AN ABSTRACT OF THE THESIS OF

Mojtaba B. Takallou for the degree of Doctor of Philosophy in Civil Engineering presented on June 13, 1985.

Title: Evaluation of Alternate Surfacing Systems for Temporary and Intermittent Use Roads.

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Robert D. Layton

The purpose of this study was to provide the USDA-Forest Service, Bureau of Land Management (BLM), and other agencies or industries that may deal with temporary and intermittent use roads with the necessary background information for the identification, economic evaluation, and selection of the alternate surfacing systems and to determine the applicability and cost effectiveness of each system compared with crushed aggregate roads. Alternate systems considered include those which: 1) are capable of being moved as the hauling or mining activity moves, 2) degrade after use, and 3) significantly reduce the amount of rock required.

A comprehensive market and literature search was performed. Potential surfacing types identified in this study are biodegradable materials, chemical stabilization, geotextile or geogrid separation, marginal aggregates, sand-sealed subgrade, metal mats, reusable aggregate with or without geotextile separation, membrane-encapsu-

lated soil layer (MESL), and Geoweb stabilization. Numerous properties of these materials are evaluated, including size, weight, cost, expected performance, mechanical properties, and availability.

A two-step evaluation procedure is developed. First is the preliminary evaluation step, which screens various alternate materials based on their characteristics, limitations, and availability. The second step is economic evaluation, which determines the most feasible economical alternatives. Two examples are analyzed to describe the evaluation procedure. The results of this analysis indicate that alternate surfacings can be economical compared to aggregate in most situations.

A probabilistic approach using the Beta estimation procedure is recommended for the analysis and evaluation of the uncertainty associated with various elements of the alternate surfacings. Furthermore, a detailed sensitivity analysis is performed for crushed aggregate and soil stabilization surfaces.

The results of this research indicate that the feasible alternatives for surfacing temporary and intermittent use roads are biodegradable materials, soil stabilization, marginal aggregates, conventional geotextile and extruded plastic mats, steel mats (M8A1), and sand-sealed native subgrade.

Evaluation of Alternate Surfacing Systems for Temporary and Intermittent Use Roads

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EVALUATION OF ALTERNATE SURFACING SYSTEMS

FOR TEMPORARY AND INTERMITTENT USE ROADS

1.0 INTRODUCTION

1.1 Problem Definition

The USDA Forest Service, Bureau of Land Management (BLM), and other agencies or industries traditionally place crushed rock, pit-run, or select borrow material on an intermittent use or temporary service road when a surfacing system is deemed appropriate to haul timber harvest or for other resource activities. When the timber haul, mining, or other activities are completed, the surfacing and the capital investment that it represents lies idle for periods ranging up to 20 years. This thesis develops an evaluation methodology for alternate surfacing systems which can reduce the total investment in intermittent use and temporary service roads (Traffic Level D). Alternatives considered herein include surfacing systems which: 1) are capable of being moved as the hauling, mining, or other activities move, 2) degrade soon after use, 3) significantly reduce the amount of surfacing required, or 4) make better use of available resources to reduce construction cost.

1.2 Purpose

The overall purpose of this thesis is to provide the USDA-Forest Service, Bureau of Land Management (BLM), and other agencies or industries that deal with temporary or intermittent use service roads with the necessary background to evaluate alternate surfacing systems and to compare their economy with normal aggregate-surfaced roads.

This thesis is developed to aid engineers in the identification, preliminary analysis, economic evaluation, and selection of temporary or intermittent surfaces. Specific objectives include:

1) Identifcation of alternate systems available through a literature and market search.
2) Identification of important criteria for the selection of alternate surfacings.
3) Identification of costs and benefits of the alternate surfacings.
4) Developing an approach to evaluate and select which alternate surfaces are most economical for temporary or intermittent surfaces.
5) Demonstrating evaluation methodology through two examples.
6) Developing a probabilistic approach to assist engineers in the selection of the most economical alternative surfacing where there is significant variation in the cost and performance of activities.
7) Performing a sensitivity analysis to test and determine the critical factors and variables that influence the selection and use of an alternate surfacing system.

The study addresses nontraditional surfacing systems including:

1) Biodegradable materials (wood or bark chips),
2) Chemical stabilization,
3) Geotextile or geogrid separation,
4) Marginal aggregates,
5) Sand-sealed subgrade,
6) Metal mats,
7) Reusable aggregate without geotextile separation,
8) Reusable aggregate with geotextile separation,
9) Membrane encapsulated soil layer (MESL), and
10) Geoweb stabilization (expandable grids).

1.3 Study Framework and Organization of Remaining Chapters

Figure 1.1 presents the study framework. Each step in the study framework is discussed comprehensively in the chapters of this thesis. The main focuses of the thesis are the identification, preliminary analysis, economic evaluation, and selection of the alternative surfacing systems that can be used for intermittent use or temporary service roads and the evaluation of their economy with respect to normal aggregate-surfaced roads.

Chapter 2 defines the functions of road surfaces, describes traffic level of service for alternate surfacings, presents steps involved in road surfacing, and identifies current practices in road surfacing. This chapter establishes the background indicating why alternative surfacings should be considered for road surfacings.

Chapter 3 presents the results of a literature review and market survey on alternate surfacing materials. This chapter provides the

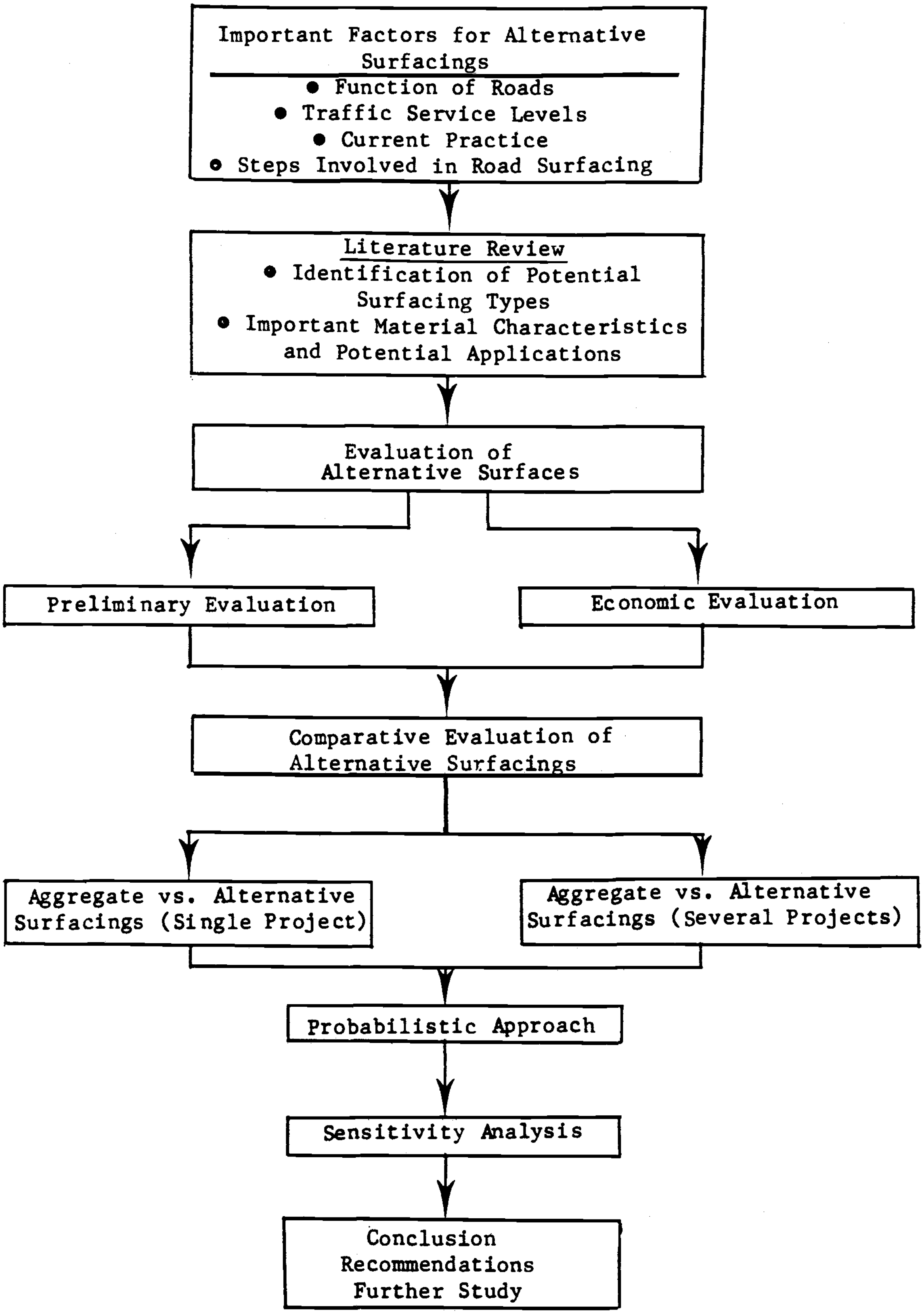

Figure 1.1. Study Framework.

needed inputs and information for the preliminary and economic evaluation of the alternate surfacings.

Chapter 4 presents the methodology that was developed to evaluate the overall effectiveness and economic viability of potential surfacing systems.

Chapter 5 presents the results of two examples that are analyzed in detail to demonstrate the evaluation methodology which was developed in Chapter 4.

Chapter 6 presents an approach to consider probabilistic variations in performance and costs into account. A procedure similar to that employed in the PERT network planning and scheduling technique is developed and applied. This procedure employs an "optimistic" estimate, a "pessimistic" estimate, and a "most likely" estimate for each element of the project to arrive at the expected performance or cost variable and its variation. Finally, a sensitivity analysis is performed which provides the decision maker with information concerning the sensitivity of the measure of economic effectiveness due to changes in various variables or factors.

Conclusions and recommendations are presented in Chapter 7.

2.0 BACKGROUND

2.1 Rationale for Alternate Surfacings Usage

Most of the roads in the United States are surfaced with native soil, naturally occurring sand and gravel, or crushed aggregate (1). Of the nation's 3.88 million miles of roads and streets, 1.86 million miles are either unsurfaced or are surfaced only with stone, slag, or gravel. An additional 1.0 million miles have a minimum of surfacing, ranging from surface treatments and chip seals to not more than 7 inch aggregate surface. Figure 2.1 shows the classification of U.S. roads network by the type of surface (1,2,3).

The U.S. Forest Service operates one of the largest low-volume road networks under the jurisdiction of a single agency in the world. This system contains approximately 330,000 miles, surfaced as follows (2,4):

Surfacing Types	Miles
Unsurfaced	221,100
Aggregate	92,400
Paved (all types)	16,500

The agency continues to construct and reconstruct 11,000 miles of road annually with an annual expenditure for construction, reconstruction, and maintenance of over $500 million. Figure 2.2 shows the classification of U.S. forest roads by type of surface. One of the largest groups of users of these roads are the haulers of wood products (2). These heavy trucks produce high stresses in the road surfacings; however, the number of repetitions are relatively

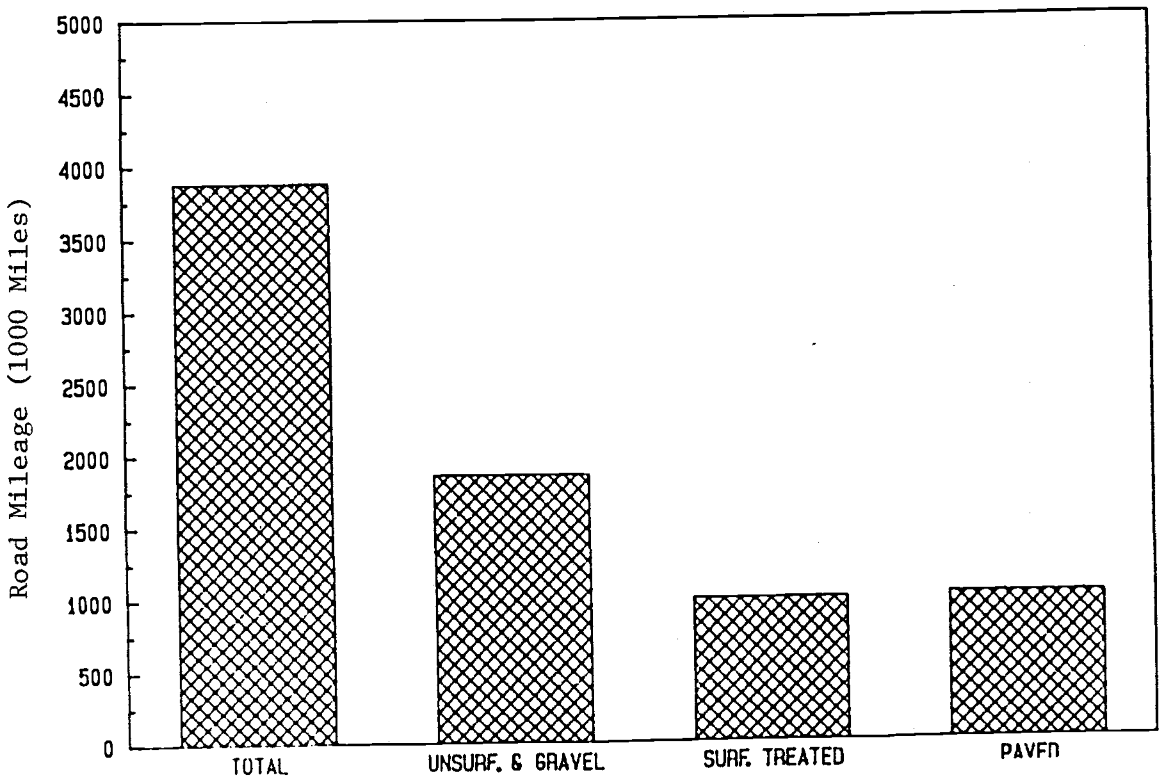

Figure 2.1. Classification of U.S. Roads Network by Type of Surface (3).

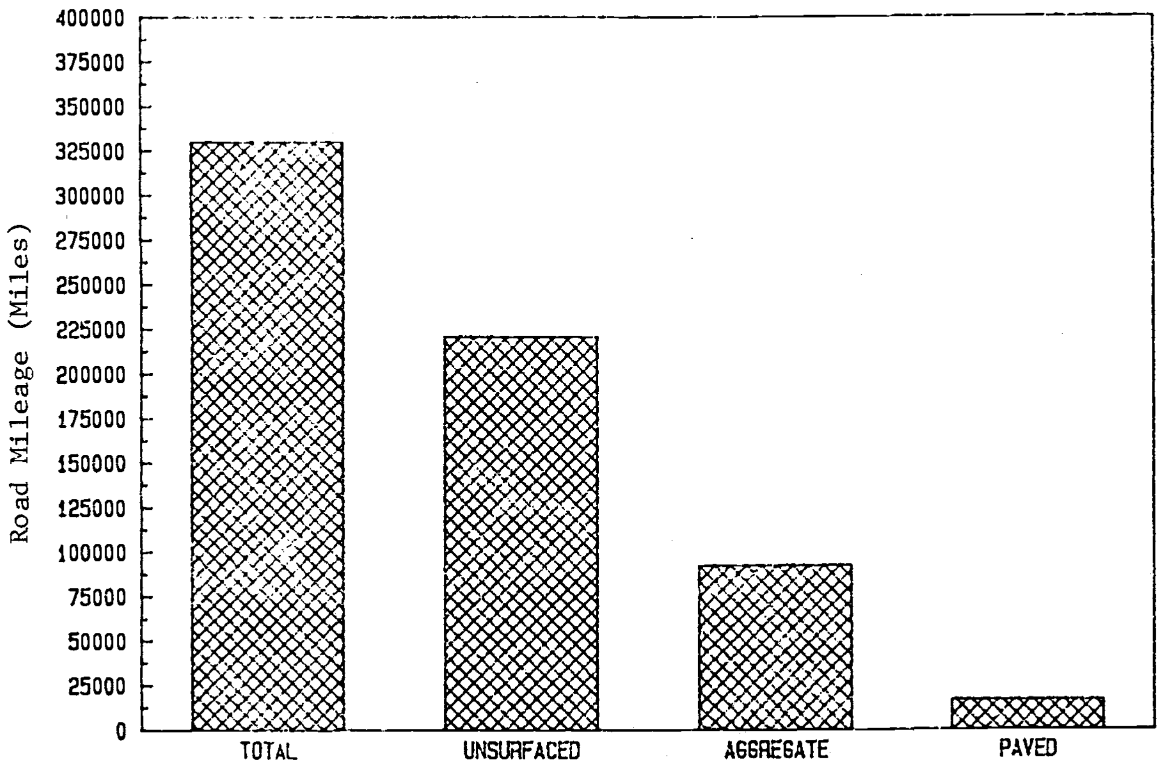

Figure 2.2 Classification of U.S. Forest Service Roads by Type of Surface (2,4).

small. About 90 percent of the crushed aggregate roads constructed by this organization are constructed totally for logging traffic (traffic level D) which might last a few seasons (or just one) and carries less than 100 vehicles per day (2). Table 2.1 and Figure 2.3 summarize the distribution of the aggregate-surfaced roads in five levels of average daily traffic (ADT).

Unfortunately, in recent years the increased demand for quality aggregates for various construction applications has resulted in shortages of aggregates in many parts of the country. Consequently, the possible use of innovative technology and unique materials for road surfaces is being investigated to find more economical surfacing materials. Some of these surfaces may be temporary or intermittent use, i.e., removed and reused again, such as aluminum, steel and geotextile mats. Others may be improved by means of soil stabilization, membrane enveloped soil layer (MESL), and expandable grids. Finally, some of the surfaces may be economical because of their availability in the desired regions, such as wood, bark chips, and marginal aggregates.

While this thesis focuses mainly on the U.S. Forest Service logging roads, this does not limit the use of this technology strictly to that organization. Other agencies or industries, such as the Bureau of Land Management (BLM) and private industry who deal with temporary or intermittent surfaces, may find the technology useful.

Table 2.1. National Summary (By U.S. Forest Service Region): Levels of ADT on the Aggregate Surfaced Roads (2)

USFS Region	ADT Both Directions				
	0 - 50	50-100	100-200	200-400	+400
1	56	28	10	3	3
2	39	29	21	7	4
3	81	14	5	0	0
4	53	25	13	9	0
5	70	16	11	3	0
6	72	19	6	2	1
8	84	11	3	1	1
9	81	15	4	0	0
10	76	18	6	0	0
National (%)	70	19	8	2	1

Note: The percentages refer to the total number of miles in each region.

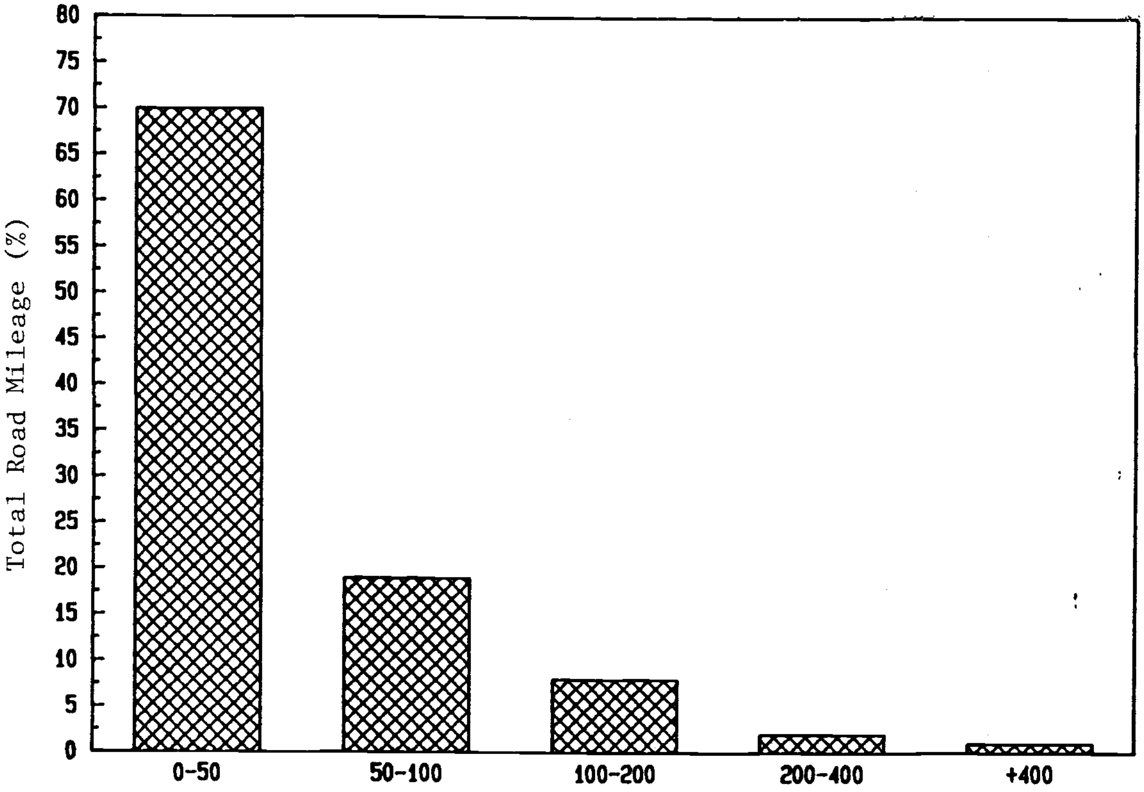

Figure 2.3. Levels of ADT on the U.S. Forest Service Aggregate-Surfaced Roads (2).

2.2 Functions of Road Surfacing

A road surface of any type with traffic service level of D must perform several functions (1):

1) provide strength enough to prevent overstressing the underlying layer,
2) resist raveling, shoving, rutting, and consolidation caused by vertical, longitudinal, and lateral forces applied by tires,
3) maintain reasonable smoothness without excessive maintenance,
4) provide adequate skid resistance,
5) provide reasonable dust control, and
6) be maintainable using normal techniques.

2.3 Traffic Service Levels

Traffic service levels describe the significant traffic characteristics and operating conditions for a road. Table 2.2 contains descriptions of the four different levels of traffic service for Forest Service roads. These traffic service levels describe the operating conditions for the road and the traffic characteristics that are significant in the selection of design criteria. The level reflects a number of factors, such as speed, travel time, traffic interruptions, freedom to maneuver, safety, driver comfort, convenience, and operating cost. These factors, in turn, affect (5):

Table 2.2. U.S. Forest Service Traffic Service Levels (5)

	A	B	C	D
FLOW	Free flowing with adequate passing facilities.	Congested during heavy traffic such as during peak logging or recreation activities.	Interrupted by limited passing facilities, or slowed by the road condition.	Flow is slow or may be blocked by an activity. Two way traffic is difficult and may require backing to pass.
VOLUMES	Uncontrolled; will accommodate the expected traffic volumes.	Occasionally controlled during heavy use periods.	Erratic; frequently controlled as the capacity is reached.	Intermittent and usually controlled. Volume is limited to that associated with the single purpose.
VEHICLE TYPES	Mixed; includes the critical vehicle and all vehicles normally found on public roads.	Mixed; includes the critical vehicle and all vehicles normally found on public roads.	Controlled mix; accommodates all vehicle types including the critical vehicle. Some use may be controlled to minimize conflicts between vehicle types.	Single Use; Not designed for mixed traffic. Some vehicles may not be able to negotiate. Concurrent use between commercial and other traffic is restricted.
CRITICAL VEHICLE	Clearances are adequate to allow free travel. Overload permits are required.	Traffic controls needed where clearances are marginal. Overload permits are required.	Special provisions may be needed. Some vehicles will have difficulty negotiating some segments.	Some vehicles may not be able to negotiate. Loads may have to be off-loaded and walked in.
SAFETY	Safety features are a part of the design.	High priority in design. Some protection is accomplished by traffic management.	Most protection is provided by traffic management.	The need for protection is minimized by low speeds and strict traffic controls.
TRAFFIC MANAGEMENT	Normally limited to regulatory, warning, and guide signs and permits.	Employed to reduce traffic volume and conflicts.	Traffic controls are frequently needed during periods of high use by the dominant resource activity.	Used to discourage or prohibit traffic other than that associated with the single purpose.
USER COSTS	Minimize; transportation efficiency is important.	Generally higher than "A" because of slower speeds and increased delays.	Not important; efficiency of travel may be traded for lower construction costs.	Not considered.
ALIGNMENT	Design speed is the predominant factor within feasible topographic limitations.	Influenced more strongly by topography than by speed and efficiency.	Generally dictated by topographic features and environmental factors. Design speeds are generally low.	Dictated by topography, environmental factors, and the design and critical vehicle limitations. Speed is not important.
ROAD SURFACE	Stable and smooth with little or no dust, considering the normal season of use.	Stable for the predominant traffic for the normal use season. Periodic dust control for heavy use or environmental reasons. Smoothness is commensurate with the design speed.	May not be stable under all traffic or weather conditions during the normal use season. Surface rutting, roughness, and dust may be present, but controlled for environmental or investment protection.	Rough and irregular. Travel with low clearance vehicles is difficult. Stable during dry conditions. Rutting and dusting controlled only for soil and water protection.

1) number of lanes,
2) turnout spacing,
3) lane widths,
4) type of driving surface,
5) sight distance,
6) design speed,
7) clearance,
8) horizontal and vertical alignment,
9) curve widening, and
10) turnouts.

Temporary and intermittent roads are usually designed for the traffic service level of D; therefore, throughout the thesis a traffic service level of D is assumed as representative of the conditions that would be relevant to roads to be surfaced with alternate surfacing materials.

2.4 Current Practice for Road Surfacing

As the traffic volume increases, the road surface quality should also increase. The most common practice for low-volume roads is to build unsurfaced roads up for low traffic volumes. As traffic volume increases, various surfacings are justified, first a gravel surface, then a surface treatment or paved surface is specified. This point of change varies from about 50 to 400 vehicles per day. For higher volume, bituminous surfacings are typically applied (6).

At present there are various types of surfacings for temporary or intermittent use roads. Table 2.3 summarizes the most commonly

Table 2.3. Current Road Surfacing Practices (6)

Type of Surface	Description
1) Earth	
a) Natural	Natural earth, graded and compacted (a dust treatment may be used)
b) Stabilized	Natural earth treated with lime, cement, asphalt emulsions or other chemicals to a 6-12 in. depth and compacted
2) Aggregate Surfaced	
a) Without Geotextile	8-12 in. of compacted aggregate placed on compacted soil
b) With Geotextile	8-10 in. of compacted aggregate placed on subgrade (compacted or uncompacted)
3) Bituminous Surface Treated	An application of emulsion and aggregate placed on a compacted aggregate base
4) Road Mix Surface	Mixing the top 2-4 in. of aggregate surface with an asphalt emulsion. The mixing is accomplished on the road using a travel plant.
5) Plant Mix Surface	Placing 2-4 in. of hot or cold mix on a prepared base. Mixing is accomplished in a central plant; placement is with conventional paving equipment

used practices where the selection of the type of surface depends primarily on the traffic volumes expected to use the facility.

The above surfaces are the most common surfacings for temporary or intermittent use roads. However, since the costs of materials used in the construction of low-volume roads are increasing every day, resources, such as good quality aggregates, are in short supply and funds are limited. It is not necessary to construct roads with permanent surfacings for a few hundred operations; therefore, alternate surfacings may be used to reduce the total capital costs.

2.5 Steps Involved in Road Surfacing

2.5.1 Design

Numerous factors must be identified and evaluated in the design of the traditional pavements (7). These factors are shown in Table 2.4 and include traffic volume, subgrade strength, surfacing materials, climatic factors, and failure criteria. The reason for each factor is described below (6,7).

Traffic. The type of surface usually depends on expected traffic volumes, that is an estimate of the traffic over the life of the pavement. The surface is often designed for a 20-year life, but may have a design life of 5 to 20 years or more. For thickness design, the traffic volume is normally converted to equivalent 18,000-pound single axle loads (18 SAL), which is the number of 18,000-pound axle loads that would cause equivalent pavement damage to that caused by the traffic volume.

Table 2.4. Pavement Design Requirements (6)

Item	Type of Data	Design Input
Traffic	Volume by Number of Axle Loads	18,000 lb. Equivalent Axles
Subgrade	Strength	CBR, R-value, Modulus
Structural Materials	Strength	CBR, R-value, Modulus
Climatic Factors	Temperature, Rainfall, Freeze-Thaw	Regional Factor
Failure Criteria	Dust Level, Rut Depth, Aggregate Loss, % Cracking, Serviceability	Function of Type of Facility
Cost	Construction, Maintenance Rehabilitation	

Subgrade Properties. The performance of the pavement is greatly affected by the characteristics of the subgrade. Desirable properties of the subgrade include strength, drainage, and ease of construction. The strength is affected by many factors including density, moisture content, soil texture, soil structure, rate of load application, and degree of confinement. The CBR, R value, and resilient modulus are commonly used to evaluate subgrade and base strength (6).

Structural Materials. The purpose of the surface is to provide a safe and smooth riding surface under various climatic conditions. The surface must provide skid resistance, resist applied loads and provide adequate dust control (8). Therefore, the types of surfacing material depend largely upon the load that will be applied to the pavement, the traffic volume, availability of construction materials, and economics. The CBR, R value, and resilient modulus are commonly used to evaluate the strength of subgrades, untreated bases, and subbase material.

Climatic Factors. Climatic factors are among the most important factors affecting pavement performance including frost action (freeze-thaw) and precipitation. Frost action includes both frost heave and loss of subgrade support during the frost melt period which may result in very high maintenance costs. Rainfall also affects pavement performance by increasing moisture content and reducing the subgrade strength. For example, a numerical factor, called the regional factor (R), is used in the AASHTO thickness design procedure to adapt it to various climatic environments.

Failure Criteria. Pavement failure may be caused by improperly compacted surface or subgrade courses, by the presence of a poor quality subgrade, subbase, base, or wearing course, or by climatic factors and effects. Common types of distress for paved roads include rutting, raveling, or cracking. The most common types of failure for aggregate pavements include rutting and aggregate loss.

The AASHTO design method combines various types of distress into a term called present serviceability index (PSI). A rating of 5.0 indicates a 'perfect' pavement, whereas a rating of 0 indicates an impassable pavement (7). The PSI takes into consideration the roughness, cracking, patching, and rut depth.

Since the design of the alternative surfacing systems are unique, various design references for alternate surfacing systems are discussed in Chapter 3.

2.5.2 Construction

The steps involved in the construction of the roads vary with the types of surfacing materials employed. Table 2.5 shows the typical steps for construction of an earth road, stabilized soil road, crushed rock surface, and paved surfaces. The construction steps for alternative surfacing types are summarized in Appendix A.

2.5.3 Maintentance and Rehabilitation

The objective of maintenance and rehabilitation activities is to improve the surface condition and to protect it from accelerated deterioration due to traffic and environmental effects. Routine maintenance activities are typically undertaken as required, are

Table 2.5. Road Construction Steps

Type of Surface	Steps
1) Earth Road	Grade Earth Road Compact Surface (at times)
2) Stabilized Soil Road	Windrow Soil/Scarify Surface Mix Stabilizing Agent and Soil Grade Surface to Elevation and Shape Compact Mixture
3) Crushed Rock Surface	Grade and Compact Subgrade Spread and Level Crushed Rock Place Leveling and Surfacing Course Compact (Roller and/or Traffic)
4) Paved Surface	Grade and Compact Subgrade Place and Compact Base Shoot Prime Coat Place Bituminous Surface Compact Surface
5) Alternate Surfacing Types	Refer to Appendix (A)

minor in nature, and usually preserve the surface in its present condition or improve it to a slightly better condition. Rehabilitation returns a surface and pavement section to a near new condition and, consequently, is more costly (6). The maintenance activities and their impacts for earth, stabilized soil, aggregate, and paved roads are described in Table 2.6. The maintenance activities for alternative surfacing are summarized in Appendix A.

2.6 Summary

This chapter has reviewed the necessary background for use of various materials to surface roads. The need to use more inexpensive alternate surfacings is justified based on the mileage of low standard roads in the United States where these alternate surfaces could be used. The function of road surfacings, traffic service levels, and current practices were discussed. The important factors to be considered in design, construction, and maintenance of roads surfacings were presented.

Table 2.6. Routine Road Maintenance Activities (6)

	Types of Surface	Activity	Impacts
1)	Earth, stabilized soil, aggregate	Dust Control	* Dust abatement; * Protects against surface deterioration
2)	Earth, stabilized soil, aggregate	Dragging	* Reduces roughness; * Reduces vehicle speeds; * Reduces vehicle operating costs
3)	Earth, stabilized soil, gravel	Blading (no wetting or compaction)	* Improves surface condition (roughness, rut depth); * Increases vehicle speeds; * Reduces vehicle operating costs
4)	Paved	Filling Potholes and Patching Cracks	* Reduces water penetration of road structure thereby decreasing deterioration of structural strength, rate of growth of road roughness and vehicle operating costs; * Patching increases surface roughness for small cracks, but decreases roughness from severe cracking and potholes
5)	Alternate Surfacing Types	Refer to Appendix (A)	

3.0 LITERATURE REVIEW AND DATA COLLECTION EFFORTS

A comprehensive literature review and data collection effort was undertaken to identify various materials, and their properties, that may be suitable for surfacing temporary and intermittent use roads. This search included:

1) computer searches,
2) review of Naval Civil Engineering Laboratory (NCEL) reports, and
3) review of U.S. Army Corps of Engineers Waterways Experiment Station (WES) and Cold Regions Research and Engineering Laboratory (CRREL) reports.

In addition, various companies in the United States were contacted requesting information on their products.

Several brainstorming meetings were also held by research personnel at Oregon State University with U.S. Forest Service personnel from Regions 5 and 6 in November 1983 to identify existing projects where alternate surfacings are being used and to discuss important properties of alternate materials and criteria for their usage.

Two field visits were made in January and February 1984 by research personnel at Oregon State University to governmental installations to discuss current research. These installations were the Waterways Experiment Station (WES) at Vicksburg, Mississippi, and the Naval Civil Engineering Laboratory (NCEL) at Port Hueneme, California.

Finally, eleven demonstration projects were constructed and evaluated, under the U.S. Forest Service Alternate Surfacings

Project, by research personnel at Oregon State University during the period from April 1984 to April 1985 to determine the feasibility of using these alternate materials for temporary or intermittent use roads. Detail writeups for each project are presented in the report entitled, "Compendium of Demonstration Projects" produced by the U.S. Forest Service Alternate Surfacing Project (9).

This chapter describes the result of the literature and market survey, the types of alternate surfaces available, their important properties and characteristics, limitations of their use, most promising and potential applications (when and where they should be used), and design references for further information. The highlights of the demonstration projects are also summarized in this chapter.

3.1 Potential Surfacing Types

Alternate surfacing types for temporary or intermittent use roads include:

1) biodegradable materials (wood or bark chips),
2) chemical stabilization,
3) geotextile or geogrid separation,
4) marginal aggregates,
5) sand-sealed subgrade,
6) metal mats,
7) reusable aggregate without geotextile separation,
8) reusable aggregate with geotextile separation,
9) membrane-encapsulated soil layer (MESL), and
10) Geoweb stabilization (expandable grids).

Each of these surfacing types is described briefly in Table 3.1 and in detail throughout this chapter.

3.2 Criteria for Viable Alternate Surfacing Applications

The decision of when, where, and under what conditions alternate surfacings should be used is based on traffic conditions, road objectives and needs, subgrade type, materials characteristics, and most importantly, economics. The following are important criteria that must be considered when using alternate surfacings.

1) Roadway Characteristics: Alternate surfaces are most likely suitable for the following conditions:

   a) Local or spur roads used on a temporary or intermittent basis,

   b) Projects that primarily serve logging traffic (50 to 100 vehicles per day),

   c) Logging Roads that require a surfacing life of 1 to 5 years,

   d) Projects that have short hauling distances from one site to another, allowing the reuse of surface materials,

   e) Areas where subgrade strength is low and alternate materials provide an increase in strength,

   f) Areas where aggregate is costly or inaccessible because of rugged mountains or long haul distances, and

Table 3.1. General Description of Potential Surfacing Types

Potential Surfacing Type	General Description
Biodegradable Materials	Bark chips and sawdust have been used in many different ways. Sawdust has been used as a lightweight fill to reclaim peat or swampy lands, and also to stabilize roads built in slide-prone areas. Bark and wood chips have been used as a road surface because it is an inexpensive method of constructing temporary logging roads. Furthermore, wood chips and sawdust are lighter than normal construction materials and easier materials with which to work (10).
Chemical Stabilization	Lime, portland cement, emulsified asphalts, fly ash, sodium chloride, calcium chloride, or magnesium chloride, and lignin sulfonate can be used to alter the following soil properties: strength, compressibility, permeability, volume stability, plasticity, and durability. The selection of the specific additives for stabilizing the materials depends on the subgrade material types as well as the availability and costs of the additives in the area (10,11,12).
Geotextile and Geogrid	Geotextiles mainly have been used in road construction for the separation and geogrids, which are high strength polymer structures, have been developed to stabilize weak soils. By reinforcing the surface of these soils, the grids effectively improve the load bearing characteristics. The grid's performance can lead to economics in both construction time and in the amount of subbase material used to achieve a stable platform (10,13)
Marginal Aggregates	Marginal aggregates do not meet standard American Association of State Highway and Transportation Officials (AASHTO) specifications for road use and may require some type of additive or special treatment to meet their role in the application and environment in which they are used. There are many types of marginal aggregates found around the country. Some of these materials include cinder, pumice, rhyolite, granite, limerock, coquina, decomposed sandstone, marginal sand, pit-run gravel, sand-clay shale, baked shale, chert, and marine basalts (10,14). For logging roads which require a life of approximately 1 to 3 years, marginal aggregates can be used by themselves without upgrading. Therefore, utilization of marginal aggregates for surfacing forest roads may offer lower construction cost.
Sand-Sealed Subgrades	The application of an emulsified asphalt on natural subgrade followed by the application of the sand as topping, which waterproofs a subgrade soil, is called sand-sealed subgrade. The sand-sealed subgrade is most effective in areas that have good and firm subgrade with high rock cost but have a plentiful source of low cost sand for reducing costs compared to crushed aggregate roads (9,10).
Metal Mats	Metal mats are surface panels prefabricated from materials such as aluminum and steel. The mats come in various panel sizes, typically 12 ft long, 2 ft wide, 1 in. thick, and can be connected together to form a continuous road surfacing. These materials may only be applicable for a short section of logging roads due to their high initial cost (10).

Table 3.1. General Description of Potential Surfacing Types (Continued)

Potential Surfacing Types	General Description
Reusable Aggregate Without Geotextile Separation	The supply of aggregates suitable for road construction has already been exhausted in many areas of the country. The demand for quality aggregates will continue to increase in all areas of the United States in the years ahead (15). Therefore, the recovery and reuse of high quality aggregate on several projects may offer lower construction cost. The reuse of the good quality aggregate can be most effective for the projects that have such high rock cost, short duration of logging, short hauling distance from one project to the alternate project, and almost equal size projects. It has been estimated that about 70 to 75% of the aggregate can be recovered each time for future use (10).
Reusable Aggregate with Geotextile Separation	Similar to the above, except a light geotextile is used as a separation layer between subgrade and surface materials to eliminate the loss of costly aggregate materials into the subgrade. It has been estimated that about 90 to 95% of the aggregate can be recovered each time for future use.
Membrane Encapsulated Soil Layer (MESL)	The MESL concept maintains a moisture content of the subgrade soil at the desired level by encapsulating the soil in a waterproof membrane to prevent water infiltration (16). MESL should generally be with fine-grained soils which are susceptible to strength loss if wetted.
Geoweb Stabilization (Expandable Grids)	Geoweb is manufactured by Presto Products of Appleton, Wisconsin. The grids are constructed of 50 mils high density polypropolene sheets, 8 in. x 11 ft x 8 in. The sheet opens like an egg crate divider into an 8 ft x 20 ft panel. The expanded panels are set in place, and the cells filled with sand. The sand is compacted and the surface is sprayed with a liquid asphalt at a rate of 1 gal/yd^2. With the cells the structural capacity is reported to be equivalent to 8 in. of high quality crushed rock. Geowebs are not economical for logging roads compared to aggregate roads, due to the high initial cost of the materials (\$1.25/ft^2) and the materials cannot be recovered (9,10).

1 in = 25.4 mm, 1 ft = 0.3048 m, 1 ft^2 = 0.0929 m^2, 1 yd^3 = 0.7645 m^3, 1 gal/yd^2 = 4.55 liters/m^2

g) Areas that have a limited or severely restricted supply of good quality aggregates available for road construction.

2) Material Characteristics: Alternate materials that have the following characteristics are most likely to be considered:

a) Materials capable of being moved as the hauling activity moves,

b) Materials that are low cost compared to good quality aggregates,

c) Low cost marginal materials that have relatively short lives but satisfy the project life,

d) Materials that are available in the desired areas which reduces the construction cost.

3.3 Description of the Potential Surfacing Types

3.3.1 Biodegradable Materials

Biodegradable materials, which include bark and wood chips, sawdust, and planks or logs, have been used as a lightweight fill to reclaim peat or swamp lands, and also to stabilize roads built in slide-prone areas. Bark and wood chips have been used as a road surface, both as a means to reduce airborne dust, as in Arkansas, and as an inexpensive method of constructing intermittent use logging roads. The cost of the wood chip materials ranges from about $3.00

to $10.00/yd^3 in-place or $0.17 to $0.55/ft^2 for a 12-inch surface layer.

The wood and bark chips used in constructing these roads have dimensions not exceeding 6 inches. The chips may be brought to the site in dump trucks or chipped on-site, and then bladed into place. Compaction from construction equipment is generally sufficient.

The advantages of using biodegradable materials include the following factors (17):

1) Use of Waste Materials: Wood chips and sawdust are excellent ways to make productive use of waste materials.

2) Costs: Wood chips and sawdust may be less expensive than borrow materials. However, their availability locally is a large factor in their cost. Also, with an increasing demand to utilize wood wastes, the price of wood chips and sawdust must inevitably rise in the future.

3) Construction and Maintenance: Handling and working with wood chips and sawdust are easier than with conventional construction materials since they are much lighter. Although rutting under traffic is a problem, it can be easily solved by periodic reworking and respreading of the chip blanket to eliminate the berms and bare areas. A dozer is sufficient for this purpose.

Potential disadvantages of using biodegradable materials include the following factors (17):

1) Environmental: The most significant environmental impact comes from the leachates and their effect on the water quality of nearby water sources. Though this is true for high embankments, it may not be a significant problem for road surfaces. With general characteristics of low pH value, virtually zero dissolved oxygen (D.O.) levels, and initial high concentrations of organic pollutants, aquatic life and water quality may be seriously impaired. Aesthetics are another concern. Stains, strong odors, and slime growths along embankments have been observed.

2) Fire Hazard: There is always the possibility of spontaneous combustion of the wood chips, particularly in dry warm regions and where compaction is at a minimum. However, this would generally be a problem when the materials are placed in great depths.

As a part of the Forest Service project, two demonstration projects with a wood chip surface have been constructed and evaluated in the Pacific Northwest. The highlights of the findings include:

1) The use of wood chips as a surface would be limited to low speed and moderate grade roads where the vertical grade does not exceed 10% to 15%.

2) Wood chip surfaces are very economical compared to crushed aggregate surfaces.

3.3.2 Soil Stabilization

Soil stabilization as a technology started to evolve about 45 years ago (18). In 1906, the United States conducted the first experiments with sand-clay mixtures (18). The favorable results prompted subsequent construction projects using various mixtures. At that time cement, bitumen, and certain chemicals were first employed to stabilize soils, and a number of different stabilization techniques were elaborated (18).

Soil stabilization is generally used to alter the following soil properties:

1) strength,
2) compressibility,
3) permeability,
4) volume stability,
5) plasticity,
6) durability, and
7) sensitivity to moisture.

Several techniques can be used to achieve these goals including:

1) Compaction: Densification of soils results in increased strength and decreased compressibility and permeability.
2) Admixture: A chemical, cement, lime, or asphalt is mixed with the soil followed by compaction in lifts.
3) Consolidation and Dewatering: Preload and surcharge fills or other means are used to "squeeze" water out of voids of soft soils prior to construction.

4) Gravity and Injection Gravity: Pore spaces and voids in the soil are filled with a stabilizing agent such as cement, bitumen, or chemicals.

5) Reinforcement: Fibrous materials or horizontal tensile strips are placed in soil masses to strengthen soft or weak soil.

The percentage of materials passing the No. 200 sieve and the plasticity index (PI) have been found to be useful criteria to determine the suitability of lime, cement, or asphalt as a stabilizing agent. Figure 3.1 presents a guide for choice of stabilizers based on these criteria. Cement is best suited for well-graded granular soils or fine-grained soils with a PI < 10. Asphalt is best suited for soils with a PI < 6, less than 25% passing the No. 200 sieve, and (PI x % passing No. 200 sieve) < 60. Lime is best suited for soils with a PI > 10. Based on these criteria, it appears that either cement or asphalt would be a logical choice as a stabilizer for poor quality aggregates owing primarily to the fact that the PI for the poor quality aggregates would be quite low (19).

Kezdi (18) developed a table for the various approaches to soil stabilization. Table 3.2 shows the approaches and the amount of admixture for various types of soils. The climatic constraints and construction safety precautions of soil stabilization are given in Table 3.3 (11).

As a part of this study several demonstration projects were evaluated during the summer of 1984 in Region 8 of the US Forest

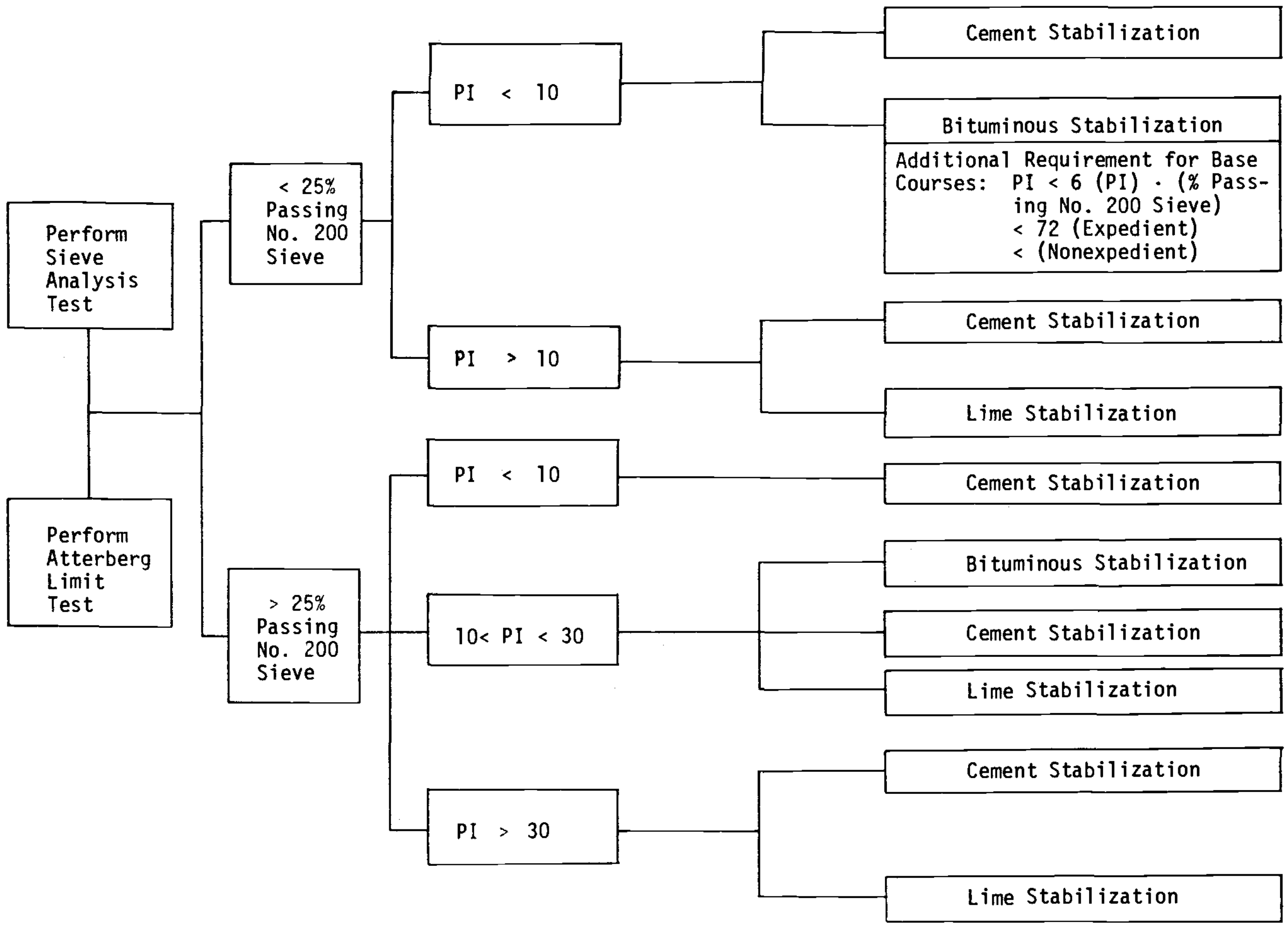

Figure 3.1. Selection of Stabilizer (20,21).

Table 3.2. Summary of Recommended Stabilization Type and Recommended Amount of Admixture (18)

Method	** Amount of Admixture (% Dry Weight)	Soil-Type: Rough Granular	Soil-Type: Fine Granular	Soil-Type: Low Plasticity Heavy	Soil-Type: High Plasticity Heavy	Special Advantage
Cement	3-5	A				Strength increases in short time
	5-9		A			
	9-12			A		
	10-16				B	
Lime	-	N/A	N/A			Rapid clay plasticity decrease insensitivity between mixing and compaction
	2-6			A		
	2-8				A	
Lime and fly ash	3-5% Lime	A				No time-factor effect
	10-20% Fly ash		A			
	5-9% Lime			B		
	10-25% Fly ash				C	
Bitumen asphalt and tar	3-6%	A				Water seal
	3-6%		A			
	5-9%			B		
	-				N/A	

where: A = Excellent suitability
B = Adaptable
C = Not applicable for these materials

Table 3.3. Climatic Limitations and Construction Safety Precautions (11)

Type of Stabilizer	Climatic Limitations	Construction Safety Precautions
Lime and Lime-Fly Ash	Do not use with frozen soils Air temperature should be 40°F (5°C) and rising Complete stabilized base construction one month before first hard freeze Two weeks of warm to hot weather are desirable prior to fall and winter temperatures	Quicklime should not come in contact with moist skin Hydrated lime [$Ca(OH)_2$] should not come in contact with moist skin for prolonged periods of time Safety glasses and proper protective clothing should be worn at all times
Cement and Cement-Fly Ash	Do not use with frozen soils Air temperature should be 40°F (5°C) and rising Complete stabilized layer one week before first hard freeze	Cement should not come in contact with moist skin for prolonged periods of time Safety glasses and proper protective clothing should be worn at all times
Asphalt	Air temperature should be above 32°F (0°C) when using emulsions Air temperatures should be 40°F (5°C) and rising when placing thin lifts (1-inch) of hot mixed asphalt concrete Hot, dry weather is preferred for all types of asphalt stabilization	Some cutbacks have flash and fire points below 100°F (40°C) Hot mixed asphalt concrete temperatures may be as high as 350°F (175°C)

1 in. = 2.54×10^{-2} m

Service. The highlights of the findings from the literature review and demonstration projects include:

1) Soil stabilization is a feasible solution for surfacing temporary or intermittent use roads due to the shortage of good quality aggregate and utilization of the marginal aggregates that are in good supply around the country. Attempts to use soil stabilization have been encouraged. This is likely to be the most economical solution for providing temporary or intermittent use roads.

2) The selection of the stabilizing agent is based on the type of soil being stabilized, the availability of the stabilizers, and cost.

3) The use of by-products such as pozzolime and bottom ash has been considered a good option for temporary or intermittent use roads. Their availability makes them economically attractive.

4) When stabilizing the fine grained soils, a traction course of crushed aggregate should be provided to prevent a slippery surface during wet weather.

5) Finally, stabilization is feasible for many areas. The choice of a specific stabilizer and the economics of its use depend on local conditions and the relative costs of other surfacing types.

3.3.3 Synthetic Mat Surfaces

Several types of synthetic mat surfaces are available. These include:

1) Heavy geotextile mats: Traffic can operate directly on these mats over prepared or natural subgrade.
2) Conventional geotextiles: These would have to be used with an aggregate cover.
3) Extruded plastic grids: These are stronger than conventional geotextiles, but would also need an aggregate cover.

Each is described in more detail below together with their advantages and disadvantages.

3.3.3.1 Heavy Geotextile Mats. One of the latest developments in constructing temporary or intermittent use roads is to use geotextile mats directly on the soft subgrade to form a temporary road. The mats can be rolled out and rolled up quickly, and thus can be reused many times (22).

There are at least two types of these materials that may appear suitable for use as surfacing on forest roads. These include "Mammothmat," manufactured by Robusta of Holland, and "Paraweb," manufactured by Linear Composites, Ltd., of England. These materials are described briefly in the following paragraphs.

1) Mammothmat. This product is made of a polypropylene woven geotextile with steel reinforcement in both transverse and longitudinal directions. Due to its high strength, the reinforcing mat has excellent

performance. The Mammothmat can be used as an instant road without any additional aggregate layers. The Mammothmat was developed in close cooperation with the Dutch Army. The mat can be used on soft clay with a CBR of greater than 3, or peat areas, or as a temporary access road. The mats can also be used on a steep slope of loose sand and sharp horizontal curves (22). The cost of materials is extremely high, about $\$5.50/ft^2$ ($\$60/m^2$).

2) Paraweb. Paraweb membranes are woven from linear composites of Paraweb. Paraweb is a structural composite constructed from closely packed, high tenacity filaments of Terylene (polyester) embedded in a tough, durable sheath of black polyethylene. Paraweb mats provide an exceptionally high strength structural mat suitable for a wide variety of civil engineering applications (23). Paraweb construction mat provides an instant roll-down/roll-up road to meet temporary road requirements (23).

The mat has only been used successfully in military operations where it has been possible to define clearly the performance required and where it is possible to train military personnel in the precise laying method required to achieve optimum performance. In military use, the mat has been especially useful on sand, gravel, and in cold climates in snow

(23). Laying the mat is a fairly simple task. It can be laid at the rate of 0.3 minute/ft (1 minute/running meter), using a team of four men. Mats are secured to the ground across their width to resist the traction reaction between ground and wheels or tracks of the vehicle on the mat, and along the edges of the mat to maintain the roadway edge.

The Paraweb temporary road alternative has been used in conditions that are normally considered impossible for wheeled traffic (23). In fact, in one application, conditions prevented metallic track laying vehicles from entering construction sites, and the only other viable alternative would have been the progressive end dumping of aggregate to form a road, which can be very expensive.

Advantages of Mammothmat and Paraweb, according to the manufacturers' reports include:

1) can be rolled out/up quickly,
2) can be reused many times,
3) can be rolled over vegetation; therefore, there is minimal cost for preparing the ground,
4) has very high tensile strength,
5) requires less maintenance than aggregate roads, and
6) can be used on a very steep slope of loose sand and sharp horizontal curves.

The disadvantages of these materials include:

1) The cost of materials are extremely high compared to crushed aggregate,

2) Mammothmat materials are not available in the United States,

3) the Paraweb surface can be applied only for light traffic, but not logging roads, because of poor performance,

4) the Mammothmat surface is very rough and can cause severe damage to tires, and

5) the operating speed possible is expected to be low.

Therefore, it appears only Mammothmat may be suitable for temporary roads as reusable surfaces because it can be rolled out/up quickly and can be reused many times. Mats require no specialized equipment or personnel for handling, and they can be quickly and manually put into place. However, they may not be economical for use on temporary or intermittent use roads because they are too expensive, about $5.50/ft^2 ($60/m^2).

3.3.3.2 Conventional Geotextiles These have been used in road construction for the following reasons:

1) Separation: Base and subbase material cannot mix with that of the subgrade. The foundation remains solid and stable (refer to Figure 3.2a).

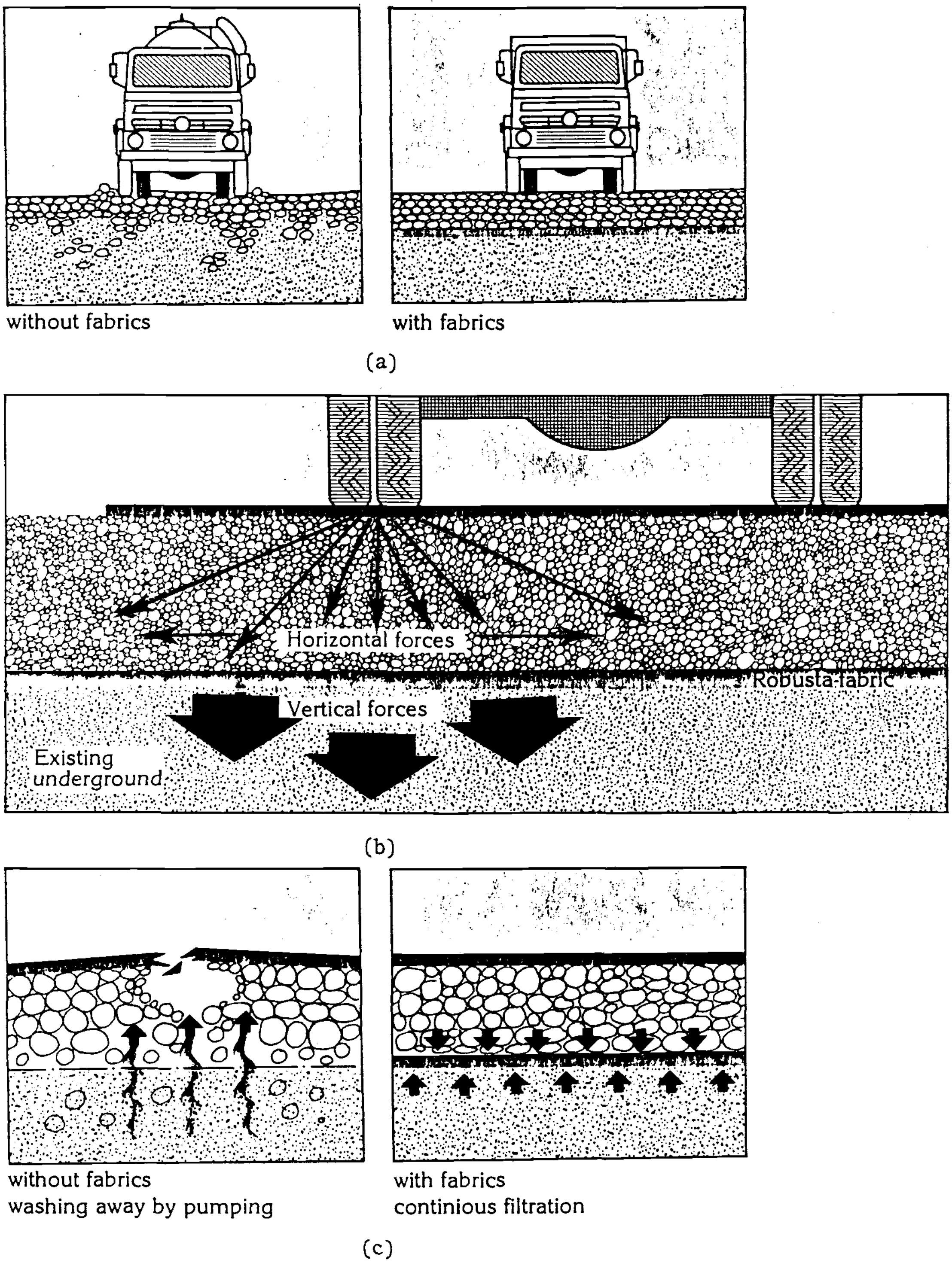

Figure 3.2. Fabrics in Road Construction (22).

2) Reinforcement: As fabrics combine a high tensile strength with a relatively low extendibility, forces exerted upon them are effectively absorbed. The result is better stabilization of the foundation (refer to Figure 3.2b).

3) Filtration: Some fabrics have excellent filtering properties; consequently loss of foundation material by "pumping" is effectively prevented (refer to Figure 3.2c).

Reported advantages of geotextiles include (22):

1) can be rolled over vegetation, thereby reducing the cost for preparing the ground,
2) reduces loss of material from foundation by pumping,
3) limits the intrusion of the fines from the subgrade into the base and/or subbase,
4) distributes the pressure on the road more evenly,
5) minimizes the formation of ruts,
6) allows the road to carry heavier vehicles than otherwise possible,
7) uses the pavement materials more efficiently,
8) permits reuse of excavated fill material,
9) requires less maintenance compared with aggregate roads
10) placing is simple, fast, and easy, and
11) minimizes risk of frost damage.

Based on the results of the literature review and the evaluation of several demonstration projects in Region 6, geotextiles are very suitable for temporary and intermittent use roads due to low cost, \$0.07 to \$0.12/ft^2 (\$0.70 to \$1.20 yd^2), aggregate savings, improvement to subbase and subgrade soils, and easy installation.

3.3.3.3 Tensar Grids. Tensar geogrids are high strength polymer structures developed by Netlon Limited, using a manufacturing technique that orients the long chain molecules within the polymers* (24).

This orientation process increases the inherent tensile strength of the polymer to levels that, in some cases, are comparable to mild steels. The polymers used in the production of "Tensar" have the advantages of being resistant to all chemical substances that normally exist in soils. Figure 3.3 shows Tensar grid SS-1 with its properties.

Tensar grid SS-1 was developed to stabilize weak soils. By reinforcing the surface of these soils, the grids effectively improve the load bearing characteristics. The grid's performance can lead to economies in both construction time and in the amount of subbase material used to achieve a stable platform. This material has several reported advantages:

1) Grids can be rolled out easily and quickly, either on a prepared foundation or onto a subgrade that has been previously cleared of rigid obstructions.

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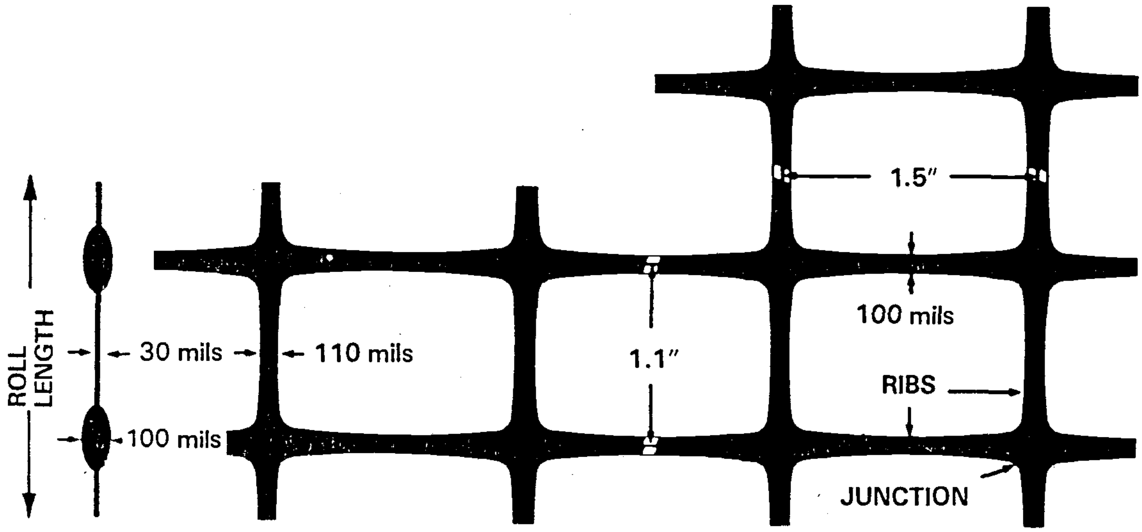
*Now produced in the United States by Tensar Corporation.



