; hence restrictions are also placed on the quality of natural aggregate material which must pass all the standard TxDOT specifications. As with all specifications, also included are the construction method and the payment procedure. Appendix E provides details about these specifications.

8.3.4 Trial Specifications for Flexible Base Using EAFS

These trial specifications describe the construction of a flexible roadbase using EAFS. EAFS was the only material which when checked for compliance with ASTM D 2940 did not require any adjustment. As the properties of EAFS may change from steel mill to steel mill, it is expected that the gradation would need to be checked for compliance. Appendix F of this document provides the complete trial specifications for a flexible roadbase using EAFS.

8.4 FINAL REMARKS

The described trial specifications for RAP, EAFS, and RPCP were based on laboratory work as well as on the experiences of other public agencies. There is still insufficient performance data available to develop statistically based quality assurance specifications for these WRMs. The objective of the developed trial specifications was to have the best possible product for the least cost, so it must allow the maximum amount of WRM without sacrificing quality. This was ensured by allowing the maximum amount of WRM in all the developed trial specifications but placing the restriction that the final product should conform to ASTM D 2940 specifications for gradation.

Any public agency must take responsibility for the adequacy of its design and must communicate with the contractor by writing simple, straight forward specifications that clearly state what is expected. The contractor must then be allowed to select the materials and methods that will accomplish the results, within the limits set forth by the provided specifications, and must be responsible for the final product. The focus of the public agency must be on the end results; it must be willing to modify standard specifications as necessary to obtain the end results using waste and reclaimed materials.

CHAPTER 9. RAP RECYCLING PROJECT IN WICHITA FALLS: A CASE STUDY

9.1 INTRODUCTION

RAP obtained from the Wichita Falls District of TxDOT was selected as a case study for use of WRMs on a portion of FM 369 in Wichita County. The reconstructed portion linked a newly constructed corrections facility with US 287 outside the Wichita Falls city limits. The primary contractor on this project, Zack Burkett County, submitted a Value Engineering Change Proposal (VECP) requesting authorization to use RAP in base course in place of the original TxDOT design, which required a crushed limestone base.

The original pavement design called for scarifying the original pavement, incorporating the old pavement into the subgrade, adding lime in slurry form, compacting, and shaping this into new subgrade. A new crushed limestone base and a hot mix asphalt concrete (HMAC) riding surface was then to be added on top of the prepared subgrade. Under the VECP, the existing pavement was left undisturbed; RAP was used as a base course directly on top of the existing pavement. A HMAC riding surface was then provided.

The results of this case study validate the results of this research, which found RAP to be the highest ranked material using the WRM evaluation procedure. Besides having environmental and societal benefits, RAP also had considerable economic benefits, which will be described later.

9.2 TXDOT FLEXIBLE PAVEMENT DESIGN SYSTEM

The TxDOT Flexible Pavement Design System, commonly called FPS11PC, is computer based and uses Dynaflect deflections to determine material properties. This system is used to identify a complete pavement design strategy. For a given design analysis, initial construction cost as well as future costs are also calculated. All these costs are calculated for various design strategies and are discounted to present value using the user-supplied discount rate.

TxDOT adopted this design procedure after encountering difficulties in developing material coefficients for materials and environments found in Texas. A new pavement life equation, called the serviceability loss equation, was developed under Research Project 32, "Application of AASHO Road Test Results to Texas Conditions." The underlying principle as defined in Research Report 32-11 [TTI 68 B] was:

> The wheel load stress acting in the pavement, particularly the tensile stress in the bottom of the asphaltic concrete layer, is believed to be approximately proportional; to the curvature of the surface produced by the load.

Work done under Research Project 32 correlated performance with pavement deflections at the AASHO Road Test. This method required that a procedure be developed to predict pavement deflections. Because laboratory tests were found to be of no use for this purpose, a field method was sought [TxDOT 83]. The Dynaflect was selected to make necessary deflection measurements, as it was readily available and a large number of observations could be made economically. Furthermore, it was easy to measure the pavement deflection curvature using the Dynaflect, and the testing was nondestructive.

An empirical equation was developed using a statistically designed field experiment to estimate the surface curvature index from the design stiffness coefficients, a_i, and layer thickness, D_i. This equation was also used in reverse to estimate the stiffness coefficients of the pavement and the subgrade materials in place. More detail about the equation can be found in various reports originating from Research Project 32 [TTI 69, TxDOT 83].

9.2.1 Pavement Design Using Crushed Limestone as Base

The FPS11PC design system was used to determine layer thickness of a pavement structure consisting of a new limestone base and an HMAC riding surface on top of the existing scarified pavement, as described earlier. Table 9.1 lists some of the design variable values.

Table 9.1 Design variable values used for thickness design in FPS11PC

Design Variable	Value Assigned
Analysis Period (years)	20.00
Discount Rate (percent per year)	7.00
Number of Traffic Lanes	1
Lane Width / Shoulder Width (one dir., m)	3.7 / 3.0
Roadbed Soil Swelling	Considered
Performance Period of Initial Pavement (yr.)	14.00
Total number 18-kip ESALs in 20 years	60354
Minimum Thickness of AC Surface (cm)	3.8
Minimum Thickness of Flexible Base (cm)	30.5
Fixed Thickness of Original Structure (cm)	24.1

The optimal design had a 30.5-cm thick flexible base layer with a 3.8-cm thick HMAC riding surface, on top of the existing 24.1-cm thick pavement. The total cost of the 2.72 km long highway was estimated to be $860,091.

9.2.2 Pavement Design Using RAP as Base Course

Under the VECP the contractor proposed to leave the existing pavement as is and provide a RAP base course with a 3.8-cm HMAC riding surface. The same variables as listed in Table 9.1 were used for design purposes, except for the minimum thickness of the RAP base course, which was fixed at 30.5 cm. The optimal design had a 40.64-cm RAP base course with a 3.8-cm HMAC layer. The original pavement with a thickness of 24.1 cm was left undisturbed. The total construction cost in this case was estimated to be $ 567,919.

The only difficulty during this process was the estimation of the structural coefficients for RAP for use with the FPS11PC procedure. Dynaflect could not be used, as a pavement having a similar layer thickness was not available. To overcome this problem, TxDOT district laboratories tested RAP using their standard method for asphalt stabilized base materials. Based on their determination that the asphalt stabilized RAP had comparable strength characteristics to those of asphalt stabilized base material, it was treated as such and was assigned a structural coefficient of 0.82. Additional information about structural coefficients is provided in Appendix F of this document [Fults 95].

9.3 ECONOMIC ANALYSIS OF ALTERNATIVE BASE COURSES

The largest economic advantage of the VECP was that 1308 cubic meters of required flexible base material was replaced with 1125 cubic meters of RAP material, which was available to the department at no cost. Converting to a RAP base course also saved on the quantities of lime treatment as well as on the required excavation, since the existing pavement was left undisturbed under the VECP. Appendix G lists the items for both the original design as well as the modified design under the VECP and the projected savings. By agreeing to the VECP, the department saved a total amount of $442,397, exclusive of overhead and profit. The contractor was entitled to 50 percent of that amount, or $221,198 as shown in Appendix G. Appendix G also shows the change in required quantities and the corresponding unit prices.

9.4 FINAL REMARKS

Besides economic savings, the department also benefited from improved public relations and earned public good will by using RAP. The use of RAP base material also expedited the project by about 7 months owing to the elimination of such time-intensive work items as the preparation of the subgrade and the flexible base course. Also, the RAP base course could be opened to traffic much sooner than the proposed limestone base. By using a RAP base course, the overall completion of the project was expedited and, as a consequence, the time during which local residents were inconvenienced was shortened. A much cleaner construction project also resulted by eliminating the flexible limestone base course and the lime slurry placement for subgrade. Dust pollution was eliminated by avoiding lime treatment of base, hence improving the overall project safety. Eliminating the latter enhanced handling of traffic through the project and the chances for lime slurry damage to vehicles traveling through the project were avoided.

The RAP recycling project in Wichita Falls concurred with the findings of this research, which identified RAP as among the top recommended materials for use as roadbase. The strength properties were demonstrated to be adequate, and comparable to standard TxDOT asphalt stabilized bases. Also, a better paving material was utilized at a lower cost.

CHAPTER 10. CONCLUSIONS AND RECOMMENDATIONS

10.1 INTRODUCTION

The purpose of this study was to evaluate the potential use of waste materials in roadbase construction. The work produced a system for evaluating WRMs based on technical, economic, societal, and environmental aspects of their use in roadbase construction. The premise behind the development of the WRM evaluation system was to define a rational basis for choosing a WRM from the available waste materials, based on objective data, for detailed laboratory testing. As it turned out, three WRMs passed the WRM evaluation system and were recommended for detailed laboratory testing that could lead to specifications. These WRMs were RAP, RPCP, and EAFS. The selected WRMs were then subjected to detailed laboratory testing to develop trial specifications for their use in roadbase construction.

The developed WRM evaluation system bases the estimation of the utilization potential on technical, economic, societal, and environmental aspects of their use in roadbase, after an initial screening process which is used to discard WRMs with low utilization potential. The technical evaluation sub-system identifies candidate WRMs based on selected technical properties, such as gradation, hardness, and toughness. The economic evaluation subsystem identifies waste materials that are potentially viable in an economic sense for use. The societal evaluation sub-system considers the interest or desire expressed by society for WRM utilization. The environmental evaluation subsystem measures the related impacts of WRM use on the surrounding environment.

A TxDOT advisory committee that includes practicing engineers was regularly updated on the progress being made on the project. Their recommendations were considered when making important research decisions, such as the selection of laboratory test methods.

10.2 FINDINGS

The findings of this study are as follows:

1. WRMs often do not equal conventional materials in technical quality but may still have a high societal, environmental, and/or economic value. When technical, economic, societal, and environmental factors are taken into account, WRMs can sometimes prove to be effective.
2. Since no satisfactory method was known for evaluating the utilization potential of WRMs in roadbase, one was developed. It bases the estimation of utilization potential on technical, economic, societal, and environmental factors.
3. An expert review panel suggested that the technical evaluation subsystem be weighted most heavily in the overall WRM evaluation system, followed by economic, environmental, and societal evaluation subsystems.
4. The WRM evaluation system developed for this project can be used to estimate the WRM utilization potential for other engineering applications by making changes and/or modifications to the evaluation criteria.

5. RAP is stockpiled in 19 of the 21 TxDOT districts that responded to the survey, and is widely available in districts that reported stockpiles. The second most abundant material is RPCP, which was reported to be stockpiled by 9 TxDOT districts. As far as commercial materials are concerned, fly ash had 33 percent stockpiled availability followed by tire chips with 29 percent availability.
6. Since all WRMs are different, and given that there is considerable variability in their properties, each WRM source must be tested individually before it is recommended for use.
7. RAP demonstrated the maximum utilization potential of 70 percent after evaluation using the developed WRM evaluation system. RAP was followed by EAFS with a utilization potential of 60 percent, RPCP with 50 percent, and coal combustion by-products, which had a utilization potential of 45 percent.
8. A standard TxDOT roadbase consisting predominantly of limestone was evaluated using the WRM evaluation system for comparison purposes. The standard roadbase was evaluated to have a utilization potential of 58 percent. This lower ranking was due to environmental and societal disadvantages.
9. Results of the case study showed that use of WRMs in roadbase is a viable alternative. This approach results in safer, cleaner, and expedited construction projects that also cost less.
10. The developed trial specifications provide a start in the right direction, though field testing remains to be done to develop performance-based specifications.

10.3 RECOMMENDATIONS

The results of this study point to several recommendations for future research and to facilitate the maximum use of waste materials in roadbase construction.

1. It is recommended that the evaluation system be modified to rationally and objectively evaluate WRMs for other engineering applications. This could be accomplished by making adjustments to the evaluating attributes for each appropriate evaluation sub-system.
2. Environmental tests such as TCLP model the behavior of WRMs only when disposed in municipal landfills and are not well-suited for testing WRMs in highway construction. The environmental evaluation subsystem could be upgraded to include the BioAssey or some other appropriate test once they are fully developed.
3. A comprehensive analytical, laboratory, and field study should be conducted to estimate the performance of the top ranked WRMs. The trial specifications could be modified in light of the results of the study.
4. Current TxDOT specifications should be modified to accommodate WRMs based on the developed trial specifications.
5. A comprehensive field experiment should be undertaken on all the tested WRMs. This work could be done by constructing, with TxDOT's assistance, a number of 0.8 km long test sections in one or two districts, using the developed trial specifications. Using this approach, material performance could be tested and both inventory and monitoring data be collected. This would help determine the long-term WRM performance.

6. A data base should be set up to store all the data generated during this research and also that collected from the field experiments.
7. The developed trial specifications should be implemented and further studied in pilot experiments. These should be made less restrictive, if possible, based on the field performance of WRMs.
8. Research should be undertaken to determine if a usable product is possible by combining different WRMs in various combinations.
9. The WRM evaluation method as proposed herein is deterministic in nature. In fact, there are many variabilities in cost and subjective attributes of the process. Clearly, a more realistic future approach would be to extend this into a stochastic process. It is therefore recommended that future work assess the variability of various input parameters in order to gain an understanding of the sensitivity of the method to these variable parameters. Subsequently, the process could be expanded to handle variability using the fuzzy set or multi-attribute utility theory.

BIBLIOGRAPHY

AASHTO 93 American Association of State Highway and Transportation Officials (AASHTO). *AASHTO Guide for Design of Pavement Structures, 1993*. AASHTO, Washington, D.C., 1993.

AASHTO 94 American Association of State Highway and Transportation Officials (AASHTO). *Use of Waste Materials in Highway Construction*. Quality Construction Task Force, AASHTO Subcommittee on Construction, AASHTO, Washington, D.C., August, 1994.

Ahmad 91 Imtiaz Ahmad. *Use of Recycled Materials in Highway Construction.* Research Report FHWA/IN/JHRP-91/3, School of Civil Engineering, Purdue University, West Lafayette, Indiana, 1991.

Ahmad 92 Imtiaz Ahmad, and C. W. Lovell. Use of Recycled Materials in Highway Construction: State of the Practice and Evaluation of Selected Waste Products. In *Transportation Research Record No: 1345: Geoenvironmental and Engineering Properties of Rock, Soil, and Aggregate,* Transportation Research Board, National Research Council, Washington, D.C., 1992.

AI 79 Asphalt Institute. *A Basic Asphalt Emulsion Manual*. Manual Series no. 19 (MS-19). Second Edition. Asphalt Institute, Lexington, Kentucky, January 1979.

AI 88 Asphalt Institute. *Asphalt Cold Mix Recycling*. Manual Series no. 21 (MS-21). First Edition. Asphalt Institute, College Park, Maryland, May 1988.

