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OW-COST BICYCLE PATH PAVEMENTS

Final Report
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16. Abstract

The proposed research involves an analytic and experimental investigation to develop realistic design criteria for bicycle path pavements. The research also included evaluation of specific designs and innovative low-cost material systems for use in bicycle path pavements. An extensive literature review of currently existing and experimental bikepath pavement was also included.

Results from this report indicate that the strength and durability of Class I bikepath pavements can be improved and the construction cost can be reduced through better design and construction practices and use of low-cost material systems.

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LOW-COST BICYCLE PATH PAVEMENT

EXECUTIVE SUMMARY REPORT

I. INTRODUCTION

This is the final report for the research program entitled "Low-Cost Bicycle Path Pavements". The objective of the research program undertaken at Georgia Institute of Technology is to develop designs for Class I bicycle path pavements of adequate strength and durability at the lowest possible cost. It is hoped that reduction of pavement costs shall encourage the construction of Class I bicycle path path on exclusive right-of-way, a measure which will considerably enhance the safety of this mode of transportation.

II. PROBLEM STUDIED

The ultimate objective of this study was to develop designs for low-cost bike path pavements which would have adequate strength and durability at the lowest possible cost. The specific objectives were to:

(1) To conduct a "state-of-the-art" review regarding current design practice for bicycle pavements as well as to evaluate the performance of existing Class I bicycle path pavements.

(2) To establish specific design requirements, parameters, and decision criteria for bikepath pavements.

(3) To develop new and improved low-cost material systems for constructing bikepath pavements.

III. RESULTS ACHIEVED

Since the initiation of the research program the following five reports have been completed:

(1) "State-of-the-Art: Class I Bicycle Path Pavements", presented the findings of the state-of-the-art of decision criteria, design method, maintenance, performance, costs associated with construction and maintenance of Class I bicycle path pavements.

(2) "Review of Design Parameters and Decision Criteria for Class I Bicycle Path Pavements", reviewed and evaluated the state-of-the-art of decision criteria, design parameters and design methods for bicycle path pavements.

(3) "Evaluation of Existing and Proposed Bike Path Pavements", evaluated the different types of existing and proposed bikepath surfaces in terms of their performance, cost, ride quality, and maintenance needs under different service conditions which included soil types, load factors and climatic conditions.

(4) "Evaluation of the Peachtree City Bikepath Pavement", presented the results of evaluation of Peachtree City, Georgia bikepath pavement through laboratory determinations of the property of material comprising the pavement system and theoretical analyses of the pavement response.

(5) "Develop New or Improved Low-Cost Material Systems for Bikepath Pavements" evaluated the feasibility of using various low-cost material systems and marginal and waste materials for bikepath pavement construction.

On the basis of the findings from this proposed research, sixteen major conclusions and four specific recommendations were offered.

IV. UTILIZATIONS

Some findings, conclusions and recommendations obtained in this report are directly implementable in terms of improving selection and design of bikepath pavements and using low-cost material systems for bikepath pavement construction.

V. CONCLUSION

Results from this research project indicate that the strength and durability of Class I bikepath pavements can be improved and the construction cost can be reduced through better design and construction practices and use of low-cost material systems for bikepath pavements.

PREFACE

This is the final report for the research program entitled "Low-Cost Bicycle Path Pavements". The objective of the research program undertaken at Georgia Institute of Technology is to develop designs for Class I bicycle path pavements of adequate strength and durability at the lowest possible cost. It is hoped that reduction of pavement costs shall encourage the construction of Class I bicycle path on exclusive right-of-way, a measure which will considerably enhance the safety of this mode of transportation.

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CHAPTER ONE. INTRODUCTION AND RESEARCH APPROACH

1.1 Introduction

There are over 73 million bicycle riders in the United States today and it is expected that bicycles will soon be outselling automobiles if the present trend continues. This boom is due to the fact that in recent years adults have become more interested in cycling.

The fact that many people have rediscovered the virtues of the bicycle, which include health, recreation, and improvement of the ecology, is probably the single most important reason for its rebirth. Ecology-minded individuals see bicycling as a means of recreation and transportation which does not detract from the environment. The bicycle causes no noise or air pollution. It uses very little space in travel and parking causing no congestion nor need for acres of high-cost parking lots. This means a potential savings in land for the community and in parking fees for the commuter. The cost of operating a bike is minimal since no fuel is required meaning still further economic savings to the cyclist as well as the conservation of natural resources. Finally, the bicycle provides an excellent opportunity for enjoyable, healthful exercise.

Unfortunately the dramatic increase in the number of cyclists has brought on an equally dramatic increase in the number of bicycle accidents and fatalities. According to the National Safety Council, more than 750 persons lose their lives and an additional 120,000 to 150,000 others suffer disabling injuries in bicycling accidents each year. The bicyclist death toll has been climbing steadily since 1960, going from 2.8 deaths per million population to 3.8 in 1967 (3).

It is clear that bicycling is hazardous where no specific provisions are made for the cyclist. Since it does not appear that the boom in bicycles will slow down in the near future, efforts must be directed toward reducing bicycle-automobile accidents. Many authorities feel that separating the two modes on exclusive rights-of-way is the direction to be taken.

Safety, recreation and transportation therefore, are three important reasons why there is a need for bike paths today. Unfortunately, the economics of constructing these paths have often been prohibitive. Bicycle paths can cost over $25,000 per mile. One reason for these costs is the high price of construction and of quality construction materials. Typical designs include 4 to 6 inches of aggregate base and 1-1/2 to 2 inches of asphalt surface course over the base. Such pavement designs are similar to those used for driveways and rural roads designed for automobiles, and can generally be considered an over-design for bicycle paths. It seems clear that an examination of the possibility of developing low-cost surfacings to reduce the construction costs of bike paths is in order. The development of low-cost pavements and structures will increase the mileage obtained from each appropriated bike path dollar and help meet the increasing demands and numbers of cyclists.

1.2 Objectives

The ultimate objective of this study was to develop designs for low-cost bike path pavements which would have adequate strength and durability at the lowest possible cost. The specific objectives were to:

(1) To conduct a "state-of-the-art" review regarding current design practice for bicycle pavements as well as to evaluate the performance of existing Class I bicycle path pavements.

(2) To establish specific design requirements, parameters, and decision criteria for bikepath pavements.

(3) To develop new and improved low-cost material systems for constructing bikepath pavements.

1.3 Work Tasks

In order to meet the objectives of this research project the following five interrelated work tasks were proposed:

(1) Task 1 - Literature Review

The major effort of this task was to obtain and review all available published and unpublished information of all currently existing and experimental bikepath pavements.

(2) Task 2 - Define Design Parameters and Decision Criteria

(3) Task 3 - Evaluate Existing and Proposed Bikepath Surface

(4) Task 4 - Evaluation of an Existing Bikepath

(5) Task 5 - Develop New or Improved Low-Cost Material Systems for Bikepath Pavements.

The five interim reports [1-5] as mentioned in the PREFACE prepared under this research project have presented the results of the research effort for these five work tasks. This final report is intended to summarize the findings from each work task and to present the conclusions and recommendations resulting from this research project.

The findings to be presented in Chapter Two are divided into five sections, with each section covering one work task. Conclusions and recommendations are presented in Chapter Three and Four.

In addition to the five work tasks mentioned above, in the course of conducting this research project, extensive communications have been made with various bicycle interest groups, transportation planners, and design engineers. As a result, a directory containing over 200 names was compiled.

CHAPTER TWO. FINDINGS

The pertinent findings of the investigation are divided into five sections to summarize the findings from the five work tasks.

2.1 Literature Review [1]

In this first task of the project, the major effort was to obtain and review all available published and unpublished information of all currently existing and experimental bikepath pavements to supplement information already available on hand. Emphasis on this work task was placed on:

(1) Defining the types of bikepath pavement systems.

(2) Determining bikeway pavement design criteria.

(3) Determining bikeway pavement design methods.

(4) Defining maintenance requirements.

(5) Determining the construction and maintenance costs.

(6) Obtaining data on field performance.

(7) Categorizing and evaluating any new materials that show promise for use in bikepath pavement systems.

Type of Bikepath Pavement Systems

In terms of the type of bikepath pavement systems, Table 1 summarizes the results from the survey study [6,7]. The results indicate that a majority of bicycle pavement surfaces are asphalt concrete (79.13%), rock, crushed stone and limestone (12.51%) and portland cement concrete (8.33%). Figures 1, 2 and 3 show the typical bicycle pavement systems recommended respectively in Guide for Bikeways by AASHTO [8], Bike Trail and Facilities by AIPE [9], and Bikeways, Design-Construction-Programs by NRPA [10]. In addition, typical bikeway pavement systems recommended by eleven agencies were also included in [1].

Table 1. Material Used for Class I Bikeway Pavement [1].

	Total	Mean	Stn. Dev.	Max.	Min.
Surface					
Asphalt Concrete					
Percent Using	79.17				
Depth, Inches		2.4	.72	4	1
Cement Concrete					
Percent Using	8.33				
Depth, Inches		3.7	1.37	6	2
Rock					
Percent Using	5.56				
Depth, Inches		2.5	1.00	4	2
Limestone Screenings					
Percent Using	5.56				
Depth, Inches		4.3	1.50	6	3
Base					
Aggregate					
Percent Using	37.84				
Depth, Inches		4.1	1.44	8	2
Crushed Stone					
Percent Using	27.03				
Depth, Inches		4.6	1.07	6	3
Gravel					
Percent Using	24.32				
Depth, Inches		4.4	3.24	12	1
Limestone					
Percent Using	2.70				
Depth, Inches		5.0	.00	5	5
Soil Cement					
Percent Using	8.11				
Depth, Inches		7.3	4.16	12	4
Subbase					
Sand					
Percent Used	2.52				
Depth, Inches		Mean = 2.8 Max. = 4.0 Min. = 0.			
Compacted Earth					
Percent Used	5.66				
Non Used					
Percent	91.82				

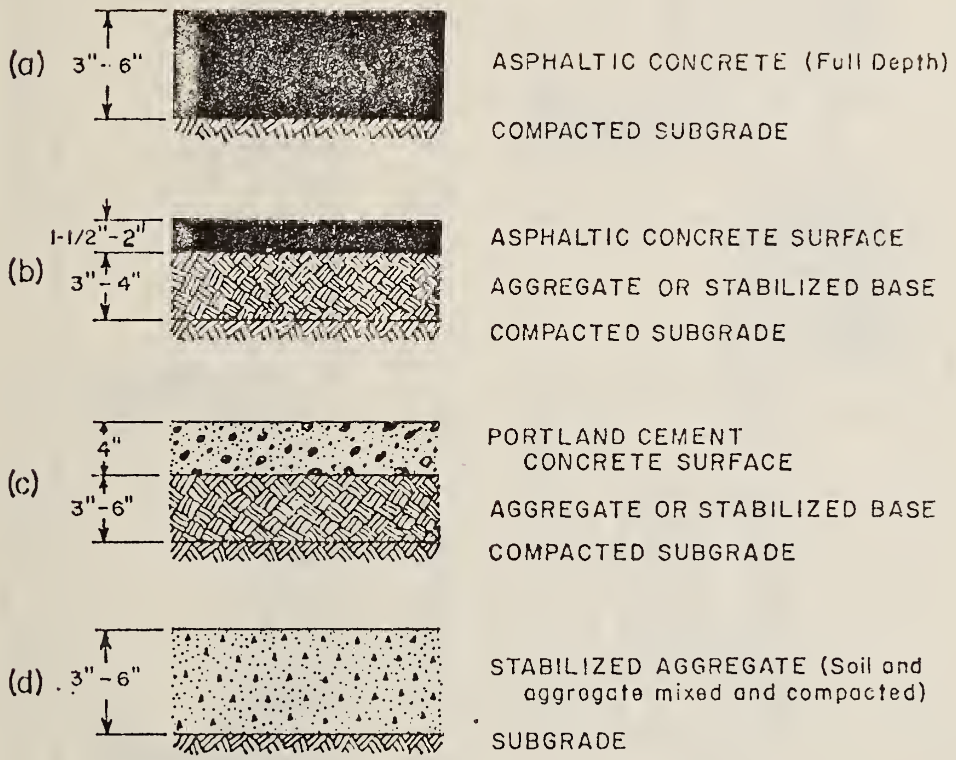
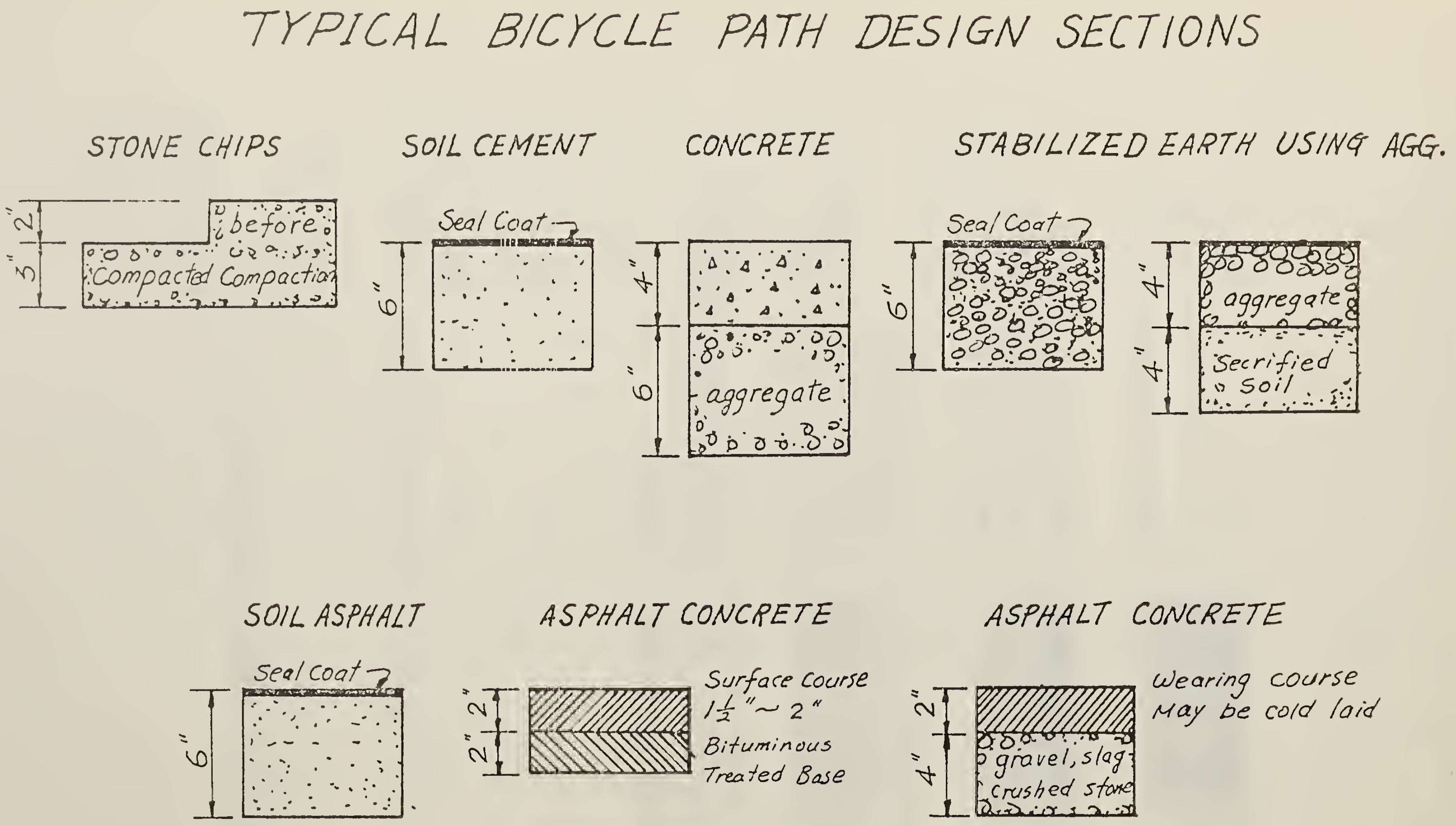


Figure 1. Typical Bicycle Path Design Sections - AASHTO.

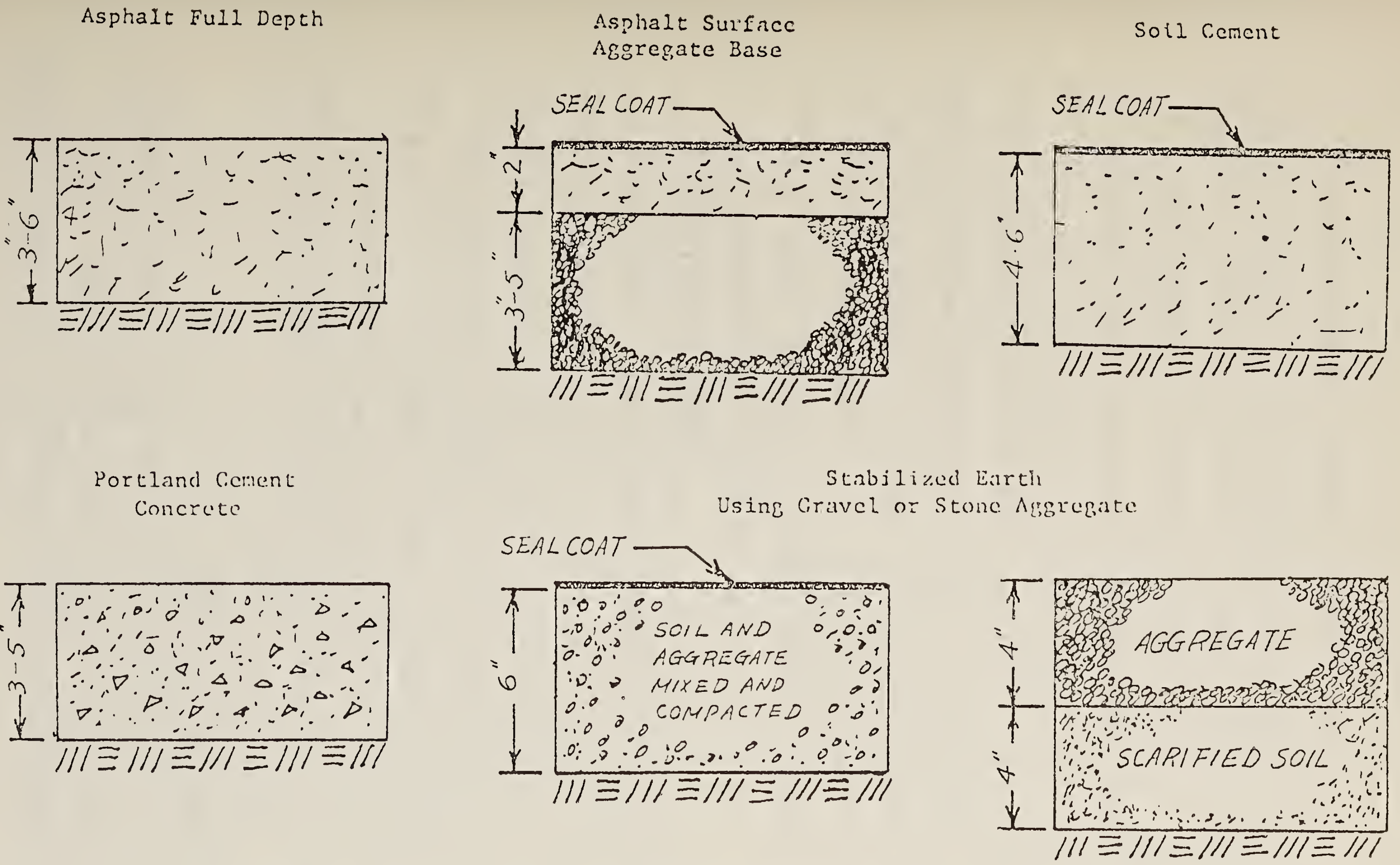
Source: AASHTO: Guide for Bike Routes [8].