Structural Characteristics:

Roll length (ft)	: 164.0
Roll width (ft)	: 9.8
Roll weight (lb)	: 67.0
Color	: Black

Mechanical Properties:

Characteristic tensile strength (lb/ft)
Across Roll width: 1430
Along Roll length: 860

NOTE. Samples, 3 junctions long and 1 rib wide, were extended at a constant rate of 2 in/min, at a temperature of 68 ± 2°F.

Raw Material–Physical & Chemical Properties:

Polymer	: Polypropylene
Shore Hardness D (Din 53505)	: 74
Vicat Softening Point (Din 53460) (°F)	: 298
Impact Strength (Din 53453) (lb/ft)	: 308
Abrasion Resistance (Din 53754E) (in^3/100 revs)	: 8.5×10^{-4}
Chemical Resistance	: Resistant to all natural occurring alkaline and acidic soil conditions
Biological Resistance	: Resistant to attack by bacteria and fungi
Sunlight Resistance	: Stabilized for long periods of exposure to U.V.
Material Cost	: $1.30/$yd^2$ (14¢/ft^2)

Figure 3.3. Tensar Grid SS-1 (24)

2) Grids stabilize weak soils at minimal cost.
3) Grids have chemical resistance to all naturally occurring alkaline and acidic soil conditions.
4) Grids save in both construction cost and in the amount of subbase material by 30%.
5) Grids are relatively inexpensive, costing $0.14/ft^2 ($1.40/m^2), available, and reusable.

Based on the results of the literature review and the evaluation of a demonstration project in the Pacific Northwest, Region 6, Tensar grids are unique in terms of their material and applications. The grids effectively improve the load bearing characteristics of weak soil and can save in both construction time and in the amount of subbase materials. Table 3.10 at the end of this chapter includes a summary of the general properties and costs of the various mat surfaces.

3.3.4 Marginal (or Degradable) Materials

Marginal materials are those that nearly meet standard American Association of State Highway and Transportation Officials (AASHTO) or American Society for Testing and Materials (ASTM) specifications for road use and may require some type of additive or special treatment to meet their role in the environment in which they are used (14).

There are many types of marginal aggregates found around the country that can provide satisfactory performance if upgraded. These materials include cinders, pumice, rhyolite, granite, limerock, coquina, decomposed sandstone, marginal sand, pit-run and river-run gravel, sand-clay, shale and baked shale, chert, basalt, stone screenings, and top soil. The most important in the Pacific Northwest are basalts, especially marine basalts, low-quality dredged materials, sandstones, and sand. Each of these aggregates can have quality deficiencies that preclude its use under normal design circumstances. The problems associated with these aggregates are summarized in Table 3.4.

Various properties of the marginal aggregates must be defined to decide whether marginal aggregates can be used as a surface for temporary or intermittent use roads. These properties, based on the Forest Service specifications, serve as a yardstick in assessing the anticipated performance of the road under various environmental and loading conditions and include:

1) Gradation: Gradation is perhaps the most important single property of an aggregate because it directly, or indirectly, affects several other properties. The Forest Service Standard specification for crushed aggregate grading requirements for base or surface courses is shown in Table 3.5.

2) Abrasion: The Los Angeles Abrasion Test (AASHTO T-96) is an indicator of aggregate response to abrasion and impact. Many agencies require a Los Angeles Abrasion loss of 40% or less for surface aggregates (1). There are four major problems with aggregates having higher abrasion losses (1). These include:

   a) shorter service life due to physical degradation,

Table 3.4. Marginal Oregon Coastal Aggregates and Associated Problems (25)

Type of Aggregate	Problems
Marine basalt	Low resistance to chemical degradation
Sandstone and siltstone	Low resistance to mechanical degradation
Sand, beach and dune	Low stability because of poor gradation Environmental restrictions
Low quality dredged materials	Poor gradation High organic content

Table 3.5. Crushed Aggregate Grading Requirements for Base or Surface Courses (26).

	Percent Passing (AASHTO T 11 and T 27)				
Sieve	Grading A	Grading B	Grading C	Grading D	Grading E
3 inch	100				
2 inch	65-95	100			
1-1/2 inch			100		
1 inch		60-90		100	
3/4 inch	40-75		60-90	70-98	100
1/2 Inch		44-70			70-98
No. 4	22-45	28-50	30-55	36-60	44-70
No. 8	16-34	20-41	22-43	25-47	30-54
No. 30	8-22	9-26	11-27	12-31	15-34
No. 200	2-10[a]	3-12[a]	3-15[a]	3-15[a]	3-15[a]
Sieve	Grading F	Grading G	Grading H	Grading J	Grading K
3 inch	100				
2 inch	65-95	100			
1-1/2 inch			100		
1 inch		50-85		100	
3/4 inch	28-70		55-90	70-98	100
1/2 inch		27-60			65-95
No. 4	10-35	15-40	20-48	25-55	33-60
No. 8				16-40	21-42
No. 30			5-20	6-22	8-24
No. 200	0-10[a]	0-12[a]	0-15[a]	0-15[a]	0-15[a]

[a]For untreated base used under bituminous materials, Sections 403, 404, 405, 406, 409, and 410 of Forest Service Standard Specifications for Construction of Roads and Bridges, the maximum percent passing the No. 200 sieve shall be 8. For surfacing, the minimum percent passing the No. 200 sieve shall be 6.

b) excessively smooth surface sometimes leading to slippery conditions in wet weather,

c) excessive dust, and

d) surface erosion during rains.

Abrasion requirements for base or surface courses used by the Forest Service are shown in Table 3.6.

3) Durability: Aggregates degrade differently in the presence of water than they do in the dry state. Rocks which produce nonplastic fines in the Los Angeles Abrasion Test (T-96) may produce highly plastic fines if water were present. These plastic fines will improve the performance of an untreated aggregate surface (1). The Forest Service standard specification for the durability (T-210) index of coarse and fine aggregates is 35 minimum (Table 3.6). Since most of the aggregates in the Siuslaw National Forest have a low durability index value, the acceptable durability index value has been lowered from 35 to 25.

4) Sand Equivalent: The Sand Equivalent Test (AASHTO T-176) began as an attempt to develop a short cut for the Atterberg limits tests in aggregate. It has been found that a S.E. value greater than 35 usually correlates with a P.I.

Table 3.6. Crushed Aggregate Quality Requirements for Base or Surface Courses (26).

Description	AASHTO Test Method	Requirement Base	Requirement Surfacing	Siuslaw N.F. Requirement Base	Siuslaw N.F. Requirement Surfacing
Dust Ratio: % Passing No. 200	Test Method	2/3 max	Surfacing	2/3 max	Surfacing
Percent Wear	T-96	40 max	40 max	40 max	40 max
Durability Index, Coarse and Fine	T-210	35 min	35 min	25 min	25 min
Liquid Limit	T-89	25 max	35 max	25 max	35 max
Plasticity Index	T-90	6 max	2-9	6 max	2-9
Dust Ratio: $\frac{\%\text{ Passing No. 200}}{\%\text{ Passing No. 30}}$	T-11	2/3 max	2/3 max	2/3 max	2/3 max
Sand Equivalent	T-176	35 min	-	27 min	-

Notes: When crushed gravel is used, at least 50% by weight of the particles retained on the No. 4 sieve shall have at least one fractured face. Naturally fractured faces may be included in the 50% requirement, provided the roughness and angularity produce strength characteristics equivalent to mechanically fractured faces.

of less than 6 (1). The Forest Service standard specification for the value of the sand equivalent is 35, as in Table 3.6. Since most of the aggregates in the Siuslaw National Forest have a low S.E. value, the acceptable S.E. value for this forest has been lowered from 35 to 27.

5) Dust Ratio: The dust ratio is defined as being the ratio of the percent passing number 200 sieve to the percent passing the number 30 sieve (AASHTO T-11,T-27). A ratio of 2:3 helps assure that the fine fraction of the aggregate is well graded; however, it is often considered to be an unimportant specification because most of the aggregate materials pass this test. The Forest Service standard specification for the value of the dust ratio is shown in Table 3.6.

The above tests are the most important tests for defining the quality of the aggregates for deciding whether marginal aggregates can be used as a surface for temporary or intermittent use roads.

Furthermore, marginal aggregates can be applied as a surfacing to provide roads that are sufficiently smooth, stable, durable, and have adequate traction. But unfortunately, many of these aggregates do not last more than 2-3 years without other treatments, due to low resistance to chemical and mechanical degradation, low stability, and poor gradation. Most of the temporary or intermittent use roads only require a life of approximately 1-3 years which the marginal aggregates can provide. However, where longer surface life is required, marginal aggregates must be upgraded. Various methods are used to upgrade marginal aggregates. The most important is admixture stabilization. Table 3.7 summarizes recommended stabilization methods for marginal coastal aggregates found on the Oregon coast. Evans (27) developed mix designs for various marginal aggregates. Table 3.8 shows the optimum emulsion contents determined for the aggregates. Chang (28) determined recommended cement contents for some of the same aggregates. These recommendations are shown in Table 3.9.

The cost of aggregate varies due to the transportation cost and material availability; the basic cost of the rock at pit ranges from about \$1.00 to \$5.00/yd^3 for 3/4-inch (1.90 cm) crushed rock (29). But, the cost of aggregate in-place may vary from \$5.00 to \$30.00/yd^3 due to the transporation cost. Assuming a surface thickness of 12 inches, this would result in material cost of \$0.04 to \$0.19/ft^2 and an in-place material and construction cost of \$0.19 to \$1.10/ft^2.

The literature review and the evaluation of several demonstration projects yielded the following findings:

1) There is a need to conserve high quality aggregates for more critical uses. Marginal aggregates can be used for intermittent service roads without treatment to reduce construction costs. If a design life longer than 2-3 years is required, marginal aggregates must be upgraded by adding the appropriate admixtures.

Table 3.7. Summary of Recommended Stabilization Methods for Oregon's Coastal Aggregates (25)

Material	Stabilization Methods
Marine basalt	Asphalt emulsion Portland cement
Sandstone and siltstone	Portland cement
Sands	Asphalt emulsion Portland cement Lime-pozzolan
Low quality dredged materials	Portland cement Lime, lime-pozzolan

Table 3.8. Optimum Emulsion Contents for Marginal Aggregates (27)

Aggregate	Emulsion type	Emulsion content %	Water content %	Dry density pcf*
Quality basalt	CMS-2	5.0	0-1	123
Marginal basalt	CMS-2	6.0	2-4	123
Marginal basalt	CMS-2	6.0	3-4	130
Marginal sandstone	CMS-2s	12.0	12-14	114 (not recommended)
Dune sand	CSS-1	8.0	9-12	104 (not recommended)
Dune sand	CSS-1 + 1.5% portland cement	7.0	9	116

*1 pcf = 16.02 kg/m^3

Table 3.9. Recommended Cement Contents for Marginal Aggregates (28)

Aggregate	Cement content, %
Quality basalt	5
Marginal basalt	6
Marginal sandstone	5
Dredged spoil	9

2) Many low quality aggregates can be economically upgraded for adequate performance for temporary or intermittent use roads.

3) A feasible solution for surfacing temporary or intermittent use roads is to utilize marginal aggregates that are in good supply. Some aggregates have performed satisfactorily when used in open-graded asphalt emulsion mixes, cement-treated bases, and with lime stabilization. Attempts to use marginal aggregates should be encouraged because they are in good supply and inexpensive.

4) Marginal aggregates provide a viable alternative for surfacing temporary or intermittent use roads in the areas where good quality aggregates are in short supply. It can be very economical since the hauling distance is typically much shorter.

5) Finally, marginal aggregates may work better for temporary or intermittent service roads if adequate drainage is provided. The road should be inspected and maintained regularly to keep the surface in good shape.

3.3.5 Sand-Sealed Subgrade

The application of an emulsified asphalt on natural subgrade followed by the application of the sand as topping which waterproofs a subgrade soil is called "sand-sealed subgrade" (9). According to the criteria established by research presonnel at Oregon State

University, the sand-sealed subgrade is most effective in areas that have good and firm subgrade (CBR > 15; R-value > 40) with high rock cost but have a plentiful source of low cost sand for reducing costs compared to crushed aggregate (9).

Reported advantages of the sand-sealed subgrade include:

1) uses a local source of low-cost sand,
2) waterproofs a poor subgrade soil,
3) reduces and/or eliminates the need for subbase and base materials, and
4) saves a great deal of expense by not using aggregates.

The disadvantages of using sand-sealed subgrade includes

1) can only be used on firm subgrade (CBR > 15, R-value > 40), and
2) requires frequent maintenance.

Based on the results of the literature review and the evaluation of a demonstration project in the Pacific Southwest, Region 5, sand-sealed subgrade surfaces are very economical for temporary or intermittent use roads. The sand-seal appears to be acting as a waterproofing membrane for the subgrade, thus maintaining the dry strength of clayey and silty soils. It is relatively flexible and is able to withstand much of the minor deformation expected on a structurally inadequate road on poor soils. Finally, based on the experience gained from the demonstration project, it appears that the sand seal will last about three years before major repairs are needed; therefore, it is very appropriate for temporary or intermittent use roads.

3.3.6 Prefabricated Mat Panels

Landing mats are surface covering panels prefabricated from materials such as aluminum, steel, and fiberglass. The mats come in various panel sizes and can be connected together to form a continuous road surfacing.

Mats can be very effective when temporary surfacings are needed to carry large and heavy trucks or equipment. As a result, they may be applicable for temporary and intermittent use roads because they can be easily reused, stored, installed, and removed.

3.3.6.1 Aluminum Landing Mats. Numerous aluminum mats have been evaluated over the years at the U.S. Army Corps of Engineers Waterways Experiment Station (WES) by Hugh L. Green, Demery W. White, Jr., and Gordon L. Carr. The summary of their evaluation and other pertinent data are given in Table 3.10; however, at the present time there are few mats still in production. These include:

1. Taber Metals Landing Mats. These landing mats are prefabricated from strong aluminum alloys. They are extruded in 24-inch (60.96 cm) wide panels, integrally stiffened and equipped with special connecting elements to connect each panel on all four sides with the adjacent panels. These panels can form a continuous covering for any area or geometrical configuration, providing a durable cover over the soft soil upon which the mats are laid. The mats are strong enough to support the heavy vehicles and have been used on soils as soft as 4-6 CBR (30).

Table 3.10. General Purpose Mat/Panel Data Comparisons (15)

Item Description	Size L" x W" x D"	Weight, lb Panel	Weight, lb Sq ft	Cost $/Sq ft	Passes**	Buckling Lb/ft Width	Rigidity Lb/ft Width	Crushing psi
Extruded aluminum 6104-T6 Wells Aluminum, North Liberty, IN	144x9.64x0.89	28.5	3.2	6.45	3000+	3,560	300	1250+
Extruded aluminum 6063-T5 Taber Metals, Russellville, AR	144x24x1	66	2.8	6.56	3000	3,920	440	1250+
Extruded aluminum 6061-T6 Alcoa, Pittsburgh, PA	144x7.125x1.25	24.6	3.5	3.18	3000	3,830	690	1250+
Formed aluminum 6061-T4 Sargent-Fletcher Co., El Monte, CA	144x22x1.5	43.3	2.1	7.10	3000	4,200	390	233
Formed aluminum 6061-T6 Woodside Engineering Co., Franklin Park, IL	144x22.5x1.56	46	2.0	14.04	3000+	4,590	745	800
Aluminum honeycomb sandwich, 6.1 density, Kaiser-Oakland & Hexcel Dublin, CA	96.25x48.25x1.46	71.5	2.2	9.76	3000+	5,990	400	1090
Aluminum honeycomb sandwich, 6.9 density, Kaiser-Oakland & Hexcel, Dublin, CA	96.25x48.25x1.49	83	2.6	9.76	3000+	7,880	500	1125
Balsa wood aluminum skin sandwich M.C. Gill Corp. El Monte, CA	144.125x48.125x1.09	93	1.9	4.96	2000	2,834	245	1250+
M8A1 rolled steel landing mat Depot storage item	141.75x19.5x1.125	144	7.5	1.06	3000+	5,310	760	1063
Aluminum sandwich with 1 in sq. egg crate core, Spur Industries (Ecolite Corp.) Spokane, WA	144x24x1.06	42.5	1.8	4.79	300	-	-	770
Aluminum skin on 1 in sq. cell egg crate core, Spur Industries (Ecolite Corp.) Spokane, WA	144x24x1.0	31.5	1.3	3.59	300	-	-	775
Aluminum egg-crate core (1 in cells), Spur Industries, (Ecolite Corp.) Spokane, WA	143.5x23.625x1.0	20	0.8	1.54	1000 (2 layers)	-	-	725
Aluminum egg crate core (1/2 in cells), Spur Industries (Ecolite Corp.) Spokane, WA	143.5x23.625x0.50	9.5	0.4	0.94	200 (2 layers)	-	-	420

1 in = 25.40 mm; 1 ft = 0.3048 m, 1 sq ft = 0.0929 m^2, 1 psi = 6.895 KPa
*M54 military cargo truck (gross weight, 40,000 lb.), CBR < 2 at surface and CBR < 4 at 6-inch depth
**CBR from 2.0 to 4.2

These landing mats are 12 ft (3.65 m) long, 24 inches (60.96 cm) wide, and weigh approximately 144 lbs (65.31 kg). The ultimate tensile strength of this material is about 38,000 psi (262,010 kPa) (30).

Laying the mat is very easy. After the laying area has been cleared, properly graded, and compacted, manual laying can begin at two points proceeding in two directions at the rate of 400 ft^2/man-hour (37.16 m^2/man-hour) by two-man teams. Mats are laid in a brickwork fashion. The cost of the material is high, about \$8.33/ft^2 (\$89.67/m^2), and may be a limitation on using these materials on low volume roads. The lighter version of this panel is called MK-18 and costs \$6.65/ft^2 (\$71.58/m^2). Figure 3.4 shows a complete mat panel.

2. Kaiser Aluminum Mats. These mats have been recently tested at WES and have the following characteristics (based communication with the marketing manager for Kaiser Aluminum):

   The mats are reusable, storable, light, and strong. The dimensions of the mats are a function of storage; the width ranges from 2 ft (.61 m) up to 60 ft (18.29 m) and the length ranges from 2 ft (.61 m) up to 110 ft (33.52 m).

   Laying the mats is easy; connections and hinges make the deployment fast. The performance of the

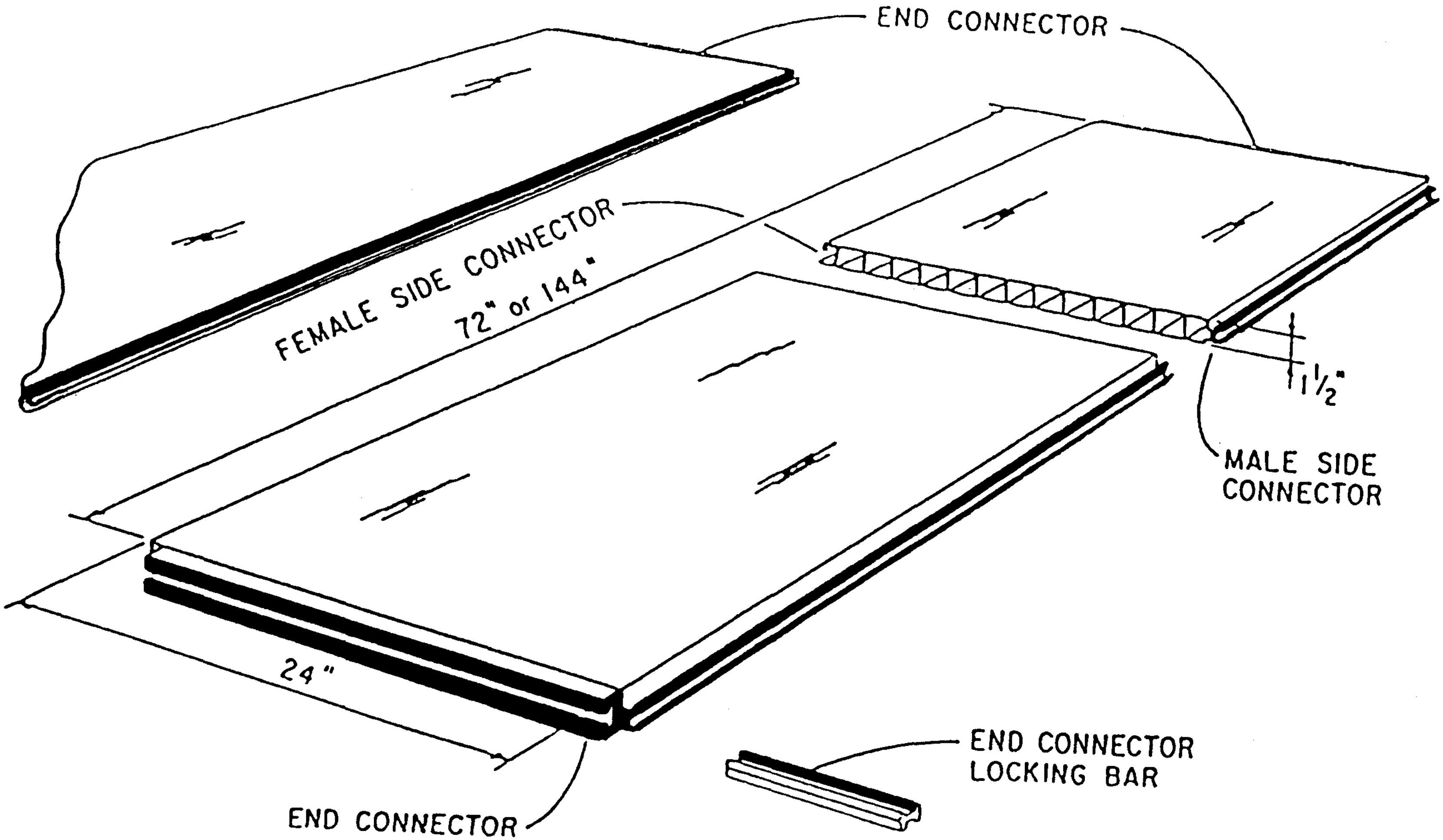


Figure 3.4. Aluminum Mats, Taber Metals, Inc. (30).

mats has been excellent, with a life of more than 3,000 passes of M54 trucks and military tanks.

The cost of the material is extremely high, about $\$60/ft^2$ ($\$645.85/m^2$), and that is a limitation for using these materials on temporary or intermittent use roads.

Based on the various studies at the U.S. Army Corps of Engineers Waterways Experiment Station, the aluminum landing mats are a feasible solution for constructing temporary roads (31,32). However, they may not be economical for use on temporary or intermittent use roads because they are too expensive, with the exception of the MK-18 by Taber Company that might be economical based on its life cycle cost.

3.3.6.2 Steel Landing Mats.

1) M8A1 steel landing mat. This panel is approximately 12 ft (3.65 m) by 19 inches (48.26 cm) wide and 1 inch (2.54 cm) thick, and weighs 144 lbs (65.23 kg) or 7.5 lb/ft^2 (36.62 kg/m^2). The individual panels were fabricated from carbon steel sheets having a minimum yield strength of 33,000 psi (227,535 KPa).

   Based on the study at the U.S. Army Corps of Engineers Waterways Experiment Station, the M8A1 landing mats are excellent performance panels (31,32). They are reusable, storable, and easy to install and remove. The materials are presently not being produced but are sometimes available through federal acquisition.

2) Others. Numerous steel mats that have been used for commercial or industrial applications can be easily applicable for reusable surfaces in forests. These include:

a) Borden steel panels

b) IKG steel panels

Based on the study by WES and field observation of a demonstration, steel mats (M8A1) provided adequate traction for normal climbing and stopping. Some skidding may occur when abrupt stops are made. These mats also have demonstrated excellent performance.

3.3.7 Reused/Recycled Aggregates

Annual aggregate requirements for road construction currently exceed one billion tons. Maintenance of existing facilities requires an additional 200 million tons annually. Approximately 48% of the total aggregate production in the United States is used in road construction and increasing at a rate of about 5% per year (14).

The supply of aggregates suitable for road construction has already been exhausted in many areas of the country. Figure 3.5 shows that well over one-half of the U.S. has a lack of quality aggregate resources.

The demand for quality aggregates will continue to increase in all areas of the United States in the years ahead. With this growing need, more and more geographic areas will become aggregate deficient. Therefore, aggregates play a major role in road construction. The

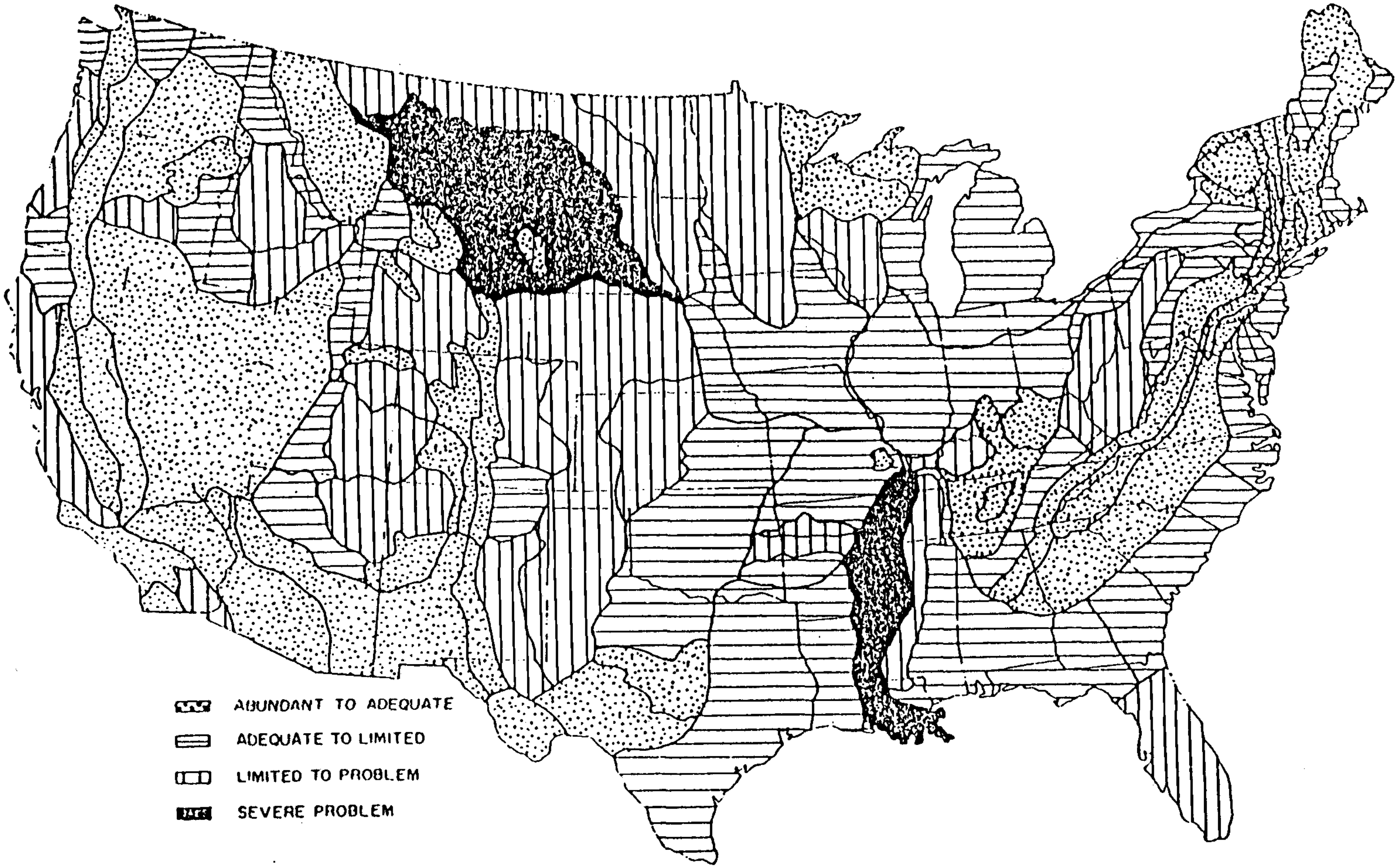


Figure 3.5. Estimated Potential Availability Rating of Quality Aggregate Resources by Physiographic Unit.

recovery and reuse of the good quality aggregate with or without geotextile as a separation layer may offer an acceptable solution to the shortage of aggregate for temporary or intermittent use roads. The use of high quality aggregates may also help to preserve and efficiently utilize the available high quality aggregates in the most efficient way.

Construction of a reusable aggregate project with a separation layer is simple. It requires laying down the fabric and spreading the aggregate over the fabric. Furthermore, Oregon State University developed a method for the recovery of the reusable aggregates. This method is discussed in detail in the "Compendium of Demonstration Projects" (9).

Finally, the decision to use good quality aggregate with geotextile as a separation layer, and reuse both materials in several other projects must be based on the consideration of several factors, such as properties of the materials, availability of materials, performance, and economics.

The following comments represent the major findings of the literature review and the evaluation of a demonstration project in the Pacific Northwest, Region 6.

1) The reuse of high quality aggregate on several projects may offer lower construction cost. It also contributes to the conservation of high quality aggregate.

2) The reuse of the good quality aggregate can be most effective for the projects that have high rock cost, short duration of logging or other activity, short hauling distance from one project to the alternate project, and almost equal size projects.

3) Recovery and reuse of the geotextile may not be economical because the chances of damaging the geotextile during recovery are high. Furthermore, it is not economical to recover the geotextile because of high costs of labor and equipment for the removal.

4) The only geotextile that may have a good chance to be recovered intact for use on future projects is MIRAFI HP1200.

5) Future projects should use a light geotextile as a separation layer to eliminate the loss of costly aggregate material into the subgrade only if the price of aggregate is above $\$12/yd^3$. The use of geotextiles as a separation layer may not be economical if the price of aggregate is below $\$12/yd^3$. This recommendation is based on the typical construction cost of the reusable aggregate with or without geotextile, as shown in Figure 3.6.

6) Reusable aggregate with geotextile separation recovers more aggregates (approximately 90% to 95%) for future projects compared to the reusable aggregates without geotextile separation (approximately 70%).

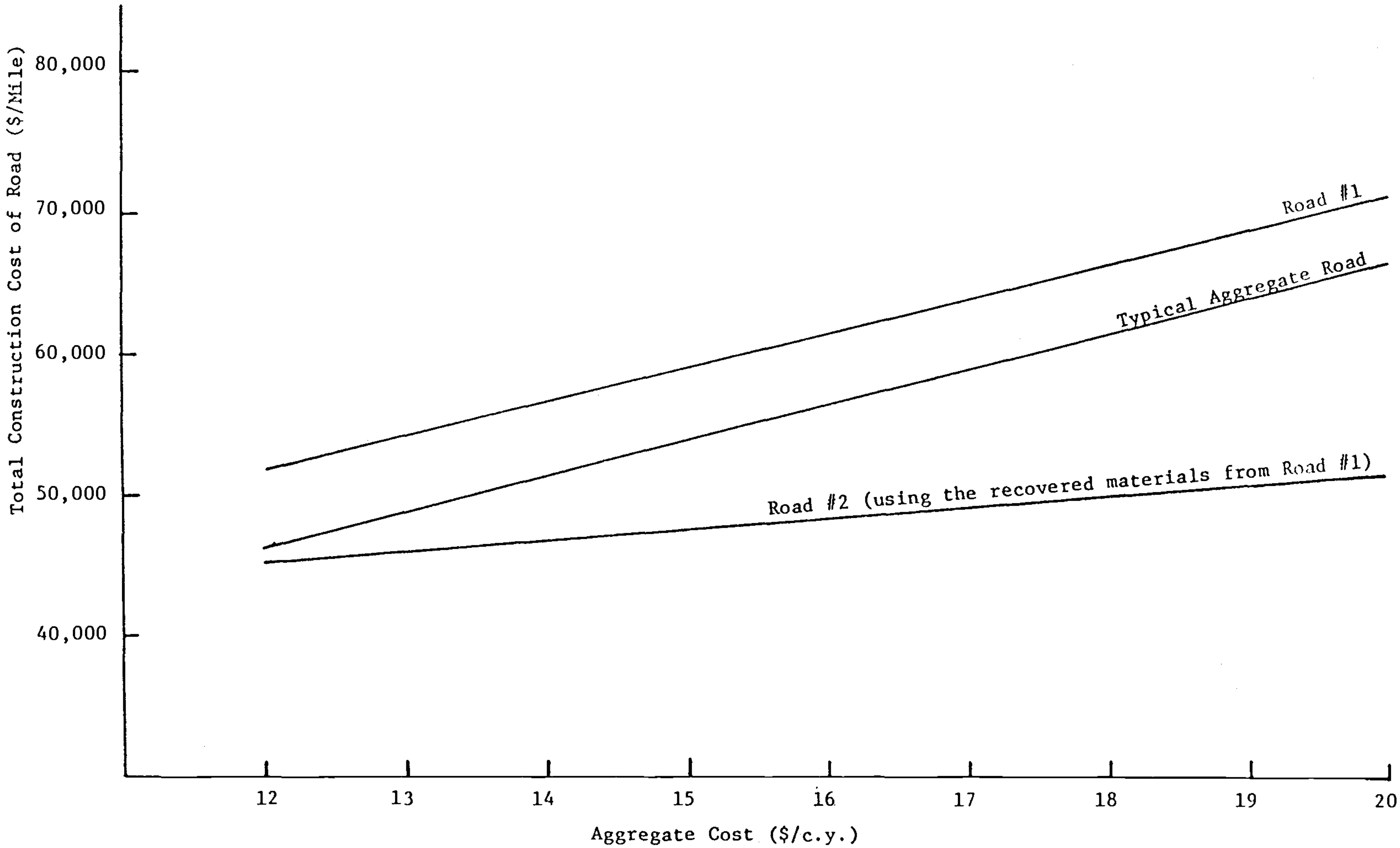


Figure 3.6. Construction Cost of the Aggregate Road Using a Light Fabric as a Separation Layer and Only the Aggregate is to be Recovered (9).

The typical construction cost of the reusable aggregate using a light fabric as a separation layer is shown in Figure 3.6.

3.3.8 The Membrane-Encapsulated Soil Layer (MESL) Concept

Fine grained soils compacted at or slightly below optimum moisture content can provide adequate bearing strengths for use as structural layers in pavements and embankments. However, if the moisture content increases after soil compaction, there may be a dramatic loss of bearing strength. The MESL concept is a method for maintaining a moisture content of the soil at the desired level by encapsulating the soil in a waterproof membrane that prevents water infiltration (16).

The Waterways Experiment Station developed a method for MESL that consists of first excavating and stockpiling fine-grained soils (16,34,35). Its moisture content is adjusted to 2-3% below the optimum moisture content for the specified compaction (a possible difficulty in moist climates). The subgrade is prepared and compacted with a grader and compactor. While not initially specified, a CRS-2 asphalt emulsion is sprayed on the subgrade to hold the polyethylene (PE) film in place in case of wind and to provide assurance against leaks if the membrane is cut or torn during placement. After the PE film is placed on the prepared subgrade, the excavated soil is replaced and compacted to the desired density and moisture content. Asphalt emulsion is sprayed on the surface and a polypropylene (PP) nonwoven membrane is installed. The top membrane is also sprayed with an asphalt emulsion and covered with a thin layer of clean sand to blot the asphalt and to provide added protection against puncture by construction equipment. The PP fabric, covered with asphalt and sand, provides a tough trafficable surface suitable for temporary use (16,34,35). Other membranes of rubber, vinyl, polyesters, and so forth, could also be used for the purposes of waterproofing the soil.

Advantages of this system include:

1) Maintaining a constant moisture content in the encapsulated section.
2) Reducing the need for a thick section of crushed gravel as base or surfacing material. Therefore, the cost of importing high quality aggregate can be reduced.
3) Eliminating the need for dust control.
4) Increasing and maintaining the strength of the subgrade material.
5) Utilizing lower quality or currently unacceptable soils in a MESL for road construction.

Disadvantages of this product are:

1) Drying of fine-grained soils for use in MESL construction can be a costly and difficult problem in some climates.
2) MESL can be costly and time consuming, and may require specialized equipment for placing the fabric.

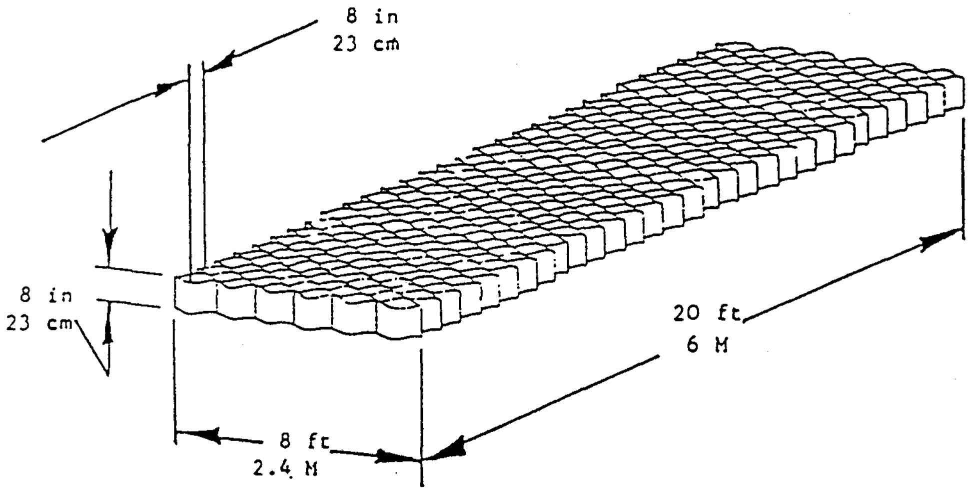
Based on the results of the literature review and evaluation of a demonstration project in the Pacific Southwest, Region 5, the MESL construction is an acceptable method to make use of lower quality materials. The construction cost for MESL for 12-inch surface thickness would be $0.75/ft^2 in place based on the U.S. Forest Service Cost Estimating Guide (1983). This method can also be used to control or reduce frost heave in cold climates.

3.3.9 Grid Confinement

Grid confinement is a new concept for pavement base course construction that is being developed at the U.S. Army Corps of Engineers Waterways Experiment Station (32). The concept involves the confinement of sand in interconnected cellular elements, called grids, to produce a load distributing pavement base layer. Poorly graded sands which are generally found in abundance around the world can be used in expedient construction of sand-grid base layers for many pavement applications. There are three types of grids available. These include paper grids (32), aluminum grids (32) and, most encouraging, plastic grids (36). The plastic grid, called "Geoweb," is described briefly in the following paragraphs.

3.3.9.1 Plastic Grids. This new lightweight plastic grid is called "Geoweb," and is manufactured by Presto Products of Appleton, Wisconsin (36). The grids are constructed of 50 mil (1.27 mm) thick high density polypropylene sheets, 8 inch (20.32 cm) x 11 ft (3.35 m) x 8 inch (20.32 cm). The strips are spot welded together on 13-inch (33.02 cm) centers, so when the system is expanded, it opens like an egg crate divider into an 8 ft (2.48 m) x 20 ft (6.10 m) panel. Figure 3.7 shows the Geoweb confinement system and typical specification data for the Geowebs. The panels are expanded, set in

SPECIFICATION DATA



GEOWEB Structural Properties	English System	Metric System
1. Expanded Dimension	8 ft. x 20 ft. x 8 in.	2.5 m x 6 m x 20 cm
2. Collapsed Dimension	11 ft. x 5 in. x 8 in.	3.4 m x 13 cm x 20 cm
3. Panel Thickness Nominal	0.047 in.	0.119 cm
4. Weight	5.7 lb./yd^2	3.1 kg/m^2
5. Cell Area	41 in.^{2}	265 cm^2
6. Cell Seam Node Pitch	13 in.	33 cm
7. Welds/Seam	7	7
8. Seams Tensile Peel Strength	150 lbs.	69 kg
9. Installation Temperature Range	-16°F to 110°F	-27°C to 43°C

Polymer Material : High Density Polyethylene
Color : Black
Carbon Black Content: 2%
Chemical Resistance : Superior

Figure 3.7. Geoweb Confinement System (36)

place, and filled with sand. Most test installations to date have been on beaches for military landing operations. The grids are filled with sand, compacted, and usually the surface is sprayed with a liquid asphalt at a rate of 1 gal/yd^2. Normally, SS-1 emulsions or RC-250 cutbacks are used (36).

All of the grids required for a half mile road 16 ft wide can be transported on one truck. The grid materials currently cost about \$1.25/ft^2 of expanded area, and the construction costs are only a few cents/ft^2 (36).

Based on the results of the literature review and evaluation of a demonstration project in the Pacific Northwest, Region 6, Geowebs are not economical for temporary or intermittent use roads when compared to crushed aggregates. Even if Geowebs appear to be cost effective for some special situation, they would have to be used on roads carrying a low volume of trucks at speeds less than about 40 miles per hour. For high volume traffic, high speeds, and/or where braking or deceleration will occur on the grids, a surface layer must be provided to provide satisfactory service. The surface course should consist of minimums of 3 inches of dense-graded crushed rock or 2 inches of asphalt-treated surface, depending upon the level of service required. With surfacing, the sand-filled Geowebs on sand subgrades are equivalent to approximately 8 inches of high quality crushed aggregate base course material. The sand-filled Geowebs on very soft fine-grained (clay-like) soils are equivalent to up to 12 inches of high quality crushed rock.

Table 3.11 at the end of this chapter includes a complete summary of the general properties and costs of the Geoweb confinement sytem.

3.4 Important Material Properties

Numerous materials properties and background information are needed to evaluate the adequacy, economy, and suitability of alternate surfacings. Some of these include:

1) Size: The size of the material, such as length, width, and depth, is important for estimating the number of units of materials needed. Also, it provides an estimate of the manpower required to handle the materials in the project.

2) Weight: The weight of the material can determine the amount of manpower and equipment needed for handling and laying the material.

3) Cost: The cost is important to evaluate the economics or overall cost effectiveness of potential surfacing systems. Some of the costs that must be considered include:

   a) initial materials cost,

   b) construction and maintenance costs,

   c) recovery costs,

   d) storage costs,

   e) reprocessing costs, and

   f) salvage costs.

4) Mechanical Properties: The mechanical proprties, such as values of tensile, compressive, and ultimate flexural strength, and modulus of elasticity are needed to allow engineers to specify the suitable materials for various loading conditions.

5) Availability: Aside from the availability of materials in the desired area, the range of conditions and regions where they can be used need to be considered because transportation costs can play an important role in the selection of the alternate surfacing. Therefore, the use of local material and labor forces is encouraged for the development of temporary or intermittent use roads since it is often more economical than importing either.

6) Applicable Conditions for Material: The nature and characteristics of some materials make them suited for use under a limited range of loading, environmental, or subgrade support conditions.

7) Expected Life: The design life of the material is needed primarily to make a valid economic assessment of a surfacing type. The physical life of a surface is a function of the design standard and the traffic type and volume to which it is subjected. For reusable surfaces, the physical life also may be a function of the number of times recovered or reused, and damage or loss during rehandling.

8) Information Needed for Design: There is a minimum set of factors or variables that must be known for the design of each surfacing.

9) Type of Road After Removal: For reusable surfaces, engineers should consider the nature and quality of the road left for recreation and administrative traffic after surface removal.

10) Installation and Removal Procedures: Since the alternate surfacing materials are unique, they require special procedures, equipment, and technology for the installation and recovery of the materials.

11) Storage Requirements: These are needed to determine where the materials are going to be stored after they have been used in a project. They also aid in the decision of whether it is more economical to leave the materials in place on the existing project until the materials are needed for the next project, or to store them for awhile and transfer them from storage for future projects.

12) Environmental Effects and Problems: Temperature, rainfall, ground water movement, and other environmental factors can significantly affect the performance of a surfacing material. These environmental factors can alter the properties and the performance of the materials being used to surface temporary or intermittent use roads. Therefore, it is important

to understand how environmental factors affect the alternate surfacing.

13) Maintenance Requirements: This is needed for estimating maintenance effort, costs, and problems. For aggregate or soil roads, maintenance may take the form of regraveling or grading, and for asphalt roads, patching, sealing, and overlaying. For reusable surfaces, maintenance may take a variety of forms, such as replacing a portion of road, checking the joints and connectors, or adding more material.

14) Prior Use: This includes information on the location of projects, performing agency, cost and performance where the materials have been used previously. Information gained from prior experiences assists in designing potential applications, solving performance problems, and improving construction techniques and materials deficiencies.

Table 3.11 summarizes the general material properties and costs that have the greatest influence on the selection of a unique type of surface. Tables are given in Appendix B describing in more detail material properties, costs, design requirements, construction and maintenance requirements, and prior applications of the various alternate surfacing types.

Table 3.11. Properties and Characteristics of the Potential Surfacing Systems.

Type of Material	General Description	Dimension and Surface Type	Weight	Material Cost	Expected Life*	Manufacturer and Availability
Biodegradable Materials (Wood or Bark Chip)	Wood or bark chip Sawdust	12"-24" of wood chip and bark chip on subgrade	50-60 lbs/yd^3	$3-7/cy or $.11-0.25/sf**	Fair	Any forest with timber
Chemical Stabilization	Lime-Lime Flyash Portland Cement Asphalt Emulsion Sodium Chloride (NaCl) Calcium Chloride ($CaCl^2$) Magnesium Chloride (MgCl) Lignin Sulfonate	3-7% Stabilizing Agent 4-8" deep Stabilized subgrade in place		$70-80/ton or 0.30-0.40 sf $60-70/ton or 0.30-0.40 sf $130-160/ton or 0.35-0.45 sf $30-50/ton or 0.20-0.30 sf $100-140/ton or 0.35-0.45 af $40-50/ton or 0.25-0.35 sf $50-60/ton or 0.25-0.35 sf (varies greatly with locality)	Good	Any local supplier or contact: Great Western Chemical Co. P.O. Box 11406 Spokane, WA 99211 Tel.: 509/928-0195
Geotextile and Geogrid Separation	Tensar Grids (SS1)	Roll length = 164 ft Roll width = 9.8 ft	Roll weight = 67 lbs	$.15/sf plus aggregate	Good	Any local supplier
	Various types of fabric	Varies	Varies	$.05-.40/sf plus aggregate		
Marginal Aggregate	Marine Basalts, Sandstone, Pumice, cinders, sand, and so forth	6"-18" of marginal aggregate placed directly on the subgrade	50-150 lbs/cy	$2-15/cy $0.07-0.56/sf	Fair	Local Forest Service rock sources or commercial pits and quarries
Sand Seal	Single seal sand Double sand seal	Bottom Layer: 0.5 gal/sy of CRS-2 30 lbs/sy sand Top Layer: 0.25 gal/sy of CRS-2 20 lbs/sy sand		Asphalt Emulsion: $130-160/ton Sand: $2-7/cy to construct .15-.25/sf	Moderate	Any local supplier

Table 3.11. Properties and Characteristics of the Potential Surfacing Systems (continued).

Type of Material	General Description	Dimension and Surface Type	Weight	Material Cost	Expected Life*	Manufacturer and Availability
Metal Mats	Aluminum (AM-2)	Length = 12 ft Width = 2 ft Depth = 1 in.	144 lbs/panel 6 lbs/sf	$200/panel $8.33/sf	Good	Taber Metals, Inc. Rt. 1, Airport Road Russellville, AK 72801 Tel.: 501/968-1021
	Steel (M8A1)	Length = 142 in. Width = 19.2 in. Depth = 1 in.	144 lbs/panel 7.5 lbs/sf	$0.9/sf (in 1960)	Good	Not in production, but may be available from surplus
Reusable Aggregate without Geotextile Separation	Crushed aggregate	6"-18" of the crushed aggregate placed directly on the subgrade	120-150 lbs/cy	$.50-1.10/sf* to construct $.20-1.30/sf to recover	Good	Any local supplier
Reusable Aggregate with Geotextile Separation	Crushed aggregate	Fabrics placed on subgrade and 6"-18" crushed aggregate placed on top	120-150 lbs/cy	$1.0-1.50/sf** to construct $.50-1.00/sf to recover	Good	Any local supplier for aggregate
	MIRAFI HP 1200	Length = 210 ft Width = 12 ft	260 lbs/roll	geotextile $.25-.30/ft^2		Construction Material Co. 2603 151st St. Pl. NE Redmond, WA 98052 Tel.: 1-800-438-1855 (for fabric)
Membrane Encapsulated Soil Layer	Subgrade soil encapsulated with various membranes	6" to 2 ft of the subgrade soil encapsulated with various membranes (6 to 36 mil). Application of asphalt emulsion (CRS-2) at rate of 0.3 gal/yd^2 plus 2 in. sand for blotting.	N/A	$0.5 to 1.3/sf	Moderate - depends mainly on surface treatment life	Any local supplier

Table 3.11. Properties and Characteristics of the Potential Surfacing Systems (continued).

Type of Material	General Description	Dimension and Surface Type	Weight	Material Cost	Expected Life*	Manufacturer and Availability
Geoweb Stabilization (Expandable Grids)	Dune sand filled plastic grids 8" deep and sealed with asphaltic binder layer	Expandable size: 8'x20'x8" shipping size: 11'x5"x8"	5.7 lbs/yd^2 110 lbs/section	$1.05-1.30/$ft^2$ $1.5-2.0/$ft^2$ in place	Good Depends mainly on surface treatment life	Presto Products P.O. Box 2399 Appleton, WI 54913 Tel.: 1-800-558-3525

*Good 5 to 10 years
Moderate 3 to 5 years
Fair 1 to 3 years
**Assume 12-inch surface thickness
***Assume 5% stabilization agent and 6-inch depth of stabilized layer

1 in. = 25.4 mm, 1 ft = 0.3048, 1 ft^2 = 0.0929 m^2, 1 yd^2 = .8361 m^2, 1 yd^3 = 0.7645 m^3,
1 lb = 0.4536 kg, 1 ton = 907.2 kg

3.5 Limitations

Certain constraints on some alternate surfacings may limit their use. For example, some of the materials may not be applicable due to the nature of the subgrade, season and climate, geometrics of the roadway, useful life, project length, and cost. Table 3.12 summarizes the general limitations that have the greatest influence on the selection of the alternate surfaces. The development of this table is based on the result of the literature review as well as the result of the demonstration projects (9).

3.6 Promising Applications

Table 3.13 summarizes the potential application of the alternate surfacing systems for future use, the degree of quality control needed to ensure success, and applicable situations for which the surfacing type should be employed. In this table, high means alternate surfaces could be applicable for up to 80% of the mileage of Forest Service or similar roads, medium means alternate surfaces could be applicable for up to 50% of the Forest Service or similar roads, and low means alternate surfaces could be applicable for less than 10% of the Forest Service or similar roads. For degree of quality control, high means 80 to 100% quality control, medium means 50 to 80% quality control, and low means the degree of quality control is 10 to 30%.

3.7 Design Reference

Table 3.14 summarizes the design references of the alternate surfacing systems on which the surface design should be based.

Table 3.12. Limitations of the Alternative Surfacing Systems.

Potential Surfacing Types	Subgrade Soil Type	Season and Climate	Geometrics of the Roadway	Project Length	Expected Life	Removal and/or Reuse	Remarks
Wood and Bark Chip	None	Snow	Not recommended for grades above 10%	None	1 to 3 years	Possible	Applicable to low volume and low speed roads
Chemical Stabilization	Depends on chemicals	Extreme rains or freeze-thaw	Not recommended on steep grades above 10%	None	3 to 5 years	No	Lime or portland cement should be available locally; may require traction rock, coat of gravel
Geotextile and Geogrid Separation	Most effective on weak subgrades (CBR < 2)	None	None	None	Same as gravel surfaced roads	Portion of gravel surfacing	Aggregate thickness can be reduced and subgrade strength increased
Marginal Aggregate	None	More sensitivity to moisture than quality aggregate	None	None	2 to 3 years	No	Can be very economical since local materials are used requiring little haul
Sand-Sealed Subgrade	May not work on weak subgrade CBR < 15 R-value < 40	None	Not recommended on steep grades above 10% or sharp curves	None	3 years	No	Bleeding, rutting, and broken surface in spots. Easily resealed
Metal Mats	Not recommended on weak subgrade (CBR < 3)	Not recommended for areas experiencing frost (slippery)	Not recommended on steep grades above 9% or sharp curves and on sharp horizontal curves	Recommended only for short sections of the project less than 500 feet (expensive)	5000 passes or 25 mmbf	Can be reused many times	Very expensive; can be economical for short projects if they can be reused many times
Reusable Aggregate without Geotextile Separation	Recommended for firmer subgrade	None	None	None	Same as normal aggregate	About 70% of aggregate can be recovered	Cost can be reduced since aggregate can be recovered and reused again

Table 3.12. Limitations of the Alternative Surfacing Systems (continued).

Potential Surfacing Types	Subgrade Soil Type	Season and Climate	Geometrics of the Roadway	Project Length	Expected Life	Removal and/or Reuse	Remarks
Reusable Aggregate with Geotextile Separation	None	None	None	None	Same as normal aggregate	Special recovery beam required about 90% of aggregate can be recovered	Cost may be reduced since aggregate can be recovered and reused again. Geotextile most likely not recoverable
Membrane-Encapsulated Soil Layer	Most effective on organic clay, wet and fine-grained subgrade	None	Not recommended on steep grades above 10%	Recommended only for short projects (expensive)	Unknown	No	Applicable for moisture sensitivity and weak soils. Economical only on short critical sections
Geoweb Stabilization (Expandable Grids)	Works best on dune sand	None	Not recommended on steep grades above 10%	Recommended only for short projects (expensive)	Unknown	No	Applicable for the weak sands, but may not be economical
Lignin Sulfonate	Clayey sand (SC) to sandy gravel decomposed	Recommended in arid regions	None	None	3 to 5 years	No	Source of Lignin Sulfonate should be available locally. It cures slowly and strength is very sensitive to moisture contents

Table 3.13. Potential Application of the Alternative Surfacing Systems (10).

	Potential Surfacing Types	Potential for Future Use	Degree of Quality Control	Applicable Situation
1.	Wood and Bark Chip	High	Low	Any subgrade with timber available
2.	Chemical Stabilization	High	High	Depends on the chemicals, clayey soils best
3.	Geotextile or Geogrid Separation	High	Medium	Wet and fine-grained subgrades
4.	Marginal Aggregate	High	Low	Any subgrade
5.	Sand Seal	Low	Medium	May not work on weak subgrades(CBR < 15)
6.	Metal Mats	Low (Alum.) Med. (Steel)	High	Economical only on short sections
7.	Reusable Aggregate Without Geotextile Separation	Medium	Medium	Firmer subgrade to control rutting which makes the recovery of aggregate much faster
8.	Reusable Aggregate With Geotextile Separation	Medium	Medium	Soft subgrade more difficult
9.	Membrane Encapsulated Soil Layer	Low	High	Economical only on short critical sections
10.	Geoweb Stabilization	Low	Medium	Uniform sands and critical sections
11.	Lignin Sulfonite Soil Stabilization	High	High	Dry climates

Table 3.14. Design References for Alternate Surfacing Systems.

Potential Surfacing Types	Design References
Wood and Bark Chip	Hicks, R.G., D.K. Johansen, and K.G. Buss, "Wood and Bark chip Roads in Mt. Baker Snoqualmie National Forest," Demonstration Project No. 1, Forest Service, USDA, San Dimas, CA, December 1984 (9).
Chemical Stabilization	"Soil Stabilization in Pavement Structures," Vols. 1 and 2, U.S. DOT, FHWA, October 1979 (11,12).
Geotextile or Geogrid Separation	Steward, J., R. Williamson, and J. Mohney, "Guidelines for Use of Fabrics in Construction and Maintenance of Low Volume Roads," Report No. FHWA-TS-78-205, U.S. Forest Service and FHWA, June 1977 (13).
Marginal Aggregate	"Chapter 50," Transportation Engineering Handbook, Forest Service, USDA, January 1974 (37).
Sand-Sealed Subgrade	Lund, J.W., "Sand Seal Project," Demonstration Project No. 5, Forest Service, USDA, San Dimas, CA, December 1984 (9).
Metal Mats	Green, H.L., D.W. White, Jr., and G.L. Carr, "Preliminary Investigation of General Purpose Mat/Panel Materials," Miscellaneous Paper S-77-9, Soil and Pavement Laboratory, U.S. Army Corps of Engineers, Waterway Experiment Station, Vicksburg, MS, 1977 (31).
Reusable Aggregate without Geotextile Separation	"Chapter 50," Transportation Engineering Handbook, Forest Service, USDA, January 1974 (37).
Reusable Aggregate with Geotextile Separation	Takallou, M.B., R.D. Layton, and J.R. Bell, "Reused/Recycled Aggregates," Demonstration Project No. 8, Forest Service, USDA, San Dimas, CA, December 1984 (9).
Membrane Encapsulated Soil Layer	Smith, N. "Construction and Performance of Membrane Encapsulated Soil Layer in Alaska," CRRL Report 79-16, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, June 1979 (15).
Geoweb Stabilization (Expandable Grids)	Bell, J.R. and D.K. Johansen, "Geoweb Stabilized Road in Siuslaw National Forest," Demonstration Project No. 9, Forest Service, USDA, San Dimas, CA, December 1984 (9).

3.8 Major Findings of the Literature and Market Survey

When good quality materials are not locally available, four alternatives exist: 1) high quality materials may be imported, 2) poor quality materials may be utilized, 3) poor quality material may be improved, or 4) alternative surfacing types may be utilized. In all of the above situations, the decision of whether to select a certain type of surfacing over another for temporary or intermittent use roads must be based on the consideration of several factors, such as soil type, availability of materials, surfacing materials, special skills required, equipment required, local experience with installation, local expertise in removal procedures, and most importantly, economics.

Unfortunately, there was little information available relating to the use of temporary and removable surfaces. Therefore, the selection and recommendations of the use of these materials had to be based on judgment, manufacturers' reports, and some government publications.

The following represent the major findings of the literature and market survey:

1) Biodegradable materials, such as bark and wood chips, slash chips, sawdust, and logs, can be very suitable for temporary or intermittent use roads because they are wood products, inexpensive and available.

2) Admixture stabilization is a feasible means of upgrading local soils and marginal aggregates for temporary or intermittent use roads.

3) Marginal aggregates have widespread availability and are recommended for use on temporary or intermittent use roads for short life projects (1-3 years). When a longer life is required than marginal aggregates alone can provide, the marginal aggregates should be upgraded to provide an adequate temporary surfacing.

4) Geotextile mat, such as Mammothmat, may be suitable on a temporary basis as reusable surfaces because it can be rolled out/up quickly, and can be reused. Unfortunately, it is not yet available in the United States. This material may not be economical for use on temporary or intermittent use roads because it is too expensive. Paraweb mats are only recommended for light duty traffic.

5) Conventional geotextiles used as a separation layer are very suitable due to their low cost, material savings, ability to improve subbase and subgrade soils, easy installation, and potential economy.

6) Extruded plastic grids can be used to stabilize weak soils. The use of these materials reduces the amount of rock required to support traffic.

7) Sand-sealed subgrade surfaces are very economical for temporary or intermittent use roads. They are most effective in areas that have good and firm subgrade (CBR $>$ 15, R-value $>$ 40) with high rock cost.

8) Based on the various studies at the WES, the aluminum landing mats may be feasible for constructing temporary or intermittent use roads, but their high initial cost may preclude their use.

9) Based on the study at WES, the M8A1 steel mats demonstrated excellent performance. They are reusable, storable, and easy to install and remove. Although they are out of production, they may be obtained at salvage yards. Some of the steel companies should be encouraged to produce M8A1 mats. Other steel mats which are manufactured by Borden and IKG may be a good substitute for the M8A1 metal mats.

10) The recovery and reuse of the good quality aggregates, with or without geotextiles as a separation layer, may offer an acceptable solution to the shortage of aggregate for temporary or intermittent use roads. This surfacing system can be most effective for the projects that have high rock cost, short duration of activities, short hauling distance from one project to the alternate project, and almost equal project size.

11) The membrane-encapsulated soil layer (MESL) is not economical for temporary or intermittent use roads. This surface should only be considered for use in areas with very fine-grained soils and high moisture content which lack quality aggregates.

12) Plastic sand grids are not economical for temporary or intermittent use surfaces compared to aggregate roads because the material cannot be removed or re-used. This material should only be considered in special cases with very poor soil and in areas where aggregates are not available at all.

Table 3.15 summarizes the feasibility of use of the alternate surfacing for temporary or intermittent use roads.

Table 3.15. Feasibility of Alternate Surfacing for Resource Roads.

Potential For Future Use	Types of Materials
Feasible	1. Biodegradable Materials (wood and bark chips)
	2. Soil Stabilization (lime, cement, chemicals, asphalt emulsion, etc.)
	3. Marginal Aggregates (sandstone, marine basalt, marginal sand, cinders, pumice, etc.)
	4. Conventional Geotextiles
	5. Extruded Plastic Grids
	6. Steel Mats (M8A1)
	7. Sand Sealed Native Subgrade
Maybe Feasible	1. Membrane-Encapsulated Soil Layer (MESL)
	2. Geotextile Mats (Mammothmat)
	3. Aluminum Mats (AM-2)
Not Considered Feasible	1. Three-Dimensional Grids (plastic)
	2. Geotextile Mats (Paraweb)

4.0 ECONOMIC EVALUATION OF ALTERNATE SURFACES

This chapter provides the user with a methodology for evaluating alternate surfaces compared with conventional crushed aggregate roads. The technique suggested employs principles of engineering economy and methods of economic evaluation. A two-step sequence identifies the potential alternate surfacings and performs an in-depth economic evaluation of each.

The evaluation methodology is developed in this chapter to aid decision makers in performing the economic evaluation of the potential alternate surfacings, with the "best" being the least total life cycle cost alternative.

4.1 Role of Economic Evaluation of Alternate Surfaces

The appropriate authority must make the decision to build a road with alternate surfaces or to use aggregate surfaces. The decision is based on factors such as costs, performance, and constraints of alternate surfaces.

On the basis that the lowest cost of providing transportation over the road produces the maximum conservation of resources, the economic analysis seeks to find that alternative of accomplishing the basic goals with the minimum total transportation costs, taking into account the time value of money.

4.2 Selected Definitions

The following definitions, concepts, and expressions apply to the alternate surfaces and economics, and are defined for clarification (38,39,40,41).

1) Evaluation: Evaluation is the process of determining the value or cost of the component parts and the overall cost or value of each potential surfacing system on a comparable base.

2) Decision Making: Decision making is the process of selecting the "best" alternative after consideration of the relative effectiveness and economy of all viable alternatives.

3) Analyst: That person who directs the economic analysis and selects the procedures and factors to be used.

4) Cash Flow: Cash flow for any one project, is the chronological listing of all dollar benefits and costs over the life of the project. When the cash flows are plotted graphically along a time scale, the result is a cash flow diagram.

5) Annual Cost: That actual or estimated cost for one year of operation which may be treated individually or as a sum of all costs. These costs could include maintenance costs, operating costs, and capital costs of depreciation and interest.

6) Capital Cost: The dollar cost of the materials, labor, and equipment. This capital cost includes the cost for planning, engineering, construction, and overhead cost of administration and supervision.

7) <u>Salvage Value</u>: At the time a surface is removed from service, it may have some value for further use or as scrap. The dollars recovered upon removal, or the potential dollar value for its service in another place is called salvage value of the surface.