AI 90 Asphalt Institute. *Asphalt Cold Mix Manual.* Manual Series no. 14 (MS-14). Third Edition. Asphalt Institute, Lexington, Kentucky, September 1990.

AI 91 Asphalt Institute. *The Asphalt Handbook*. Manual Series No. 4 (MS-4). 1989 Edition, Printed December 1991. Asphalt Institute, Lexington, Kentucky, December 1991.

Allemen 96 Allemen, J. E., and K. C. Bastian. BIOASSAY Determination of Spent Foundry Sand Toxicity. Appendix A for *Use of Coal Combustion Residue and Waste Foundry Sands in Flowable Fills*. Joint Highway Research Project. Unpublished Draft Final Report FHWA/IN/JHRP-96/2. Purdue University, West Lafayette, Indiana, 1996.

ARRA 86 Asphalt Recycling and Reclaiming Association (AARA). *Guidelines for Cold In-Place Recycling*. ARRA, Annapolis, Md., 1986.

ASTM C 127 American Society for Testing and Materials (ASTM). *Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate*. ASTM C 127 - 93. ASTM Committee C - 9 on Concrete and Concrete Aggregates, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1993.

ASTM C 128 American Society for Testing and Materials (ASTM). *Standard Test Method for Specific Gravity and Absorption of Fine Aggregate*. ASTM C 128 - 93. ASTM Committee C - 9 on Concrete and Concrete Aggregates, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1993.

ASTM C 136 American Society for Testing and Materials (ASTM). *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates.* ASTM C 136 - 93. ASTM Committee C - 9 on Concrete and Concrete Aggregates, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1993.

ASTM D 1633 American Society for Testing and Materials (ASTM). *Standard Test Method for Compressive Strength of Molded Soil-Cement Cylinders.* ASTM D 1633 - 90. ASTM Committee D - 18 on Soil and Rock, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1990.

ASTM D 2216 American Society for Testing and Materials (ASTM). *Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock.* ASTM D 2216 - 92. ASTM Committee D - 18 on Soil and Rock, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1992.

ASTM D 2940 American Society for Testing and Materials (ASTM). *Standard Specifications for Graded Aggregate Material for Bases or Subbases for Highways or Airports.* ASTM D 2940 - 92. ASTM Committee D - 4 on Road and Paving Materials, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1992.

ASTM D 3397 American Society for Testing and Materials (ASTM). *Standard Methods for Triaxial Classification of Base Materials, Soils, and Soil Mixtures.* ASTM D 3397 - 81. ASTM Committee D - 4 on Roads and Paving Materials, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1981.

ASTM D 698 American Society for Testing and Materials (ASTM). Standard *Test Method for Laboratory Compaction Characteristics of Soils Using Standard Effort.* ASTM D 698-91. ASTM Committee D - 4 on Roads and Paving Materials, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1991.

ASTM D 1557 American Society for Testing and Materials (ASTM). *Standard Test Method for Laboratory Compaction Characteristics of Soils Using Modified Effort.* ASTM D 1557 - 91. ASTM Committee D - 4 on Roads and Paving Materials, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1991.

ASTM D 1883 American Society for Testing and Materials (ASTM). *Standard Test Method for CBR (California Bearing Ratio) of Laboratory - Compacted Soils.* ASTM D 1883 - 94. ASTM Committee D - 18 on Soil and Rock, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1994.

ASTM D 3398 American Society for Testing and Materials (ASTM). *Standard Test Method for Index of Aggregate Particle Shape and Texture.* ASTM D 4318 - 93. ASTM Committee D - 4 on Roads and Paving Materials, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1993.

ASTM D 4318 American Society for Testing and Materials (ASTM). *Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils.* ASTM D 4318 - 93. ASTM Committee D - 18 on Soil and Rock, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1993.

Bergren 77 Bergren, Jerry V. *Portland Cement Concrete Utilizing Recycled Pavements.* Iowa Department of Transportation, January 1977.

Berry 83 Barry, L. G., and M. Brian. *Mineralogy.* 2nd Edition, 1983.

Bhat 96 — Bhat, S. T., and C. W. Lovell. *Use of Coal Combustion Residue and Waste Foundry Sands in Flowable Fills.* Joint Highway Research Project. Unpublished Draft Final Report FHWA/IN/JHRP-96/2. Purdue University, West Lafayette, Indiana, 1996.

Boles 86 — W. F. Boles. *Fly Ash Facts for Highway Engineers.* Technology Transfer Report FHWA-DP-59-8, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1986.

Bronson 85 — Bronson, A., and G. R. Pierre. Electric Furnace Slags. In *Electric Furnace Steel Making*. Iron and Steel Industry. Book Crafters, Inc., Chelsea, Michigan, 1985.

Burke 92 — Burke, Thomas T., Menashi D. Cohen, and Charles F. Scholer. *Synthesis Study in the Use of Concrete Recycled from Pavements and Building Rubble in the Indiana Highway System.* Joint Highway Research Project. Final Report FHWA/IN/JHRP-92/15. School of Civil Engineering, Purdue University. West Lafayette, Indiana, 1992.

Burkett 95 — Zack Burkett Co. *Value Engineering Change Proposal, Wichita County, FM 369, Project AR 802-1-17.* VECP by Zack Burket Co., General Contractor, Graham, Texas. July 11, 1995.

Calvert 77 — G. Calvert. *Iowa DOT's Experience with Recycling Portland Cement Pavement and Asphalt Cement Pavement.* Research Report MLR 77-4, Iowa Department of Transportation, Iowa, 1977.

CAR 95 — Center for Aggregate Research (CAR). *3rd Annual Symposium Proceedings: Concrete, Bases, and Fines.* March 2-4, 1995, J. J. Pickle Research Center. CAR. The University of Texas at Austin, Austin, Texas, March 1995.

Clemen 90 — Clemen, Robert T. *Making Hard Decisions: An Introduction to Decision Analysis.* Duxbury Press, Wadsworth Publishing Company, Belmont, California, 1990.

Emery 82 — J. J. Emery. *Slag Utilization in Pavement Construction, Extending Aggregate Resources.* American Society for Testing Materials (ASTM) Standard Testing Protocol (STP) 774, ASTM, Philadelphia, Pennsylvania, 1982.

EPA 85 — Environmental Protection Agency (EPA). *Test Methods for Evaluating Solid Wastes: Physical, Chemical Methods, Second Edition.* EPA Research Report EPA/SW-846. United States Environmental Protection Agency, Washington, D.C., 1985.

EPA 90 — Environmental Protection Agency (EPA). *Characterization of Municipal Waste in the United States: 1990 Update.* EPA Research Report EPA/530-SW-042. United States Environmental Protection Agency, Washington, D.C., 1990.

Epps 80 — Epps, J. A. *State-of-the-Art Cold Recycling.* In *Transportation Research Record 780: Proceedings of the National Seminar on Asphalt Pavement Recycling*, Transportation Research Board, National Research Council, Washington, D.C., 1980.

EPRI 87 — Western Research Institute. Evaluation of the Toxicity Characterization Leaching Procedure on Utility Wastes. Research Report EPRI CS-5355, Electric Power Research Institute, Palo Alto, California, 1987.

Ferreira 87 M. A. Ferreira, V. P. Servas, and C. P. Marsais. Accelerated Testing of Recycled Asphalt Concrete. *Proceedings, Association of Asphalt Paving Technologies*, Volume 56, Technical Session, 1987.

FHWA 86 Boles, William F. *Fly Ash facts for Highway Engineers*. Technology Transfer Demonstration Project. FHWA-DP-59-8. FHWA, Washington, D.C., July 1986.

Forster 95 Forster, S. W. *Recycled Concrete as Coarse Aggregate in Concrete. Proceedings of the 3rd Annual Symposium "Aggregates: Concrete, Bases, and Fines"*. Center for Aggregate Research. J. J. Pickle Research Center, The University of Texas at Austin. Austin, Texas, March 1995.

Fults 95 Fults, Ken. *Typical Stiffness Coefficients, TxDOT Memorandum to all District and Pavement Engineers*. Office of the Director of Pavements. Pavements Section, Design Division. Texas Department of Transportation. Austin, Texas, June 7, 1995.

Gantz 85 Gantz, J. E. Electric Arc Furnace Practice for Plain Carbon and Low-Alloy Steels. In *Electric Furnace Steel Making*. Iron and Steel Industry. Book Crafters, Inc., Chelsea, Michigan, 1985.

Han 95 Chunhua Han, and Ann M. Johnson. *Waste Products in Highway Construction*. Braun Intertec Corporation. Sixth International Conference on Low-Volume Roads, Transportation Research Board, 1995.

Huang 62 Huang, E. Y. *A Test for Evaluating the Geometric Characteristics of Coarse Aggregate Particles*. American Society for Testing and Materials Proceedings. ASTM, Philadelphia, Pennsylvania, 1993.

Huang 90 W. H. Huang. *The Use of Bottom Ash in Highway Embankment and pavement Construction*. doctoral dissertation, Department of Civil Engineering, Purdue University, West Lafayette, Indiana, 1990.

Hughes 90 C. S. Hughes. *Feasibility of Using Recycled Glass in Asphalt*. Research Report VTRC90-R3, Virginia Transport Research Council, Charlottesville, Virginia, 1990.

Inberg 80 Inberg, R. C. Specifications Related to Project Selection. In *Transportation Research Record 780: Proceedings of the National Seminar on Asphalt Pavement Recycling*. Transportation Research Board, National Research Council, Washington, D.C., 1980.

ISS 85 Iron and Steel Society. *Electric Furnace Steelmaking*. Electric Furnace Slags (chapter 22) by A. Bronson., and G. R. Pierre. Iron and Steel Industry. Book Crafters, Inc., Chelsea, Michigan, 1985.

Keller 90 G. R. Keller. Retaining Forest Roads. In *Civil Engineering*, American Society of Civil Engineers, Vol. 60, No. 12, 1990.

Kimbell 92 D. Kimbell. *Recycling in America: a reference handbook*. ABC-CLIO, Inc. Santa Barbara, California, 1992.

Lawrence 85 Lawrence, G. D. Electric Steel Melting Furnace Design. In *Electric Furnace Steel Making*. Iron and Steel Industry. Book Crafters, Inc., Chelsea, Michigan, 1985.

Lum 92 Lum, K. M., Y. D. Wong, and S. L. See. Electric Arc Furnace (EAF) Slag as an Aggregate in Asphalt Concrete, in *Utilization of Waste Materials in Civil Engineering Construction*. Edited by Hilary I. Inyang, and Kenneth L. Bergeson.

Proceedings of Sessions sponsored by the Materials Engineering Division of the American Society of Civil Engineers (ASCE) in conjunction with the ASCE National Convention. New York, New York, September 1992.

Marks 84 V. J. Marks. *Recycled Portland Cement Concrete Pavement in Iowa — Final Report.* Research Report HR-506, Iowa Department of Transportation, Iowa, 1984.

Monex 89a Monex Resources Inc. *Material Safety Data Sheet — Fly Ash.* Monex Resources Inc. San Antonio, Texas, February 1989.

Monex 89b Monex Resources Inc. *Material Safety Data Sheet — Bottom Ash.* Monex Resources Inc. San Antonio, Texas, February 1989.

MPCA 90 Twin City Testing Corporation. *Waste Tires in Sub-grade Road Beds, A Report on the Environmental Study of the Use of Shredded Waste Tires for Roadway Sub-grade Support.* Waste Tire Management Unit. Ground Water and Solid Waste division, Minnesota Pollution Control Agency, Minnesota, February 1990.

NCHRP 76 R. H. Miller, and R. J. Collins. *Waste Materials as Potential Replacements for Highway Aggregates.* NCHRP Report no. 166, Transportation Research Board, National Research Council, Washington, D.C., 1976.

NCHRP 80 J. A. Epps, D. N. Little, and R. J. Holmgreen. *Guidelines for Recycling Pavement Materials.* National Cooperative Highway Research Program Report No. 224. National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C., 1980.

NCHRP 90 Jon A Epps. *Synthesis of Highway Practice Report 160: Cold-Recycled Bituminous Concrete Using Bituminous Materials.* National Cooperative Highway Research Program (NCHRP), Transportation Research Board, National Research Council, Washington, D.C., 1990.

NSA 91 Barksdale, Richard D. *The Aggregate Handbook.* National Stone Association. Washington, D. C., 1991.

OSHD 91 Amy Edwards, Jim Huddleston, Luci Moore. and Jeff Gower. *Establishing Layer Coefficients for Cement Treated Base (CTB), Plant Mix Bituminous Base (CMBB), and Recycled Asphalt Pavement (RAP).* HPR 5282. Prepared for the Materials and Research. Oregon Department of Transportation. Pavements Unit. Oregon State Highway Division, Salem, OR.

Paulsen 88 G. Paulsen, M. Stroup-Gardiner, and J. Epps. *Roofing Waste in Asphalt Paving Mixtures.* Department of Civil Engineering, University of Nevada, Reno, Nevada, 1988.

R&B 85 Special Report: Asphalt Recycling and Reclaiming '85. In *Roads & Bridges.* Vol. 23, No. 10, October 1985.

R&B 93 Flynn, Larry. Innovation can Turn 'trashphalt' to asphalt. In *Roads & Bridges*, Volume 31, No. 7, July 93.

Read 90 J. Read, T. Dodson and J. Thomas. *Use of Shredded Tires for Lightweight Fill.* Research Report DTFH-71-90-501-OR-11, Oregon Department of Transportation, Salem, Oregon, 1990.

Roberts 92 Roberts, F. L., P. S. Kandhal, E. R. Brown, D. Y. Lee, and T. W. Kennedy. *Hot Mix Asphalt Materials, Mixture Design, and Construction.* First Edition. NAPA Education Foundation. Lanham, Maryland, March 92.

Saaty 80 Saaty, Thomas L. *The Analytic Hierarchy Process: Planning, setting Priorities, and Resource Allocation.* McGraw Hill International Book Co., New York, 1980.

Saaty 82 a Saaty, Thomas L., and Luis G. Vargas. *The Logic of Priorities: Applications in Business, Energy, Health, and Transportation.* Kluwer-Nijhoff Publishing, Boston, 1982.

Saaty 82 b Saaty, Thomas L. *Decision Making for Leaders: The Analytical Hierarchy Process for Decisions in the Complex World.* Lifetime Learning Publications, California, 1982.

Saeed 95 Saeed, A., W. R. Hudson, and P. Anaejionu. *Location and Availability of Waste and Recycled Materials in Texas and Evaluation of their Utilization Potential in Roadbase.* Research Report 1348-1, Research Study No. 0-1348 . Center for Transportation Research, The University of Texas at Austin. Austin, Texas, October 1995.