NOTE: All of the above types of bicycle paths must be constructed on a well drained subgrade or subbase to prevent settling, or heaving through frost action.

Figure 2. Typical Bicycle Path Design Sections. (Generally the same as sidewalk design sections)

Source: American Institute of Park Executives [9].



Asphalt Full Depth

Asphalt Surface Aggregate Base

Soil Cement

Portland Cement Concrete

Stabilized Earth Using Gravel or Stone Aggregate

NOTE: All of the above types of bicycle paths must be constructed on a well-drained subgrade or subbase to prevent settling, or heaving through frost action.

Figure 3. Typical Bicycle Path Design Sections.

Source: National Recreation and Park Association, Bikeways, Design-Construction-Program [10].

Bikepath Pavement Design Criteria

Selection of a proper pavement system is a function of vehicle characteristics, design load, subgrade condition and environmental condition. The bicycle has a relatively small area in contact with the surface in proportion to the weight of the bicycle and rider. The pavement must be able to withstand this type of stress. Bicycle tires are also quite narrow and on soil surfaces, especially clayey soils when moist, rutting may occur. This indicates that some sort of binder material should be used. For proper riding during adverse weather, or in areas of excessive rainfall, a water-tight pavement material is needed.

The pavement must also be able to support the automotive vehicles that will be used. Most municipalities do not have specially made maintenance vehicles for bikeways and must, therefore, rely on small trucks. Police and security cars may on occasion patrol bikeways and the need may arise when ambulances or other emergency vehicles may have to use the facility. Although Class I bikeways are intended solely for use by the cyclist, the loads that these automotive vehicles exert must be considered in the pavement design. As a result, the weight of these vehicles may be a more critical factor in bikeway pavement design than the stresses caused by a bicycle's high tire pressure.

The design criteria mentioned above has been used by most of the agencies. These include AASHTO [8], AIPE [9], The Asphalt Institute [11] as well as many other agencies [12-15].

Bikeway Pavement Design Methods

Although it is recognized by most of the agencies that the selection of a bikeway pavement system should be based upon the soils, climate, materials and construction practices in addition to the expected vehicular loads, no specific design method has been developed to guide the design and selection of bikeway pavement section from a given set of design parameters; e.g., soil support conditions, local weather conditions and drainage conditions. As a result, most of the design manuals provide only a general guide and recommend certain typical sections such as those shown in Figures 1,2,3. These typical cross-sections for bikeway pavements are usually laid out to the same specifications as low volume roads, driveways and service roads or sidewalks. The range of variations in thickness in each suggested cross-section is provided to accommodate for the wide variations in soils, climate conditions and construction practices. To properly select the type of pavement system and the thickness of each component will depend upon the experience and wisdom of the project engineer or designer.

Maintenance Requirements

The information with respect to the maintenance requirements for bikeway was reported in [6,7]. In that survey study it was reported that only 14% of those responding indicated that maintenance was required. Of those, 48% was for sweeping, 20% was for cleaning of refuse, 32% was for repairing and repaving rutts. The problems of rutts, pot holes, and extensive cracks which need repairing and repaving were caused by flooding and wash-outs of non water-tight surfaces. Rutting problems occurred mainly with limestone and crushed stone surfaces.

Only four agencies from those responding indicated that specially designed maintenance vehicles for bikeways were being used. The others indicated no special designed maintennace vehicles were being used. Among those agencies, 55.33% were using light maintenance vehicles, 17.7% were using street sweepers.

Construction and Maintenance Costs

In the survey study [6,7] the cost information on construction of various facilities were also reported. These statistics are shown in Table 2. In addition, construction cost information from twelve agencies was also included in [1].

Field Performance

Most of the agencies responsible for bikeway maintenance indicated good to satisfactory performance from their pavements. Only those pavements constructed with non water-tight surface had less than satisfactory performance. In general the performance of the pavements are rated by the existance and severity of pot holes, extensive cracks, rutts and other minor defects.

The fact that most of the pavements using asphalt and portland cement concrete surfaces receiving good and satisfactory performance may be attributed to the fact that most of the Class I bikeways are less than four years in age [6,7] and that many pavements may be overdesigned.

It appears that a more definitive pavement performance criteria other than just good, satisfactory, fair and poor is needed.

Use of New Materials

With cost of bikeway construction running between \$20,000 and \$30,000 per mile, agencies implementing Class I bikeway facilities are finding it difficult to build them. One way to overcome this problem is to develop low-cost pavements through the use of low-cost materials and "waste materials". This subject will be discussed in detail in Section 2.5.

Table 2. Cost of Construction of Class I Bikeway.

	Mean	Stn. Dev.	Max.	Min.
Cost of Construction $/Mile(1)	$26,429.7	8,159.28	80,000	1,000
Allocation of Cost- Percent of Total Cost(2)				
(1) Right of Way Acquisition	30.03	23.71	50	8
(2) Leveling & Grading	16.1	7.68	33	5
(3) Materials	38.8	16.85	87	20
(4) Construction Costs	28.7	16.67	80	1
(5) Labor Costs	28.1	12.02	65	1
(6) Signing, Lighting, Landscaping	9.9	7.76	25	1

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(1) Mean width of the path 7.7 ft.

(2) In answering this part of the questionnaire, many respondents did not include all six categories in their respective percentage breakdown. Hence, the total of the mean percentage is greater than 100 percent.

2.2 Review of Design Parameters and Decision Criteria [2]

The objective of this work task was to review and evaluate the information obtained from Task 1 to determine if there were significant data on the design factors and decision criteria available for use in selecting the types of pavements for bikepaths. The following design parameters and decision parameters were evaluated:

(1) Load variables

(2) Material properties

(3) Environmental variables

(4) Construction variables

(5) Maintenance variables

(6) Performance standards

(7) Decision criteria

The interrelations of these variables from a system approach viewpoint is shown in Figure 4.

In order to analyze the effect of load variables, material properties and environmental variables on bikepath pavement systems, two theoretical pavement models were investigated to simulate asphalt concrete bikepath pavement systems and portland cement concrete pavement systems.

Load Variables

Basically two types of loads can be expected on bicycle path pavements. The first type of load is due to the weight of the bicycle and rider. This bicycle wheel load is characterized by the small wheel load, about 100 pounds, and high tire pressure, up to 80 pounds per square inch. The second type of load is from motor vehicles, which may include maintenance vehicles, patrol cars, and ambulances or other emergency vehicles. A typical wheel load from these types of vehicles has 2000 pounds total load per wheel and tire pressure of about 30 psi. Thus, most of the

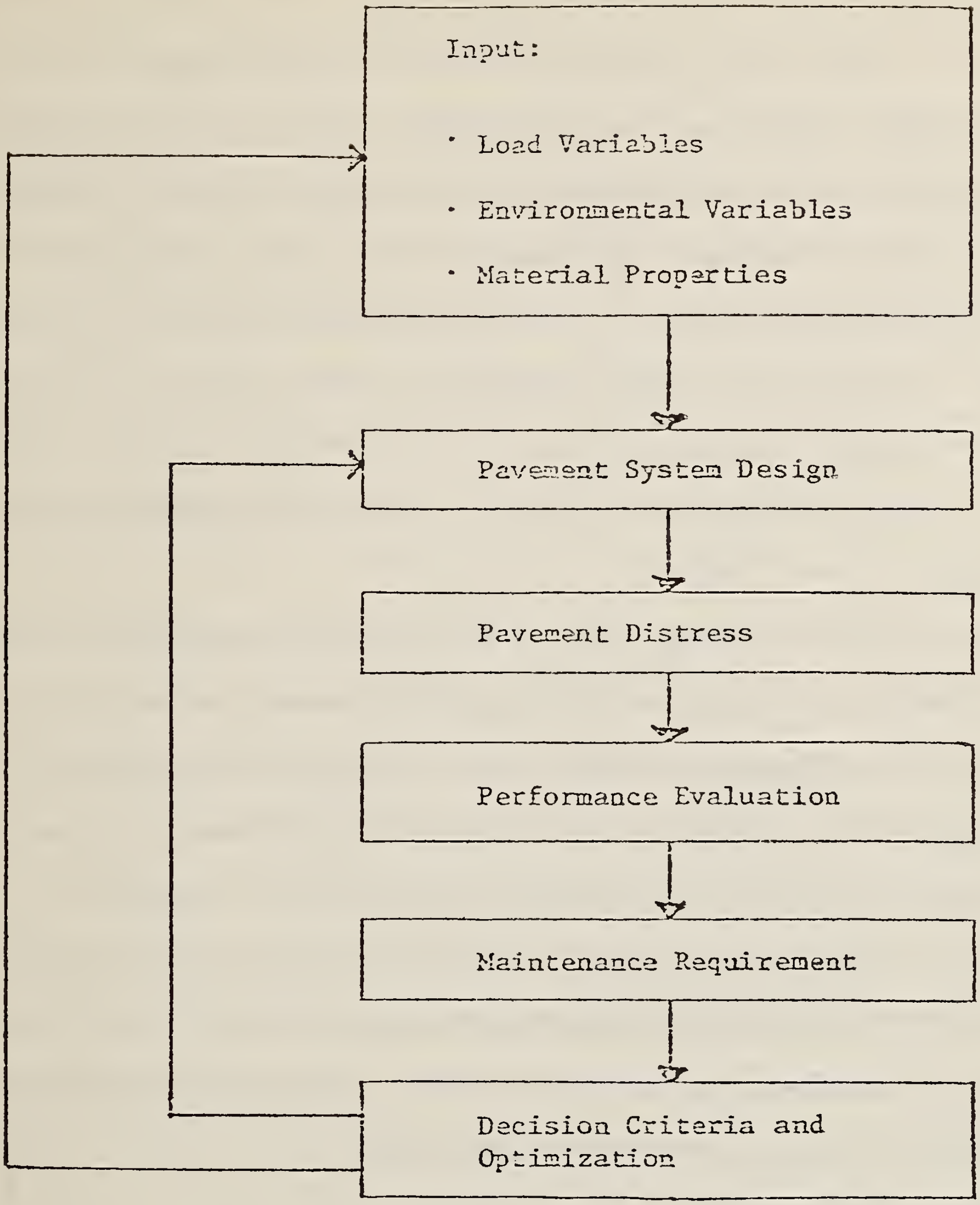


Figure 4. System Approach to the Design of Bicycle Path Pavements.

agencies, including AASHTO [8], AIPE [9] as well as many others [10-15] consider the design criteria governing a bicycle path pavement is its ability to support both types of wheel loads. On the other hand, some bicycle pavements have been designed to support only the bicycle wheel loads with the maintenance of the pavements to be done by specially designed light-weight vehicles. Under this design criteria, the resultant pavement structure is generally much lighter. For example, 1-1/2 in. to 2 in. of asphalt concrete was paved directly on clay (Georgia clay) over 15 miles of Class I bicycle path pavement at Peachtree City, Georgia [4].

In addition to the wheel load and tire pressure, other load variables which may affect the design and performance of bikeway pavements are (1) number of load applications per day or within the design life, (2) distribution of wheel loads over a pavement and (3) distance between the wheel path and the edge of the pavement. The first two variables determine the actual number of load applications on the wheel paths, which relate to the load associated cracking and rutting. With regard to the third variable, pavement distress under a wheel load is greatest when the load travels close to the pavement edge.

Material Properties

Although, most of the literature provided a set of pavement systems, such as the one shown in Fig. 1-3, few literatures gave detailed information with regard to the properties of the materials being used. Since most of the materials used for pavement construction such as portland cement concrete, and asphalt concrete, etc. are heterogeneous materials, their properties depend greatly upon their compositions and and construction processes. An improper proportioning of the compositions and/or lack of proper construction standards could dramatically weaken the properties of the materials. Most of the experience on the use of these materials has been from highway and runway pavement construction. It would be assumed that the specifications for highway pavement construction were followed. Some deviation and/or modifications should be made to reflect the relatively light wheel loads and smaller number of load repetitions encountered on the bikeway pavements. In the following, the properties of asphalt concrete, portland cement concrete and subgrade soils will be reviewed.

Asphalt Concrete. The important parameters affecting the properties of asphalt concrete are type of asphalt, asphalt content, gradation of aggregate, compaction and air voids in the mixture. Specifications for the type of asphalt concrete to be used for bikeway pavement surfaces, in most cases are based upon the type of asphalt concrete used for the surface course in a highway pavement. Usually asphalt concrete made from a fine graded aggregate such as ASTM Standard D1663 Asphalt Concrete Mix Designation 6A, is selected to ensure a smooth texture. Many agencies follow the recommendation by The Asphalt Institute [11] which suggests that asphalt content should be one-half percent higher than used on a regular highway mix. AASHTO [8] also recommends that air voids be no more than 10 percent. It is evidenced from this brief review of the literature that various agencies do have some type of specifications for asphalt concrete for use on bikeway pavement.

On the basis of laboratory test results, higher asphalt content has generally resulted in better fatigue properties. The percent air voids in the mix has also shown to have a significant effect on the fatigue property. This factor is directly related to the compaction effort. If the compaction during the construction of asphalt pavement is not properly controlled, the actual air voids in the pavement can be substantially higher than the original design value.

In view of this, it is felt that using a one to one-half percent higher asphalt content than is normally used in the highway pavement mix is a good practice. This will tend to improve the fatigue life through decreasing the modulus value, and reducing the air voids. The problems of bleeding, and excessive rutting of pavement surface associated with use of high asphalt content in the normal highway pavements should not be a problem in bikeway pavement since the maximum wheel load is much lower and the total number of repetitions is smaller. If rutting is a concern, it is suggested that a small percent of fibers can be added in the mix to increase the toughness. The presence of fibers in the mix will also improve the fatigue property.

Portland Cement Concrete. The parameters affecting the properties of portland cement concrete are cement factors (bags of cement/cu. yard of concrete) water cement ratio (gallons of water/cu. yard of concrete), percent of air voids, and the placing and curing of concrete. Cement factor ranges from 5.5 to 6 bags per cubic yard of concrete, and water cement ratio ranges from 5.5 gallons to 6.5 gallons should be adequate. Normal placing practices, including the slip formed method, have been used. Normal curing practice such as using water-proofing papers, and plastic sheets, is required.

Subgrade. Proper preparation of subgrade is essential to ensure a long lasting satisfactory performance of the pavement structure. Proper compaction and good drainage are essential for subgrade to develop the strength. Basically, there are two alternatives to constructing a bikeway pavement structure on a given subgrade, particularly on poor subgrade. The first approach is to build a stronger pavement structure, such as using a thicker surface course or adding a base course. The other approach is to improve the subgrade soil. In terms of improvement of subgrade soils, several proven methods have been used. These include soil cement and various soil stabilization methods. Section 2.5 will cover this subject in detail.

Environmental Variables

Temperature and moisture are the two main factors affecting the design of pavement structures. The effects are due to the change of material properties under unfavorable conditions of temperature, moisture and the combination of both.

Asphalt concrete exhibits thermorheological properties, a phenomenon which exhibits excessive creep at high temperature and at long duration of loading. This results in lowering the modulus of the material as well as exhibiting excessive permanent deformation under repeated wheel loads. At low temperatures, the thermally induced low temperature cracking of pavement surface has been observed in northern regions of the U.S. and in Canada. Under this circumstance, increase of pavement thickness cannot reduce the fatigue cracking. The solution to this problem is to choose a relatively "soft" asphalt which tends to retain a certain degree of flexibility at low temperature. The effect of moisture on asphalt concrete may be significant in so far as stripping is concerned.

For portland cement concrete, shrinkage due to loss of moisture and low temperature could result in development of cracking on pavement surface. Thus, joints are installed to control the cracking. Joint spacing and the width of the joints usually depend on the temperature range and temperature at placing. Joint spacing from 10 ft. to 50 ft. on unreinforced concrete pavements have been used. Width of the joints from 1/8 in. to 3/8 in. at normal temperature ranges have been used.

In addition to the temperature change which causes shrinkage and expansion, temperature differential between the top and bottom surfaces of the pavement will induce warping stress. In addition, portland cement concrete is susceptible to freezing and thawing. The durability of PCC is significantly reduced when subjected to freezing and thawing environment. Ordinary use of air-entrained PCC can improve the durability of the material.

The presence of moisture in excess of its optimum moisture content could dramatically reduce the subgrade strength. This results in reducing the overall load carrying capacity of the pavement structures. The spring breakup, a phenomenon associated with subgrade weakened during frost melt, and localized upward movements of pavements due to swelling of the subgrade or some portion of the pavement structure are the typical damages of flexible pavements due to moisture and temperature.

Construction Variables

Construction variables involved in the construction of bikeway pavements include preparation of subgrade and construction of base and surface courses.

The preparation of subgrade, includes adequate surface and subsurface drainage, proper compaction during construction and soil sterilization treatment. Also, if trees are removed, it is important to remove all surface and near surface roots.

The following steps should be carefully controlled in the construction of an asphalt concrete surface:

(1) Weather limitation: the mixing and placing of asphalt concrete should be performed only when weather conditions are suitable. Construction should not be done when the subgrades are frozen, or show any excessive moisture, nor when the air temperature is less than 40°F.

(2) Preparation of Asphalt Mixture

(3) Transporting, Spreading and Finishing

(4) Compaction.

In order to facilitate proper compaction, the asphalt mix temperature should be closely controlled. With regard to the paving equipments for bicycle path construction, there are small pavers available, but most asphalt paving machines in use today place widths ranging from 8 to 12 ft. Thus when a narrower pavement is to be constructed, it may require modification of the conventional paver, if it is at all feasible, or may have to be placed by hand. Both of the alternatives will increase the construction costs and the latter could possibly decrease the quality of the surface. Because of this reason, during the planning stage, the decision of using narrower width pavement should be weighed carefully against the use of normal width pavement.