8) <u>Interest</u>: Rent paid and received on borrowed money, or credit in advance and normally expressed as a percentage rate per year. In economic analysis, the terms discount rate, vestcharge rate, and minimum attractive rate of return are used to designate the economic cost of money.

9) <u>Present Worth Value</u>: This is the current value of a future sum or future cash flow of benefits or costs at a specified interest rate.

10) <u>Service Life</u>: That period of time extending from the date of beginning of service to the date of retirement from service.

11) <u>Analysis Period</u>: The length of time (usually the number of years) chosen for consideration and study of an economic analysis.

12) <u>Road User Costs</u>: The summary of a) motor vehicle running cost, b) the value of vehicle user travel time, and c) traffic accidents.

a) Motor Vehicle Running Cost: The mileage-dependent cost of running automobiles, trucks, and other motor vehicles on the road, including the expense of fuel, tires, engine oil, maintenance, and that portion of vehicle depreciation attributable to highway mileage traveled.

b) Value of Travel Time: The result of vehicle travel time multiplied by the average unit value of time.

c) Traffic Accident Costs: The cost attributable to motor vehicle traffic accidents, usually estimated by multiplying estimated accident rates by the average cost per accident.

13) Inflation: The price increase of goods. As prices rise, the value of money, i.e., its purchasing power, decreases.

14) Actual Dollars: The actual dollar value at the time they occur. Sometimes called current dollars.

15) Constant Dollar: Dollars of purchasing power at some point in time, regardless of when the actual dollars occur. Sometimes called constant noninflated dollars.

16) Probability: Has been defined as a way of measuring uncertainty or likelihood of an event occurring.

17) Risk and Uncertainty: An element or analysis involves risk if the probabilities of the alternative possible outcomes are known. It is characterized as uncertainty if the frequency distribution of the possible outcome is not known.

18) Sensitivity: The variation of the results as various important input variables or factors are changed measures the sensitivity of the decision to the variable changed. The sensitivity analysis is employed to determine the range of the results that would occur with changed forecasts or judgments. For road construction, it is applied to such factors as discount rate, length of analysis period, construction cost, annual maintenance cost, vehicle operating cost, expected life of materials, salvage values, production rate, and so forth.

4.3 Engineering Economic Analysis Methods

In comparing investment alternatives, a number of methods can be used to put sums of money at different points in time chronologically on a comparable basis. The most widely used approaches are:

1) Present Worth: The term present worth (P.W.) means an amount of money at some beginning or base time that is equivalent to a particular schedule of receipts and/or disbursements under consideration. If disbursements only are considered, the term can be best expressed as present worth-cost (39).

A determination of the present worth (P.W.) involves the conversion of each individual future sum or cash flow to its present worth equivalent (39). Since alternate surfacings perform essentially identical services, benefits, or receipts savings, benefits are constant. Therefore, it is recommended to compare them on the basis of present worth-cost (P.W.-cost). The alternative with the lowest present worth-cost would be accepted as "best".

In comparing alternate surfacings by the present worth method, it is essential that all alternatives be considered over the same length of time. If the alternatives each have the same expected life, there is no problem and that life can be used as the service life. When the alternative, such as metal mats, has a longer expected life than the crushed aggregate and can be used in a number of projects, it is common to use a study period equal to the lowest common multiple of the lives, or the length of time during which the service of the chosen surface will be needed, whichever is less (39). For example, if a crushed aggregate has an expected life of 2 years and metal mats 5 years, respectively, the lowest common multiple of the lives to use as a study period is 15 years. However, if the service for which the surfaces are being compared is expected to be needed for only 7 years, then a 7-year study period should be used.

2) Annual Worth: The term annual worth (A.W.) means a uniform annual series of money for a certain period of time which is equivalent in amount to a particular schedule of receipts and/or disbursements under consideration. If disbursements only are considered, the term is usually expressed as annual cost (A.C.) or equivalent uniform annual cost (E.U.A.C) (39).

Annual worth converts the cash flow to an equivalent annual annuity over duration N at interest i (42).

In comparing surfacing alternatives, the equivalent annual cost method converts construction costs and maintenance costs to a uniform annuity over the analysis period. Since alternate surfacings perform essentially identical functions and services, receipts, savings, or benefits are constant. Alternatives could be compared on the basis of annual worth-cost (A.W.-cost). The alternative with the lowest annual worth-cost is the best.

3) Future Worth (F.W.) Method: The term future worth (F.W.) means an amount at some ending or termination time that is equivalent to a particular schedule of receipts and/or disbursements under consideration. If disbursements only are considered, the term can be

best expressed as future worth-cost (F.W.-cost) or future cost (39). The future worth (F.W.) is obtained by converting each individual sum or cash flow to its future worth equivalent.

In comparing the alternate surfacings, the future cost method converts construction costs and maintenance costs to the future worth-cost. The alternative with the lowest future worth-cost is the best. Furthermore, most of the costs associated with the alternate surfacings are initial construction costs. Maintenance costs, which occur in the future, are very minor compared with initial construction costs. Therefore, present worth of cost is more meaningful for comparing alternate surfacings than the future cost.

4) Internal Rate of Return Method: The internal rate of return (I.R.R.) method involves finding the interest rate at which the present worth of costs equals the present worth of benefits, or, at which P.W. of costs minus present worth of benefits equal 0. The I.R.R. could also be calculated using the same procedure with either A.W.'s or F.W.'s.

In comparing the alternate surfacings, the I.R.R. cannot be used because savings or benefits are assumed to be constant and cannot be estimated.

5) Benefit-Cost Ratio Method of Comparing Alternatives:

The benefit-cost ratio is a method of comparing alternatives. The benefit-cost ratio (B/C) can be defined as the ratio of the equivalent worth of costs. The equivalent worths can be P.W.'s, A.W.'s, or F.W.'s (39).

The two factors to be employed in benefit-cost analysis are the consumption of resources to build the road and, on the other hand, its services, cost reduction, and other measurable economic or resources savings (38). The steps in the use of the benefit-cost ratio are:

a) Identify the costs of each alternative.

b) Identify the benefits of each alternative.

c) Value the costs of each alternative.

d) Value the benefits of each alternative.

e) Calculate the benefit-cost ratio of each alternative.

f) List the alternatives in order of increasing costs.

g) Calculate the incremental benefit of the alternative with next higher alternative.

h) Calculate the incremental cost.

i) Calculate the incremental benefit-cost ratio.

j) Omit the alternatives with benefit-cost ratios of less than one.

k) Start with the lowest investment alternative as a challenger, if this challenger is acceptable over the defender $B/C > 1$ and $\Delta B/\Delta C > 1$, then the current challenger becomes the defender and the next alternative becomes the challenger. If the challenger is not acceptable over the defender $B/C < 1$ and $\Delta B/\Delta C < 1$, then defender remains and the alternative becomes the challenger. Continue this process until the optimal solution is resulted.

l) The best alternative is the alternative which satisfies the goals and with the higher benefit-cost ratio assuming feasibility within budget constraint.

Risk, uncertainty, inflation, and depreciation must also be considered in benefit-cost ratio calculation.

The first step in the benefit-cost ratio is valuing the cost of each alternative. The cost of the road surface is composed of two main items, the initial capital investment and the annual maintenance costs. These items can be easily estimated. But, the benefits of the alternative surfacings, which may include reduced operating costs, reduced maintenance costs, increased speeds, reduced travel time, increased safety, added comfort and convenience, energy savings, and environmental benefits of reduced air and/or water pollution, are not expected to vary greatly from one surfacing material to another, are intangible, and are difficult to estimate. Consequently, the benefit-cost ratio method cannot be used without extensive work on the definition, quantification, and valuing of benefits.

The decision criterion selected for comparing the relative economic worth of the various potential surfacing alternatives is the present worth of total costs over the life of the project or set of projects. The total of the present worths of all cost items for each alternative must be defined. The alternative having the least total present worth of costs is the most economical alternative. Since maintenance costs, rehabilitation costs, and salvage value for an alternative surfacing happens at various points in time, it is essential to understand the fundamental interest formula that expresses the relationship between present worth (P), future worth (F), and annual worth (A) in terms of interest rate (i) and interest periods (n). Table 4.1 gives these relationships, and Figure 4.1 shows their relation graphically. The equations given in Table 4.1 are tabulated in Appendix C for various periods of analysis (n) and interest rates (i). A few simple examples using the interest formulas (or Tables in Appendix C) are given in Table 4.1.

Table 4.1. Fundamental Interest Formula and Symbols (39)

To find	Given	Multiply "Given" by factor below	Factor name	Factor functional symbol	Example (answer for $i = 5\%$) (Note: All uniform series problems assume end of period payments.)
P	F	$\frac{1}{(1+i)^n}$	Single sum present worth	(P/F,i%,n)	A company desires to have $1,000 8 years from now. What amount is needed now to provide for it? Ans: $676.84
P	A	$\frac{(1+i)^n-1}{i(1+i)^n}$	Uniform series present worth	(P/A,i%,n)	How much should be deposited in a fund to provide for 5 annual withdrawals of $100 each? Ans: $432.95

Key: i = Interest rate per interest period
n = Number of interest periods
P = Present worth
A = Uniform series amount
F = Future worth

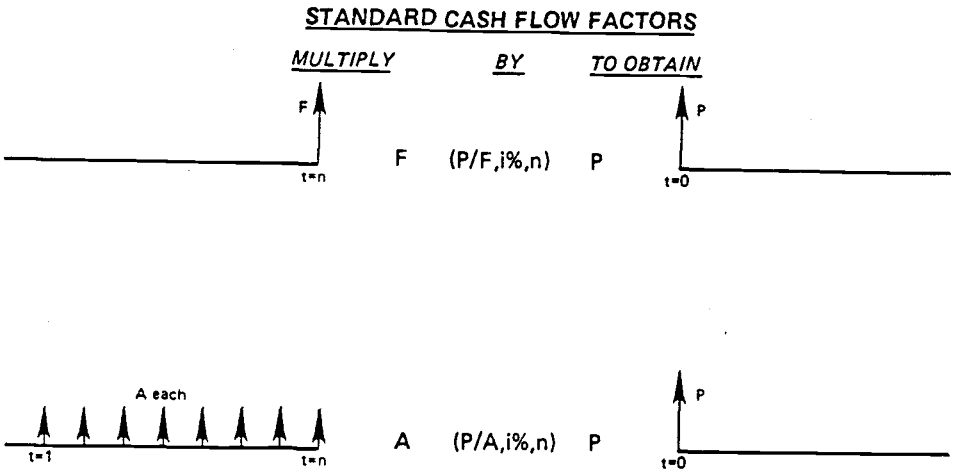


Figure 4.1. Standard Cash Flow Factors

4.4 Structure of Evaluation Methodology

The evaluation methodology is structured as a two-step process:

1) Preliminary evaluation step which screens the various alternative materials based on their characteristics, limitations, and availability to determine if they have potential for use, and

2) Economic evaluation step which performs an in-depth economic evaluation of the total costs of each potential alternative identified in the preliminary evaluation step.

4.4.1 Preliminary Evaluation Step

The potential for use of a particular surfacing system may depend on a variety of environmental, subgrade or loading conditions that restrict or preclude its use. This first step in the evaluation process screens the various materials to determine if they could meet the objectives and needs of the road projects. This step in the evaluation process is shown in Figure 4.2 and is described below:

1) Define Project Objectives: The objectives to be achieved by the surfacing must be defined at the outset. Examples of these objectives are:

   a) a surfaced road to serve logging only,

   b) an all-weather surface,

   c) temporary or intermittent use of the road, for example, a 1- to 5-year period,

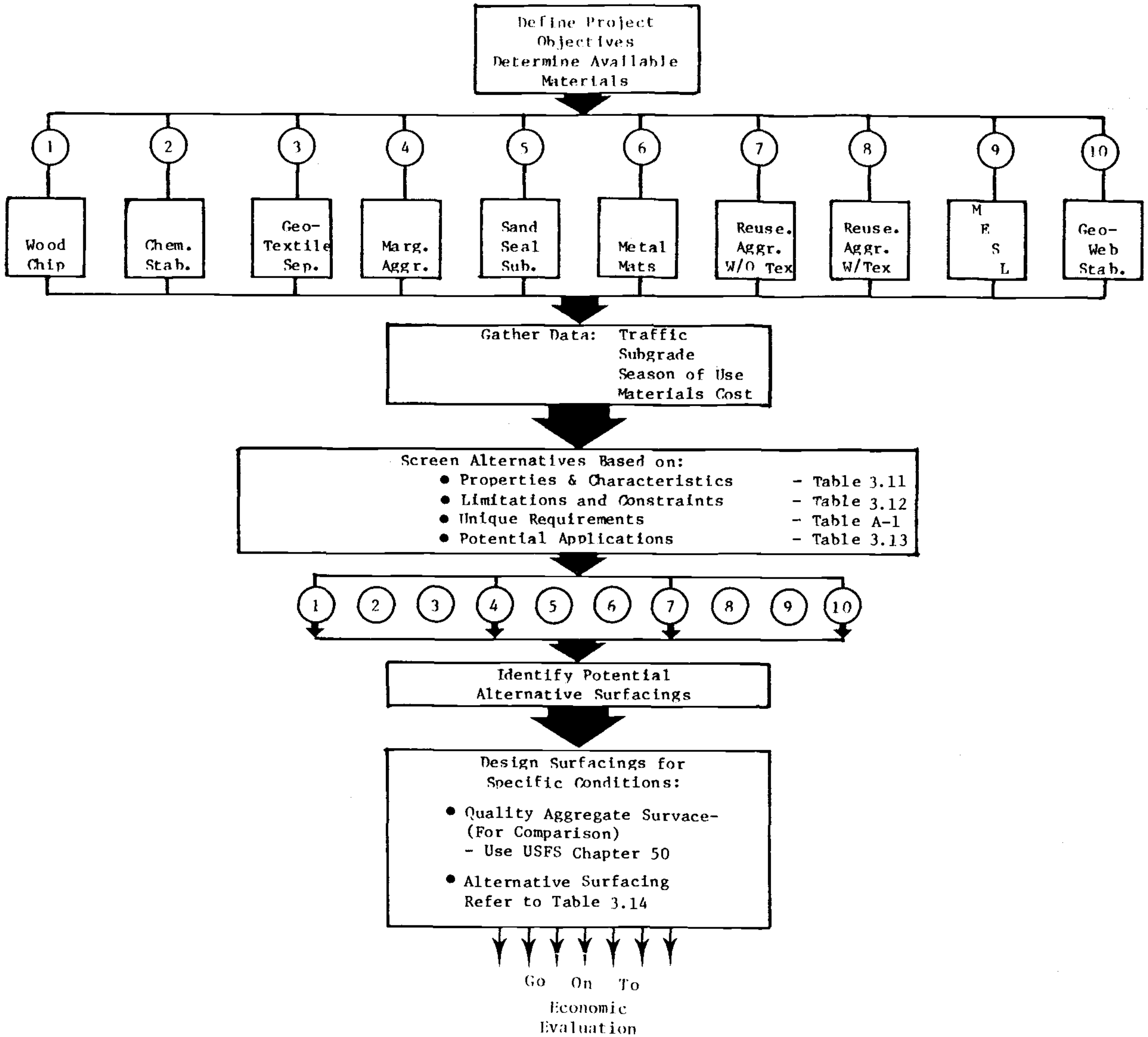


Figure 4.2. Preliminary Evaluation Step.

d) economic alternative to a permanent road, and

e) low initial cost construction.

2) Determine Available Materials: Identify any materials that are readily available for use on the projects, such as slash for a wood chip surfacing.

3) Gather Data: Collect and assemble data concerning the project and possible materials, including the volumes and loading conditions, subgrade type and strength, season of use and expected climatic conditions, materials' costs, and other pertinent materials information.

4) Screen Possible Alternate Surfacings: Those materials that have a strong potential of being used can be identified by comparison of the material's properties, characteristics, limitations, unique requirements, and potential applications with the projects, objectives, needs, and characteristics.

5) Identify Potential Alternate Surfacings: The screening in 4) above identifies those alternate surfacings with the strongest potential of being effective but does not take into account their relative economic efficiency.

6) Design Surfacings for Specific Conditions: Each of the potential alternate surfacings must be designed to meet the loading requirements, subgrade

conditions, and environmental conditions using accepted design approaches. Appropriate design methods were referenced in Table 3.14. A design for a quality aggregate-surfaced road must also be prepared as a basis for comparison purposes.

4.4.2 Economic Evaluation Step

Once the alternate surfacings with the strongest potential of being used have been identified and designed, the next step is the in-depth economic evaluation of each of the potential alternatives. The elements of this step are shown in Figure 4.3:

1) Estimate Project's Costs: The construction, maintenance, recovery, and storage, as well as salvage values for each of the projects in the set are estimated. The "set" of projects includes all projects where the material use, or reuse, is planned.

2) Convert Costs to Present Worth of Costs: The expected construction, maintenance, recovery and storage costs, and the salvage value for all projects in the set of projects are converted to their present worth by the appropriate engineering economic factor for the period, n and the accepted interest rate, i.

3) Compute Present Worth of Costs For Analysis Period: The sum of the present worth of all costs incurred on the project over their analysis period is computed.

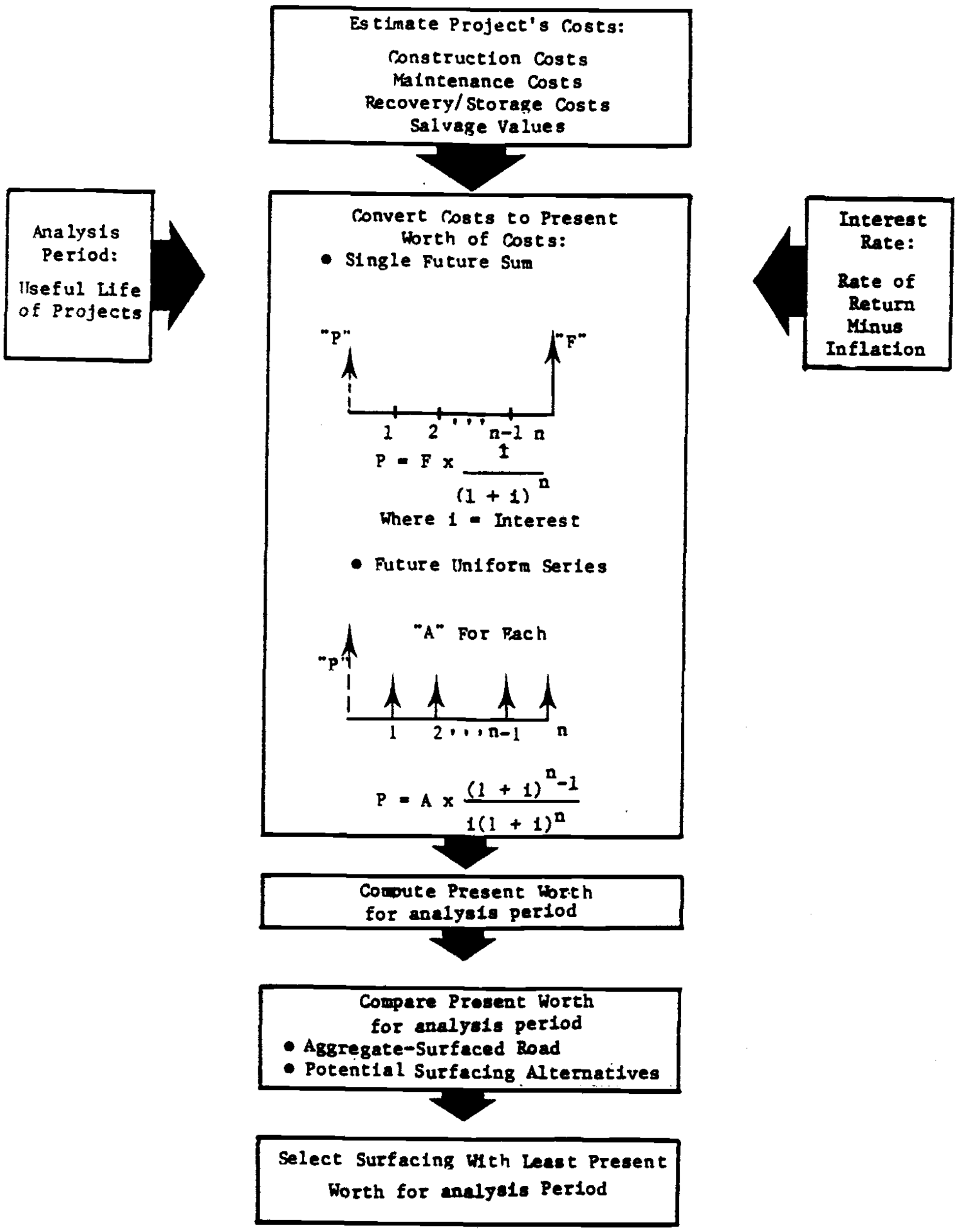


Figure 4.3. Economic Evaluation Step

4) Compare Present Worth for Various Alternatives: The present worth of the various surfacing alternatives, identified by the preliminary evaluation, are compared with the costs for a normal aggregate-surfaced road, and with each other.

5) Select Surfacing with Least Present Worth: The surfacing alternatives (or normal aggregate surfacing) with the least present worth is selected as the most economical.

4.5 Major Elements of the Preliminary Evaluation Step

The alternate surfacings currently available for temporary or intermittent use roads each have their strengths and limitations. As indicated in Figure 4.2, the screening of the alternate surfacings to identify those that could be used takes account of the materials properties and characteristics, limitations and constraints, unique requirements, and potential applications. The major elements of the preliminary step to identify potential alternate surfacings are discussed below.

4.5.1 Material Properties and Characteristics

Typical design thicknesses, initial material costs and weights are given in Table 3.11. These factors may give adequate information in some situations to determine if a material could be used. For example, the initial cost of metal mats preclude their use unless they are reused frequently or for a project carrying a high volume of logging traffic.

4.5.2 Subgrade Type and Strength

The subgrades encountered may vary over a wide range of strengths and types, such as gravel, silt, sand, and clay. Some alternate surfacings are applicable for only certain subgrade types or strengths. Those alternate surfacings that are not applicable are deleted from further consideration. The subgrade limitations of the various alternate surfacing materials are given in Table 3.12.

4.5.3 Season and Climate

The use of some materials is constrained by specific climatic and seasonal conditions. Table 3.12 gives the seasonal and climatic constraints for the alternate surfacing materials.

4.5.4 Geometrics of the Roadway

The grade or curvature of the roadway may preclude the use of alternate surfacings. For example, metal mats cannot be used for projects with grades of 9 percent or greater, or on roads with severe horizontal curvature. The geometric limits of the other materials are given in Table 3.12.

4.5.5 Project Length

The project length can limit the use of some alternate surfacings. Some of the materials are very expensive, such as metal mats, and may be only used on very small projects (1,000 feet or less). Others, such as marginal aggregates, may be very cheap and are applicable to projects of any size. Recommendations of practical project length are given in Table 3.12. The effect of project length often can be determined only by an in-depth economic evaluation.

4.5.6 Frequency of Use and Useful Life

Some of the materials, such as metal mats and reusable aggregates, can be recycled and reused for several projects. Others are permanent, such as marginal aggregates and soil stabilization. The economy is affected by how many times a material is used, and consequently, the number of logging operations over which the capital investment can be spread.

Project useful life is an important consideration because some materials have excellent performance for a limited time while others last indefinitely. Those materials that require major rehabilitation or rebuilding may be more costly in the long run than materials that have a higher initial cost and a long useful life.

Typical values of the expected life for surfacings are given in Table 3.12. A tradeoff exists between frequency of use and the useful life for the various materials. A material that has a long useful life, such as metal mats, typically must be used many times to spread its high initial cost over many projects for it to be economical.

4.5.7 Special Requirements for Equipment and Labor

The equipment and labor required to construct the surface must be available. Specific construction and maintenance requirements for each alternate surfacing are listed in Table A.1. Special equipment, unique technology, or expertise may be difficult to provide continuously on a long-term basis if not used frequently.

4.5.8 Availability

The materials must be available in the desired areas of use for them to be economical. The sources of these materials are identified in Table 3.11, including addresses and phone numbers of suppliers. The final measure of a material's availability is the cost of the material, including its purchase price and the cost to ship it to the site where it is to be used. The material's availability might only be assessed by an in-depth economic evaluation.

4.5.9 Budget Constraints

Although the source and amount of financing for a road surface material does not affect the comparative economic analysis of alternatives, it could become a consideration in the decision making if there were a budget constraint. The preferred alternative may require more funds than are available. For example, the use of aluminum mats may be very attractive on the life cycle basis because they can be reused for many alternative projects. But, the initial purchase and construction cost is very high, approximately $\$9/ft^2$. The road owner may not be able to afford the initial investment of funds required to get the long-term benefit of this material.

Finally, from the above preliminary evaluation steps, those alternatives that meet the physical and financial requirements can pass on to the economic evaluation phase of the process.

4.6 Major Elements of the Economic Evaluation Methodology

Those alternatives that meet the physical and financial requirements are evaluated in the economic evaluation step of the process. The economic evaluation methodology for alternate surfacings is based on the least total life cycle cost. The analysis period is defined as the life of the set of planned projects, rather than for the life of the surfacing. The total costs include the cost of construction, maintenance and repair cost, cost of recovery and replacement, and storage costs. These are converted to a comparable economic basis by reducing all costs to their present worth.

The total present worth of the life cycle costs is recommended as the decision criterion rather than the benefit cost ratio because the benefits do not vary significantly for the various alternate surfacings. Further, the benefits are difficult to quantify for the various surfacings. Therefore, reliable benefit cost ratio values could not be provided.

4.6.1 Benefits Estimation

The benefits that are realized from surfacing a road may include reduced operating costs, reduced maintenance costs, increased speeds (i.e., reduced travel time), increased safety, added comfort and convenience, energy savings, and environmental benefits of reduced air and/or water pollution. The potential benefits for the various alternate surfacings are compared to the benefits for a crushed aggregate surface in Table 4.2. For vehicle operating costs, only a wood chip surfacing is expected to have a significant increase in vehicle operating costs, as a result of its high rolling resistance.

Table 4.2. Benefits of Alternate Surfacings Compared to Crushed Aggregate Surfacing.

Alternative Surfacing	Vehicle Operating Costs	Maintenance Cost	Speeds (Travel Time Saving)	Risk of Accident	Comfort and Convenience	Environmental Benefits Air, Water
Wood and Bark Chip	Increase	Increase	Decrease	Unchanged	Possible Decrease	Possible Decrease
Chemical Stabilization	Decrease	Decrease	May Increase	May Increase	May Increase	Possible Decrease
Geotextile and Geogrid Separation	Unchanged	Decrease	Unchanged	Unchanged	Unchanged	Unchanged
Marginal Aggregate	Slight Increase	Increase	Slight Decrease	Unchanged	Unchanged	Unchanged
Sand Seal	Unchanged	Decrease	Increase	Decrease	Increase	Increase
Geoweb Stabilization	Decrease	Decrease	Increase	May Decrease	Increase	Increase
Reused/Recycled Aggregates	Unchanged	Unchanged	Unchanged	Unchanged	Unchanged	Unchanged
Metal Mats	May Increase	Decrease	May Decrease	May Increase	Aluminum Increase Steel Decrease	Increase
Membrane Encapsulated Soil Layer	Unchanged	Decrease	May Increase	Unchanged	Unchanged	Possible Increase

Vehicle operating costs are unchanged or are expected to decrease with other surfaces. Maintenance costs are expected to increase for wood chip surfaces and marginal aggregates; other surfaces are likely to experience decreased or unchanged maintenance costs. Wood chip roads and metal mats are expected to experience decreased speeds, or increased travel times. Safety is not likely to be affected negatively by any surface except metal mats, and perhaps not even them. Comfort and convenience are likely to decrease with wood chip surfaces and steel mats because of an uneven surface. Wood chips and chemically stabilized surfaces may result in increased water pollution if water sources are next to the road.

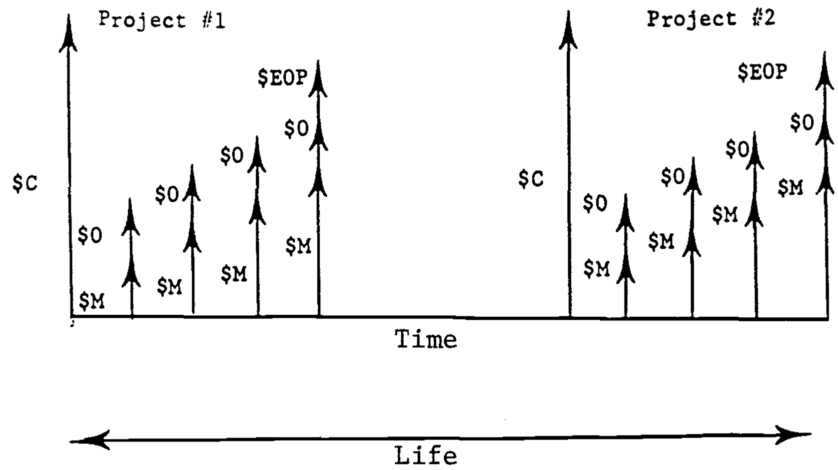
4.6.2 Total Present Worth for Analysis Period

The life cycle cost concept requires that the cost of all activities associated with constructing, repairing, maintaining, recovering, and replacing road surfacings to provide equivalent service over the economic lives of the surfacings, be compared. The analysis period cycle used here is the life of a set of projects where the materials are used, and/or reused. To make the costs of nonrecoverable materials comparable to recoverable materials, the same set of projects must be evaluated. For a recoverable material, its salvage value is the amount of its life that has not been expended at the end of the last project in the project set, compared to its expected life.

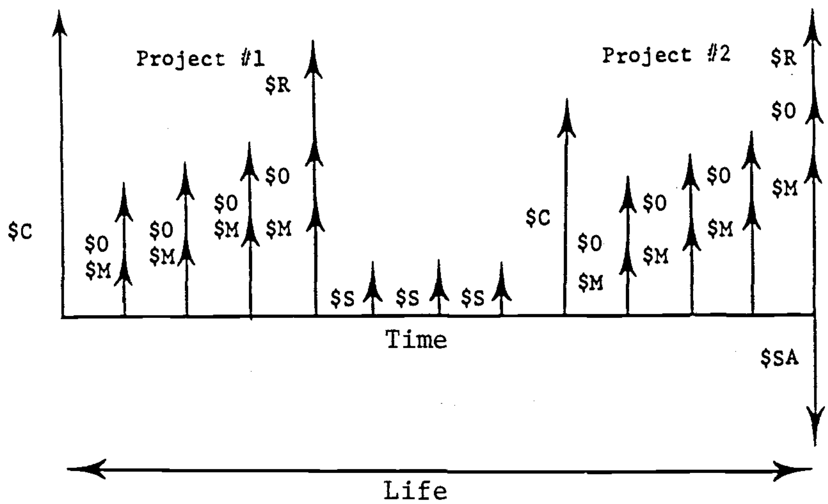
The evaluation approach varies depending on whether the material is recoverable or nonrecoverable. A recoverable material is placed for a use period, and then recovered and moved to another project or stored until it is needed again on that same or other road section. A nonrecoverable material, such as a biodegradable material, is assumed to have no value at the end of use. On the accompanying Figure 4.4, these situations are shown on a cost-time diagram.

The construction costs are incurred at the beginning of each project, and include only those costs directly related to the surfacing. Maintenance costs occur periodically and may be a constant amount, or may be increased as the surfacing age increases. Operating costs are not likely to vary a great deal for the various alternate surfacings; consequently, although they are shown, they are not typically included in the evaluation. Further, operating costs are not considered important on Maintenance Level D roads which would include many of the roads where these alternate materials would be used. The non-recoverable surfacings may have end-of-period costs to put the road in a form to serve incidental traffic after logging is completed. Recoverable surfacings have costs of recovery, rehabilitation, and storage between projects in the project set. At the end of the last project in the project set, the salvage value of the material is estimated.

All these costs are converted to their present worth and compared with the present worth of costs for a conventional crushed aggregate surface, as well as with other potential temporary surfacings.



a) Non-Recoverable Alternative Surfacings



b) Recoverable Reusable Alternative Surfacings

where: $C = Construction cost
$0 = Operating cost
$M = Repair and routine maintenance costs
$S = Storage cost
$R = Recovery and rehabilitation costs
$SA = Salvage cost
$EOP = End-of-period costs

Figure 4.4. Cost-Time Diagrams for Alternative Surfacings (10)

4.6.3 Estimate Costs for Each Alternative Surfacing

For each alternative, the following costs must be estimated:

1) Initial Construction Costs: The analyst should be aware that the term "construction cost" refers only to the cost of material, equipment, and labor used for placement of the surface, including any extra fine grading required by the material. The normal subgrade preparation costs which include right-of-way cost, excavating, clearing and grubbing, grading, and compaction costs are not included in the construction cost because the subgrade is prepared in almost the same way for all of the alternative surfacings. Therefore, the initial construction cost is the amount of money that must be spent for surface materials, labor, equipment, and overhead to construct the alternate surface over a prepared subgrade. The costs can be estimated by referring to Appendix D. Appendix D gives typical equipment costs for alternate surfacings.

2) Maintenance Costs: Includes major and routine maintenance costs.

   a) Major maintenance costs include the costs of regraveling or reconstruction that brings the surface back to its original constructed condition. Major maintenance is undertaken at specified times during the life of the surface. Knowing the frequency of the maintenance, cost of materials, equipment, labor, and production rate, the total maintenance cost can then be calculated.

b) Routine maintenance costs include the cost for correction of surface distress as it occurs, rather than at specified periods of time after construction. This type of maintenance includes filling the potholes, replacing the broken pieces of metal mats, patching, and so forth. Unfortunately, precise cost data for routine maintenance and repair are not generally available for alternate surfacings. Some information has been derived from manufacturers' demonstration projects.

3) Recovery Costs: At the end of a period of use, some materials can be recovered for later use or use on another road. The recovery costs can be estimated using Appendix D.

4) Vehicle Operating Costs: The reduction in motor vehicle operating costs and travel time are significant elements in economic comparison on high volume roads, often the major source of benefits that make

one alternative preferable over another one. Components of the vehicle operating costs are as follows:

Running Cost Factors	Design and Traffic Factors
Fuel consumption	Distance
Tire wear	Grades and horizontal curves
Oil consumption	Roadway surface
Maintenance and repair	Speed
Depreciation	Speed changes
Accidents	Roadway surface, alignment,
Travel time	and speed

The vehicle operating costs are typically less for paved surfaces than for crushed aggregate roads (43). Overall, the haul costs of well-maintained paved roads are about 20 to 25% less than for the aggregate roads. With alternative surfacings, roads with volume of traffic less than 100 vehicles per day, and the length of road a few miles, a reduction in vehicle running costs may not be sufficient to support one alternate surfacing over other alternatives. Furthermore, all of the alternate surfacings considered in this report have almost similar characteristics, consequently there will be a very slight difference in the motor vehicle running costs. Therefore, vehicle operating costs are not considered for the economical evaluation of alternative surfacing.

Vehicle operating cost may play a major role when comparing paved versus aggregate and earth roads or single lane versus double lane roads. Tables 4.3 and 4.4 give examples of haul costs on paved, aggregate, and earth roads for double lane and single lane roads, respectively (43).

5) Time Value: Time values provide one of the key factors for full cost comparison of alternate surfacings. According to the study by Beesley an in-vehicle-time value is approximately 40% of the traveler's wage rate. The time can be valued into two different categories, "low" and "high" time value. Low time value is associated with the recreational vehicles where riders are willing to incur extra time to visit the recreational areas. High time value would be found with logging or mining companies who would be willing to pay extra money to save travel time. Again, with alternate surfacings for temporary and intermittent use roads, traffic volume of less than 100 vehicles per day, and the length of road a few miles, a reduction in travel time may not be sufficient to support one alternate surfacing over another alternate surfacing. Furthermore, those alternatives which increase the travel time

Table 4.3. Round Trip Haul Cost for 'on Highway' Logging Trucks ($/MBF/mile) For Single Lane Road (43)

Road Surface	Horizontal Alignment	Adverse Grades (+) 10	10-7	7-4	4-0
Paved	Excellent	1.15	.99	.63	.42
	Good	1.20	.92	.68	.49
	Fair	1.55	1.26	.82	.59
	Poor	1.97	1.62	1.06	.97
Gravel	Excellent	1.56	1.32	.93	.61
	Good	1.72	1.43	.98	.70
	Fair	2.19	1.73	1.08	.80
	Poor	2.86	2.30	1.42	1.31
Graded and Drained	Excellent	2.24	1.82	1.21	.89
	Good	2.96	2.24	1.33	.97
	Fair	4.01	3.21	1.78	1.64
	Poor	5.09	3.86	2.72	2.14
Primitive	Excellent	4.02	2.87	1.61	1.21
	Good	5.74	4.36	2.19	2.01
	Fair	8.04	4.52	3.23	2.68
	Poor	8.44	5.74	3.73	3.01

Table 4.4. Round Trip Haul Cost for 'on Highway' Logging Trucks ($/MBF/mile) For Double Lane Road (43)

Road Surface	Horizontal Alignment	Unit Cost ($/MBF/mile) Adverse Grades (+)			
		10	10-7	7-4	4-0
Paved	Excellent	.86	.70	.50	.30
	Good	.96	.79	.58	.33
	Fair	1.11	.89	.63	.38
	Poor	1.20	1.02	.70	.42
Gravel	Excellent	1.60	1.16	.87	.53
	Good	1.90	1.42	.96	.55
	Fair	2.10	1.66	1.11	.62
	Poor	2.35	1.81	1.73	.74
Graded and Drained	Excellent	1.60	1.55	.87	.52
	Good	1.90	1.43	.96	.55
	Fair	2.10	1.66	1.03	.62
	Poor	2.35	1.82	1.18	.74

substantially, such as wood and bark chip roads will be deleted during the preliminary evaluation for long sections of roads. Therefore, time value is not considered for the economical evaluation of alternate surfacings.

6) Safety Costs: The safety of the roads can be affected by roadway alignment, horizontal and vertical curves, cross section, lane width, shoulder widths, sight distance, and pavement condition.

The costs of traffic accidents are generally divided by three major groups. The following costs were reported for the accidents on low volume roads (44):

a) Fatal accident = $235,000

b) Injury accident = $11,200

c) Property damage accident = $500

There is one fatal accident for every 25 injury accidents. Therefore, the average cost of an accident in the fatal plus injury category is estiamted at $19,600. Forty-seven percent of the total accidents are fatal and injury, and 53% are property damage. Therefore, the average cost of all accidents is calculated at $9,500 (44).

For alternate surfacings, most of the surfacing materials are expected to have the same characteristics except those materials, such as chemical stabilization or metal mats that can cause more accidents due to a slippery surface during the wet period of the year. Additional treatment, such as applying an emulsion and traction sand, is required to make the road surface as safe as possible.

Figure 4.5 shows estimated safety performance of existing low volume rural roads. This figure can be used to compare the safety performance of the alternate surfacings with the crushed aggregate. If there are noticeable differences in the number of accidents of the alternate surfacings compared to a crushed aggregate surface, then it is necessary to consider the accident costs.

Appendix D can be used to determine the equipment and the labor costs for construction, maintenance, and recovery of the alternate surfacings.

4.6.4 Select Interest Rate, Analysis Period, and Estimate Salvage Value

In order to convert costs to present worth of costs, several key items of information need to be determined. These items include, selection of interest rate, selection of analysis life, and estimation of the salvage value. These factors are briefly discussed below.

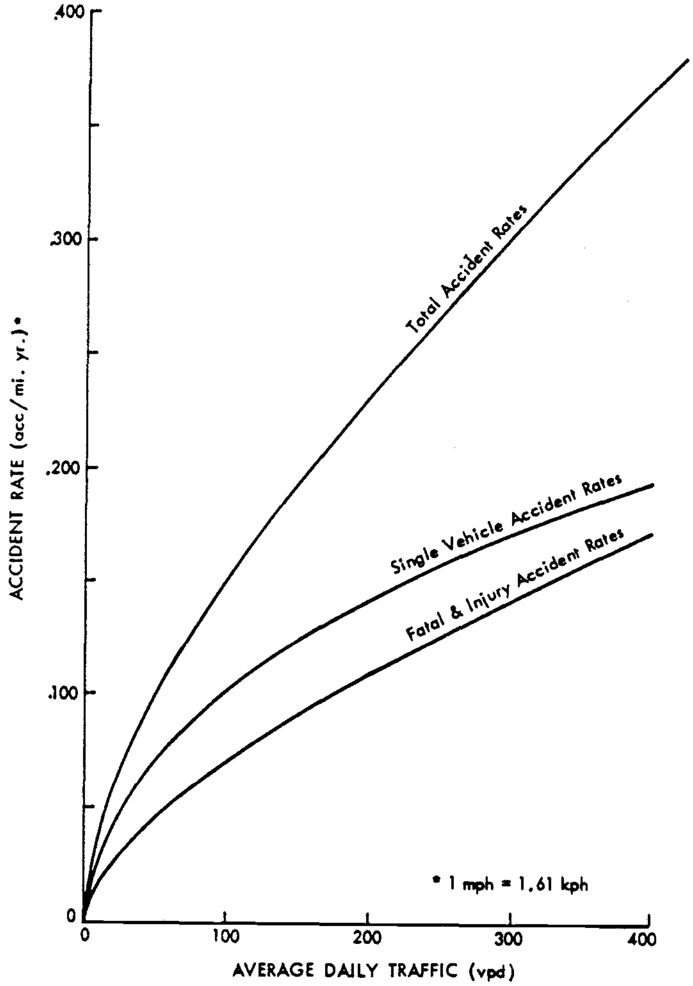


Figure 4.5. Estimated Safety Performance of Existing Low-volume Rural Roads (44).

1) Interest Rate: The interest rate should reflect the real cost of capital which is the current acceptable rate of return minus the inflation rate. The real long-term rate of return on capital has been between 3.7 and 4.4 percent since 1966 (41,45,46), and the current acceptable rate of return (12 percent) minus the inflation rate (8 percent) is 4 percent. Therefore, an interest rate of return of 4 percent is suggested in this guide when constant dollars (non-inflated dollars) are used to estimate future rehabilitation, maintenance, recovery costs, and salvage value.

2) Analysis Period: The analysis period is taken as the life of a set of projects for which the loading conditions and scheduling are known. This is then the useful life of the set of projects. For the example shown in Figure 4.4, the project set is comprised of two projects. The analysis period spans the period from the start of the first project to the end of the last project.

Economic analysis should use an identical time period to evaluate all factors and all alternatives because the present worth of total costs is being compared. Any difference in the time span for the period of evaluation of surfacing alternatives would lead to inconsistent and incompatible comparisons.

3) Salvage value: Salvage value is the economic residual value of the surface material at the end of the analysis period for the project (45). The salvage value of the nonrecoverable materials is assumed to be zero. The salvage value of the recoverable materials for sale or use on another project can be estimated based on its anticipated remaining life. The equation given below can be used for the estimation of the salvage value (45):

$$SV = 1 - \frac{L_A}{L_E} C \qquad (4.1)$$

where

SV = salvage value of the alternative surfaces in dollars,

L_A = cumulative life of all projects in the project set, in years or repetitions of 18 KIP single axle loads (SAL),

L_E = expected total life of the alternate surfaces, in years or repetitions of 18 KIP single axle loads (SAL), and

C = initial cost of the materials for alternate surfaces in dollars.

4.6.5 Compute Present Worth of Costs for Each Alternative

The present worth of costs for each alternate surfacing should be calculated using a discount rate of four percent and analysis life equal to the useful life (service life) of the project. Salvage values should be calculated based on the equation given in the previous section.

The basic equations for computing total present worth of the life cycle cost are shown below. These equations do not include the vehicle operating cost

$$\text{PW Nonrecoverable} = C + M_1 \left(\frac{1}{1+i}\right)^{n_1} + \text{----} + M_k \left(\frac{1}{1+i}\right)^{n_k} \qquad (4.2)$$

$$\text{PW Recoverable} = C + M_1 \left(\frac{1}{1+i}\right)^{n_1} + \text{----} + M_k \left(\frac{1}{1+i}\right)^{n_k} + R \left(\frac{1}{1+i}\right)^{n_r} - S_A \left(\frac{1}{1+i}\right)^{n_r} \qquad (4.3)$$

where:

PW = present worth or present value of total life cycle cost,

C = initial construction cost,

M_k = cost of the k^{th} repair or routine maintenance,

R = recovery and rehabilitation cost,

S_A = salvage value,

i = interest rate (4 percent suggested for use in this thesis),

n_k = number of years from present to the k^{th} maintenance, rehabilitation, recovery activity,

n_r = number of years from the present to the recovery date, and

$\frac{1}{(1+i)^n}$ = (P/F, i%, n) = the single payment present worth factor.

The above equations have been used for the computations of the total present worth of life cycle cost.

Typical project situations are evaluated in Chapter 4 for the determination of the present worth of cost for alternate surfacing systems.

4.6.6 Select the Preferred Alternative

After all of the costs for various alternate surfacings are converted to the present worth of costs over the life of the project, or set of projects, and compared with the present worth of costs for the base conventional crushed aggregate surface. The selected alternative is the alternative with the least present worth of costs.

4.6.7 Make Final Decision and Prepare Report

The last step of the evaluation process is making the decision for selecting the best alternative surface. This is management's responsibility, and involves people such as the project engineer, Forest engineer, or your supervisor.

A report on the selection of the best alternative material should be prepared documenting all of the assumptions and supporting data.

4.7 Summary

The economic evaluation of alternate surfacings, which was developed and discussed in this chapter, provides a valid procedure to evaluate the ovreall effectiveness and economic viability of potential surfacing systems. A two-step evaluation procedure was developed and recommended for evaluation of alternate surfacings. These steps are as follows:

1) Preliminary Evaluation Step: This screens various alternative matrials based on their characteristics, limitations, and availability to identify those materials that have the strongest potential of being effective.

2) Economic Evaluation Step: Those alternate surfacings that show a potential for being effective are subjected to an in-depth economic evaluation to determine the material with the least total present worth of life cycle costs.

Various methods of economic evaluation are discussed, and the total present worth of the life cycle costs is selected for comparing alternate suracings. The benefit-cost ratio can not be used because the benefits of the alternate surfacings, such as reduced operating costs, reduced maintenance costs, increased speeds, reduced travel time, increased safety, added comfort and convenience, energy savings, and environmental benefits of reduced air and/or water pollution, are not expected to vary greatly from one surfacing to another. Furthermore, the benefits are intangible and cannot be quantified.

5.0 COMPARATIVE EVALUATION OF SURFACING ALTERNATIVES

The purpose of this chapter is to describe the step-by-step solutions of two examples to demonstrate the evaluation methodology described in Chapter 4. All relevant life cycle costs are included in the determination of the total costs. The potential surfacings are all designed for level D roads.

Example 1 involves a single project, and since the second, follow-up project is not defined, the recovery of the aggregates is not considered.

Example 2 involves three projects which will be constructed at different periods. In this example, the recovery of the aggregates for the use on subsequent projects is considered.

Costs inputs needed for solving these examples are first discussed and developed. A learning curve for adjusting the production rates of alternate surfacing is then discussed and developed.

5.1 Cost Estimations

Costs inputs needed for solving these examples include:

1) Material costs,

2) Equipment costs,

3) Wage rates,

4) Haul costs, and

5) Salvage value.

Estimates of the above costs and rates allow determination of the total construction, maintenance, and recovery costs for the various alternate systems. Typical construction costs for alternate surfacings are summarized in Table 5.1 and are shown in Figures 5.1 and 5.2. The elements of the costs are discussed below.

5.1.1 Material Costs

Cost data developed herein were derived from: 1) an average of bid prices and supplier price quotes; 2) "Cost Estimating Guide for Road Construction," USDA Pacific NW Region, March 1984 (29); 3) "Price Trends for Federal Aid Highway Construction," USDOT, FHWA, 4th Quarter, 1983 (47); and 4) the eleven demonstration projects conducted as a part of this study (9). These costs were previously reported in Table 3.11 of Chapter 3.

5.1.2 Equipment Cost

The equipment costs used for these examples are for modern equipment (recommended for each alternate surfacing in Appendix A), in good working condition, usually two to five years old. These rates include fuel, oil, lubrication, repairs, maintentance, insurance, taxes, major overhaul, and purchase price (48).

These rates were developed by using references (48,49). Tables in Appendix D summarize the typical equipment and wage rates for construction, maintenance, and recovery of the alternate surfacing systems.

5.1.3 Wage Rates

The wage rates used for these examples are public works rates based on the latest David-Bacon wage rate decision for Zone 5. The zone "e" rates were used (more than 80 miles from town). Added to this rate were all fringe benefits and profit and risk (48,51). The

Table 5.1. Typical Construction Costs for Alternate Surfacings based on (26,47,48,49).

Surfacing Material	\$/Mile/Lane[a]		\$/ft^2		\$/yd^3	
	Average	Range	Average	Range	Average	Range
Crushed Aggregate[c] (Comparison base)	38,000	13,000-70,000[b]	0.60	0.2-1.00	16	5.50-26.50
Wood and Bark Chip[d]	22,750	10,500-35,000[b]	0.36	0.17-.55	6.5	3-10
Chemical Stabilization	25,500	19,000-32,000[e]	0.40	0.3-0.5	---	---
Geotextile and Geogrid Separation	12,750 plus aggregate surface cost	6,500-19,000[f]	0.20 plus aggregate surface cost	0.1-0.3	---	---
Marginal Aggregate[c]	31,750	6,500-57,000[b]	0.50	0.1-0.9	14	3-25
Sand Seal	15,000	10,000-20,000[b]	0.24	0.16-0.32	---	---
Geoweb Stabilized	158,000	126,000-190,000	2.5	2-3	---	---
Reused/ Recycled Aggregates[c]						
a. Construct	45,000	20,000-70,000[b]	.7	.30-1.10	19	8.50-29.50
b. Recover[g]	9,000	6,000-12,000[h]	.15	.10-.20	6.00	4.00-8.00
Metal Mats						
a. Steel[i]	110,500	95,000-126,000	1.75	1.5-2.0	---	---
b. Aluminum	565,000	500,000-630,000	9.0	8-10.0	---	---
Membrane Encapsulated Soil Layer	48,000	32,000-64,000[b+f]	0.75	0.5-1.0	---	---

Assumptions:
[a]assumes lane width of 12 feet
[b]variation is due to the transportation cost of the materials
[c]assumes 12-inch surface thickness
[d]assumes 18-inch surface thickness
[e]variation is due to the types of stabilizing agents as well as the percent of stabilizing agents
[f]variation is due to the cost of the materials
[g]assumes 70% of the aggregates can be recovered
[h]variation is due to the recovery production rate. This cost includes only the recovery of the aggregate from existing project and loading into the dump trucks, haul cost of the aggregate to the next project is not included
[i]not in production. Estimate is based on the material cost from surplus

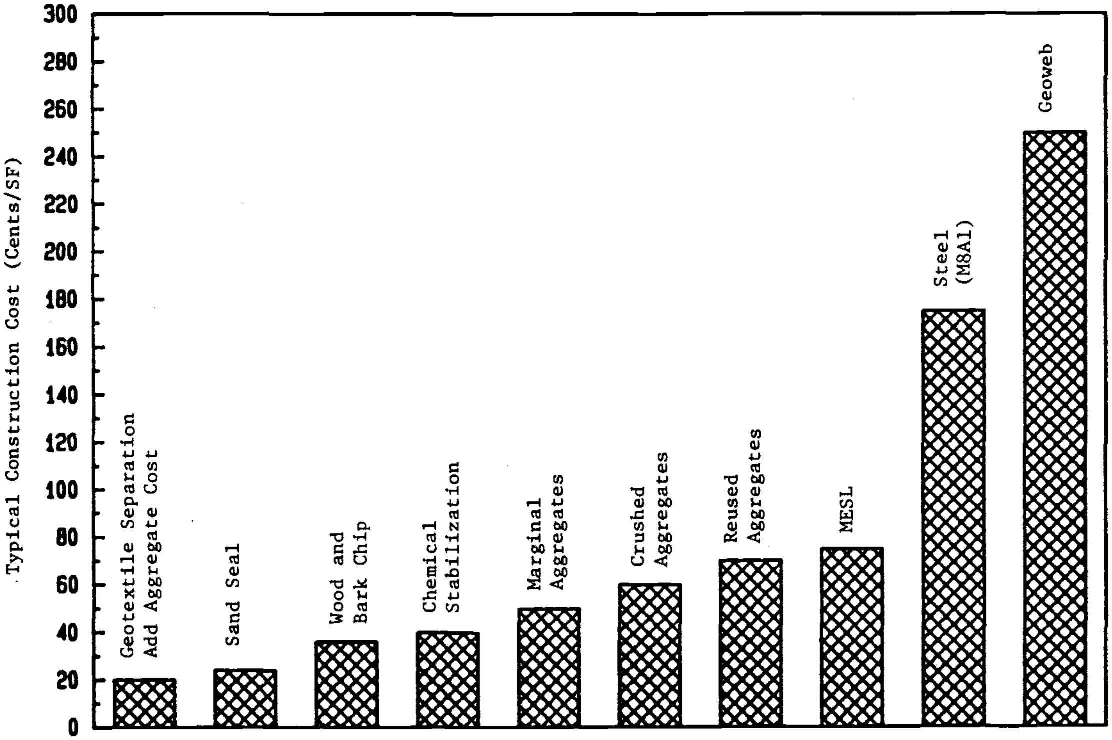


Figure 5.1. Typical Construction Costs for Alternate Surfacing Types (Cents/SF).

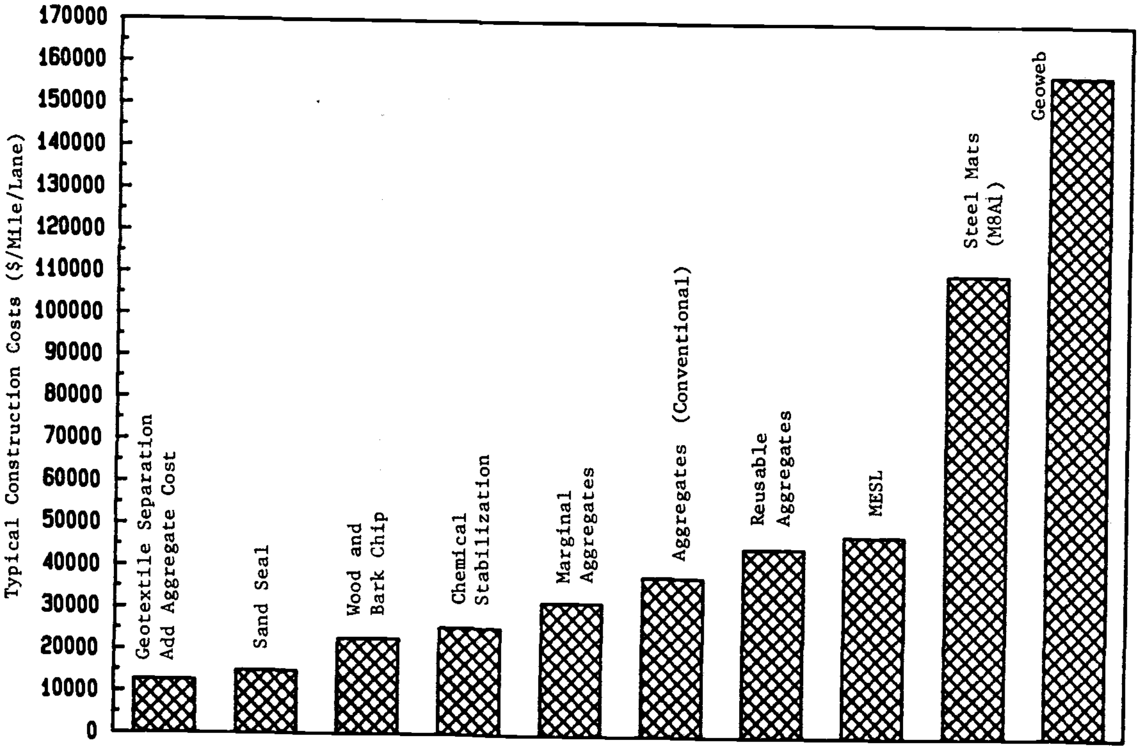


Table 5.2. Typical Construction Costs for Alternate Surfacing Types ($/Mile/12'-Lane)

zone descriptions for laborers and equipment operators are described below (51), and tables in Appendix D summarize the wage rates for various types of equipment which can be used for the construction, maintenance, and recovery of the alternate surfacings:

Zone a - All jobs or projects located within 30 miles of the respective city hall,

Zone b - More than 30 miles but less than 40 miles from the respective city hall,

Zone c - More than 40 miles but less than 50 miles from the respective city hall,

Zone d - More than 50 miles but less than 80 miles from the respective city hall,

Zone e - More than 80 miles from the respective city hall.

All operator rates listed with equipment are for Zone e. To adjust the rates, use the following:

Zone a - 0 to 30 miles reduce $2.75 per hour,

Zone b - 30 to 40 miles reduce $2.10 per hour,

Zone c - 40 to 50 miles reduce $1.60 per hour,

Zone d - 50 to 85 miles reduce $1.05 per hour,

Zone e - greater than 85 miles, rate as shown with equipment.

5.1.4 Haul Costs

The haul costs vary with the type of materials, average haul distance, travel speed, and so forth. Typical haul costs for aggregates, sand, and bark chips are given in Table 5.2. Haul costs for

Table 5.2. Haul Cost for Aggregates, Sand, and Bark Chips $/Mile

Alternative Surfacings	Hauling Distance One Way (Mile)		
	1-10	10-30	More than 30
Aggregates[a]	0.35-0.38 cy	0.35-0.30 cy	0.30 cy
Sand[b]	0.17-0.19 ton	0.15-0.17 ton	0.15 ton
Bark Chips[c]	0.18-0.16 cy	0.16-0.07 cy	0.07 cy

Vehicle Speed: 40 MPH (64 Km/hr)
[a]Dump Truck Capacity: 10 cy; Rental Fee: $57.50/hr; Loading and Unloading: 10 minutes
[b]Dump Truck Capacity: 20 ton (21,772 Kg); Rental Fee: $57.50/hr; Loading and Unloading: 10 minutes
[c]Chip Truck Capacity: 40 cy; Rental Fee: $65/hr; Loading and Unloading: 30 minutes

other types of materials will depend on the availability of the materials in the desired area and are added to the materials cost on a lump-sum basis.

5.1.5 Salvage Value

Salvage value is the economic residual value of the surface material at the end of the analysis period for the project (45). This item is previously discussed in detail in Chapter 4 of this report.

5.2 Production Rates

The production rates are rough estimates based on the experience gained from the demonstration projects (9), literature review, and use of a learning curve. The productivity may vary substantially from one project to another, from one district to another, and from one part of the country to another, due to the various conditions and constraints. These include (51):

1) Type and size of equipment that is used,
2) Length of the project,
3) Labor force (trained versus untrained),
4) Operator efficiency,
5) Types of materials (common excavation to rock),
6) Job efficiency (minutes worked per 60-minute hour),
7) Grades (adverse and favorable),
8) Terrain (flat, mountain),
9) Limited space for operation,

10) Constraints on getting haul units to the loading and unloading area,

11) Climatic conditions, and

12) Uniqueness of the project (e.g., reusable aggregates with geotextile separation).

Based on the above factors, it is obvious that each project is different. Furthermore, the outcome of one or two demonstration projects does not provide an adequate data base on which to estimate the production rates for the entire country. A learning curve is recommended to adjust these values since there is little experience with some of these materials. Table 5.3 summarizes the production rates for the alternate surfacings. The average production rates are based on the 8 hours per day of actual construction work, excluding the travel time to and from the project. The estimates are also based on the construction of a 1-mile roadway, using trained labor forces, appropriate equipment and favorable conditions. The production rates of demonstration projects, along with the use of a learning curve, were used to develop this table. This learning curve is discussed below.

5.2.1 Learning Curve

The more roads that are built with alternate surfacings, the more efficient the construction of the road becomes due to experience gained by individual operators and by engineering-management support. Therefore, direct labor and equipment costs decrease, and the production rates increase. The total effect of the experience is called the "learning curve".

Table 5.3. Production Rate for Potential Surfacing Types (26,42,50).

Potential Surfacing Types	Activities Description	Production Unit	Production Rate Average	Production Rate Range
Crushed Aggregate and Marginal Aggregate	Spreading Aggregate	cy/hr	100	50 - 150
	Compaction	14' lane mile/day	1	0.5 - 1.5
	Grading	14' lane mile/day	2	1 - 3
Wood and Bark Chip	Chipping	cy/hr	100	50 - 150
	Spreading Wood Chip	cy/hr	100	50 - 150
	Compaction	14' lane mile/day	0.5	.2 - 1.0
	Grading	14' lane mile/day	2	1 - 3.0
Chemical Stabilization	Soil Pulverization	14' lane mile/day	.33	.2 - .5
	Spreading	14' lane mile/day	.33	.2 - .5
	Mixing Stabilizing Agent	ton/hr	6	2 - 10
	Watering	14' lane mile/day	.33	.2 - .5
	Compaction	14' lane mile/day	.33	.2 - .5
	Spreading Traction Sand	14' lane mile/day	2	1 - 3
Geotextile or Geogrid Separation	Geotextile Placement	sy/hr	1000	500 - 1500
	Spreading Aggregate	cy/hr	100	50 - 150
	Compaction	14' lane mile/day	1	.5 - 1.5
Sand Seal	Sand and Seal Application	14' lane mile/day (double layer)	2	1 - 3
	Compaction	14' lane mile/day (double layer)	2	1 - 3
	Brooming	14' lane mile/day	4	2 - 6
Metal Mat	Placing Mats	sf/hr	1000	500 - 1500
	Recovery	sf/hr	1000	500 - 1500
	Cleaning	sf/hr	1000	500 - 1500
	Repairing	sf/hr	1000	500 - 1500
Reusable Aggregate Without Geotextile Separation	Spreading Aggregate	cy/hr	100	50 - 150
	Compaction	14' lane mile/day	1	0.5 - 2.5
	Grading	14' lane mile/day	2	1.0 - 3.0
	Recovery	cy/hr	60	40 - 80
Reusable Aggregate With Geotextile Separation	Geotextile Placement	sy/hr	1000	500 - 1500
	Spreading Aggregate	cy/hr	80	60 - 100
	Compaction	14' lane mile/day	1	.5 - 2.5
	Recovery of Aggregate	cy/hr	60	40 - 80
Membrane Encapsulated Soil Layer (MESL)	Ripping	14' lane mile/day	.50	.3 - .7
	Excavation	cy/hr	150	100 - 200
	Stockpiling	cy/hr	150	100 - 200
	Membrane Placement	sy/hr	1000	500 - 1500
	Spreading	cy/hr	150	100 - 200
	Grading	14' lane mile/day	2	1 - 3
	Compaction	cy/hr	150	100 - 200
	Seal Application	14' lane mile/day	2	1 - 3
	Watering	14' lane mile/day	2	1 - 3
Geoweb Stabilization	Geoweb Placement	sf/hr	1600	1200 - 2000
	Spreading Sand	14' lane mile/day	.50	.30 - .70
	Compaction	14' lane mile/day	1	0.5 - 1.5
	Asphalt Application	14' lane mile/day	1	0.5 - 1.5
	Spreading Traction Sand	14' lane mile/day	2	1.0 - 3.0

A learning curve is specified by the decrease in cost or decrease in time of production each time a given quantity is produced. For example, an 80 percent learning curve is a fairly representative situation for many large-scale repetitive projects (42). This means that there will be a 20 percent reduction in worker-hours per unit between doubled units (22). That is, if it took 100 hours to build the first mile of road, it will take 100 x (0.80) = 80 hours to build the second mile of the similar road. Then, the fourth mile of road would taken 80 x (0.80) = 64 hours; the eighth mile of similar road (double unit 4) would take 64 x (0.80) = 51 hours; and so forth. This is shown graphically in Figure 5.3.