Scanner 71 Scanner, W. S. and D. E. Wolfson. *Pyrolysis of Municipal and Industrial Waste.* Centennial Symposium on Technology for the Future to Control Industrial and Urban Wastes. University of Missouri at Rolla, February 1971.

Scherocman 83 Scherocman, J. A. Cold In-Place Recycling of Low-Volume Roads. In *Transportation Research Record 898: Low-Volume Roads: Third International Conference, 1983,* Transportation Research Board, National Research Council, Washington, D.C., 1983.

Svedala 95 Archer, Kelly. Project Coordinator. *Personal Communication about Recycling Plants Manufactured by Svedala Industries.* Svedala Industries, Inc. Universal Engineering Division, Cedar Rapids, Iowa, November 20, 1995.

Tex-100-E 95 Test Method Tex-100-E. *Surveying and Sampling Soils for Highways.* 100-E Series. Soils Section. Manual of Testing Procedures. Materials and Test Division. Texas Department of Transportation. Austin, Texas, September 1995.

Tex-103-E 95 Test Method Tex-103-E. *Determination of Moisture Content in Soil Materials.* 100-E Series. Soils Section. Manual of Testing Procedures. Materials and Test Division. Texas Department of Transportation. Austin, Texas, September 1995.

Tex-104-E 95 Test Method Tex-104-E. *Determination of Liquid Limit of Soils.* 100-E Series. Soils Section. Manual of Testing Procedures. Materials and Test Division. Texas Department of Transportation. Austin, Texas, September 1995.

Tex-106-E 95 Test Method Tex-106-E. *Determination of Plastic Limit of Soils.* 100-E Series. Soils Section. Manual of Testing Procedures. Materials and Test Division. Texas Department of Transportation. Austin, Texas, September 1995.

Tex-110-E 95 Test Method Tex-110-E. *Determination of Particle Size Analysis of Soils.* 100-E Series. Soils Section. Manual of Testing Procedures. Materials and Test Division. Texas Department of Transportation. Austin, Texas, September 1995.

Tex-113-E 95 Test Method Tex-113-E. *Determination of Moisture-Density Relationship of Soils and Base Materials.* 100-E Series. Soils Section. Manual of Testing Procedures.

Materials and Test Division. Texas Department of Transportation. Austin, Texas, September 1995.

Tex-117-E 95 Test Method Tex-117-E. *Triaxial Compression Test for Disturbed Soils and Base Materials.* 100-E Series. Soils Section. Manual of Testing Procedures. Materials and Test Division. Texas Department of Transportation. Austin, Texas, September 1995.

Tex-120-E 95 Test Method Tex-120-E. *Soil-Cement Compressive Strength Test Methods.* 100-E Series. Soils Section. Manual of Testing Procedures. Materials and Test Division. Texas Department of Transportation. Austin, Texas, September 1995.

Tex-126-E 95 Test Method Tex-126-E. *Molding, Testing, and Evaluation of Bituminous Black Base Materials.* 100-E Series. Soils Section. Manual of Testing Procedures. Materials and Test Division. Texas Department of Transportation. Austin, Texas, September 1995.

Tex-200-F 95 Test Method Tex-200-F. *Sieve Analysis of Fine and Coarse Aggregate.* 200-F Series. Bituminous Section. Manual of Testing Procedures. Materials and Test Division. Texas Department of Transportation. Austin, Texas, September 1995.

Tex-201-F 95 Test Method Tex-201-F. *Bulk Specific Gravity and Water Absorption of Aggregate.* 200-F Series. Bituminous Section. Manual of Testing Procedures. Materials and Test Division. Texas Department of Transportation. Austin, Texas, September 1995.

Tex-206-F 95 Test Method Tex-206-F. *Method of Compacting Test Specimens of Bituminous Mixtures.* 200-F Series. Bituminous Section. Manual of Testing Procedures. Materials and Test Division. Texas Department of Transportation. Austin, Texas, September 1995.

Tex-208-F 95 Test Method Tex-208-F. *Test for Stabilometer Value of bituminous Mixtures.* 200-F Series. Bituminous Section. Manual of Testing Procedures. Materials and Test Division. Texas Department of Transportation. Austin, Texas, September 1995.

Tex-210-F 95 Test Method Tex-210-F. *Determination of Asphalt Content of Bituminous Mixtures by Extraction.* 200-F Series. Bituminous Section. Manual of Testing Procedures. Materials and Test Division. Texas Department of Transportation. Austin, Texas, September 1995.

Tex-211-F 95 Test Method Tex-211-F. *Recovery of Asphalt from Bituminous Mixtures by the Abson Process.* 200-F Series. Bituminous Section. Manual of Testing Procedures. Materials and Test Division. Texas Department of Transportation. Austin, Texas, September 1995.

Tex-907-K 95 Test Method Tex-907-K. *Verification of the Accuracy of Wire-Cloth Sieves.* 900-K Series. Certification Section. Manual of Testing Procedures. Materials and Test Division. Texas Department of Transportation. Austin, Texas, September 1995.

TGLO 93 G. Mauro. *Texas Recycles: Marketing our Neglected Resources.* Texas General Land Office, Austin, Texas, 1993.

TRB 76 NCHRP Report 166: *Waste Materials as Potential Replacements for Highway Aggregates.* Transportation Research Board, National Research Council, Washington, D. C., 1976.

TRB 78 *NCHRP Report 54: Recycling Materials for Highways.* Transportation Research Board, National Research Council, Washington, D. C., 1978.

TSGCA 95 Transportation Rates. Texas Sand and Gravel Motor Carriers Association. 400 West 15th Street. Austin, Texas, January 1995.

TTI 68 a Scrivner, F. H., and W. M. Moore. *An Empirical Equation for Predicting Pavement Deflections.* Research Report 32-12. Texas Transportation Institute, Texas A&M University, College Station, Texas, October 1968.

TTI 68 b Scrivner, F. H., W. M. Moore, W. F. McFarland, and Gary R. Carey. *A Systems Approach to the Flexible Pavement Design Problem.* Research Report 32-11. Extension of AASHO Road Test Results, Research Study 2-8-62-32. Sponsored by Texas Highway Department, in corporation with U. S. Department of Transportation, Federal Highway Administration, Bureau of Public Roads. Texas Transportation Institute, Texas A&M University, College Station, Texas, October 1968.

TTI 69 Scrivner, F. H., and C. H. Michalak. *Flexible Pavement Performance Related to Deflections, Axle Applications, Temperature, and Foundation Movement.* Research Report 32-13. Extension of AASHO Road Test Results, Research Study 2-8-62-32. Sponsored by Texas Highway Department, in corporation with U. S. Department of Transportation, Federal Highway Administration, Bureau of Public Roads. Texas Transportation Institute, Texas A&M University, College Station, Texas, January 1969.

TTI 94 Estakhri, Cindy K, and John Bohuslav. *Routine Maintenance Uses for Milled Reclaimed Asphalt Pavement (RAP).* Research Report 1272-2F, Research Study No. 0-1272. Texas Transportation Institute, Texas A&M University. College Station, Texas, April 1994.

TxDOT *Make a Difference — Recycle.* Informational brochure about recycling in TxDOT, Texas Department of Transportation, Austin, Texas.

TxDOT 83 *Pavement Design System. Part I. Flexible Pavement Designer's Manual.* Highway Design Division. Texas State Department of Highways and Public Transportation. Revised May 1993.

TxDOT 92a *Department Use of Reclaimed Asphalt Pavement During FY 1992.* Annual Report to Legislative Audit Committee, Prepared by the Construction and Maintenance Division, Texas Department of Transportation, Austin, Texas, December 1992.

TxDOT 92b Mikulin, Robert L. *Microcomputer Programs for Flexible and Rigid Pavement Designs.* Pavement Design Section. Division of Highway Design. Texas Department of Transportation, March 1992.

TxDOT 93 *Department Use of Reclaimed Asphalt Pavement During FY 1993.* Annual Report to Legislative Audit Committee, Prepared by the Construction and Maintenance Division, Texas Department of Transportation, Austin, Texas, December 1993.

TxDOT 94 *Department Use of Reclaimed Asphalt Pavement During FY 1994.* Annual Report to Legislative Audit Committee, Prepared by the Construction and Maintenance Division, Texas Department of Transportation, Austin, Texas, December 1994.

TxDOT 95 Texas Department of Transportation. *Standard Specifications for Construction of Highways, Streets and Bridges.* Adopted by the Texas Department of Transportation in March 1995. Austin, Texas, March 1995.

TxDOT PO 94 Texas Department of Transportation. *Crushing Concrete Rubble, TxDOT Special Specifications 962-99-80010.* Service Requisition / Purchase Order HW-21-5-80010, Order # 5-0138. Pharr District, Texas Department of Transportation. July 1994.

Universal 91 Universal Engineering. *Universal Concrete and Asphalt Recycling Plants.* Information Brochure. Division of Pettibone Corporation. Cedar Rapids, Iowa, 1991.

Vallerga 85 Vallerga, B. A., and W. R. Lovering. *Evolution of the Hveem Stabilometer Method of Designing Asphalt Paving Mixtures.* Proceedings of Association of Asphalt Paving Technologists (AAPT), Volume 54. AAPT, 1985.

Wood 89 Wood, L. E., Thomas D. White, and Thomas B. Nelson. Current Practice of Cold In-Place Recycling of Asphalt Pavements. In *Transportation Research Record 1178: Proceedings of the National Seminar on Asphalt Pavement Recycling.* Transportation Research Board, National Research Council, Washington, D.C., 1989.

Yoder 75 Yoder, E. J., and M. W. Witczak. *Principles of Pavement Design.* Second Edition. John Wiley and Sons, Inc., New York, New York, 1975.

APPENDIX A

WRM UTILIZATION POTENTIAL USING THE DEVELOPED WRM EVALUATION SYSTEM

Table A.1. *Estimation of Utilization Potential of RPCC*

Factor	Score	Remarks
Initial Screening		
Acc / Ann Produced Quantity	OK	19,000 tons
Material Location	OK	Various locations, accessible
Material Toxicity	OK	Non-toxic
Water Solubility	OK	Non-soluble
Material Durability	OK	Proven durability
Technical Evaluation		
Gradation	2.34	Cu ≈ 4.68
Particle Shape and Texture	3.25	Angular
Hardness	3.50	≈ 7.00
Resistance to Applied Load	1.95	≈ 30%
Economic Evaluation		
Quantity	0.26	19,000 tons
Transportation Cost	1.50	Distances > 96 km
Disposal Cost	5.00	Maximum savings
Stab / Mod / Add Material Cost	2.50	50% natural material required
Processing Cost of Reuse	4.00	Site mixed, minimal
Societal Evaluation		
Govt./Sp. Group Interest	3.00	No statutes
Health / Safety Risk	1.00	None / minimal
Storage Site Aesthetics	4.00	Highly visible, less locations
Environmental Evaluation		
Benefit of Recycling	2.50	50 % saving of virgin aggregate
Noise Pollution	5.00	No processing required
Dust Pollution	5.00	No processing required
Leaching Potential	5.00	None
WRMUP = 50.20%		

Table A.2. *Estimation of Utilization Potential of Fly Ash*

Factor	Score	Remarks
Initial Screening		
Acc / Ann Produced Quantity	OK	2 ,000 tons
Material Location	OK	Various locations, accessible
Material Toxicity	OK	Non-toxic
Water Solubility	OK	Soluble, but not applicable
Material Durability	OK	Not applicable
Technical Evaluation		
Gradation	5.00	Material obtainable as desired
Particle Shape and Texture	3.91	Angular
Hardness	3.00	≈ 6.00
Resistance to Applied Load	1.77	≈ 32.33%
Economic Evaluation		
Quantity	0.03	2,000 tons
Transportation Cost	0.75	Power plant locations
Disposal Cost	3.00	Considerable savings
Stab / Mod / Add Material Cost	1.50	100 % natural material required
Processing Cost of Reuse	2.00	Site mixed, minimal
Societal Evaluation		
Govt./Sp. Group Interest	2.50	No statutes
Health / Safety Risk	2.00	Hazardous
Storage Site Aesthetics	2.00	Hidden plant locations
Environmental Evaluation		
Benefit of Recycling	0.00	No saving of natural aggregate
Noise Pollution	5.00	No processing required
Dust Pollution	5.00	No processing required
Leaching Potential	2.50	None
WRMUP	**= 45.20 %**	

Table A.3. *Estimation of Utilization Potential of Bottom Ash*

Factor	Score	Remarks
Initial Screening		
Acc / Ann Produced Quantity	OK	2,000 tons
Material Location	OK	Various locations, accessible
Material Toxicity	OK	Non-toxic
Water Solubility	OK	Soluble, but not applicable
Material Durability	OK	Not applicable
Technical Evaluation		
Gradation	5.00	Material obtainable as desired
Particle Shape and Texture	3.91	Angular
Hardness	3.00	≈ 6.00
Resistance to Applied Load	1.77	≈ 32.33%
Economic Evaluation		
Quantity	0.02	2,000 tons
Transportation Cost	0.75	Power plant locations
Disposal Cost	3.00	Maximum savings
Stab / Mod / Add Material Cost	1.50	100 % natural material required
Processing Cost of Reuse	2.00	Site mixed, minimal
Societal Evaluation		
Govt./Sp. Group Interest	3.00	No statutes
Health / Safety Risk	2.00	Hazardous
Storage Site Aesthetics	2.00	Hidden plant locations
Environmental Evaluation		
Benefit of Recycling	0.00	No saving of natural aggregate
Noise Pollution	5.00	No processing required
Dust Pollution	5.00	No processing required
Leaching Potential	2.50	None
WRMUP	**= 45.20 %**	

Table A.4. *Estimation of Utilization Potential of Pond Ash*

Factor	Score	Remarks
Initial Screening		
Acc / Ann Produced Quantity	OK	2,000 tons
Material Location	OK	Various locations, accessible
Material Toxicity	OK	Non-toxic
Water Solubility	OK	Soluble, but not applicable
Material Durability	OK	Not applicable
Technical Evaluation		
Gradation	5.00	Material obtainable as desired
Particle Shape and Texture	3.91	Angular
Hardness	3.00	≈ 6.00
Resistance to Applied Load	1.77	≈ 32.33%
Economic Evaluation		
Quantity	0.02	2 thousand tons
Transportation Cost	0.75	Power plant locations
Disposal Cost	3.00	Maximum savings
Stab / Mod / Add Material Cost	1.50	100 % natural material required
Processing Cost of Reuse	2.00	Site mixed, minimal
Societal Evaluation		
Govt./Sp. Group Interest	2.50	No statutes
Health / Safety Risk	2.00	Hazardous
Storage Site Aesthetics	2.00	Hidden plant locations
Environmental Evaluation		
Benefit of Recycling	0.00	No saving of natural aggregate
Noise Pollution	5.00	No processing required
Dust Pollution	5.00	No processing required
Leaching Potential	2.50	None
WRMUP	**= 45.00 %**	