The construction of portland cement concrete surfaces should be relatively straight forward. Bikeways could be built much like sidewalks or even slipformed using the common slipform curb and gutter machines. This may reflect to the fact that in the literature and interviews, most of the PCC bikeway pavements have performed satisfactorily.

Maintenance Variables

Maintenance needs to improve or restore the performance standards included: (1) Major rehabilitation; to correct the inadequate pavement width, shoulders, horizontal and vertical curves, and to remove or relocate curbs and gutters, (2) Major to minor maintenance such as patching, re-dragging, cracking sealing, and resurfacing to correct the pavement distress. This will also include restoring a proper crown for pavement surface so that run-off will occur, (3) Routine maintenance by sweeper units to preserve an obstacle-free surface.

Major rehabilitations could be very costly and, in addition, it also causes the disruption of the use of bikeway facilities. The best approach is to plan and design the facilities carefully at the beginning. The major and minor maintenances were related to the pavement distresses, which, in turn were related to the initial design strength of the pavement structure, and the wheel load characteristics.

Performance Standards

In order to facilitate the systems approach as discussed before, a definitive performance criteria must be established. The level of performance requirements on a bikeway pavement will dictate the initial design and construction standards and the future maintenance needs. Also, a clearly defined performance standard for a proposed bikeway project will permit the design engineer to develop various design alternatives.

Decision Criteria

With all the information on various design variables, construction variables, performance criteria and maintenance variables, and the costs associated with the various variables, it is possible to optimize the overall initial construction cost and maintenance cost. The overall cost will be related to the level of performance established for the system. The higher the performance standards the higher the overall cost. Therefore the major decision criterion should be on the level of performance. The second decision should be on the type of maintenance vehicles to be used for the bikeway system. Type of maintenance vehicles itself will affect the cost and efficiency of doing the maintenance works. Also, the weight of maintenance vehicles will affect the selection of different types of pavement structures and also the bikeway bridge structures as well. Therefore the decision should be made at the initial planning stage as to the type of vehicles to be used for doing the routine maintenance works. The third decision criterion is the esthetics. This factor may not necessarily effect the overall cost, but on the other hand it may be the major factor. For example, a bikeway meandering with the natural topography to avoid excessive clearing of trees and to blend the trail with the environment may be desirable from the esthetics point of view. However, the potential problems such as longer traveling distance, higher construction costs, premature pavement cracking, drainage problems, accumulation of tree leaves on the surface which requires more frequent maintenance, to name a few, should be recognized.

Analysis of Bikepath Pavement Systems

The effects of load variables, material properties, environmental variables, and thickness of pavement surface on the development of rutting and cracking on bikeway pavement systems were analyzed.

The distresses sought in the analyses are rutting and cracking, although other types of distress also exists in bikeway pavement structures and are not necessarily less important in relating to the overall performance of the structure. However, the mechanics of cracking and rutting of pavement structures are better understood at the present time and the effect of the various aforementioned variables on cracking and rutting can be determined. It is hoped that the analyses will lend itself to better understanding the effect of the various design variables on the performance of pavement structures.

The mechanisms associated with the cracking and rutting of bikeway pavement structures are, in principle, no different from that of highway pavements and runway pavements. Basically, cracking of the pavement surface is due to the repetitive tensile stress and strain induced in the pavement surface. This repetitive tensile stress could be due to externally applied wheel loads, fluctuation of air temperature, and uneven settlements or heaves of subgrade. On the other hand, rutting of a thin pavement surface is mainly due to the accumulative permanent deformation of subgrade due to vertical compressive stress and strain applied on the subgrade. Thus, cracking and rutting are the stress and/or strain induced phenomena which in turn depend on the characteristics of wheel loads, types of pavement systems, material properties, and environmental variables such as temperature and moisture.

In the following analyses, two different basic types of pavement structures are considered. They are flexible-type pavements, and rigid pavements. Load variables to be considered include a bicycle wheel load with a typical weight of 100 pounds with 80 psi tire pressure, and a typical motor vehicle wheel load of 2000 pounds with 30 psi tire pressure. Properties of materials to be included in the analyses are three different types of subgrade soils which represent poor, moderate and good soils. In the flexible pavement structures, two different values are used to represent the properties of surface materials, and four different thicknesses of surface course are included. The effect of temperature and moisture is indirectly included in the properties of surface material and subgrade soils. In the rigid pavement structures, two thicknesses of portland cement concrete (PCC) are considered, and the effect of temperature is analyzed separately.

<u>Flexible Pavement Systems</u>. In Appendix A, the stresses, strains and deflections of bikeway pavement structures were analyzed. The following parameters were included in the analyses:

(a) Load variables: W_1 = 100 pounds with 80 psi tire pressure
W_2 = 2000 pounds with 30 psi tire pressure

(b) Thickness of surface course: T_1 = 1 in.
T_2 = 1-1/2 in.
T_3 = 2 in.
T_4 = 3 in.

(c) Modulus of asphalt concrete: $E_{a1} = 50,000$ psi

$E_{a2} = 200,000$ psi

(d) Modulus of subgrade: $E_{S1} = 3,000$ psi

$E_{S2} = 12,000$ psi

$E_{S3} = 45,000$ psi

The load variables chosen herein represent the typical bicycle and motor vehicle wheel loads, respectively. The two moduli chosen represent the moduli of asphalt concrete under high temperature long duration of loading and low temperature, respectively. Three subgrade moduli represent the modulus of poor, moderate and good soils having CBR values approximately at 2, 5 and 15, respectively.

From the experience of the performance of highway pavements, the critical parameters related to the performance of pavement system are:

(1) maximum horizontal tensile strain (ε_t), at the bottom surface of the surface course, See Fig. A1 in Appendix A.

(2) the maximum vertical compressive strain (ε_Z) exerted on the top of the subgrade.

The first parameter is related to the fracture and/or fatigue cracking of the pavement surface. The second parameter is related to the permanent deformation and rutting of the subgrade and pavement surface under the wheel paths. For example, Table 3 gives the permissible tensile strain in the asphalt layer and the conpressive strain on subgrade as suggested by Dorman and Metcalf [16]. Although those values were intended to be used for highway pavement designs, the fundamental mechanisms governing the fatigue cracking and rutting of highway pavements, and bikeway pavements are the same in that all are related to the fundamental properties of asphalt concrete and

Table 3. Permissible Strains Under Different Load Applications

No. of 18K Load Application	Compressive Strain on Subgrade x 10^{-3} in/in.	Tensile Strain in Asphalt Layer x 10^{-3}
10^5	1.05	0.23
10^6	0.65	0.145
10^7	0.42	0.092

From Dorman and Metcalf [16].

subgrade soils under repeated loading. The failures depend more on the magnitudes of the maximum strains and the number of repetitions rather than the type of wheel loads. Thus, those values shown in this table can be used as a guide for selecting tentative limiting strain values at a different number of load repetitions to prevent fatigue cracking and rutting for bikeway pavements.

In order to relate the total number of bicycles and motor vehicles, to the actual wheel loads applied at wheel paths, the distribution of vehicles over a pavement has to be determined. This is related primarily with the width of the pavement. Bicycle traffic is more likely to be less concentrated on a wheel path. On the other hand, motor vehicles traveling on bikeway pavements are likely to be highly channelized, particularly on relatively narrow pavements. Furthermore, the "wheel paths" for the motorized vehicles could be different than the "wheel paths" due to bicycles.

Figures A2 - A5 in Appendix A show the tensile strains in asphalt concrete layer and compressive strains on subgrade under different aforementioned parameters.

Based on Table 3, 0.25×10^{-3} in./in. and 1.0×10^{-3} in./in., respectively are chosen tentatively to be the permissible values for tensile strain in asphalt concrete layers and compressive strains on subgrade for asphalt bikeway pavements.

Based on the criterion of 0.25×10^{-3} in./in. permissible tensile strain in asphalt concrete, 1 in. to 1-1/2 in. of asphalt concrete built on top of good subgrade, is sufficient for both bicycle wheel loads and for vehicle wheel loads. If the subgrade is weak, 2 in. of asphalt concrete is not sufficient to prevent fatigue cracking.

If 1.0×10^{-3} in./in. of compressive strain on the top of subgrade is chosen as the limiting value for preventing excessive rutting, Figure A4 indicates again that with poor soil subgrade, $E_{S1} = 2000$ psi, two inches of asphalt concrete surface is not sufficient for both types of wheel loads. For the moderate subgrade soil, 1-1/2 in. of asphalt concrete is sufficient, and for the good subgrade, 1 in. of asphalt concrete is sufficient for both types of wheel loads.

When the modulus of the surface course is low, there is no significant difference between the bicycle wheel load and the vehicle wheel load insofar so far as their damages to the pavement are concerned. It is only when the modulus of the surface course is high, that the vehicle wheel load will have relatively greater damage to the pavement than the bicycle wheel load.

It is interesting to note that when the subgrade modulus is low, increasing the thickness of surface course tends to further increase the tensile strain when the pavement is subjected to the vehicle load. This indicates that further increase of the thickness of the surface course is not a viable solution. A better approach is to strengthen the subgrade through various stabilization methods or add several inches of granular base.

If pavement is subjected to bicycle wheel load only, 3 in. of asphalt concrete probably will be sufficient to prevent cracking and rutting even if the pavement is constructed on poor subgrade.

Rigid Pavement Systems. In Appendix B, the critical tensile stresses induced in a portland cement concrete pavement due to the externally applied load and temperature change were analyzed. The external load considered in the analysis was motor vehicle load only. Two pavement thicknesses of 3 in. and 4 in. were considered, and three subgrade reaction moduli K = 50, 200, and 500 pci, which represented poor, moderate and good subgrade soils were used.

When a vehicle travels on a narrow PCC pavement, the critical stresses induced by the wheel loads, as illustrated in Fig. B-1 of Appendix B, can be occurred at the corner or at the edges of the joints. The results shown in Table B-1 of Appendix B indicate that edge stress is higher than the corner stress. The tensile stresses induced by the bicycle wheel load were estimated to be about 30 psi which is too small to be of any significance in inducing any cracking.

In addition to the load associated stresses, the difference in temperature between the top and bottom of the pavement surface will induce warping stress. This thermally induced stress depends on the temperature gradient, the thickness of the pavement and the thermal expansion coefficient of PCC as shown in eq. (B-4). The results shown in Table B-1 indicate that the thermal stress increases with increase of pavement thickness. The maximum tensile stress induced in a PCC pavement is the sum of the thermal stress and the load induced stress--in this case the edge stress.

In Table B-1 the total stresses are also shown. Under the repetitive action of the tensile stress, the pavement eventually may fail when the "fatigue life" of the concrete under a given stress intensity has been reached. The fatigue life of concrete is usually expressed as a function of the ratio of maximum tensile stress to the modulus of rupture as shown in Fig. B-2. This figure shows that the fatigue life increased as the ratio decreased and when the ratio is equal to or less than 0.5, concrete will have infinite fatigue life. Using the results shown in this figure and assuming the modulus of rupture of concrete equals 750 psi, the fatigue life of each pavement system can be determined. The results of the fatigue life corresponding to different pavement thickness and different subgrade reaction modulus are shown also in Table B-1. Notice that except for the 3 in. PCC pavement resting on the poor subgrade which results in the fatigue life of about 5000 cycles, the other pavement systems have virtually infinite fatigue life. The rutting problem is not being considered in the analysis. Generally, rutting is virtually negligible in a rigid pavement due to the high modulus of the surface course.

2.3 Evaluation of Existing and Proposed Bikepath Surfaces [3]

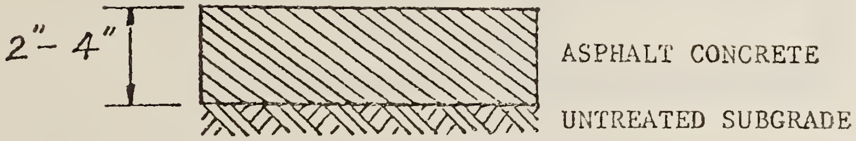
The objective of this report is to further evaluate these various types of existing pavement systems as well as new and innovative pavement systems for bicycle path. All the pavement systems will be evaluated in terms of performance, ride quality, and cost under different service conditions. The service conditions to be considered are types of loads, soil conditions, climatic conditions and function of bikepath. Based on the evaluation, the pavement systems will be rated to determine which ones are best suited for providing an overall low-cost pavement for a wide range of the service conditions.

Types of Bikepath Pavement Systems

Based on the characteristic of the surface materials, the pavement systems can be classified into four categories; asphalt concrete, portland cement concrete, asphalt surface treatment and non-water tight surfaces. Types of pavement systems under each category are shown in Figs. 5,6,7,8 respectively.

The pavement systems shown in Fig. 5-8 represent only those typical pavement systems that have been used in the past or have the potential of being implemented in all regions. There are virtually unlimited numbers of other pavement systems that can be constructed using various different types of locally available materials. The layer thickness of the pavement systems shown in these figures represents the typical values for the materials. These thicknesses can be changed based on the actual needs

(1-a) FULL DEPTH ASPAHLT CONCRETE SURFACE



(1-b) AGGREGATE OR STABILIZED BASE

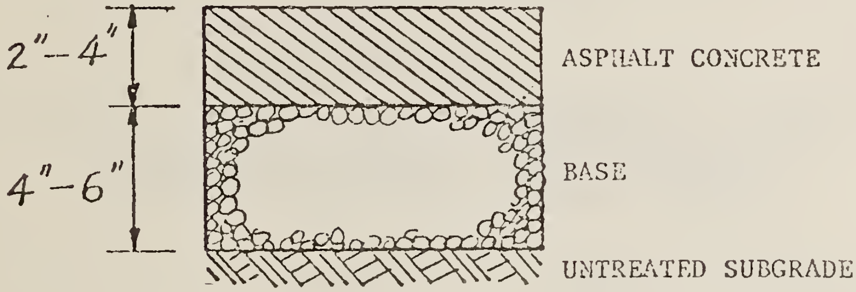
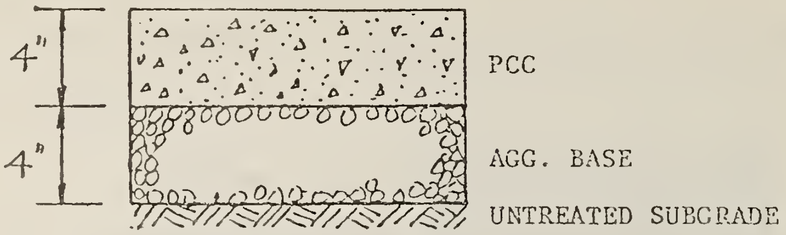
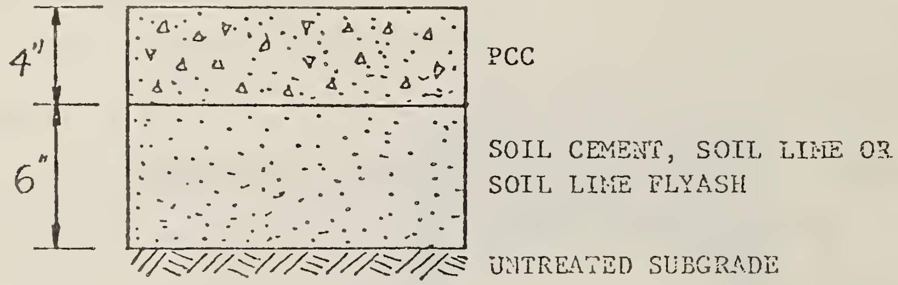


Figure 5. Pavement Systems with Asphalt Concrete Surface.

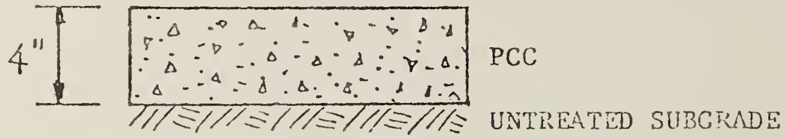
(2-a) PCC WITH BASE



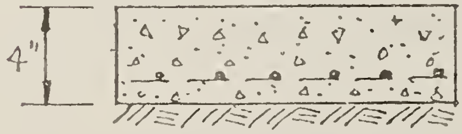
(2-b) PCC STABILIZED SUBGRADE



(2-c) PCC ON UNTREATED SUBGRADE



(2-d) WIRE-MESH REINFORCED PCC



(2-e) STEEL FIBER REINFORCED PCC

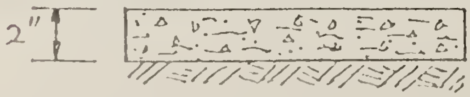
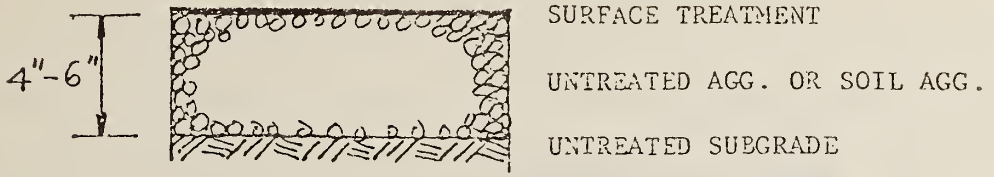
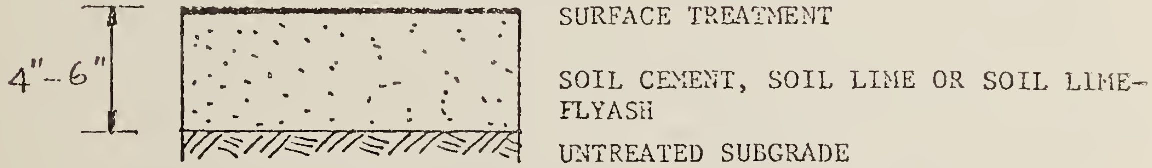


Figure 6. Pavement Systems with Portland Cement Concrete Surface.

(3-a) SURFACE TREATMENT ON GRAVEL BASE



(3-b) SURFACE TREATMENT ON TREATED SUBGRADE



(3-c) SURFACE TREATMENT ON UNTREATED SUBGRADE

(3-d) RUBBER ASPAHLT SURFACE TREATMENT

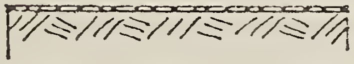
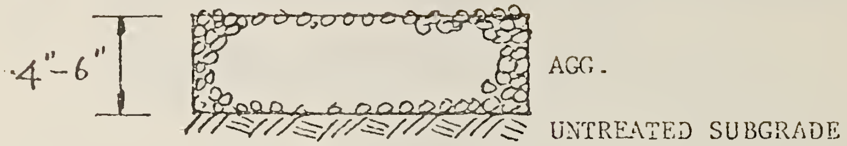


Figure 7. Pavement Systems with Surface Treatment Surfaces.