The time to construct the nth mile of road is given by (50)

$$T_n = T_1(n_1)^b \tag{5.1}$$

The total time to build a portion of road from mile n_1 to n_2 is given by

$$\int_{n_1}^{n_2} T_n d_n = \frac{T_1}{(1+b)} \left[(n_2 + \tfrac{1}{2})^{1+b} - (n_1 - \tfrac{1}{2})^{1+b} \right] \tag{5.2}$$

where: T_1 = the time to build the first mile of road,

T_n = the time to build the n^{th} mile of road,

n = the total number of miles of road that is built,

b = the learning or improvement parameter,

so:

b = [log (learning rate)]/(log 2), as in

log (0.8)/ log (2) = -0.322.

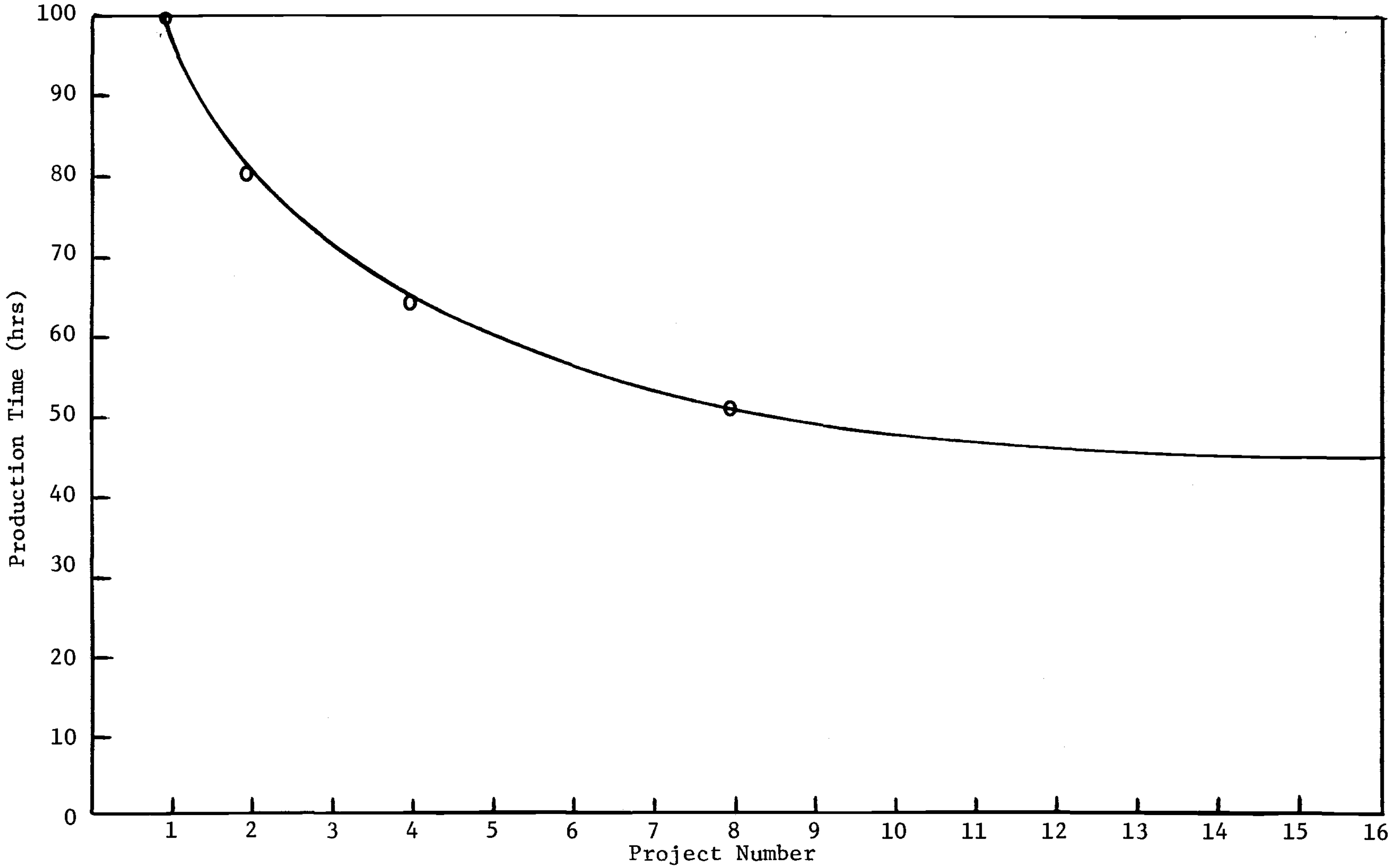


Figure 5.3. Learning Curve for a Typical Alternate Surfacing with 80% Learning Rate.

Table 5.4 shows values of the learning improvement parameter "b" as it is related to various learning rates.

Learning curves are very effective in high-cost projects and low frequency projects. In cost estimating for alternate surfacings, the existence of a learning curve is likely, with a major effect on project costs. Therefore, bids should be lower on successive road projects.

To establish a good learning rate for an alternate surfacing, theoretically at least 4 miles of each surface must be built at eight different time periods with the same crew, labor, and equipment. The production of each half-mile of road must be recorded to establish the learning rates.

Based on the knowledge gained from demonstration projects of the alternate surfacings, an average recommended learning rate of 80 per-ent for the construction of alternate surfaces is recommended. The use of the learning curve would estimate a reduction in production time of almost 50% for the eighth project compared to the initial project. Subsequent projects are not likely to experience a significant reduction in production time.

It is important to remember that learning curve reductions apply only to direct labor and equipment costs. They are not applied to indirect material costs. An example of the use of the learning curve is given in Appendix D.

The remainder of this chapter describes the step-by-step solution of the two examples using the cost and production rates

Table 5.4. Learning Rates and Associated Learning Improvement Parameter,"b" (42).

Learning Rate	Learning Improvement Parameter (b)
1.0 (no learning)	0
0.95	-0.075
0.90	-0.152
0.85	-0.234
0.80	-0.322
0.75	-0.415
0.70	-0.515
0.65	-0.621
0.60	-0.737
0.55	-0.861
0.50	-1.000

developed herein to demonstrate the evaluation methodology described in Chapter 4.

5.3 Example 1 - Logging Road Project

This example is for a single project with the following characteristics and requirements:

> "The Forest Service will construct a 1-mile long local road for the removal of 5.0 mmbf of timber on the west slope of the Cascade Mountains in Oregon. The road will be 14 feet wide with drainage ditches and side slopes of 2:1. The geometrics provide minimum curve radii of 50 feet with appropriate curve widening and turnouts spaced at 500 feet, on the average. The maximum grades are 12 percent for 2000 feet (favorable to log hauls) with 1 to 6 percent for the remainder. Design is in accordance with the current Forest Service Manual and Handbook standards with construction by the timber purchaser. The subgrade material is a silty sand with rock fragments (SMd) a CBR of 8. All timber is to be removed in one season. No further timber traffic will be experienced for 40 years. Quality crushed aggregate must be hauled 30 miles, while marginal aggregate is available 10 miles from the project."

The design data for the example are summarized in Table 5.5. The design thickness for a quality aggregate-surfaced road for these conditions would be 8 inches, using a layer coefficient of 0.14 and

Table 5.5. Design Data for Example No. 1.

Length of the Road (ft)	5,280
Width of Road (ft)	14
Timber Volume (mmbf)	5.0
Project Life (month)	6.0
Maximum Grade (%)	12
Side Slopes	2:1
Soil Type	Silty-Sand (SMd)
CBR @ 95% of AASHTO T 180	8
Regional Factor (R)	2.00
Layer Coefficient (a)	0.14
Design Aggregate Thickness[a]	7.2 say 8"
Design Wood and Bark Chip[b]	12"
General Assumptions	
Area Necessary for Curve and Turnout Widening	20 percent of the roadway area

[a]Using USFS Chapter 50, simplified design chart for aggregate surfaced road (37), page 50-71.

[b]One inch of aggregate = 1.5 inch wood and bark chips.

regional factor of 2.0, based on USFS Chapter 50, Forest Service Handbook (37).

5.3.1 Example 1 Preliminary Evaluation

Employing the screening process described earlier (Figure 4.2), the alternate surfacings that have a strong potential of being effective are selected as follows.

1) Identify Project Objectives:
   a) construction of temporary local road for logging access,
   b) one season of use,
   c) next logging in 40 years.
2) Identify Available Alternate Surfacings:
   a) all alternate surfacings are available.
3) Gather Data:
   a) project data are summarized in Table 5.5.
4) Screen Alternatives:

   The surfacing alternatives are screened based on their properties, limitations, and unique requirements relative to the project characteristics and requirements. This screening process is documented in Table 5.6. As a result of this initial screening, wood chips, chemical stabilization, and marginal aggregates are the alternatives that have a strong potential to be effective.

Table 5.6. Example Preliminary Evaluation for Example No. 1.

Potential Surfacing Systems	Availability	Project Length	Material Cost	Subgrade Type and Strength	Geometrics of the Roadway	Season of Use	Useful Life	Frequency of Use	Selected Alternatives for Economical Evaluation
Wood and Bark Chip	X	X	X	X	X	X	X	X	X
Chemical Stabilization	X	X	X	X	X	X	X	X	X
Geotextile and Geogrid Separation	X	X	X	Subgrade strenth[a] doesn't require geotextile					
Marginal Aggregate	X	X	X	X	X	X	X	X	X
Sand Seal	X	X	X	Subgrade too weak[d]					
Metal Mats	X	Too Long[b]							
Reusable Aggregate without Geotextile Separation	X	X	X	Subgrade too weak[d]					
Reusable Aggregate with[c] Geotextile Separation	X	X							
Membrane Encapsulated Soil Layer (MESL)	X	X	Too expensive[e]						
Geoweb Stabilization Expandable Grids)	X	X	Too expensive [f]						

X - Accepted alternatives
a - Deleted based on Tables 3.12 and 3.13
b - Deleted based on Table 3.12
c - Deleted since the alternative project for using the recovered materials is not defined
d - Deleted based on Table 3.13
e - Deleted based on Tables 3.12 and 3.13
f - Deleted based on Tables 3.11, 3.12, and 3.13

5.3.2 Example 1 Economic Evaluation

The three potential surfaces, together with a crushed aggregate surface, are next evaluated economically. First, detailed cost estimates are made for the construction and maintenance costs of each material. This includes the cost of the material, placement costs, and material haul cost. Tables 5.7 to 5.10 show a sample calculation of these costs for the crushed aggregate, marginal aggregate, bark chips, and chemical stabilization. Table 5.11 gives a summary of the construction and maintenance costs for a crushed aggregate surface and the three potential alternate surfaces. As shown in this table, the maintenance costs are converted to their present worth by multiplying by a present worth factor, $1/(1+i)^n$.

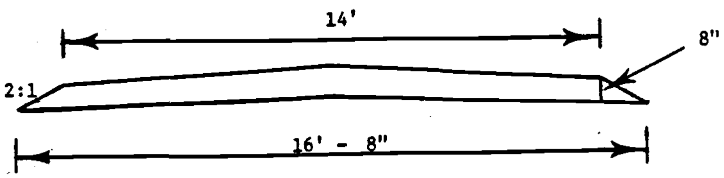
In Table 5.12, the total present worth of life cycle costs for all surfacings are calculated. The result of this calculation is shown in Figure 5.4. The first material is a conventional crushed aggregate surface, which gives the base of comparison to usual construction practices. As seen from these results, all alternate surfaces would result in lower total life cycle costs than a crushed aggregate surface for this example project. The most economical alternative is a chemical stabilization surfacing, at a present worth of $23,033.

5.4 Example 2 - Logging Roads Project

This project has the following characteristics and requirements:

"The Forest Service will construct three local roads for the removal of timber on the west slope of the Cascade Mountains in Oregon. The roads will be 14 feet wide with

Table 5.7. Example of Material and Haul Cost for Crushed Aggregate. (Example No. 1)



General Information

Depth of Material (in.)	8
Average Width of Roadway (ft) $\frac{14 + 16.67}{2}$ =	15.33
Cost of Crushed Aggregate Grading D ($/c.y.)	5
Haul Distance (miles)	30
Haul cost ($/cy - mile)	.30
1 cy Compacted Material = 1.25 cy loose material	

Material Cost

Compacted Volume of Crushed Aggregate for Roadway

$$\frac{(L)(W)(D)}{(12\ in/ft)(\frac{27\ ft^3}{1\ cy})} = \frac{(5280\ ft)(15.33\ ft)(8\ in)}{(12\ in/ft)(\frac{27\ ft^3}{1\ cy})} = 2000\ cy$$

Compacted Volume of Crushed Aggregate for Curve Widening and Turnouts*
(2000 cy)(.20) = 200 cy
Total Compacted Volume = 2000 + 400 = 2400 cy
Total Loose Volume = (Total Compacted Volume)(Loose Factor)
= 2400 cy)(1.25) = 3000 cy
Total Cost of Crushed Aggregate = (3000 cy)($5/cy) = $15,000

Haul Cost

Haul Cost = (Volume of Materials)(Haul Cost)(Haul Distance)
= (3000 cy)($0.3/cy-mile)(30) = $27,000

where:

D = Depth of Material (in.)
L = Length of the Road (ft)
W = Average width of roadway (ft)
*Volume of materials for curve widening and turnouts = 20% volume of materials for roadway

Table 5.8. Material and Haul Cost for Marginal Aggregate. (Example No. 1)

The same assumptions and design data as crushed aggregate except:

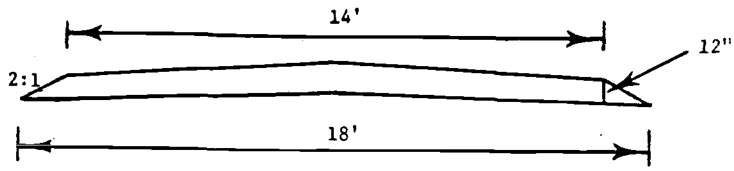
Haul Distance (miles)	10
Total loose volume of marginal aggregates (Table 4.3)	3000 cy
Total cost of marginal aggregate (3000 cy)($5/cy) =	$15,000

Haul Cost

Haul Cost = (volume of materials)(haul cost)(haul distance)

= (3000 cy)($0.3/cy-mile)(10) = $9,000

Table 5.9. Material and Haul Cost for Wood and Bark Chip. (Example No. 1)



Depth of Material (in.)	12
Average Width of roadway (ft) $\frac{14 + 18}{2}$ =	16
Cost of Bark Chips at the Chipping Site ($)	0
Haul Distance (miles)	10
Haul Cost ($/cy-mile)	.15
1 cy Compacted Material - 1.5 cy Loose Material	

<u>Material Cost</u>

Compacted Volume of Bark Chips for Roadway

$$\frac{(L)(W)(D)}{(12\ in./ft)\left(\frac{27^3 ft}{1\ cy}\right)} = \frac{(5280\ ft)(16\ ft)(12\ in.)}{(12\ in/ft)\left(\frac{27\ ft^3}{1\ cy}\right)} = 3130\ cy$$

Compacted Volume of Bark Chips for Curve Widening and Turnouts[a]
(3130 cy)(0.20) = 620 cy
Total Compacted Volume = 3130 + 626 = 3756 cy
Total Loose Volume = (Total Compacted Volume)(Loose Factor)
= (3756 cy)(1.50) = 5634 cy
Total Cost of Materials = (5634 cy)($0.[b]/cy) = 0

<u>Haul Cost</u>

Haul Cost = (Volume of Materials)(Haul Cost)(Haul Distance)
= (5634 cy)($.15/cy-mile)(10 mile) = $8,451

where:
D = Depth of Material (in.)
L = Length of the road (ft)
W = Average width of roadway (ft)
[a]Volume of the Materials for curve widening and turnouts = 20% volume of materials for roadway
[b]Assumes the materials for chipping are available free of charge

Table 5.10. Material and Haul Cost for Chemical Stabilization (Example No. 1)

Selected Stabilizing Agent for (SMd) Soil	portland cement
Percent of Stabilizing Agent (%)	5
Depth of Stabilized layer (in.)	6
Sand* Cost Including Freight (\$/ton)	10
Sand Application Rate (lb/yd^2)	30
Portland Cement Cost Including Freight (\$/ton)	80
Compacted Unit Weight of Soil (γ PCF)	110
Side Slope	2:1
Average Width of Roadway (ft) $\frac{14 + 16}{2}$ =	15

Material Cost

Compacted Volume of Soil to be Stabilized for Roadway:

$$\frac{(L)(W)(D)}{(12 \text{ in./ft})(\frac{27 \text{ ft}^3}{1 \text{ c.y.}})} = \frac{(5280 \text{ ft})(15 \text{ ft})(6 \text{ in.})}{(12 \text{ in./ft})(\frac{27 \text{ ft}^3}{1 \text{ c.y.}})} = 1467 \text{ c.y.}$$

Compacted Volume of Soil to be Stabilized for Curve Widening and Turnouts:

(1467 cy)(0.20) = 297 cy

Total Compacted Volume = 1467 + 294 = 1761 cy

a) Cement Cost

Weight of Stabilized Agent:

$$\frac{(\frac{lb}{ft^3})(\% \text{ of St. Agent})(\frac{27 \text{ ft}^3}{1 \text{ cy}})(\text{compacted volume})}{(2000 \text{ lb/ton})}$$

$$= \frac{(110 \frac{lb}{ft^3})(0.05)(\frac{27 \text{ ft}^3}{1 \text{ cy}})(1651 \text{ cy})}{2000 \text{ lb/1 ton}} = 131 \text{ ton}$$

Total Cost of portland cement = (131 ton)(\$80/ton) = \$10,480

b) Sand Cost - Total surface area of roadway = surface area of material + area of turnouts and curve widening

$$\text{Total surface area of roadway} = \frac{(L)(W)}{9 \text{ ft}^2/yd^2} + \frac{0.2 \ (L)(W)^b}{9 \text{ ft}^2/yd^2}$$

$$\text{Total surface area of roadway} = \frac{(5280 \text{ ft})(15 \text{ ft})}{(9 \text{ ft}^2/yd^2)} + \frac{(0.2)(5280 \text{ ft})(15 \text{ ft})}{(9 \text{ ft}^2/yd^2)} = 10560 \text{ yd}^2$$

$$\text{volume of sand}^b = \frac{(\text{App. Rate lb/yd}^2)(\text{Total Surface Area yd}^2)}{(2000 \text{ lbs/ton})}$$

$$\text{volume of sand} = \frac{(30 \text{ lbs/yd}^2)(10560 \text{yd}^2)}{(2000 \text{ lb/ton})} = 158 \text{ Ton}$$

Total Cost of Sand = (158 ton)(\$10/ton) = \$1580

Haul Cost = 0

where:

L = Lengh of the road (ft)

D = Depth of material (in.)

W = Average width of roadway (ft)

[a]Area of the materials for curve widening and turnouts - 20% area of materials for roadway

[b]Application of sand for traction

Table 5.11. Equipment and Labor Cost for Construction, Maintenance, and Recovery Activities for Example No. 1.

(1) Potential Surfacing Types	(2) Construction or Maintenance or Recovery	(3) Activity Description	(4) Equipment[a] Cost ($/hr)	(5) Operator[a] Cost ($/hr)	(6) Total Laborer's $/hr (Quant) (Unit Rate)	(7) Total Cost (4)+(5)+(6) ($/hr)	(8) Quantities of the Materials	(9) Production[b] Rate	(10) Hours[c] Required for each Activity (8) + (9)	(11) Total Cost of Activity ($)	(12) Present[d] Worth Value of Maintenance $P = Fx \frac{1}{(1+i)^n}$ ($)
Crushed Aggregate and Marginal Aggregate	Construction	Spreading	74.19	28.13	(1)(23.06)	125.38	3000 cy	100 cy/hr	30 say 32	4,012	
		Compaction	26.15	26.99	(1)(23.06)	76.20	3000 cy	1 mile/day	8	610	
									Total	4,622	
	Maintenance	Grading (on third month)	49.39	28.38	-	77.78		1 mile/day	8	622	$P = 622 \times \frac{1}{(1+.04)^{0.25}} = 615$
Wood and Bark Chip	Construction	Chipping	120.00	30.00	-	150.00	5634 cy	100 cy/hr	56.34 say 60	9,000	
		Spreading	72.03	28.13	(1)(23.03)	123.22	5634 cy	100 cy/hr	60	7,393	
		Compaction	26.15	28.13	(1)(23.06)	76.20		.5 mile/day	16	1,219	
										17,612	
	Maintenance	Grading (on third month)	49.39	28.38	-	77.78	-	1 mile/day	8	622	$P = 622 \times \frac{1}{(1+0.04)^{0.25}} = 615$
Chemical Stabilization	Construction	Soil Pulverization	49.39	28.38	(1)(23.06)	100.83		0.33 mile/day	24	2,420	
		Spreading Stabilizing Agent	41.95	26.23	(1)(23.06)	91.24		0.33 mile/day	24	2,190	
		Mixing	49.39	28.38	(1)(23.06)	100.83	131 (ton)	6 ton/hr	21.83 say 24	2,420	
		Watering	39.00	26.16	(1)(23.06)	88.22		.33 mile/day	24	2,117	
		Compaction	26.15	26.99	(1)(23.06)	76.21		.33 mile/day	24	1,826	
		Spreading Sand	44.41	26.23	(1)(23.06)	93.70		2 mile lane/day	4	325	
									Total	11,298	
	Maintenance	Since the life of the project is only six months, maintenance is not expected.									

[a] Equipment and labor costs are based on cost estimating guide. Equipment costs are based on monthly equipment rental, except chipper based on hourly, and asphalt distributor based on weekly equipment rental rate for road construction, Zone V, Siuslaw National Forest and also rental rate blue book.

[b] Production rates are based on the judgement, experience gained from demonstration projects, literature review, and also specific type and size of equipment. This equipment is listed in Appendix A.

[c] Since the operator and equipment are at least tied-up for half a day, the number of hours required for each activity should be corrected to full or half day.

[d] P = Present worth or present value of total life cycle cost
F = Future worth or future value of cost
n = Number of years from present to the maintenance activity
i = Interest rate (4% suggested for use in this report)

Table 5.12. Life Cycle Cost of Alternate Surfacings for Example No. 1.
($)

Costs	Crushed Aggregate	Marginal Aggregates	Wood and Bark Chip	Chemical Stabilization
Material Costs	15,000	15,000	0[a]	12,060
Haul Costs	27,000	9,000	8,451	0[b]
Construction Cost	4,622	4,622	17,612	10,973
Maintenance Cost	615	615	615	0
Total Life Cycle Costs	46,622	28,622	26,698	23,033

[a]Chipping cost, which is part of the material cost, is included in the construction cost.
[b]Included in the material cost.

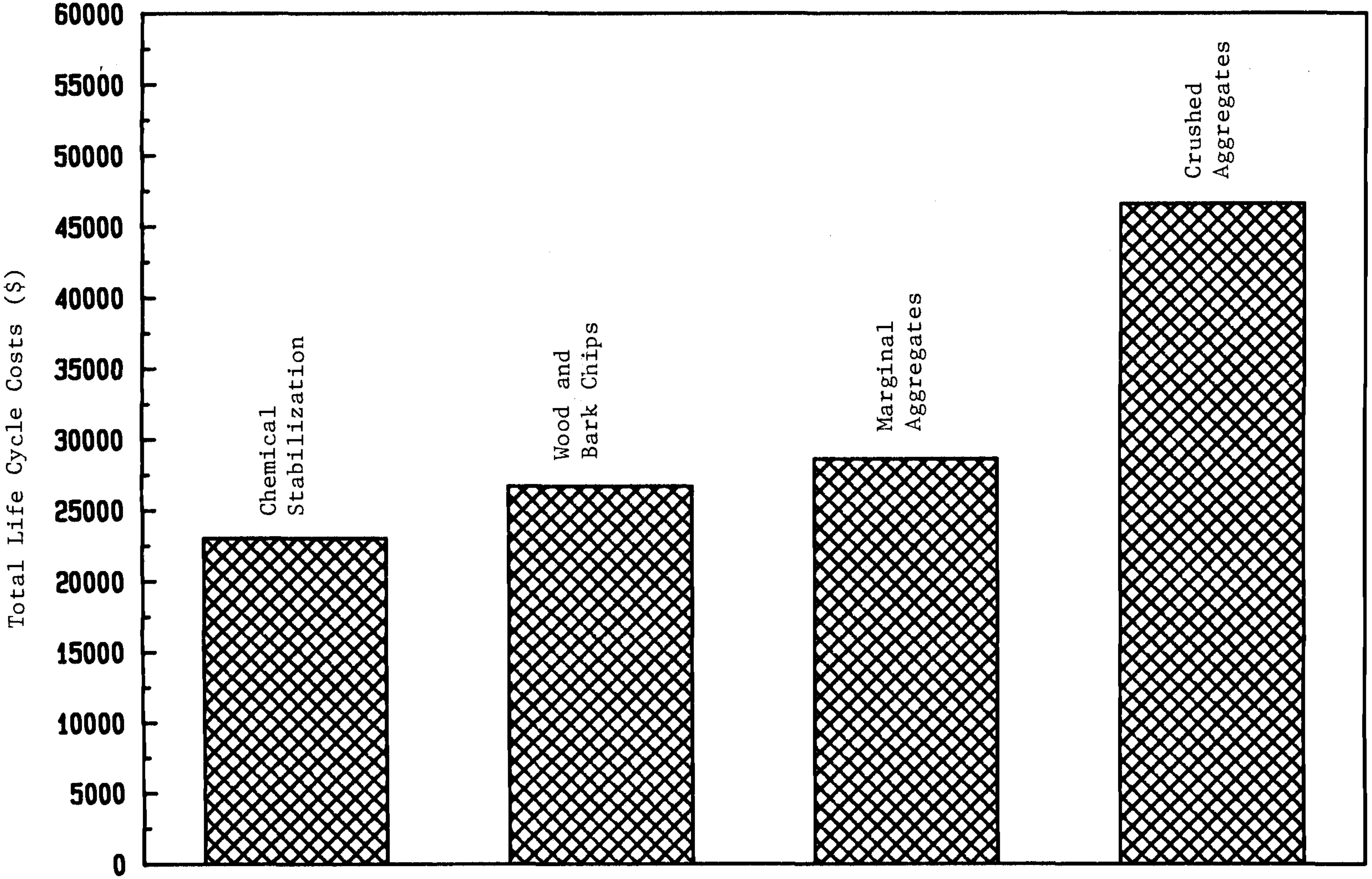


Figure 5.4. Life Cycle Cost of Alternative Surfacings (Example No. 1)

drainage ditches and side slopes of 2:1. The geometrics provide appropriate curve widening and turnouts which is assumed to be 20 percent of the roadway surface area on the average. The maximum grades are 12 percent for 2000 feet (favorable to log haul) with 1 to 6 percent for the remainder. Design is in accordance with the current Forest Service Manual and handbook standards with construction by the timber purchaser. Subgrade materials are silty sand with rock fragments (SMd). The projects are different in lengths, subgrade strength timber volume to be removed, and the date of construction, but all timber for these projects is expected to be removed in one season. No further timber traffic will be experienced for 40 years."

The materials from Project 1 can be used for Project 2 and then for Project 3. Quality crushed aggregate must be hauled 30 miles, marginal aggregate, wood and bark chips are available 10 miles and traction sands for chemical stabilization project are available 15 miles from Project 1. The projects are spaced 5 miles from each other. Figure 5.5 shows the location of the materials and projects. The design data for the example are summarized in Table 5.13, while the material, haul cost, and general assumptions are summarized in Table 5.14. The design thicknesses for quality aggregate surface for these conditions are shown in Table 5.13, using a layer coefficient of 0.14 and regional factor of 2.0, and based on reference (37).

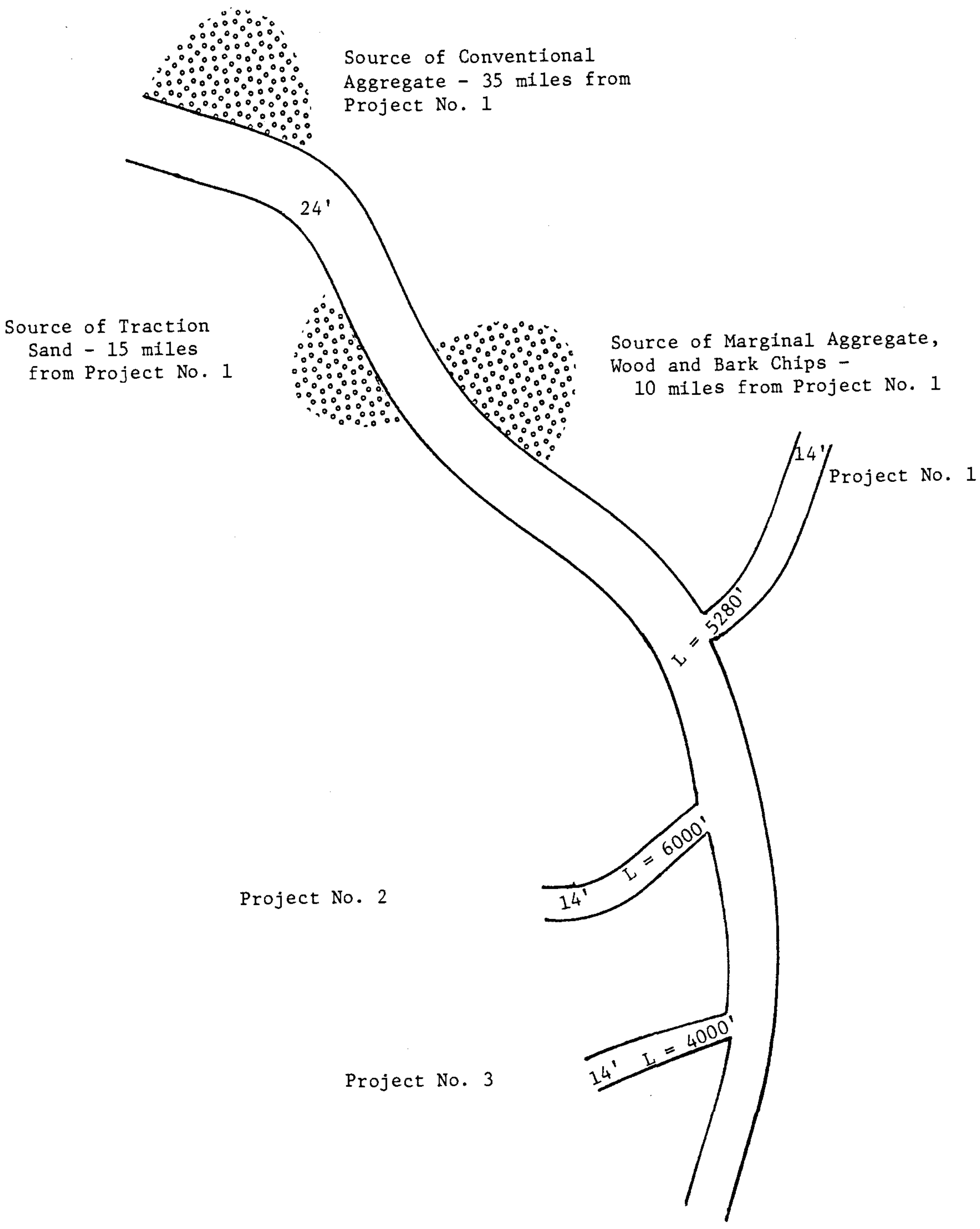


Figure 5.5. Location of Materials and Projects for Example No. 2.

Table 5.13. Design Data for Example No. 2.

Items	Project No.1	Project No.2	Project No. 3
Length of the road (ft)	5280	6000	4000
Width of road (ft)	14	14	14
Timber volume (mmbf)	5	8	10
Maximum grade (%)	12	10	12
Side slopes	2:1	2:1	2:1
Cross slope (ft/ft)	.05	.05	.05
Subgrade type	Silty Sand (SMd)	Silty Sand (SMd)	Silty Sand (SMd)
CBR @ 95% of AASHTO T 180	8	7	6
Regional factor (R)	2	2	2
Layer coefficient (a)	0.14	0.14	0.14
Wood and bark chip layer thickness equivalent factor compared to rock	1.5	1.5	1.5
Depth of stabilized layer (in.)	6	6	6
Percent of stabilized agent (%)	5	5	5
Compacted unit weight of soil (pcf)	110	110	110
Month and year project begins	3/86	3/87	3/89
Month and year project ends	8/86	8/87	8/89
Project life (month)	6	6	6
Aggregate design thickness (in.)	7.2 say 8	8.6 say 9	9.8 say 10
Wood and bark chip design thickness (in.)	12	13.5	15
Average width of roadway for[b] quantity of aggregate calculation (ft)	15.33	15.5	15.67
Average width of roadway for[b] quantity of wood and bark chip calculations (ft)	16	16.25	16.5

[a]Using U.S.F.S. Chapter 50, simplified design chart for aggregate surface road, page 50-71.

[b]Since the side slope is 2:1, the width at the bottom of the surface (on subgrade) is larger than the width on the surface, therefore, the average width which is the sum of the width at the bottom and top divided by two, to be used for quantity of material calculation.

Table 5.14. Material, Haul Cost, and General Assumptions for Example 2.

Items	Project No.1	Project No.2	Project No. 3
A. General Data			
Basic conventional aggregate cost ($/cy)	5	5	5
Source of conventional aggregate (miles)[a]	30	35	40
Basic marginal aggregate cost ($/cy)	5	5	5
Source of marginal aggregate (miles)[a]	10	15	20
Basic traction sand cost ($/ton)	10	10	10
Source of traction sand (miles)[a]	30	35	40
Basic wood and bark chip cost ($/cy)[b]	0	0	0
Source of wood and bark chips (miles)[a]	10	15	20
Cost of cement including freight ($/ton)	80	80	80
Haul distance from Project 1 to alternative projects[a]	0	5	10
Haul distance from Project 2 to alternative projects[a]	5	0	5
Haul distance from Project 3 to alternative projects[a]	10	5	0
Haul cost for aggregates from source or pit ($/cy-mile)	.30	.30	.30
Haul cost for aggregates from one project to alternative projects ($/ton-mile)	.35	.35	.35
Haul cost for sand from source or pit ($/ton-mile)	.15	.15	.15
Haul cost for wood and bark chips ($/cy-mile)	.15	.15	.15
B. General Assumptions			
Area necessary for curve widening and turnouts	20% of the roadway area	20% of the roadway area	20% of the roadway area
Projects recovered	recovered	recovered	not recovered
Percent of recovered aggregate from one project to alternative projects	70	70	70

[a]Haul distance is the one-way distance from pit or source (miles).

[b]Assume materials for chipping available free of charge.

5.4.1 Example 2 Preliminary Evaluation

Employing the screening process described in Chapter 4, the alternate surfacings having the strongest potential of being effective are selected. This screening process is documented in Table 5.15. As a result of this initial screening, wood and bark chips, chemical stabilization, marginal aggregates, and reusable aggregates with geotextile as a separation layer are the alternatives that have the strongest potential of being effective.

5.4.2 Example 2 Economic Evaluation

The four potential surfaces, together with a crushed aggregate surface, are next evaluated economically. First, detailed cost estimates are made for the construction, maintenance, and recovery of each type of material. This includes the cost of materials, placement costs, recovery costs, and material haul costs. Tables 5.16 to 5.23 summarize the step-by-step calculations of this example. Figure 5.6 shows the total life cycle cost for this example. Table 5.16 shows a sample calculation for material quantities. Using this table, the volume or area of the surfacing alternatives can be calculated. Each column of the table is supported with the appropriate formula for the calculation of the material quantities.

Table 5.17 shows a sample calculation for material costs, based on the calculated values for the quantities of the materials from previous tables. Columns 5 and 6 of this table are only used for the chemical stabilization while column 7 can only be used for the sand seal surface.

Table 5.15. Example of Preliminary Evaluation for Example No. 2.

Potential Surfacing Systems	Availability	Project Length	Material Cost	Subgrade Type and Strength	Geometrics of the Roadway	Season of Use	Useful Life	Frequency of Use	Selected Alternatives for Economical Evaluation
Wood and Bark Chip	X	X	X	X	X	X	X	X	X
Chemical Stabilization	X	X	X	X	X	X	X	X	X
Geotextile and Geogrid Separation	X	X	X	Subgrade strenth[a] doesn't require geotextile					
Marginal Aggregate	X	X	X	X	X	X	X	X	X
Sand Seal	X	X	X	Subgrade too weak[d]					
Metal Mats	X	Too Long[b]							
Reusable Aggregate without Geotextile Separation	X	X	X	Subgrade too weak[c]					
Reusable Aggregate with Geotextile Separation	X	X							
Membrane Encapsulated Soil Layer (MESL)	X	X	Too expensive[d]						
Geoweb Stabilization Expandable Grids)	X	X	Too expensive [e]						

X - Accepted alternatives
a - Deleted based on Tables 3.12 and 3.13
b - Deleted based on Table 3.12
c - Deleted based on Tables 3.12 and 3.13
d - Deleted based on Table 3.13
e - Deleted based on Tables 3.12 and 3.13

Table 5.16. Materials Quantities Calculations for Example No. 2

1	2	3	4	5	6	7	8	9
Project No.	Name of Materials	Compacted Volume of Materials $\frac{(L)(W)(D)}{(12\ in/ft)(27\ ft^3/cy)}$	Area of Materials $\frac{(L)(W)}{(9\ ft^2/yd^2)}$	Volume For Curve Widening and Turnouts (col.3)(0.20)[d]	Area For Curve Widening and Turnouts (col.4)(0.20)[d]	Total Loose Volume Needed (Col.3 + 5) (Loose Factor)[b]	Actual Loose Volume Needed or Volume of Soil to be Treated (Col.7)(Volume of the Project to be Recovered Recovery Rate %)[c]	Total Area of Materials or Area to be Treated (Col. 4 + 6)
		cy	yd^2	cy	yd^2	cy	cy	yd^2
1	Crushed Aggregate	2,000	-	400	-	3,000	3,000	-
	Marginal Aggregate	2,000	-	400	-	3,000	3,000	-
	Wood and Bark Chip	3,130	-	626	-	5,634	5,634	-
	Chemical Stabilization							
	1. Stabilized Agent	1,467	-	294	-	1,761	1,761	-
	2. Traction Sand		8,213	-	1,643	-	-	9,856
	Reusable Aggregate							
	1. Aggregate	2,000	-	400	-	3,000	3,000	-
	2. Geotextile	-	10,560	-	2,112	12,672	-	12,672
2	Crushed Aggregate	2,555	-	512	-	3,834	4,092	-
	Marginal Aggregate	2,555	-	512	-	3,834	4,092	-
	Wood and Bark Chip	4,062	-	812	-	7,311	7,640	-
	Chemical Stabilization							
	1. Stabilized Agent	1,667	-	334	-	2,001	2,112	-
	2. Traction Sand		9,333	-	1,867	-	-	11,200
	Reusable Aggregate							
	1. Aggregate	2,555	-	512	-	3,833	1,733[d]	-
	2. Geotextile	-	12,000		2,400	-	-	14,400
3	Crushed Aggregate	1,934	-	386	-	2,900	2,900	-
	Marginal Aggregate	1,934	-	386	-	2,900	2,900	-
	Wood and Bark Chip	3,055	-	610	-	5,498	5,498	-
	Chemical Stabilization							
	1. Stabilized Agent	1,111	-	222	-	1,333	1,333[d]	-
	2. Traction Sand	-	6,222	-	1,244	-	-	7,466
	Reuseable Aggregate	1,934	-	386	-	2,900	217	-

L = Length of the Road (ft)
W = Average Width of Road (ft)
D = Surface Thickness (in.)
N = Number of Turnouts
a = Area or volume of materials for curve widening and turnouts which is assumed to be equal to 20 percent of the entire roadway area.
b = Loose Factor for Aggregate = 1.25 compacted volume; Wood Chip = 1.5 compacted volume.
c = Seventy percent (70%) of the previous project is recovered for future projects.
d = (Volume of materials needed for project) - (Volume of recovered materials from previous project)

Table 5.17. Cost of Materials for Example No. 2.

1 Project No.	2 Name of Materials	3 or Volume of Soil to be Treated	4 Area of Roadway to be Treated	5 Total Weight of Stabilized Agent*	6 Sand Requirement**	7 Seal Requirement***	8 Quant.	Unit	Materials ($)	($)
		cy	sy	ton	ton	ton				
1	Crushed Aggregate	3,000					3,000	cy	5	15,000
	Marginal Aggregate	3,000					3,000	cy	5	15,000
	Wood and Bark Chip	5,634					5,634	cy	0^{α}	0
	Chemical Stabilization									
	1. Stabilized Agent	1,746	-	131			131	ton	80	10,480
	2. Traction Sand		9,856		148		148	ton	10	1,480
	Reusable Aggregate								Total	11,960
	1. Aggregate	3,000	-				3,000	cy	5	15,000
	2. Geotextile	-	12,672				12,672	sy	1	12,672
									Total	27,672
2	Crushed Aggregate	3,834					3,834	cy	5	19,170
	Marginal Aggregate	3,834					3,834	cy	5	19,170
	Wood and Bark Chip	7,311					7,311	cy	0^{α}	0
	Chemical Stabilization									
	1. Stabilized Agent	2,001	-	148			148	ton	80	11,840
	2. Traction Sand	-	11,200	-	168		168	ton	10	1,680
	Reusable Aggregate								Total	13,520
	1. Aggregate[b]	1,733[c]					1,733	cy	5	8,665
	2. Geotextile	-	14,400				14,400	sy	1	14,400
									Total	23,065
3	Crushed Aggregate	2,900	-				2,900	sy	5	14,500
	Marginal Aggregate	2,900					2,900	cy	5	14,500
	Wood and Bark Chip	5,498					5,498	cy	0^{α}	0
	Chemical Stabilization									
	1. Stabilized Agent	1,333	-	99			99	ton	80	7,920
	2. Traction Sand		7,466		112		112	ton	10	1,120
	Reusable Aggregate								Total	9,040
	1. Aggregate	217[d]					217	cy	5	1,085
	2. Geotextile									

where γ = Compacted unit weight of soil (110 pcf)
App. rate = Application Rate of Sand (30 lbs/yd^2)
c.y. = Cubic Yard (yd^3) sy = square yard (yd^2)
a = Assume materials for chipping available free of charge. Chipping cost which is part of the material cost is included in construction cost.
b = Seventy percent (70%) of the recovered previous project is expected to be recovered for this project.
c = Materials needed for project 2 - Volume of recovered materials from project 1)
c = (4092 - 0.7[3135]) = 1897 cy
d = (Volume of Material needed for project 3 - volume of recovered materials from project 2)

$$* \frac{(PCF)(\%\ of\ Stabl\ Agent)\left(\frac{27\ ft^3}{cy}\right)(Col.\ 3)}{(2000\ lbs/ton)}$$

$$** \frac{(App.\ rate\ lbs/yd^2)(Col.\ 4)}{(2000\ lbs/ton)}$$

$$*** \frac{(App.\ Rate\ gal/yd^2)(Col.4)}{(240\ gal/ton)}$$

Table 5.18. Haul Cost of the Alternative Surfacings for Various Projects for Example No. 2.

1	2	3	4	5	6	7	8	9
Project No.	Potential Surfacing Types	Volume of Material	Volume of Recovered Material (0.7) (volume of previous project)	Additional Volume Needed from pit (3)-(4)	Distance From pit (mile)	Distance From One Project to Alternate Project	Haul Cost $/cy-mile or $/ton-mile	Total Haul Cost ($)
1	Crushed Aggregate	3,000 cy	-	-	30	-	0.3	27,000
	Marginal Aggregate	3,000 cy	-	-	10	-	0.3	9,000
	Wood and Bark Chips	5,634 cy	-	-	10	-	0.15	8,451
	Chemical Stabilization							
	1. Stabilized Agent	131/ton[a]	-	-	-	-	-	0
	2. Traction Sand	148/ton	-	-	30		0.15	666
	Reusable Aggregate	3,000 cy	-	-	30	-	0.30	27,000
2	Crushed Aggregate	3,834 cy	-	-	35	-	0.30	40,257
	Marginal Aggregate	3,834 cy	-	-	15	-	0.30	17,253
	Wood and Bark Chips	7,311 cy	-	-	15	-	0.15	16,450
	Chemical Stabilization							
	1. Stabilized Agent	-	-	-	-	-	-	0
	2. Traction Sand	168/ton	-	-	35	-	0.15	882
	Reuseable Aggregate							
	1. Aggregate	3,834 cy	2,100 cy	1,734 cy	35	5	0.30 from pit	18,207
	2. Geotextile						0.35 from project to alternate project	3,675 21,882 Total
3	Crushed Aggregate	2,900 cy	-	-	40	-	0.3	34,800
	Marginal Aggregate	2,900 cy	-	-	20	-	0.3	17,400
	Wood and Bark Chips	5,498 cy	-	-	20	-	0.15	16,494
	Chemical Stabilization							
	1. Stabilized Agent[a]	-	-	-	-	-	-	0
	2. Traction Sand	112/ton	-	-	40	-	0.15	672
	Reusable Aggregate							
	1. Aggregate	2,900 cy	2,684 cy	216 cy	40	5	0.30 from pit	2,592
	2. Geotextile[b]						0.35 from project to alternate project	4,697 7,289 Total

[a] Haul cost included in the material costs.
[b] Geotextile was not used for this project.

Table 5.19. Equipment and Labor for Construction and Maintenance Recovery Activities for Example No. 2 (Project No. 1).

(1) Potential Surfacing Types	(2) Construction or Maintenance or Recovery	(3) Activity Description	(4) Equipment[a] Cost ($/hr)	(5) Operator[a] Cost ($/hr)	(6) Total Laborer's $/hr (Quant) (Unit Rate)	(7) Total Cost $/hr (4)+(5)+(6)	(8) Quantities of the Materials	(9) Number of[c] Hours Required Production[b] Rate	(10) Total for each Activity (8) ÷ (9)	(11) Cost of Activity ($)	(12) Present[d] Worth Value of Maintenance $P = F x \frac{1}{(1+i)^n}$ ($)
Crushed Aggregate and Marginal Aggregate	Construction	Spreading	74.19	28.13	(1)(23.06)	125.38	3,000 cy	100 cy/hr	30 say 32	4,012	
		Compaction	26.15	26.99	(1)(23.06)	76.20	3,000 cy	1 mile/day	8	610	
								Total	4,622		
	Maintenance	Grading (on third month)	49.39	28.38	-	77.78		1 mile/day	8	622	$P = 622 \times \frac{1}{(1+0.04)^{0.25}} = 615$
Wood and Bark Chip	Construction	Chipping	120.00	30.00	-	150.00	5,634 cy	100 cy/hr	56.34 say 60	9,000	
		Spreading	72.03	28.13	(1)(23.03)	123.22	5,634 cy	100 cy/hr	60	7,393	
		Compaction	26.15	28.13	(1)(23.06)	76.20		.5 mile/day	16	1,219	
								Total	17,612		
	Maintenance	Grading (on third month)	49.39	28.38	-	77.78	-	1 mile/day	8	622	$P = 622 \times \frac{1}{(1+0.04)^{0.25}} = 615$
Chemical Stabilization	Construction	Soil Pulverization	49.39	28.38	(1)(23.06)	100.83		0.33 mile/day	24	2,420	
		Spreading Stabilizing Agent	41.95	26.23	(1)(23.06)	91.24		0.33 mile/day	24	2,190	
		Mixing	49.39	28.38	(1)(23.06)	100.83	131 (ton)	6 ton/hr	21.83 say 24	2,420	
		Watering	39.00	26.16	(1)(23.06)	88.22		.33 mile/day	24	2,117	
		Compaction	26.15	26.99	(1)(23.06)	76.21		.33 mile/day	24	1,826	
		Spreading Sand	44.41	26.23	(1)(23.06)	93.70		2-mile lane/day	4	325	
								Total	11,298		
	Maintenance	Since the life of the project is only six months, maintenance is not expected.									
Reusable Aggregate With Cheap Geotextile as a Separation Layer	Construction	Geotextile Placement and Spreading Aggregate	74.19	28.13	(3)(23.06)	171.50	3,000 cy	80 cy/hr	37.50 say 40	6,860	
		Compaction	26.15	26.99	(1)(23.06)	76.20	-	1 mile/day	8	610	
								Total	7,470		
	Maintenance	Since the life of the project is only six months, maintenance is not expected.									
	Recovery	Scrapping Aggregate	39.05	28.13	(1)(23.06)	90.24	2,100 cy	60 cy/hr	35 say 36	3,249	
		Loading Aggregate	54.85	28.13	-	92.98	2,100 cy	60 cy/hr	36	2,987	
								Total	6,236		

[a]Equipment and labor costs are based on cost estimating guide for road construction, Zone V, Suislaw National Forest and also rental rate blue book for constructiion equipment, Dataquest, Incorporated, 1984. Equipment costs are based on monthly equipment rental, except chipper based on hourly, and asphalt distributor based on weekly equipment rental rate

[b]Production rates are based on the judgment, experience gained from demonstration project, literature review, and also the specific type and size of equipment. These equipments rates have been listed in Appendix A.

[c] Since the operator and equipment are at least tied-up for half a day, the number of hours required for each activity should be corrected to full or half days.

[d]P = present worth or present value of total life cycle cost
F = Future worth or future value of cost.
n = Number of years from present to the maintenance activity
i = Interest rate (4% suggested for use in this guide)

Table 5.20. Equipment and Labor for Construction, Maintenance, and Recovery Activities for Example No. 2 (Project No. 2).

(1) Potential Surfacing Types	(2) Construction or Maintenance or Recovery	(3) Activity Description	(4) Equipment[a] Cost ($/hr)	(5) Operator[a] Cost ($/hr)	(6) Total Laborer's $/hr (Quant) (Unit Rate)	(7) Total Cost $/hr (4)+(5)+(6)	(8) Quantities of the Materials	(9) Production[b] Rate	(10) Number of[c] Hours Required for each Activity (8) ÷ (9)	(11) Total Cost of Activity ($)	(12) Present[d] Worth Value of Maintenance $P = F \times \frac{1}{(1+i)^n}$
Crushed Aggregate and Marginal Aggregate	Construction	Spreading	74.19	28.13	(1)(23.06)	125.38	3834 cy	100 cy/hr	38.34 say 40	5,015	
		Compaction	26.15	26.99	(1)(23.06)	76.20	-	1 mile/day*	9.09 say 12	914	
									Total	5,929	
	Maintenance	Grading (on third month)	49.39	28.38	-	77.78	-	1 mile/day	9.09 say 12	933	$P = 933 \times \frac{1}{(1+0.04)^{0.25}} = 924$
Wood and Bark Chip	Construction	Chipping	120.00	30.00	-	150.00	7311 cy	100 cy/hr	73.11 say 76	11,400	
		Spreading	72.03	28.13	(2)(23.03)	123.22	7311 cy	100 cy/hr	76	9,365	
		Compaction	26.15	28.13	(1)(23.06)	76.20		0.5 mile/day	18.18 say 20	1,524	
									Total	22,289	
	Maintenance	Grading (on third month)	49.39	28.38	-	77.78		1 mile/day	9.09 say 12	933	$P = 933 \times \frac{1}{(1+.04)^{0.24}} = 924$
Chemical Stabilization	Construction	Soil Pulverization	49.39	28.38	(1)(23.06)	100.83	-	0.33 mile/day	27.54 say 28	2,823	
		Spreading Stabilizing Agent	41.95	26.23	(1)(23.06)	91.24	-	0.33 mile/day	28	2,554	
		Mixing	49.39	28.38	(1)(23.06)	100.83	148 ton	6 ton/hr	24.66 say 28	2,823	
		Watering	39.00	26.16	(1)(23.06)	88.22	-	.33 mile/day	28	2,470	
		Compaction	26.15	26.99	(1)(23.06)	76.21	-	.33 mile/day	28	2,133	
		Spreading Sand	44.41	26.23	(1)(23.06)	93.70	-	2-mile lane/day	4.55 say 8	750	
									Total	13,553	
	Maintenance	Since the life of the project is only six months, maintenance is not expected.									
Reusable Aggregate with Cheap Geotextile as a Separation Layer	Construction	Geotextile Placement and Spreading Aggregate	74.19	28.13	(3)(23.06)	171.50	3834	80 cy/hr	47.92 say 48	8,232	
		Compaction	26.15	26.99	(1)(23.06)	76.20	-	1 mile/day	9.09 say 12	914	
									Total	9,146	
	Maintenance	Since the life of the project is only six months, maintenance is not expected.									
	Recovery	Scrapping Aggregate	39.05	28.13	(1)(23.06)	90.24	2689 cy[c]	60 cy/hr	44.73 say 48	4,331	
		Loading	54.85	28.13	-	82.98	2689 cy	60 cy/hr	44.73 say 48	3,967	
									Total	8,297	

[a] Equipment and labor costs are based on cost estimating guide for road construction Zone V, Suislaw National Forest and also rental rate blue book for construction equipment, Dataquest, Incorporated, 1984. Equiment costs are based on monthly equipment rental, except chipper based on hourly, and asphalt distributor based on weekly equipment rental rate.

[b] Production rates are based on the judgment, experience gained from demonstration project, literature review and also the specific type and size of equipment. This equipment has been listed in Appendix A.

[c] Since the operator and equipment are at least tied-up for half a day, the numberof hours required for each activity should be corrected to full or half days.

[d] P = Present worth or present value of total life cycle cost
F = Future worth or future value of cost
n = Number of years from present to the maintenance activity
i - Interest rate (4% suggested for use in this guide)

Table 5.21. Equipment and Labor for Construction, Maintenance, and Recovery Activities for Example No. 2 (Project No. 3).

(1) Potential Surfacing Types	(2) Construction or Maintenance or Recovery	(3) Activity Description	(4) Equipment[a] Cost $/hr	(5) Operator[a] Cost $/hr	(6) Total Laborer's $/hr (Quant) (Unit Rate)	(7) Total Cost $/hr (4)+(5)+(6)	(8) Quantities of the Materials	(9) Production[b] Rate	(10) Number of[c] Hours Required for each activity (8) ÷ (9)	(11) Total Cost of Activity ($)	(12) Present[d] Worth Value of Maintenance $P = F \times \frac{1}{(1+i)^n}$ ($)
Crushed Aggregate and Marginal Aggregate	Construction	Spreading	74.18	28.13	(1)(23.06)	125.38	2,900 cy	100 cy/hr	29 say 32	4,012	
		Compaction	26.15	26.99	(1)(23.06)	76.20	2,900 cy	1 mile/day[c]	6.06 say 8	609	
									Total	4,621	
	Maintenance	Grading (on third month)	49.39	28.38	-	77.78		1 mile/day	6.06 say 8	622	$P = 622 \times \frac{1}{(1+0.04)^{.25}} = 616$
Wood and Bark Chip	Construction	Chipping	120.00	30.00	-	150.00	5,498 cy	100 cy/hr	54.98 say 56	8,400	
		Spreading	72.03	28.13	(1)(23.03)	123.22	5,498 cy	100 cy/hr	56	6,900	
		Compaction	26.15	28.13	(1)(23.06)	76.20		0.5 mile/day[c]	12	914	
									Total	16,214	
	Maintenance	Grading (on third month)	49.39	28.38	-	77.78		1 mile/day	6 say 8	622	$P = 622 \times \frac{1}{(1+0.04)^{.25}} = 616$
Chemical Stabilization	Construction	Soil Pulverization	49.39	28.38	(1)(23.06)	100.83	-	0.33 mile/day	18.36 say 20	2,016	
		Spreading Stabilizing Agent	41.95	26.23	(1)(23.06)	91.24		0.33 mile/day	20	1,824	
		Mixing	49.39	28.38	(1)(23.06)	100.83	99 ton	6 ton/hr	16.5 say 20	2,016	
		Watering	39.00	26.16	(1)(23.06)	88.22		.33 mile/day	20	1,764	
		Compaction	26.15	26.99	(1)(23.06)	76.21		.33 mile/day[c]	20	1,524	
		Spreading Sand	44.41	26.23	(1)(23.06)	93.70		2-mile lane/day	3.03 say 4	325	
									Total	9,469	
	Maintenance	Since the life of the project is only six months, maintenance is not expected.									
Reuseable[e] Aggregate with Cheap Geotextile as a Separation Layer	Construction	Spreading Aggregate	74.19	28.13	(1)(23.06)	125.38	2,900 cy	100 cy/hr	29 say 32	4,012	
		Compaction	26.15	26.99	(1)(23.06)	76.20	2,499 cy	1 mile/day	6.06 say 8	609	
									Total	4,621	
	Maintenance	Since the life of the project is only six months, maintenance is not expected.									
	Recovery	End of projects, the material is not going to be recovered.									

[a] Equipment and labor costs are based on cost estimating guide for road construction Zone V, Suislaw National Forest and also rental rate blue book for construction equipment, Datasquest, Incorporated, 1984. Equipment costs are based on monthly equipment rental, except chipper based on hourly, and asphalt distributor based on weekly equipment rental rate.

[b] Production rates are based on the judgment, experience gained from demonstration project, literature review and also the specific type and size of equipment. This equipment has been listed in Appendix A.

[c] Since the operator and equipment are at least tied-up for half a day, the number of hours required for each activity should be corrected to full or half day.

[d] P = Present worth or present value of total life cycle cost
F = Future worth or future value of cost
n = Number of years from present to the maintenance activity
i = Interest rate (4%) suggested for use in this guide.

[e] Since this is the last project to be constructed, therefore, the aggregate of this project is not going to be recovered and the use of geotextile as a separation layer is not necessary.

Table 5.22. Life Cycle Cost of Alternative Surfacings for Example No. 2. ($)

Project 1	Costs	Crushed Aggregate	Marginal Aggregate	Wood and Bark Chip	Chemical Stabilization	Reusable Aggregate
1	Material Costs	15,000	15,000	0[a]	11,960	27,672
	Haul Cost	27,000	9,000	8,451	666	27,000
	Equipment & Labor Cost for Construction	4,622	4,622	17,612	11,298	7,470
	Equipment & Labor Cost for Maintenance	615	615	615	-	-
	Total Life Cycle Cost	47,237	29,237	26,678	23,924	62,142
2	Material Costs	19,170	19,170	0[a]	13,520	23,065
	Haul Cost	40,257	17,253	16,450	882	21,882
	Equiment & Labor Cost for Construction	5,929	5,929	22,289	13,553	9,146
	Equipment & Labor Cost for Recovery of Project 1, for use of Materials by Project 2	-	-	-	-	6,236
	Total Life Cycle Cost	65,356	42,352	38,739	27,955	60,329
3	Material Costs	14,500	14,500	0[a]	9,040	1,085
	Haul Cost	34,800	17,400	16,494	672	7,289
	Equipment & Labor Cost for Construction	4,621	4,621	16,214	9,469	4,612
	Equipment & Labor Cost for Maintenance	616	616	616	-	-
	Equipment & Labor Cost for Recovery of Project 2 for use of Material by Project 3	-	-	-	-	8,297
	Total Life Cycle Cost	54,537	37,137	33,324	19,181	21,292

[a] Chipping cost, which is part of the material cost, is included in the construction cost.

Table 5.23. Calculation of Present Worth Value of the Entire Projects ($).

Potential Surfacing Types	Project 1 $P = F \times \frac{1}{(1+i)^n}$ i = 4% N = 1 ($)	Project 2 $P = F \times \frac{1}{(1+i)^n}$ i = 4% N = 2 ($)	Project 3 $P = F \times \frac{1}{(1+i)^n}$ i = 4% N = 4 ($)	Project 1 + 2 + 3 Total Present Worth Value of the Entire Projects ($)
Crushed Aggregate	$P = (47237 \times \frac{1}{(1+.04)^1}$ P = 45,420	$P = (65356) \times \frac{1}{(1+.04)^2}$ P = 60,425	$P = 54537 \times \frac{1}{(1+.04)^4}$ P = 46,618	152,463
Marginal Aggregate	$P = (29237) \times \frac{1}{(1+.04)^1}$ P = 28,112	$P = 42352 \times \frac{1}{(1+.04)^2}$ P = 39,157	$P = 37137 \times \frac{1}{(1+.04)^4}$ P = 31,745	99,014
Wood and Bark Chip	$P = (26678) \times \frac{1}{(1+.04)^1}$ P = 25,652	$P = 38739 \times \frac{1}{(1+.04)^2}$ P = 35,816	$P = 33324 \times \frac{1}{(1+.04)^4}$ P = 28,485	89,953
Chemical Stabilization	$P = 23924 \times \frac{1}{(1+.04)^1}$ P = 23,004	$P = 27955 \times \frac{1}{(1+.04)^2}$ P = 25,846	$P = 19181 \times \frac{1}{(1+.04)^4}$ P = 16,396	65,246 (Best Alternative)
Reusable Aggregate With Geotextile Separation	$P = 62142 \times \frac{1}{(1+.04)^1}$ P = 59,752	$P = 60329 \times \frac{1}{(1+.04)^2}$ P = 55,778	$P = 21292 \times \frac{1}{(1+.04)^4}$ P = 18,200	133,730

P = Present Worth of the Cost
F = Future Worth of the Cost
i = Interest Rate (%)
n = Analysis Period (Years)

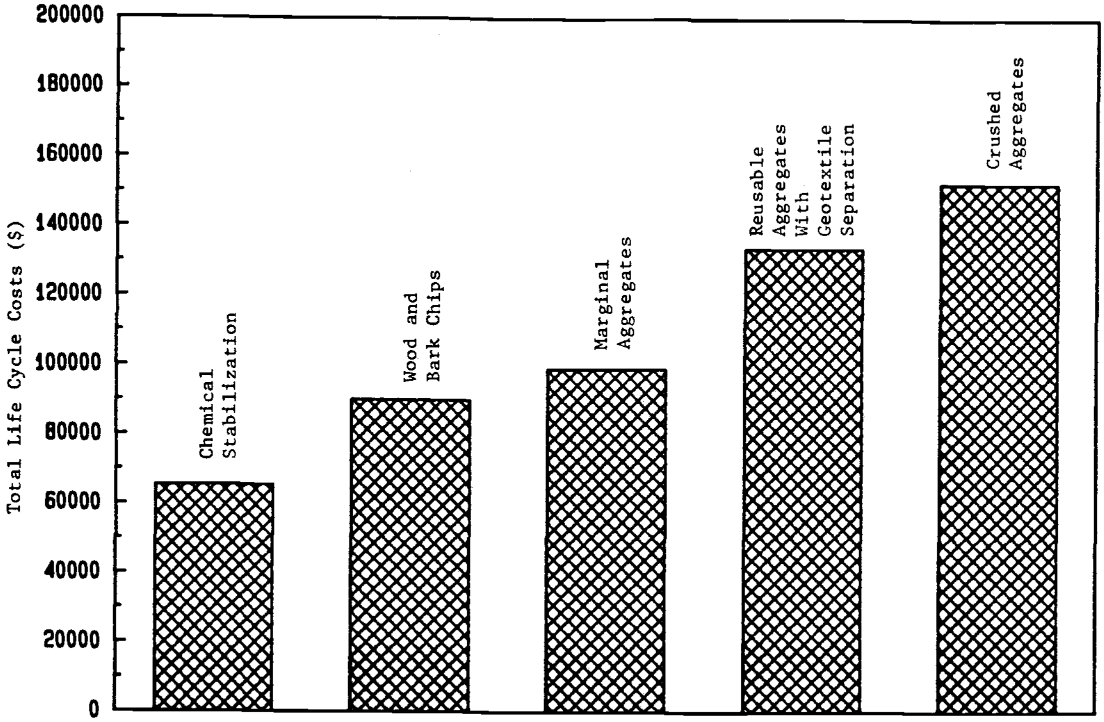


Figure 5.6. Life Cycle Costs of Alternative Surfacings (Example No. 2)

Table 5.18 gives the haul cost of the alternative surfacings for various projects. As shown in this table, the volume of recovered aggregates, which is 70 percent of the volume of the recovered project, is calculated. The recovered volume is then subtracted from the actual volume needed for the construction of the next project. Finally, the recovered volume is multiplied by the haul distance from the recovered project to the next project.