Table A.5. *Estimation of Utilization Potential of Electric Arc Furnace Slag*

Factor	Score	Remarks
Initial Screening		
Acc / Ann Produced Quantity	OK	130,000 tons
Material Location	OK	Various locations, accessible
Material Toxicity	OK	Non-toxic
Water Solubility	OK	Non-soluble
Material Durability	OK	Proven durability
Technical Evaluation		
Gradation	3.41	Cu ≈ 6.82
Particle Shape and Texture	3.75	Angular
Hardness	4.00	≈ 8.00
Resistance to Applied Load	2.80	≈ 22%
Economic Evaluation		
Quantity	1.83	130,000 tons
Transportation Cost	0.50	Steel plant location
Disposal Cost	5.00	Maximum savings
Stab / Mod / Add Material Cost	5.00	None required
Processing Cost of Reuse	5.00	None required
Societal Evaluation		
Govt./Sp. Group Interest	2.50	No statutes
Health / Safety Risk	1.00	None / minimal
Storage Site Aesthetics	2.50	Hidden, less locations
Environmental Evaluation		
Benefit of Recycling	5.00	100 % saving of virgin aggregate
Noise Pollution	5.00	No processing required
Dust Pollution	5.00	No processing required
Leaching Potential	2.50	Under Consideration

WRMUP = 60.40%

Table A.6. *Estimation of Utilization Potential of Natural Crushed Limestone*

Factor	Score	Remarks
Initial Screening		
Acc / Ann Produced Quantity	OK	Freely available
Material Location	OK	Various locations, accessible
Material Toxicity	OK	Non-toxic
Water Solubility	OK	Non-soluble
Material Durability	OK	Proven durability
Technical Evaluation		
Gradation	5.00	Available in any combination
Particle Shape and Texture	3.91	PI ≈ 15.60
Hardness	3.00	≈ 6.00
Resistance to Applied Load	1.77	≈ 32.33%
Economic Evaluation		
Quantity	5.00	Freely available
Transportation Cost	5.00	No fixed destination
Disposal Cost	0.00	Maximum savings
Stab / Mod / Add Material Cost	1.00	Cost : $ 5.00 per ton
Processing Cost of Reuse	5.00	None required
Societal Evaluation		
Govt./Sp. Group Interest	0.00	No statutes
Health / Safety Risk	0.00	None / minimal
Storage Site Aesthetics	3.00	Hidden, quarry locations
Environmental Evaluation		
Benefit of Recycling	0.00	No saving of SNA
Noise Pollution	3.00	Crusher at quarry
Dust Pollution	4.00	Crusher at quarry
Leaching Potential	5.00	None
WRMUP = 58.85%		

APPENDIX B

LABORATORY TEST DATA FOR RECLAIMED ASPHALT CONCRETE PAVEMENT ELECTRIC ARC FURNACE SLAG RECLAIMED PORTLAND CEMENT CONCRETE PAVEMENT

Table B.1. *Determination of OMC and Maximum Dry Density for RAP*

Sample Number	**1**	**2**	**3**
Assumed Water Content, %	5.00	7.00	9.00
Actual Water Content, w%	7.24	9.27	11.48
Weight of Mold, grams	2045.80	2045.80	2045.80
Weight of Soil + Mold, grams	3935.70	4066.90	4161.60
Weight of Soil in Mold, Wt grams	1889.90	2021.10	2115.80
Bulk Density, BD = Wt/V, kg/m^3	2071.54	2215.36	2319.29
Dry Density, DD = BD / (1+w), kg/m^3	1931.77	2027.43	2080.29
Sample Number	**4**	**5**	**6**
Assumed Water Content, %	11.00	13.00	
Actual Water Content, w%	11.48	12.61	
Weight of Mold, grams	2045.80	2045.80	
Weight of Soil + Mold, grams	4161.60	4150.00	
Weight of Soil in Mold, Wt grams	2115.80	2104.20	
Bulk Density, BD = Wt/V, pcf	2319.29	2306.48	
Dry Density, DD = BD / (1+w)	2080.29	2048.35	

Table B.2. Determination of Actual Moisture Content for OMC Determination for RAP

Sample Number	**1**	**2**	**3**
Container Number	6	P-5	3
Weight of Container, grams	7.20	9.00	21.00
Weight of Container + Wet Soil, grams	56.10	53.80	64.80
Weight of Container + Dry Soil, grams	52.80	50.00	60.80
Weight of Water, W_w grams	3.30	3.80	4.00
Weight of Dry Soil, W_s	45.60	41.00	39.80
Water Content, $w = W_w / W_s * 100$	7.24	9.27	10.05
Sample Number	**4**	**5**	**6**
Container Number	P-4	1	
Weight of Container, grams	7.30	9.20	
Weight of Container + Wet Soil, grams	53.90	62.80	
Weight of Container + Dry Soil, grams	50.00	56.80	
Weight of Water, W_w grams	3.80	6.00	
Weight of Dry Soil, W_s	41.00	47.60	
Water Content, $w = W_w / W_s * 100$	11.48	12.61	

Table B.3. *Determination of CBR at Various Compactive Efforts for RAP*

Penetration (mm)	Compaction		
	10 Blows	25 Blows	56 Blows
	Stress (kPa)		
0.635	1271.55	3996.2	4406.5
1.270	2488.25	4713.38	5677.98
1.905	3792.60	5151.86	6269.90
2.540	4844.91	5261.48	6686.40
3.175	5107.97	5480.65	6554.87
3.810	5634.16	5512.00	7366.03
4.445	5765.69	5580.90	8462.16
5.080	6335.70	6050.66	7782.60
5.715	6247.99	6890.00	7563.36
6.350	6116.46	7165.60	7870.24
6.985	6861.82	7453.74	8064.40
7.620	6861.82	7651.00	8327.53
8.255	6532.96	7923.50	8283.64
8.890	6028.75	7992.40	8502.88
9.525	9580.20	8061.30	9029.00
10.160	7738.71	8268.00	8963.27
10.795	8396.43	10961.37	9010.26
11.430	6905.64	8242.92	10059.40
12.065	7037.17	8612.50	9818.25
12.700	7300.30	8681.40	10059.40
CBR at 2.54 mm, %	70.32	76.36	97.05
CBR at 5.08 mm, %	61.30	58.88	75.30

Table B.4. Determination of OMC and Maximum Dry Density for EAFS

Sample Number	1	2	3
Assumed Water Content, %	3.00	4.00	5.00
Actual Water Content, w%	2.87	3.52	4.75
Weight of Mold, grams	2046.3	2046.3	2045.9
Weight of Soil + Mold, grams	2600.5	4763.4	4926.0
Weight of Soil in Mold, Wt grams	2554.6	2717.1	2879.7
Bulk Density, BD = Wt/V, pcf	2854.53	2982.46	3160.98
Dry Density, DD = BD / (1+w)	2774.91	2881.12	3017.64
Sample Number	**4**	**5**	**6**
Assumed Water Content, %	5.50	6.00	6.50
Actual Water Content, w%	5.43	6.31	6.65
Weight of Mold, grams	2046.3	2046.3	2046.3
Weight of Soil + Mold, grams	5018.0	5062.9	5085.0
Weight of Soil in Mold, Wt grams	2971.7	3016.6	3038.7
Bulk Density, BD = Wt/V, pcf	3261.83	3311.12	3335.44
Dry Density, DD = BD / (1+w)	3239.61	3114.60	3127.41

Table B.5. Determination of Actual Moisture Content for OMC Determination for EAFS

Sample Number	**1**	**2**	**3**
Container Number	2	3	P-2
Weight of Container, grams	9.2	21.1	10.0
Weight of Container + Wet Soil, grams	37.9	56.4	45.3
Weight of Container + Dry Soil, grams	37.1	55.2	47.3
Weight of Water, W_w grams	.8	1.2	1.6
Weight of Dry Soil, W_s	27.9	34.10	33.7
Water Content, $w = W_w / W_s * 100$	2.87	3.52	4.75
Sample Number	**4**	**5**	**6**
Container Number	1	L-6	P-4
Weight of Container, grams	9.1	9.2	7.4
Weight of Container + Wet Soil, grams	38.2	52.5	29.3
Weight of Container + Dry Soil, grams	36.7	49.8	28.0
Weight of Water, W_w grams	1.5	2.7	1.3
Weight of Dry Soil, W_s	27.6	40.6	20.6
Water Content, $w = W_w / W_s * 100$	5.43	6.65	6.31

Table B.6. *Determination of CBR at Various Compactive Efforts for EAFS*

Penetration	Compaction		
(mm)	10 Blows	25 Blows	56 Blows
	Stress (kPa)		
0.635	3178.77	2893.8	5524.54
1.270	3639.16	3704.96	6664.49
1.905	3989.93	4209.17	8462.16
2.540	4318.79	4735.29	9295.23
3.175	4603.76	5261.48	10698.31
3.810	4866.82	5677.98	11575.20
4.445	5217.59	6160.28	12495.98
5.080	5371.10	6620.67	13372.87
5.715	5656.07	6993.35	14205.94
6.350	6050.66	7366.03	14863.59
6.985	6138.37	7753.73	15773.41
7.620	6489.14	8067.57	16376.29
8.255	6708.38	8462.16	16924.32
8.890	6796.02	8791.02	17340.89
9.525	6927.55	9119.88	18020.45
10.160	7102.97	9382.94	18327.40
10.795	7387.94	9558.29	18809.70
11.430	7541.45	9777.53	19072.76
12.065	7782.60	10062.50	19576.97
12.700	8067.57	10391.36	19971.63
CBR at 2.54 mm, %	62.682	68.727	134.909
CBR at 5.08 mm, %	51.97	64.0607	129.394

Table B.7. *Determination of OMC and Maximum Dry Density of Cement-Stabilized EAFS*

Sample Number	**1**	**2**	**3**
Assumed Water Content, %	4.00	5.00	6.00
Actual Water Content, w%	5.01	6.07	6.46
Weight of Mold, grams	2045.90	2045.90	2045.90
Weight of Soil + Mold, grams	4600.50	4711.00	4815.00
Weight of Soil in Mold, Wt grams	2554.60	2665.10	2769.10
Bulk Density, BD = Wt/V, pcf	2800.21	2921.33	3035.31
Dry Density, DD = BD / (1+w)	2666.60	2754.16	2851.12
Sample Number	**4**	**5**	**6**
Assumed Water Content, %	7.00	8.00	9.00
Actual Water Content, w%	9.30	9.79	10.00
Weight of Mold, grams	2045.90	2045.90	2045.90
Weight of Soil + Mold, grams	4921.50	4922.50	4761.50
Weight of Soil in Mold, Wt grams	2875.60	2876.60	2715.60
Bulk Density, BD = Wt/V, pcf	3152.06	3153.19	2976.78
Dry Density, DD = BD / (1+w)	2883.87	2871.87	2706.16

Table B.8. *Estimation of Actual Moisture Content for OMC Determination Cement-Stabilized EAFS*

Sample Number	**1**	**2**	**3**
Container Number	P -2	# 3	# 2
Weight of Container, grams	9.90	21.10	9.20
Weight of Container + Wet Soil, grams	47.60	54.30	40.50
Weight of Container + Dry Soil, grams	45.80	52.40	38.60
Weight of Water, W_w grams	1.80	1.90	1.90
Weight of Dry Soil, W_s	35.90	31.30	29.40
Water Content, $w = W_w / W_s * 100$	5.01	6.07	6.46
Sample Number	**4**	**5**	**6**
Container Number	# 5	# 6	# 1
Weight of Container, grams	8.70	7.30	9.10
Weight of Container + Wet Soil, grams	36.90	55.50	54.20
Weight of Container + Dry Soil, grams	34.50	51.20	50.10
Weight of Water, W_w grams	2.40	4.30	4.10
Weight of Dry Soil, W_s	25.80	43.90	41.00
Water Content, $w = W_w / W_s * 100$	9.30	9.79	10.00

Table B.9. *Dimensions and Weights of Cement Stabilized EAFS Test Cylinders*

#	Weight (kg)		Mean		Density (kg/m^3)			H/D
	Wet	Dry	Height (mm)	Dia. (mm)	Wet	Dry	Mean (Dry)	
	Batch #1, 4% Cement, 7.75% Water (Optimum Moisture Content)							
1	8.67	8.35	192.10	144.48	2783.99	2675.36		1.33
2	8.63	8.49	192.35	144.98	2745.08	2702.92	2691.57	1.33
3	8.72	8.40	192.10	144.48	2798.59	2696.44		1.33
	Batch #2, 6% Cement, 8.00% Water (Optimum Moisture Content)							
1	9.44	9.03	197.92	148.16	2790.48	2676.98		1.34
2	9.76	9.31	195.78	147.37	2954.24	2816.42	2754.81	1.33
3	9.90	9.60	198.96	149.76	2848.85	2771.02		1.33
	Batch #3, 8% Cement, 8.25% Water (Optimum Moisture Content)							
1	10.12	9.90	202.41	151.33	2811.56	2741.84		1.33
2	9.90	9.81	209.02	138.13	3187.73	3165.03	2754.81	1.51
3	9.67	9.58	199.24	148.44	2829.39	2808.31		1.34
	Batch #4, 10% Cement, 8.50% Water (Optimum Moisture Content)							
1	10.03	9.99	192.35	144.98	3194.21	3179.62		1.33
2	10.44	10.44	195.78	146.84	3182.86	3182.86	3113.14	1.33
3	10.44	10.35	199.49	149.76	3004.51	2978.56		1.33

Table B.10. *Calculation of Unconfined Compressive Strengths for Cement-Stabilized EAFS Cylinders*

#	Unconfined Crushing		Corrected Unconfined	
	Load (N)	Strength (kPa)	Compressive Strength (kPa)	
	Batch #1, 4% Cement, 7.75% Water (Optimum Moisture Content)			
1	38270.0	2331.6	2211.69	
2	34042.5	2058.7	1956.76	(Mean: 2060.11)
3	34710.0	2114.5	2011.88	
	Batch #2, 6% Cement, 8.00% Water (Optimum Moisture Content)			
1	129495.0	7499.1	7131.15	
2	143290.0	8387.9	7971.73	(Mean: 7895.94)
3	159310.0	9031.4	8578.05	
	Batch #3, 8% Cement, 8.25% (Optimum Moisture Content)			
1	279460.0	15512.1	14737.71	
2	276790.0	18448.0	17914.00	(Mean: 18282.02)
3	240300.0	13866.1	13187.46	
	Batch #4, 10% Cement, 8.50% Water (Optimum Moisture Content)			
1	417855.0	25269.8	24004.76	
2		30067.3	28565.94	(Mean: 24425.05)
3		21795.8	20704.45	