(4-a) AGGREGATE SURFACE



(4-b) SOIL CEMENT, SOIL LIME OR SOIL LIME-FLYASH SURFACE

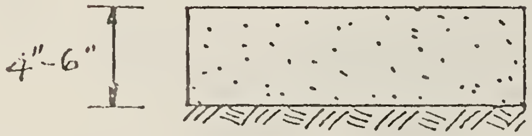


Figure 8. Pavement Systems with Non-Watertight Surface.

nevertheless, the values shown in Fig. 5-8 represent the thicknesses that have been used in most service conditions either from the load carrying capacity requirement and/or from the practical construction limitation standpoint. In Section 2.2 and [2], methods of determining the thickness requirements based on service conditions (climate, loads, soil conditions) can be found.

Performance of the Pavement Systems

In general performance of the pavements is rated by the existance and severity of pot holes, extensive cracks, rutts and other minor defects after the pavement has been in service for a certain period of time. The performance of any type of pavements will depend upon the service conditions. The service conditions that could effect the performance are climate, soil type and load factors. Therefore in evaluation of the performance of the various pavements shown in Fig. 5-8, the effect of these three conditions were considered. In the following, these three factors are described briefly.

Climate. Frost action and precipitation are the two important interrelated factors affecting pavement performance. The effect of frost action includes both frost heave and loss of subgrade support during frost melting periods. Increase of moisture content in subgrade due to adverse rainfall or improper drainage can result in weakening the load bearing capacity of a pavement system. Thus two factors are interrelated in that loss of pavement strength during frost-melting period are dependent upon rainfall and temperature. For rigid pavement, the problems of pumping, shrinkage and swell of certain subgrade are also related to the precipitation. The extent of the effects of the climatic factors on pavement performance is further dependent upon the types of soils in the subgrade pavement structures and loading conditions. For pavements with water-tight surface and with proper drainage facilities, the adverse moisture conditions in the subgrade can be kept at a minimum, thus, the problem of frost action can be minimized even if the pavement is subjected to adverse climatic conditions, prolonged rainfall coupled with frequent freezing and thawing temperatures. For non-water-tight pavement surface heavy rainfall will reduce the load carrying capacity of the pavement structure. Erosion of the pavement surface due to surface runoff will further contribute to the degradation of the pavement surface. In evaluating the performance of bicycle path pavements under different climatic conditions, the climatic conditions are loosely divided into following four groups:

(1) low precipitation; low freezing index

(2) low precipitation; high freezing index

(3) high precipitation; low freezing index

(4) high precipitation; high freezing index

The "high" and "low" here are understandably somewhat arbitrary. Loosely speaking 20 inches of average annual precipitation and 0 degree days below 32°F may be used to classify the high and low for the precipitation and freezing index. The distribution of mean annual precipitation and mean freezing-index in U.S. is shown in figure 9 and 10.

Soil Types. The effects of soil types on the performance of pavements are load bearing capacity, frost susceptibility and swelling and shrinkage under moisture changes. In the following, soils are loosely divided into three categories; good, fair, and poor. They are briefly described as follows:

(1) Good: CBR over 10, no swelling and shrinkage, not frost-susceptible.

(2) Fair: CBR from 4-10, moderate swelling and shrinkage, moderate frost susceptible.

(3) Poor: CBR less than 4, severe swelling and shrinkage, severe frost susceptible.

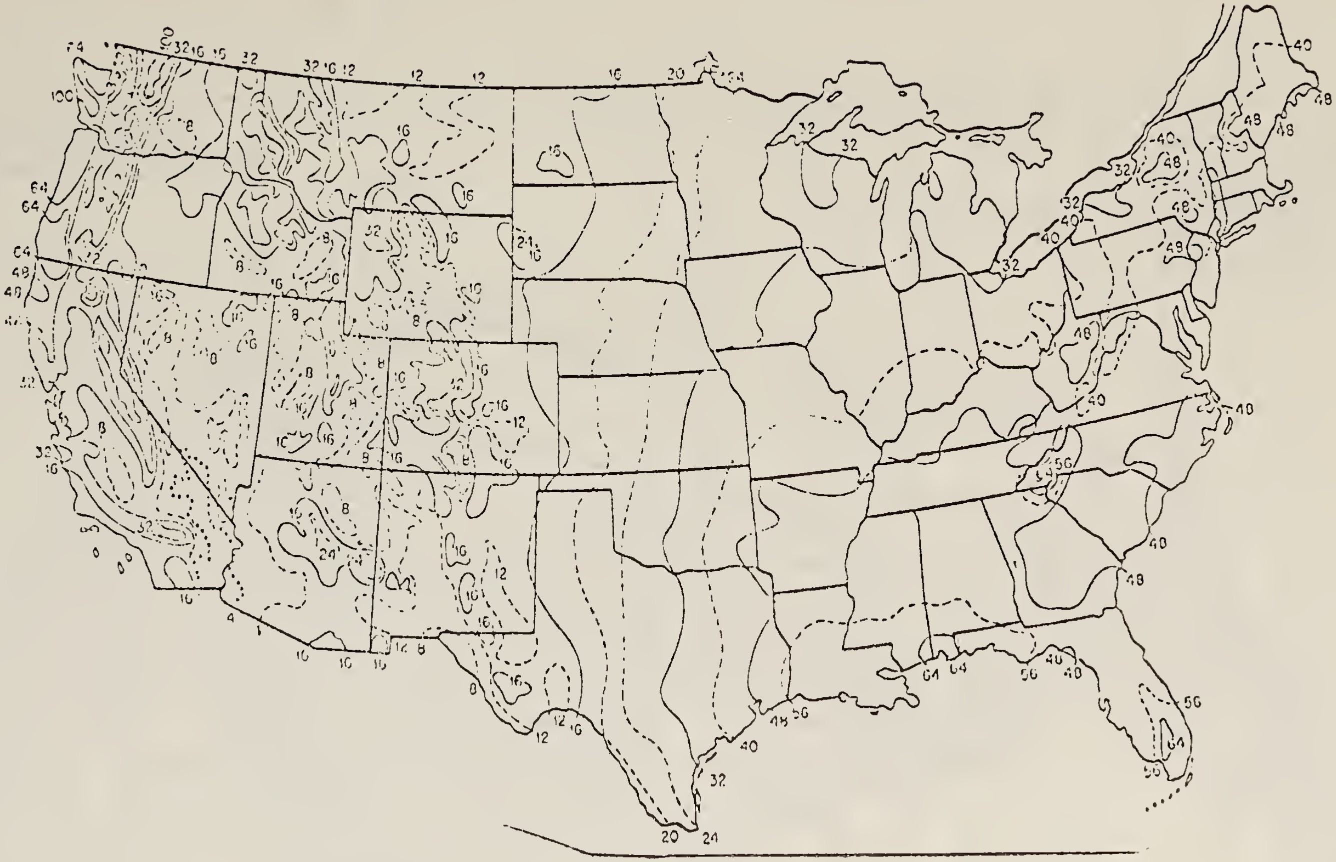
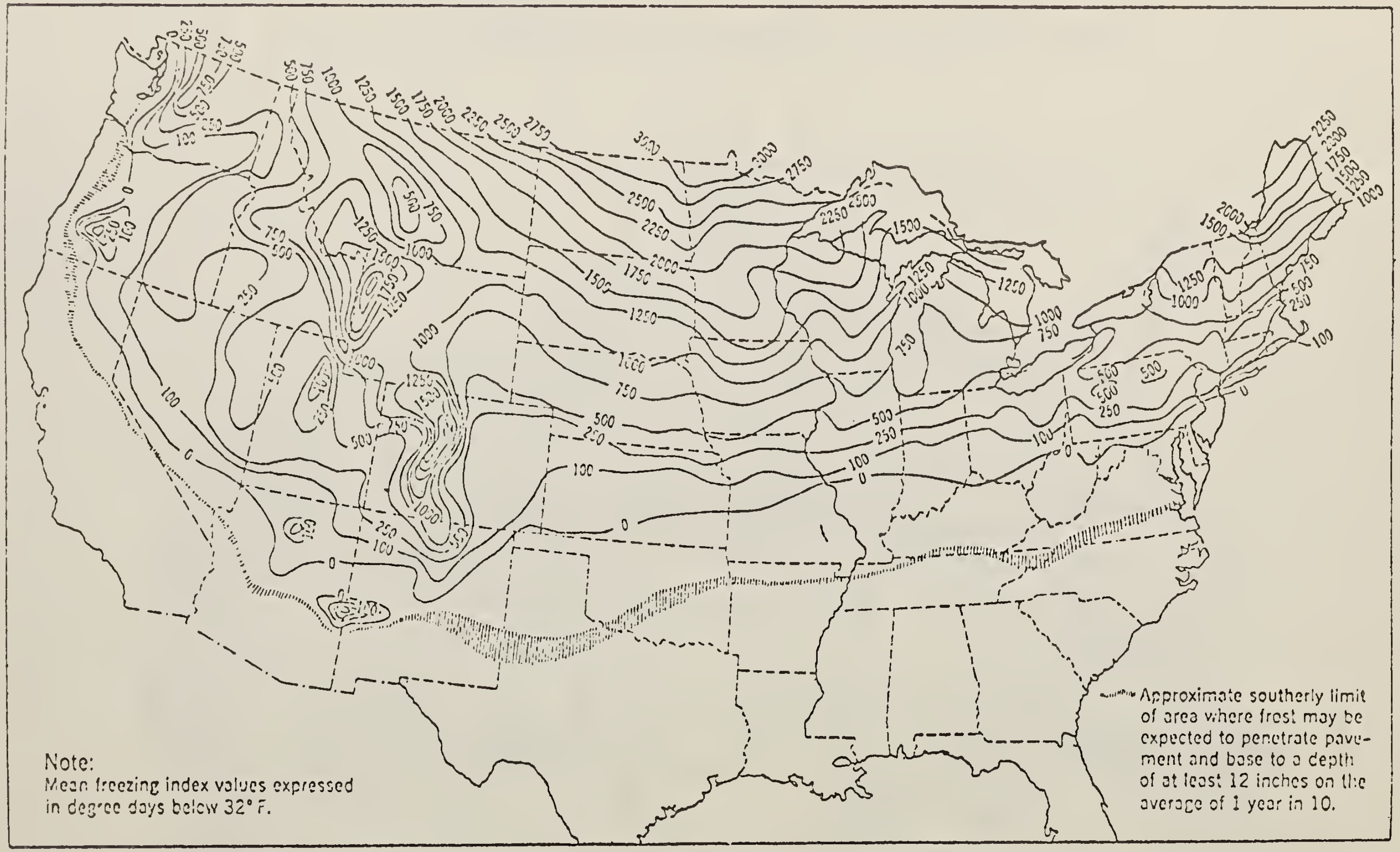


Figure 9. Mean Annual Precipitation in the United States, in Inches.



Note:
Mean freezing index values expressed in degree days below 32° F.

Approximate southerly limit of area where frost may be expected to penetrate pavement and base to a depth of at least 12 inches on the average of 1 year in 10.

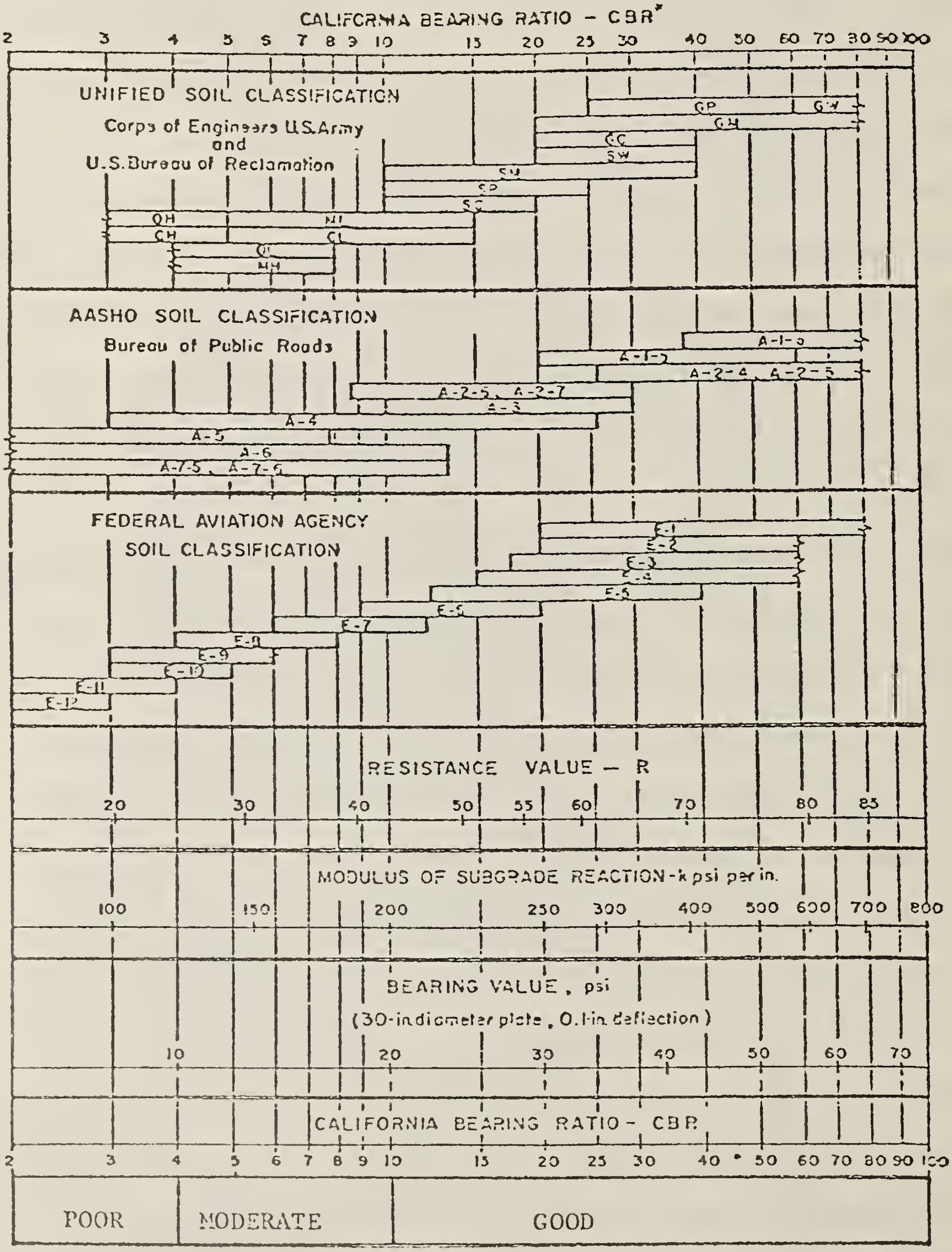
Figure 10. Distribution of Mean Freezing-Index Values in Continental United States. (From Corps of Engineers EM 1110-345-306.)

The relation of this classification with the other soil classification systems is shown in Fig. 11.

Load Factors. Basically two types of loads can be expected on bicycle path pavements. The first type of load is due to the weight of bicycle and the rider. This bicycle wheel load is characterized by the small wheel load, about 100 pounds, and high tire pressure, up to 80 psi. The second type of load is from motor vehicles, which may include maintenance vehicles, patrol cars, and ambulances or other emergency vehicles. A typical wheel load in this category has 2000 pounds load per wheel with tire pressure of about 40 psi. A more detailed discussion of this subject, such as the effect of the types of wheel loads on the pavement responses has been presented in [1,2].

Although it is recognized that climate, soil type and type of loading will effect the performance of bike path pavements, evaluation of the performance of bike path pavements has not been done systematically in the past. As a result, there is a lack of a consentaneous performance criteria for bikepath pavements. The concept of Present Serviceability Index developed in the AASHO Road Test [17] for measuring "high" types highway pavements and the surface condition rating system for asphalt treatment type highway pavements [18] deserve serious consideration for applying to bikepath pavement surfaces.

The evaluation of the performance presented in this report on the various types of bikepath pavements shown in Figure 5-8, based on the various aforementioned service conditions has been done through communications between the author and the various organizations and individuals that have been involved in the design, construction, maintenance and use of bicycle path pavements. The results of the evaluations are shown in Table 5. The performance is rated in four categories: They are excellent, good, fair, and poor. Unfortunately the author cannot further



* Sources for values shown are given in PCA Soil Primer

Figure 11. Approximate Interrelationships of Soil Classifications and Bearing Values.

elaborate and give a more precise definition of each category, as in most cases, these were the inputs from the various agencies and individuals involved in making the evaluations. The performance of a pavement system can be defined as its ability to maintain the structural integrity, and to resist weathering and surface wearing. In addition to the performance rating, there are three other ratings, ride quality, maintenance needs and overall evaluation for each pavement type under the given service conditions. These three ratings will be discussed in the next section.

Evaluation of the Pavement Systems

All of the existing and proposed bikepath pavement systems as shown in Figure 5-8 were evaluated in terms of performance, cost of construction, ride quality and safety. It seems that if some kinds of rating can be provided among the various pavement systems under the different service conditions, it would be of some usefulness in helping the pavement designers to determine which ones are more suitable for providing low-cost pavements under a given set of service conditions. Unfortunately, this turns our to be a rather difficult task due to many reasons. Some items such as ride quality and safety are basically non-quantatized variables and cannot be readily converted to the equivalent "costs". In a similar situation in the economic analysis of transportation facilities, highways, rapid transits, etc., there is still a great dispute over assigning realistic "values" for comfort, convenience and safety of utilizing these facilities. Although in principle, performance of the pavement systems can be related to the maintenance need, which in turn can be coverted to cost. In order to do so, however, it requires a rather definitive performance criteria such that the performance of bikepath pavements can be related to the maintenance needs. The ride quality of a given type of pavement surface can vary considerably due to a great variation of construction practice, particularly of surface treatment type pavement surfaces. These are some of the problems that make the numerical rating of the pavement surface rather difficult.

Even under such circumstances, it is felt that a rating albeit crude would still serve some useful purposes and hopefully may be able to stimulate the readers' interest toward further improvement of the rating system.

Four different ratings were made for each pavement system under a given set of service conditions (climate, soil type and load factors). These four ratings are performance, ride quality, maintenance need, and overall rating taking into consideration of the first three ratings and the construction costs given in Table 4. These ratings are shown in Table 5. Table 6 summarizes the rating scales for each type of rating used in Table 5.