Tables 5.19, 5.20, and 5.21 give a summary of equipment and labor costs for construction, maintenance, and recovery activities for a crushed aggregate surface and the four potential alternate surfaces. As shown in these tables, the maintenance costs are converted to the beginning of the construction period by multiplying by a present worth factor, $\frac{1}{(1+i)^n}$.

Table 5.22 gives the total life cycle costs for all surfacings. Since the projects are going to be constructed at various dates in the future, the total life cycle cost must be converted to their present worth. Table 5.23 shows the total life cycle costs, which are future costs because the projects are going to be constructed in the future, converted to their present worth by multiplying future costs by a present worth factor, $\frac{1}{(1+i)^n}$.

In Tables 5.22 and 5.23, the total present worth of life cycle costs for all surfacings are calculated. The first material is a conventional crushed aggregate surface, which gives a normal construction practices base for comparison. As seen from these results, all alternate surfaces would result in lower total life cycle costs than a crushed aggregate surface for these example projects. The most economical alternative is a chemically stabilized surface (cement), at a present worth of $65,246 for the entire project.

5.5 Summary

This chapter presented the results of comparative deterministic evaluation of two examples which are analyzed in detail to present the evaluation procedure developed in Chapter 4. All of the estimates used for this evaluation are based on one value representing an average value. The result of the comparative evaluation for these examples indicated the alternate surfacings can be economical in most of the situations analyzed.

The most promising surfaces based on these examples, in the order of increasing costs, are:

1) Chemical stabilization,
2) Wood and bark chips,
3) Marginal aggregates,
4) Reusable aggregate with or without geotextile, and
5) Crushed aggregates.

6.0 PROBABILISTIC APPROACH AND SENSITIVITY ANALYSIS

The economic evaluation of alternate surfacing types is a study of present costs and of the forecasts of costs into the future to the end of the time period chosen for analysis. Variables, such as material costs, haul costs, production rates, discount rate, analysis period, road construction costs, road maintenance costs, removal costs, expected life of materials, salvage values, and construction production rates which have been discussed in Chapters 4 and 5 of this report, are based on judgments and experience from the construction of a few demonstration projects and a review of the literature. Thus, the analysis results are based on a limited data base. They are good representations of the relative economy to be expected from each alternate surfacing type under specific conditions when compared to crushed aggregate.

All of the economic evaluations in Chapter 5 of this report are for conditions of "certainty," because all elements of the costs used for examples in that chapter were estimated, or specified, by a single value. Generally, such factors as haul costs, material costs, production rates, expected life of materials, and so forth, are random variables rather than known deterministic values, which were used in those examples. These factors can vary substantially from one project to another, from one district to another, and from one part of the country to another. Therefore, it is desirable to consider the risk and uncertainty involved with these factors of the project.

This chapter describes the causes of risk and uncertainty for alternate surfacing materials, and presents several methods for estimating the effect of the uncertainty of the construction costs of the alternate surfacing types on the selection of alternate surfacings. The methods presented herein are a probabilistic approach based on the PERT approach of three time estimates, using a Beta II distribution (52). A sensitivity analysis is also performed to demonstrate the variation in evaluation results with changes in the various factors of the alternate surfacings.

6.1 Probabilistic Approach

This section describes the probabilistic approach for analyzing and evaluating the uncertainty associated with various cost elements of the alternate surfacing.

6.1.1 Definition of the Probability

Probability has been defined as a way of measuring uncertainty (52). In order to express the probability, it is convenient to express probabilities on a scale from 0 to 1. On this scale, zero represents impossibility and one represents certainty; the numbers in between represent varying degrees of likelihood (52).

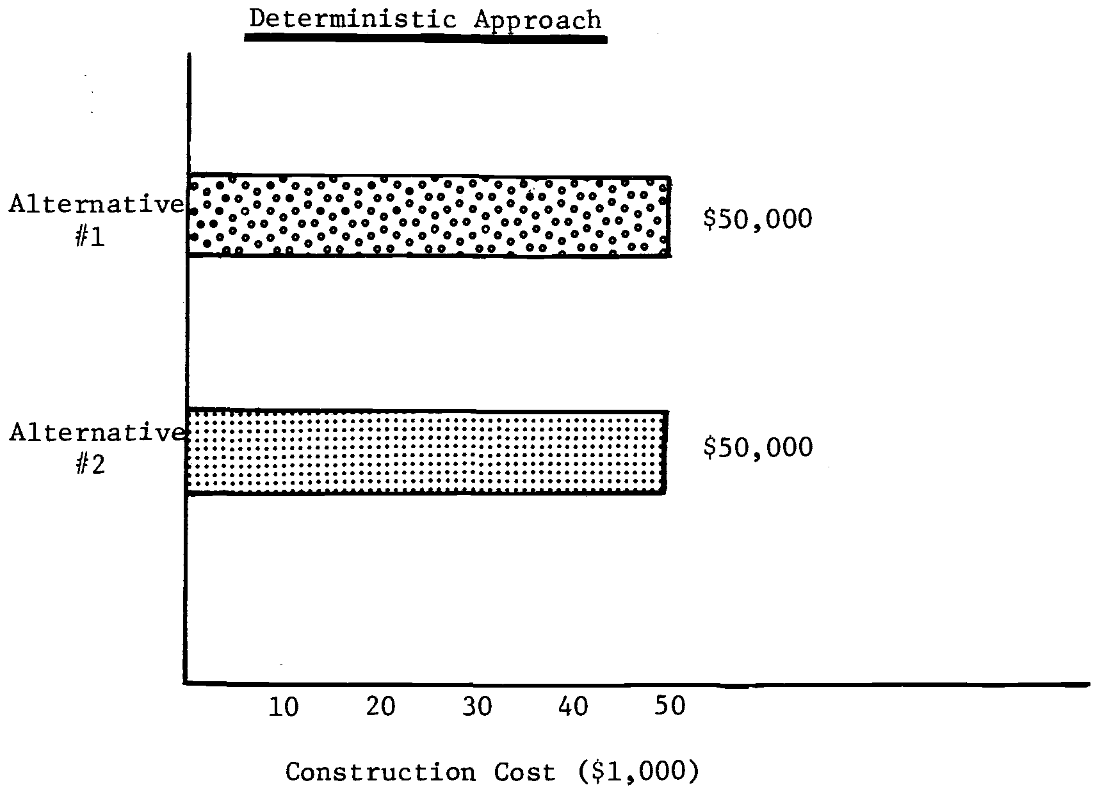
6.1.2 Difference Between Probabilistic and Deterministic Approaches

The major difference between probabilistic and deterministic approaches is that the deterministic approach assumes "certainty," involves a single estimate, and does not consider the spread or dispersion in the distribution of possible values. The deterministic estimate is essentially the average value, i.e., approximately the 50 percentile value, which means the outcome can exceed the estimated value every other time.

The probabilistic approach measures the "uncertainty," and employs three estimates take the uncertainty into account. Estimates include an "optimistic estimate," a "pessimistic estimate," and a "most likely estimate." To describe and measure the variation, or dispersion, in the distribution, two measures are frequently employed for the probabilistic approach. The first measure locates the point about which the distribution is centered, a measure of its central tendency which is called "mean" (μ). The second measure, which indicates the spread or dispersion in the distribution, a measure of its variability, is called the standard deviation (S) (52). Once the mean and standard deviation of the distribution have been calculated, assuming the distribution of the estimates is approximately a normal distribution, or bell-shaped curve. The 95th percentile values of the distribution may be calculated based on the standardized normal distribution. For a standardized normal distribution, 95% of the area under the curve is included between ±2 standard deviations from the mean.

To understand the difference between the deterministic and probabilistic approaches, two example situations are described below.

Figure 6.1 illustrates the difference between deterministic approach vs. probabilistic approach for Example 1. Figure 6.1a shows the deterministic approach where the total construction costs of the two alternatives are $50,000 each. These deterministic estimates



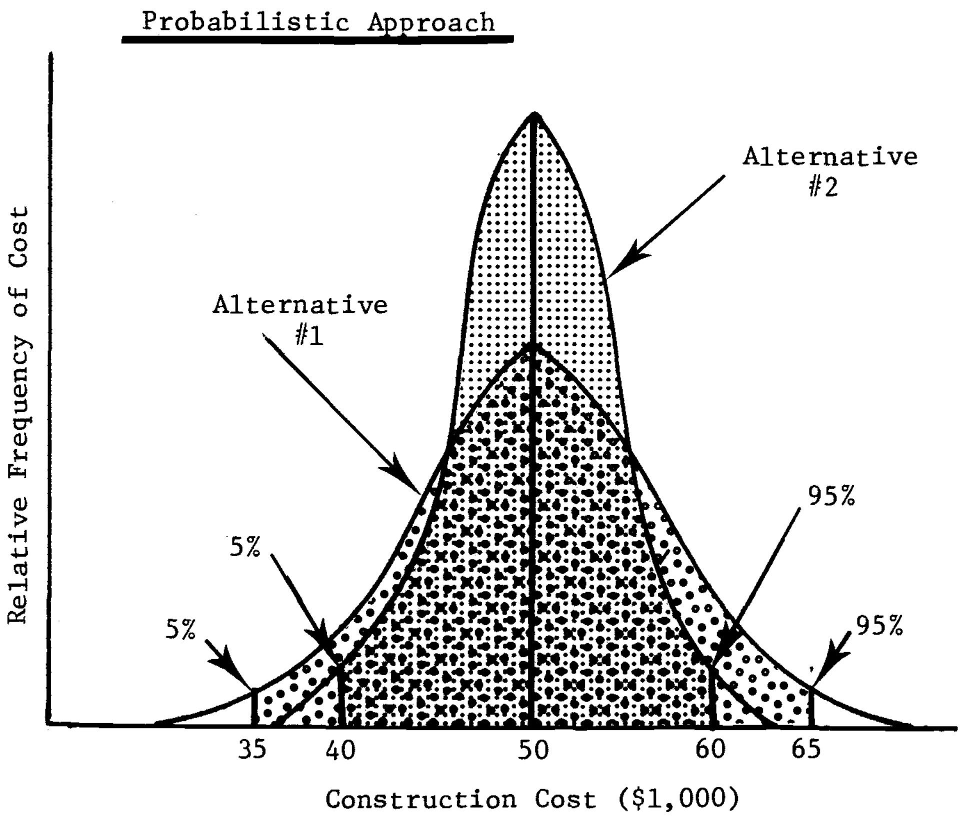
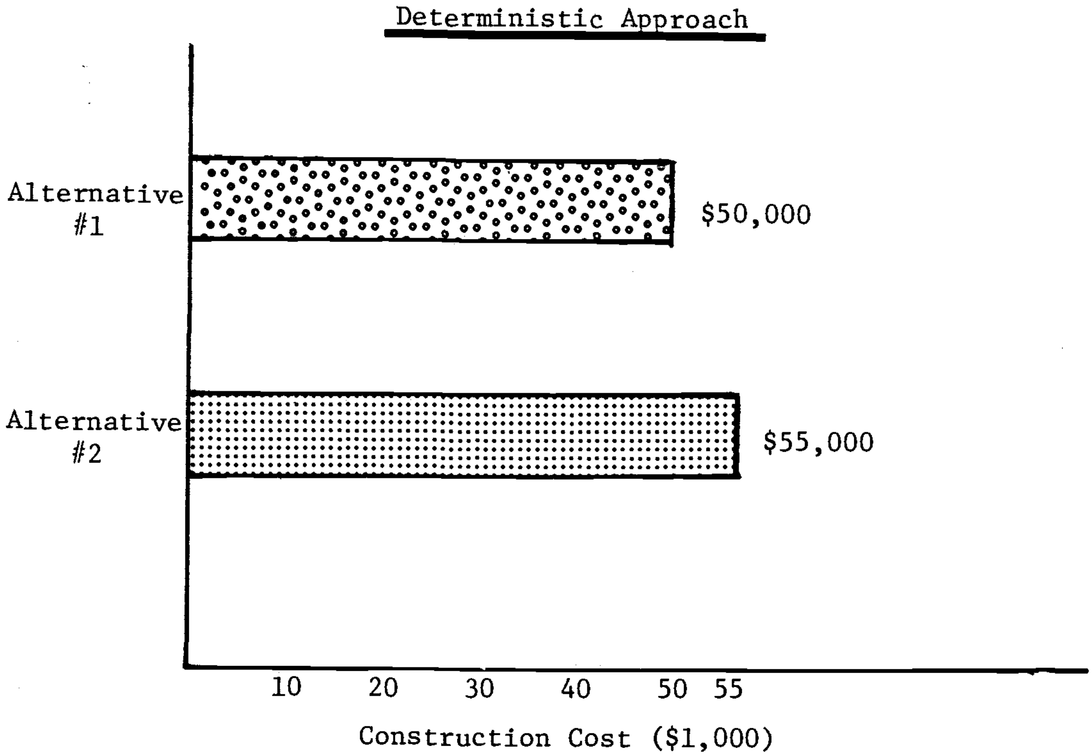


Figure 6.1. Comparison of Deterministic vs. Probabilistic Approach (Example 1)

reflect average, or 50th percentile, values. Based on this approach, either of the alternatives can be selected because the total construction costs are identical for both alternatives. But, typically engineering decisions are based on the 95th percentile values rather than the 50th percentile, where probabilistic variation is known to exist. The 95th percentile value means the estimated value would be expected to be exceeded only one time in twenty. By using the probabilistic approach, and calculating mean and variance (which is the standard deviation squared) and the 95th percentile value of each alternative, alternative two involves less dispersion and results in a lower 95th percentile value ($60,000) than alternative one ($65,000). Therefore, based on the 95th percentile values, alternative two is preferred over alternative one because its construction cost would be at or below $60,000 nineteen out of twenty times. The result of this comparison is shown graphically in Figure 6.1.

Now consider two alternatives which are shown in Figure 6.2 for Example 2. Based on the deterministic approach (50th percentile values), alternative one is preferred over alternative two because it has the lower construction cost ($50,000) compared to alternative two ($55,000). But, based on the probabilistic approach if it is desired to be 95% confident (95th percentile value) that the least construction cost alternative has been selected, alternative two is preferred. It has less spread or dispersion in the distribution, which results in the lower 95th percentile construction cost ($58,000) compared to alternative one ($68,000). The results of this comparison is shown graphically in Figure 6.2. Therefore, there is 95%



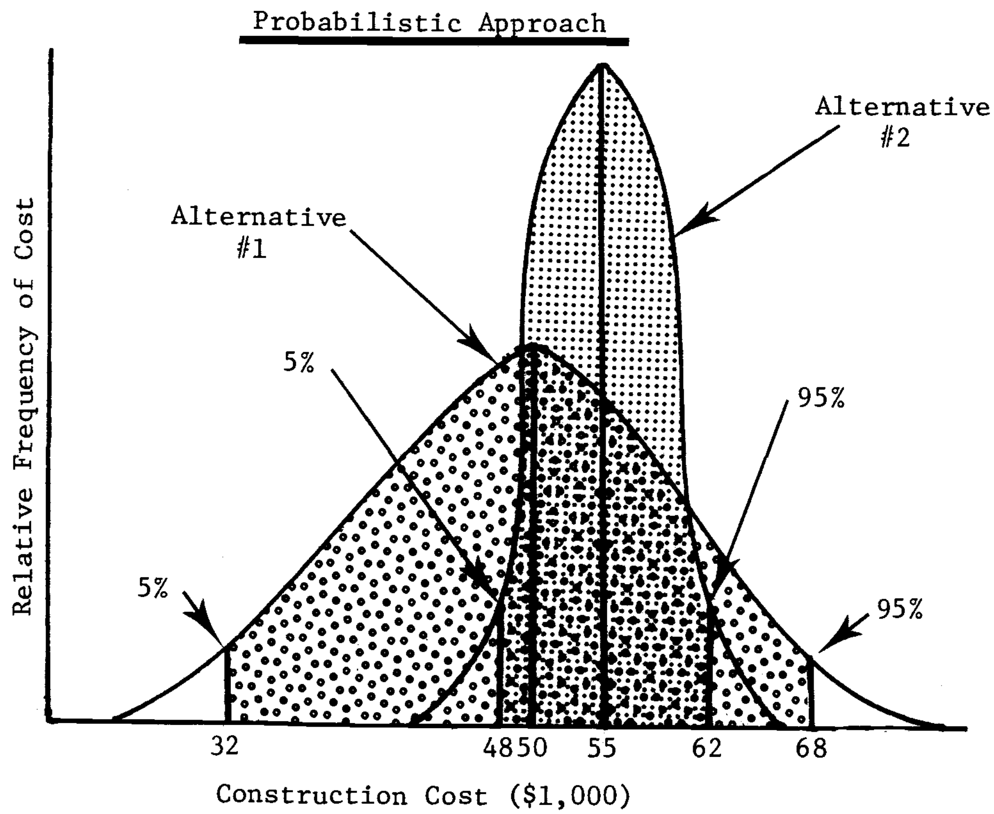


Figure 6.2. Comparison of Deterministic vs. Probabilistic Approach (Example Two)

confidence that the construction cost for alternative one would not exceed $58,000, while alternative two could have a construction cost that exceeds $68,000 one in twenty times.

6.1.3 Difference Between Risk and Uncertainty

It is important to define risk and uncertainty before describing the probabilistic approach. Risk and uncertainty are defined as follows:

1. An element or analysis involves risk if the probabilities and the frequency distribution of the probabilities of the possible outcomes for the alternative are known (39).
2. An element or analysis involves uncertainty if the frequency distribution of the probabilities of the possible outcomes is not known (39).

For example, risk and uncertainty for an expected life of an alternate surfacing are shown in Figure 6.3. In this example, certainty assumes a single value of life; that is, life is deterministic. Risk has a known mean value of failure and is normally distributed. When the distribution of outcomes, or failures, is not known, uncertainty exists.

6.1.4 Causes of Risk and Uncertainty for Alternate Surfacing Materials and Ways to Change the Degree of Uncertainty

There are many factors that involve risk and uncertainty with alternate surfacing materials. Below is a brief description of some of these factors:

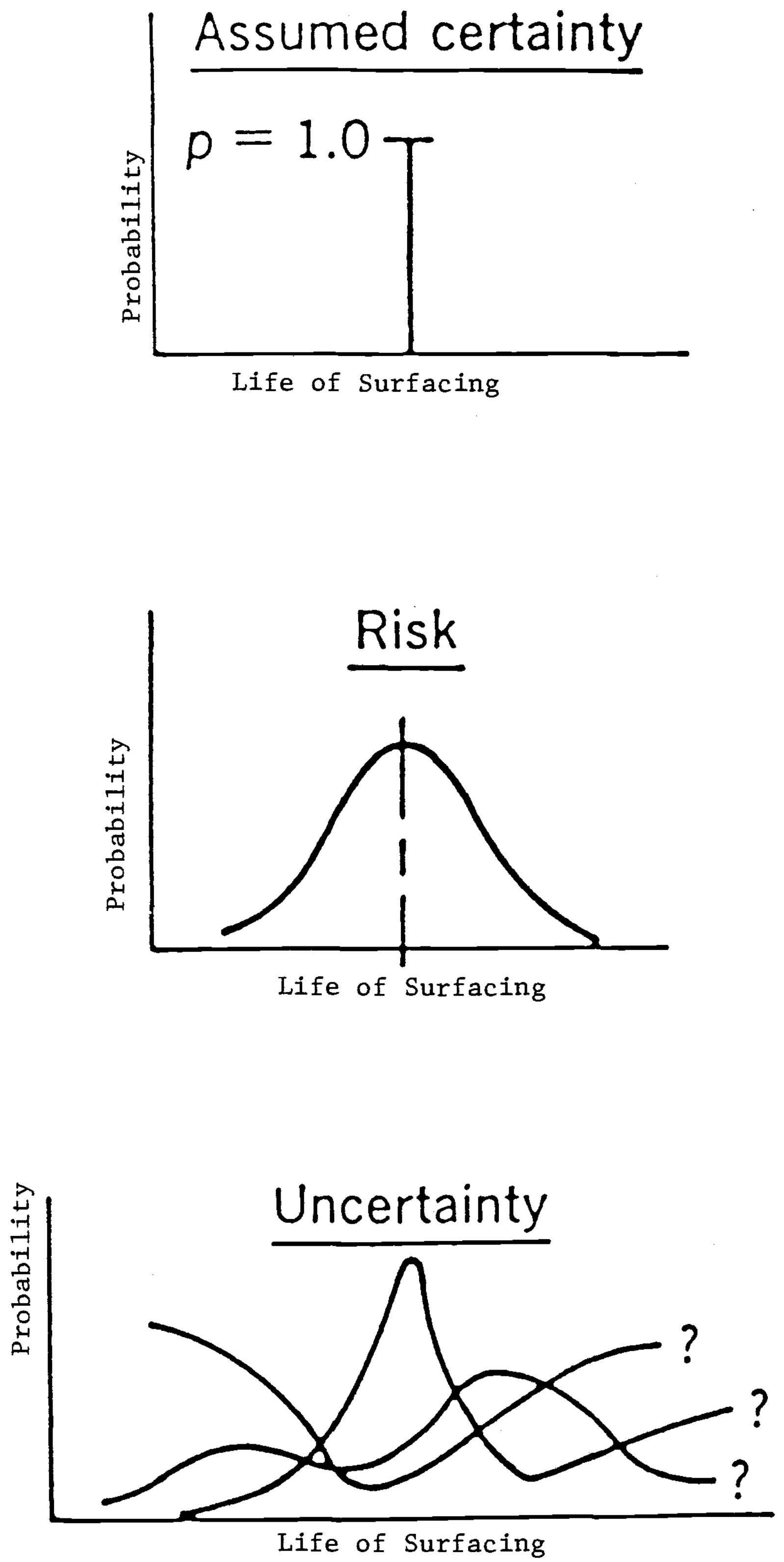


Figure 6.3. Illustrations of Assumed Certainty, Risk, and Uncertainty as Applied to Life of an Alternate Surfacing (39)

1. <u>Insufficient Numbers of Demonstration Projects or Experience</u>: Alternate surfacing methods are unique in terms of characteristics of the materials, expected life, availability of the materials in the construction area, haul costs, and so forth. These properties are not constant and could change from one project to another project. Therefore, judging from the outcome of one or two demonstration projects which have been evaluated for this study leads to a high degree of uncertainty in the characteristics of the materials as well as in the estimation of the construction costs. Additional demonstration projects must be evaluated around the country in order to minimize the degree of uncertainty.
2. <u>Random Variation in Project Elements</u>: It is likely that even with projects where the materials characteristics and performance are well-defined, a random variation of performance or costs can result in quite different project results.
3. <u>Changing External Economic Environment, Invalidating Past Experience</u>: Whenever cost estimates are made of future conditions, the usual bases are past results for similar situations whenever possible (39). For alternate surfacing materials the past information is very valuable, but there is risk in using it directly without adjustments for expected future conditions.

For example, when an estimate is made to build a road in a certain area, the availability and cost of the materials in the desired area could vary over a wide range of values, increasing the cost of the materials and having a major impact on the total construction cost.

4) Errors of Evaluation: Since alternate surfacing materials are so new and have not been evaluated by many individuals, errors can occur in the evaluation of the alternate surfacing system. The best alternative to achieve the goal, which is to provide a surfacing for the duration of the activities at minimal cost, may be deleted from consideration due to an individual's lack of experience.

5) Recovery of the Reusable Materials and Salvage Values: The amount of the materials recovered for reuse on an alternative project may vary substantially due to the excessive amount of rutting, geometrics of the road, environmental conditions, equipment used, and so forth. Furthermore, the salvage value of the reusable materials, such as metal mats, can change substantially over time or from one part of the country to another due to the demand for that material. Therefore, there is a considerable amount of risk and uncertainty involved in the amount of

materials that are recoverable and their salvage value.

The following sections describe the methods for analyzing and estimating the construction costs of alternate surfacings which involve a high degree of uncertainty or risk.

6.1.5 Probabilistic Estimates of Production and Costs

There are several ways to estimate and take account of uncertainty of elements of alternate surfacings. Two methods that are appropriate for alternate surfacings are the cumulative probability distribution and Beta distribution. These methods are discussed below.

6.1.5.1 Cumulative Probability Distribution. One way to estimate the uncertainty of an element of the alternate surfacing, such as material costs, expected life, and salvage value, is based on a cumulative probability distribution. For example, suppose it is desired to estimate the expected life of metal mats for a certain condition. The expected life estimates for metal mats were developed based on the recorded experiences for similar projects by other agencies, reviewing the manufacturers' catalogs, observing the results of a demonstration project that was constructed for this study, and making the necessary adjustment for the subgrade materials factors, such as soil strength, CBR, and environmental factors, rainfall, duration of freeze and thaw. It is concluded that there is practically zero probability that the actual life of metal mats for soils with CBR $>$ 5, will be equal to or less than 1000 passes; 20%

probability that the actual life will be equal to or less than 1500 passes; 40% that the actual life will be equal to or less than 2000 passes. By making similar estimates until the maximum expected life is reached, i.e. when there is 100% chance that the expected life will not be exceeded, a complete set of estimates can be derived. The results for this example are given in Table 6.1, and then are graphed as a continuous distribution in Figure 6.4.

This graph can be very valuable for making an estimate of the salvage value of a certain material at a given time.

6.1.6 Beta II Distribution for Analyzing the Problem of Uncertainty

Another method for taking into account the uncertainty of the various elements of the alternate surfacing sytems is the use of Beta estimation procedure. The Beta distribution is a left-skew or right-skew distribution and has been employed for the PERT network planning and scheduling technique (39).

With alternate surfacings, there is little knowledge or past data available about the actual construction cost, expected production rate, haul costs, salvage value, recovery costs, and so forth, and most of the estimates are based on the outcome of one or two demonstration projects. Therefore, there is a high degree of uncertainty involved in the estimation of the construction costs. For example, there is uncertainty involved in the amount of time and labor required for the construction, as well as in material and haul costs.

Table 6.1. Estimated Life of Metal Mats Expressed in Cumulative Form.

Expected Life (Passes)	Probability that Actual Life of Metal Mat Will be Equal to or Less than the Expected Life
1,000	0.00
1,500	0.20
2,000	0.30
2,500	0.40
3,000	0.50
5,000	0.75
7,000	0.90
10,000 or more	1.00

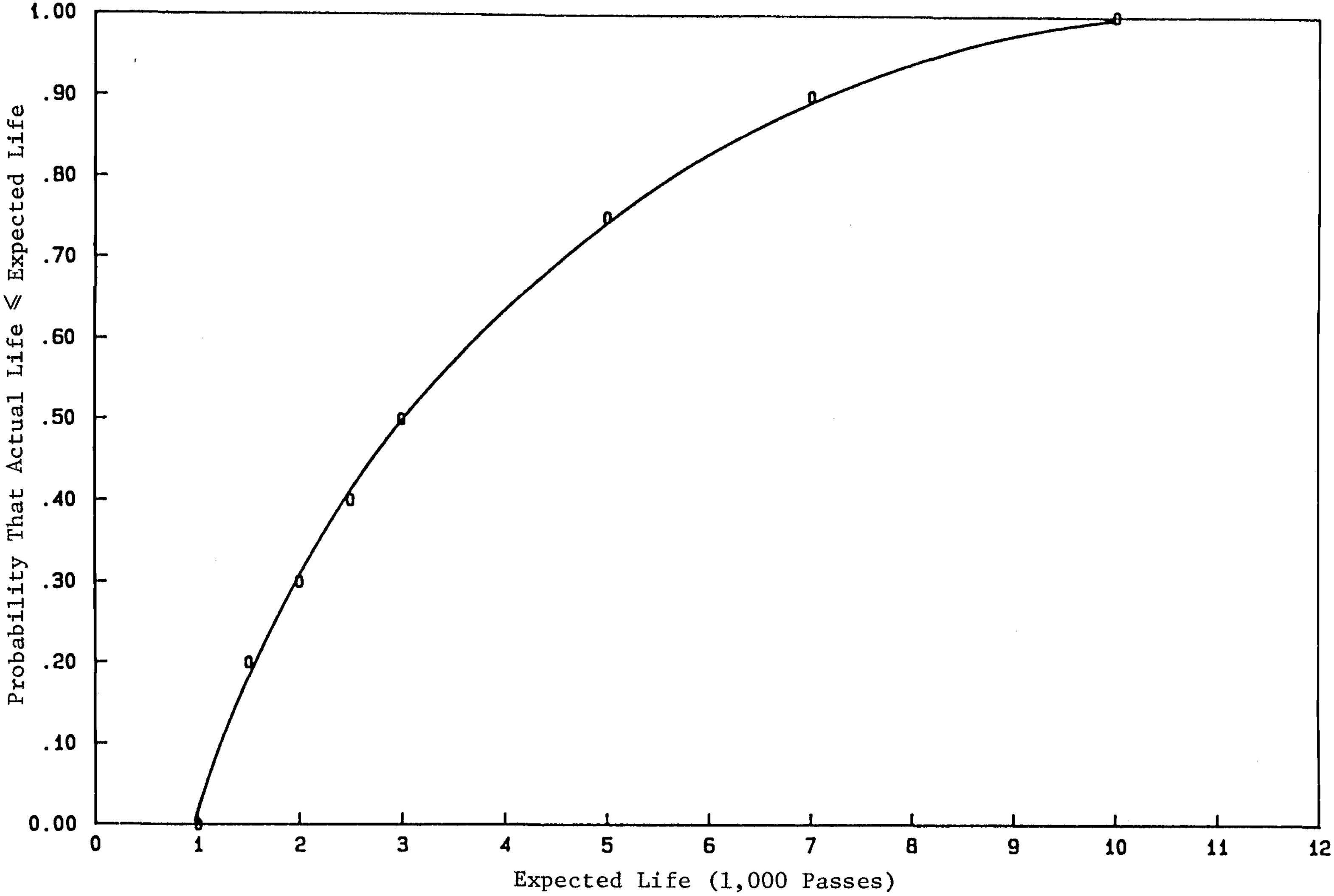


Figure 6.4. Cumulative Probability Graph for Metal Mats

The Beta distribution as used in PERT employs three estimates to take these uncertainties into account. These include an "optimistic estimate," a "pessimistic estimate," and a "most likely estimate" (39). It is assumed that these three estimates yield the upper limit, the lower limit, and the mode for some performance or cost variable. These estimates are based on the judgment of the person in charge of the project as well as past experience of similar projects.

The Beta distribution is a very good method for estimating the uncertainty of these elements because it involves three estimates rather than a single estimate. Figure 6.5 shows an assumed Beta distribution for a typical element. In this case the distribution happens to be left-skewed (39). Once the three estimates of element outcome have been made, the approximate mean and variance of the Beta distribution for the element may be calculated (39,52). Equation (6.2) is based on 5th and 95th percentile values of the distribution as the lower and upper limits. About 90% of the area under probability distribution is included between +1.6 standard deviation from the mean and -1.6 standard deviations from the mean. Equation (6.3) uses the optimistic and pessimistic estimates as the upper and lower limits with about 100% of the area under the curve being included between ±3 standard deviations. Z and A are estimates of the upper and lower limits of outcomes, respectively. They are based on demonstration projects as well as past experience. It is unlikely that the absolute minimum and maximum values would have been observed, thus the 0th and 100th percentile values of the distribution would be very difficult to estimate for various elements of alternate

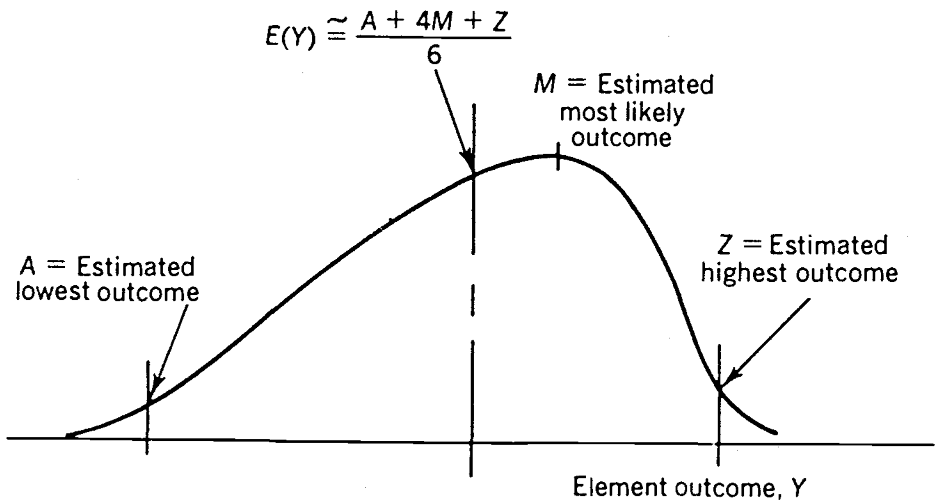


Figure 6.5. Demonstration of Estimates with Beta Distribution (39).

$$E(Y) \approx \frac{A + 4M + Z}{6} \tag{6.1}$$

$$V[Y] \approx \left(\frac{Z - A}{3.2}\right)^2 \quad \text{For 5 and 95 percentile limits of the distribution} \tag{6.2}$$

$$V[Y] \approx \left(\frac{Z - A}{6}\right)^2 \quad \text{For 0 and 100 percentile limits of the distribution} \tag{6.3}$$

where E[Y] = Estimated expected outcome (Mean)

V[Y] = Estimated variance of outcome

A = Estimated lowest outcome

M = Estimated most likely outcome

Z = Estimated highest outcome

surfacings. Therefore, it is more realistic to use Eq. (6.2), that is, the 5th and 95th percentile values.

In further explanation of the use of Eq. (6.2), A, M, and Z are defined as follows (52):

A = optimistic performance outcome, the outcome which would be bettered only one time in twenty if the activity could be performed repeatedly under essentially the same conditions.

M = most likely outcome, the outcome which is likely to occur more than any other value.

Z = pessimistic performance outcome, the outcome which would be exceeded only one time in twenty if the activity could be repeated under essentially the same conditions.

The outcomes could include materials costs, labor costs, equipment costs, construction production rate, haul distance, haul costs, and so forth.

6.1.6.1 Important Factors to be Considered. The following points are helpful in obtaining reliable values for these estimates.

1) All of the variables and activities are assumed to be independent of each other. Therefore, the estimates of A, M, and Z should be obtained so the assumption of independence is satisfied (52).

   Independence means that what may occur in any activity or element of the project doesn't have any effect on the other activities or elements of the project.

2) The estimates of A, M, and Z should not be influenced by the time or budget available to complete the project. The engineers should use their best judgment to estimate these values. Time and cost estimates should be revised only when the scope of the activity is changed, or when the material cost, manpower, and facilities assigned to a particular project are changed (52).

3) The engineers or estimators should be clear that A, M, and Z are only estimates and not budget and schedule commitments (52).

4) The estimates of A, M, and Z should include allowances for the location of the project, material availability, environmental factors, production rates, and so forth. The engineers or estimators should not rely completely on the various cost estimates guides because each project is unique.

6.1.6.2 Estimation of the Mean and Variance for Total Project. If several elements or activities of a project are assumed to be independent, random variables and are added together, the distribution of the total outcome is, according to the central limit theorem, approximately normal (39). The mean of this total outcome distribution can be calculated by adding the means of the individual elements. Further, the variance of this total outcome distribution can be calculated by adding the variances of the distribution of the individual elements (52).

$$E\ [Y] = E\ [Y_1] + E\ [Y_2] + E\ [Y_3] + \ldots \tag{6.4}$$

$$V\ [Y] = V\ [Y_1] + V\ [Y_2] + V\ [Y_3] + \ldots \tag{6.5}$$

Since the estimate of mean and variance have been determined for the 5 and 95 percentile of the distribution, the area under the curve is 95-5 = 90% or 45% on each side of mean, assuming the total outcome distribution of the project is approximately normal. Then, by using the normal distribution tables in Appendix E, when the probability is 90%, the measurement lies within ±1.645 standard deviation of its expected or mean value. For alternate surfacings, the upper limit value is important for decision making. Therefore, for evaluation it is recommended to use the upper tail test value, the 95th percentile value, $X_{95\%}$.

$$X_{95\%} = E\ [Y] + 1.645\ [V_Y]^{1/2} \tag{6.6}$$

NOTE: Standard Deviation (S) = $[V_y)^{1/2}$

Figure 6.6 shows the area under the normal distribution curve for ±1 standard deviation = 68%, ±2 standard deviations = 95%, and ±3 standard deviations = 99.7%.

6.1.6.3 Examples

This section describes the step-by-step solution of an example to demonstrate the probabilistic evaluation approach. The example is

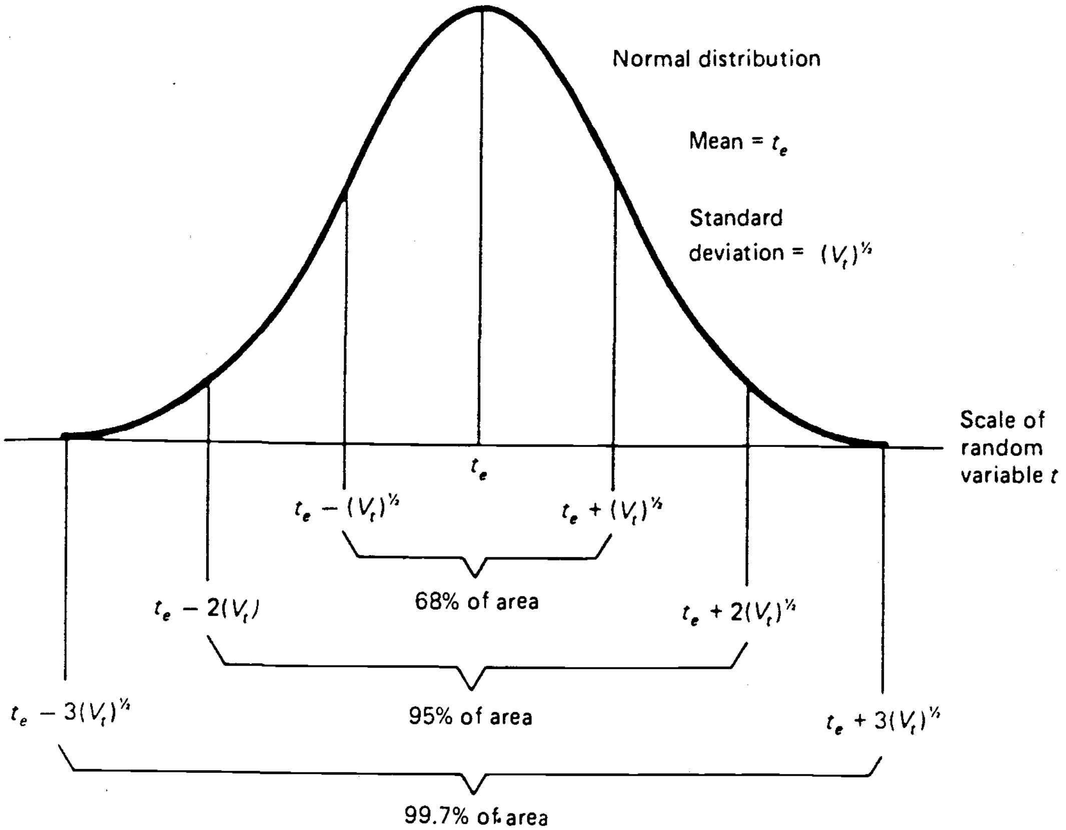


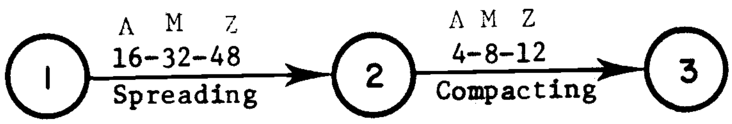
Figure 6.6. Selected Areas Under the Normal Distribution Curve(5)

compared with the total life cycle cost estimates for Example 1 of Chapter 5.

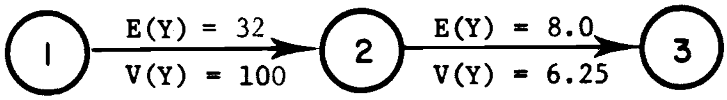
Example 1 - Crushed Aggregate

Use Example 1 of Chapter 5, with the exception that material costs, equipment, labor, and haul costs are treated as distributions of which three estimates are available rather than the single estimate (deterministic value) which is used in Chapter 5.

A. Equipment and Labor Cost



	Spreading	Compaction
Optimistic time (hrs), A	16	4
Most likely time (hrs), M	32	8
Pessimistic time (hrs), Z	48	16
Equipment and labor cost (\$/hr)	125.38	76.20
Expected value E(Y): $\frac{(A + 4M + Z)}{6}$ (hrs)	32	8
Variance: $(\frac{A - Z}{3.2})^2$ (hrs)	100	6.25



Total equipment and labor cost (\$) = (total expected equipment and labor hours)(Equipment and labor cost per hour)

E(Y) = (32 hrs)(125.38 \$/hr) + (8 hrs)(76.20 \$/hr)

E(Y) = \$4622

Standard deviation of equipment and labor cost (\$) =

(equipment and labor cost per hour)(variance of equipment and labor hours)

$S = (125.38)(100)^{1/2} + (76.20)(6.25)^{1/2}$

S = \$1268

Upper tail 95% value = E (Y) + 1.645 S

= 4622 + 1.645 (1268)

= \$6708

B. Material Cost

Length (feet)	5280
Width (feet)	15
Depth (inches)	6
Estimated volume (yd^3)	2997.87
Estimated cost of materials (\$/yd^3):	
Optimistic, A	3
Most likely, M	5
Pessimistic, Z	7

Expected cost of materials $E(Y) = \frac{A + 4M + Z}{6}$

$= \frac{3 + 4(5) + 7}{6}$

$= 5$

Standard deviation (\$/yd^3): $S = V(Y)^{1/2} = \frac{Z - A}{3.2}$

$S = \frac{7 - 3}{3.2} = \frac{4}{3.2} = 1.25$

Expected material cost (\$) = (expected value)(volume of materials)

= (\$5/yd^3)(3000 yd^3)

= \$15000

Increment for variation in material cost (\$)

$$= (\$1.25/yd^3)(3000\ yd^3)$$

$$= \$3750$$

Upper tail 95% value = E (Y) + 1.645 S

$$= 15000 + 1.645\ (3750)$$

$$= \$\underline{21169}$$

C. Haul Cost:

Optimistic (\$/yd^3/mile), A	.25
Most likely (\$/yd^3/mile), M	.30
Pessimistic (\$/yd^3/mile), Z	.35
Haul distance (mile)	30

Expected haul cost rate

$$E(Y)\ (\$/yd^3/mile) = \frac{A + 4M + Z}{6} = \frac{.25 + 4(.30) + .35}{6}$$

$$= .30$$

Expected total haul cost = $(2997.87\ yd^3)(.3\ \$/yd^3/mile)(30\ mile)$

$$= 26980.8$$

Standard deviation of haul cost

$$V\ (Y)^{1/2} = \frac{(Z - A)}{3.2} = \left(\frac{.35 - .25}{3.2}\right)$$

$$S = 0.03125$$

Increment for variation in haul cost

$$= (2997.87\ yd^3)(.03125\ \$/yd^3/mile)(30\ mile)$$

$$= 2810.50$$

Upper tail 95% value = E (Y) + 1.645 $(V_Y)^{1/2}$

$$= 26980.8 + 1.645\ (2810.5)$$

$$= \$\underline{31604}$$

D. Maintenance cost (from Chapter 5) = $615

Table 6.2 summarizes the results of this example in which each element of the project had three estimates.

Tables 6.3 and 6.4 show the computer analysis results and the step-by-step calculation for estimating the upper tail 95 percentile costs of the equipment and labor, material costs, haul costs, maintenance costs, and total life cycle costs of crushed aggregates and soil stabilization. VISICALC was used for these calculations. Furthermore, LOTUS 1,2,3, Symphoney, SUPERCALC, or any other computer software which has a spreadsheet can be used very effectively to make these calculations. These computations were demonstrated by the hand calculations in Example 1 of Section 6.1.6.3.

6.2 Sensitivity Analysis

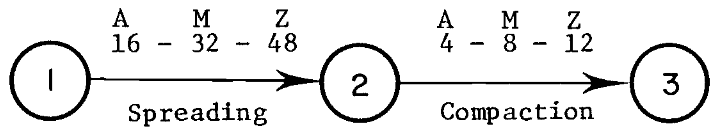
Economics studies for alternate surfacing materials are based on forecasts of the cost of such items as construction, maintenance, recovery, and salvage values. Most of these costs are estimated based on judgment and construction of a few demonstration projects. Therefore, the analysis results presented in Chapter 5 of this report have a high degree of uncertainty for various elements of costs or performance.

Sensitivity analysis determines the impact of changes in input variables and provides the decision maker with information on how the measûres of effectiveness, and consequently, the decision, may vary with these changes. Additional analyses are made using different values of the factors over a range of conditions including the

Table 6.2. Life Cycle Cost of Crushed Aggregate Based on Beta Distribution.

Costs	Upper Tail 95% Estimate (Beta Distribution)
Material Costs	21,169
Haul Costs	31,604
Equipment and Labor Costs	6,708
Maintenance Costs	615
TOTAL 95% Life Cycle Costs ($)	60,096

Table 6.3. Computer Output for Crushed Aggregate.



CRUSHED AGGREGATE

	A	M	Z	
PRODUCTION RATE:	OPTIMISTIC	MOST LIKELY	PESSIMISTIC	EXPECTED VALUE
SREADING-	16	32	48	32
COMPACTION-	4	8	12	8

AVERAGE VALUE:		AVERAGE COST
SPREADING-	32	4012.16
COMPACTION	8	609.6
	TOTAL AVERAGE COST:	4621.76

VARIANCE	COST PER HOUR	EXPECTED VALUE	EXPECTED VARIANCE
100	125.38	4012.16	1572014.4396
6.2499999964	76.2	609.6	36290.249949
	TOTAL----->	4621.76	1608304.6895
		STANDARD DEVIATION>	1268.1895319
		UPPER TAIL VALUE ->	6707.93177997

Table 6.3. Computer Output for Crushed Aggregate (continued).

COST OF MATERIAL:			
LENGTH-	5280	ESTIMATED COST OF MATERIAL:	
WIDTH-	15.33		
THICKNESS-	8	OPTIMISTIC-	3
		MOST LIKELY-	5
COMPACTED VOLUME OF CRUSHED AGGREGATE	1998.57777777	PESSIMISTIC-	7
		EXPECTED COST OF MATERIAL	5
COMPACTED VOLUME OF CRUSHED AGGREGATE FOR CURVE WIDENING AND TURNOUTS ---->	399.71555555	VARIANCE ------->	1.5624999999
		STANDARD DEVIATION:	1.2499999999
LOOSE FACTOR --->	1.25	UPPER TAIL VALUE -->	21153.696665
TOTAL LOOSE VOLUME:	2997.86666665		

HAUL COST:			
OPTIMISTIC	.25	HAUL COST:	26980.799999
MOST LIKELY	.3		
PESSIMISTIC	.35		
HAUL DISTANCE:	30	UPPER TAIL VALUE:	31604.072479
EXPECTED HAUL COST PER MILE:	.3		
VARIANCE OF HAUL COST:	.00097656249167		
STANDARD DEVIATION:	.031249999868		

	UPPER LIMIT
MATERIAL COST:	21153.696665
HAUL COSTS:	31604.072479
EQUIPMENT AND LABOR COST:	6707.93177997
MAINTENANCE COST:	615

TOTAL UPPER TAIL COST FOR CRUSHED AGGREGATE---------> 60080.700923

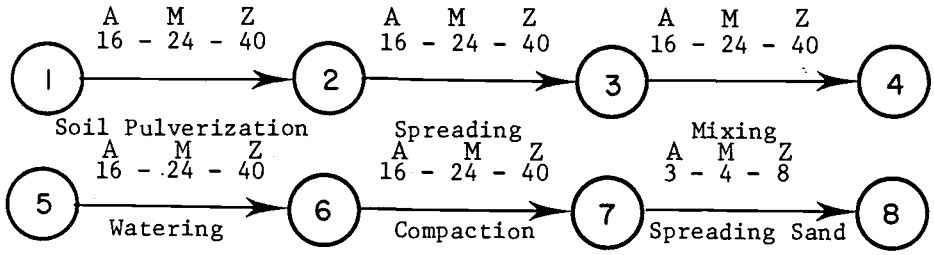
Table 6.4. Computer Output for Soil Stabilization.

```
SOIL STABILIZATION

EQUIPMENT AND LABOR
COST..........

SOIL PULVERIZATION                      EXPECTED VALUE      VARIANCE OF
OPTIMISTIC-          16                  25.3333333333      EXPECTED VALUE
MOST LIKELY-         24                                      56.249999945
PESSIMISTIC-         40
(ABOVE IN HOURS)                                            STANDARD DEVIATION:
                                                             7.49999998
--------------------------------------------------------------------------------

SPREADING                               EXPECTED VALUE      VARIANCE OF
OPTIMISTIC-          16                  25.3333333333      EXPECTED VALUE
MOST LIKELY-         24                                      56.249999945
PESSIMISTIC-         40
(ABOVE IN HOURS)                                            STANDARD DEVIATION:
                                                             7.49999998
--------------------------------------------------------------------------------
MIXING                                  EXPECTED VALUE      VARIANCE OF
OPTIMISTIC-          16                  25.3333333333      EXPECTED VALUE
MOST LIKELY-         24                                      56.249999945
PESSIMISTIC-         40
(ABOVE IN HOURS)                                            STANDARD DEVIATION:
                                                             7.49999998
--------------------------------------------------------------------------------
WATERING                                EXPECTED VALUE      VARIANCE OF
OPTIMISTIC-          16                  25.3333333333      EXPECTED VALUE
MOST LIKELY-         24                                      56.249999945
PESSIMISTIC-         40
(ABOVE IN HOURS)                                            STANDARD DEVIATION:
                                                             7.49999998
--------------------------------------------------------------------------------
COMPACTION                              EXPECTED VALUE      VARIANCE OF
OPTIMISTIC-          16                  25.3333333333      EXPECTED VALUE
MOST LIKELY-         24                                      56.249999945
PESSIMISTIC-         40
(ABOVE IN HOURS)                                            STANDARD DEVIATION:
                                                             7.49999998
--------------------------------------------------------------------------------
SPREADING SAND                          EXPECTED VALUE      VARIANCE OF
OPTIMISTIC-          3                   4.5                EXPECTED VALUE
MOST LIKELY-         4                                       2.4414062509
PESSIMISTIC-         8
(ABOVE IN HOURS)                                            STANDARD DEVIATION:
                                                             1.5625000002
--------------------------------------------------------------------------------
COSTS PER HOUR:                         TOTAL EXPECTED      THE UPPER TAIL VALUE
SOIL PULVERIZATION-  100.83             COST:                17890.490474
SPREADING-           91.24               12007.343333
MIXING-              100.83
WATERING-            88.22              STANDARD DEVIATION:
```

Table 6.4. Computer Output for Soil Stabilization (continued).

COMPACTION-	76.21	3576.38124084
SPREADING SAND-	93.7	
MATERIAL COST:		
LENGTH(FEET)-	5280	
WIDTH(FEET)-	15	
DEPTH(INCHES)-	6	
COMPACTED VOLUME OF SOIL TO BE STABILIZED:-	1466.66666666	TOTAL COMPACTED VOLUME: 1759.99999999
COMPACTED VOLUME OF SOIL TO BE STABILIZED FOR CURVE WIDENING AND TURN-OUT	293.33333333	
STABILIZED AGENT COST		
UNIT WEIGTH OF SOIL:	110	TOTAL COST OF STABILIZED AGENT: 10454.399999
% OF STABILIZED AGENT:	.05	
COST PER TON:	80	
TRACTION SAND COST		TOTAL SURFACE AREA OF ROADWAY: 10560
LENGTH(FEET)-	5280	
WIDTH(FEET)-	15	
APPLICATION RATE LBS/SQ YARD-	30	VOLUME OF SAND: 158.4
COST OF SAND DOLLAR/TON:	10	TOTAL COST OF SAND: 1584
TOTAL COST OF MATERIAL: 12038.399999		
HAUL COST:		
OPTIMISTIC-	.15	TOTAL HAUL COST: 2187.89999983
MOST LIKELY-	.17	
PESSIMISTIC-	.19	
(DOLLAR PER TON)_		
HAUL DIST. STAB. AG.	50	(MILES)
HAUL DIST. SAND	40	
EXPECTED HAUL COST PER TON MILE	.17	
VARIANCE OF HAUL COST:	.00015624999999	UPPER TAIL VALUE: 2187.90025686
STANDARD DEVIATION:	.012499999999	

Table 6.4. Computer Output for Soil Stabilization (continued).



MATERIAL COST:	12038.399999
HAUL COST:	2187.90025686
EQUIPMENT AND LABOR COST:	17890.490474
MAINTEANCE COST:	615
TOTAL:	32731.790729

expected value. This procedure, which defines the relationship between the relative change in forecast of some element of an economy study and the measure of effectiveness of an alternative, is called the analysis of sensitivity (40).

A sensitivity analysis is performed by changing a variable over a range of conditions to determine the value of some measure of effectiveness (38). If one particular factor or element can be varied over a wide range of values without affecting the selection of the recommended alternative, the alternative in question is insensitive to uncertainties about that factor or element. On the other hand, if a small change in the estimate of an element or factor alters the selection of the recommended alternative, the alternative is said to be sensitive to uncertainties about that element or factor (40).

Alternate surfacing types for temporary and intermittent use roads are not expected to be sensitive to either the length of the analysis period or discount rate because the life of the project or analysis period are very short (1-3 years) and the expected maintenance costs which occur in the future are low. Examples 1 and 2 of Chapter 5 demonstrate this lack of importance. On the other hand, material cost, production rates, and haul costs can be very sensitive to uncertainties. These three factors are now tested for sensitivity.

6.2.1 Sensitivity Analysis of Crushed Aggregate Surfacing

Table 6.5, developed using VISICALC computer software, shows the result of the sensitivity analysis of the crushed aggregate with respect to haul distance, material cost, and productivity of the

Table 6.5. Sensitivity of Total Life Cyle Costs for Crushed Aggregates for Various Haul Distances, Material Costs, and Productivity of Equipment and Labor.

	A. Haul Distance (Miles)			B. Material Cost ($/C.Y.)		
	10	30	60	5	10	20
Total Life Cycle Cost ($)	$29,220	$47,207	$74,188	$47,207	$62,196	$92,175

C. Productivity of Equipment and Labor (hrs)

Activity	High Production	Average Production	Low Production
Spreading	16	32	64
Compaction	4	8	16
Total Life Cycle Cost ($)	$44,896	$47,207	$51,829

equipment and labor. Example 1 of Chapter 5 was used for this evaluation. All variables, other than the one being investigated, are held constant.

In Table 6.5, the total life cycle costs for crushed aggregate surfacing under various conditions are calculated. As shown in this table, the total life cycle cost is extremely sensitive to haul distance of the construction materials. By changing the haul distance for aggregate from 10 miles to 60 miles, the total life cycle cost increased from $29,220 to $74,188. This result is shown in Figure 6.7.

The crushed aggregate surfacing was also highly sensitive to material costs in Table 6.5. By changing the material cost from 5 ($/c.y.) to 20 ($/c.y.) the total life cycle cost increased from $47,207 to $92,175. This result is shown in Figure 6.8.

The crushed aggregate surfacing is less sensitive to the production rate of equipment and labor than material cost and haul distance. Table 6.5 and Figure 6.9 summarize and show these results.

As a result of this sensitivity analysis, it can be seen that many other alternate surfacings can be more attractive than crushed aggregate if haul distance or material costs are high. Therefore, where input factors can vary, it is recommended that sensitivity analysis be performed.

6.2.2 Sensitivity Analysis of Soil Stabilization

Table 6.6, developed by using VISICALC computer software, shows the result of sensitivity analysis of the soil stabilized surface with respect to haul distance, material cost, percent of stabilizing

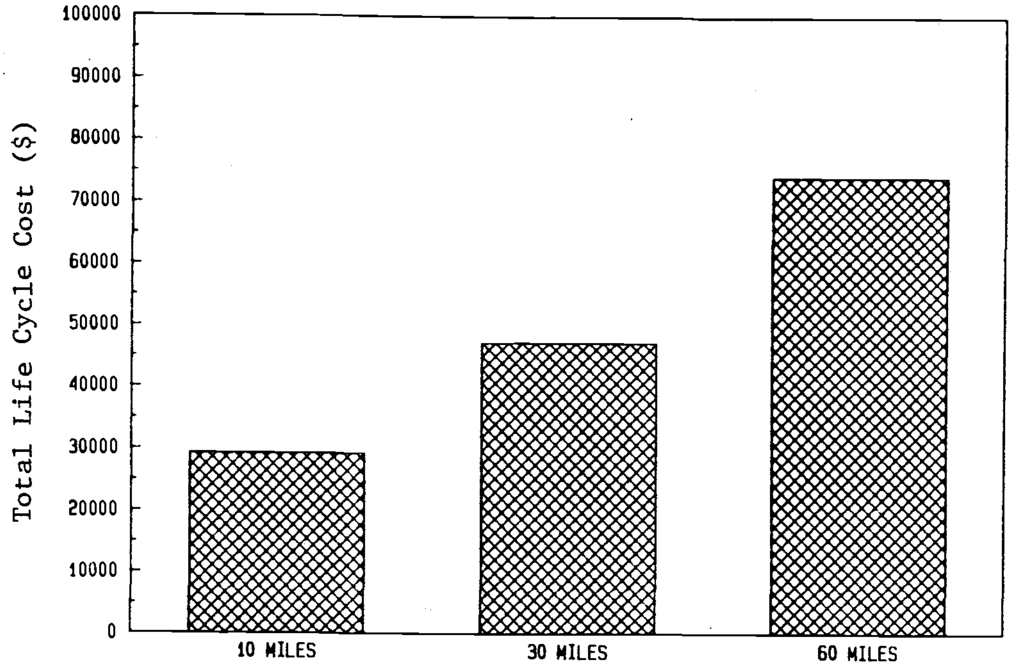


Figure 6.7. Sensitivity of Cost of Crushed Aggregates to Haul Distance

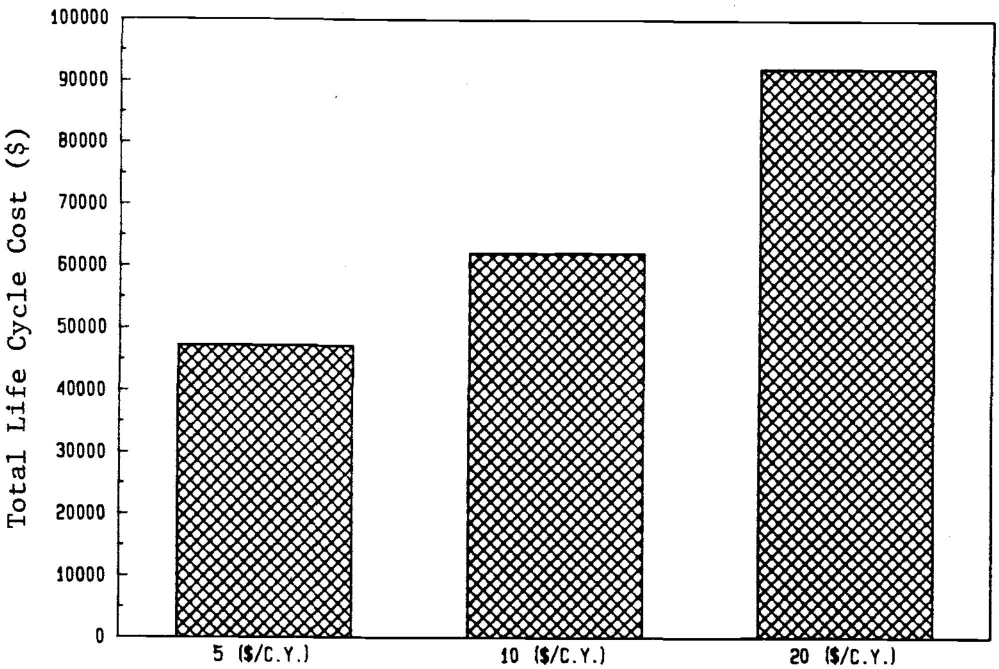


Figure 6.8. Sensitivity of Cost of Crushed Aggregates to Material Cost

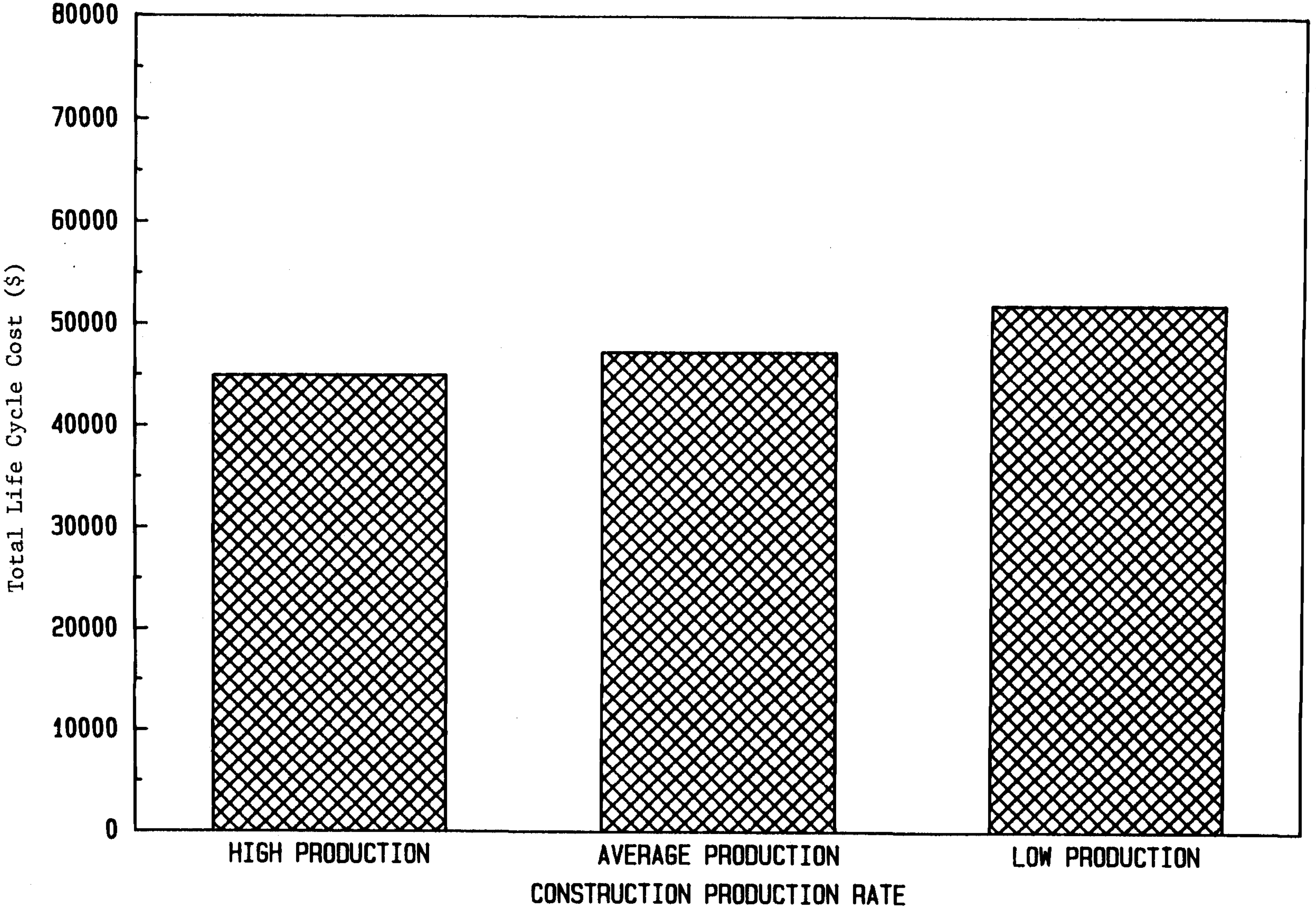


Figure 6.9. Sensitivity of Cost of Crushed Aggregates to Construction Production Rate

Table 6.6. Sensitivity of Total Life Cycle Costs for Chemical Stabilization for Various Hauling Distances, Material Costs, Percent Stabilizing Agent, and Productivity of Equipment and Labor.