Table B.11. *Determination of OMC and Maximum Dry Density for RPCP*

Sample Number	1	2	3
Assumed Water Content, %	5.00	7.00	9.00
Actual Water Content, w%	7.79	9.33	10.74
Weight of Mold, grams	2045.60	2045.60	2045.60
Weight of Soil + Mold, grams	3885.00	4049.50	4078.10
Weight of Soil in Mold, Wt grams	1839.40	2003.90	2032.50
Bulk Density, BD = Wt/V, kg/m^3	2016.25	2196.55	2228.01
Dry Density, DD = BD / (1+w), kg/m^3	1870.64	2009.11	2011.71
Sample Number	**4**	**5**	**6**
Assumed Water Content, %	11.00	13.00	15.00
Actual Water Content, w%	12.26	13.32	13.87
Weight of Mold, grams	2045.60	2045.60	2045.60
Weight of Soil + Mold, grams	4149.50	4103.00	4126.00
Weight of Soil in Mold, Wt grams	2103.90	2057.40	2080.40
Bulk Density, BD = Wt/V, kg/m^3	2306.16	2255.25	2280.38
Dry Density, DD = BD / (1+w), kg/m^3	2054.19	1990.14	2002.79

Table B.12. *Determination of Actual Moisture Content for OMC Determination of RPCP*

Sample Number	**1**	**2**	**3**
Container Number	6	2	3
Weight of Container, grams	7.20	9.20	21.10
Weight of Container + Wet Soil, grams	42.50	46.70	61.30
Weight of Container + Dry Soil, grams	39.95	43.50	57.40
Weight of Water, W_w grams	2.55	3.20	3.90
Weight of Dry Soil, W_s	32.75	34.30	36.30
Water Content, $w = W_w / W_s * 100$	7.79	9.33	10.74
Sample Number	**4**	**5**	**6**
Container Number	1	L-6	5
Weight of Container, grams	9.1	9.2	8.70
Weight of Container + Wet Soil, grams	56.70	54.30	62.90
Weight of Container + Dry Soil, grams	51.50	49.00	56.30
Weight of Water, W_w grams	5.20	5.30	6.60
Weight of Dry Soil, W_s	42.40	39.80	47.60
Water Content, $w = W_w / W_s * 100$	12.26	13.32	13.87

Table B.13. *Determination of CBR at Various Compactive Efforts for RPCP*

Penetration	Compaction		
(mm)	10 Blows	25 Blows	56 Blows
	Stress (kPa)		
0.635	1666.14	2455.32	3485.72
1.270	1973.02	3639.16	4516.05
1.905	2543.03	4472.23	5436.83
2.540	3047.24	4976.44	6138.37
3.175	3683.05	5568.36	6642.58
3.810	4384.52	6138.37	7322.21
4.445	4143.37	6598.76	8001.77
5.080	4406.50	7037.17	8703.31
5.715	5502.63	7585.27	9054.08
6.350	5656.07	8111.39	9382.94
6.985	5612.25	8571.78	10084.48
7.620	5393.01	8944.46	10435.25
8.255	6138.37	9448.67	10764.04
8.890	6204.10	9733.71	11290.23
9.525	7585.27	10084.48	11465.58
10.160	7124.88	10303.65	11794.44
10.795	7146.79	10479.07	12145.21
11.430	7146.79	10676.40	12320.56
12.065	7146.79	10873.66	12824.77
12.700	7168.70	11158.70	13000.19
CBR at 2.54 mm, %	44.23	72.23	89.09
CBR at 5.08 mm, %	42.64	68.09	84.21

Table B.14. *Determination of OMC and Maximum Dry Density of Cement-Stabilized RPCP*

Sample Number	**1**	**2**	**3**
Assumed Water Content, %	8.00	10.00	12.00
Actual Water Content, w%	9.64	11.65	15.03
Weight of Mold, grams	2047.80	2047.80	2047.80
Weight of Soil + Mold, grams	3957.00	4006.40	4031.00
Weight of Soil in Mold, Wt grams	1909.20	1958.60	1983.20
Bulk Density, BD = Wt/V, kg/m^3	2092.78	2146.93	2173.85
Dry Density, DD = BD / (1+w), kg/m^3	1908.75	1922.85	1889.94
Sample Number	**4**	**5**	**6**
Assumed Water Content, %	14.00	17.00	
Actual Water Content, w%	17.79	20.61	
Weight of Mold, grams	2047.80	2047.80	
Weight of Soil + Mold, grams	4057.50	3991.60	
Weight of Soil in Mold, Wt grams	2009.70	1943.80	
Bulk Density, BD = Wt/V, kg/m^3	2202.87	2130.72	
Dry Density, DD = BD / (1+w), kg/m^3	1870.32	1766.71	

Table B.15. *Determination of Actual Moisture Content for OMC Determination of Cement-Stabilized RPCP*

Sample Number	**1**	**2**	**3**
Container Number	# 1	# 2	# 6
Weight of Container, grams	9.10	9.20	7.30
Weight of Container + Wet Soil, grams	18.20	20.70	29.50
Weight of Container + Dry Soil, grams	17.40	19.50	26.60
Weight of Water, W_w grams	0.80	1.20	2.90
Weight of Dry Soil, W_s	8.30	10.30	19.30
Water Content, $w = W_w / W_s * 100$	9.64	11.65	15.03
Sample Number	**4**	**5**	**6**
Container Number	# 5	# 3	
Weight of Container, grams	8.80	21.10	
Weight of Container + Wet Soil, grams	33.30	41.00	
Weight of Container + Dry Soil, grams	29.60	37.60	
Weight of Water, W_w grams	3.70	3.40	
Weight of Dry Soil, W_s	20.80	16.50	
Water Content, $w = W_w / W_s * 100$	17.79	20.61	

Table B.16. *Dimensions and Weights of Cement-Stabilized RPCP Test Cylinders*

#	Weight (kg)	Mean (mm)		Density (kPa)		H/D
		Height	Dia.	Dry	Mean	
	Batch #1, 4% Cement, 12.25% Water (OMC)					
1	9.13	232.31	144.48	2422.41		1.61
2	8.56	225.96	149.76	2174.34	2339.72	1.51
3	8.94	219.61	147.12	2422.41		1.49
	Batch #2, 6% Cement, 12.50% Water (OMC)					
1	9.40	237.59	139.70	2790.48		1.34
2	9.17	230.99	135.74	2954.24	2754.81	1.33
3	8.78	224.89	147.65	2848.85		1.33
	Batch #3, 8% Cement, 8.25% Water (OMC)					
1	10.12	202.41	151.33	2811.56		1.33
2	9.90	209.02	138.13	3187.73	2905.60	1.51
3	9.67	199.24	148.44	2829.39		1.34
	Batch #4, 10% Cement, 8.50% Water (OMC)					
1	10.03	192.35	144.98	3194.21		1.33
2	10.44	195.78	146.84	3182.86	3113.14	1.33
3	10.44	199.49	149.76	3004.51		1.33

Table B.17. *Calculation of Unconfined Compressive Strengths of Cement-Stabilized RPCP Test Cylinders*

#	Unconfined Crushing		Corrected Unconfined	
	Load (N)	**Strength (kPa)**	**Compressive Strength (kPa)**	
	Batch #1, 4% Cement, 12.00% Water (Optimum Moisture Content)			
1	33152.5	1840.3	1085.18	
2	32485.0	1803.1	1750.06	(Mean: 1818.96)
3	35155.0	1965.0	1901.64	
	Batch #2, 6% Cement, 12.50% Water (Optimum Moisture Content)			
1	79655.0	4437.2	4383.04	
2	73870.0	4202.2	4147.78	(Mean: 4320.03)
3	79210.0	4554.3	4430.27	
	Batch #3, 8% Cement, 12.75% (Optimum Moisture Content)			
1	197135.0	11539.4	11196.25	
2	161868.8	8922.6	8971.64	(Mean: 9453.08)
3	155527.5	8662.8	8385.13	
	Batch #4, 10% Cement, 13.00% Water (Optimum Moisture Content)			
1	70755.0	4112.0	3954.86	
2	99235.0	5585.7	5422.43	(Mean: 4230.46)
3	60075.0	3358.2	3314.09	

APPENDIX C

TRIAL SPECIFICATIONS FOR FLEXIBLE BASE USING RAP

C.1 Description

This work shall consist of construction of a base course using either previously reclaimed and stockpiled asphaltic concrete or pulverizing the existing asphaltic concrete pavement, hereinafter called RAP. If RAP has to be transported in, it shall be done so from TxDOT-approved stock piles and in case of pulverization, portions of underlying base material may also be included to the depth and width shown on the plans, without damaging the underlying layers. Water will then be incorporated into the RAP. This reclaimed material will then be spread and compacted in accordance with the plans and specifications and as directed by the engineer.

C.2 Materials

RAP shall meet the following gradation requirements prior to the addition of the natural aggregate material for gradation adjustment:

Sieve Size	% Passing
50.80 mm	100
31.75 mm	95

The top size of RAP shall not exceed 1/2 the depth of the base layers. No additional natural aggregate material shall be added unless dictated by the job mix requirements or if required to increase the thickness of the base course, and shall meet the requirements as shown in Table C.1.

The natural aggregate material shall be used with the approval of the project engineer and shall meet the requirements of Item 247, "Flexible Base," as outlined in "Texas Department of Transportation Standard Specifications for Construction of Highways, Streets and Bridges." An overall effort shall be made to maximize the use of RAP within the limits of the job mix formula.

Table C.1. *Grading Requirements for Final Base Mixtures (after ASTM D 2490)*

Square Sieve Size (mm)	Percentage Passing by Weight	Job Mix Tolerances
50.00	100	- 2
37.50	95 - 100	± 5
19.00	70 - 92	± 8
9.50	50 - 70	± 8
4.75	35 - 55	± 8
0.60	12 - 25	± 5
0.075	0 - 8	± 3

C.3 Construction Method

Prior to the delivery of the base material, the subgrade or existing roadbed shall be shaped to conform to the typical sections, shown on the plans or established by the Engineer.

RAP and any required natural material, when specified on plans, shall be mixed in a manner which does not disturb the underlying material in the existing roadway. Furthermore, base construction operations shall not be performed when the weather is foggy, rainy, or when the weather conditions are such that in the judgment of the engineer, proper mixing, spreading, and compacting cannot be accomplished.

The required in place density will be 95% of the laboratory molded density and will be determined using Test Method Tex-113-E, "Determination of Moisture-Density Relations of Soils and Base Materials." After each section of flexible base is completed, tests as necessary will be made by the Engineer in accordance with Test Method Tex-115-E, "Field Method for Determination of In-Place Density of Soils and Base Materials." The selected rolling pattern shall be followed unless change in the mixture or placement conditions occur which affect compaction which would require a new rolling pattern to be established. Water used for compaction shall conform to the requirements of Item 204, "Sprinkling," as outlined in "Texas Department of Transportation Standard Specifications for Construction of Highways, Streets and Bridges."

After placing and compaction of the waste material it shall be allowed to cure for a period of at least two hours before any traffic, including contractors equipment, is allowed on the completed RAP base course. It may then be open to traffic and allowed to cure till the moisture content drops to below 2% by weight of the mix before the placement of any hot mix asphaltic concrete material.

C.4 Equipment

The contractor shall furnish a self propelled machine capable of pulverization in-situ materials, if so required, to the depth shown on the plans. The contractor shall furnish equipment capable of mixing RAP and the required amount of water to a homogenous mixture and placing the mixture in a windrow or directly into the hopper of a paver. Said machine shall be capable of screening and crushing capabilities to reduce all the oversized particles to size prior to mixing. The method of placing the mixed material shall be such that segregation does not occur. The mixing equipment shall be capable of registering the rate of flow and total delivery of the water introduced into the mixture. The mixed RAP base shall be spread in one continuous pass, without segregation, to the lines and grades established by the engineer.

Rolling shall be considered subsidiary to this Item and all rollers shall meet the requirements specified in the Item 210, "Rolling (flat wheel)," and Item 213, "Rolling (pneumatic tire)," as outlined in "Texas Department of Transportation Standard Specifications for Construction of Highways, Streets and Bridges." The number, weight, and type of rollers shall be sufficient to obtain the required compaction while the mixture is in a workable condition. Any type of rolling that results in cracking, movement, or other type of pavement distress shall be discontinued until such time as the problem can be resolved. Discontinuation and commencement of rolling operation shall be at the discretion of the project engineer.

C.5 Measurement

Work as prescribed for this item will be measured by the square meter of the completed sections for the depth specified. The asphalt emulsion shall be measured by the liter. Water used in this operation will not be paid for directly but will be considered subsidiary to this bid item.

C.6 Payment

The work performed and materials furnished, as prescribed by this item, and measured as provided under "measurements", will be paid for at the unit prices bid for this item and "asphalt emulsion", and such prices shall be full compensation for the removal, and processing of the existing pavement, for furnishing, preparing, hauling, and placing all materials, including RAP from other sources; for all freight involved; for all manipulations, including rolling and broming and for all labor, tools, equipment, and incidentals necessary to complete this work.

APPENDIX D

TRIAL SPECIFICATIONS FOR ASPHALT STABILIZED BASE USING RAP

D.1 Description

This work shall consist of construction of a base course using either previously reclaimed and stockpiled asphaltic concrete or pulverizing the existing asphaltic concrete pavement, hereinafter called RAP. If RAP has to be transported in, it shall be done so from TxDOT approved stock piles and in case of pulverization, portions of underlying base material may also be included to the depth and width shown on the plans, without damaging the underlying layers. An emulsified binder agent and water, if required, will then be incorporated into the RAP. This reclaimed material will then be spread and compacted in accordance with the plans and specifications and as directed by the engineer.

D.2 Materials

RAP shall meet the following gradation requirements prior to the addition of the emulsified binder agent:

Sieve Size	% Passing
50.80 mm	100
31.75 mm	95

The top size of RAP shall not exceed 1/2 the depth of the base layers. No additional natural aggregate material shall be added unless dictated by the job mix requirements or if required to increase the thickness of the base course. The natural aggregate material shall be used with the approval of the project engineer and shall meet the requirements of Item 247, "Flexible Base," as outlined in "Texas Department of Transportation Standard Specifications for Construction of Highways, Streets and Bridges." An overall effort shall be made to maximize the use of RAP within the limits of the job mix formula.