The ratings were made by the authors in consultation with several individuals around the country. It is to be emphasized that in assigning the ratings, there is a great degree of arbitrariness and uncertainty due to the reasons mentioned before. It is hoped, however, that through a continuous feedback from the concerned individuals throughout the country, the ratings can be improved or a better rating system can be developed.

Table 4. Pavement Costs

Pavement Type (see Fig. 2,3,4,5)	Unit Cost (8 ft. wide by 100 ft. long)	Remarks
1-a, Full Depth Asphalt Concrete	$400 - %550 (4" AC) $200 - $300 (2" AC)	
1-b, Asphalt Concrete Agg. or Stabilized Base	$360 - $500 (2" AC) $550 - $700 (4" AC)	
2-a, PCC, Agg. Base	$550 - $850	4" of PCC
2-b, PCC, Stabilized Subgrade	$630 - $950	
2-c, PCC	$430 - $650	
2-d, Wire-Mesh Reinf. PCC	$600 - $850	
2-e, Steel Fiber Reinf. PCC	$450 - $550	
3-a, Surface Treatment Agg. Base	$180 - $280	For Rubber-Asphalt Surface Treatment Use the Cost Difference Between 3-d and 3-c
3-b, Surface Treatment, Stabilized Subgrade	$235 - $350	" "
3-c, Surface Treatment	$40 - $60	
3-d, Rubber Asphalt Surface Treatment	$120 - $200	
4-a, Agg. Surface	$150 - $250	
4-b, Treated Soil Surface	$200 - $300	

Table 5. Ratings of Performance, Ride Quality, Maintenance Need and Overall Evaluation of Bikepath Pavements.

A. Good Soil Condition

Service Conditions	Pavement Type (see Fig. 2-5)	I				II					III				IV	
Load	Climate	A 4"	A 2"	B 2"	B 4"	A	B	C	D	E	A	B	C	D	A	B
Light	1	E e L 4	E e L 5	E e L 4	E e L 4	E e L 3	E e L 3	E e L 4	E e L 3	E e L 4	G f M 2	G f M 2	G f M 3	G f M 3	F p H 1	G g M 4
	2	E e L 4	E e L 5	E e L 4	E e L 4	E e L 3	E e L 3	E e L 4	E e L 3	E e L 4	G f M 2	G f M 2	F f H 2	G f M 3	F p H 1	F f M 3
	3	E e L 4	E e L 5	E e L 4	E e L 4	E e L 3	E e L 3	E e L 4	E e L 3	E e L 4	G f M 2	G f M 2	F f H 2	G f M 3	P p H 0	P p H 0
	4	E e L 4	E e L 5	E e L 4	E e L 4	E e L 3	E e L 3	E e L 4	E e L 3	E e L 4	G f M 2	G f M 2	F f H 2	G f M 3	P P H 0	P P H 0
Heavy	1	E e L 4	E e L 5	E e L 4	E e L 4	E e L 3	E e L 3	E e L 4	E e L 4	G e L 3	F f H 2	G f M 2	F f H 2	F f H 1	F p H 1	F g M 2
	2	E e L 4	G e L 4	E e L 5	E e L 4	E e L 4	E e L 3	G e L 3	E e L 4	G e L 3	F f H 1	G f M 2	P p H 0	F f H 1	P p H 0	P f M 0
	3	E e L 4	G e L 4	E e L 5	E e L 4	E e L 4	E e L 3	G e L 3	E e L 4	G e L 3	F e H 1	G f M 2	P f H 0	P p H 0	P p H 0	P p H 0
	4	E e L 4	F e L 3	E e L 5	E e L 4	E e L 4	E e L 4	F e M 3	E e L 4	F e M 2	F f H 1	F f H 1	P p H 0	P p H 0	P p H 0	P p H 0

Table 5. Ratings of Performance, Ride Quality, Maintenance Need and Overall Evaluation of Bikepath Pavements.

B. Moderate Soil Condition

Pavement Type (see Fig. 2-5) Service Conditions		I				II					III				IV	
Load	Climate	A 4"	A 2"	B 2"	B 4"	A	B	C	D	E	A	B	C	D	A	B
Light	1	E e L 4	G e L 5	E e L 5	E e L 4	E e L 3	E e L 3	E e L 4	E e L 3	E e L 4	G f M 2	G f M 2	F f H 1	G f M 3	F p H 1	F g M 3
	2	E e L 4	G e L 5	E e L 5	E e L 4	E e L 3	E e L 3	E e L 4	E e L 3	E e L 4	G f M 2	G f M 2	F f H 1	G f M 3	F p H 1	F f M 2
	3	E e L 4	G e L 5	E e L 5	E e L 4	E e L 3	E e L 3	E e L 4	E e L 3	E e L 4	G f M 2	G f M 1	P f H 0	F f H 1	P p H 0	P p H 0
	4	E e L 4	F e M 3	E e L 5	E e L 4	E e L 3	E e L 3	G e L 4	E e L 3	E e L 4	G f M 2	G f M 1	P p H 0	F f H 1	P p H 0	P p H 0
Heavy	1	G e L 5	F e M 3	G e L 5	E e L 5	E e L 5	E e L 4	G e L 4	E e L 5	G e L 4	F f H 1	G f M 2	P p H 0	P p H 0	P p H 0	F f M 1
	2	G e L 5	F e M 3	G e L 4	E e L 5	E e L 5	E e L 4	F e M 4	E e L 5	F e H 3	F f H 2	F f H 1	P p H 0	P p H 0	P p H 0	P f H 1
	3	F e M 3	P e M 2	F e M 3	E e M 5	E e L 5	F e L 4	E e M 3	P e L 5	F e M 0	F f H 2	F f H 1	P p H 0	P p H 0	P p H 0	P p H 0
	4	F e M 3	P e M 0	F e M 3	E e M 5	E e L 5	E e L 4	F e M 3	E e L 5	P e M 0	P f H 0	P f H 0	P p H 0	P p H 0	P p H 0	P p H 0

Table 5. Ratings of Performance, Ride Quality, Maintenance Need and Overall Evaluation of Bikepath Pavements.

C. Poor Soil Condition

Service Conditions	Pavement Type (see Fig. 2-5)	I				II					III				IV	
Load	Climate	A 4"	A 2"	B 2"	B 4"	A	B	C	D	E	A	B	C	D	A	B
Light	1	E e L 4	F e M 3	E e L 5	E e L 4	E e L 3	E e L 3	E e L 4	E e L 3	G e L 4	F f H 2	G f M 3	F f H 2	F f H 2	P p H 0	F g M 2
	2	E e L 5	F e M 3	E e L 5	E e L 4	G e L 4	G e L 3	G e L 3	E e L 4	G e L 3	F f H 1	G f M 2	P p H 0	F f H 1	P p H 0	F f M 1
	3	E e L 5	F e M 3	E e L 5	E e L 4	E e L 4	E e L 3	E e L 4	E e L 4	G e L 4	F f H 1	G f M 2	P p H 0	P p H 0	P p H 0	P p H 0
	4	G e L 4	P e M 2	E e L 5	E e L 4	G e L 4	G e L 3	G e L 4	E e L 4	G e L 4	F f H 1	F f H 1	P p H 0	P p H 0	P p H 0	P p H 0
Heavy	1	F e M 4	P e M 1	F e M 4	E e L 5	E e L 5	E e L 4	F e M 4	E e L 5	F e M 4	F f H 2	G f M 3	P p H 0	P p H 0	P p H 0	P f H 0
	2	P e M 2	P e M 1	F e M 4	E e L 5	F e M 3	F e M 3	P e M 1	E e L 5	P e M 0	P p H 0	P p H 0	P p H 0	P p H 0	P p H 0	P f H 0
	3	P e M 2	P e M 1	P e M 2	E e L 5	F e L 3	E e L 4	P e M 1	E e L 5	P e M 0	P p H 0	P p H 0	P p H 0	P p H 0	P p H 0	P p H 0
	4	P e M 2	P e M 1	P e M 2	E e L 5	F e M 3	F e M 3	P e M 1	E e L 5	P e M 0	P p H 0	P p H 0	P p H 0	P p H 0	P p H 0	P p H 0

Table 6. Summary of the Ratings Used in Table 5.

Type of Rating	Rating Scale
1. Performance	E, G, F, P Excellent, Good, Fair, Poor
2. Ride Quality	e, g, f, p Excellent, Good, Fair, Poor
3. Maintenance Need	H, M, L High, Moderate, Low
4. Overall Rating	5 - 0 Excellent - Poor

2.4 Evaluation of Peachtree City Bikepath Pavement [4]

The objective of this work task was to evaluate an existing bikepath pavement through laboratory determinations of material properties of the bikepath, and theoretical analyses of the pavement system using the procedure proposed in [2]. The bikepath pavement used in this study is located in Peachtree City, Georgia.

In general, the bikepath is constructed by the following procedures. After the path is cleared of vegetation by a motor grader, two inches of asphalt concrete is placed directly onto the clay subgrade. The width of the pavement is 8 feet wide.

The service conditions including climate, soil type, load factors are described briefly in the following. The mean annual precipitation is about 50 in. with zero freezing index. The soil in the area ranges from silty sand to fine sand. The detailed soil test results are shown in the next section. The bikepaths are limited to bicycles and golf cart use only. The maintenance of the path is done by the specially designed light-weight vehicles.

The test program for evaluation of the material properties, of the asphalt concrete and soil samples obtained from the Peachtree City bikepath and the results are given in Appendix C.

The findings from the theoretical analysis using the material properties determined in this work task are presented in the following.

In Task 2 it has been shown that the pavement performance as related to the potential development of rutting and cracking could be predicted by analyzing the pavement responses under the actual loading conditions and the properties of the materials comprising the pavement system. The theoretical pavement model proposed in [2] as shown in Fig. C-3 was used for the analyses.

In analysis the pavement responses of the Peachtree City bikepath, the following parameters were used:

(a) Load parameter: W = 100 lb. with 80 psi tire pressure

(b) Thickness of asphalt concrete: $T_1 = 1.5$ in.
$T_2 = 2$ in.
$T_3 = 3$ in.

(c) Asphalt Concrete Properties
Resilient Modulus $E_{a1} = 50,000$ psi
$E_{a2} = 260,000$ psi
Poisson's Ratio 0.35

(d) Subgrade Soil
Resilient Modulus $E_{S1} = 15,000$ psi
$E_{S2} = 30,000$ psi
$E_{S3} = 45,000$ psi
Poisson's Ratio 0.50

The load and pressure were chosen to represent the typical bicycle wheel load characteristics. During the coring of the asphalt concrete samples from the pavement, the thickness of the asphalt concrete layer was found to be varying from 1.5 inches to 2.5 inches. Thus, three thicknesses were used in the analyses to reflect the actual variation of the pavement thickness. Two resilient moduli of asphalt concrete were chosen to represent the estimated moduli at normal temperature (77°F) and at high summer temperature (95°F) from the corresponding laboratory testing. The resilient modulus of the subgrade soil determined in the laboratory as shown in Figure C-4 ranged from 26,000 psi to 34,000 psi. Because of the possible large variation of soil property in the field due to change in moisture and compaction effort, three moduli were used in the analyses. The Poisson's ratio used for asphalt concrete and soil represented the typical values for these materials. The effect of the Poisson's ratio on the pavement responses has been found to be small from the various studies.

Using the theoretical pavement analysis computer program mentioned in [2] and the input data discussed above, the pavement responses in terms of the maximum tensile strains in the subgrade and the deviatoric stress at 0.5 in. below the top of the subgrade were determined. These results are shown in Fig. 12 and 13. In these figures, the effects of the various input parameters, pavement thickness, resilient modulus of asphalt concrete and subgrade soil are clearly indicated.

It was pointed out in [2] that the tensile strain in the asphalt concrete layer and the compressive strain in the subgrade soil respectively were related to the potential development of pavement cracking and rutting of the pavement.

In [2], 0.25×10^{-3} in./in. and 1.0×10^{-3} in./in., respectively were chosen as the permissible values for the tensile strain in asphalt concrete and the compressive strain in subgrade for asphalt bikepath pavements for design purpose to prevent premature cracking and rutting in the pavement.

Based on these criteria the 2 inch thick asphalt concrete pavement in the Peachtree City bikepath is probably adequate to resist a potential development of cracking and rutting. When the thickness is reduced by only 0.5 in., the potential crack development is greatly increased, particularly in view of potential large variations of field subgrade properties due to variation of moisture content in the subgrade and inadequate field compaction.

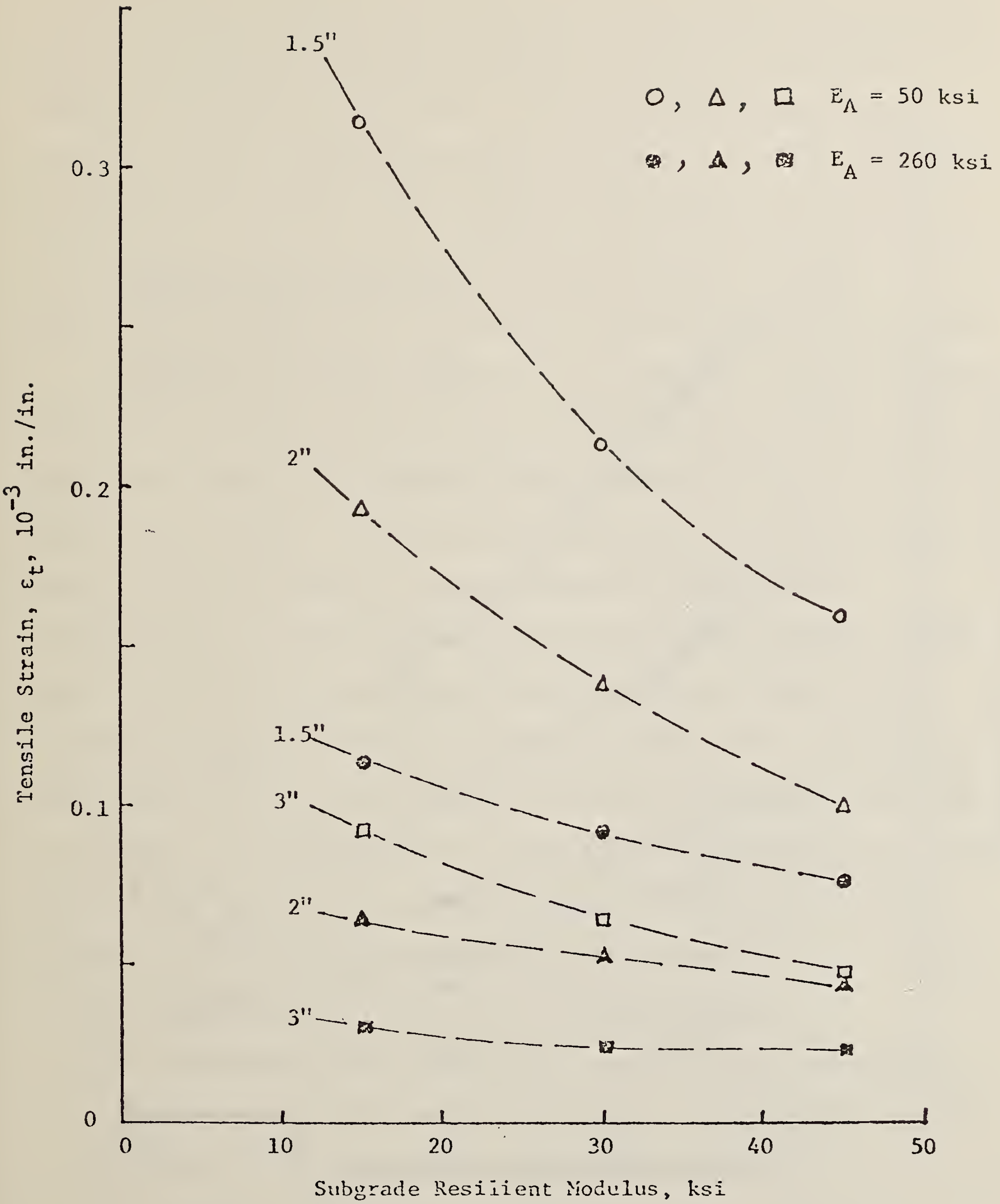


Figure 12. Maximum Tensile Strain in Asphalt Concrete.

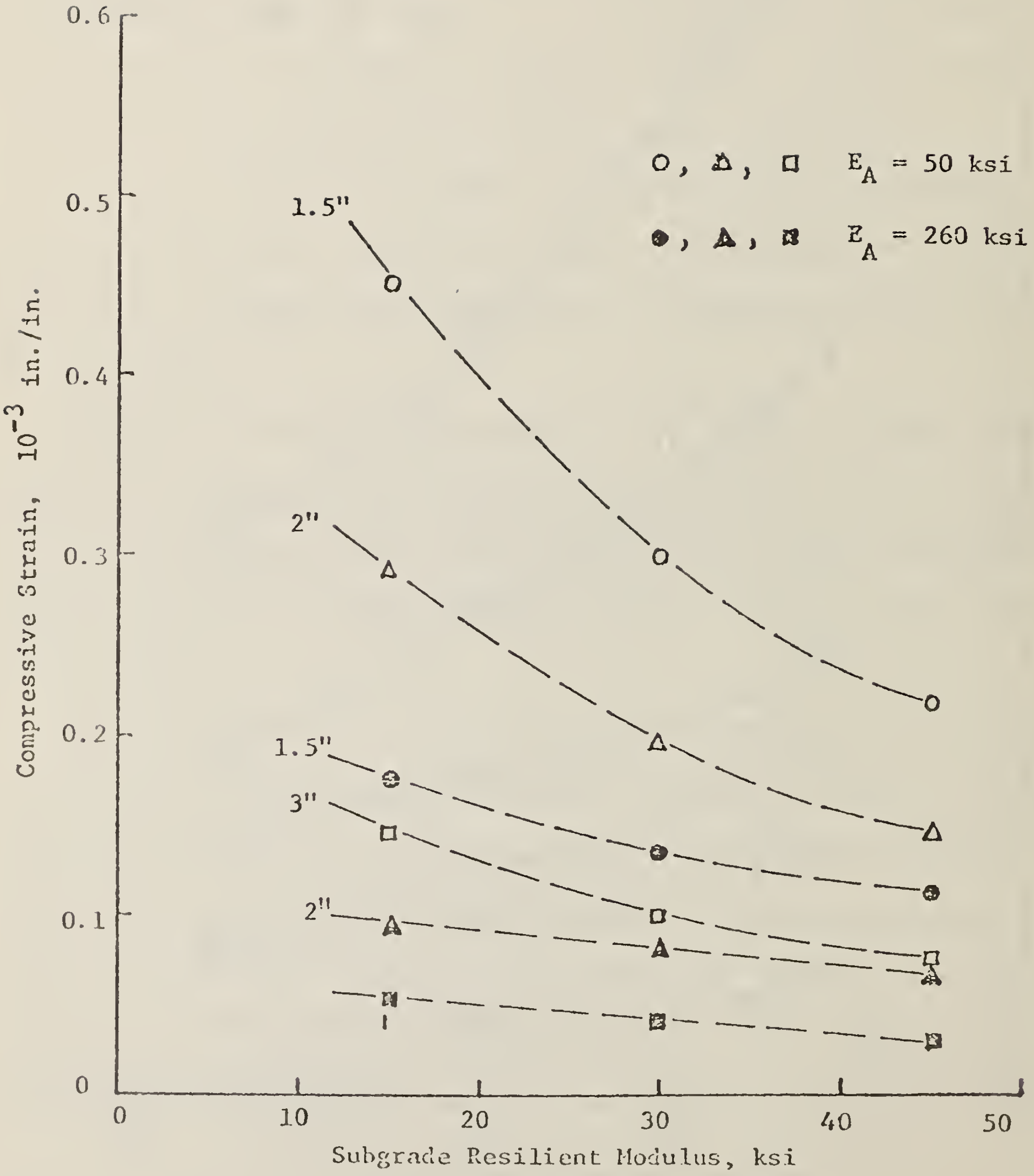


Figure 13. Maximum Compressive Strain in the Subgrade

2.5 Develop New or Improved Low-Cost Material Systems for Bikepath Pavements [5]

With cost of bikepath construction running from $20,000 to $30,000 per mile [1], agencies implementing Class I bikepath facilities are finding it difficult to build them. If inflationary trends continue, the cost for Class I bikepath may be too expensive to warrant their construction. One way to reduce the cost of construction bikepath is to develop low-cost pavement systems through the use of low-cost materials. This work task is concentrated mainly on this subject.