	A. Haul Distance (Miles)			B. Material Cost ($/Ton)			C. Percent of Stabilized Agent (%)		
	20	50	200	50	80	160	2	5	10
Total Life Cycle Cost ($)	$25,347	$25,935	$28,875	$22,014	$25,935	$36,389	$19,074	$25,935	$37,369

D. Productivity of Equipment and Labor (hrs)

Activity	High Production	Average Production	Low Production
Soil Pulverization	12	24	48
Spreading	12	24	48
Mixing	12	24	48
Watering	12	24	48
Compaction	12	24	48
Spreading Sand	2	4	8
Total Life Cycle Cost ($)	$20,259	$25,935	$33,655

agent, and productivity of the equipment and labor. Example 1 of Chapter 5 was used for this evaluation. All variables, other than the one being investigated, are held constant.

In Table 6.6, the total life cycle costs for soil stabilized surface under various conditions are calculated. As shown in this table, the total life cycle cost is not sensitive to the haul cost of the stabilizing agent. By changing the haul distance for the stabilizing agent from 20 miles to 200 miles, the total life cycle cost only increased from $25,526 to $28,875. This result is shown in Figure 6.10.

The stabilized surfaces are sensitive to the stabilizing agent cost. As shown in Table 6.6 and Figure 6.11, changing the material cost from $50/ton to $160/ton, the total life cycle cost increased from $22,014 to $36,389.

The stabilized surfaces are quite sensitive to the percentage of stabilizing agent used. As shown in Table 6.6 and Figure 6.12, changing the percentage of stabilizing agent from 2 to 10 percent, the total life cycle cost increased from $19,074 to $37,369.

Stabilized surfaces are sensitive to the productivity of the equipment and labor because the construction of these surfaces requires more equipment and labor than crushed aggregate surfaces. By changing the productivity from high production to low production, the total life cycle cost changed from $20,259 to $33,655. Table 6.6 summarizes and Figure 6.13 shows these results. Furthermore, the computer output for developing these tables is documented in Appendix E.

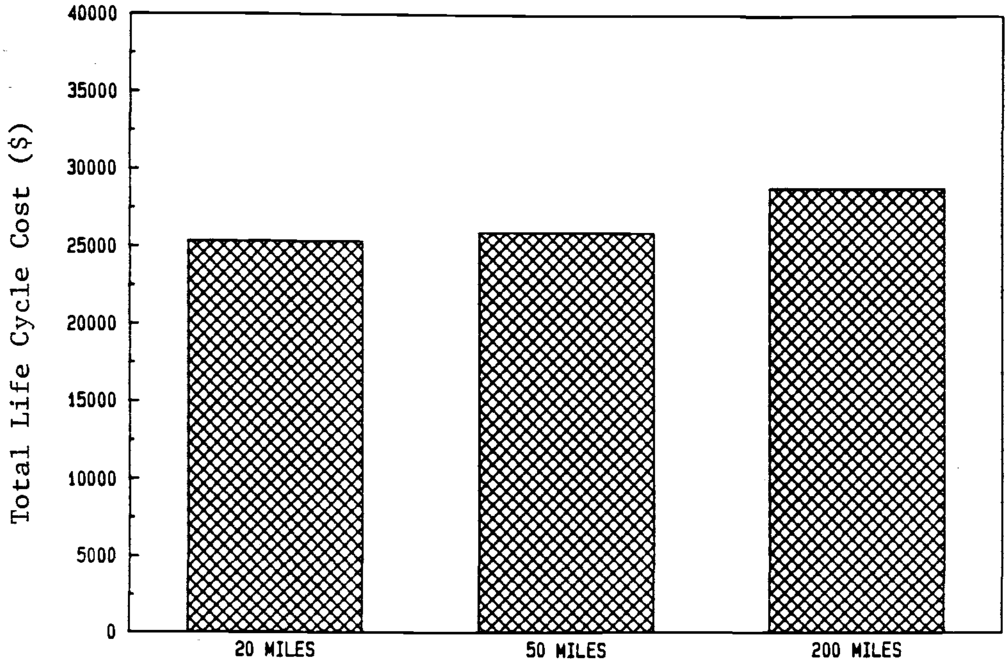


Figure 6.10. Sensitivity of Cost of Chemical Stabilization to Haul Distance of Chemical Agent

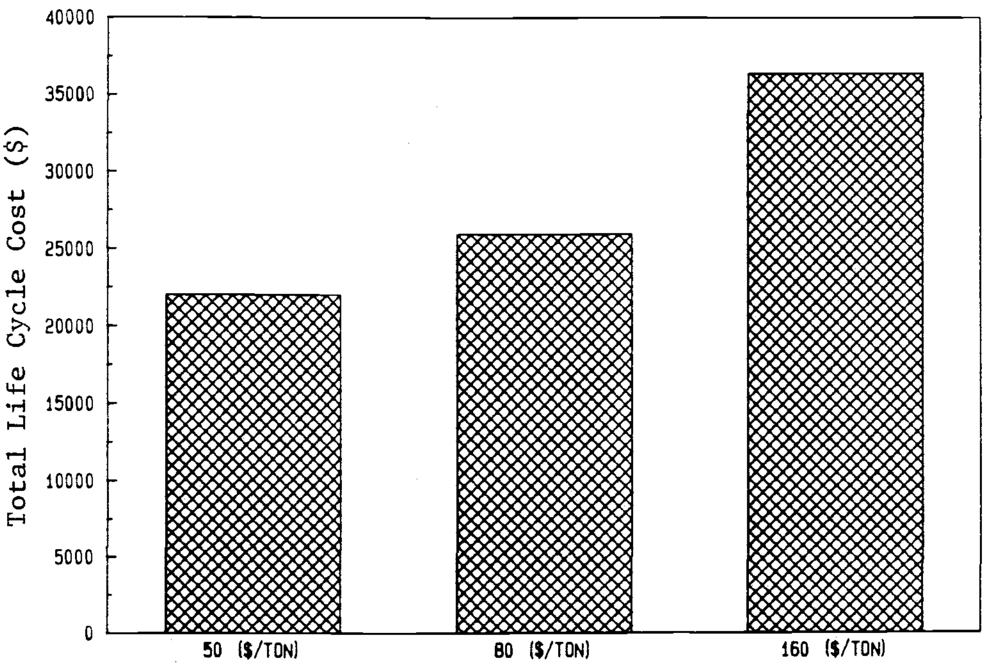


Figure 6.11. Sensitivity of Cost of Chemical Stabilization to Cost of Chemical Agent

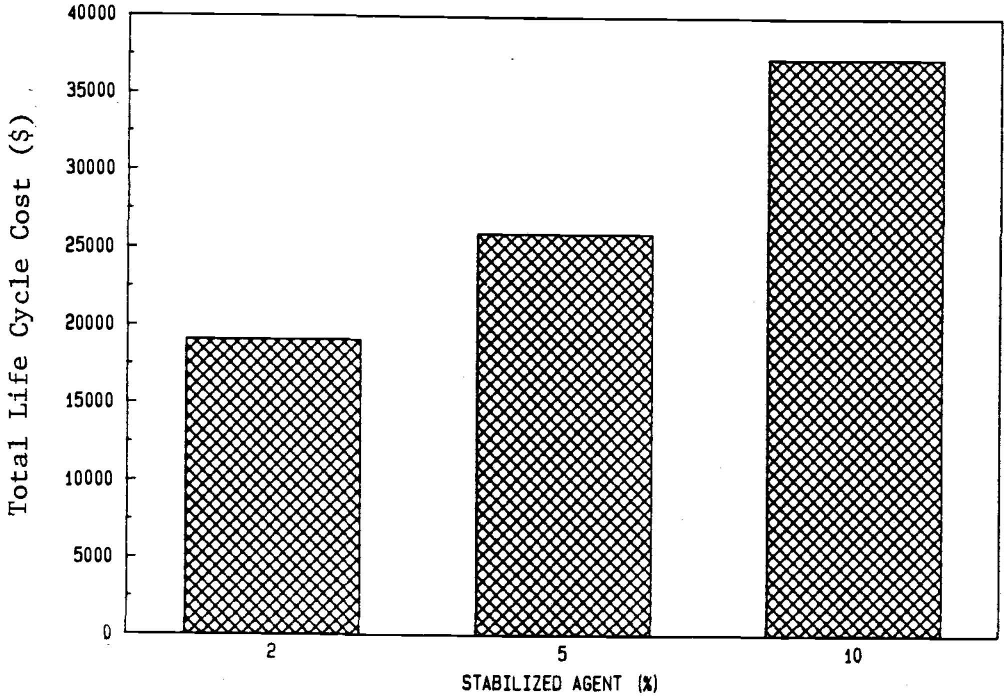


Figure 6.12. Sensitivity of Cost of Chemical Stabilization to the Percent of Chemical Agent (%)

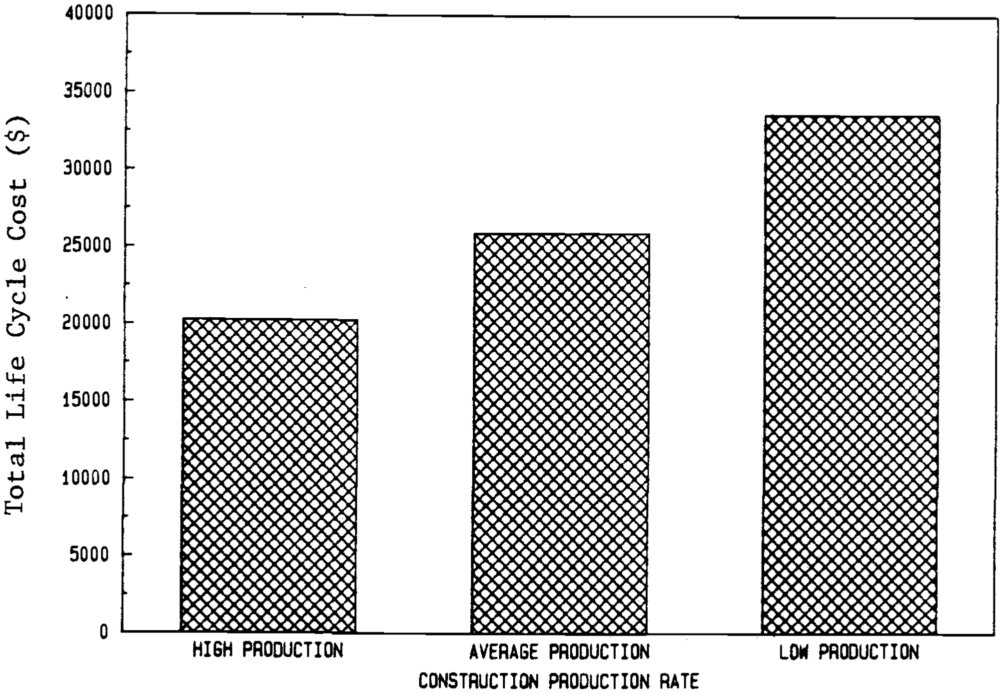


Figure 6.13. Sensitivity of Cost of Chemical Stabilization to Construction Production Rate

Again, it can be seen from this sensitivity analysis that other alternate surfacing types can be more attractive than stabilized surfaces. If there is much variation in the amount of stabilizing agent required, the cost of the stabilizing agent, or the productivity of equipment and labor, other surfaces may be more economical.

Furthermore, Tables 6.7 and 6.8 show the computer output and the step-by-step calculation of the sensitivity analysis for estimating the total life cycle costs of crushed aggregates and soil stabilized surface in which VISICALC was used for the calculation. Finally, the full documentation of the computer outputs for developing the sensitivity analysis tables are given in Appendix E.

Table 6.7. Computer Output for Sensitivity Analysis of Crushed Aggregate

CRUSHED AGGREGATE

1) COST OF MATERIAL:

LENGTH (FEET)	5280
WIDTH (FEET)	15.33
DEPTH (INCHES)	8
COMPACTED VOLUME OF CRUSHED AGGREGATE (C.Y.)	1998.57777777
COMPACTED VOLUME OF CRUSHED AGGREGATE FOR CURVE WIDENING AND TURNOUTS (C.Y.)	399.71555555
SWELL FACTOR-------->	1.25
TOTAL LOOSE VOLUME (C.Y.)	2997.86666665
AVERAGE COST OF MATERIALS ($/C.Y.)	20
AVERAGE TOTAL COST OF MATERIALS ($)	59957.333333

2) AVERAGE EQUIPMENT AND LABOR COST :

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS.)	TOTAL COST OF ACTIVITY ($)
SPREADING	32	125.38	4012.16
COMPACTION	8	76.2	609.6
	TOTAL AVERAGE COST ($):		4621.76

3) AVERAGE HAUL COST :

HAUL COST ($/C.Y.-MILE)	.3
HAUL DISTANCE (MILE)	30
TOTAL AVERAGE HAUL COST($)	26980.799999

Table 6.7. Computer Output for Sensitivity Analysis of Crushed Aggregate (Continued)

```
    AVERAGE MAINTENANCE COST $ 615
---------------------------------------------------------------------
5) TOTAL LIFE CYCLE COST :

   AVERAGE MATERIAL COST ($)    59957.333333

   AVERAGE  EQUIPMENT AND       4621.76
   LABOR COST ($)

   AVERAGE HAUL COST ($)        26980.799999

   AVERAGE MAINTENANCE COST $   615
                                ---------------
   TOTAL LIFE CYCLE COST
   FOR CRUSHED AGGREGATE
   ROADS ($)----------->        92174.893332
                                ===============
```

Table 6.8. Computer Output for Sensitivity Analysis of Soil Stabilization

SOIL STABILIZATION

1) COST OF MATERIAL:

LENGTH(FEET)	5280
WIDTH(FEET)	15
DEPTH(INCHES)	6
COMPACTED VOLUME OF SOIL TO BE STABILIZED (C.Y.)	1466.66666666
COMPACTED VOLUME OF SOIL TO BE STABILIZED FOR CURVE WIDENING AND TURNOUTS (C.Y.)	293.33333333
TOTAL COMPACTED VOLUME (C.Y.)	1759.99999999

STABILIZED AGENT COST:

UNIT WEIGHT OF SOIL (POUND/CUBIC FEET)	110
% OF STABILIZED AGENT	.05
COST ($/TON)	160
TOTAL WEIGHT OF STABILIZED AGENT (TON)	130.67999999
TOTAL COST OF STABILIZED AGENT($)	20908.799998

Table 6.8. Computer Output for Sensitivity Analysis of the Soil Stabilization (Continued)

TRACTION SAND COST

LENGTH (FEET)	5280
WIDTH (FEET)	15
APPLICATION RATE (LBS/SQ YARD)	30
COST OF SAND ($/TON)	10
TOTAL SURFACE AREA OF ROADWAY (SQ YARD)	10560
WEIGHT OF SAND (TON)	158.4
TOTAL COST OF SAND ($)	1584

TOTAL COST OF MATERIALS ($)------------------> 22492.799998

---

2) AVERAGE EQUIPMENT AND LABOR COST:

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS)	TOTAL COST OF ACTIVITY ($)
SOIL PULVERIZATION	24	100.83	2419.92
SPREADING	24	91.24	2189.76
MIXING	24	100.83	2419.92
WATERING	24	88.22	2117.28
COMPACTION	24	76.21	1829.04
SPREADING SAND	4	93.7	374.8
	TOTAL AVERAGE COST($):		11350.72

Table 6.8. Computer Output for Sensitivity Analysis of the Soil Stabilization (Continued)

3) AVERAGE HAUL COST:

HAUL COST ($/TON-MILE)	.15
HAUL DIST.STABILIZING AGENT (MILE)	50
HAUL DIST.SAND (MILE)	40
TOTAL HAUL COST OF STABILIZING AGENT ($)	980.09999992
TOTAL HAUL COST OF TRACTION SAND ($)	950.4

TOTAL AVERAGE HAUL COST ($)--------->	1930.49999992

---

4) AVERAGE MAINTENANCE COST($)----------> 615

TOTAL LIFE CYCLE COST:

AVERAGE MATERIAL COST ($)	22492.799998
AVERAGE EQUIPMENT AND LABOR COST ($)	11350.72
AVERAGE HAUL COST ($)	1930.49999992
AVERAGE MAINTENANCE COST ($)	615

TOTAL LIFE CYCLE COST FOR STABILIZED ROAD ($)----------------->	36389.019997
	===============

7.0 SUMMARY AND CONCLUSIONS

This chapter presents the summary and the significant conclusions resulting from this study, as well as recommendations for various agencies or industries that may build temporary and intermittent use roads in the future.

7.1 Summary

The background information on alternate surfacings and important factors to be considered for temporary and intermittent use roads are given in Chapter 2.

The results of a comprehensive market and literature search are presented in Chapter 3, which identifies surfacing systems and materials capable of being used for temporary and intermittent use roads and after the logging, mining, or other activities are finished, removed, and reused for alternative projects or left to degrade in-place. The results of this literature and market study, along with the background provided in Chapter 2, indicated that when good quality materials are not locally available, four alternatives exist:

1) Poor quality materials may be utilized as a surfacing to provide a surface that is sufficiently smooth, stable, durable, and has adequate traction,
2) Chemical stablization may be used to improve the strength and durability of the soil,
3) High quality materials may be imported, which may be very costly, or
4) Alternate surfacing systems may be used.

Furthermore, it can be concluded that the decision of whether to select any of the above surfacing materials over another for temporary and intermittent use roads must be based on the consideration of several important factors, such as soil type, availability of materials, local experience for the construction method, expected life of materials, and most importantly, economics. Considering all of the above factors, the major findings of the literature and market survey indicate that the feasible alternatives for surfacing and intermittent use roads include:

1) Biodegradable materials,
2) Soil stabilization,
3) Marginal aggregates,
4) Conventional geotextile and extruded plastic mats,
5) Steel mats (M8A1), and
6) Sand-sealed native subgrade.

The economic evaluation of alternate surfacings which is developed and discussed in Chapter 4 provides a valid procedure to evaulate the overall effectiveness and economic viability of potential surfacing systems. A two-step evaluation procedure was developed and recommended for evaluation of the alternate surfacing types. These steps are as follows:

1) Preliminary Evaluation Step: This screens various alternative materials based on their characteristics, limitations, and availability to identify those materials that have the strongest potential of being effective.

2) Economic Evaluation Step: Those alternate surfacings that show a potential for being effective are subjected to an in-depth economic evaluation to determine the material with the least total present worth of life cycle costs.

Furthermore, various methods of economic evaluation are discussed, and it is concluded that for comparing alternate surfacings the total present worth of the life cycle costs should be used. The benefit-cost ratio can not be used because the benefits of the alternate surfacings that may include reduced operating costs, reduced maintenance costs, increased speeds, reduced travel time, increased safety, added comfort and convenience, energy savings, and environmental benefits of reduced air and/or water pollution are not expected to vary greatly from one surfacing to another and are intangible and cannot be estimated.

Chapter 5 presents the results of comparative deterministic evaluation of two examples which are analyzed in detail to present the evaluation procedure developed in Chapter 4. All of the estimates used for this evaluation were based on the mean value. The result of the comparative evaluation for these examples indicated that alternate surfacings can be economical in most of the situations analyzed. The most promising surfaces for these examples, in the order of increasing costs, include:

1) Chemical stabilization,
2) Wood and bark chips,
3) Marginal aggregates,
4) Reusable aggregate with or without geotextile, and
5) Crushed aggregates.

Chapter 6 presents the probabilistic approach for analyzing and evaluating the uncertainty associated with various elements of the alternative surfacing. The results of this chapter indicate that one of the best methods for analyzing the uncertainty of the various elements of the alternate surfacing types is the use of the Beta estimation procedure which involves the use of an "optimistic," a "pessimistic," and a "most likely" estimate for each element of the project.

A discussion of sensitivity analysis is also presented in this chapter. Finally, to demonstrate this procedure in-depth, a comprehensive sensitivity analysis was performed for crushed aggregate and soil stabilization surfaces. The result of this analysis indicated that crushed aggregates surfaces are highly sensitive to haul distance and material cost and less sensitive to the construction production rates. On the other hand, soil stabilization surfaces are highly sensitive to the construction production rates, percentage and cost of the stabilizing agent, and less sensitive to the hauling distance of the stabilizing agent.

7.2 Conclusions and Recommendations

Specific conclusions and recommendations resulting from this project include:

1) Biodegradable materials, such as bark and wood chips, can be very suitable for temporary roads, especially logging roads because they are inexpensive and available. Furthermore, it is an excellent method to make productive use of wastes and extremely economical where rock is not available.

   Its use as a surface is recommended for short length projects (1-2 miles), low speed, and moderate grade roads.

2) Admixture stabilization, such as lime, portland cement, emulsified asphalt, fly ash, sodium chloride, calcium chloride, magnesium chloride, and lignin sulfonate, can be used for upgrading local soils and marginal aggregates. The selection of the specific additives for stabilizing the materials depends on the subgrade material types as well as the availability and costs of the additives in the area. Basically, portland cement is recommended for well-graded granular soils or fine-grained soils with a plasticity index, PI, < 10. Emulsified asphalt is recommended for soils with a PI < 6, less than 25% passing the No. 200 sieve, and (PI X% passing No. 200 sieve)

< 60. Lime is recommended for soils with a PI > 10.

Numerous such projects have been constructed on temporary and intermittent use roads. This is likely to be the most economical solution. Therefore, these surfaces are strongly recommended for temporary or intermittent use roads.

3) Marginal aggregates have widespread availability and low initial cost and are recommended for short life projects (1-3 years).

4) Conventional geotextiles and extruded plastic grids can be used to stabilize weak soils and are recommended for areas with high cost rock to reduce the amount of rock required.

5) Sand-sealed subgrades are recommended for areas that have good and firm subgrade (CBR > 15, R-value > 40). The soft nature of the sand-seal probably prevents its use on steep grades or sections with sharp curves. Therefore, the use of this material should be limited to roads with firm subgrades, moderate grades, and short project life (1-3 years).

6) Metal mats, such as steel and aluminum, may only be applicable for short sections of roads due to their high initial cost. These materials are recommended for situations where several projects are constructed

in the same area and have short duration of logging or mining with high rock costs.

7) Recovery and reuse of the good quality aggregates with geotextile as a separation layer may not be economical due to the high cost of the geotextile.

Recovery and reuse of the good quality aggregates without geotextile as a separation layer on several projects may offer lower construction cost. It also contributes to the conservation of high quality aggregates. These surfaces are recommended for the projects that have high rock cost, short duration of logging or mining, and a short hauling distance from one project to the alternate project. It is expected that about 70 to 75% of the aggregates may be recovered each time for future use. To avoid the soil contamination of the recovered aggregates, it may be required that the recovered aggregates be washed before use on the future projects.

8) The membrane-encapsulated soil layer (MESL) concept is a method for maintaining a moisture content of the soil at the desired level by encapsulating the soil in a waterproof membrane that prevents water infiltration. These surfaces may be considered only for use in areas with very fine-grained soils, high moisture content, and lacking quality aggregate.

9) Geowebs are not economical for temporary or intermittent use roads when compared to crushed aggregates due to the high initial cost of materials. Therefore, they should not be considered for temporary or intermittent use roads.

10) The economic evaluation approach developed in this study should be used to evaluate the alternatives which are recommended by preliminary evaluation.

11) For comparing alternate surfacings, the total present worth of the life cycle costs is recommended for the economic evaluation. The benefit-cost ratio can not be used because the benefits of the alternate surfacings are not expected to vary greatly from one surfacing to another and are intangible and cannot be estimated.

12) Since the construction of the alternate surfacings are unique and the more roads that are built with alternate surfacings, the more efficient the construction of the road becomes due to experience gained by individual operators. Therefore, an 80% learning curve, as described in Chapter 5, is recommended for adjusting the construction production rates. The use of this learning curve would result in a reduction of production time of almost 50% for the eighth project compared to the initial project.

Subsequent projects are not likely to experience significant reduction in production time.

13) The probabilistic evaluation approach using the Beta distribution is recommended for taking account of the uncertainty of the various elements of the alternative surfacing types. This method uses three estimates to take into account the amount of uncertainty involved.

14) Sensitivity analysis, which determines the impact of changes in input variables, is recommended for comparing alternate surfacings. This provides the decision maker with additional information for making a better decision when there is a high degree of uncertainty involved for various elements of the alternate surfacings.

15) Training programs instructing engineers how to evaluate, design, construct, maintain, and recover various alternate surfacings should be implemented around the country. This will encourage the engineers to consider these materials for their future projects.

7.3 Recommendations for Further Study

Much work remains to be done before a complete understanding and economic feasibility of alternate surfacings can be developed. This study is based on the summary of existing literature as well as construction and evaluation of 11 demonstration projects for given situations. Drawing conclusions for the entire country from the observation of one or two demonstration projects for each material could generate misleading information and lead to inappropriate applications.

The following specific suggestions are made for future research in this subject area:

1) Construction of additional demonstration projects for various physical and environmental situations are necessary to obtain a more comprehensive understanding of the use of alternate surfacings. This will help in establishing a set of minimum and maximum operating criteria for alternate surfacings including:

   a) loading requirements (weight and volume),

   b) applicable subgrade conditions,

   c) season of use,

   d) geometrics of the roadway, and

   e) economics of the materials.

2) The recommended additional demonstration projects include:

   a) Biodegradable materials, to determine the expected performance under various environmental conditions.

   b) Sand-sealed subgrade, which may only work with good and firm subgrade (CBR > 15, R-value > 40), to develop the performance data for various subgrade strengths.

c) Reusable aggregates without geotextile separation, to determine an accurate estimate of the percentages of the recovered materials.

d) Metal mats, to develop an accurate performance data, as well as observing the problems in recovery and reuse of materials in other projects.

Marginal aggregates, crushed aggregates, geotextiles for stabilization and separation, chemical soil and aggregate stabilization have been used for many years and have demonstrated their practicality, performance, and associated costs. Therefore, additional demonstration projects are not recommended for these materials.

3) The influence of the various types of surfacing on vehicle operating cost, travel time, and safety may play a major role in the economic evaluation for high volume or long projects. Therefore, it is essential to do an in-depth study of this area.

4) Various agencies and industries which deal with temporary and intermittent use roads should review a few of their existing projects to obtain a better understanding of costs and performance. Constructing a road with $25-30/yd^3 crushed aggregate that will only

be used for 1 to 3 years out of 20 years is totally unacceptable.

5) Develop an alternate surfacing task force to assist the engineers in the evaluation, design, construction, and maintenance of the various alternate surfacing types. This may encourage the engineers in understanding and considering these materials for their future projects.

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APPENDICES

APPENDIX A

CONSTRUCTION, MAINTENANCE, AND RECOVERY PROCEDURES OF THE POTENTIAL SURFACING SYSTEMS

APPENDIX A

CONSTRUCTION, MAINTENANCE, AND RECOVERY PROCEDURES OF THE POTENTIAL SURFACING SYSTEMS

This appendix describes the construction, maintenance, and recovery procedures for the alternate surfacings. The general procedures given are based on the actual field observation of demonstration projects (9), as well as the procedures that have been recommended by the manufacturers and other researchers. The unique equipment, technology, or expertise for construction, maintenance, and recovery of the various alternative surfacing materials are summarized in Table A-1. Typical maintenance problems and methods of correction for various alternative surfacing systems are summarized in Table A-2.

1.0 WOOD CHIP

1.1 Construction Procedures

The procedures used in the construction of the wood chip road are as follows:

1) Subgrade Preparation. After clearing has been completed, the ground should be leveled and smoothed using a grader.

2) Chipping On Site. The chipping can be done at the project site by a chipper.

3) Hauling Chips. Chips are typically hauled in wood chip trucks of 40 to 50 yd^3 (30.58 to 38.23 m^3) capacity.

Table A-1. Unique Requirements of the Alternative Surfacing Systems.

Potential Surfacing Types	Construction, Recovery, and Maintenance Technology	Special Equipment	Special Expertise
Wood and Bark Chip	The same as aggregate roads	Chipper	None Required
Chemical Stabilization	May be unique for construction of sodium chloride (NaCl), calcium chloride ($CaCl_2$), magnesium chloride ($Mg\breve{C}l$), and lignon sulfonate	Pulva-mixer or twin disk harrow, distributor tanker	Special expertise is needed for spreading and mixing the additives
Geotextile or Geogrid Separation	Special construction methods necessary	None required	None required
Marginal Aggregate	None required	None required	None required
Sand-Sealed Subgrade	None required	None required	None required
Metal Mats	None, mats easily placed together in field	Fork lift or truck-mounted crane, pressure washer, mobile welder	None required
Reusable Aggregate without Geotextile Separation	None required	None required	None required
Reusable Aggregate with Geotextile Separation	Requires special techonology for the recovery of the materials	Sewing machine and special recovery system	Trained laborers are needed for sewing the fabric around the recovery beam
Geoweb Stabilization (Expandable Grids)	The construction technology is very unique and requires special knowledge for subgrade preparation, geoweb placement, filling, leveling, and compacting the surface	None required	Trained laborers are needed for various parts of the construction activities
Membrane Encapsulated Soil Layer	The construction technology is unique in terms of laying the fabric, applying emulsion, and compacting	None required	None required

Table A-2. Typical Maintenance Problems and Methods of Correction for Alternative System.

Potential Surfacing Types	Rutting	Potholing	Slick Surface	Bearing Failure	Breakup	Bleeding
Wood Chip	Fill with chips and compace	Same	Add gravel for traction	thicken section with chips	N/A	N/A
Chemical Stabilization	Fill with aggregate and compact or restabilize	Same	Add gravel for traction	Add gravel to strengthen or restabilize	Restabilize or remove and add gravel	N/A
Geotextile and Geogrid Separation	Fill with aggregate and compact	Same	Add gravel for traction	Thicken section with gravel	N/A	N/A
Marginal Aggregates	Blade Surface and compact	Same	Add gravel for traction	Thicken section with gravel	N/A	N/A
Sand-Sealed Subgrade	Rebuild and strengthen subgrade	Fill with gravel and compact	Rebuild Sand Seal	Add gravel to strengthen or restabilize	Patch surface	Apply blot sand
Metal Mats	N/A	N/A	Apply emulsion and sand or chips	Strengthen subgrade or use different pavement system	Repair or replace mats	N/A
Resuable Aggregate Without Geotextile Separation	Blade surface and compact	Same	Add gravel for traction	Thicken section with gravel	N/A	N/A
Reusable Aggregate With Geotextile Separation	Fill with aggregate or blade surface and compact	Same	Add gravel for traction	Thicken section with gravel	N/A	N/A
Membrane Encapsulated Soil Layer	Reconstruct or add structural surfacing	N/A	Rebuild chip seal	Reconstruct or use different pavement system	Patch surface	Apply blot sand
Geoweb Stabilization	Fill with aggregate and compact	Same	Repair surface, add sand	Replace geoweb and add an additional layer or apply a structural surfacing	N/A	Apply blot sand
Crushed Aggregate For Comparison	Blade surface and compact	Same	Add gravel for traction	Thicken section with gravel	N/A	N/A

4) Spreading. The wood chips should be placed and spread to the designated thickness using a dozer D-5 or equivalent.

5) Compaction. According to the literature review, the wood chip materials should be compacted to 60 percent of the original volume.

1.2 Maintenance

The only maintenance problem expected for the wood chip roads is rutting. Ruts can be easily and quickly filled by blading the surfacing with a grader, or by filling with additional chips from a stockpile.

1.3 Equipment and Labor

An itemized list of the typical equipment and labor requirements for construction and maintenance of the wood chip project is given in Table A-3.

2.0 CHEMICAL STABILIZATION

2.1 Construction Procedures

The typical procedure for the construction of chemical stabilization are as follows:

1) Soil Pulverization. This can be done by a variety of methods, including ripping and blading with a road grader, pulverization with a pulva-mixer, or disking with a disk harrow. When the soil is unusually dry, water should be added to aid pulverization; if extremely wet, a rotary mixer or disk harrow can be

Table A-3. Suggested Equipment and Labor Requirements.

(Wood Chips)

Activity	Equipment	Labor
A. Construction		
1. Chipping	Large Mobile or Stationary Chipper (140 hp)[a]	Operator
2. Spreading	Dozer With Straight Blade (200 hp)	Operator Foreman
3. Compaction	Vibratory Roller (80-100 hp)	Operator Foreman
B. Maintenance		
1. Chipping	Chipper (140 hp)	Operator
2. Spreading	Dozer or Road Grader (100 hp)	Operator Foreman
2. Compaction	Vibratory Roller (80-100 hp)	Operator Foreman

[a]hp = horsepower

used to aerate and dry the soil. For clay soils, a pulva-mixer works better than other methods, although it is more expensive.

2) Stabilizer Application. Materials such as lime, portland cement, and fly ash can either be released from a belly dump truck or by pumping dry through distributor nozzles from the back of a tank truck. Emulsified asphalt can be distributed with an asphalt distributor with a 12-foot (3.66 m) spray bar.

The addition of water prior to the introduction of emulsified asphalt into the windrow is often necessary in asphalt stabilization operations. This water (usually 3 to 5 percent) aids mixing. Dry soil and cement or lime should be premixed prior to the addition of water for better uniformity.

3) Pulverization and Mixing. Mixing should be accomplished to assure that the stabilizer is uniformly distributed. Single- and multiple-shaft rotary (flat-type) mixers are often utilized to pulverize and mix lime, lime-fly ash, portland cement, and asphalt with subgrade soils. Motor graders and agricultural-type equipment are most commonly used in the Forest Service; however, they do not always obtain the desired uniformity. Windrow- and hopper-type mixers are not typically used in subgrade stabilization operations.

For lime stabilization, pulverization and mixing should continue until 100 percent of the soil binder passes a 1-inch screen and at least 60 percent passes the No. 4 sieve.

For portland cement stabilization, the soil should be pulverized so that 100 percent of the soil-cement mixture will pass a 1-inch sieve and that a minimum of 80 percent will pass a No. 4 sieve, exclusive of any gravel or stone, at the time of compaction.

4) Compaction. Compaction should commence as soon as possible after uniform mixing of water and the stabilizer. For lime stabilization, the materials should be compacted within 4 hours of mixing and always be completed on the same day the soil is mixed with the stabilizers while, for the portland cement stabilization, the materials should be compacted within 1 hour of mixing. Emulsified asphalt should be compacted immediately before, or at the same time as, the emulsion starts to break.

Compaction can be achieved with a variety of equipment, including pneumatic, steel-wheeled, vibratory, and sheepsfoot rollers.

5) Curing. To prevent excessive drying of the road surface for portland cement and lime stabilization during curing, the road should be sprinkled with

water to keep the surface damp, and light rolling is recommended to keep the surface knitted together.

Membrane curing can be more effective than sprinkling water. In membrane curing, the stabilized soil should be sealed with one shot of emulsified asphalt (0.10 to 0.25 gal/yd^2 (0.5 to 1.2 liters/m^2)) within one day after final rolling.

For asphalt emulsion, it is desirable to place a sand or aggregate seal as a protective layer during the curing period.

The above procedures are a brief overview of the construction steps of the chemical stabilization projects. References (9), (11), and (12) can provide additional guidelines for the construction of the chemical stabilization projects.

2.2 Maintenance Procedure

The expected maintenance problems expected with these surfaces are potholing, slick surface, and bearing failures during wet periods. Repair techniques are described below.

1) Potholing. The least expensive method is to fill the potholes with aggregate. Potholing can also be repaired by ripping the failed section with a motor grader or dozer and breaking it into aggregate size, remixing with the proper admixture, compacting the materials, and finally, sealing the surface with a surface treatment.

2) Slick Surface and/or Bearing Failures During Wet Periods. These problems are difficult to repair until the surface dries out. When dry, use a road grader to rework and recompact the materials and finally add gravel for traction.

2.3 Equipment and Labor Requirements

An itemized list of the typical equipment and labor requirements for construction and maintenance for chemically stabilized surfaces is given in Table A-4.

3.0 GEOTEXTILE AND GEOGRID PROJECTS

3.1 Construction Procedures

The typical procedure for the construction of the geotextile and geogrid projects is as follows:

1) Subgrade Preparation. Regardless of subgrade strength, the site should be cleared of all sharp objects, tree stumps, and large stones that could puncture the geotextile. Unless it is necessary to achieve final grade, the vegetation mat need not be removed; it provides extra support during aggregate placement until final compaction is obtained (13).

2) Geotextile Placement. Geotextile should be rolled out onto the subgrade by a two-man team, beginning at a point that allows easy access for construction equipment. Longitudinal and transverse joints shall

Table A-4. Suggested Equipment and Labor Requirements. (Chemical Stabilization)

Activity	Equipment	Labor
A. Construction		
1. Soil Pulverization	Pulver Mixer, Disc Harrow, or Grader (135-150 hp)	Operator Foreman
2. Spreading		
a. Solid	Belly Dump Truck (20 cy)	Operator Foreman
b. Liquid	Tanker (5000 gal)	Operator Foreman
c. Emulsion	Asphalt Distributor (3000 gal)	Operator Foreman
3. Mixing	Pulver Mixer, Disc Harrow, or Grader (135-150 hp)	Operator Foreman
4. Watering	Water Tanker (5000 gal)	Operator
5. Compaction	Vibratory Roller and/or Rubber Tired Roller (80-100 hp)	Operator Foreman
B. Maintenance		
1. Spreading		
a. Solid	Flat Bed Dump Truck (20 cy)	Operator Foreman
b. Liquid	Tanker (5000 gal)	Operator Foreman
c. Emulsion	Asphalt Distributor (3000 gal)	Operator Foreman
2. Mixing	Grader (135-150 hp)	Operator Foreman
3. Watering	Water Tanker (5000 gal)	Operator
4. Compaction	Vibratory Roller (80-100 hp)	Operator

hp = horsepower
cy = cubic yard
gal = gallon
1 yd^3 = 0.7645 m^3
1 gal = 3.785 liters

be overlapped at least 3 feet and stapled at the ends (13).

3) Patching Geotextile. Torn, or separated, sections of the fabric should be repaired by installing a fabric patch over the hole prior to placing the borrow or base course material. The patch should be at least three feet larger in horizontal dimensions than the hole to be repaired (13).

4) Aggregate Placement. Aggregate shall be placed to designated thickness in one lift and spread in the direction of fabric overlap by a dozer. Hauling equipment should not be operated on the fabric until the total thickness of surface is placed.

5) Aggregate Compaction. To obtain full stability, each layer of aggregate must be compacted to a density of at least 95 percent of the maximum density, as determined by AASHTO T180. Initial compaction should be made by "driving" the tracked bulldozer back and forth over the aggregate while waiting for the next aggregate load. Final compaction is achieved by rolling the area with a vibratory compactor, first without vibration for 4 to 6 passes, then with full vibration. Reference (37) can provide additional guidelines for the aggregate compaction.

3.2 Maintenance Procedures

The only maintenance problem expected is rutting of the surface under loaded trucks. Shallow ruts (< 2 inches) can often be easily removed by blading the surface, using a motor grader. For geotextiles or geogrids, deep ruts should be maintained by adding aggregate to fill the ruts before grading to prevent damage to the geotextiles or geogrids.

3.3 Equipment and Labor Requirements

An itemized list of the typical equipment and labor requirements for construction and maintenance of the geotextile or geogrid projects is given in Table A-5.

4.0 MARGINAL AGGREGATES

4.1 Construction Procedures

The typical procedure for the construction of marginal aggregate roads is similar to that used for conventional aggregate roads as follows:

1) Subgrade Preparation. This includes clearing and grubbing, removal of obstructions, adjusting the subgrade, moisture content, and compaction of the subgrade using a sheepsfoot, smooth-wheel, or vibratory roller (37).

2) Aggregate Placement. Aggregate should be placed in one lift and spread on the prepared subgrade to a loose depth that provides the required thickness when compacted. The spreading can be accomplished with

Table A-5. Suggested Equipment and Labor Requirements.

(Geotextile and Geogrid)

Activity	Equipment	Labor
A. Construction		
1. Geotextile Placement	-	Foreman 2 laborers
2. Spreading	Dozer (100 hp)[a]	Operator Foreman
3. Compaction	Vibratory Roller (80-100 hp)	Operator Foreman
B. Maintenance		
1. Spreading	Dozer (100 hp)	Operator Foreman
2. Compaction	Vibratory Roller (80-100 hp)	Operator Foreman

[a]hp = horsepower

using a dozer. If the required compacted depth of the aggregate course exceeds 6 inches (15.24 cm), it should be placed in two or more layers of approximately equal thickness (37). The maximum compacted thickness of any one layer should not exceed 6 inches (15 cm).

3) Aggregate Compaction. To obtain stability, each layer of aggregate must be compacted to a density of at least 95 percent of the maximum density, as determined by AASHTO T180. Initial compaction should be made by "driving" the tracked bulldozer back and forth over the aggregate while waiting for the next aggregate load. Final compaction is achieved by rolling the area with a vibratory compactor, first without vibration for several passes, then with full vibration (37).

4.2 Maintenance Procedures

The principal maintenance problems expected of the surface under loaded trucks includes rutting, rock loss, and roughness. Shallow ruts can often be easily removed by using a grader to blade the surface. Deep ruts should be repaired by adding aggregate to fill the ruts before grading.

4.3 Equipment and Labor Requirements

An itemized list of the typical equipment and labor requirements for construction and maintenance of aggregate roads is given in Table A-6.

5.0 SAND SEAL

5.1 Construction Procedures

The typical procedure for the construction of the doubled[a] sand seal roads (26,37) is as follows:

1) Subgrade Preparation. This includes clearing and grubbing, removal of obstructions, grading, watering, and compaction of the subgrade using a sheepsfoot, pneumatic, smooth-wheel, or vibratory roller.

2) Application of Bituminous Material. Emulsified asphalt (CRS-2) should be applied in a uniform, continuous spread at a temperature of 140°F (60°C) and an application rate of 0.40 to 0.50 gal/yd^2 (1.82 to 2.28 liters/m^2) for the bottom layer and 0.2 to 0.3 gal/yd^2 (0.91 to 1.37 liters/m^2) for the top layer.

   The length of spread of bituminous material should not be in excess of that which sand spreading equipment can immediately cover.

3) Application of Cover Sand. Immediately following the application of bituminous material, sand should be

[a]The construction of single sand seal projects are the same as double sand seal projects with the exception that one layer of sand and seal is applied.

Table A-6. Suggested Equipment and Labor Requirements.

(Marginal or Conventional Aggregate)

Activity	Equipment	Labor
A. Construction		
1. Spreading	Dump Trucks and Motor Grader or Dozer (200 hp)[a]	Operator Foreman
2. Compaction	Vibratory Roller (80-100 hp)	Operator Foreman
B. Maintenance		
1. Spreading	Motor Grader or Dozer (200 hp)	Operator Foreman
2. Compaction	Vibratory Roller (80-100 hp)	Operator Foreman

[a]hp = horsepower

spread at the rate of 25 to 30 lbs/yd^2 (13.56 to 16.27 Kg/m^2) for the bottom layer and 20 to 25 lbs/yd^2 (10.85 to 13.56 Kg/m^2) for the top layer using a tailgate spreader on a dump truck.

4) Surface Preparation. After the cover sand has been spread on the bituminous material, any piles or uneven distributions should be carefully removed to prevent permanent ridges, bumps, or depressions in the completed surface.

5) Compaction. The surface should be compacted using a steel-wheeled roller. Rolling should continue until four complete coverages of the entire surface have been obtained. All rolling should be completed within 2 hours.

6) Final Surface Preparation. After the cover sand is set in the bituminous material, but not earlier than the following day, concentrations of loose cover sand should be redistributed.

   Four days after construction, excess cover sand should be removed using a rotary power broom without displacing the cover sand set in the bituminous materials.

5.2 Maintenance Procedures

Typical maintenance problems are raveling and breakup of the surface, excessive bleeding, and the development of soft spots causing rutting. The raveling and broken areas should be scarified and then recombined with the subgrade material and recompacted. Bleeding is corrected with the application of additional sand. Soft spots should be excavated and backfilled with crushed aggregate.

For resurfacing, the procedure discussed earlier should be repeated.

5.3 Equipment and Labor Requirements

An itemized list of the typical equipment and labor requirements for construction and maintenance of the sand seal surface is given in Table A-7.

6.0 METAL MATS

6.1 Construction Procedures

The typical procedure for the construction of the metal mats is as follows:

1) Subgrade Preparation. This includes clearing and grubbing, removal of obstructions, grading, water content adjustment, and compaction of the subgrade using a sheepsfoot, smooth-wheel, or vibratory roller.

2) Laying of the Mat. After subgrade preparation, mat placement should begin at two points and proceed in two directions using three-man teams. Mats interlock with adjacent mats as the mats are laid parallel with the previous row. Mat ends are interlocked with ends of adjacent mats by slipping couplers (dog-bone-shaped extrusions) into the dove-tailed recesses of

Table A-7. Suggested Equipment and Labor Requirements.

(Sand Seal)

Activity	Equipment	Labor
A. Construction		
1. Seal Application	Asphalt Distributors (3000 gal)	Operator Foreman
2. Sand Application	Chip Spreader, Self-Propelled 14-foot Spread Hopper	Operator Foreman Laborer
3. Compaction	Vibratory Roller (80-100 hp)	Operator Foreman
4. Removing Excess Sand	Power Broom	Operator
B. Maintenance[a]		
1. Excavating (Patching)	Backhoe (60-80 hp)	Operator Foreman 2 Laborers
2. Scarification	Grader	Operator Foreman
3. Seal Application	Asphalt Distributors (3000 gal)	Operator Foreman
4. Sand Application	Chip Spreader, Self-Propelled 14-foot Spread Hopper	Operator Foreman 2 Laborers
5. Compaction	Vibratory Roller (80-100 hp)	Operator Foreman
6. Removing Excess Sand	Power Broom	Operator

[a]Includes minor maintenance and also resurfacing.
hp = horsepower
gal = gallon
1 ft = 0.3048 m
1 gal = 3.785 liters

each mat end. Reference (31) provides additional details on the construction of the metal mat projects.

6.2 Maintenance Procedures

Maintenance procedures for metal mats are primarily of a periodic visual inspection of the mat surface for indication of impending failure, such as joint failure. Broken mats should be replaced as soon as possible using a three-man team to remove and replace the new panels.

6.3 Recovery Procedure

The typical procedure for the recovery of the metal mats consists of the following steps:

1) Dismantling Surface. Use a three-man team.
2) Loading and Transporting Mats to Storage Site. Use a three-man team and a truck-mounted crane or forklift to load the panels.
3) Unloading Mats. Use a truck-mounted crane.
4) Clean and Store Mats. Use a high pressure water jet.
5) Painting Mats. Use a mobile painter to paint mats for protection against corrosion.

6.4 Equipment and Labor Requirements

An itemized list of the typical equipment and labor requirements for construction and maintenance of the metal mats is given in Table A-8.

Table A-8. Suggested Equipment and Labor Requirements.

(Metal Mats)

Activity	Equipment	Labor
A. Construction and Removal		
1. Metal Mat Placement and Removal	Forklift, 6,000 lbs. Highlift, Four Wheel Drive	Operator 3 Laborers Foreman
B. Maintenance		
1. Recovery	Forklift	4 Laborers Operator
2. Cleaning	Pressure Washer	2 Laborers
3. Repairing	Mobile Welder	2 Laborers

7.0 REUSABLE/RECYCLABLE AGGREGATES WITHOUT GEOTEXTILE SEPARATION

7.1 Construction Procedure

The construction procedure for this surface is the same as for marginal aggregate roads described in Section 4.1.

7.2 Maintenance Procedure

The typical maintenance procedure is the same as marginal aggregate roads as previously described in Section 4.2.

7.3 Recovery Procedure

The typical procedure for the recovery of the reusable aggregate without geotextiles consists of the following steps:

1) Scraping the Aggregate. Aggregate should be scraped as close as possible to the subgrade without disturbing the subgrade materials or picking up contaminated aggregate by a road grader or a dozer. A narrow blade will be more capable of removing this lost volume of aggregate since it can be more carefully adjusted to the uneveness of the subgrade.

2) Stockpiling and Loading of the Recovered Aggregate. The recovered aggregate should be stockpiled at the lower portion of the road and then loaded into dump trucks and hauled to the next project using a loader.

7.4 Equipment and Labor Requirements

An itemized list of the equipment and labor requirments for construction and maintenance of the reusable/recyclable aggregates without geotextile separation is given in Table A-9.

Table A-9. Suggested Equipment and Labor Requirements.

(Reusable Aggregate Without Geotextile Separation)

Activity	Equipment	Labor
A. Construction		
1. Spreading	Dozer (200 hp)	Operator Foreman
2. Compaction	Vibratory Roller or others (80-100 hp)	Operator Foreman
3. Hauling Aggregate	2 Dump Trucks (10 cy)	2 Operators
B. Maintenance		
1. Spreading	Grader (135-150 hp)	Operator Foreman
2. Compaction	Vibratory Roller or others (80-100 hp)	Operator Foreman
3. Hauling Aggregate	Dump Trucks (10 cy)	2 Operators
C. Aggregate Recovery		
1. Scraping Aggregate	Motor Grader or Dozer (100 hp)	Operator Foreman
2. Loading Aggregate	Front End Loader (3-4 cy)(150-200 HP)	Operator
3. Hauling Aggregate	2 Dump Trucks (10 cy)	2 Operators

hp = Horsepower

cy = Cubic Yard; 1 cy = 0.7645 m^3

8.0 REUSABLE/RECYCLABLE AGGREGATES WITH GEOTEXTILE SEPARATION

8.1 Construction Procedure

The construction procedure for this surface is the same as geotextile and geogrid projects as described in Section 3.1. This surface may recover more aggregate (approximately 90 to 95 percent) compared to the reusable aggregates without geotextile separation (70 percent).

8.2 Maintenance Procedure

The typical maintenance procedure for this surface is the same as geotextile and geogrid projects as described in Section 3.2.

8.3 Recovery Procedure

The typical procedure for the recovery of the reusable/recyclable aggregate with geotextile separation consists of the following steps:

a) Non reusable geotextiles (follow steps 1 and 2).

b) Recoverable geotextile (follow steps 1 through 7).

1) Scraping Aggregate. Aggregate should be scraped as close to the top of the geotextile as possible, without disturbing and damaging the geotextile, using a dozer or grader, and a front end loader.

2) Stockpiling and Loading of the Recovered Aggregate. The recovered aggregate should be stockpiled at the lower portion of the road and then loaded into dump trucks and hauled to the next project using a loader.

3) Exposing the Edge of Geotextile. After scraping the aggregate as close to the top of the geotextiles as possible, the edge of the geotextile should be removed from the surface layer using shovels, by a three-man team.

4) Preparation for Sewing. After exposing at least 3 feet (0.91 m) of the edge of the geotextile, the recovery system should be laid on top of the geotextile for sewing.

5) Sewing Fabric Around the Beam. The fabric should be sewn around the beam starting at one end using a three-man team. Two men are needed to hold the fabric firmly and a third man to sew the fabric around the recovery beam.

6) Attaching the Recovery System. Turnbuckles are attached to the beam connections, and one end of each cable to a turnbuckle. Then the other end of the cables are attached to a safety shackle. Finally, the safety shackle is attached to the end of the front end loader, dozer, or similar construction equipment.

7) Pulling the Fabric. After attaching the shackle to the end of the construction equipment, the tension on the cables is adjusted using the turnbuckles. Finally, the fabric is pulled. The length of remaining aggregate and fabric pulled should be limited to

25 feet (7.62 m) at a time to avoid overstressing the fabric. The aggregate pile should then be removed, and the recovery cycle should be repeated until all of the fabric and aggregates are recovered. Moving and sewing the recovery beam every 25 feet is not necessary. It may be desirable to leave it in one position for recovering a 50, or 100 foot length of fabric. Reference (6) provides additional details for the construction of the reusable/recyclable aggregates with geotextile separation.

8.4 Equipment and Labor Requirements

An itemized list of the typical equipment and labor requirements for construction and maintenance of the reusable/recyclable aggregate with geotextile separation is given in Table A-10.

9.0 MEMBRANE ENCAPSULATED SOIL LAYER (MESL)

9.1 Construction Procedures

The procedure for the construction of MESL, which was developed at the U.S. Army Corps of Engineers Waterway Experiment Station (15), is as follows:

1) Excavating and Stockpiling. The fine-grained soil should be excavated and stockpiled for reuse to the thickness desired along the roadside with a dozer or grader. Its moisture content should be adjusted, if necessary, to 2 to 3 percent below the optimum moisture content for the specified compaction.

Table A-10. Suggested Equipment and Labor Requirements. (Reusable Aggregate with Geotextile Separation)

Activity	Equipment	Labor
A. Construction		
1. Geotextile Placement	-	Foreman 3 laborers
2. Spreading	Dozer (200 hp)	Operator Foreman
3. Compaction	Vibratory Roller (80-100 hp)	Operator Foreman
4. Hauling Aggregate	2 Dump Trucks (10 cy)	2 Operators
B. Maintenance		
1. Spreading	Grader (135-150 hp)	Operator Foreman
2. Compaction	Vibratory Roller (80-100 hp)	Operator Foreman
C. Aggregate Recovery		
1. Excavation	Dozer (100 hp)	Operator
2. Loading	Front End Loader (3-4 cy)(150-200 hp)	Operator
3. Hauling Aggregate	2 Dump Trucks (10 cy)	2 Operators
4. Labor		3 Laborers Foreman
D. Geotextile Recovery[a]		
1. Attaching Recovery System	Recovery System and Geotextile Sewing Machine	Foreman 3 Laborers
2. Pulling Recovery System	Dozer or Loader (3-4 cy)(150-200 hp)	Operator Foreman
3. Dump Trucks	10 cy (2)	2 Operators

[a]This item should be deleted if a light geotextile is used as a separation layer and only the aggregate is recovered.

hp = Horsepower

cy = cubic yard; 1 cy = 0.7345 m^3

2) Subgrade Preparation. The subgrade should be graded and compacted with a sheepsfoot, rubber-tired, or vibratory roller.

3) Asphalt Emulsion Application on the Subgrade. Emulsified asphalt (CRS-2) should be applied to the subgrade using a distributor at a temperature of 140°F (60°C) and an application rate of 0.30 gal/yd^2 (1.36 liters/m^2). This serves as a sealant under the bottom membrane and is helpful in holding the membrane in place during windy conditions.

4) Placement of Bottom Membrane. The bottom membrane should be polyethylene approximately 6 mil (0.0254 mm) thick or heavier and should be rolled out onto the subgrade using a 3-man team. The membrane should be placed in 100-foot (30.5 m) sections with 1 foot (0.3 m) overlapping transverse joints and in widths sufficient to provide a 2-foot (0.6 m) overlapping longitudinal joint with the top membrane. All joints must be completely sealed with asphalt emulsion. One piece membranes are preferable.

5) Placement of MESL Fill Materials. After the polyethylene film is placed on the prepared subgrade, the excavated soil is replaced and spread using a front end loader, and dozer. It is then compacted to the desired density and moisture content using a sheepsfoot roller or other type suitable for the fill

material. It is also recommended that the final compaction of the fill material be accomplished with a rubber-tired roller.

If the required compacted depth of the fill materials exceeds 6 inches (15.24 cm), it should be placed in two or more layers of approximately equal thickness. The maximum compacted thickness of any one layer shall not exceed 6 inches (15.24 cm).

6) Surface Preparation for Placement of Top Membrane. Before placement of the top membrane, the surface of the fill material should be sprinkled lightly with water to prevent balling of the emulsified asphalt (CRS-2) in the dry surface dust. Then, asphalt emulsion should be sprayed onto the surface using the same rate used on the subgrade, 0.3 gal/yd^2 (1.36 liters/m^2), before placement of the top membrane.

7) Placement of the Top Membrane. The top membrane should be a nonwoven polypropylene needle-punched fabric with a unit weight of approximately 3 to 5 oz/yd^2 (0.07 to 0.12 kg/m^2), available in 300-foot (30.5 m) rolls, 15.5 feet (4.7 m) wide. It should be rolled out onto the prepared subgrade by a 3-man team. The longitudinal joints should be overlapped 1 foot (0.3 m), thus, the width should be sufficient to make the lapped joints with the bottom membrane at the roadway shoulder line.

8) Asphalt Emulsion Application on the Top Membrane. Another application of asphalt emulsion (CRS-2) should be sprayed on the top of the top membrane at an application rate of 0.3 gal/yd^2 (1.36 liters/m^2) after the bottom membrane is folded up over the ends of the fill to make a sealed joint with the top membrane.

9) Final Surface Layer. About 2 inches (5.08 cm) of clean sand should be spread as a blotting and cushioning layer on the emulsion-coated top membrane. The polypropylene nonwoven fabric with asphalt and sand provides a tough trafficable surface suitable for temporary use.

9.2 Maintenance Procedures

The most typical maintenance problem would be the replacement or repair of the surfacelayer by tapplying another application of the asphalt emulsion (CRS-2) on top of the polypropylene fabric layer and covering it with sand.

9.3 Equipment and Labor Requirements

An itemized list of the typical equipment and labor requirements for construction and maintenance of the MESL is given in Table A-11.

10.0 GEOWEB STABILIZATION (EXPANDABLE GRIDS

10.1 Construction Procedures

The procedure for the construction of the expandable grids, developed by the manufacturer (Presto Products, Inc.) and tested by

Table A-11. Suggested Equipment and Labor Requirements.
(Membrane Encapsulated Soil Layer (MESL))

Activity	Equipment	Labor
A. Construction		
1. Ripping	Dozer or Grader (135-180 hp) with Hydraulic Ripper	Operator Foreman
2. Excavation	Rubber Tired Grader, Dozer, or Track Mounted Loader (3-4 cy)(150-200 hp)	Operator Foreman
3. Stockpiling	2 Dump Trucks (12 cy)	2 Operators
4. Placement of Membrane	-	4 Laborers Foreman
5. Asphalt Application	Asphalt Distributor (3000 gal)	Operator
6. Hauling Fill Materials	2 Dump Trucks (10 cy)	2 Operators
7. Loading	Loader-Crawler (3-4 cy) (150-200 hp)	Operator
8. Spreading	Dozer or Grader (135-180 hp)	Operator Foreman
9. Compaction	Vibratory Roller Sheepsfoot, or others (50-80 hp)	Operator Foreman
10. Watering	Water Truck (5000 gal)	Operator
B. Maintenance		
1. Spreading and Grading	Dozer or Grader (135-150 hp)	Operator Foreman
2. Compaction	Vibratory Roller, or others (80-100 hp)	Operator Foreman
3. Asphalt Application	Asphalt Distributor (3000 gal)	Operator

the U.S. Army Corps of Engineers Waterway Experiment Station (36), is as follows:

1) Subgrade Preparation. The subgrade should be carefully prepared to give a level surface at the elevation necessary to provide the roadway surface configuration required. This is accomplished using a road grader.

2) Geoweb Placement. The geoweb sections should be unfolded and stretched out on the prepared subgrade. Four to six men are needed to stretch the grid sections to the desired dimensions. The stretched grid sections should be held in place by wooden stakes driven at the corners. To anchor the grids in the desired positions further, a few cells along the edges should be filled by hand with sand.

3) Filling the Cells. After the geoweb has been expanded and positioned, the network of cells should be filled in, with native fill, using a rubber-tired front-end loader.

4) Spreading the Fill Materials. The fill material should be spread with a dozer-type machine that has a short blade to control the thickness of the fill materials over the geowebs. The compacted thickness of the materials above the geoweb should be between 1 and 4 inches (7.62 to 10.16 cm).

5) Compaction. After the cells are filled and the materials are leveled, compaction should be applied to achieve 95 percent of standard AASHTO T99 using a rubber-tired or vibrating drum roller.

6) Final Grading. After compaction, the surface should be graded to within 1 inch (2.54 cm) or less of the top of the cells using a small motor grader with a narrow blade.

7) Asphalt Emulsion Placement. The final step is to apply the asphalt emulsion (CSS-1). Laboratory testing to assure the asphalt will penetrate is essential. The surface of the fill materials should be sprinkled lightly with water to prevent balling of the asphalt emulsion in the dry surface dust. Then asphalt emulsion should be applied onto the surface at a rate of 1 gal/yd^2 (4.55 liters/m^2) using an asphalt distributor with a 12-foot (3.66 m) spray bar. The distributor may not be able to drive directly on the sand at this point without rutting the surface.

10.2 Maintenance Procedures

The only maintenance problem likely is the replacement of a grid section that has been seriously distressed and applying another application of the asphalt emulsion on top of the surface. The replacement of the grids follows the construction process described above in the construction procedure section.

10.3 Equipment and Labor Requirements

An itemized list of the typical equipment and labor requirements for construction and maintenance of the expandable grids is given in Table A-12.

Table A-12. Suggested Equipment and Labor Requirements.