The emulsified binder agent shall be polymerized high float emulsion of the type and grade as directed by the engineer. The polymerized high float emulsion shall meet the requirements of Item 300, "Asphalts, Oils and Emulsions" as outlined in "Texas Department of Transportation Standard Specifications for Construction of Highways, Streets and Bridges."

D.3 Construction Method

Prior to the delivery of the base material, the subgrade or existing roadbed shall be shaped to conform to the typical sections, shown on the plans or established by the Engineer.

RAP and any required material, when specified on plans, shall be cold mixed in a manner which does not disturb the underlying material in the existing roadway. Base construction operations shall not be performed when the air temperature in the shade is below 60° F or when the weather is foggy, rainy, or when the weather conditions are such that in the judgment of the engineer, proper mixing, spreading, and compacting cannot be accomplished. The air temperature shall be taken in the shade and away from artificial heat.

Application of the emulsified binder to RAP shall be at the initial design rate determined by the engineer. Existing field conditions may require the engineer to vary the binder application rate. An allowable tolerance of ± 0.2 % by weight of the emulsified binder agent will be maintained unless otherwise directed by the engineer.

The contractor may add water to RAP, when approved by the engineer, to facilitate uniform mixing with the emulsified binder agent. The water may be added to the material before the addition of the emulsion or may be added concurrently with the emulsion. The moisture content after addition of water to the mixture shall not exceed 5% of the dry weight of RAP. Water used for this purpose and to facilitate compaction shall conform to the requirements of Item 204, "Sprinkling," as outlined in "Texas Department of Transportation Standard Specifications for Construction of Highways, Streets and Bridges."

The required in place density will be 95% of the laboratory molded density and will be determined using test method Tex-126-E "Molding, Testing, and Evaluation of Bituminous Black Base Materials." Rolling patterns shall be established as outlined in test method Tex-207-F, part III, " Determination of In Place Density of Compacted Bituminous Mixtures (Nuclear Method)" to achieve the maximum compaction. The selected rolling pattern shall be followed unless change in the mixture or placement conditions occur which affect compaction which would require a new rolling pattern to be established.

After placing and compaction of the recycled material it shall be allowed to cure for a period of at least two hours before any traffic, including contractors equipment, is allowed on the completed RAP base course. It may then be open to traffic and allowed to cure till the moisture content drops to below 2% by weight of the mix before the placement of any hot mix asphaltic concrete material.

D.4 Equipment

The contractor shall furnish a self propelled machine capable of pulverization in-situ materials, if so required, to the depth shown on the plans. The contractor shall furnish equipment capable of mixing RAP and the bituminous binder to a homogenous mixture and placing the mixture in a windrow or directly into the hopper of a paver. Said machine shall be capable of screening and crushing capabilities to reduce all the oversized particles to size prior to mixing with the emulsified binder. The method of placing the mixed material shall be such that segregation does not occur. The mixing equipment shall be capable of registering the rate of flow and total delivery of the binder introduced into the mixture. The mixed RAP base shall be spread in one continuous pass, without segregation, to the lines and grades established by the engineer.

Rolling shall be considered subsidiary to this Item and all rollers shall meet the requirements specified in the Item 210, "Rolling (flat wheel)," and Item 213, "Rolling (pneumatic tire)" as outlined in "Texas Department of Transportation Standard Specifications for Construction of Highways, Streets and Bridges." The number, weight, and type of rollers shall be sufficient to obtain the required compaction while the mixture is in a workable condition. Any type of rolling that results in cracking, movement, or other type of pavement distress shall be discontinued until such time as the problem can be resolved. Discontinuation and commencement of rolling operation shall be at the discretion of the project engineer.

D.5 Measurement

Work as prescribed for this item will be measured by the square meter of the completed sections for the depth specified. The asphalt emulsion shall be measured by the gallon. Water used in this operation will not be paid for directly but will be considered subsidiary to this bid item.

D.6 Payment

The work performed and materials furnished, as prescribed by this item, and measured as provided under "measurements," will be paid for at the unit prices bid for this item and "asphalt emulsion," and such prices shall be full compensation for the removal, and processing of the existing pavement, for furnishing, preparing, hauling, and placing all materials, including RAP from other sources; for all freight involved; for all manipulations, including rolling and brooming and for all labor, tools, equipment, and incidentals necessary to complete this work.

APPENDIX E

TRIAL SPECIFICATIONS FOR FLEXIBLE BASE USING RPCP

E.1 Description

This work shall consist of construction of a base course, using either previously reclaimed and stockpiled Portland cement concrete or pulverizing the existing Portland cement concrete pavement, hereinafter called RPCP. If RPCP has to be transported in, it shall be done so from TxDOT approved stock piles and in case of pulverization, portions of underlying base material may also be included to the depth and width shown on the plans. Any natural aggregate material and water, if required, will then be incorporated in this mixture. This properly mixed material will then be spread and compacted in accordance with the plans and specifications and as directed by the project engineer.

E.2 Materials

The constructed base course shall consist at most 50% RPCP by weight of the final mixed material, and the remaining material shall be at least Group 4A conforming to the ASTM soil classification. The natural material added must conform to the specifications of Item 247, "Flexible Base" as outlined in "Texas Department of Transportation Standard Specifications for Construction of Highways, Streets and Bridges." RPCP shall be substantially free of all foreign matter and the final base mixture shall meet the gradation requirements, as shown in Table E.1. The top size of RPCP shall not exceed 1/2 the depth of the recycled mat.

E.3 Construction Method

Prior to the delivery of the base material, the subgrade or existing roadbed shall be shaped to conform to the typical sections, shown on the plans or established by the Engineer. Recycling operations shall not be performed when the weather is foggy, rainy, or when the weather conditions are such that in the judgment of the engineer, proper mixing, spreading, and compacting cannot be accomplished.

Table E.1. *Grading Requirements for Final Base Mixtures (after ASTM D 2940)*

Square Sieve Size (mm)	Percentage Passing by Weight	Job Mix Tolerances
50.00	100	- 2
37.50	95 - 100	± 5
19.00	70 - 92	± 8
9.50	50 - 70	± 8
4.75	35 - 55	± 8
0.60	12 - 25	± 5
0.075	0 - 8	± 3

The contractor may add water to RPCP, when approved by the engineer, to facilitate uniform mixing and compaction. The water may be added to the material before the addition of the binder or may be added concurrently with the binder. The moisture content after addition of water to the mixture shall not exceed 5% of the dry weight of RPCP.

Rolling patterns shall be established as outlined in test method Tex-207-F, part III, to achieve the maximum compaction. The selected rolling pattern shall be followed unless change in the mixture or placement conditions occur which affect compaction which would require a new rolling pattern to be established.

After placing and compaction of the recycled material it shall be allowed to cure for a period of at least two hours before any traffic is allowed on the completed recycled Portland cement concrete base. It may then be open to traffic and allowed to cure till the moisture content drops to below 2% by weight of the mix before the placement of any hot mix asphaltic concrete material.

E.4 Equipment

The contractor shall furnish a self propelled machine capable of pulverizing in-situ materials, if required, to the depth shown on the plans. The contractor shall furnish equipment capable of mixing RPCP and the natural aggregate material to a homogenous mixture and placing the mixture in a windrow or directly into the hopper of a paver. Said machine shall be capable of screening and have crushing capabilities to reduce all the oversized particles to size prior to mixing. The method of disposing the mixed material shall be such that segregation does not occur.

Placing of the recycled Portland cement concrete base course shall be accomplished by means of a self-propelled paver. The recycled material shall be spread in one continuous pass, without segregation, to the lines and grades established by the engineer.

Rolling shall be considered subsidiary to this item and all rollers shall meet the requirements specified in Item 210, "Rolling (flat wheel)," and Item 213, "Rolling (pneumatic tire)." The number, weight, and type of rollers shall be sufficient to obtain the required compaction while the mixture is in a workable condition. Any type of rolling that results in cracking, movement, or other type of pavement distress shall be discontinued until such time as the problem can be resolved. Discontinuation and commencement of rolling operation shall be at the discretion of the project engineer.

E.5 Measurement

Work as prescribed for this item will be measured by the square meter of the completed sections for the depth specified. The cementing agent shall be measured by the gallon. Water used in this operation will not be paid for directly but will be considered subsidiary to this bid item.

E.6 Payment

The work performed and materials furnished, as prescribed by this item, and measured as provided under "measurements," will be paid for at the unit prices bid for "recycling of Portland cement concrete material" and "Portland cement," and such prices shall be full compensation for the removal and processing of the existing pavement, for furnishing, preparing, hauling, and placing all materials, including RPCP from TxDOT approved sources; for all freight involved; for all manipulations, including rolling and brooming and for all labor, tools, equipment, and incidentals necessary to complete this work.

APPENDIX F

TRIAL SPECIFICATIONS FOR FLEXIBLE BASE USING EAFS

F.1 Description

This work shall consist of construction of a base course, using previously reclaimed and stockpiled Electric Arc Furnace Slag, hereinafter called EAFS. EAFS shall be transported in from TxDOT approved stock piles. Any water, if required, will then be incorporated in this mixture. This properly mixed material will then be spread and compacted in accordance with the plans and specifications and as directed by the project engineer.

F.2 Materials

The maximum amount of EAFS shall be incorporated in the base course within the limits of the job mix formula. EAFS shall be substantially free of all foreign matter and shall meet the gradation requirements, as shown in Table F.1. The top size of EAFS shall not exceed 1/2 the depth of the recycled mat. No additional natural aggregate material shall be added unless dictated by the job mix requirements or if required to increase the thickness of the base course. The natural aggregate material shall be used with the approval of the project engineer and shall meet the requirements of Item 247, "Flexible Base," as outlined in "Texas Department of Transportation Standard Specifications for Construction of Highways, Streets and Bridges."

F.3 Construction Method

Prior to the delivery of the base material, the subgrade or existing roadbed shall be shaped to conform to the typical sections, shown on the plans or established by the Engineer.

Recycling operations shall not be performed when the weather is foggy, rainy, or when the weather conditions are such that in the judgment of the engineer, proper mixing, spreading, and compacting cannot be accomplished.

Table F.1. *Grading Requirements for Final Base Mixtures (after ASTM D 2290)*

Square Sieve Size (mm)	Percentage Passing by Weight	Job Mix Tolerances
50.00	100	- 2
37.50	95 - 100	± 5
19.00	70 - 92	± 8
9.50	50 - 70	± 8
4.75	35 - 55	± 8
0.60	12 - 25	± 5
0.075	0 - 8	± 3

The contractor may add water to EAFS, when approved by the engineer, to facilitate uniform mixing and compaction. The required in place density will be 95% of the laboratory molded density and will be determined using Test Method Tex-113-E, "Determination of Moisture-Density Relations of Soils and Base Materials." After each section of flexible base is completed, tests as necessary will be made by the Engineer in accordance with Test Method Tex-115-E, "Field Method for Determination of In-Place Density of Soils and Base Materials." The selected rolling pattern shall be followed unless change in the mixture or placement conditions occur which affect compaction which would require a new rolling pattern to be established. Water used for compaction shall conform to the requirements of Item 204, "Sprinkling," as outlined in "Texas Department of Transportation Standard Specifications for Construction of Highways, Streets and Bridges." Rolling patterns shall be established as outlined in test method Tex-207-F, part III, to achieve the maximum compaction. The selected rolling pattern shall be followed unless change in the mixture or placement conditions occur which affect compaction which would require a new rolling pattern to be established.

After placing and compaction of the recycled material it shall be allowed to cure for a period of at least two hours before any traffic is allowed on the completed recycled EAFS base. It may then be open to traffic and allowed to cure till the moisture content drops to below 2% by weight of the mix before the placement of any hot mix asphaltic concrete material.

F.4 Equipment

Placing of the EAFS base course shall be accomplished by means of a self-propelled paver. The recycled material shall be spread in one continuous pass, without segregation, to the lines and grades established by the engineer.

Rolling shall be considered subsidiary to this item and all rollers shall meet the requirements specified in Item 210, "Rolling (flat wheel)," and Item 213, "Rolling (pneumatic tire)." The number, weight, and type of rollers shall be sufficient to obtain the required compaction while the mixture is in a workable condition. Any type of rolling that results in cracking, movement, or other type of pavement distress shall be discontinued until such time as the problem can be resolved. Discontinuation and commencement of rolling operation shall be at the discretion of the project engineer.

F.5 Measurement

Work as prescribed for this item will be measured by the square meter of the completed sections for the depth specified. The cementing agent shall be measured by the gallon. Water used in this operation will not be paid for directly but will be considered subsidiary to this bid item.

F.6 Payment

The work performed and materials furnished, as prescribed by this item, and measured as provided under "measurements," will be paid for at the unit prices bid for "recycling of electric arc furnace slag material" and such prices shall be full compensation for the removal and processing of the existing pavement, for furnishing, preparing, hauling, and placing all materials, including RPCP from TxDOT approved sources; for all freight involved; for all manipulations, including rolling and brooming and for all labor, tools, equipment, and incidentals necessary to complete this work.

APPENDIX G

STRUCTURAL COEFFICIENTS OF VARIOUS MATERIALS AS RECOMMENDED BY TXDOT DESIGN OFFICE

MEMORANDUM

TO: All District Engineers
Attn: All Pavement Engineers

DATE: June 7, 1995

FROM: Design Division

Originating Office
Pavements Section

SUBJECT: Typical Stiffness Coefficients

There have been several inquiries concerning the most appropriate stiffness coefficients to use when designing asphalt concrete pavements. Since FPS-11PC will continue to be used as the primary design system for Texas asphalt pavements, we are providing typical values that may be used to characterize pavement layers. We cannot give you definitive values to use in your district; each district must determine the most appropriate values to use.

The ranges of values listed below are general values used only in the design of new (or reconstructed) pavements. Because the values for new pavements are assumed, they must be specific to the materials encountered in each district.

Asphalt Concrete Pavement	*(Item 340)*	*0.96*
Asphalt Stabilized Base	*(Item 345, Grade 1 & 2)*	*0.92-0.96*
Asphalt Stabilized Base	*(Item 345, Grade 3 & 4)*	*0.8-0.9*
Cement Stabilized Base	*(Item 275 & 276)*	*0.7*
Lime Treated Flexible Base	*(Item 262, 263 & 266)*	*0.4-0.65*
Flexible Base (non-stablized and PI treated)		*0.4-0.6*
Lime Stabilized Subgrade (pH 12.4)		*0.28-0.35*
Lime Treated Subgrade (PI treatment)		*0.18-0.3*
Raw Subgrade		*0.18-0.30*

Again, these are only general values for use in design. If you have any questions, please call one of the Pavement Design Branch staff; they can be reached at (512) 465-3674.