Development of low-cost materials and utilization of waste materials have been undertaken vigorously, particularly by the government agencies, and private organizations involved in the transportation facility construction [19,20]. The aim is to reduce the use of petroleum-based materials (such as asphalt), energy intensive materials (such as portland cement), to overcome shortages of conventional aggregates and also to solve the waste materials disposal problems. Many of their findings can be directly applied to bikepath construction. Furthermore, some marginal materials and waste materials which have been found to be not suitable for highway pavement construction may be suitable for bikepath pavement construction due to different traffic characteristic applied to these two different types of pavement structures.

The following topics were covered in this work task.

(1) Soil stabilizations using lime, portland cement, lime-flyash and asphalt.

(2) Asphalt and rubberized-asphalt surface treatments.

(3) Marginal materials and waste materials.

Soil Stabilizations Using Lime, Portland Cement, Lime-Flyash, Asphalt

Use of lime, portland cement, lime-flyash and asphalt to stabilize and strengthen subgrade soils have been used successfully and beneficially for highway constructions [21-26]. As pointed out in task 2 and task 3, when bikepath pavement is to be constructed on poor subgrade soil, it may be more economical to strengthen the subgrade using various stabilizers and build a watertight thin surfacing on top of it than to build a thick surfacing directed on poor subgrade soil.

In order to utilize soil stabilization successfully, it is necessary to know the particular types of soils which can most readily be stabilized by the various stabilizing agents. A proper design of the mixtures and proper construction control are essential for a successful soil stabilization project. In Appendix D, various aspects associated with the use of lime, portland cement, lime-flyash and asphalt for soil stabilization construction are discussed in detail.

Asphalt Surface Treatment

Asphalt surface treatment has been used for bicycle path surface as well as for many low-cost, low volume roads. For a single surface treatment construction, it consists of an application of asphalt at a rate of about 0.2 gal. per sq. yard to the road surface and is immediately covered by a single layer of uniform size aggregate at a rate of about 15 to 20 pounds of aggregate per sq. yard. For bicycle path surfaces, small aggregate size, such as using #89 aggregate, is preferable than larger ones. To provide a better riding quality, a double asphalt surface treatment may be used. It is suggested that coarse sand should be used in the second layer. A more detailed information with regard to the design and construction of surface treatment is given in [27]. The ride quality of this type of surface is less satisfactory than that of asphalt concrete and portland cement concrete surfaces as discussed in [3]. However, if properly constructed and using smaller size of aggregate, the ride quality should be acceptable. Excluding the cost for base course material, the cost for constructing this type of pavement is very low. Various locally available marginal material and waste material to be discussed in this section can be used for base course materials to reduce the overall construction cost.

Rubberized Asphalt Surface Treatment

Instead of using regular asphalt for surface treatment construction, rubberized asphalt [28] can be used with some advantages. Rubber reclaimed from discarded automobile tires is ground into size between #16 and #25 sieve size. The rubber particles (25% to 30%) were mixed with hot asphalt to form a tough and elastic binder. It has been used very successfully in many seal coat construction. Rubberized asphalt surface treatment provides a stiffer and yet more elastic surface which is capable of resisting uneven subgrade movement and subgrade cracking.

The rubber, asphalt surface treatment construction procedures are about the same as the regular asphalt surface treatment construction procedures. The major concern has been the uniform distribution of the binder from a conventional asphalt distributor. Two problems had to be overcome. One is to reduce the viscosity of the binder so that the rubberized asphalt binder will flow evenly from the distributor nozzles. This is accomplished by the addition of 5 - 8% by volume of kerosene to the binder such that the viscosity of the binder will be temporarily decreased. After a period of time (about one-half hour) the kerosene will evaporate and the viscosity of the binder will rise again. It is therefore imperative that the spray operation be completed before this phenomenon occurs. The other problem that had to be overcome is that the undissolved rubber in the distributor tends to settle to the bottom of the tank. The high concentration of rubber particles also increase the probability of the spray nozzles becoming plugged. Use of a large size of nozzle, such as No. 5 distributor nozzle is therfore recommended [28].

In a small job operation asphalt kettle may be used. In this case, the blending of rubber with hot asphalt (300^o - 450^oF) and adding of kerosene will be done in the kettle.

Marginal Materials and Waste Materials

In addition to the large amount of flyash and chopped up rubber tires readily available and can be used beneficially for bikepath construction as discussed in this work task, there are many nationally or locally available materials that, if used properly, can result in a great savings in bikepath construction. In the following, some of these materials, along with their applications to the bikepath construction will be discussed. It is important to point out that the feasibility of using any supplemental materials in bikepath construction should be determined by its cost and field performance under local climatic conditions. The effects of climatic conditions on the performance of bikepath pavements were discussed in Task 2 and Task 3.

Marginal Materials. Many available natural aggregates have serious deficiencies such as poor abrasion resistance, reactive constituent, or poor gradation. These materials which do not meet specifications for regular highway construction may be suitable for bikepath construction due to different traffic load characteristics. Depending on the natural deficiencies, some marginal materials may require certain degree of treatment to improve their properties before they can be used for bikepath construction.

A good example of marginal material is marine deposits. In several coastal states, large quantities of reef shell and beach sand are available. Mixtures of sand and shell can be used at substantial savings (as little as $1 per ton) for use in asphalt concrete, portland cement concrete, cement stabilization, and/or use as the base course materials in the surface treatment construction. Use of sand shell mixture for these various operations are basically no different than if regular aggregate was used. Although care should be exercised to determine the proper amount of cement and water needed in the portland cement concrete and cement stabilization applications. Determination of asphalt content in asphalt concrete is critical in that the properties of asphalt concrete is very much dependent on the gradation of the "aggregate" and the asphalt content. Certain amount of fillers may have to be added in sand shell mixtures in the asphalt concrete construction to improve the stability of the material.

Waste Materials. In reference [19], a list of 53 waste materials that have a potential for use as an aggregate, filler, partial binder replacement, or binder as shown in Table 7 have been identified. Some of the waste materials can be used readily as the supplemental materials, some materials require a small amount of capital investment to process the materials, some materials require large amounts of capital investment and some materials require additional research and are therefore not immediately usable.

Thus, in the following only those waste materials that are in the first two categories, immediately usable with at most small captial investment, will be discussed. It is felt that use of any waste materials that required a major capital investment is not justified for bikepath construction.

(1). Lime-Flyash

Use of lime-flyash has been discussed in this task as a modifier or binder in soil stabilization construction.

(2). Waste Glass

Glass in the form of non-returnable bottles has created refuse problems despite efforts at recycling. Crushed glass can be readily used

Table 7. Waste Materials [19].

Material	Probable Use Binder	 Aggregate	Annual Quantity[a] (× 10⁶ tons)	Extent of Material	Additional Energy Required	Cost	Potential Use	Research Required[b]
Sulfur-asphalt	X	X	NA	National	Low to moderate	Moderate	Probable	Yes, short
Sulfur-primary binder	X		NA	National	Moderate	High	No	Yes, long
Fly ash-lime-cement	X		32	Regional	Moderate	Moderate	Yes	Yes, short
Fly ash, sintered		X	32	Regional	High	High	Yes	Nominal
Fly ash, fill		X	32	Regional	Low	Low	Yes	Nominal
Mine tailings		X	NA	National	Moderate	Moderate	Yes	Nominal
Crusher wastes		X	NA	National	Low	Low	Yes	Nominal
Incinerator residue		X	10	Local	Moderate	Low	Yes	Yes, short
Rubber tires, granulated	X	X	3 to 5	Local	Moderate	Moderate	Yes	Nominal
Rubber tires, vulcanized	X	X	3 to 5	Local	Moderate	Moderate	Yes	Nominal
Waste glass		X	12	Local	Low	High	Yes	None
Blast furnace slag		X	30	Regional	Low	Moderate	Yes	None
Steel slag		X	10 to 15	Regional	Low	Moderate	Yes	None
Dry bottom ash		X	10	Regional	Low	Moderate	Yes	None
Bricks		X	NA	Local	Low	Low	Yes	Nominal
Tile			NA	Local	Low	Low	Yes	Nominal
Stack dust		X	NA	Local	Low to moderate	Low	Yes	Nominal
Stack dust	X		NA	Local	Low	Low	Probable	Yes, short
Resins and lignins	X		NA	Regional	Unknown	Unknown	No	Yes, long
Sulfate and sulfite sludges	X	X	5 to 10	Regional	Low	Low	Yes	Yes, long
Scrubber sludges		X	NA	National	Low	Low	Yes	Yes, short
Slag cements	X		NA	Regional	Moderate	Moderate	Yes	Yes, short
Waste oils	X		NA	National	Low to moderate	Low	Yes	None
Sulfuric acid	X		NA					
Salt water	Low		NA	Local	Low	Low	Yes	Nominal
Oil shale asphalt								
Plastic wastes	X	X	2.5 to 3.0					
Sewage sludge		X	8 to 10					
Wood chips and saw dust			NA					
Pyrolysis	X	X	NA	National	Unknown		Yes	Yes, long
Wet bottom boiler slag		X	5	Regional	Low	Moderate	Yes	None
Foundry wastes		X	20	Local	Low to moderate	Moderate	Yes	Yes, short
Alumina red and brown mud	X	X	5 to 6					
Phosphogypsum	X		5					
Phosphate slimes		X	20					
Anthracite coal refuse		X	10					
Bituminous coal refuse		X	100					
Asbestos tailings		X	1					
Copper tailings		X	200					
Dredge spoil		X	300 to 400					
Feldspar tailings		X	0.25 to 0.50					
Gold mining waste		X	5 to 10					
Iron ore tailings		X	20 to 25					
Lead tailings		X	10 to 20					
Nickel tailings		X	NA					
Phosphate slag		X	4					
Slate mining		X	NA					
Waste taconite tailings		X	150 to 200					
Zinc tailings		X	10 to 20					
Smelter waste		X	NA					
Building rubble		X	20					
Ceramic wastes		X	NA					
Rice hulls								
Concrete pipe								

Note: 1 ton = 907 kg.

[a] NA = not applicable. [b] Short or long indicates whether the research has a short- or long-term payoff.

to replace aggregate for portland cement concrete and asphalt concrete construction. Normal procedures in mix design, manufacturer and construction for asphalt concrete and portland cement concrete using aggregate are directly applicable to the products using crushed glass. Thus, any local asphalt concrete and portland cement concrete contractor should be able to handle the products using crushed glass.

The crusher needed for crushing glass bottles should be available in any aggregate plant.

(3). Rubber Tires

Rubber reclaimed from discarded automobile tires can be either ground in granulated form of size between #16 to #25 sieve size (about 1 mm diameter) or vulcanized. Both of these can be used as binder and/or aggregate supplement. As discussed before, ground up rubber used in the rubberized-asphalt surface treatment is one potential use of this material.

Ground tread tire rubber is available from rubber reclaiming companies throughout the country.

(4). Slags

Blast furnace slag, steel slag and other metallurgical slags are excellent aggregate replacements. They are tough and have an excellent wear-resistance property. Use of these materials in asphalt concrete and portland cement concrete should produce the products having the quality equal or better than the products using regular aggregate. In terms of manufacturing and construction processes, there will be no difference whether regular aggregate or slags are used.

Some precautions should be exercised, however, in the mix designs. Slags are more porous and tend to have higher absorption. Thus, when used in portland cement concrete, the mixture usually requires higher cement factor and needs more water to account for the high absorption and poor workability. When used in asphalt concrete, somewhat higher asphalt content is needed to compensate for the high absorption also.

Slags should make an excellent base material for any type of pavement system.

(5). Mine Tailings

Coal mine tailings and other mine tailings can be used as a filler and aggregate supplement. These materials may be stabilized to improve the strength and durability.

(6). Recycling Construction Materials

These include building rubble, ceramic waste, old portland cement concrete, and asphalt concrete pavements, various treated and untreated base course materials. Use the materials in bikepath construction is certainly feasible. However, it is important that all the material should be crushed into reasonably small particles (not larger than 1 inch), particularly for a relatively thin section. This in some cases may increase the construction cost.

Recycled asphalt concrete has been used for base course and surface course materials for highway pavement construction [29].

Experiments using "scrap" asphalt concrete available from a parking lot resurfacing on a test section of a bikepath has been carried out by the East Point, Georgia chapter of the Southern Bicycle League. Waste asphalt concrete was placed using low heat and compacted with a hand roller. The bikepath was surfaced with a thin layer of portland cement mortar mix.

CHAPTER THREE. CONCLUSIONS

On the basis of the findings reported herein, together with more detailed information in the Appendices, the following conclusions are drawn:

1. Results from the literature review indicated that the primary criteria governing the design of bikeway pavement section are to withstand the maintenance vehicles, construction vehicles and other vehicles which may have to ride on it.
2. Most bikeway pavements are maintained using conventional highway maintenance equipment. Use of this relatively heavy equipment is the main reason for using the high design load. Use of maintenance equipment specially designed for bikeway could substantially reduce the thickness of pavement structures.
3. A more definitive performance criterion for bikeway pavement is lacking. Particularly, data relating the performance to the pavement structural section is not available.
4. The concept of system approach may be used in the design and selection of bikeway pavements. All the factors, including type of vehicles, materials, environmental variables, construction variables, maintenance variables and performance criteria, should be considered in order to obtain an eventual cost effective bikeway system.
5. The stress analyses techniques used by highway pavement designers can be used to analyze the stresses, strains and deflections induced in bikeway pavements due to different types of wheel loads.

6. In order to prevent the development of excessive cracking and rutting on asphalt concrete bikeway pavements, 1 in. to 1-1/2 in. of asphalt concrete built on top of good subgrade is sufficient for both the bicycle wheel loads and motor vehicle wheel loads. On a poor subgrade, 3 in. of asphalt concrete probably will be sufficient if the pavement is restricted to bicycle wheel loads only. To support motor vehicles, subgrade has to be strengthened or a base course has to be added.
7. On portland cement concrete pavements 3-1/2 in. to 4 in. of concrete surface is probably sufficient to support motor vehicles even when the pavement is built on poor subgrades.
8. For asphalt concrete surface course, using a one to one-half percent higher asphalt content in the asphalt mixture than is normally used in the highway pavements can improve its resistance to fatigue cracking.
9. At the present time, it seems that the lack of proper maintenance on bikeway pavements is the major complaint from the cyclist. In order to encourage the riders to use bicycle facilities, proper maintenance should be provided.
10. Decision criteria for the selection of bikeway systems should include level of performance required, types of vehicles allowed to ride on the facilities, and esthetics. Each one of the parameters will affect the overall cost for the construction and maintenance of bikeway facilities.
11. Performance of any type of bikepath pavements will depend upon the service conditions. The service conditions that could affect the performance are climate, soil type and load factors.

Therefore in evaluation of the performance of the various pavement systems, these service conditions should be considered.

12. Selection of the most suitable pavement system should take into consideration the cost, performance, ride quality, and esthetics of the various pavement systems under the prevailing service conditions. Also, local contractor's experience on handling various materials should be considered. In this respect overall ratings of the various pavement systems under different service conditions proposed in this study should be of some usefulness.
13. The laboratory test program used in this study for determination of the properties of asphalt concrete and the subgrade soil in conjunction with the proposed theoretical pavement analysis can be used to evaluate the performance of existing bikepath pavements and to select the proper pavement thickness for new pavement design as demonstrated by the results of evaluation of the Peachtree City bikepath pavement presented in this report.
14. Soil stabilization using lime, flyash, portland cement and asphalt can provide a low-cost bikepath pavement under certain types of soils and climatic conditions. Proper design of soil stabilizer mixtures and proper construction control are essential.
15. Asphalt surface treatment provides a low-cost and watertight surfacing for bikepath pavements. If properly constructed, the ride quality of the pavement surface should be acceptable.
16. Proper use of locally available marginal materials and waste material such as reef shell, beach sand, crushed glass, slags, mine tailings and recycled constructions could result in cost

reduction for bikepath construction.

CHAPTER FOUR. RECOMMENDATIONS

Based on the findings and conclusions of this study, the following recommendations are drawn:

1. Although it is recognized that climate, soil type and type of loading will effect the performance of bikepath pavement, evaluation of the performance of bikepath pavement has not been done systematically in the past. As a result, there is a lack of a consentaneous performance criteria for bikepath pavements. It is recommended that a practical performance rating for bikepath pavement should be developed and be verified by various users.
2. Soil stabilization using various stabilizing agents has a great potential for providing low-cost bikepath pavements. Currently, several bikepath demonstration projects using stabilized soils for surfacings are in progress. It is recommended that the results from these projects in terms of mix design, construction process, cost and performance should be documented and published.
3. The overall ratings of various pavement systems based on ride quality, cost, maintenance need, and esthetics under different service conditions as proposed in this study should be further refined and verified by the various users.
4. Based on the results of evaluation of Peachtree City bikepath pavement a practical laboratory test program for determination of properties of materials as shown in Table 8 are recommended. The desired properties can be obtained directly from the "direct testing method" or can be estimated from the less elaborate "indirect testing methods".