(Geoweb Stabilization)

Activity	Equipment	Labor
A. Construction		
1. Grading	Dozer (100 hp)	Operator Foreman
2. Compaction	Vibratory Roller (80-100 hp)	Operator Foreman
3. Geoweb Placement	-	4 Laborers
4. Hauling Fill Materials	Loader (2-3 cy) (100-150 hp)	Operator
	3 Dump Trucks	
5. Spreading	Dozer (100 hp)	Operator Foreman
6. Asphalt Application	Asphalt Distributor With Spray Bar (3000 gal)	Operator
B. Maintenance		
1. Geoweb Excavation and Placement	Loader (1-1.5 cy) (50-80 hp)	Operator Foreman 4 Laborers
2. Loading and Hauling Fill Material	Loader and Dump Trucks (5-10 cy)	Operator 3 Operators
3. Spreading and Grading	Grader (100 hp)	Operator Foreman

hp = Horsepower
cy = Cubic Foot
1 cy = $0.7645m^3$

APPENDIX B

REQUIREMENTS, PROPERTIES, AND COSTS OF ALTERNATE MATERIALS

Table B.1.a. General Properties of Alternate Surfacing - Geotextile Mats, Expandable Grids, Tensar Grids

Type of Material	Manufacturer	Dimension	Weight	Material Cost	Mechanical Properties	Availability	References
Paraweb	Linear Composites, Ltd. Hookstone Road Harrogate North Yorkshire England HG28QN 0423 68021 Telex: 579451C1F1BG	L = 66 to 100' W = 14.5'	From 0.10 -0.60 lb/ft^2	N/A	Tensile strength range from 1900 to 8000 lb/ft^2	Good; Linear Composites, Ltd.	Manufacturer's catalog
Mammothmat	Robusta Tech. Fabrics PO Box 41 8280AA Genemuiden, Holland 05208-54866 Telex: 42454 TELENL	L = 33 to 164' W = 3.3 to 16.5'	3 lb/ft^2	5.50/ft^2	Tensile strength = 116 Psi in length direction; = 290 in cross section	Not available at the present time in the U.S.A	Manufacturer's catalog
Expandable Grids (Geoweb)	Presto Products PO Box 2399 Appleton, WI 54913 800/558-3525	Expanded size 8'x20'x8" Shipping size = 11'x5"x8" Thickness = 0.047". Cell area = 41 in^2	5.7 lb/yd^2 Shipping wt. = 110 lbs.	0-180,000 = 1.25/ft^2; 180,000 - 360,000 = 1.15/ft^2 > 360,000 = \$1.05/ft^2	Seam's tensile peel strength 150 lbs.	Good	Manufacturer's catalog
Tensar Grids (SS1)	Nelton Limited Kelly Street Blackburn, England BB24PJ 0254-62431 Telex: 63313	Roll length = 164'; Roll width = 9.8'	Roll weight = 67 lbs.	\$1.3/yd^2	Tensile strength Across roll width width 1430 lb/ft. Along roll length 860 lb/ft	Good; currently in production	Manufacturer's catalog

L = length; W = width; D = depth; N/A = not available

1 in = 25.4 mm; 1 ft = 0.3048 m; 1 ft^2 = 0.0929 m^2; 1 lb = 0.4536 kg; 1 psi = 6.895 KPa

Table B.1.b. Design Requirements of Alternate Surfacing Materials - Geotextile Mats, Expandable Grids, Tensar Grids.

Type of Material	APPLICABLE CONDITIONS FOR MATERIAL: Subgrade Type	Climate	Topography	Design Vehicle	Expected Life	Information Need for Design	Type of Road After Removal	References
Paraweb	Sand & gravel	Cold and snow	Moderate grades	Tanks and military vehicles	Expected to be short to moderate	N/A	Native soil, sand, or gravel	Manufacturer's catalog
Mammothmat	Soft clay or loose sands	Not important	Steep grades up to 30%	Tanks and 64 wheel vehicles total weight 133 tons	Expected to be short to moderate	N/A	Native soil, sand, or gravel	Manufacturer's catalog
Expandable Grids (Geoweb)	Soft soils & sand beach	Not important	May have some difficulty when used on steep grades.	Tandem axle truck load of 53,000 lbs.	10,000 passes or more	Types of soil and traffic	Native soil, sand, or gravel	Manufacturer's catalog

Table B.1.c. Special Construction and Maintenance Requirements - Geotextile Mats, Expandable Grids, Tensar Grids.

Type of Material	Installation Procedures	Removal Procedures	Storage Requirements	Quality Control Needs	Environmental Problems	Maintenance Requirements	References
Interwoven Paraweb	Mats can be laid at rate of 1 min per running meter using a 4-man team. Mats are secured to the ground at ends/edges	Can be rolled very easily	Supplied in rolls; overall dimension of 30 m; long roll has approximate dimensions of D = 32"; L = 185"	N/A	None	Mats must be checked to make sure sides are secured to the ground	Manufacturer's catalog
Mammothmat	Easy; roll in and out.	Can be rolled very easily	Moderate	N/A	None	N/A	Manufacturer's catalog
Expandable Grids	Easy; grids are expanded, placed on prepared terrain and filled with sand which is compacted by a 4-man team.	Cannot be removed; a 1" layer of asphalt emulsion is sprayed on the surface of compacted native fill	Truck load quantity is 374 sections; covers 60,000 ft^2; approximately 1 truckload/ lane.	N/A	None	May be necessary to to apply emulsion every few years	Manufacturer's catalog
Tensar Grids (SS1)	Easy; grids can be rolled out easily onto a subgrade that has been previously cleared of rigid obstructions.	Can be removed but may require extensive labor to remove the top material	Minimal	N/A	None	Maintenance	Manufacturer's catalog

1 in = 25.4 mm; 1 ft = 0.3048 m; 1 ft^2 = 0.0929 m^2

Table B.1.d Prior Use - Geotextile Mats, Expandable Grids, Tensar Grids

Type of Material	Project Location & Performing Agency	Project Length (mi)	Construction Cost* ($/mi/lane)	Performance	Remarks
Interwovem Paraweb	England, military	N/A	N/A	Low to moderate	These mats have been used for reusable surfaces. Performance expected to be low. May not be suitable for forest roads due to low performance.
Mammothmat	Holland, military	N/A	400,000*	Moderate	These mats look very promising for reusable surfaces. The materials are not available at the present time in the USA. The use of this material may not be economical for use on temporary or intermittent use roads because the materials are very expensive.
Expandable Grids (Geoweb)	Ft. Story, VA, 1983 (WES)	1/4 mile section	$105,600**	Excellent	Easy installation and high performance. Based on the study at WES and Dr. Bell's trip report, Geoweb can be very suitable for sandy soil. They are not economical for temporary roads because they cannot be removed or reused.
Tensar Grids (SS1)	England, Netlon Limited	N/A	$10,677	Excellent	Grids improve the load bearing characteristics of weak soil. Save in both construction time and in the amount of subbase materials. Can be used as a separation layer with reusable aggregates. Should be recommended for demonstration project.

*assume single lane with a 14-foot lane width.

**assume single lane with a 16-foot lane width.

1 yd^2 = 0.8361 m^2; 1 mile = 1.609 km; 1 KIP = 4.448 KN

Table B.2.a. General Properties of Alternate Surfacing - Aluminum Mats

Type of Material	Manufacturer	Dimension	Weight	Material Cost	Mechanical Properties	Availability	References
Kaiser Aluminum Panel	Kaiser Aluminum 300 Lakeside Drive Oakland, CA 94643 415/271-5625 Telex: 335315	L = 2' up to 110' W = 2' up to 60'	N/A	$60/ft^2$	High strength	Good	Interview w/ Mr. Jim Agness Market. Mgr. Aluminum Div.
Extruded Aluminum 1) AM-2	Taber Metals, Inc. Rt. 1 Airport Rd. Russellville, AR 72801 501/968-1021	L = 12' W = 2' D = 1"	144 lb/ panel 6 lb/ft^2	$1.4/lb $8.33/$ft^2$ $200/panel	Ultimate strength = 38000 Psi Yield strength = 35000 Psi for military use	Good Currently these are produced in in large volume 2/19/84	Telephone call Mr. R.E. Rains VP & Gen. Mgr. Taber Metals, Inc.
2) MK-18	same as above	same as above	114 lb/ panel 4.75 lbs/ ft^2	$1.4/lb $6.65/$ft^2$ $159.6/panel	same as above	same as above	same as above
Aluminum Landing Mats	ALFAB Co. Enterprise, AL 205/347-9616	L = 12' W = 2' D = 1"	144 lb/ panel 6 lb/ft^2	$3.33/lb $20/$ft^2$ $480/panel	Ultimate strength = 40000 Psi duced in large volume for military use	Good Currently pro-	Telephone call 2/24/84
Extruded Aluminum 6063-T6 IAL Swage-Locked Rectangular Bar Aluminum Grating	IKG Industries 1819 Tenth St. Oakland, CA 94607 415/763-6500	L = 24' W = 2 or 3' D = 1" D = 1 1/2"	2.6 lb/ ft^2 3.76 lb/ ft^2	$5.20/$ft^2$ $7.25/$ft^2$	High strength	Good 2/24/84	Telephone call
Other companies:	Kelemp Grating 1132 West Blackhawk St. Chicago, IL 60622 312/440-3855		Borden Gratings 7953 Second Ave., South Seattle, WA 98108 206/762-6400				

L = length; W - width; D = depth; N/A = not available

1 in = 25.4 mm; 1 ft 0.3048 m; 1 ft^2 = 0.0929 m^2; 1 lb = 0.4536 kg; 1 psi = 6.895 KPa

Table B.2.b. Design Requirements of Alternate Surfacing Materials - Aluminum Mats.

	APPLICABLE CONDITIONS FOR MATERIAL							
Type of Material	Subgrade Type	Climate	Topography	Design Vehicle	Expected Life	Information Need for Design	Type of Road After Removal	References
Kaiser Aluminum Panels	Very poor subgrade	Not important	Steep grades	Tanks and military vehicles	More than 4000 passes	None	Native soil, gravel, sand, etc.	Personal interview
Extruded Aluminum 1) AM-2 2) MK-18	Very poor subgrade	Not important. It is corrosion-resistant. Nonrusting	Steep grades	Military vehicles, heavy tanks	More than 3000 passes	None	Native soil, gravel, sand etc.	Telephone call
Aluminum Landing Mats	Very poor subgrade	Not important	Very steep grades	Military vehicles, tanks, C5A aircraft	More than 4000 passes	None	Native soil, gravel, sand, etc.	Telephone call
Extruded Aluminum 6063-T6	Very poor subgrade	Not important since it is corrosion-resistant. Nonrusting.	Very steep grades	None since these panels have been used for industrial usage.	Not known	None	Native soil gravel, sand, etc.	Telephone call

Table B.2.c. Special Construction and Maintenance Requirements - Aluminum Mats.

Type of Material	Installation Procedures	Removal Procedures	Storage Requirements	Quality Control Needs	Environmental Problems	Maintenance Requirements	References
Kaiser Aluminum Panels	Easy; connections & hinges make deployment fast	Easy; depress latches & wedge in open position to permit dis-engagement	Minimal 5280 ft^3/mile 2 ft^3/panel	N/A	None	None	Personal interview 1/31/84
Extruded Aluminum 1) AM-2 and 2) MK-18	Easy; connections & hinges make deployment fast. Mats are laid in brickwork fashion	Easy; connector can be open to permit disen-gagement	Minimal 5280 ft^3/mile 2 ft^3/panel	N/A	None	None	Telephone call
Aluminum Landing Mats	Easy; connections & hinges make deployment fast	Easy; connectors can be open to permit disen-gagement	Minimal 5280 ft^3/mile 2 ft^3/panel	N/A	None	None	Telephone call
Extruded Aluminum 6063-T6 IAL SWAGE-locked Rectangular Aluminum Grating	Easy; individual panels can be joined together by using hinges	Easy	Minimal for D = 1 in 5280 ft^3/mile	N/A	None	None	Telephone call

1 ft^3 = 0.02832 m^3; 1 mile = 1.609 km

Table B.2.d. Prior Use - Aluminum Mats.

Type of Material	Project Location & Performing Agency	Project Length (mi)	Construction Cost* ($/mi/lane)	Performance	Remarks
Kaiser Aluminum Panels	Waterways Experiment Station (WES)	13' x 115'	$4,435,200	Very good; more than 4000 passes	Too expensive; steel mats might be more appropriate.
Extruded Aluminum TABER					
1) AM-2	WES	20' x 120'	$615,753	Very good; more than 3000 passes	Too expensive; based on the life cycle cost may be economical. It has high salvage value about 45 to 50% of the original cost.
2) MK-18	WES	20' x 120'	$491,568		
Aluminum Landing Mats (ALFAB Co)	WES	N/A	$1,478,400	Very good; more than 4000 passes	Too expensive; materials purchased from Taber Co. Finished to the military specification and sold at this high price.
Extruded Aluminum 6063-T6 IAL Swage-Locked Rectangular Aluminum Grating (IKG)	Has not been tested	-	D = 1 in $384,384 D = 1 1/2 in $535,920	Not known	Moderate cost compared to the other aluminum mats; material has not been for reusable surfaces. Basically used for commercial & industrial applications.

Note: Strength is one of the greatest advantages of aluminum panels.
Aluminum panels are available in variable widths and lengths, which can significantly reduce the installation labor cost.
Assembly rate is about 400 square feet per man hour by two man teams or 79.2 hr/mile/lane by a two-man team.
Aluminum panels are strong, lightweight, maintenance-free, easy to install, remove, and store.
It has high salvage value about 45 to 50 percent of the original cost.
It may not be economical for U.S. Forest applications due to high initial cost.

*Assume single lane with a 14-foot lane width.

1 in. - 15.4 mm; 1 ft = 0.3048 m

Table B.3.a. General Properties of Alternate Surfacing - Steel Mats

Type of Material	Manufacturer	Dimension	Weight	Material Cost	Mechanical Properties	Availability	References
M8A1 Rolled Steel Landing Mat	Republic Steel Mfg. Div. 1315 Albert St. Youngstown, OH 44505 216/742-5600	L = 142" W = 19.5" D = 1/8"	144 lb/ panel 7.5 lb/ft^2	\$1.06/ft^2 (in 1960)	N/A	Not in production	Telephone call (15)
Steel Grating Panels (welded tread) ASTM A-569	Bordon Metal Products 7953 Second Ave., S. Seattle, WA 98108 206/762-6400	L = 24' W = 3' Bar size: 1 x 1/8"	5.2 lb/ ft^2	\$2.48/ft^2	High strength	Good; currently in production in various sizes and thicknesses	Telephone call 2/24/84
	1 1/2 x 1/8"	7.4 lb/ ft^2	\$3.46/ft^2				
Steel Grating Panels (welded rectangular)	IKG Industries 1819 Tenth St. Oakland, CA 94607 415/763-6500	L = 20 or 24' W = 2 or 3' Bar size: 1 x 1/8"	5.2 lb/ ft^2	\$2.41/ft^2	High strength	Same as above	Telephone call 2/24/84
	1 1/2 x 1/8"	7.4 lb/ ft^2	\$3.20/ft^2				

Other suppliers: Kelemp Corporation
1132 West Blackhawk St.
Chicago, IL 60622
312/440-3855

L = length; W = width; D = depth; N/A = not available

1 in = 25.4 mm; 1 ft = 0.3048 m; 1 ft^2 = 0.0929 m^2; 1 lb = 0.4536 kg; 1 psi = 6.895 PKa

Table B.3.b. Design Requirements of Alternate Surfacing Materials - Steel Mats.

Type of Material	APPLICABLE CONDITIONS FOR MATERIAL Subgrade Type	Climate	Topography	Design Vehicle	Expected Life	Information Need for Design	Type of Road After Removal	References
M8A1 Rolled Steel Landing Mat	Sand sub-grade corrosion problems	Dry climate to prevent	N/A vehicles	Tanks and military	More than 3000 passes	None gravel	Native soil, sand or	(31) and telephone call
Steel Grating Panels (welded treads) ASTM A-569	Sand sub-grade problems	Dry climate to prevent corrosion	N/A	All vehicles	Not known; has not been tested	None	Native soil, sand or	Telephone call
Steel Grating Panels (welded rectangular)	Same as above	Same as above	Same as above	N/A	Same as above	Same as above	Same as above	Same as above

Table B.3.c. Special Construction and Maintenance Requirements - Steel Mats.

Type of Material	Installation Procedures	Removal Procedures	Storage Requirements	Quality Control Needs	Environmental Problems	Maintenance Requirements	References
M8Al Rolled Steel Landing Mat	Easy; panels are connected together with H connectors	Easy	Minimal 5280 ft^3/mile 1.8 ft^3/panel	None	Corrosion	None	(31)
Steel Grating Panels (welded tread) ASTM Z-569	Easy; but the handling may be difficult due to weight	Handling may be difficult due to weight	Minimal 5280 ft^3.mile 6 ft^3/panel	None	Corrosion	None	Telephone call
Steel Grating Panels (welded rectangular)	Same as above	Same as above	Same as above	Same as above	Same as above	Same as above	Same as above

1 ft^3 = 0.02832 m^3; 1 mile = 1.609 km

Table B.3.d. Prior Use - Steel Mats.

Type of Material	Project Location & Performing Agency	Project Length (mi)	Construction Cost* ($/mi/lane)	Performance	Remarks
M8A1 Rolled Steel Landing Landing Mats	Waterways Experiment Station (WES)	15' x 19.5'	$78,355 (in 1960)	Excellent; more than 3000 passes	Excellent performance. Attractive alternative for temporary roads; unfortunately it is no longer in production.
Steel Grating Panels (welded tread) ASTM A-569 (Borden Co.)	Has not been tested for reusable surfaces	Has not been tested for reusable surfaces	$183,321 for 1 x 1/8 in. bar size $255,763 for 1-1/2 x 1/8 in. bar size	Not known; but expected to be high	Strong, heavy. Lower cost than aluminum fiberglass panels. The material has not been tested. Has been used for commercial and industrial applications. May be suitable for reusable surfaces.
Steel Grating Panels (welded rectangular) (IKG Co.)	Has not been tested for reusable surfaces	Has not been tested for reusable surfaces	$178,147 for 1 x 1/8 in. bar size $236,544 for 1-1/2 x 1/8 in. bar size	Same as above	Same as above

Note: The steel panels are strong with very high ultimate strength.
The cost is relatively low compared to aluminum and fiberglass panels.
M8A1 steel panels have been tested in WES with excellent test results for reusable surfaces, but unfortunately it is no longer in production.
Other steel panels, such as steel grating panels by IKG Industries, Borden Metal Products, and Kelemp Corporation, that have been used for commercial or industrial applications can be easily applicable for reusable surfaces in forests.

* assumes single lane with a 14-foot lane width.

1 in. = 25.4 mm; 1 ft = 03048 m

APPENDIX C

COMPOUND INTEREST TABLES

Figure C-1 (50)

STANDARD CASH FLOW FACTORS

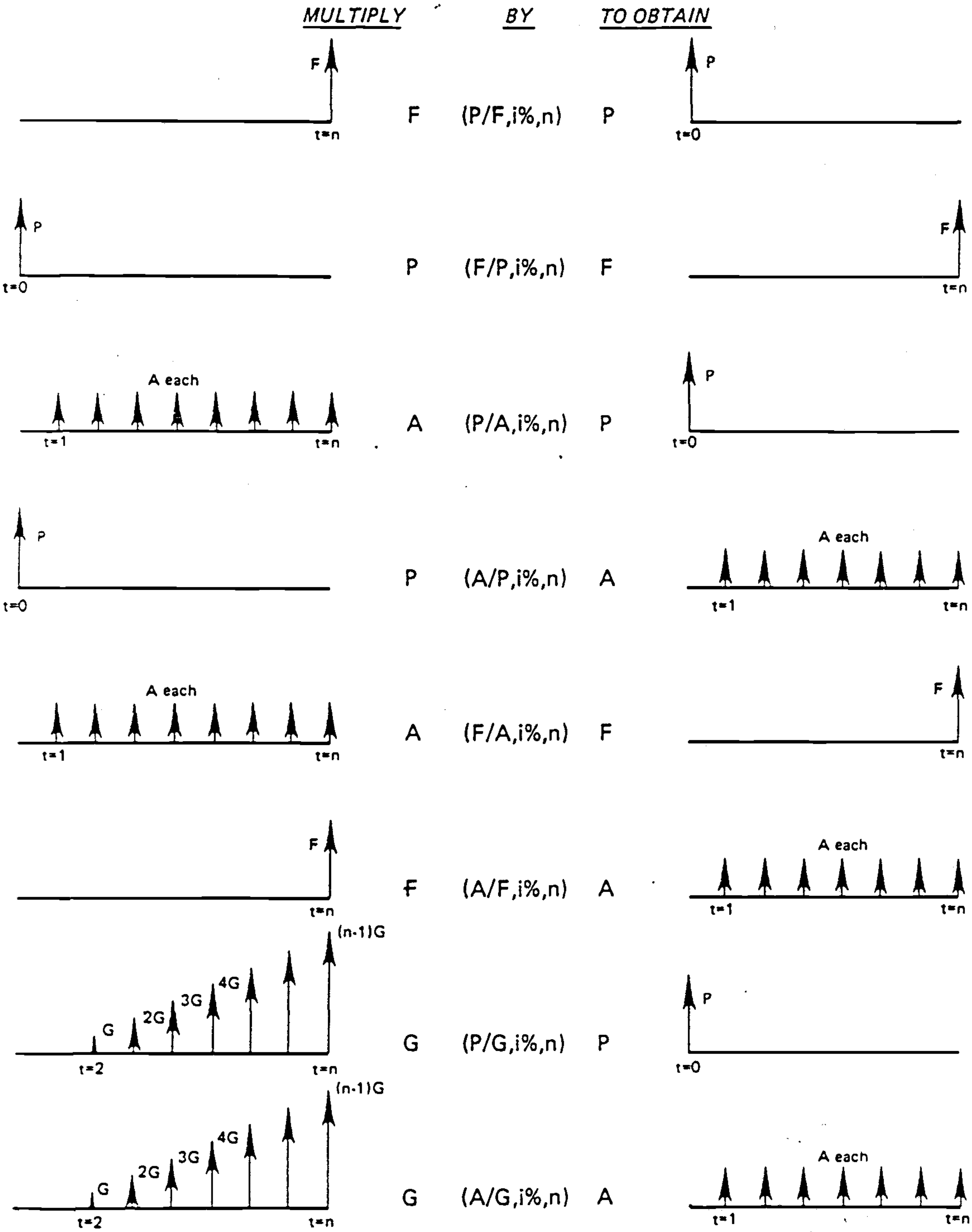

Table C-1 Typical Examples Using the Compound Interest Tables (39)

SUMMARIZATION OF DISCRETE COMPOUND INTEREST FACTORS AND SYMBOLS

To find	*Given*	*Multiply "Given" by factor below*	*Factor name*	*Factor functional symbol*	*Example (answer for i = 5%) (Note: All uniform series problems assume end of period payments.)*
F	*P*	$(1+i)^N$	Single sum compound amount	$(F/P,i\%,N)$	A firm borrows $1,000 for 5 years. How much must it repay in a lump sum at the end of the fifth year? *Ans.:* $1,276
P	*F*	$\frac{1}{(1+i)^N}$	Single sum present worth	$(P/F,i\%,N)$	A company desires to have $1,000 8 years from now. What amount is needed now to provide for it? *Ans.:* $676.84
P	*A*	$\frac{(1+i)^N-1}{i(1+i)^N}$	Uniform series present worth	$(P/A,i\%,N)$	How much should be deposited in a fund to provide for 5 annual withdrawals of $100 each? *Ans.:* $432.95
A	*P*	$\frac{i(1+i)^N}{(1+i)^N-1}$	Capital recovery	$(A/P,i\%,N)$	What is the size of 10 equal annual payments to repay a loan of $1,000? First payment 1 year after receiving loan. *Ans.:* $129.50
F	*A*	$\frac{(1+i)^N-1}{i}$	Uniform series compound amount	$(F/A,i\%,N)$	If 4 annual deposits of $2,000 each are placed in an account, how much money has accumulated immediately after the last deposit? *Ans.:* $8,620
A	*F*	$\frac{i}{(1+i)^N-1}$	Sinking fund	$(A/F,i\%,N)$	How much should be deposited each year in an account in order to accumulate $10,000 at the time of the fifth annual deposit? *Ans.:* $1,809.70

Key: i = Interest rate per interest period; N = Number of interest periods; A = Uniform series amount; F = Future worth; P = Present worth

Table C-2 Compound Interest Factors (40)

1% compound interest factors

	Single payment		Uniform series				Uniform gradient		
n	Compound amount factor F/P	Present worth factor P/F	Sinking fund factor A/F	Capital recovery factor A/P	Compound amount factor F/A	Present worth factor P/A	Gradient conversion factor A/G	Present worth factor P/G	n
1	1.0100	0.9901	1.000 00	1.010 00	1.000	0.990	0.000	0.000	1
2	1.0201	0.9803	0.497 51	0.507 51	2.010	1.970	0.498	0.980	2
3	1.0303	0.9706	0.330 02	0.340 02	3.030	2.941	0.993	2.921	3
4	1.0406	0.9610	0.246 28	0.256 28	4.060	3.902	1.488	5.804	4
5	1.0510	0.9515	0.196 04	0.206 04	5.101	4.853	1.980	9.610	5
6	1.0615	0.9420	0.162 55	0.172 55	6.152	5.795	2.471	14.321	6
7	1.0721	0.9327	0.138 63	0.148 63	7.214	6.728	2.960	19.917	7
8	1.0829	0.9235	0.120 69	0.130 69	8.286	7.652	3.448	26.381	8
9	1.0937	0.9143	0.106 74	0.116 74	9.369	8.566	3.934	33.696	9
10	1.1046	0.9053	0.095 58	0.105 58	10.462	9.471	4.418	41.843	10

2% compound interest factors

	Single payment		Uniform series				Uniform gradient		
n	Compound amount factor F/P	Present worth factor P/F	Sinking fund factor A/F	Capital recovery factor A/P	Compound amount factor F/A	Present worth factor P/A	Gradient conversion factor A/G	Present worth factor P/G	n
1	1.0200	0.9804	1.000 00	1.020 00	1.000	0.980	0.000	0.000	1
2	1.0404	0.9612	0.495 05	0.515 05	2.020	1.942	0.495	0.961	2
3	1.0612	0.9423	0.326 75	0.346 75	3.060	2.884	0.987	2.846	3
4	1.0824	0.9238	0.242 62	0.262 62	4.122	3.808	1.475	5.617	4
5	1.1041	0.9057	0.192 16	0.212 16	5.204	4.713	1.960	9.240	5
6	1.1262	0.8880	0.158 53	0.178 53	6.308	5.601	2.442	13.680	6
7	1.1487	0.8706	0.134 51	0.154 51	7.434	6.472	2.921	18.903	7
8	1.1717	0.8535	0.116 51	0.136 51	8.583	7.325	3.396	24.878	8
9	1.1951	0.8368	0.102 52	0.122 52	9.755	8.162	3.868	31.572	9
10	1.2190	0.8203	0.091 33	0.111 33	10.950	8.983	4.337	38.955	10

3% compound interest factors

	Single payment		Uniform series				Uniform gradient		
n	Compound amount factor F/P	Present worth factor P/F	Sinking fund factor A/F	Capital recovery factor A/P	Compound amount factor F/A	Present worth factor P/A	Gradient conversion factor A/G	Present worth factor P/G	n
1	1.0300	0.9709	1.000 00	1.030 00	1.000	0.971	0.000	0.000	1
2	1.0609	0.9426	0.492 61	0.522 61	2.030	1.913	0.493	0.943	2
3	1.0927	0.9151	0.323 53	0.353 53	3.091	2.829	0.980	2.773	3
4	1.1255	0.8885	0.239 03	0.269 03	4.184	3.717	1.463	5.438	4
5	1.1593	0.8626	0.188 35	0.218 35	5.309	4.580	1.941	8.889	5
6	1.1941	0.8375	0.154 60	0.184 60	6.468	5.417	2.414	13.076	6
7	1.2299	0.8131	0.130 51	0.160 51	7.662	6.230	2.882	17.955	7
8	1.2668	0.7894	0.112 46	0.142 46	8.892	7.020	3.345	23.481	8
9	1.3048	0.7664	0.098 43	0.128 43	10.159	7.786	3.803	29.612	9
10	1.3439	0.7441	0.087 23	0.117 23	11.464	8.530	4.256	36.309	10

Table C-2 Compound Interest Factors (40) (continued)

4% compound interest factors

	Single payment		Uniform series				Uniform gradient		
n	Compound amount factor F/P	Present worth factor P/F	Sinking fund factor A/F	Capital recovery factor A/P	Compound amount factor F/A	Present worth factor P/A	Gradient conversion factor A/G	Present worth factor P/G	n
1	1.0400	0.9615	1.000 00	1.040 00	1.000	0.962	0.000	0.000	1
2	1.0816	0.9246	0.490 20	0.530 20	2.040	1.886	0.490	0.925	2
3	1.1249	0.8890	0.320 35	0.360 35	3.122	2.775	0.974	2.703	3
4	1.1699	0.8548	0.235 49	0.275 49	4.246	3.630	1.451	5.267	4
5	1.2167	0.8219	0.184 63	0.224 63	5.416	4.452	1.922	8.555	5
6	1.2653	0.7903	0.150 76	0.190 76	6.633	5.242	2.386	12.506	6
7	1.3159	0.7599	0.126 61	0.166 61	7.898	6.002	2.843	17.066	7
8	1.3686	0.7307	0.108 53	0.148 53	9.214	6.733	3.294	22.181	8
9	1.4233	0.7026	0.094 49	0.134 49	10.583	7.435	3.739	27.801	9
10	1.4802	0.6756	0.083 29	0.123 29	12.006	8.111	4.177	33.881	10

5% compound interest factors

	Single payment		Uniform series				Uniform gradient		
n	Compound amount factor F/P	Present worth factor P/F	Sinking fund factor A/F	Capital recovery factor A/P	Compound amount factor F/A	Present worth factor P/A	Gradient conversion factor A/G	Present worth factor P/G	n
1	1.0500	0.9524	1.000 00	1.050 00	1.000	0.952	0.000	0.000	1
2	1.1025	0.9070	0.487 80	0.537 80	2.050	1.859	0.488	0.907	2
3	1.1576	0.8638	0.317 21	0.367 21	3.153	2.723	0.967	2.635	3
4	1.2155	0.8227	0.232 01	0.282 01	4.310	3.546	1.439	5.103	4
5	1.2763	0.7835	0.180 97	0.230 97	5.526	4.329	1.903	8.237	5
6	1.3401	0.7462	0.147 02	0.197 02	6.802	5.076	2.358	11.968	6
7	1.4071	0.7107	0.122 82	0.172 82	8.142	5.786	2.805	16.232	7
8	1.4775	0.6768	0.104 72	0.154 72	9.549	6.463	3.245	20.970	8
9	1.5513	0.6446	0.090 69	0.140 69	11.027	7.108	3.676	26.127	9
10	1.6289	0.6139	0.079 50	0.129 50	12.578	7.722	4.099	31.652	10

6% compound interest factors

	Single payment		Uniform series				Uniform gradient		
n	Compound amount factor F/P	Present worth factor P/F	Sinking fund factor A/F	Capital recovery factor A/P	Compound amount factor F/A	Present worth factor P/A	Gradient conversion factor A/G	Present worth factor P/G	n
1	1.0600	0.9434	1.000 00	1.060 00	1.000	0.943	0.000	0.000	1
2	1.1236	0.8900	0.485 44	0.545 44	2.060	1.833	0.485	0.890	2
3	1.1910	0.8396	0.314 11	0.374 11	3.184	2.673	0.961	2.569	3
4	1.2625	0.7921	0.228 59	0.288 59	4.375	3.465	1.427	4.946	4
5	1.3382	0.7473	0.177 40	0.237 40	5.637	4.212	1.884	7.935	5
6	1.4185	0.7050	0.143 36	0.203 36	6.975	4.917	2.330	11.459	6
7	1.5036	0.6651	0.119 14	0.179 14	8.394	5.582	2.768	15.450	7
8	1.5938	0.6274	0.101 04	0.161 04	9.897	6.210	3.195	19.842	8
9	1.6895	0.5919	0.087 02	0.147 02	11.491	6.802	3.613	24.577	9
10	1.7908	0.5584	0.075 87	0.135 87	13.181	7.360	4.022	29.602	10

Table C-2 Compound Interest Factors (40) (continued)

7% compound interest factors

	Single payment		Uniform series				Uniform gradient		
n	Compound amount factor F/P	Present worth factor P/F	Sinking fund factor A/F	Capital recovery factor A/P	Compound amount factor F/A	Present worth factor P/A	Gradient conversion factor A/G	Present worth factor P/G	n
1	1.0700	0.9346	1.000 00	1.070 00	1.000	0.935	0.000	0.000	1
2	1.1449	0.8734	0.483 09	0.553 09	2.070	1.808	0.483	0.873	2
3	1.2250	0.8163	0.311 05	0.381 05	3.215	2.624	0.955	2.506	3
4	1.3108	0.7629	0.225 23	0.295 23	4.440	3.387	1.416	4.795	4
5	1.4026	0.7130	0.173 89	0.243 89	5.751	4.100	1.865	7.647	5
6	1.5007	0.6663	0.139 80	0.209 80	7.153	4.767	2.303	10.978	6
7	1.6058	0.6227	0.115 55	0.185 55	8.654	5.389	2.730	14.715	7
8	1.7182	0.5820	0.097 47	0.167 47	10.260	5.971	3.147	18.789	8
9	1.8385	0.5439	0.083 49	0.153 49	11.978	6.515	3.552	23.140	9
10	1.9672	0.5083	0.072 38	0.142 38	13.816	7.024	3.946	27.716	10

8% compound interest factors

	Single payment		Uniform series				Uniform gradient		
n	Compound amount factor F/P	Present worth factor P/F	Sinking fund factor A/F	Capital recovery factor A/P	Compound amount factor F/A	Present worth factor P/A	Gradient conversion factor A/G	Present worth factor P/G	n
1	1.0800	0.9259	1.000 00	1.080 00	1.000	0.926	0.000	0.000	1
2	1.1664	0.8573	0.480 77	0.560 77	2.080	1.783	0.481	0.857	2
3	1.2597	0.7938	0.308 03	0.388 03	3.246	2.577	0.949	2.445	3
4	1.3605	0.7350	0.221 92	0.301 92	4.506	3.312	1.404	4.650	4
5	1.4693	0.6806	0.170 46	0.250 46	5.867	3.993	1.846	7.372	5
6	1.5869	0.6302	0.136 32	0.216 32	7.336	4.623	2.276	10.523	6
7	1.7138	0.5835	0.112 07	0.192 07	8.923	5.206	2.694	14.024	7
8	1.8509	0.5403	0.094 01	0.174 01	10.637	5.747	3.099	17.806	8
9	1.9990	0.5002	0.080 08	0.160 08	12.488	6.247	3.491	21.808	9
10	2.1589	0.4632	0.069 03	0.149 03	14.487	6.710	3.871	25.977	10

9% compound interest factors

	Single payment		Uniform series				Uniform gradient		
n	Compound amount factor F/P	Present worth factor P/F	Sinking fund factor A/F	Capital recovery factor A/P	Compound amount factor F/A	Present worth factor P/A	Gradient conversion factor A/G	Present worth factor P/G	n
1	1.0900	0.9174	1.000 00	1.090 00	1.000	0.917	0.000	0.000	1
2	1.1881	0.8417	0.478 47	0.568 47	2.090	1.759	0.478	0.842	2
3	1.2950	0.7722	0.305 05	0.395 05	3.278	2.531	0.943	2.386	3
4	1.4116	0.7084	0.218 67	0.308 67	4.573	3.240	1.393	4.511	4
5	1.5386	0.6499	0.167 09	0.257 09	5.985	3.890	1.828	7.111	5
6	1.6771	0.5963	0.132 92	0.222 92	7.523	4.486	2.250	10.092	6
7	1.8280	0.5470	0.108 69	0.198 69	9.200	5.033	2.657	13.375	7
8	1.9926	0.5019	0.090 67	0.180 67	11.028	5.535	3.051	16.888	8
9	2.1719	0.4604	0.076 80	0.166 80	13.021	5.995	3.431	20.571	9
10	2.3674	0.4224	0.065 82	0.155 82	15.193	6.418	3.798	24.373	10

Table C-2 Compound Interest Factors (40) (continued)

10% compound interest factors

n	Single payment: Compound amount factor F/P	Single payment: Present worth factor P/F	Uniform series: Sinking fund factor A/F	Uniform series: Capital recovery factor A/P	Uniform series: Compound amount factor F/A	Uniform series: Present worth factor P/A	Uniform gradient: Gradient conversion factor A/G	Uniform gradient: Present worth factor P/G	n
1	1.1000	0.9091	1.000 00	1.100 00	1.000	0.909	0.000	0.000	1
2	1.2100	0.8264	0.476 19	0.576 19	2.100	1.736	0.476	0.826	2
3	1.3310	0.7513	0.302 11	0.402 11	3.310	2.487	0.937	2.329	3
4	1.4641	0.6830	0.215 47	0.315 47	4.641	3.170	1.381	4.378	4
5	1.6105	0.6209	0.163 80	0.263 80	6.105	3.791	1.810	6.862	5
6	1.7716	0.5645	0.129 61	0.229 61	7.716	4.355	2.224	9.684	6
7	1.9487	0.5132	0.105 41	0.205 41	9.487	4.868	2.622	12.763	7
8	2.1436	0.4665	0.087 44	0.187 44	11.436	5.335	3.004	16.029	8
9	2.3579	0.4241	0.073 64	0.173 64	13.579	5.759	3.372	19.421	9
10	2.5937	0.3855	0.062 75	0.162 75	15.937	6.144	3.725	22.891	10

11% compound interest factors

n	Single payment: Compound amount factor F/P	Single payment: Present worth factor P/F	Uniform series: Sinking fund factor A/F	Uniform series: Capital recovery factor A/P	Uniform series: Compound amount factor F/A	Uniform series: Present worth factor P/A	Uniform gradient: Gradient conversion factor A/G	Uniform gradient: Present worth factor P/G	n
1	1.1100	0.9009	1.000 00	1.110 00	1.000	0.901	0.000	0.000	1
2	1.2321	0.8116	0.473 93	0.583 93	2.110	1.713	0.474	0.812	2
3	1.3676	0.7312	0.299 21	0.409 21	3.342	2.444	0.931	2.274	3
4	1.5181	0.6587	0.212 33	0.322 33	4.710	3.102	1.370	4.250	4
5	1.6851	0.5935	0.160 57	0.270 57	6.228	3.696	1.792	6.624	5
6	1.8704	0.5346	0.126 38	0.236 38	7.913	4.231	2.198	9.297	6
7	2.0762	0.4817	0.102 22	0.212 22	9.783	4.712	2.586	12.187	7
8	2.3045	0.4339	0.084 32	0.194 32	11.859	5.146	2.958	15.225	8
9	2.5581	0.3909	0.070 60	0.180 60	14.164	5.537	3.314	18.352	9
10	2.8394	0.3522	0.059 80	0.169 80	16.722	5.889	3.654	21.522	10

12% compound interest factors

n	Single payment: Compound amount factor F/P	Single payment: Present worth factor P/F	Uniform series: Sinking fund factor A/F	Uniform series: Capital recovery factor A/P	Uniform series: Compound amount factor F/A	Uniform series: Present worth factor P/A	Uniform gradient: Gradient conversion factor A/G	Uniform gradient: Present worth factor P/G	n
1	1.1200	0.8929	1.000 00	1.120 00	1.000	0.893	0.000	0.000	1
2	1.2544	0.7972	0.471 70	0.591 70	2.120	1.690	0.472	0.797	2
3	1.4049	0.7118	0.296 35	0.416 35	3.374	2.402	0.925	2.221	3
4	1.5735	0.6355	0.209 23	0.329 23	4.779	3.037	1.359	4.127	4
5	1.7623	0.5674	0.157 41	0.277 41	6.353	3.605	1.775	6.397	5
6	1.9738	0.5066	0.123 23	0.243 23	8.115	4.111	2.172	8.930	6
7	2.2107	0.4523	0.099 12	0.219 12	10.089	4.564	2.551	11.644	7
8	2.4760	0.4039	0.081 30	0.201 30	12.300	4.968	2.913	14.471	8
9	2.7731	0.3606	0.067 68	0.187 68	14.776	5.328	3.257	17.356	9
10	3.1058	0.3220	0.056 98	0.176 98	17.549	5.650	3.585	20.254	10

Table C-2 Compound Interest Factors (40)(continued)

13% compound interest factors

	Single payment		Uniform series				Uniform gradient		
n	Compound amount factor F/P	Present worth factor P/F	Sinking fund factor A/F	Capital recovery factor A/P	Compound amount factor F/A	Present worth factor P/A	Gradient conversion factor A/G	Present worth factor P/G	*n*
1	1.1300	0.8850	1.000 00	1.130 00	1.000	0.885	0.000	0.000	1
2	1.2769	0.7831	0.469 48	0.599 48	2.130	1.668	0.469	0.783	2
3	1.4429	0.6931	0.293 52	0.423 52	3.407	2.361	0.919	2.169	3
4	1.6305	0.6133	0.206 19	0.336 19	4.850	2.974	1.348	4.009	4
5	1.8424	0.5428	0.154 31	0.284 31	6.480	3.517	1.757	6.180	5
6	2.0820	0.4803	0.120 15	0.250 15	8.323	3.998	2.147	8.582	6
7	2.3526	0.4251	0.096 11	0.226 11	10.405	4.423	2.517	11.132	7
8	2.6584	0.3762	0.078 39	0.208 39	12.757	4.799	2.869	13.765	8
9	3.0040	0.3329	0.064 87	0.194 87	15.416	5.132	3.201	16.428	9
10	3.3946	0.2946	0.054 29	0.184 29	18.420	5.426	3.516	19.080	10

14% compound interest factors

	Single payment		Uniform series				Uniform gradient		
n	Compound amount factor F/P	Present worth factor P/F	Sinking fund factor A/F	Capital recovery factor A/P	Compound amount factor F/A	Present worth factor P/A	Gradient conversion factor A/G	Present worth factor P/G	*n*
1	1.1400	0.8772	1.000 00	1.140 00	1.000	0.877	0.000	0.000	1
2	1.2996	0.7695	0.467 29	0.607 29	2.140	1.647	0.467	0.769	2
3	1.4815	0.6750	0.290 73	0.430 73	3.440	2.322	0.913	2.119	3
4	1.6890	0.5921	0.203 20	0.343 20	4.921	2.914	1.337	3.896	4
5	1.9254	0.5194	0.151 28	0.291 28	6.610	3.433	1.740	5.973	5
6	2.1950	0.4556	0.117 16	0.257 16	8.536	3.889	2.122	8.251	6
7	2.5023	0.3996	0.093 19	0.233 19	10.730	4.288	2.483	10.649	7
8	2.8526	0.3506	0.075 57	0.215 57	13.233	4.639	2.825	13.103	8
9	3.2519	0.3075	0.062 17	0.202 17	16.085	4.946	3.146	15.563	9
10	3.7072	0.2697	0.051 71	0.191 71	19.337	5.216	3.449	17.991	10

15% compound interest factors

	Single payment		Uniform series				Uniform gradient		
n	Compound amount factor F/P	Present worth factor P/F	Sinking fund factor A/F	Capital recovery factor A/P	Compound amount factor F/A	Present worth factor P/A	Gradient conversion factor A/G	Present worth factor P/G	*n*
1	1.1500	0.8696	1.000 00	1.150 00	1.000	0.870	0.000	0.000	1
2	1.3225	0.7561	0.465 12	0.615 12	2.150	1.626	0.465	0.756	2
3	1.5209	0.6575	0.287 98	0.437 98	3.472	2.283	0.907	2.071	3
4	1.7490	0.5718	0.200 26	0.350 27	4.993	2.855	1.326	3.786	4
5	2.0114	0.4972	0.148 32	0.298 32	6.742	3.352	1.723	5.775	5
6	2.3131	0.4323	0.114 24	0.264 24	8.754	3.784	2.097	7.937	6
7	2.6600	0.3759	0.090 36	0.240 36	11.067	4.160	2.450	10.192	7
8	3.0590	0.3269	0.072 85	0.222 85	13.727	4.487	2.781	12.481	8
9	3.5179	0.2843	0.059 57	0.209 57	16.786	4.772	3.092	14.755	9
10	4.0456	0.2472	0.049 25	0.199 25	20.304	5.019	3.383	16.979	10

APPENDIX D

DOCUMENTATIONS OF THE COSTS, AND AN EXAMPLE OF LEARNING CURVE

Table D-1. Equipment and Wage Rates (48, 49)
(New Equipment)

Graders	Cu.Yd. Capacity	H.P.	176/hr Month + Maint.	Zone e Oper./hr.
12 G (cat)		135	49.39	28.38
14 G (cat)		180	68.78	28.38
Loaders - Crawlers				
931 B (cat)	1	65	18.85	27.74
943 (cat)	1-1/2	80	33.53	27.74
953 (cat)	2	110	41.33	27.74
963 (cat)	2-1/2	150	53.98	27.74
973 (cat)	3-3/4	210	80.64	28.13
Loaders - Rubber Tire				
920 (cat)	1-1/2	80	28.69	27.74
930 (cat)	2	100	33.65	27.74
950 B (cat)	3	155	54.85	28.13
966 D (cat)	4	200	69.55	28.13
980 C (cat)	5-1/4	260	92.09	29.07

Tractors	Dozer Blade	Cu.Yd. Capacity	H.P.	176/hr Month + Maint.	Zone e Oper./hr.
D3	Angle/Tilt (cat)	1.29	65	20.06	28.13
D4D	Straight (cat)	1.77	75	25.63	28.13
D5B	Straight (cat)	2.81	105	39.05	28.13
D6D	Straight (cat) Non-Productive	3.98	140	49.99	28.13
D6D	Straight (cat) Production	3.98	140	51.34	28.13
D6D	Angling (cat) Pioneer	3.13	140	52.52	28.13
D7G	Straight (cat) Production	5.49	200	72.03	28.13
D7G	Angling (cat) Pioneer	3.7	200	71.74	28.13
D7G	Universal (cat) Production	7.7	200	74.19	28.13
D8K	Straight (cat) Production	14.4	300	92.77	28.13
D8K	Angling (cat) Pioneering	7.8	300	93.85	28.13
D8K	Universal (cat) Production	17.8	300	93.12	30.87

Tractor - Loader - Backhoe

John Deere	Dig Width	Capacity Cu.Yd.	H.P.	Month	Week	176/hr Month	Maint. Hr.	Zone e Oper./hr.
JD 310 A	14' 7"	3/4	58	1,981.00	650.00	11.26	5.50	27.84
JD 410	15'10"	1	66	2,454.00	800.00	13.94	6.50	27.84
JD 500 C	15'10"	1	80	3,318.00	1,085.00	18.85	8.45	27.84
JD 510	17'	1-1/8	80	3,754.00	1,225.00	21.33	9.05	27.84

Table D-1. Equipment and Wage Rates (48, 49) (continued)
(New Equipment)

Compaction Equipment

Static Rollers Tandem (Self-propelled)

Hyster	Tons	H.P.	Month	Week	Maint. Hr.	Zone e Operator
C330A	4-6	56	1,717.00 9.76/hr	471.00 11.78/hr	3.25	26.99 rock & dirt
C340A	8-10	83	1,327.00 7.54/hr	439.00 10.98/hr	3.50	27.84 asphalt
C350C	10-14	83	2,509.00 14.26/hr	829.00 20.73/hr	5.10	

Static Rollers, Rubber Tired (Pull Type)

	Tons	Wheels	Month	Week	Maint. Hr.	Zone e Operator
Tampo R13	14	15	712.00 4.05/hr	241.00 6.03/hr	0.85	26.99 dirt & rock
Hercules PT 13	17	13	733.00 4.18/hr	246.00 6.15/hr	0.85	27.84 asphalt

Static Rollers, Rubber Tired (Self-Propelled)

	Wheels	H.P.	Month	Week	Maint. Hr.	Zone e Operator
Ingram 9-2800 PA	9	107	1,969.00 11.19/hr	669.00 16.73/hr	6.70	26.99 dirt & rock
Ingram 11-2700	11	107	2,194.00 12.47/hr	744.00 18.60/hr	6.90	27.84 asphalt

Static Roller, Grid Pattern (Pull Type)

	Month	Week	Maint. Hr.	Zone e Operator
Hyster D - Grid	1,375.00 7.81/hr	455.00 11.38/hr	1.45	26.99 dirt & rock

Static Rollers, Sheeps Foot/Wedge Foot (Pull Type)

	Drums	Foot	Month	Week	Maint. Hr.	Zone e Operator
Southwest 2DHRR	2	Sh Foot	2,022.00 11.49/hr	690.00 17.25/hr	2.40	26.99
SO West 2DH-WS	2	Sh Foot/ Wdg Post	1,616.00 9.18/hr	551.00 13.78/hr	1.90	26.99

Table D-1. Equipment and Wage Rates (48, 49) (continued)
(New Equipment)

Static Rollers, Sheeps Foot/Wedge Foot (Self-propelled)

	Drums	Foot	Month	Week	Maint. Hr.	Zone e Operator
Hyster C455B	2	Sheeps Ft.	13,027.00 74.00/hr	4,430.00 110.75/hr	28.05	26.99

Vibratory Rollers, Smooth (Pull Type)

	Drum Size	Month	Week	Maint. Hr.	Zone e Operator
Bomag BW6	67"	2,686.00 15.26/hr	915.00 22.87/hr	4.30	26.99
Bomag BW10	77"	3,638.00 20.67/hr	1,236.00 30.90/hr	5.85	26.99
Bomag BW15	83"	5,280.00 30.00/hr	1,798.00 44.94/hr	8.50	26.99

Vibratory Rollers, Sheeps Foot/Wedge Type (Pull Type)

	Drum Size	Month	Week	Maint. Hr.	Zone e Operator
Bomag BW4S	63"	3,215.00 18.27/hr	1,091.00 27.29/hr	4.70	26.99 Dirt & Rock
Bomag BW6S	67"	3,510.00 19.94/hr	1,193.00 29.83/hr	4.95	
Bomag BW10S	77"	4,483.00 25.47/hr	1,525.00 38.12/hr	6.45	

Vibratory Roller, Rubber & Steel (Smooth) (Self-propelled)

	Drum Size	Month	Week	Maint. Hr.	Zone e Operator
Hyster C610B	72"	3,344.00 19.00/hr	1,140.00 28.49/hr	7.15	26.99 Dirt & Rock
Hyster C620B	84"	3,643.000 20.70/hr	1,241.00 31.03/hr	7.55	27.84 Asphalt

Vibratory, Pan Type (Hand held)

Size	Month	Week	Day	Maint. Hr.	Zone e Operator
21"x24"	139.00 0.79/hr	46.81 1.17/hr	15.84 1.98/hr	0.30	23.06
24"x34"	337.00 1.92/hr	112.35 2.81/hr	37.99 4.75/hr	0.75	

Table D-1. Equipment and Wage Rates (48, 49) (continued)
(New Equipment)

Rear Dump on/off Highway Type

	Capacity Cu.Yd.	H.P.	Month	Week	Maint. Hr.	Zone e Oper./hr.
Dump	8	195	2,285.00 12.98/hr.	710.00 17.75/hr.	10.95	26.10
Dump	10	210	2,820.00 16.02/hr.	875.00 21.88/hr.	15.25	26.23
Dump	12	275	3,665.00 20.82/hr.	1,135.00 28.38/hr.	18.25	26.23
Dump	16-20	285	4,580.00 26.02/hr.	1,420.00 35.50/hr.	23.65	26.23
Pull Trailer	10		1,080.00 6.14/hr.	370.00 9.25/hr.	2.25	

Belly Dumps - Highway Type

	Capacity Cu.Yd.	Month	Week	Daily	Maint. Hr.	Zone e Oper./hr.
250 h.p. Tractor with Double Gate 35-ton Trailer	20	3,880.00 22.05/hr	1,260.00 31.50/hr	350.00 43.75/hr	19.90	26.23

Rear Dump, Off-highway Type

	H.P.	Cu.Yd.	Month	Week	Maint. Hr.	Zone e Operator
Euclid R-25	220	14.7	6,775.00 38.49/hr	2,100.00 52.50/hr	14.70	26.23
Euclid R-36	400	22.2	10,290.00 58.47/hr	3,190.00 79.75/hr	25.00	26.29
Euclid R-50	576	30.8	13,240.00 75.75/hr	4,105.00 103.28/hr	34.05	26.29

Low Boy Tractors

Size	H.P.	Month	Week	Daily	Maint. Hr.	Zone e Operator
35-40,000 GVW	250	1,980.00 11.25/hr	615.00 15.38/hr	155.00 19.38/hr	12.40	26.16
45-50,000 GVW	275	3,235.00 18.38/hr	1,000.00 25.00/hr	250.00 31.25/hr	14.80	26.16
55-75,000 GVW	375	4,135.00 23.49/hr	1,280.00 32.00/hr	320.00 40.00/hr	19.55	26.16

Table D-1. Equipment and Wage Rates (48, 49) (continued)
(New Equipment)

Highway Trucks

Size	Month	Week	Daily	Maint. Hr.	Zone e Operator
1/2-ton Pickup	395.00 2.24/hr	120.00 3.00/hr	30.50 3.81/hr	6.40	26.03
3/4-ton Crew Cab	505.00 2.87/hr	155.00 3.88/hr	39.00 4.88/hr	6.50	26.03
4x4 3/4-ton	470.00 2.67/hr	145.00 3.63/hr	36.50 4.56/hr	6.50	26.03
4x4 3/4 Crew Cab	610.00 3.47/hr	190.00 4.75/hr	47.50 5.94/hr	14.60	26.03
3-1/2 ton Flatbed	565.00 3.21/hr	175.00 4.38/hr	44.00 5.50/hr	14.60	26.03

Flatbed Trucks

GVW	H.P.	Monthly	Weekly	Daily	Hourly	Maint/Hr.	Zone e Operator
Diesel Powered							
4,000	130	$ 685.00	$210.00	$ 53.00	$ 7.95	$ 5.85	26.03
15,000	175	1,095.00	340.00	84.75	12.70	8.20	26.03
20,000	175	1,120.00	350.00	87.00	13.00	8.25	26.03

Water Tanker

Gallons	H.P.	Monthly	Weekly	Daily	Maint. Hourly	Zone e Operator
1,500	gas 175	1,355.00 7.70/hr	420.00 10.50/hr	105.00 13.13/hr	10.25	26.03
2,000	gas 175	1,465.00 8.08/hr	455.00 10.97/hr	115.00 14.33/hr	10.35	26.10
3,000	gas 210	2,610.00 8.81/hr	810.00 11.99/hr	200.00 25.00/hr	13.75	26.10
4,000	diesel 250	3,165.00 12.00/hr	980.00 16.32/hr	245.00 30.63/hr	11.30	26.16
5,000	diesel 250	4,610.00 16.00/hr	1,430.00 21.80/hr	355.00 44.38/hr	12.80	26.16

Table D-1. Equipment and Wage Rates (48,49) (continued) (New Equipment)

Brush Chippers, Trailer Mounted, Gasoline Powered

Model	Log Diameter	HP	Monthly	Weekly	Daily	Hourly	Maint/Hr	Zone e Operator
Chipmore								
TM.160-G4	16"	114	$1,345.00	$415.00	$110.00	16.90	8.05	26.23
C-12T	12"	150	990.00	305.00	82.75	1240	9.80	26.23
C-16T	16"	150	1,340.00	415.00	110.00	16.80	10.05	26.23

Fork Lifts - Rough Terrain, High Lift/Four-Wheel Drive

Lift Height	Capacity (Lbs)	HP	Monthly	Weekly	Daily	Hourly	Maint/Hr	Zone e Operator
Gasoline Powered								
22'0"	4,000	106	$2,935.00	$ 970.00	$250.00	$37.75	$11.20	$26.16
24'0"	6,000	106	3,220.00	1,060.00	275.00	41.50	11.60	26.16
24'0"	8,000	103	3,505.00	1,155.00	300.00	45.00	11.80	26.16

Cleaners, Pressure Washers

Gal/Hr @	PSI	HP	Monthly	Weekly	Daily	Hourly	Maint/Hr	Zone e Operator
Electric Powered/Oil Fired								
Portable								
240	1,000		$ 675.00	$230.00	$ 71.25	$10.70	$ .40	$23.06
360	1,200		1,055.00	360.00	110.00	16.70	.60	23.06
600	1,000		1,725.00	585.00	180.00	27.25	.95	23.06

Welders-Portable

Type/Amps	HP	Monthly	Weekly	Daily	Hourly	Maint/Hr	Zone e Operator
Gasoline Powered							
DC (With Highway Trailer)							
200	30	$470.00	$155.00	$37.00	$5.55	$3.20	$23.06
300	34	560.00	185.00	44.25	6.65	3.50	23.06
600	84	720.00	240.00	57.00	8.55	8.00	23.06

Brooms & Sweepers, Sel-Propelled

Model	Trans.	Broom Length	HP	Monthly	Weekly	Daily	Hourly	Maint/Hr	Zone e Operator
Gasoline Powered									
Broce									
T-10	4.Sp.	7'	91	$1,130.00	$395.00	$125.00	$19.00	$7.00	$26.16
H-10	Hydrostatic	8'	91	1,270.00	445.00	140.00	21.30	7.20	26.16
Rosco									
BH-7	Hydrostatic	8'	68-1/2	1,670.00	585.00	185.00	28.00	6.45	26.16

Labor Rates, Zone e = $23.06

Table D-1. Equipment and Wage Rates (48,49) (continued) (New Equipment)

Asphalt & Bituminous Distributors for Truck Mounting

NOTE: Complete With Burners, Insulated Tank, Power Unit, and 12' Full Circulating Spray Bar

Capy.(Gal.)	Monthly	Weekly	Daily	Hourly	Maint/Hr.	Zone e Operator
Diesel Powered						
1,000	$2,320.00	$ 765.00	$220.00	$33.25	$2.35	$26.16
2,000	2,555.00	845.00	245.00	36.75	2.55	26.16
3,000	2,905.00	960.00	280.00	41.75	2.90	26.16
4,000	3,460.00	1,140.00	330.00	49.75	3.45	26.16
5,000	3,890.00	1,285.00	370.00	55.75	3.90	26.16

Chip Spreaders - Aggregates

Size/Type	HP	Monthly	Weekly	Daily	Hourly	Maint/Hr.	Zone e Operator
Self-Propelled							
Gasoline powered							
10' Spread Hopper	185	$4,495.00	$1,530.00	$460.00	$68.75	$17.40	26.23
14' Spread Hopper	185	4,720.00	1,605.00	480.00	72.25	17.60	26.23
Diesel Powered							
10' Spread Hopper	130	5,125.00	1,745.00	525.00	78.50	10.00	26.23
14' Spread Hopper	130	5,350.00	1,820.00	545.00	82.00	10.20	26.23

Sand Spreaders

	Monthly	Weekly	Daily	Hourly	Maint/Hr.	Zone e Operator
For Truck Mounting (10 Yd.)	1,800.00	610.00	185.00	27.50	1.30	26.16
For Dump Body Mounting	1,100.00	375.00	110.00	16.80	.80	26.16

Stabilizer - Self-Propelled

Model	HP	Monthly	Weekly	Daily	Hourly	Maint/Hr.	Zone e Operator
Diesel Powered							
Bomag							
MPH-50	152	7,330.00	2,420.00	700.00	205.00	12.65	26.23
MPH-100	304	12,415.00	4,095.00	1,190.00	177.50	23.05	26.23

LEARNING CURVE EXAMPLE

LEARNING CURVE EXAMPLE

An 80% learning curve is used with the construction of the reusable aggregate project. The first mile of the road took 100 hours to construct. Assuming the roadway has the same physical characteristics, and the equipment and labor will remain constant throughout the entire project, determine:

a) How long will it take to construct the fifth mile of the roadway?

b) How long will it take to construct the fifth through the eighth mile of the roadway?

c) How long will it take to construct the eighth mile of the roadway?

d) How long will it take to construct the tenth mile of road?