Ken Fults, P.E.
Director of Pavements

KF/MWM/mwm

APPENDIX H

RAP RECYCLING PROJECT IN WICHITA FALLS: A CASE STUDY

ECONOMIC ANALYSIS OF ALTERNATIVE ROADBASE MATERIALS

Economic Analysis of Roadbase Construction Alternatives in Wichita Falls

Item Description	Unit	Estmated Quantity		Cost	Difference
		Original	VECP	$	
Excavaion	m^3	23148	21312	3.46	- 6,360
Embankment	m^3	8277	6747	3.46	-5,297
Flexible Base	m^3	13068	0	33.3	- 435,591
Reworking Base Material	Sta	90.50	0	265	- 23,982
Lime Treatment Subgrade	m^2	55235	0	1.32	- 72,677
Lime Type A	T	1,090	0	82.0	- 89,412
Haul, Stockpile RAP	m^3	973	0	6.53	-6,360
Asphalt Emulsion (AE-P)	l	51862	0	0.50	- 26,033
Aggregate (Ty B, Gr 3)	m^3	402	0	39.9	- 16, 012
Asphalt Emulsion (CRS-2)	l	86449	0	.296	- 25,580
Barricades, Traffic Control	M	12	5	2350	- 16,450
Construct Detours	Sta	86	0	235	- 20,210
Reflective Pav Marking	m	14653.7	4162	.492	- 5,160
RAP Base Material	m^3	0	11226	28.4	319,181
				Total Savings Due to VECP	- 442,397
				Contractors Bonus (50%)	221,198
				TxDOT Savings	- 221,198

APPENDIX I

SURVEY OF COMMERCIAL SOURCES FOR WASTE MATERIALS IN TEXAS

prepared by

DR. PAUL ANAEJIONU
HUSTON-TILLOTSON COLLEGE
AUSTIN, TEXAS

SURVEY OF COMMERCIAL SOURCES FOR WASTE MATERIALS IN TEXAS

Introduction: Link To Previous Survey

This present report is presented as a complement to the first report dealing with waste material availability and location survey. In first report, the focus was on the availability of waste materials from TxDOT sources. The previous survey was conducted to determine the quantities of potential roadbase materials available in TxDOT districts, and to classify them by quantity, location, and type. Data collection methods for that study included:

- mail questionnaires administered to TxDOT district engineers;
- telephone interviews; and
- limited site visits.

Among other things, the survey showed that reclaimed asphaltic concrete and reclaimed portland cement concrete are the most widely used waste materials within TxDOT districts. In terms of materials with potential roadbase applications, the findings of the first survey are summarized in Table 1.

Table 1. Types of Materials with Potential Roadbase Applications Identified in TxDOT Districts

Materials Identified	**Percent of Districts**
Old Asphaltic Concrete (OA)	90
Old Portland Cement Concrete (OC)	67
Blast Furnace Slag (BF)	14
Fly Ash (FA)	33
Bottom Ash (BA)	19
Open-graded Aggregate (OG)	14
Power Plant Pond Ash (PA)	14
Tire Chips & other Rubber Products (TC)	38
Cement Kiln Dust (CD)	10
Plastics (PL)	5
Rice Husks (RH)	5
Ceramic Products (CP)	14
Other (OR)	5

Of the 21 responding TxDOT districts, 19 (90 percent) reported that old asphaltic concrete and old portland cement concrete could be used as roadbase material, with 90 percent favoring old asphaltic concrete and 67 percent selecting old concrete. Also, the table gives figures for materials from commercial sources. These include tire chips and related products (38 percent), fly ash (33 percent), bottom ash (19 percent), blast furnace slag (14 percent), and ceramic products (14 percent). Table 2 presents a summary of findings for stockpiled materials.

Table 2. Types of Recycled Materials Stockpiled in TxDOT Districts

Materials Identified	Percent of Districts
Old Asphaltic Concrete (OA)	90
Old Portland Cement Concrete (OC)	67
Blast Furnace Slag (BF)	14
Fly Ash (FA)	33
Bottom Ash (BA)	19
Open-graded Aggregate (OG)	14
Power Plant Pond Ash (PA)	14
Tire Chips & other Rubber Products (TC)	38
Cement Kiln Dust (CD)	10
Plastics (PL)	5
Rice Husks (RH)	5
Ceramic Products (CP)	14

As the table shows, nearly all of the responding districts 19 out of 21 (90 percent) have stockpiles of old asphaltic concrete. Of the 21 responding districts, 9 (43 percent) stockpile old portland cement concrete. With respect to stockpiles in commercial operations, fly ash has 33 percent and tire chips with other rubber products have 29 percent availability in the districts. Approximately, 19 percent of the districts report bottom ash stockpiles, while open-graded aggregates, power plant pond ash, and ceramic products are stockpiled approximately at 14 percent each.

In terms of the use of identified materials in roadbase construction and maintenance, information from the first survey suggests that several types of materials are being used throughout Texas. These include: old asphaltic concrete, old portland cement concrete, ash, tire chips and other rubber products, ceramic products, open-graded aggregate, blast furnace slag, and cement kiln dust.

Table 3. Pattern of Recycled Materials Utilization in TxDOT Districts

Type of Material	Percent of Districts Using Material
Old Asphaltic Concrete (OA)	80
Old Portland Cement Concrete (OC)	25
Fly Ash (FA)	10
Bottom Ash (BA)	10
Power Plant Pond Ash (PA)	5
Tire Chips and other Rubber (TC)	10
Rice Husk (RH)	5
Ceramic Products (CP)	10

As the table indicates, a great majority of districts, 16 out of 20 (80 percent) responding to the relevant questions, have used old asphaltic concrete as roadbase material. For old portland cement concrete, the figure is 25 percent. While fly ash, bottom ash, tire chips and other rubber products, and ceramic products each has 10 percent utilization figure; bottom ash and rice husks have 5 percent each. In terms of the availability of these waste materials, table 4 gives a summary of estimated stockpile amounts, 2,000 tons or more for five materials.

Table 4. Districts with Stockpiles of Two Thousand Tons or More

District	Material	Estimated Quantity
Abilene	OA	6,000
Atlanta	OA	200,000
Beaumont	OA	57,000
Bryan	OA	4,000
Childress	FA	2,000
Childress	BA	2,000
Childress	PA	2,000
Fort Worth	OA	2,000
Paris	OA	2,000
Pharr	OA	4,000
Pharr	OC	13,000
San Antonio	OA	2,000
Waco	OA	2,000
Wichita Falls	OA	4,000

Key: OA = Old Asphaltic Concrete; OC = Old Portland Cement Concrete
FA = Fly Ash; BA = Bottom Ash;
PA = Power Plant Pond Ash

As the table shows, old asphaltic concrete has the largest amount of tonnage stockpiled in ten TxDOT districts. The first survey showed that this material was available in 13 stockpiles each with more than 2,000 tons. Comparatively, old portland cement concrete had 2 stockpiles with 2,000 tons or more. Additionally, the first survey revealed that extensive amounts of fly ash, bottom ash, and power plant pond ash were available in Childress and Atlanta districts through commercial operations.

A close examination of the data presented in these tables indicates the need for the survey of commercial sources for waste materials in roadbase. First, TxDOT has ownership of only two of the reported materials: old asphaltic concrete and old portland cement concrete. Accordingly, TxDOT districts were able to give estimates of amounts of these two materials available in stockpiles. Alternately, the districts could not give firm estimates of materials in commercial stockpiles. District engineers suggested that we find out from relevant sources.

Second, while Table 3 suggests a widespread utilization pattern for other non-TxDOT waste materials, table 4 implies that availability of commercial materials is limited to fly ash, bottom ash, and power plant pond ash in two districts: Childress and Atlanta. Third, during the first survey this research team learned from TxDOT offices that there is room for expanded utilization of waste materials in roadbase other than asphaltic concrete and old portland cement concrete.

Specifically, the team learned that problems associated with widespread use of these materials included limited knowledge about the availability of materials, environmental regulations, and gaps in scientific and engineering knowledge about the behavior of these materials in roadbase applications. Additionally, the research team learned that several companies produce waste material by-products, (such as ceramic shell, gypsum wastes, and foundry sand), which can be used in roadbase.

The report concluded with the following observation: Whether the waste material is gypsum waste, ceramic shell, spent foundry sand, cement dust, blast furnace slag, or fly ash, questions remain to be answered. How much of the material is produced? Where is it produced? What are the alternate uses for the materials? How much of the production could be available for roadbase construction and maintenance? Are engineering test results available concerning the suitability of these materials for roadbase construction? These and other questions suggest the need for more research regarding recycled roadbase materials from commercial operations. The present report deals with the second survey designed to provide answers to some of these questions. This report is limited to an examination of the major types, quantities, locations, and availability of waste base materials from commercial sources in Texas. It is in four sections: (1) introduction which shows the relationship between the two surveys; (2) data collection, which discusses the research methodology; (3) results and analysis which summarizes the results and presents pertinent observations; and (4) the conclusion which outlines associated benefits with concluding remarks.

II. DATA COLLECTION

Research Tasks and Methodology

In order to facilitate data collection and presentation of the results of the commercial survey, the research team planned the following tasks:

- develop the survey questionnaire in order to elicit appropriate responses;
- compile a listing of commercial producers and distributors of potential roadbase materials
- contact these companies/individuals to verify the names, addresses, and phone/fax numbers of potential respondent;
- contact companies to conduct limited telephone interviews and/or arrange for selected site visits;
- mail and/or fax questionnaires to selected potential respondents;
- undertake field trips to selected commercials operations;
- code questionnaire responses;
- analyze questionnaire responses; and
- prepare a report based on the responses.

All of the tasks identified above have been accomplished. With respect to questionnaire preparation, the research team decided to use the same questionnaire that it had developed for the first level survey of TxDOT districts. However, the research team made some changes in the questionnaire because of problems encountered in the first survey. In the previous survey, respondents were asked to give estimates of amounts of stockpiled materials in thousands of tons. For example, a respondent who reported 2,000 tons as the amount of fly ash available actually was reporting 2,000,000 tons simply because the information was requested in thousands of tons.

What the research team did was to call each TxDOT district office to correct or verify estimated amounts of materials reported. In order to avoid a similar problem in recording amounts of waste materials available, the research team labeled requested figures in thousands or millions of tons. A sample of the questionnaire is provided in the appendix.

The research team made two other changes. In question two, material "01", "Old Asphaltic Concrete" was changed to "Reclaimed Asphaltic Concrete" Similarly, for material "02", "Reclaimed Portland Cement Concrete" was used to replace "Old Concrete." Finally, the team made changes on the first page in the wording of the questionnaire to reflect the commercial focus of the second survey. The questionnaire covers a variety of topics including types of materials, locations of stockpiles, estimated amounts of materials available, means of transportation to facilitate access, locations where materials have been used, performance of materials where used, and access to engineering test results. Overall, the questionnaire covers twelve questions as outlined in table 5 on the next page.

Selecting People to Survey

In order to identify individuals or commercial operations for the survey, the research team used the "chain referral" or "snowball" sampling method. Generally, this approach of sampling is conducted in stages. Usually, people who are surveyed or interviewed in the first stage provide the names of individuals to be surveyed in the second stage. In this study, for example, TxDOT district offices gave the research team the names of companies for the second survey.
One problem with the referral method of selecting survey respondents is that the process is slow and uses much time. For example, what the research team first did was to use multiple sources to develop a working list of contacts (table 6).Then, through the working list of contacts, the research team was able to identify and contact representatives of 16 commercial sources, as shown in table 7.

Table 5. The 12 Questions on the Questionnaire

1. Please give us the name, address, and telephone number of your organization or company.
2. What types of materials are you aware of personally that could be available to be recycled for roadbase construction?
3. At what location(s) is (are) the identified material(s) stockpiled?
4. What do you estimate is/are the approximate amount(s) of stockpiled material(s)?
5. What type(s) of shipment facility(ies) is (are) there to transport the material(s)?
6. Do you know any location(s) where some of the material(s) you identified has (have) been used in roadbase construction?
7. At what location(s) has (have) the material(s) been used in roadbase construction?
8. In your professional opinion, how would you rate the performance of the waste material(s) at the location(s) where it (they) has (have) been used?
9. Please give the name, address, and telephone number of the contact person who has knowledge of the trial specifications for the waste material used in roadbase construction.
10. Do you have personal knowledge of any scientific/engineering tests done on the material(s) you identified?
11. Please give the name, address, and telephone number of the person who has the data from the test.
12. Would you be willing to supply us with five pounds of sample material?

Table 6. A Working list of Contacts

Names	Comments
Mr. Jerry Weiss of Tiregator	Surveys and Crumb Rubber Information
Gulf States Materials	Surveys and Gypsum Waste Information
Cagle Crushed Concrete	No Response
American Rice, Inc.	Rice Husks; 30 loads/day (1=2 tons)
Gulf Pacific Rice	Rice Husks; 3 loads/day
Mr. Al Farrell	TxDOT, Houston office for names
Colorado Materials	Calls not returned
Austin Bridge & Road	Calls not returned
Mr. Lenny Bobrowski	TxDOT Austin supplied names
Cercon	Ceramic Shells
Mr. Martin Whitworth, Cercon	Gave names for survey
Mr. Steve Juneau	TxDOT Marshall - Fly Ash data
Mr. Kenneth Call	Negative about slag as base material
JTM	Fly Ash survey and data
Monex Resources	Coal Combustion by products
Mr. Bob Lee	SMI, Seguin for slag and names
Mr. Charles W. Baucom	Mailed materials on products
Mr. Joe Seal (LaFarge Corp.)	Fly Ash, Bottom Ash, etc.
Mr. Gary Brown	Mailed materials on products
Mr. Tom Hill	Redland Stone - Survey
Mr. Erv Dukatz	Vulcan Materials - No response
Mr. Robert Tomasini	Survey - Responded
Mr. Rockie Simpler	Fly Ash/Bottom Ash - Responded
Mr. Scott Green	Spent Sand information
TX Metals Association	Survey of members

Table 7. Companies Participating in Survey

Company Name	Contact Person	Phone	Fax
Structural Metals, Inc.	Mr. Bob Lee	(210)372-8492	(210)372-8502
Neste/Wright	Mr. Charles Baucom	(214)384-9366	(903)498-4929
Lafarge Crop.	Mr. Joe Seal	(903)389-4620	(903)389-4133
Gulf/State Materials	Mr. Gary Brown	(713)470-8645	(713)470-2607
Redland Stone	Mr. Tony Hill	(210)696-8500	(210)697-0972
Vulcan Materials	Mr. Erv Dukatz	(210)349-3311	(210)524-3555
Dean Word Company	Mr. Robert Tomasini	(210)625-2365	(210)606-5008
Colorado Materials	Mr. John Janek	(512)396-1555	(512)396-1558
Cagle Crushed Concrete	Mr. Bob Nolan	(713)466-4007	(713)466-3123
Gulf Pacific Rice	Mr. Kenneth Munso	(713)466-5441	(713)466-8377
Gifford Hill	Mr. Rocky Simpler	(903)856-6568	(903)856-0951
Monex Resources	Mr. Bill Barrow	(800)292-5352	(210)349-8518
International Mill service	Mr. Kenneth Call	(817)467-0071	(817)467-9815
JTM	Mr. Bob Sparacino	(713)343-0071	(713)240-4173
CSA Material, Inc.		(915)655-4511	
Cercon	Mr. Martin Whitworth	(817)582-3413	(817)582-2486

After contacting company representatives and conducting limited telephone interviews, the research team faxed survey instruments to designated individuals. Additionally, the team went on four field trips to collect more information regarding the production, stockpiling, use, and performance of selected materials. The team visited four commercial operations: (1)Gulf State Materials in Houston; (2) Gulf Pacific Rice Houston; (3) SMI in Seguin and; (4)Cercon of Hillsboro, Texas. Data and information from these field trips are incorporated in the next section.