Table 8. Material System Evaluation for Bikepath Pavement Design

Material	Property	Direct Testing Method	Can Be Estimated From
Subgrade Soil	(1) Resilient Modulus	Triaxial Repeated Test	•Atterberg Limit & Grain Size Analysis CBR Plate Bearing Test
	(2) Poisson's Ratio	Triaxial Test	$\nu \approx 0.5$
Asphalt Concrete	(3) Resilient Modulus	Resilient Test (unconfined or diametral test)	•Marshall Test •Penetration & softening point test of asphalt and volume ratio of aggregate
	(4) Poisson's Ratio	Same	$\nu \approx 0.4$
Stabilized Soil	(5) Resilient Modulus	Repeated Test	CBR
Portland Cement Concrete	(6) Modulus of Rupture	Beam Bending Test	•Compression Test •Estimate from Water-Cement Ratio

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14. Pennsylvania Department of Transportation, "Guidelines for the Development of Bikeways".

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18. "Surface Condition Rating System for Bituminous Pavements", Research Result Digest No. 48, Transportation Research Board, 1973.

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21. Lime Stabilization Construction Manual, Bulletin 326, National Lime Association, Washington, D.C., 1972.

22. Soil-Cement Inspector's Manual, Portland Cement Association, Skokie, Illinois, 1963.

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24. "Flyash: A Highway Construction Material", Implementation Package 76-16, Federal Highway Administration, June, 1976.

25. "State-of-the-Art: Lime Stabilization", Transportation Research Circular No. 180, Transportation Research Board, September, 1976.

26. "Lime-Flyash-Stabilized Bases and Subbases", NCHRP Synthesis No. 37, Transportation Research Board, 1976.

27. "Asphalt Surface Treatment", MS-13, The Asphalt Institute, November, 1969.

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APPENDICES

APPENDIX A

ANALYSIS OF ASPHALT CONCRETE BIKEWAY PAVEMENTS

The objective of this appendix is to illustrate the difference in response of bikeway pavements under different load variables, material properties and different pavement thicknesses. In this appendix, a bikeway pavement is represented by a two-layer model, with the upper layer having finite depth and the lower layer being of infinite extent. Each layer is assumed to be of infinite extent in the horizontal directions. The pavement system is subjected to axially symmetric loads. Figure A1 shows schematically the idealized pavement system.

Under this idealized conditions, the stresses, strains,and deflections in the pavement system can be readily obtained from the various existing elastic or viscoelastic layer analysis computer programs, developed for the analysis of highway and runway pavement systems under vehicle loads. The computer program used in this analysis is called CHEVRON V, developed originally by Chevron Research Laboratory *. It was pointed out by Monismith** that the results of stresses, strains and deflection predicted from the various layered systems compared favorably with some limited field test results.

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* Michelow, J., Warren, H., and Dieckman, W. L., "Numerical Computation of Stresses and Strains in a Multiple - Layered Asphalt Pavement System", California Research Corporation, Richmond, Calif. 1963.

** Seed, H. B., Mitry, E. G., Monismith, C. L., and Chan, C. K., "Prediction of Flexible Pavement Deflections From Laboratory Repeated - Load Tests", NCHRP Report 35, Highway Research Board, 1967.

To illustrate the difference in pavement response under bicycle loads and motorized vehicle loads, the following variables are included in the analysis.

(1) Load Variables: W_1 = 100 lb., tire pressure = 20 psi

W_2 = 2000 lb., tire pressure = 30 psi

(2) Thickness of Surface Course: $T_1 = 1.0$ in.

$T_2 = 1.5$ in.

$T_3 = 2.0$ in.

$T_4 = 3.0$ in.

(3) Modulus of Elasticity of Surface Course: E_{A1} = 50,000 psi

E_{A2} = 200,000 psi

(4) Modulus of Elasticity of Subgrade: E_{S1} = 3,000 psi

E_{S2} = 12,000 psi

E_{S3} = 45,000 psi

The Poisson's ratios for the surface course and subgrade are assumed to be 0.35 and 0.4 respectively. The load variables W_1 and W_2 represent a typical bicycle wheel load and a 8000 pound maintenance vehicle respectively. It should be noted the high tire pressure assumed for the bicycle wheel load. E_{A1} and E_{A2} represent the "modulus" of asphalt concrete at high temperature and low temperature respectively under normal duration of loading. E_{S1}, E_{S2} E_{S3} represent three different types of subgrade soils ranking from poor, moderate, to good subgrade soils.

The critical parameters which have been identified by the pavement designs as relating to the pavement distresses, particularly for thin pavement surface are:

(1) ε_t: the maximum tensile strain in the asphalt concrete. This value has been related to the fatigue cracking of the pavement surface.

(2) ε_z: the maximum vertical compressive strain on the top of subgrade.

This parameter has been used to relate the permanent deformation of subgrade.

The effects of load variables, modulus of asphalt concrete and subgrade, and thickness of surface course on these two parameters are shown in Fig. A2-A5.

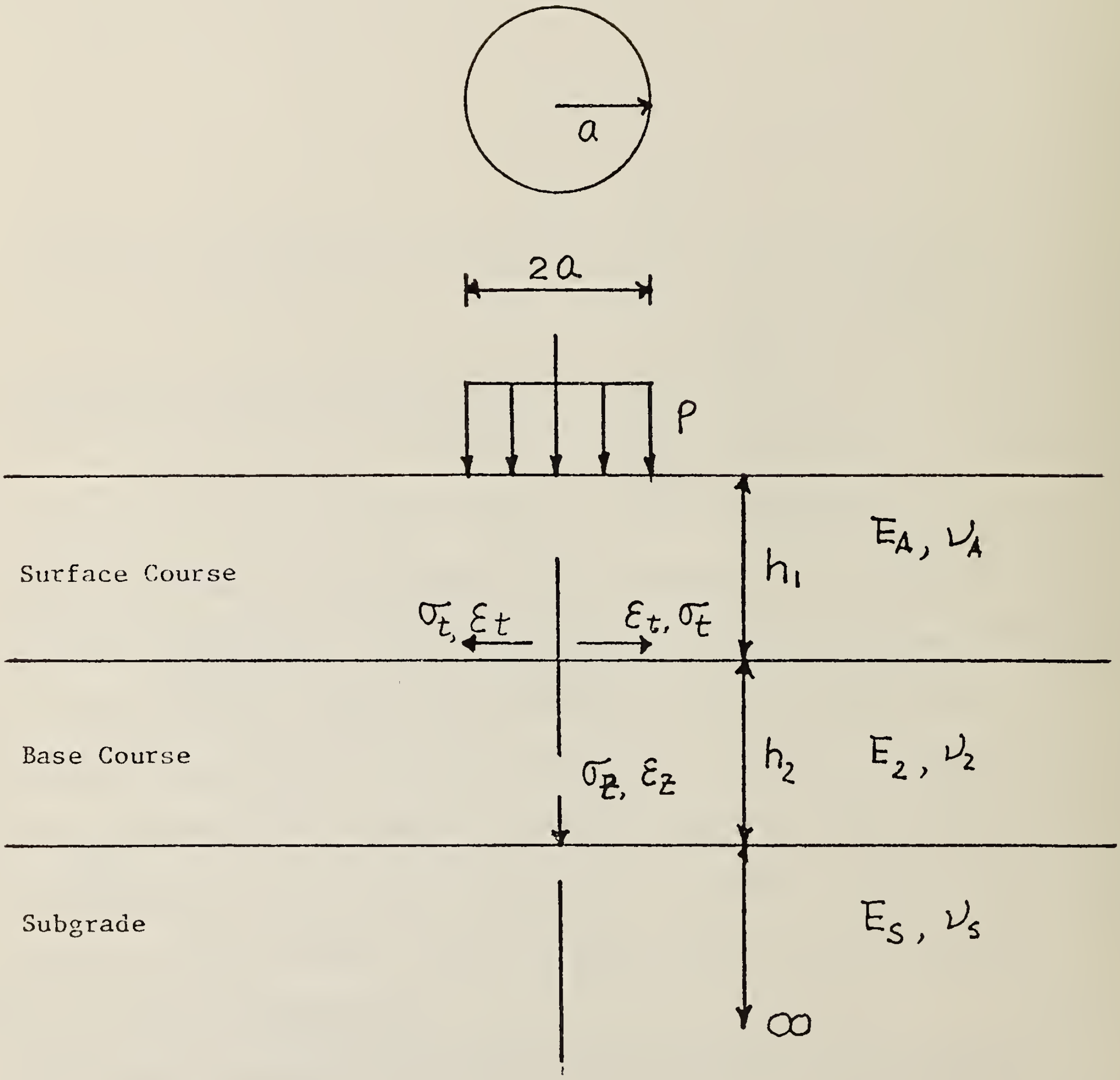

Figure A-1. Idealized Model for Bicycle Path Pavement.

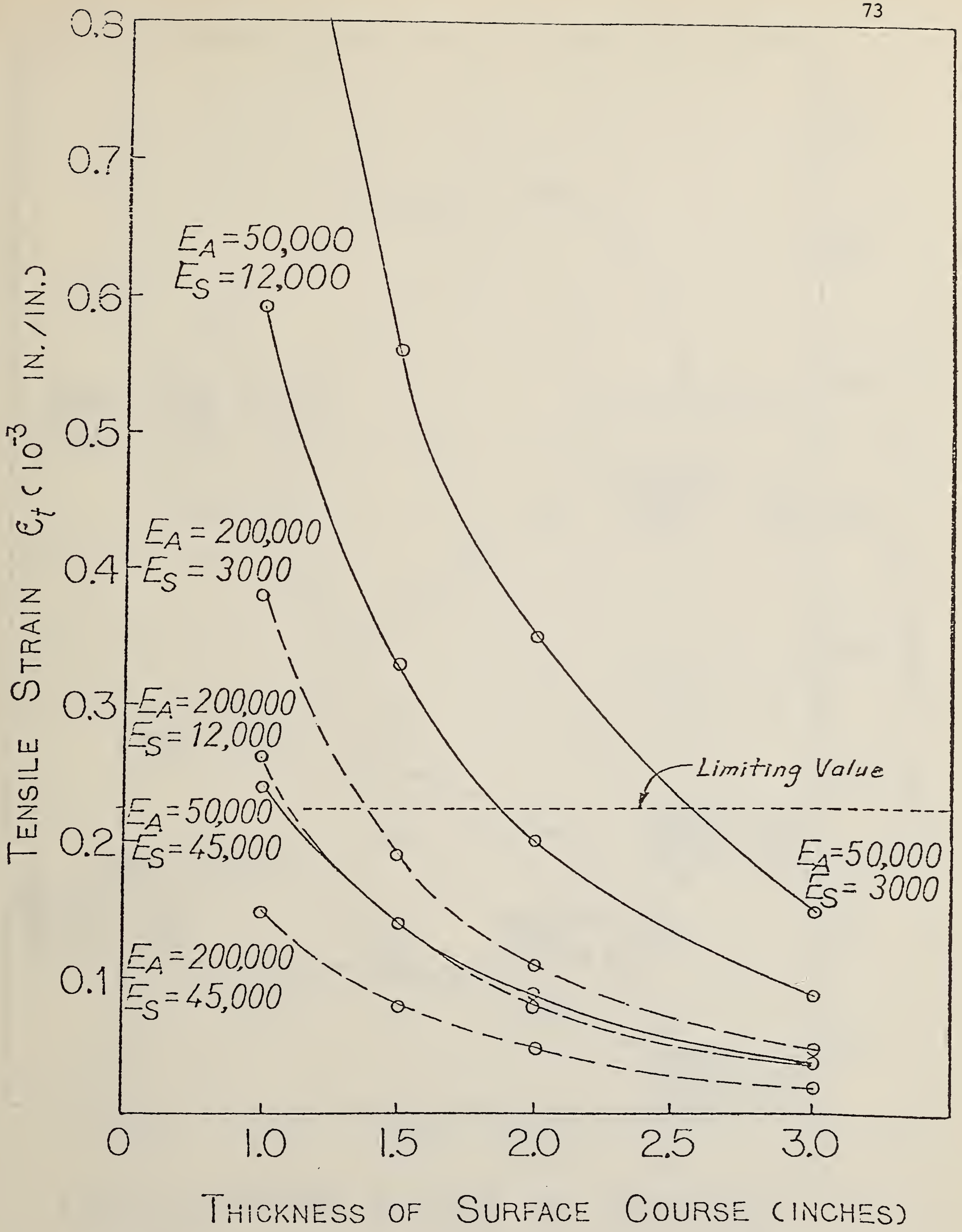

Fig. A-2. Max. Tensile Strain (ϵ_t) in Asphalt Concrete Due to Bicycle Wheel Load.

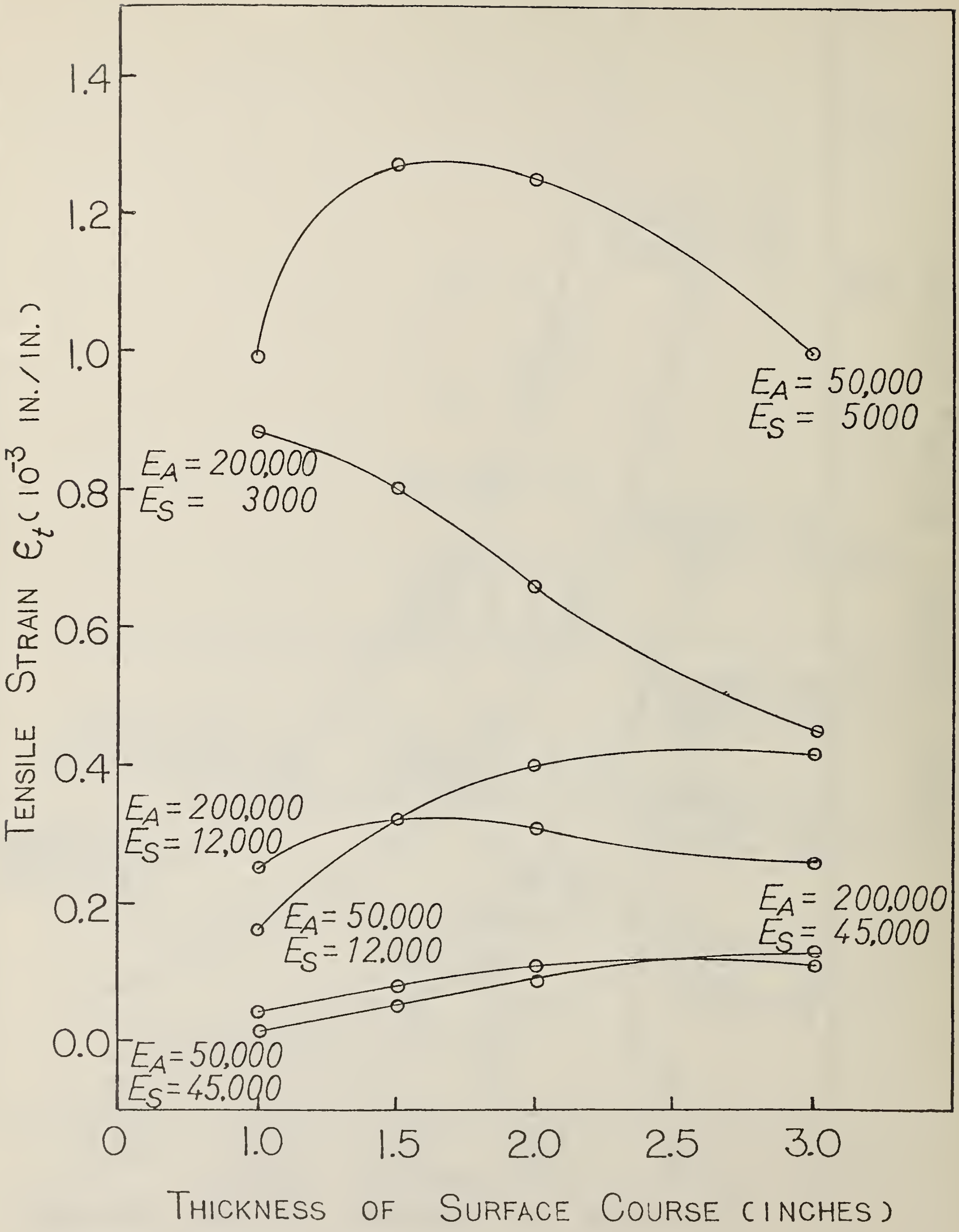

Fig. A-3. Maximum Tensile Strain in Asphalt Due to Vehicle Wheel Load.

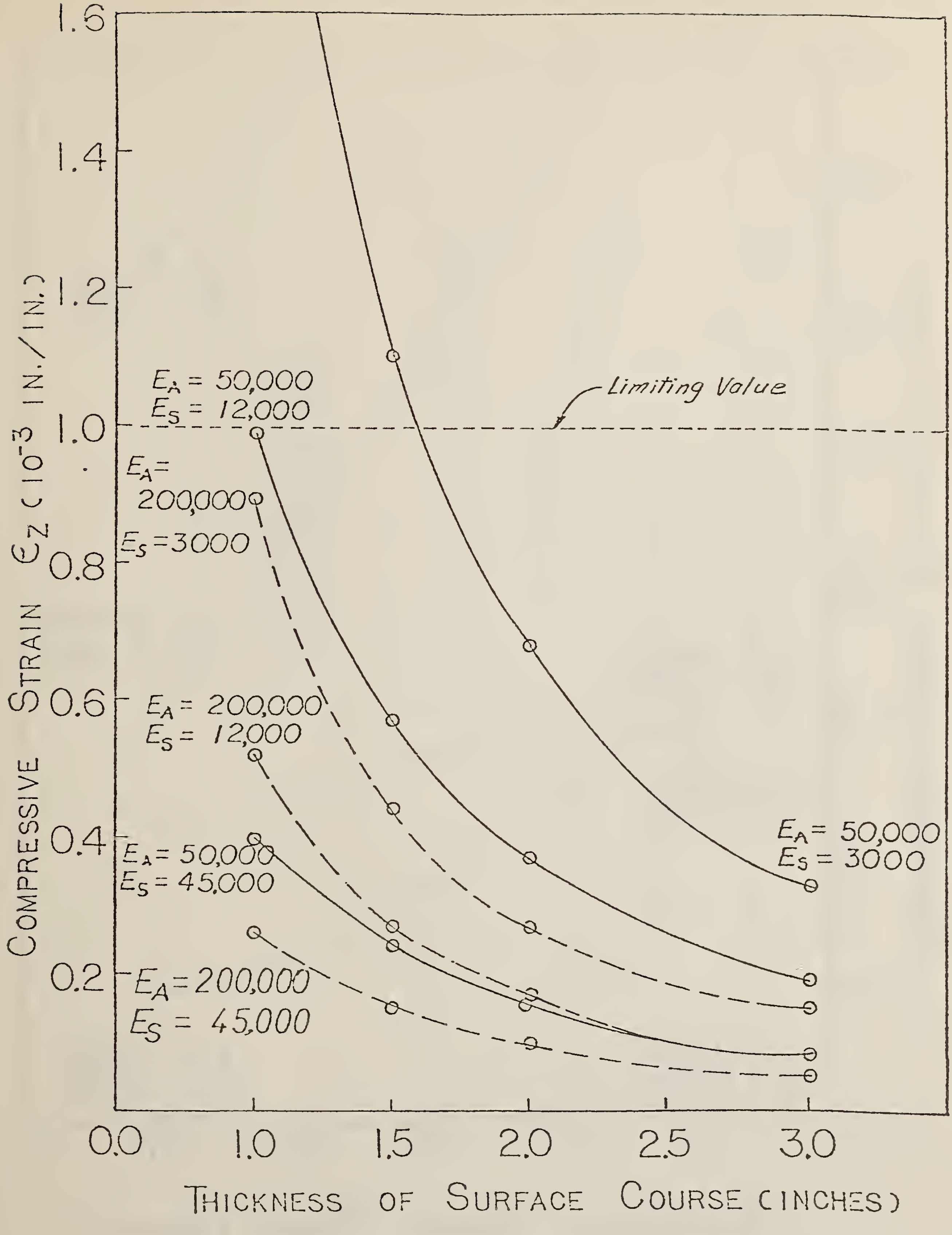

Fig. A-4. Maximum Compressive Strain on Top of Subgrade Due To Bicycle Wheel Load.