Solution:

a) $T_n = T_1 \, (n_1)^b$

$T_5 = 100 \, (5)^{-0.322}$

$T_5 = 59.55$ hours

b) The time to construct the fifth mile of the roadway through the eighth mile is approximately:

$$T_{5-8} = \frac{T_1}{(1+b)} \left[\left(n_2 + \frac{1}{2}\right)^{1+b} - \left(n_1 - \frac{1}{2}\right)^{1+b} \right]$$

$$T_{5-8} = \frac{100}{1-.415} \left[\left(8 + \frac{1}{2}\right)^{1-.415} - \left(5 - \frac{1}{2}\right)^{1-.415} \right]$$

$T_{5-8} = 185.64$ hours

c) The time to construct the eighth mile of the roadway is approximately

$$T_n = T_1 \ (n_1)^b$$

$$T_8 = 100 \ (8)^{-0.322}$$

$$T_8 = 51.19 \text{ hours}$$

d) Since no significant learning is expected after the construction of the eighth mile of the roadway, the time to construct the tenth mile of roadway is the same as the eighth mile of roadway.

$$T_{10} = 51.19 \text{ hours}$$

APPENDIX E

CUMULATIVE NORMAL DISTRIBUTION TABLES

AND

COMPUTER OUTPUT FOR SENSITIVITY ANALYSIS

Table E.1.a (52)

THE CUMULATIVE NORMAL DISTRIBUTION FUNCTION†

$\Phi(z)=\int_{-\infty}^{z}\phi(t)dt$

for $(-\infty < z \leq 0)$

z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
-.0	.5000	.4960	.4920	.4880	.4840	.4801	.4761	.4721	.4681	.4641
-.1	.4602	.4562	.4522	.4483	.4443	.4404	.4364	.4325	.4286	.4247
-.2	.4207	.4168	.4129	.4090	.4052	.4013	.3974	.3936	.3897	.3859
-.3	.3821	.3783	.3745	.3707	.3669	.3632	.3594	.3557	.3520	.3483
-.4	.3446	.3409	.3372	.3336	.3300	.3264	.3228	.3192	.3156	.3121
-.5	.3085	.3050	.3015	.2981	.2946	.2912	.2877	.2843	.2810	.2776
-.6	.2743	.2709	.2676	.2643	.2611	.2578	.2546	.2514	.2483	.2451
-.7	.2420	.2389	.2358	.2327	.2297	.2266	.2236	.2206	.2177	.2148
-.8	.2119	.2090	.2061	.2033	.2005	.1977	.1949	.1922	.1894	.1867
-.9	.1841	.1814	.1788	.1762	.1736	.1711	.1685	.1660	.1635	.1611
-1.0	.1587	.1562	.1539	.1515	.1492	.1469	.1446	.1423	.1401	.1379
-1.1	.1357	.1335	.1314	.1292	.1271	.1251	.1230	.1210	.1190	.1170
-1.2	.1151	.1131	.1112	.1093	.1075	.1056	.1038	.1020	.1003	.09853
-1.3	.09680	.09510	.09342	.09176	.09012	.08851	.08691	.08534	.08379	.08226
-1.4	.08076	.07927	.07780	.07636	.07493	.07353	.07215	.07078	.06944	.06811
-1.5	.06681	.06552	.06426	.06301	.06178	.06057	.05938	.05821	.05705	.05592
-1.6	.05480	.05370	.05262	.05155	.05050	.04947	.04846	.04746	.04648	.04551
-1.7	.04457	.04363	.04272	.04182	.04093	.04006	.03920	.03836	.03754	.03673
-1.8	.03593	.03515	.03438	.03362	.03288	.03216	.03144	.03074	.03005	.02938
-1.9	.02872	.02807	.02743	.02680	.02619	.02559	.02500	.02442	0.2385	.02330
-2.0	.02275	.02222	.02169	.02118	.02068	.02018	.01970	.01923	.01876	.01831
-2.1	.01786	.01743	.01700	.01659	.01618	.01578	.01539	.01500	.01463	.01426
-2.2	.01390	.01355	.01321	.01287	.01255	.01222	.01191	.01160	.01130	.01101
-2.3	.01072	.01044	.01017	$.0^{2}9903$	$.0^{2}9642$	$.0^{2}9387$	$.0^{2}9137$	$.0^{2}8894$	$.0^{2}8656$	$.0^{2}8424$
-2.4	$.0^{2}8198$	$.0^{2}7976$	$.0^{2}7760$	$.0^{2}7549$	$.0^{2}7344$	$.0^{2}7143$	$.0^{2}6947$	$.0^{2}6756$	$.0^{2}6569$	$.0^{2}6387$
-2.5	$.0^{2}6210$	$.0^{2}6037$	$.0^{2}5868$	$.0^{2}5703$	$.0^{2}5543$	$.0^{2}5386$	$.0^{2}5234$	$.0^{2}5085$	$.0^{2}4940$	$.0^{2}4799$
-2.6	$.0^{2}4661$	$.0^{2}4527$	$.0^{2}4396$	$.0^{2}4269$	$.0^{2}4145$	$.0^{2}4025$	$.0^{2}3907$	$.0^{2}3793$	$.0^{2}3681$	$.0^{2}3573$
-2.7	$.0^{2}3467$	$.0^{2}3364$	$.0^{2}3264$	$.0^{2}3167$	$.0^{2}3072$	$.0^{2}2980$	$.0^{2}2890$	$.0^{2}2803$	$.0^{2}2718$	$.0^{2}2635$
-2.8	$.0^{2}2555$	$.0^{2}2477$	$.0^{2}2401$	$.0^{2}2327$	$.0^{2}2256$	$.0^{2}2186$	$.0^{2}2118$	$.0^{2}2052$	$.0^{2}1988$	$.0^{2}1926$
-2.9	$.0^{2}1866$	$.0^{2}1807$	$.0^{2}1750$	$.0^{2}1695$	$.0^{2}1641$	$.0^{2}1589$	$.0^{2}1538$	$.0^{2}1489$	$.0^{2}1441$	$.0^{2}1395$
-3.0	$.0^{2}1350$	$.0^{2}1306$	$.0^{2}1264$	$.0^{2}1223$	$.0^{2}1183$	$.0^{2}1144$	$.0^{2}1107$	$.0^{2}1070$	$.0^{2}1035$	$.0^{2}1001$
-3.1	$.0^{3}9676$	$.0^{3}9354$	$.0^{3}9043$	$.0^{3}8740$	$.0^{3}8447$	$.0^{3}8164$	$.0^{3}7888$	$.0^{3}7622$	$.0^{3}7364$	$.0^{3}7114$
-3.2	$.0^{3}6871$	$.0^{3}6637$	$.0^{3}6410$	$.0^{3}6190$	$.0^{3}5976$	$.0^{3}5770$	$.0^{3}5571$	$.0^{3}5377$	$.0^{3}5190$	$.0^{3}5009$
-3.3	$.0^{3}4834$	$.0^{3}4665$	$.0^{3}4501$	$.0^{3}4342$	$.0^{3}4189$	$.0^{3}4041$	$.0^{3}3897$	$.0^{3}3758$	$.0^{3}3624$	$.0^{3}3495$
-3.4	$.0^{3}3369$	$.0^{3}3248$	$.0^{3}3131$	$.0^{3}3018$	$.0^{3}2909$	$.0^{3}2803$	$.0^{3}2701$	$.0^{3}2602$	$.0^{3}2507$	$.0^{3}2415$
-3.5	$.0^{3}2326$	$.0^{3}2241$	$.0^{3}2158$	$.0^{3}2078$	$.0^{3}2001$	$.0^{3}1926$	$.0^{3}1854$	$.0^{3}1785$	$.0^{3}1718$	$.0^{3}1653$
-3.6	$.0^{3}1591$	$.0^{3}1531$	$.0^{3}1473$	$.0^{3}1417$	$.0^{3}1363$	$.0^{3}1311$	$.0^{3}1261$	$.0^{3}1213$	$.0^{3}1166$	$.0^{3}1121$
-3.7	$.0^{3}1078$	$.0^{3}1036$	$.0^{4}9961$	$.0^{4}9574$	$.0^{4}9201$	$.0^{4}8842$	$.0^{4}8496$	$.0^{4}8162$	$.0^{4}7841$	$.0^{4}7532$
-3.8	$.0^{4}7235$	$.0^{4}6948$	$.0^{4}6673$	$.0^{4}6407$	$.0^{4}6152$	$.0^{4}5906$	$.0^{4}5669$	$.0^{4}5442$	$.0^{4}5223$	$.0^{4}5012$
-3.9	$.0^{4}4810$	$.0^{4}4615$	$.0^{4}4427$	$.0^{4}4247$	$.0^{4}4074$	$.0^{4}3908$	$.0^{4}3747$	$.0^{4}3594$	$.0^{4}3446$	$.0^{4}3304$
-4.0	$.0^{4}3167$	$.0^{4}3036$	$.0^{4}2910$	$.0^{4}2789$	$.0^{4}2673$	$.0^{4}2561$	$.0^{4}2454$	$.0^{4}2351$	$.0^{4}2252$	$.0^{4}2157$
-4.1	$.0^{4}2066$	$.0^{4}1987$	$.0^{4}1894$	$.0^{4}1814$	$.0^{4}1737$	$.0^{4}1662$	$.0^{4}1591$	$.0^{4}1523$	$.0^{4}1458$	$.0^{4}1395$
-4.2	$.0^{4}1335$	$.0^{4}1277$	$.0^{4}1222$	$.0^{4}1168$	$.0^{4}1118$	$.0^{4}1069$	$.0^{4}1022$	$.0^{5}9774$	$.0^{5}9345$	$.0^{5}8934$
-4.3	$.0^{5}8540$	$.0^{5}8163$	$.0^{5}7801$	$.0^{5}7455$	$.0^{5}7124$	$.0^{5}6807$	$.0^{5}6503$	$.0^{5}6212$	$.0^{5}5934$	$.0^{5}5668$
-4.4	$.0^{5}5413$	$.0^{5}5169$	$.0^{5}4935$	$.0^{5}4712$	$.0^{5}4498$	$.0^{5}4294$	$.0^{5}4098$	$.0^{5}3911$	$.0^{5}3732$	$.0^{5}3561$
-4.5	$.0^{5}3398$	$.0^{5}3241$	$.0^{5}3092$	$.0^{5}2949$	$.0^{5}2813$	$.0^{5}2682$	$.0^{5}2558$	$.0^{5}2439$	$.0^{5}2325$	$.0^{5}2216$
-4.6	$.0^{5}2112$	$.0^{5}2013$	$.0^{5}1919$	$.0^{5}1828$	$.0^{5}1742$	$.0^{5}1660$	$.0^{5}1581$	$.0^{5}1506$	$.0^{5}1434$	$.0^{5}1366$
-4.7	$.0^{5}1301$	$.0^{5}1239$	$.0^{5}1179$	$.0^{5}1123$	$.0^{5}1069$	$.0^{5}1017$	$.0^{6}9680$	$.0^{6}9211$	$.0^{6}8765$	$.0^{6}8339$
-4.8	$.0^{6}7933$	$.0^{6}7547$	$.0^{6}7178$	$.0^{6}6827$	$.0^{6}6492$	$.0^{6}6173$	$.0^{6}5869$	$.0^{6}5580$	$.0^{6}5304$	$.0^{6}5042$
-4.9	$.0^{6}4792$	$.0^{6}4554$	$.0^{6}4327$	$.0^{6}4111$	$.0^{6}3906$	$.0^{6}3711$	$.0^{6}3525$	$.0^{6}3348$	$.0^{6}3179$	$.0^{6}3019$

Example: $\Phi(-3.57) = .0^{3}1785 = 0.0001785$.

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Table E.1.b (52)

THE CUMULATIVE NORMAL DISTRIBUTION FUNCTION†

$\Phi(z) = \int_{-\infty}^{z} \phi(t)\,dt$  for $(0 \leq z < \infty)$

z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
.0	.5000	.5040	.5080	.5120	.5160	.5199	.5239	.5279	.5319	.5359
.1	.5398	.5438	.5478	.5517	.5557	.5596	.5636	.5675	.5714	.5753
.2	.5793	.5832	.5871	.5910	.5948	.5987	.6026	.6064	.6103	.6141
.3	.6179	.6217	.6255	.6293	.6331	.6368	.6406	.6443	.6480	.6517
.4	.6554	.6591	.6628	.6664	.6700	.6736	.6772	.6808	.6844	.6879
.5	.6915	.6950	.6985	.7019	.7054	.7088	.7123	.7157	.7190	.7224
.6	.7257	.7291	.7324	.7357	.7389	.7422	.7454	.7486	.7517	.7549
.7	.7580	.7611	.7642	.7673	.7703	.7734	.7764	.7794	.7823	.7852
.8	.7881	.7910	.7939	.7967	.7995	.6023	.8051	.8078	.8106	.8133
.9	.8159	.8186	.8212	.8238	.8264	.8289	.8315	.8340	.8365	.8389
1.0	.8413	.8438	.8461	.8485	.8508	.8531	.8554	.8577	.8599	.8621
1.1	.8643	.8665	.8686	.8708	.8729	.8749	.8770	.8790	.8810	.8830
1.2	.8849	.8869	.8888	.8907	.8925	.8944	.8962	.8980	.8997	.90147
1.3	.90320	.90490	.90658	.90824	.90988	.91149	.91309	.91466	.91621	.91774
1.4	.91924	.92073	.92220	.92364	.92507	.92647	.92785	.92922	.93056	.93189
1.5	.93319	.93448	.93574	.93699	.93822	.93943	.94062	.94179	.94295	.94408
1.6	.94520	.94630	.94738	.94845	.94950	.95053	.95154	.95254	.95352	.95449
1.7	.95543	.95637	.95728	.95818	.95907	.95994	.96080	.96164	.96246	.96327
1.8	.96407	.96485	.96562	.96638	.96712	.96784	.96856	.96926	.96995	.97062
1.9	.97128	.97193	.97257	.97320	.97381	.97441	.97500	.97558	.97615	.97670
2.0	.97725	.97778	.97831	.97882	.97932	.97982	.98030	.98077	.98124	.98169
2.1	.98214	.98257	.98300	.98341	.98382	.98422	.98461	.98500	.98537	.98574
2.2	.98610	.98645	.98679	.98713	.98745	.98778	.98809	.98840	.98870	.98899
2.3	.98928	.98956	.98983	$.9^{2}0097$	$.9^{2}0358$	$.9^{2}0613$	$.9^{2}0863$	$.9^{2}1106$	$.9^{2}1344$	$.9^{2}1576$
2.4	$.9^{2}1802$	$.9^{2}2024$	$.9^{2}2240$	$.9^{2}2451$	$.9^{2}2656$	$.9^{2}2857$	$.9^{2}3053$	$.9^{2}3244$	$.9^{2}3431$	$.9^{2}3613$
2.5	$.9^{2}3790$	$.9^{2}3963$	$.9^{2}4132$	$.9^{2}4297$	$.9^{2}4457$	$.9^{2}4614$	$.9^{2}4766$	$.9^{2}4915$	$.9^{2}5060$	$.9^{2}5201$
2.6	$.9^{2}5339$	$.9^{2}5473$	$.9^{2}5604$	$.9^{2}5731$	$.9^{2}5855$	$.9^{2}5975$	$.9^{2}6093$	$.9^{2}6207$	$.9^{2}6319$	$.9^{2}6427$
2.7	$.9^{2}6533$	$.9^{2}6636$	$.9^{2}6736$	$.9^{2}6833$	$.9^{2}6928$	$.9^{2}7020$	$.9^{2}7110$	$.9^{2}7197$	$.9^{2}7282$	$.9^{2}7365$
2.8	$.9^{2}7445$	$.9^{2}7523$	$.9^{2}7599$	$.9^{2}7673$	$.9^{2}7744$	$.9^{2}7814$	$.9^{2}7882$	$.9^{2}7948$	$.9^{2}8012$	$.9^{2}8074$
2.9	$.9^{2}8134$	$.9^{2}8193$	$.9^{2}8250$	$.9^{2}8305$	$.9^{2}8359$	$.9^{2}8411$	$.9^{2}8462$	$.9^{2}8511$	$.9^{2}8559$	$.9^{2}8605$
3.0	$.9^{2}8650$	$.9^{2}8694$	$.9^{2}8736$	$.9^{2}8777$	$.9^{2}8617$	$.9^{2}8856$	$.9^{2}8893$	$.9^{2}8930$	$.9^{2}8965$	$.9^{2}8999$
3.1	$.9^{3}0324$	$.9^{3}0646$	$.9^{3}0957$	$.9^{3}1260$	$.9^{3}1553$	$.9^{3}1836$	$.9^{3}2112$	$.9^{3}2378$	$.9^{3}2636$	$.9^{3}2886$
3.2	$.9^{3}3129$	$.9^{3}3363$	$.9^{3}3590$	$.9^{3}3810$	$.9^{3}4024$	$.9^{3}4230$	$.9^{3}4429$	$.9^{3}4623$	$.9^{3}4810$	$.9^{3}4991$
3.3	$.9^{3}5166$	$.9^{3}5335$	$.9^{3}5499$	$.9^{3}5658$	$.9^{3}5811$	$.9^{3}5959$	$.9^{3}6103$	$.9^{3}6242$	$.9^{3}6376$	$.9^{3}6505$
3.4	$.9^{3}6631$	$.9^{3}6752$	$.9^{3}6869$	$.9^{3}6982$	$.9^{3}7091$	$.9^{3}7197$	$.9^{3}7299$	$.9^{3}7398$	$.9^{3}7493$	$.9^{3}7585$
3.5	$.9^{3}7674$	$.9^{3}7759$	$.9^{3}7842$	$.9^{3}7922$	$.9^{3}7999$	$.9^{3}8074$	$.9^{3}8146$	$.9^{3}8215$	$.9^{3}8282$	$.9^{3}8347$
3.6	$.9^{3}8409$	$.9^{3}8469$	$.9^{3}6527$	$.9^{3}8583$	$.9^{3}8637$	$.9^{3}8689$	$.9^{3}8739$	$.9^{3}8787$	$.9^{3}8834$	$.9^{3}8879$
3.7	$.9^{3}8922$	$.9^{3}8964$	$.9^{4}0039$	$.9^{4}0426$	$.9^{4}0799$	$.9^{4}1158$	$.9^{4}1504$	$.9^{4}1838$	$.9^{4}2159$	$.9^{4}2468$
3.8	$.9^{4}2765$	$.9^{4}3052$	$.9^{4}3327$	$.9^{4}3593$	$.9^{4}3848$	$.9^{4}4094$	$.9^{4}4331$	$.9^{4}4558$	$.9^{4}4777$	$.9^{4}4988$
3.9	$.9^{4}5190$	$.9^{4}5385$	$.9^{4}5573$	$.9^{4}5753$	$.9^{4}5926$	$.9^{4}6092$	$.9^{4}6253$	$.9^{4}6406$	$.9^{4}6554$	$.9^{4}6696$
4.0	$.9^{4}6833$	$.9^{4}6964$	$.9^{4}7090$	$.9^{4}7211$	$.9^{4}7327$	$.9^{4}7439$	$.9^{4}7546$	$.9^{4}7649$	$.9^{4}7748$	$.9^{4}7843$
4.1	$.9^{4}7934$	$.9^{4}8022$	$.9^{4}8106$	$.9^{4}8186$	$.9^{4}6263$	$.9^{4}8338$	$.9^{4}8409$	$.9^{4}8477$	$.9^{4}8542$	$.9^{4}8605$
4.2	$.9^{4}8665$	$.9^{4}8723$	$.9^{4}8778$	$.9^{4}8832$	$.9^{4}8882$	$.9^{4}8931$	$.9^{4}8378$	$.9^{5}0226$	$.9^{5}0655$	$.9^{5}1066$
4.3	$.9^{5}1460$	$.9^{5}1837$	$.9^{5}2199$	$.9^{5}2545$	$.9^{5}2876$	$.9^{5}3193$	$.9^{5}3497$	$.9^{5}3788$	$.9^{5}4066$	$.9^{5}4332$
4.4	$.9^{5}4587$	$.9^{5}4831$	$.9^{5}5065$	$.9^{5}5288$	$.9^{5}5502$	$.9^{5}5706$	$.9^{5}5902$	$.9^{5}6089$	$.9^{5}6268$	$.9^{5}6439$
4.5	$.9^{5}6602$	$.9^{5}6759$	$.9^{5}6908$	$.9^{5}7051$	$.9^{5}7187$	$.9^{5}7318$	$.9^{5}7442$	$.9^{5}7561$	$.9^{5}7675$	$.9^{5}7784$
4.6	$.9^{5}7888$	$.9^{5}7987$	$.9^{5}8081$	$.9^{5}8172$	$.9^{5}8258$	$.9^{5}8340$	$.9^{5}8419$	$.9^{5}8494$	$.9^{5}8566$	$.9^{5}8634$
4.7	$.9^{5}8699$	$.9^{5}8761$	$.9^{5}8821$	$.9^{5}8877$	$.9^{5}8931$	$.9^{5}8983$	$.9^{6}0320$	$.9^{6}0789$	$.9^{6}1235$	$.9^{6}1661$
4.8	$.9^{6}2067$	$.9^{6}2453$	$.9^{6}2822$	$.9^{6}3173$	$.9^{6}3508$	$.9^{6}3827$	$.9^{6}4131$	$.9^{6}4420$	$.9^{6}4696$	$.9^{6}4958$
4.9	$.9^{6}5208$	$.9^{6}5446$	$.9^{6}5673$	$.9^{6}5889$	$.9^{6}6094$	$.9^{6}6289$	$.9^{6}6475$	$.9^{6}6652$	$.9^{6}6821$	$.9^{6}6981$

Example: $\Phi(3.57) = .9^{3}8215 = 0.9998215$.

† By permission from A. Hald, *Statistical Tables, and Formulas*, John Wiley & Sons, Inc., New York, 1952.

Table E.2.a. Summary of the Life Cycle Cost for Crushed Aggregate (Material Cost, 5 $/C.Y.)

CRUSHED AGGREGATE

1) COST OF MATERIAL:

LENGTH (FEET)	5280
WIDTH (FEET)	15.33
DEPTH (INCHES)	8
COMPACTED VOLUME OF CRUSHED AGGREGATE (C.Y.)	1998.57777777
COMPACTED VOLUME OF CRUSHED AGGREGATE FOR CURVE WIDENING AND TURNOUTS (C.Y.)	399.71555555
SWELL FACTOR-------->	1.25
TOTAL LOOSE VOLUME (C.Y.)	2997.86666665
AVERAGE COST OF MATERIALS ($/C.Y.)	5
AVERAGE TOTAL COST OF MATERIALS ($)	14989.333333

2) AVERAGE EQUIPMENT AND LABOR COST :

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS.)	TOTAL COST OF ACTIVITY ($)
SPREADING	32	125.38	4012.16
COMPACTION	8	76.2	609.6
	TOTAL AVERAGE COST ($):		4621.76

3) AVERAGE HAUL COST :

HAUL COST ($/C.Y.-MILE)	.3
HAUL DISTANCE (MILE)	30
TOTAL AVERAGE HAUL COST($)	26980.799999

Table E.2.a. Summary of the Life Cycle Cost for Crushed Aggregate (Material Cost, 5 $/C.Y.) (Continued)

AVERAGE MAINTENANCE COST $ 615

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5) TOTAL LIFE CYCLE COST :

AVERAGE MATERIAL COST ($)	14989.333333
AVERAGE EQUIPMENT AND LABOR COST ($)	4621.76
AVERAGE HAUL COST ($)	26980.799999
AVERAGE MAINTENANCE COST $	615
TOTAL LIFE CYCLE COST FOR CRUSHED AGGREGATE ROADS ($)----------->	47206.893332

Table E.2.b. Summary of the Life Cycle Cost for Crushed Aggregate (Material Cost, 10 $/C.Y.)

CRUSHED AGGREGATE

1) COST OF MATERIAL:

LENGTH (FEET)	5280
WIDTH (FEET)	15.33
DEPTH (INCHES)	8
COMPACTED VOLUME OF CRUSHED AGGREGATE (C.Y.)	1998.57777777
COMPACTED VOLUME OF CRUSHED AGGREGATE FOR CURVE WIDENING AND TURNOUTS (C.Y.)	399.71555555
SWELL FACTOR-------->	1.25
TOTAL LOOSE VOLUME (C.Y.)	2997.86666665
AVERAGE COST OF MATERIALS ($/C.Y.)	10
AVERAGE TOTAL COST OF MATERIALS ($)	29978.666666

2) AVERAGE EQUIPMENT AND LABOR COST :

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS.)	TOTAL COST OF ACTIVITY ($)
SPREADING	32	125.38	4012.16
COMPACTION	8	76.2	609.6
	TOTAL AVERAGE COST ($):		4621.76

3) AVERAGE HAUL COST :

HAUL COST ($/C.Y.-MILE)	.3
HAUL DISTANCE (MILE)	30
TOTAL AVERAGE HAUL COST($)	26980.799999

Table E.2.b. Summary of the Life Cycle Cost for Crushed Aggregate (Material Cost, 10 $/C.Y.) (Continued)

AVERAGE MAINTENANCE COST $ 615

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5) TOTAL LIFE CYCLE COST :

AVERAGE MATERIAL COST ($)	29978.666666
AVERAGE EQUIPMENT AND LABOR COST ($)	4621.76
AVERAGE HAUL COST ($)	26980.799999
AVERAGE MAINTENANCE COST $	615

TOTAL LIFE CYCLE COST FOR CRUSHED AGGREGATE ROADS ($)----------->	62196.226665
	===============

Table E.3.a. Summary of the Life Cycle Cost for Crushed Aggregate (Haul Distance, 10 Miles)

CRUSHED AGGREGATE

1) COST OF MATERIAL:

LENGTH (FEET)	5280
WIDTH (FEET)	15.33
DEPTH (INCHES)	8
COMPACTED VOLUME OF CRUSHED AGGREGATE (C.Y.)	1998.57777777
COMPACTED VOLUME OF CRUSHED AGGREGATE FOR CURVE WIDENING AND TURNOUTS (C.Y.)	399.71555555
SWELL FACTOR-------->	1.25
TOTAL LOOSE VOLUME (C.Y.)	2997.86666665
AVERAGE COST OF MATERIALS ($/C.Y.)	5
AVERAGE TOTAL COST OF MATERIALS ($)	14989.333333

2) AVERAGE EQUIPMENT AND LABOR COST :

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS.)	TOTAL COST OF ACTIVITY ($)
SPREADING	32	125.38	4012.16
COMPACTION	8	76.2	609.6
	TOTAL AVERAGE COST ($):		4621.76

3) AVERAGE HAUL COST :

HAUL COST ($/C.Y.-MILE)	.3
HAUL DISTANCE (MILE)	10
TOTAL AVERAGE HAUL COST($)	8993.5999999

Table E.3.a. Summary of the Life Cycle Cost for Crushed Aggregate (Haul Distance, 10 Miles) (Continued)

AVERAGE MAINTENANCE COST $ 615

---

5) TOTAL LIFE CYCLE COST :

AVERAGE MATERIAL COST ($)	14989.333333
AVERAGE EQUIPMENT AND LABOR COST ($)	4621.76
AVERAGE HAUL COST ($)	8993.5999999
AVERAGE MAINTENANCE COST $	615
TOTAL LIFE CYCLE COST FOR CRUSHED AGGREGATE ROADS ($)----------->	29219.693332

Table E.3.b. Summary of the Life Cycle Cost for Crushed Aggregate (Haul Distance, 30 Miles)

CRUSHED AGGREGATE

1) COST OF MATERIAL:

LENGTH (FEET)	5280
WIDTH (FEET)	15.33
DEPTH (INCHES)	8
COMPACTED VOLUME OF CRUSHED AGGREGATE (C.Y.)	1998.57777777
COMPACTED VOLUME OF CRUSHED AGGREGATE FOR CURVE WIDENING AND TURNOUTS (C.Y.)	399.71555555
SWELL FACTOR-------->	1.25
TOTAL LOOSE VOLUME (C.Y.)	2997.86666665
AVERAGE COST OF MATERIALS ($/C.Y.)	5
AVERAGE TOTAL COST OF MATERIALS ($)	14989.333333

2) AVERAGE EQUIPMENT AND LABOR COST :

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS.)	TOTAL COST OF ACTIVITY ($)
SPREADING	32	125.38	4012.16
COMPACTION	8	76.2	609.6
	TOTAL AVERAGE COST ($):		4621.76

3) AVERAGE HAUL COST :

HAUL COST ($/C.Y.-MILE)	.3
HAUL DISTANCE (MILE)	30
TOTAL AVERAGE HAUL COST($)	26980.799999

Table E.3.b. Summary of the Life Cycle Cost for Crushed Aggregate (Haul Distance, 30 Miles) (Continued)

AVERAGE MAINTENANCE COST $ 615

---

5) TOTAL LIFE CYCLE COST :

AVERAGE MATERIAL COST ($)	14989.333333
AVERAGE EQUIPMENT AND LABOR COST ($)	4621.76
AVERAGE HAUL COST ($)	26980.799999
AVERAGE MAINTENANCE COST $	615
TOTAL LIFE CYCLE COST FOR CRUSHED AGGREGATE ROADS ($)----------->	47206.893332

Table E.3.c. Summary of the Life Cycle Cost for Crushed Aggregate (Haul Distance, 60 Miles)

CRUSHED AGGREGATE

1) COST OF MATERIAL:

LENGTH (FEET)	5280
WIDTH (FEET)	15.33
DEPTH (INCHES)	8
COMPACTED VOLUME OF CRUSHED AGGREGATE (C.Y.)	1998.57777777
COMPACTED VOLUME OF CRUSHED AGGREGATE FOR CURVE WIDENING AND TURNOUTS (C.Y.)	399.71555555
SWELL FACTOR-------->	1.25
TOTAL LOOSE VOLUME (C.Y.)	2997.86666665
AVERAGE COST OF MATERIALS ($/C.Y.)	5
AVERAGE TOTAL COST OF MATERIALS ($)	14989.333333

2) AVERAGE EQUIPMENT AND LABOR COST :

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS.)	TOTAL COST OF ACTIVITY ($)
SPREADING	32	125.38	4012.16
COMPACTION	8	76.2	609.6
	TOTAL AVERAGE COST ($):		4621.76

3) AVERAGE HAUL COST :

HAUL COST ($/C.Y.-MILE)	.3
HAUL DISTANCE (MILE)	60
TOTAL AVERAGE HAUL COST($)	53961.599999

Table E.3.c. Summary of the Life Cycle Cost for Crushed Aggregate (Haul Distance, 60 Miles) (Continued)

AVERAGE MAINTENANCE COST $ 615

---

5) TOTAL LIFE CYCLE COST :

AVERAGE MATERIAL COST ($)	14989.333333
AVERAGE EQUIPMENT AND LABOR COST ($)	4621.76
AVERAGE HAUL COST ($)	53961.599999
AVERAGE MAINTENANCE COST $	615
TOTAL LIFE CYCLE COST FOR CRUSHED AGGREGATE ROADS ($)----------->	74187.693332

Table E.4.a. Summary of the Life Cycle Cost for Crushed Aggregate (Low Production Rate)

CRUSHED AGGREGATE

1) COST OF MATERIAL:

LENGTH (FEET)	5280
WIDTH (FEET)	15.33
DEPTH (INCHES)	8
COMPACTED VOLUME OF CRUSHED AGGREGATE (C.Y.)	1998.57777777
COMPACTED VOLUME OF CRUSHED AGGREGATE FOR CURVE WIDENING AND TURNOUTS (C.Y.)	399.71555555
SWELL FACTOR-------->	1.25
TOTAL LOOSE VOLUME (C.Y.)	2997.86666665
AVERAGE COST OF MATERIALS ($/C.Y.)	5
AVERAGE TOTAL COST OF MATERIALS ($)	14989.333333

2) AVERAGE EQUIPMENT AND LABOR COST :

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS.)	TOTAL COST OF ACTIVITY ($)
SPREADING	64	125.38	8024.32
COMPACTION	16	76.2	1219.2
	TOTAL AVERAGE COST ($):		9243.52

3) AVERAGE HAUL COST :

HAUL COST ($/C.Y.-MILE)	.3
HAUL DISTANCE (MILE)	30
TOTAL AVERAGE HAUL COST($)	26980.799999

Table E.4.a. Summary of the Life Cycle Cost for Crushed Aggregate (Low Production Rate) (Continued)

AVERAGE MAINTENANCE COST $ 615

---

5) TOTAL LIFE CYCLE COST :

AVERAGE MATERIAL COST ($)	14989.333333
AVERAGE EQUIPMENT AND LABOR COST ($)	9243.52
AVERAGE HAUL COST ($)	26980.799999
AVERAGE MAINTENANCE COST $	615
TOTAL LIFE CYCLE COST FOR CRUSHED AGGREGATE ROADS ($)----------->	51828.653332

Table E.4.b. Summary of the Life Cycle Cost for Crushed Aggregate (Average Production Rate)

CRUSHED AGGREGATE

1) COST OF MATERIAL:

LENGTH (FEET)	5280
WIDTH (FEET)	15.33
DEPTH (INCHES)	8
COMPACTED VOLUME OF CRUSHED AGGREGATE (C.Y.)	1998.57777777
COMPACTED VOLUME OF CRUSHED AGGREGATE FOR CURVE WIDENING AND TURNOUTS (C.Y.)	399.71555555
SWELL FACTOR-------->	1.25
TOTAL LOOSE VOLUME (C.Y.)	2997.86666665
AVERAGE COST OF MATERIALS ($/C.Y.)	5
AVERAGE TOTAL COST OF MATERIALS ($)	14989.333333

2) AVERAGE EQUIPMENT AND LABOR COST :

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS.)	TOTAL COST OF ACTIVITY ($)
SPREADING	32	125.38	4012.16
COMPACTION	8	76.2	609.6
	TOTAL AVERAGE COST ($):		4621.76

3) AVERAGE HAUL COST :

HAUL COST ($/C.Y.-MILE)	.3
HAUL DISTANCE (MILE)	30
TOTAL AVERAGE HAUL COST($)	26980.799999

Table E.4.b. Summary of the Life Cycle Cost for Crushed Aggregate (Average Production Rate) (Continued)

AVERAGE MAINTENANCE COST $ 615

---

5) TOTAL LIFE CYCLE COST :

AVERAGE MATERIAL COST ($)	14989.333333
AVERAGE EQUIPMENT AND LABOR COST ($)	4621.76
AVERAGE HAUL COST ($)	26980.799999
AVERAGE MAINTENANCE COST $	615
TOTAL LIFE CYCLE COST FOR CRUSHED AGGREGATE ROADS ($)----------->	47206.893332

Table E.4.c. Summary of the Life Cycle Cost for Crushed Aggregate (High Production Rate)

CRUSHED AGGREGATE

1) COST OF MATERIAL:

LENGTH (FEET)	5280
WIDTH (FEET)	15.33
DEPTH (INCHES)	8
COMPACTED VOLUME OF CRUSHED AGGREGATE (C.Y.)	1998.57777777
COMPACTED VOLUME OF CRUSHED AGGREGATE FOR CURVE WIDENING AND TURNOUTS (C.Y.)	399.71555555
SWELL FACTOR-------->	1.25
TOTAL LOOSE VOLUME (C.Y.)	2997.86666665
AVERAGE COST OF MATERIALS ($/C.Y.)	5
AVERAGE TOTAL COST OF MATERIALS ($)	14989.333333

2) AVERAGE EQUIPMENT AND LABOR COST :

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS.)	TOTAL COST OF ACTIVITY ($)
SPREADING	16	125.38	2006.08
COMPACTION	4	76.2	304.8
	TOTAL AVERAGE COST ($):		2310.88

3) AVERAGE HAUL COST :

HAUL COST ($/C.Y.-MILE)	.3
HAUL DISTANCE (MILE)	30
TOTAL AVERAGE HAUL COST($)	26980.799999

Table E.4.c. Summary of the Life Cycle Cost for Crushed Aggregate (High Production Rate) (Continued)

AVERAGE MAINTENANCE COST $ 615

---

5) TOTAL LIFE CYCLE COST :

AVERAGE MATERIAL COST ($)	14989.333333
AVERAGE EQUIPMENT AND LABOR COST ($)	2310.88
AVERAGE HAUL COST ($)	26980.799999
AVERAGE MAINTENANCE COST $	615

TOTAL LIFE CYCLE COST FOR CRUSHED AGGREGATE ROADS ($)----------->	44896.013332
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Table E.5.a. Summary of the Life Cycle Cost for Soil Stabilization (Material Cost, 50 $/Ton)

SOIL STABILIZATION

1) COST OF MATERIAL:

LENGTH(FEET)	5280
WIDTH(FEET)	15
DEPTH(INCHES)	6
COMPACTED VOLUME OF SOIL TO BE STABILIZED (C.Y.)	1466.66666666
COMPACTED VOLUME OF SOIL TO BE STABILIZED FOR CURVE WIDENING AND TURNOUTS (C.Y.)	293.33333333
TOTAL COMPACTED VOLUME (C.Y.)	1759.99999999

STABILIZED AGENT COST:

UNIT WEIGHT OF SOIL (POUND/CUBIC FEET)	110
% OF STABILIZED AGENT	.05
COST ($/TON)	50
TOTAL WEIGHT OF STABILIZED AGENT (TON)	130.67999999
TOTAL COST OF STABILIZED AGENT($)	6533.9999995

TAble E.5.a. Summary of the Life Cycle Cost for Soil Stabilization (Material Cost, 50 $/Ton) (Continued)

TRACTION SAND COST	
LENGTH (FEET)	5280
WIDTH (FEET)	15
APPLICATION RATE (LBS/SQ YARD)	30
COST OF SAND ($/TON)	10
TOTAL SURFACE AREA OF ROADWAY (SQ YARD)	10560
WEIGHT OF SAND (TON)	158.4
TOTAL COST OF SAND ($)	1584
TOTAL COST OF MATERIALS ($)------------------->	8117.9999995

2) AVERAGE EQUIPMENT AND LABOR COST:

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS)	TOTAL COST OF ACTIVITY ($)
SOIL PULVERIZATION	24	100.83	2419.92
SPREADING	24	91.24	2189.76
MIXING	24	100.83	2419.92
WATERING	24	88.22	2117.28
COMPACTION	24	76.21	1829.04
SPREADING SAND	4	93.7	374.8
	TOTAL AVERAGE COST($):		11350.72

Table E.5.a. Summary of the Life Cycle Cost for Soil Stabilization (Material Cost, 50 $/Ton) (Continued)

3) AVERAGE HAUL COST:

HAUL COST ($/TON-MILE)	.15
HAUL DIST.STABILIZING AGENT (MILE)	50
HAUL DIST.SAND (MILE)	40
TOTAL HAUL COST OF STABILIZING AGENT ($)	980.09999992
TOTAL HAUL COST OF TRACTION SAND ($)	950.4

TOTAL AVERAGE HAUL COST ($)--------->	1930.49999992

4) AVERAGE MAINTENANCE COST($)----------> 615

TOTAL LIFE CYCLE COST:

AVERAGE MATERIAL COST ($)	8117.9999995
AVERAGE EQUIPMENT AND LABOR COST ($)	11350.72
AVERAGE HAUL COST ($)	1930.49999992
AVERAGE MAINTENANCE COST ($)	615

TOTAL LIFE CYCLE COST FOR STABILIZED ROAD ($)---------------->	22014.219998
	==============

Table E.5.b. Summary of the Life Cycle Cost for Soil Stabilization (Material Cost, 80 $/Ton)

SOIL STABILIZATION

1) COST OF MATERIAL:

LENGTH(FEET)	5280
WIDTH(FEET)	15
DEPTH(INCHES)	6
COMPACTED VOLUME OF SOIL TO BE STABILIZED (C.Y.)	1466.66666666
COMPACTED VOLUME OF SOIL TO BE STABILIZED FOR CURVE WIDENING AND TURNOUTS (C.Y.)	293.33333333
TOTAL COMPACTED VOLUME (C.Y.)	1759.99999999

STABILIZED AGENT COST:

UNIT WEIGHT OF SOIL (POUND/CUBIC FEET)	110
% OF STABILIZED AGENT	.05
COST ($/TON)	80
TOTAL WEIGHT OF STABILIZED AGENT (TON)	130.67999999
TOTAL COST OF STABILIZED AGENT($)	10454.399999

Table E.5.b. Summary of the Life Cycle Cost for Soil Stabilization (Material Cost, 80 $/Ton) (Continued)

TRACTION SAND COST

LENGTH (FEET)	5280
WIDTH (FEET)	15
APPLICATION RATE (LBS/SQ YARD)	30
COST OF SAND ($/TON)	10
TOTAL SURFACE AREA OF ROADWAY (SQ YARD)	10560
WEIGHT OF SAND (TON)	158.4
TOTAL COST OF SAND ($)	1584
TOTAL COST OF MATERIALS ($)------------------->	12038.399999

2) AVERAGE EQUIPMENT AND LABOR COST:

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS)	TOTAL COST OF ACTIVITY ($)
SOIL PULVERIZATION	24	100.83	2419.92
SPREADING	24	91.24	2189.76
MIXING	24	100.83	2419.92
WATERING	24	88.22	2117.28
COMPACTION	24	76.21	1829.04
SPREADING SAND	4	93.7	374.8
	TOTAL AVERAGE COST($):		11350.72

Table E.5.b. Summary of the Life Cycle Cost for Soil Stabilization (Material Cost, 80 $/Ton) (Continued)

3) AVERAGE HAUL COST:	
HAUL COST ($/TON-MILE)	.15
HAUL DIST.STABILIZING AGENT (MILE)	50
HAUL DIST.SAND (MILE)	40
TOTAL HAUL COST OF STABILIZING AGENT ($)	980.09999992
TOTAL HAUL COST OF TRACTION SAND ($)	950.4

TOTAL AVERAGE HAUL COST ($)--------->	1930.49999992
4) AVERAGE MAINTENANCE COST($)---------->	615
TOTAL LIFE CYCLE COST:	
AVERAGE MATERIAL COST ($)	12038.399999
AVERAGE EQUIPMENT AND LABOR COST ($)	11350.72
AVERAGE HAUL COST ($)	1930.49999992
AVERAGE MAINTENANCE COST ($)	615

TOTAL LIFE CYCLE COST FOR STABILIZED ROAD ($)----------------->	25934.619998
	==============

Table E.6.a. Summary of the Life Cycle Cost for Soil Stabilization (2% Stabilized Agent)

SOIL STABILIZATION

1) COST OF MATERIAL:

LENGTH(FEET)	5280
WIDTH(FEET)	15
DEPTH(INCHES)	6
COMPACTED VOLUME OF SOIL TO BE STABILIZED (C.Y.)	1466.66666666
COMPACTED VOLUME OF SOIL TO BE STABILIZED FOR CURVE WIDENING AND TURNOUTS (C.Y.)	293.33333333
TOTAL COMPACTED VOLUME (C.Y.)	1759.99999999

STABILIZED AGENT COST:

UNIT WEIGHT OF SOIL (POUND/CUBIC FEET)	110
% OF STABILIZED AGENT	.02
COST ($/TON)	80
TOTAL WEIGHT OF STABILIZED AGENT (TON)	52.271999999
TOTAL COST OF STABILIZED AGENT($)	4181.75999992

Table E.6.a. Summary of the Life Cycle Cost for Soil Stabilization (2% Stabilized Agent) (Continued)

TRACTION SAND COST

LENGTH (FEET)	5280
WIDTH (FEET)	15
APPLICATION RATE (LBS/SQ YARD)	30
COST OF SAND ($/TON)	10
TOTAL SURFACE AREA OF ROADWAY (SQ YARD)	10560
WEIGHT OF SAND (TON)	158.4
TOTAL COST OF SAND ($)	1584
TOTAL COST OF MATERIALS ($)------------------>	5765.75999992

2) AVERAGE EQUIPMENT AND LABOR COST:

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS)	TOTAL COST OF ACTIVITY ($)
SOIL PULVERIZATION	24	100.83	2419.92
SPREADING	24	91.24	2189.76
MIXING	24	100.83	2419.92
WATERING	24	88.22	2117.28
COMPACTION	24	76.21	1829.04
SPREADING SAND	4	93.7	374.8
	TOTAL AVERAGE COST($):		11350.72

Table E.6.a. Summary of the Life Cycle Cost for Soil Stabilization (2% Stabilized Agent) (Continued)

3) AVERAGE HAUL COST:	
HAUL COST ($/TON-MILE)	.15
HAUL DIST.STABILIZING AGENT (MILE)	50
HAUL DIST.SAND (MILE)	40
TOTAL HAUL COST OF STABILIZING AGENT ($)	392.03999999
TOTAL HAUL COST OF TRACTION SAND ($)	950.4

TOTAL AVERAGE HAUL COST ($)--------->	1342.43999999
4) AVERAGE MAINTENANCE COST($)---------->	615
TOTAL LIFE CYCLE COST:	
AVERAGE MATERIAL COST ($)	5765.75999992
AVERAGE EQUIPMENT AND LABOR COST ($)	11350.72
AVERAGE HAUL COST ($)	1342.43999999
AVERAGE MAINTENANCE COST ($)	615

TOTAL LIFE CYCLE COST FOR STABILIZED ROAD ($)---------------->	19073.919998
	==============

Table E.6.b. Summary of the Life Cycle Cost for Soil Stabilization (5% Stabilized Agent)

SOIL STABILIZATION

1) COST OF MATERIAL:

LENGTH(FEET)	5280
WIDTH(FEET)	15
DEPTH(INCHES)	6
COMPACTED VOLUME OF SOIL TO BE STABILIZED (C.Y.)	1466.66666666
COMPACTED VOLUME OF SOIL TO BE STABILIZED FOR CURVE WIDENING AND TURNOUTS (C.Y.)	293.33333333
TOTAL COMPACTED VOLUME (C.Y.)	1759.99999999

STABILIZED AGENT COST:

UNIT WEIGHT OF SOIL (POUND/CUBIC FEET)	110
% OF STABILIZED AGENT	.05
COST ($/TON)	80
TOTAL WEIGHT OF STABILIZED AGENT (TON)	130.67999999
TOTAL COST OF STABILIZED AGENT($)	10454.399999

Table E.6.b. Summary of the Life Cycle Cost for Soil Stabilization (5% Stabilized Agent) (Continued)

TRACTION SAND COST	
LENGTH (FEET)	5280
WIDTH (FEET)	15
APPLICATION RATE (LBS/SQ YARD)	30
COST OF SAND ($/TON)	10
TOTAL SURFACE AREA OF ROADWAY (SQ YARD)	10560
WEIGHT OF SAND (TON)	158.4
TOTAL COST OF SAND ($)	1584
TOTAL COST OF MATERIALS ($)------------------->	12038.399999

2) AVERAGE EQUIPMENT AND LABOR COST:

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS)	TOTAL COST OF ACTIVITY ($)
SOIL PULVERIZATION	24	100.83	2419.92
SPREADING	24	91.24	2189.76
MIXING	24	100.83	2419.92
WATERING	24	88.22	2117.28
COMPACTION	24	76.21	1829.04
SPREADING SAND	4	93.7	374.8
	TOTAL AVERAGE COST($):		11350.72

Table E.6.b. Summary of the Life Cycle Cost for Soil Stabilization (5% Stabilized Agent) (Continued)

3) AVERAGE HAUL COST:	
HAUL COST ($/TON-MILE)	.15
HAUL DIST.STABILIZING AGENT (MILE)	50
HAUL DIST.SAND (MILE)	40
TOTAL HAUL COST OF STABILIZING AGENT ($)	980.09999992
TOTAL HAUL COST OF TRACTION SAND ($)	950.4
TOTAL AVERAGE HAUL COST ($)--------->	1930.49999992
4) AVERAGE MAINTENANCE COST($)---------->	615
TOTAL LIFE CYCLE COST:	
AVERAGE MATERIAL COST ($)	12038.399999
AVERAGE EQUIPMENT AND LABOR COST ($)	11350.72
AVERAGE HAUL COST ($)	1930.49999992
AVERAGE MAINTENANCE COST ($)	615
TOTAL LIFE CYCLE COST FOR STABILIZED ROAD ($)----------------->	25934.619998

Table E.6.c. Summary of the Life Cycle Cost for Soil Stabilization (10% Stabilized Agent)

SOIL STABILIZATION

1) COST OF MATERIAL:

LENGTH(FEET)	5280
WIDTH(FEET)	15
DEPTH(INCHES)	6
COMPACTED VOLUME OF SOIL TO BE STABILIZED (C.Y.)	1466.66666666
COMPACTED VOLUME OF SOIL TO BE STABILIZED FOR CURVE WIDENING AND TURNOUTS (C.Y.)	293.33333333
TOTAL COMPACTED VOLUME (C.Y.)	1759.99999999

STABILIZED AGENT COST:

UNIT WEIGHT OF SOIL (POUND/CUBIC FEET)	110
% OF STABILIZED AGENT	.1
COST ($/TON)	80
TOTAL WEIGHT OF STABILIZED AGENT (TON)	261.35999998
TOTAL COST OF STABILIZED AGENT($)	20908.799998

Table E.6.c. Summary of the Life Cycle Cost for Soil Stabilization (10% Stabilized Agent) (Continued)

TRACTION SAND COST

LENGTH (FEET)	5280
WIDTH (FEET)	15
APPLICATION RATE (LBS/SQ YARD)	30
COST OF SAND ($/TON)	10
TOTAL SURFACE AREA OF ROADWAY (SQ YARD)	10560
WEIGHT OF SAND (TON)	158.4
TOTAL COST OF SAND ($)	1584
TOTAL COST OF MATERIALS ($)------------------->	22492.799998

2) AVERAGE EQUIPMENT AND LABOR COST:

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS)	TOTAL COST OF ACTIVITY ($)
SOIL PULVERIZATION	24	100.83	2419.92
SPREADING	24	91.24	2189.76
MIXING	24	100.83	2419.92
WATERING	24	88.22	2117.28
COMPACTION	24	76.21	1829.04
SPREADING SAND	4	93.7	374.8
	TOTAL AVERAGE COST($):		11350.72

Table E.6.c. Summary of the Life Cycle Cost for Soil Stabilization (10% Stabilized Agent) (Continued)

3) AVERAGE HAUL COST:

HAUL COST ($/TON-MILE)	.15
HAUL DIST.STABILIZING AGENT (MILE)	50
HAUL DIST.SAND (MILE)	40
TOTAL HAUL COST OF STABILIZING AGENT ($)	1960.19999985
TOTAL HAUL COST OF TRACTION SAND ($)	950.4

TOTAL AVERAGE HAUL COST ($)--------->	2910.59999985

4) AVERAGE MAINTENANCE COST($)----------> 615

TOTAL LIFE CYCLE COST:

AVERAGE MATERIAL COST ($)	22492.799998
AVERAGE EQUIPMENT AND LABOR COST ($)	11350.72
AVERAGE HAUL COST ($)	2910.59999985
AVERAGE MAINTENANCE COST ($)	615

TOTAL LIFE CYCLE COST FOR STABILIZED ROAD ($)----------------->	37369.119997
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Table E.7.a. Summary of the Life Cycle Cost for Soil Stabilization (Haul Distance, 20 Miles)

SOIL STABILIZATION

1) COST OF MATERIAL:

LENGTH(FEET)	5280
WIDTH(FEET)	15
DEPTH(INCHES)	6
COMPACTED VOLUME OF SOIL TO BE STABILIZED (C.Y.)	1466.66666666
COMPACTED VOLUME OF SOIL TO BE STABILIZED FOR CURVE WIDENING AND TURNOUTS (C.Y.)	293.33333333
TOTAL COMPACTED VOLUME (C.Y.)	1759.99999999

STABILIZED AGENT COST:

UNIT WEIGHT OF SOIL (POUND/CUBIC FEET)	110
% OF STABILIZED AGENT	.05
COST ($/TON)	80
TOTAL WEIGHT OF STABILIZED AGENT (TON)	130.67999999
TOTAL COST OF STABILIZED AGENT($)	10454.399999

Table E.7.a. Summary of the Life Cycle Cost for Soil Stabilization (Haul Distance, 20 Miles) (Continued)

TRACTION SAND COST

LENGTH (FEET)	5280
WIDTH (FEET)	15
APPLICATION RATE (LBS/SQ YARD)	30
COST OF SAND ($/TON)	10
TOTAL SURFACE AREA OF ROADWAY (SQ YARD)	10560
WEIGHT OF SAND (TON)	158.4
TOTAL COST OF SAND ($)	1584
TOTAL COST OF MATERIALS ($)------------------>	12038.399999

2) AVERAGE EQUIPMENT AND LABOR COST:

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS)	TOTAL COST OF ACTIVITY ($)
SOIL PULVERIZATION	24	100.83	2419.92
SPREADING	24	91.24	2189.76
MIXING	24	100.83	2419.92
WATERING	24	88.22	2117.28
COMPACTION	24	76.21	1829.04
SPREADING SAND	4	93.7	374.8
	TOTAL AVERAGE COST($):		11350.72

Table E.7.a. Summary of the Life Cycle Cost for Soil Stabilization (Haul Distance, 20 Miles) (Continued)

3) AVERAGE HAUL COST:	
HAUL COST ($/TON-MILE)	.15
HAUL DIST.STABILIZING AGENT (MILE)	20
HAUL DIST.SAND (MILE)	40
TOTAL HAUL COST OF STABILIZING AGENT ($)	392.03999997
TOTAL HAUL COST OF TRACTION SAND ($)	950.4

TOTAL AVERAGE HAUL COST ($)--------->	1342.43999997
4) AVERAGE MAINTENANCE COST($)---------->	615
TOTAL LIFE CYCLE COST:	
AVERAGE MATERIAL COST ($)	12038.399999
AVERAGE EQUIPMENT AND LABOR COST ($)	11350.72
AVERAGE HAUL COST ($)	1342.43999997
AVERAGE MAINTENANCE COST ($)	615

TOTAL LIFE CYCLE COST FOR STABILIZED ROAD ($)----------------->	25346.559998
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Table E.7.b. Summary of the Life Cycle Cost for Soil Stabilization (Haul Distance, 50 Miles)

SOIL STABILIZATION

1) COST OF MATERIAL:

LENGTH(FEET)	5280
WIDTH(FEET)	15
DEPTH(INCHES)	6
COMPACTED VOLUME OF SOIL TO BE STABILIZED (C.Y.)	1466.66666666
COMPACTED VOLUME OF SOIL TO BE STABILIZED FOR CURVE WIDENING AND TURNOUTS (C.Y.)	293.33333333
TOTAL COMPACTED VOLUME (C.Y.)	1759.99999999

STABILIZED AGENT COST:

UNIT WEIGHT OF SOIL (POUND/CUBIC FEET)	110
% OF STABILIZED AGENT	.05
COST ($/TON)	80
TOTAL WEIGHT OF STABILIZED AGENT (TON)	130.67999999
TOTAL COST OF STABILIZED AGENT($)	10454.399999

Table E.7.b. Summary of the Life Cycle Cost for Soil Stabilization (Haul Distance, 50 Miles) (Continued)

TRACTION SAND COST

LENGTH (FEET)	5280
WIDTH (FEET)	15
APPLICATION RATE (LBS/SQ YARD)	30
COST OF SAND ($/TON)	10
TOTAL SURFACE AREA OF ROADWAY (SQ YARD)	10560
WEIGHT OF SAND (TON)	158.4
TOTAL COST OF SAND ($)	1584
TOTAL COST OF MATERIALS ($)------------------->	12038.399999

2) AVERAGE EQUIPMENT AND LABOR COST:

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS)	TOTAL COST OF ACTIVITY ($)
SOIL PULVERIZATION	24	100.83	2419.92
SPREADING	24	91.24	2189.76
MIXING	24	100.83	2419.92
WATERING	24	88.22	2117.28
COMPACTION	24	76.21	1829.04
SPREADING SAND	4	93.7	374.8
	TOTAL AVERAGE COST($):		11350.72

Table E.7.b. Summary of the Life Cycle Cost for Soil Stabilization (Haul Distance, 50 Miles) (Continued)

3) AVERAGE HAUL COST:	
HAUL COST ($/TON-MILE)	.15
HAUL DIST.STABILIZING AGENT (MILE)	50
HAUL DIST.SAND (MILE)	40
TOTAL HAUL COST OF STABILIZING AGENT ($)	980.09999992
TOTAL HAUL COST OF TRACTION SAND ($)	950.4

TOTAL AVERAGE HAUL COST ($)--------->	1930.49999992
4) AVERAGE MAINTENANCE COST($)---------->	615
TOTAL LIFE CYCLE COST:	
AVERAGE MATERIAL COST ($)	12038.399999
AVERAGE EQUIPMENT AND LABOR COST ($)	11350.72
AVERAGE HAUL COST ($)	1930.49999992
AVERAGE MAINTENANCE COST ($)	615

TOTAL LIFE CYCLE COST FOR STABILIZED ROAD ($)----------------->	25934.619998
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Table E.7.c. Summary of the Life Cycle Cost for Soil Stabilization (Haul Distance, 200 Miles)

SOIL STABILIZATION

1) COST OF MATERIAL:

LENGTH(FEET)	5280
WIDTH(FEET)	15
DEPTH(INCHES)	6
COMPACTED VOLUME OF SOIL TO BE STABILIZED (C.Y.)	1466.66666666
COMPACTED VOLUME OF SOIL TO BE STABILIZED FOR CURVE WIDENING AND TURNOUTS (C.Y.)	293.33333333
TOTAL COMPACTED VOLUME (C.Y.)	1759.99999999

STABILIZED AGENT COST:

UNIT WEIGHT OF SOIL (POUND/CUBIC FEET)	110
% OF STABILIZED AGENT	.05
COST ($/TON)	80
TOTAL WEIGHT OF STABILIZED AGENT (TON)	130.67999999
TOTAL COST OF STABILIZED AGENT($)	10454.399999

Table E.7.c. Summary of the Life Cycle Cost for Soil Stabilization (Haul Distance, 200 Miles) (Continued)

TRACTION SAND COST

LENGTH (FEET)	5280
WIDTH (FEET)	15
APPLICATION RATE (LBS/SQ YARD)	30
COST OF SAND ($/TON)	10
TOTAL SURFACE AREA OF ROADWAY (SQ YARD)	10560
WEIGHT OF SAND (TON)	158.4
TOTAL COST OF SAND ($)	1584
TOTAL COST OF MATERIALS ($)------------------->	12038.399999

2) AVERAGE EQUIPMENT AND LABOR COST:

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS)	TOTAL COST OF ACTIVITY ($)
SOIL PULVERIZATION	24	100.83	2419.92
SPREADING	24	91.24	2189.76
MIXING	24	100.83	2419.92
WATERING	24	88.22	2117.28
COMPACTION	24	76.21	1829.04
SPREADING SAND	4	93.7	374.8
	TOTAL AVERAGE COST($):		11350.72

Table E.7.c. Summary of the Life Cycle Cost for Soil Stabilization (Haul Distance, 200 Miles) (Continued)

3) AVERAGE HAUL COST:	
HAUL COST ($/TON-MILE)	.15
HAUL DIST.STABILIZING AGENT (MILE)	200
HAUL DIST.SAND (MILE)	40
TOTAL HAUL COST OF STABILIZING AGENT ($)	3920.3999997
TOTAL HAUL COST OF TRACTION SAND ($)	950.4

TOTAL AVERAGE HAUL COST ($)--------->	4870.7999997
4) AVERAGE MAINTENANCE COST($)---------->	615
TOTAL LIFE CYCLE COST:	
AVERAGE MATERIAL COST ($)	12038.399999
AVERAGE EQUIPMENT AND LABOR COST ($)	11350.72
AVERAGE HAUL COST ($)	4870.7999997
AVERAGE MAINTENANCE COST ($)	615

TOTAL LIFE CYCLE COST FOR STABILIZED ROAD ($)----------------->	28874.919998
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Table E.8.a. Summary of the Life Cycle Cost for Soil Stabilization (Low Production Rate)

SOIL STABILIZATION

1) COST OF MATERIAL:

LENGTH(FEET)	5280
WIDTH(FEET)	15
DEPTH(INCHES)	6
COMPACTED VOLUME OF SOIL TO BE STABILIZED (C.Y.)	1466.66666666
COMPACTED VOLUME OF SOIL TO BE STABILIZED FOR CURVE WIDENING AND TURNOUTS (C.Y.)	293.33333333
TOTAL COMPACTED VOLUME (C.Y.)	1759.99999999

STABILIZED AGENT COST:

UNIT WEIGHT OF SOIL (POUND/CUBIC FEET)	110
% OF STABILIZED AGENT	.05
COST ($/TON)	80
TOTAL WEIGHT OF STABILIZED AGENT (TON)	130.67999999
TOTAL COST OF STABILIZED AGENT($)	10454.399999

Table E.8.a. Summary of the Life Cycle Cost for Soil Stabilization (Low Production Rate) (Continued)

TRACTION SAND COST

LENGTH (FEET)	5280
WIDTH (FEET)	15
APPLICATION RATE (LBS/SQ YARD)	30
COST OF SAND ($/TON)	10
TOTAL SURFACE AREA OF ROADWAY (SQ YARD)	10560
WEIGHT OF SAND (TON)	158.4
TOTAL COST OF SAND ($)	1584
TOTAL COST OF MATERIALS ($)------------------->	12038.399999

2) AVERAGE EQUIPMENT AND LABOR COST:

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS)	TOTAL COST OF ACTIVITY ($)
SOIL PULVERIZATION	12	100.83	1209.96
SPREADING	48	91.24	4379.52
MIXING	48	100.83	4839.84
WATERING	48	88.22	4234.56
COMPACTION	48	76.21	3658.08
SPREADING SAND	8	93.7	749.6
	TOTAL AVERAGE COST($):		19071.56

Table E.8.a. Summary of the Life Cycle Cost for Soil Stabilization (Low Production Rate) (Continued)

3) AVERAGE HAUL COST:	
HAUL COST ($/TON-MILE)	.15
HAUL DIST.STABILIZING AGENT (MILE)	50
HAUL DIST.SAND (MILE)	40
TOTAL HAUL COST OF STABILIZING AGENT ($)	980.09999992
TOTAL HAUL COST OF TRACTION SAND ($)	950.4
TOTAL AVERAGE HAUL COST ($)--------->	1930.49999992
4) AVERAGE MAINTENANCE COST($)---------->	615
TOTAL LIFE CYCLE COST:	
AVERAGE MATERIAL COST ($)	12038.399999
AVERAGE EQUIPMENT AND LABOR COST ($)	19071.56
AVERAGE HAUL COST ($)	1930.49999992
AVERAGE MAINTENANCE COST ($)	615
TOTAL LIFE CYCLE COST FOR STABILIZED ROAD ($)----------------->	33655.459998

Table E.8.b. Summary of the Life Cycle Cost for Soil Stabilization (Average Production Rate)

SOIL STABILIZATION

1) COST OF MATERIAL:

LENGTH(FEET)	5280
WIDTH(FEET)	15
DEPTH(INCHES)	6
COMPACTED VOLUME OF SOIL TO BE STABILIZED (C.Y.)	1466.66666666
COMPACTED VOLUME OF SOIL TO BE STABILIZED FOR CURVE WIDENING AND TURNOUTS (C.Y.)	293.33333333
TOTAL COMPACTED VOLUME (C.Y.)	1759.99999999

STABILIZED AGENT COST:

UNIT WEIGHT OF SOIL (POUND/CUBIC FEET)	110
% OF STABILIZED AGENT	.05
COST ($/TON)	80
TOTAL WEIGHT OF STABILIZED AGENT (TON)	130.67999999
TOTAL COST OF STABILIZED AGENT($)	10454.399999

Table E.8.b. Summary of the Life Cycle Cost for Soil Stabilization (Average Production Rate) (Continued)

TRACTION SAND COST

LENGTH (FEET)	5280
WIDTH (FEET)	15
APPLICATION RATE (LBS/SQ YARD)	30
COST OF SAND ($/TON)	10
TOTAL SURFACE AREA OF ROADWAY (SQ YARD)	10560
WEIGHT OF SAND (TON)	158.4
TOTAL COST OF SAND ($)	1584
TOTAL COST OF MATERIALS ($)------------------->	12038.399999

2) AVERAGE EQUIPMENT AND LABOR COST:

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS)	TOTAL COST OF ACTIVITY ($)
SOIL PULVERIZATION	24	100.83	2419.92
SPREADING	24	91.24	2189.76
MIXING	24	100.83	2419.92
WATERING	24	88.22	2117.28
COMPACTION	24	76.21	1829.04
SPREADING SAND	4	93.7	374.8
	TOTAL AVERAGE COST($):		11350.72

Table E.8.b. Summary of the Life Cycle Cost for Soil Stabilization (Average Production Rate) (Continued)

3) AVERAGE HAUL COST:

HAUL COST ($/TON-MILE)	.15
HAUL DIST.STABILIZING AGENT (MILE)	50
HAUL DIST.SAND (MILE)	40
TOTAL HAUL COST OF STABILIZING AGENT ($)	980.09999992
TOTAL HAUL COST OF TRACTION SAND ($)	950.4

TOTAL AVERAGE HAUL COST ($)--------->	1930.49999992

4) AVERAGE MAINTENANCE COST($)----------> 615

TOTAL LIFE CYCLE COST:

AVERAGE MATERIAL COST ($)	12038.399999
AVERAGE EQUIPMENT AND LABOR COST ($)	11350.72
AVERAGE HAUL COST ($)	1930.49999992
AVERAGE MAINTENANCE COST ($)	615

TOTAL LIFE CYCLE COST FOR STABILIZED ROAD ($)---------------->	25934.619998
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Table E.8.c. Summary of the Life Cycle Cost for Soil Stabilization (High Production Rate)

SOIL STABILIZATION

1) COST OF MATERIAL:

LENGTH(FEET)	5280
WIDTH(FEET)	15
DEPTH(INCHES)	6
COMPACTED VOLUME OF SOIL TO BE STABILIZED (C.Y.)	1466.66666666
COMPACTED VOLUME OF SOIL TO BE STABILIZED FOR CURVE WIDENING AND TURNOUTS (C.Y.)	293.33333333
TOTAL COMPACTED VOLUME (C.Y.)	1759.99999999

STABILIZED AGENT COST:

UNIT WEIGHT OF SOIL (POUND/CUBIC FEET)	110
% OF STABILIZED AGENT	.05
COST ($/TON)	80
TOTAL WEIGHT OF STABILIZED AGENT (TON)	130.67999999
TOTAL COST OF STABILIZED AGENT($)	10454.399999

Table E.8.c. Summary of the Life Cycle Cost for Soil Stabilization (High Production Rate) (Continued)

TRACTION SAND COST

LENGTH (FEET)	5280
WIDTH (FEET)	15
APPLICATION RATE (LBS/SQ YARD)	30
COST OF SAND ($/TON)	10
TOTAL SURFACE AREA OF ROADWAY (SQ YARD)	10560
WEIGHT OF SAND (TON)	158.4
TOTAL COST OF SAND ($)	1584
TOTAL COST OF MATERIALS ($)------------------->	12038.399999

2) AVERAGE EQUIPMENT AND LABOR COST:

ACTIVITIES DESCRIPTION	PRODUCTION TIME(HRS)	COST ($/HRS)	TOTAL COST OF ACTIVITY ($)
SOIL PULVERIZATION	12	100.83	1209.96
SPREADING	12	91.24	1094.88
MIXING	12	100.83	1209.96
WATERING	12	88.22	1058.64
COMPACTION	12	76.21	914.52
SPREADING SAND	2	93.7	187.4
	TOTAL AVERAGE COST($):		5675.36

Table E.8.c. Summary of the Life Cycle Cost for Soil Stabilization (High Production Rate) (Continued)

3) AVERAGE HAUL COST:

HAUL COST ($/TON-MILE)	.15
HAUL DIST.STABILIZING AGENT (MILE)	50
HAUL DIST.SAND (MILE)	40
TOTAL HAUL COST OF STABILIZING AGENT ($)	980.09999992
TOTAL HAUL COST OF TRACTION SAND ($)	950.4
TOTAL AVERAGE HAUL COST ($)--------->	1930.49999992

4) AVERAGE MAINTENANCE COST($)----------> 615

TOTAL LIFE CYCLE COST:

AVERAGE MATERIAL COST ($)	12038.399999
AVERAGE EQUIPMENT AND LABOR COST ($)	5675.36
AVERAGE HAUL COST ($)	1930.49999992
AVERAGE MAINTENANCE COST ($)	615
TOTAL LIFE CYCLE COST FOR STABILIZED ROAD ($)----------------->	20259.259998