III. Results and Analysis

Order of Presentation

This section of the report covers questionnaire response rate, materials identified by responding companies, locations of stockpiles and estimated amounts, locations where materials have been used in roadbase, related performance assessment of materials where used, and access to engineering test data. Also, the section compares selected responses given by company representatives with similar responses presented by TxDOT engineers in the first survey.

Questionnaire Response Rate and Materials Identified

Out of the sixteen companies surveyed, twelve (75 percent) responded by returning copies of the survey. Of the responding companies, one produces reclaimed portland cement concrete. Similarly, materials that have one company producer or marketer include building rubber (BR), power plant pond ash (PA), cement kiln dust (CD), rice husks (RH), calcium sulfate (CS), ceramic products (CP), reclaimed asphaltic concrete (RA), and coal combustion byproducts (CB) (Table 8).

It is important to note that the class of coal combustion byproducts includes fly ash (FA), bottom ash (BA), and flue gas desulfurization (FGD) material. While some companies reported coal combustion byproducts as "other" with code number "17" in the questionnaire, other companies reported FGD material or spent sand as "other." The point must be made that in spite of this inconsistency in reporting, five companies listed in Table 8 produce, market, or blend coal combustion byproducts for specialty base materials. These companies include Monex Resources, Gifford-Hill, J.T.M. Industries, and De Pauw Fly Ash, and Dean Word Co., Ltd.

In addition to identifying companies that responded to the survey, Table 8 summarizes the answers to the second question in the survey instrument. That question asks: "What types of materials are you aware of personally that could be available to be used for roadbase construction?" Respondents identified the following materials: bottom ash (BA), blast furnace slag (BF), building rubble (BR), coal combustion byproducts (CB), ceramic products (CP), calcium sulfate (CS), fly ash (FA), reclaimed asphaltic concrete (RA), power plant pond ash (PA), reclaimed portland cement concrete (CC), cement kiln dust (CD) and "other" materials such as spent blast sand.

Respondents' answers to questions three, four, five, seven, and eight are summarized in Tables 9, 10, 11, and 12. While question three deals with stockpile locations, four with estimates of stockpile amounts, five with the means of transport, questions seven and eight deal with locations where materials have been used and the performance of materials where used respectively. With respect to questions three and five, Table 9 shows that identified materials are stockpiled in eleven counties. Seven of the eleven counties (64 percent) have stockpiles of power plant ash including other coal combustion byproducts.

Table 8. Companies and Types of Recycled Base Materials They Produce

Company	RA	TC	OR	RH	CS	CP	BF	FA	BA	CC	CB	BR	PA	BA	RP	CB	CD
Cercon						X											
Gulf Rice Pacific				X													
Big City Crushed Concrete										X					X		
De Pauw Fly Ash			X					X	X					X			
J.T.M. Industries								X	X					X			
Structural Metals, Inc.			X				X										
Gulf States Materials, Inc.					X												
Gifford-Hill & Co.							X	X									
International Mill Service							X										
Monex Resources Inc.											X					X	
Neste/Wright		X															
Dean word Co., Ltd.	X	X					X	X							X	X	X

CS = Calcium Sulfate
CP = Ceramic Product
BF = Blast Furnace Slag
TC = Tire Chips & Other Rubber Products
CB = Coal Combustion Byproducts (Blend of BA and FA)
RA = Reclaimed Asphaltic Concrete
FA = Fly Ash
BA = Bottom Ash
CD = Cement Kiln Dust
CC = Reclaimed Portland Cement Concrete
OR = Other eg. Spent Blast Sand
RH = Rice Husks
BR = Building Rubble

Table 9. Counties Where Materials Are Stockpiled and Means of Transport

	Materials												
Counties	BA	BF	BR	CB	CD	CP	CS	FA	OR	PA	RA	CC	
Bexar			X	X	X						X		TR
Dallas												X	T
Fayette				X									TR
Fort Bend	X	X						X		X			TR
Guadulape		X							X				TR
Harris							X						TR
Hill						X							T
Lamb	X			X				X					TR
Limestone	X			X				X		X			TR
Potter	X			X				X					TR
Titus	X							X		X			T

Key:
BA = Bottom Ash
BF = Blast Furnace Slag
BR = Building Rubble
CB = Coal Combustion Byproducts Including FGD material
CC = Reclaimed Portland Cement Concrete
CD = Cement Kiln Dust
CP = Ceramic Products
CS = Calcium Sulfate
FA = Fly Ash
OR = Other Materials
PA = Power Plant Pond Ash
RA = Reclaimed Asphaltic Concrete
T = Truck; R = Rail; b = Barge

Table 10. Estimated Amounts of Stockpiled Materials

Material	**Where Stockpiled**	**Estimated Amount (tons)**
Blast Furnace Slag	Seguin-Guadalupe(County)	<499,000
Calcium Sulfate	LaPorte-Harris County	>2 million
Ceramic Product	Hillsboro-Hill County	<499,000
Reclaimed Portland Cement	Dallas-Dallas County	<499,000
Fly Ash	Amarillo & Mule Shoe, Titus	<499,000
Bottom Ash	Amarillo, Mule Shoe, Titus	<499,000
Monex Roadmix Base	Bexar & Fayette	<499,000
Other	Amarillo & Mule Shoe	<499,000

Table 11. Counties Where Materials Are Used

	Materials											
Counties	BA	BF	BR	CB	CD	CP	CS	FA	OR	PA	PA	RP
Atascosa				X								
Austin				X								
Bastrop				X								
Bexar			X	X	X	X				X	X	
Bowie	X							X		X		
Brazoria							X					
Chambers							X					
Dallas												X
Denton												X
Ellis												X
Fort Bend	X						X	X		X		
Galveston							X					
Guadalupe		X							X			
Harris	X											
Harrison	X							X		X		
Henderson												X
Lamb	X			X				X				
Lavaca				X								
Liberty							X					
Limestone	X							X		X		
Potter	X			X				X				
Rockwall												X
Tarrant												X
Titus	X							X		X		
Upsur	X							X		X		
Wilson				X								
	29%	4%	4%	29%	4%	4%	23%	29%	4%	27%	4%	23%

The exceptions are Dallas, Guadalupe, Harris, and Hill counties. A comparison between the data shown in table 9 and information contained in figure 1 (Texas map showing locations of coal ash and cement generators) and table 13 (Coal Combustion Byproduct- Generators in Texas) suggests that power plant ash and other FGD materials are stockpiled in several other counties than this limited survey reveals.

In terms of transportation access, Table 9 indicates that all of the reported materials can be transported by truck from their stockpile locations. Barge transport is available in Harris county for the movement of calcium sulfate. Additionally, rail service is available in eight of the eleven (73 percent) counties.

With respect to the quantities of materials in stockpiles, table 10 indicates that calcium sulfate has the highest quantity, more than 2 million tons. Also, the table shows that power plant ash and other FGD materials have large and extensive stockpiles. Data from the Texas General Land Office (Table 13) support this conclusion. For example, 1984 data indicated that Texas generated more than 13 million tons of coal combustion byproducts that year. There is no reason to believe that production is lower today than it was 10 years ago.

In terms of patterns of the utilization of reported materials, table 11 indicates that these materials have been used in roadbase construction or maintenance in 26 counties. As this table shows 8 of the 26 counties (29 percent) have used bottom ash. Also, fly ash, and other coal combustion byproducts have been used to the same extent, 29 percent each.

Similarly, 23 percent and 27 percent of the 26 counties identified have locations where calcium sulfate, power plant ash, or reclaimed portland cement concrete has been used. Materials that have been used the least include blast furnace slag and ceramic products. The research team found two reasons for this low rate of utilization for blast furnace slag and ceramic products. For the latter the smallness of materials available and sporadic access are factors that contribute the cost-ineffectiveness of using the material.

For the former, information collected from SMI in Seguin and discussions with a representative of International Mill Service indicate that (1) large quantities of slag are produced each year and (2) any decision to use it as base material will depend on results of research efforts organized to determine its performance where used. While Mr. Bob Lee of SMI was enthusiastic about the viability of slag as a roadbase material, Mr. Kenneth Call of International Mill Service was persistent in discouraging efforts to use slag in roadbase construction.

Respondents gave answers to other questions in the survey. With respect to the performance of these materials, every respondent gave a "fair," "good" or "excellent" rating for the materials reported (table 12). Materials that receive excellent performance rating include blast furnace slag, calcium sulfate, reclaimed portland cement concrete, fly ash, bottom ash, and other ash products. Additionally, respondents were very cooperative in submitting documented engineering test results. Some of these supporting documents are included in the Appendix. Alternatively, there were some potential respondents who were not as cooperative. Some individuals did not return telephone calls or respond to faxed questionnaires.

Some Benefits from the Study

Overall, this survey was worth the effort that the research team put into it for a number of reasons. First, the survey gave the research team the opportunity to add to the information and knowledge acquired in the precious survey. For example, the team learned about calcium sulfate and its use as base material. Also, the team learned about Monex Resources' line of base products which the company is eager to market to TxDOT contractors.

Second, the survey enabled the research team to identify people in the commercial operations who want to engage in collaborative research projects designed to promote enhanced utilization of such materials as ceramic shell in Hillsboro, Texas or blast furnace slag in Seguin, Texas.

Finally, the research team has learned that gaps still exist in our knowledge of the amounts, locations, and competing uses for waste roadbase materials from commercial sources. For example, it would be good to know how much of available coal combustion byproducts could be used in roadbase construction. Also, it would be important to have current data on the production and stockpile accumulation of these materials.

IV. Concluding Observations

On the basis of availability and widespread usage, the research team believes that calcium sulfate and fly ash should receive more attention as base materials. With respect to fly ash, a few observations are in order. First, the observation in Atlanta, Texas and Amarillo that fly ash is a "good" base material is consistent with literature review findings that its performance rating goes from "poor" in S. Carolina, Florida, and Michigan, to "good" in several states including Wisconsin, New York and Virginia, and "excellent" in Kansas and Wyoming. Second, the mixed review in the literature also is evident in Texas. For example, in Marshall, Texas TxDOT has discontinued its usage as base material.

A TxDOT engineer informed a member of the research team that TxDOT has used fly ash in subgrade and base material in the Marshall area. He said that the problem they encountered in both cases was cracking. Two possible solutions to the problem included reducing the amount of fly ash or eliminating its use. When the amount of fly ash was reduced, it became necessary to add hot mix, thus making the material suitable for subgrade construction. This is not cost-effective. However, crushed fly ash in base prevents seal coat to stick. Research is needed to find out what could promote bonding between asphalt and base. The TxDOT engineer insisted that solution of this problem would result in an extensive use of fly ash as base material.

Third, the other fact to note at this point is that Texas produces more than 10 million tons of fly ash and bottom ash combined each year. Even though there is a competing demand by the cement industry for fly ash, collaborative research efforts should be undertaken to find ways to increase its usage in roadbase construction.

The performance rating for other materials is provided in Table 12. As the table indicates calcium sulfate is used extensively throughout Texas. According to Gulf State Materials, Inc., the company in 9 years has sold over 4,500,000 tons of calcium sulfate into the base material market. The company can produce between 2,000 to 3,000 tons per day. The research team feels that with this volume of production, aggressive research should be undertaken to determine its durability in base construction. A similar research effort should be taken to verify the durability of Monex Resources' base materials which the company produces using blends of coal combustion byproducts.

Table 12: Summary of Materials Performance Where Used

Material	Where Used	Rating
Blast Furnace Slag	Seguin, Texas	Excellent
Calcium Sulfate	State-wide 20 cities, 9 county governments, 3 state agencies, & 91 companies	Excellent
Ceramic Products	Not Available	NA
Reclaimed Portland Cement	Dallas, Tarrant, Ellis, Henderson, Denton, & Rockwall	Excellent
Fly Ash	Amarillo, Mule Shoe, Atlanta, Marshall, etc.	Excellent Good, Fair
Bottom Ash	Amarillo, Mule Shoe	Excellent
Reclaimed Asphaltic Concrete	Bexar County	Excellent
Tire Chips and Other Rubber Products	Bexar County	Good
Monex Roadmix Base (Bottom Ash & Fly Ash)	Bastrop, Austin, Wilson, Atascosa, and Lavaca	Excellent
Other---Ash Products	Amarillo Mule Shoe	Excellent

Table 13: Coal Combustion Byproduct Generators in Texas

In Thousand Tons					
Facility	Utility	Fly Ash	Bottom Ash	FGD Material	Total
Coleto Creek	CP&L	84	50	0	143
Limestone	HL&P	0	456	1,426	1,882
W.A.	HL&P	308	116	135	559
Fayette	LCRA-COA	205	111	51	367
J.T. Deely	CPS	128	69	0	197
San Miguel	S.M. Electric	558	186	242	986
Pirkey	SWEPCO	267	49	204	520
Welsh	SWEPCO	179	66	0	245
Harrington	SW Pub.Svc.	138	35	0	173
Tolk	SW Pub.Svc.	144	41	0	185
Gibbons Creek	TMPA	433	522	133	1,088
Big Brown	TU	571	380	0	951
Martin Lake	TU	975	706	516	2,197
Monticello	TU	1,587	648	99	2,334
Sandow	ALCOA-TU	555	185	146	886
TNP	TNP	307	108	0	415
Oklaunion	WTU	98	36	21	155
Total		6,537	3,764	2,973	13,274

Source: U.S. Department of Energy

Figure 1. Coal Ash and Cement Generators in Texas