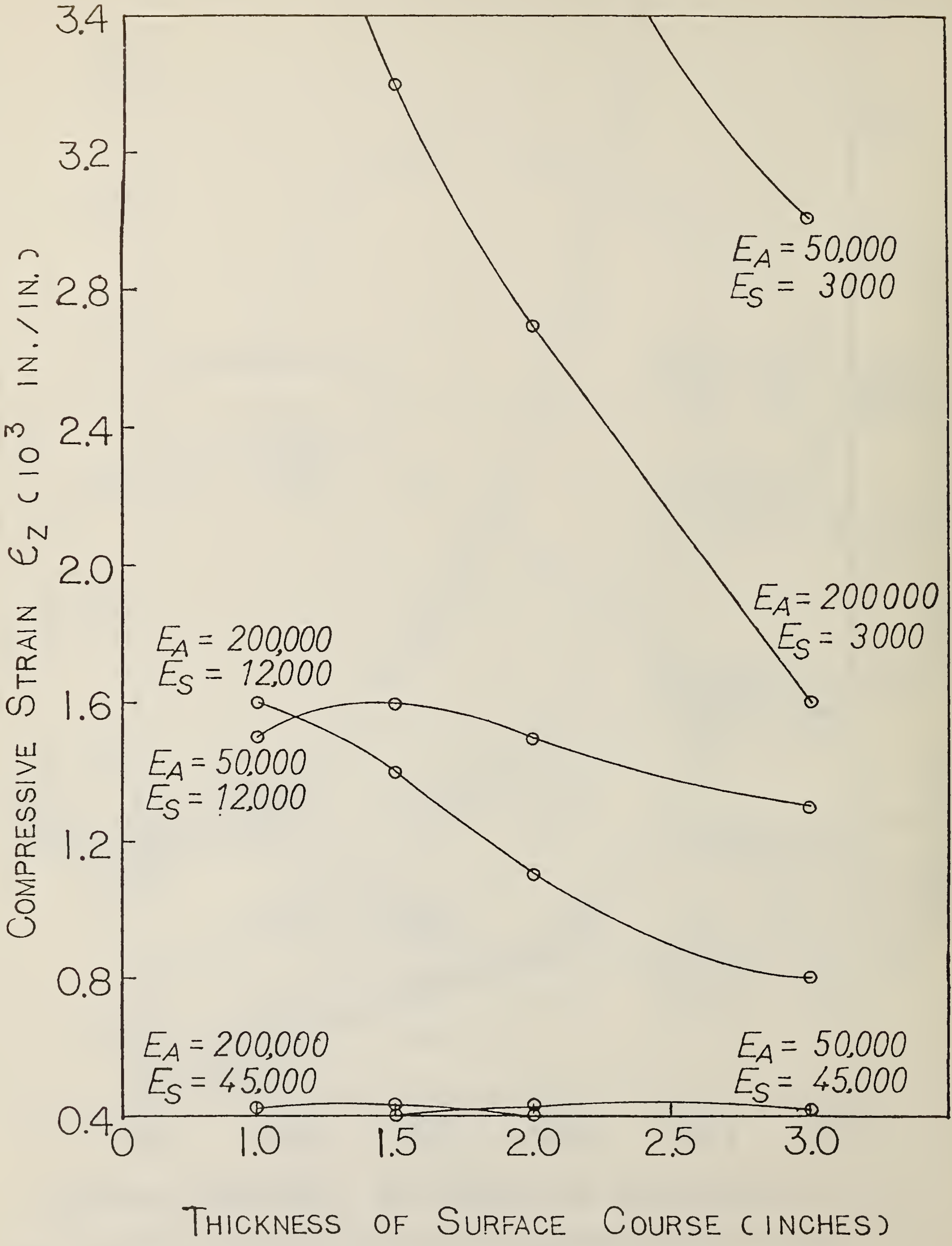

Fig. A-5. Maximum Compressive Strain on Top of Subgrade Due to Vehicle Wheel Load.

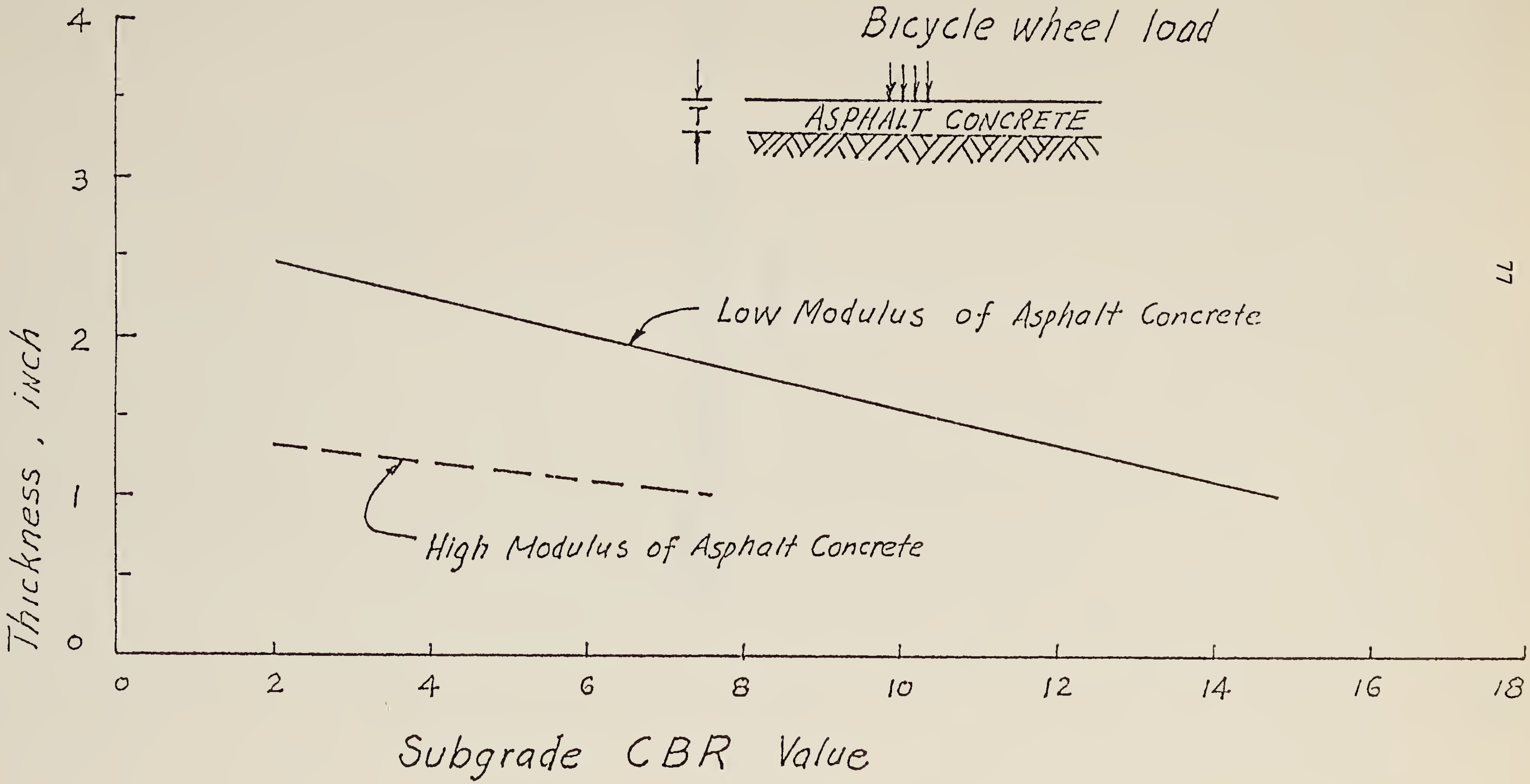

Figure A-6. Relationships Between Thickness of Asphalt Concrete Surfaces and Subgrade Soil Properties Under Bicycle Wheel Load.

APPENDIX B

STRESSES IN PORTLAND CEMENT CONCRETE PAVEMENT

APPENDIX B

STRESSES IN PORTLAND CEMENT CONCRETE PAVEMENT

Stresses in rigid pavement can be induced from a variety of causes, including wheel loads, cyclic change in temperature, change in moisture, and volume changes in the subgrade. In the following, the stresses induced by the externally applied loads and temperature differential between top and bottom surfaces of the pavement will be analyzed. Detail analysis of the stresses induced by the various causes can be obtained elsewhere [16,17].

The most critical stress induced in jointed portland cement concrete (PCC) pavements by the externally applied loads is the wheel loads applied at the corner and at the edge of the pavement, as shown in Figure B1. In the following tensile stress induced under these two loading conditions is duscussed briefly.

Corner Stress

Under corner load, the critical tensile stress developed at the bottom of the PCC slab, (see Figure B1), can be determined by the following equation:

$$\sigma_c = \frac{3P}{h^2} \left[1-\left(\frac{\sqrt{2a}}{\ell}\right)^{0.6}\right] \qquad \text{(B-1)}$$

$$\ell = \sqrt[4]{\frac{Eh^3}{12(1-\mu^2)K}} \qquad \text{(B-2)}$$

where ℓ = radius of relative stiffness (in.)

E = modulus of elasticity of the PCC (psi)

μ = Poisson's ratio of the PCC

h = thickness of the pavement (in.)

K = modulus of subgrade reaction (pci)

Typical E and μ for PCC are 4×10^6 psi and 0.15 respectively, and typical K values for subgrade are 50, 200, and 500 (for poor, moderate and good subgrade soils).

Edge Stress

Stress induced due to load applied at edge can be determined by the following equation:

$$\sigma_e = \frac{0.572\ P}{h^2} \left[4 \log_{10} \left(\frac{\ell}{a}\right) + 0.359 \right] \qquad \text{(B-3)}$$

Equations, B-1 and B-3, indicate that stresses are almost inversely proportional to the square of the pavement depth.

Warping Stress

If a pavement slab is subjected to a temperature gradient through its depth, its surface will tend to warp. The tendency to warp is restrained by the weight of the slab itself. For example, if the top of the slab is cooler than the bottom, the corners will tend to curl upwards, but the weight of concrete will tend to hold the slab in its original position resulting in stresses induced in the slab. The stress induced along the edge of the pavement can be estimated by the following equation:

$$\sigma_T = \frac{C\ E\alpha(\Delta T)h}{2} \qquad \text{(B-4)}$$

where σ_T = the tensile stress

E = elastic modulus of PCC

α = thermal expansion coefficient of PCC = 5×10^{-6} in./in./°F

ΔT = temperature differential per inch in the pavement

C = coefficient dependent on the ratio of the length of the pavement and ℓ, tje radius of relative stiffness.

In Table B-1 , the corner stress, edge stress and thermal stress were calculated for 3 in. and 4 in. PCC pavements for three different modulus of subgrade reaction and for a vehicle having wheel load equal 2000 pounds and tire pressure equal 30 psi. It can be seen that edge stresses are always greater than corner stress. Thus, the total maximum stress will be the sum of the edge stress, due to load, and the warping stress. The fatigue life of portland cement concrete as shown in Fig. B-2, depends on the ratio σ_t/M_c where σ_t is the maximum stress in the PCC pavement and M_c is the modulus of rupture of the same material. Using a typical value of 750 psi for modulus of rupture the corresponding fatigue life of the pavement can be estimated. The fatigue life of each pavement system is also shown in Table B-1.

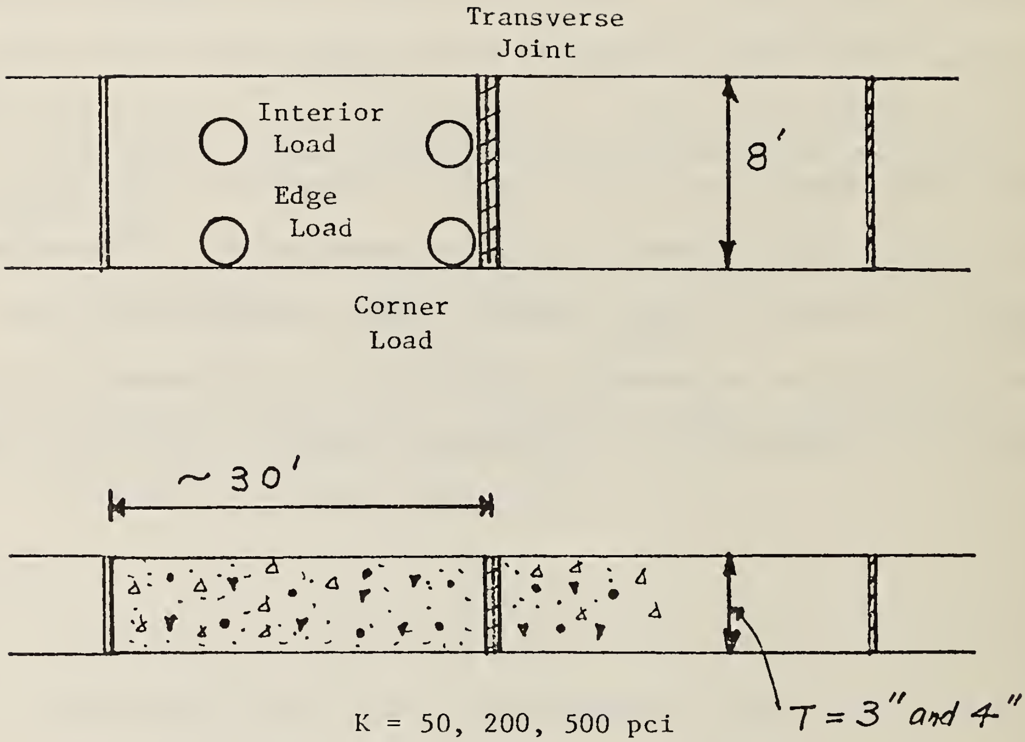

Fig. B-1. Position of Wheel Loads on Jointed Portland Cement Concrete Pavement.

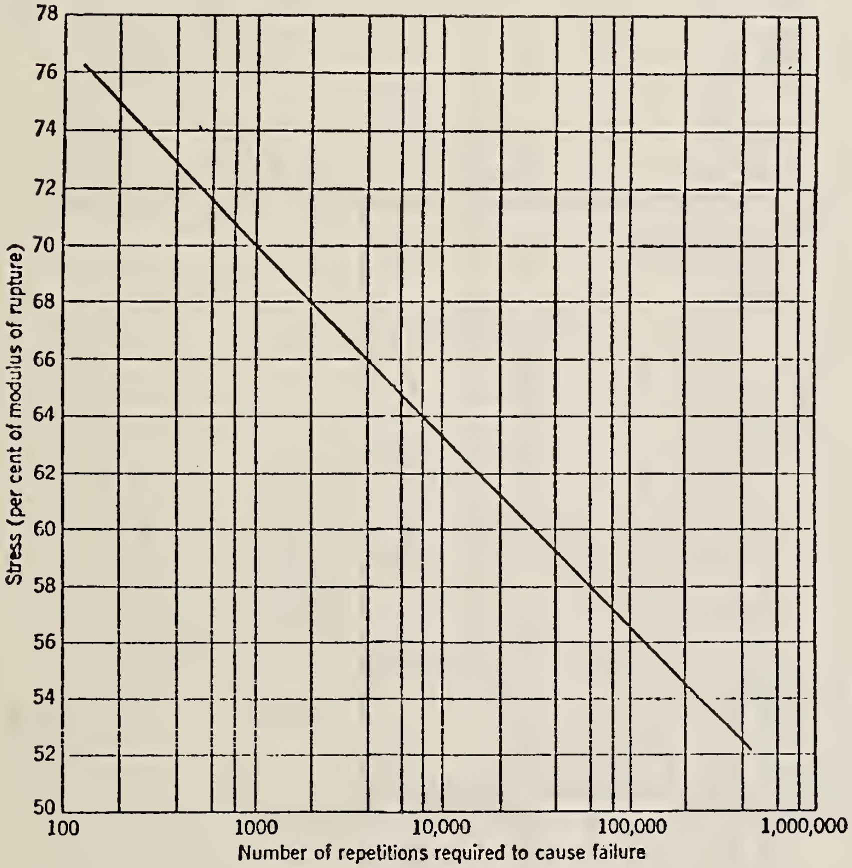

Fig. B-2. Fatigue Curve for Plain Concrete in Flexure [16].

Table B-1.

Thickness of PCC	h = 3 in.						h = 4 in.					
Subgrade K Value (pci)	Corner Stress psi	Edge Stress	Warping Stress	Total Stress	$\frac{\sigma}{M_c}$	Fatigue Life	Corner Stress	Edge Stress	Wraping Stress	Total Stress	$\frac{\sigma}{M_c}$	Fatigue Life
50	333	381	104	684	0.65	5,000	187	212	138	350	0.45	∞
200	256	301	104	405	0.54	200,000	144	169	138	307	0.41	∞
500	196	250	104	364	0.5	∞	110	141	138	279	0.37	∞

$P = 2000$ pounds

$p = 30$ psi

$a = 4.61$ in.

$E = 4 \times 10^6$ psi

$\mu = 0.15$

$M_c = 750$ psi

$\alpha = 5 \times 10^{-6}$ in./in. °F

$\Delta T = 5°F/in.$

$C = 1.0$

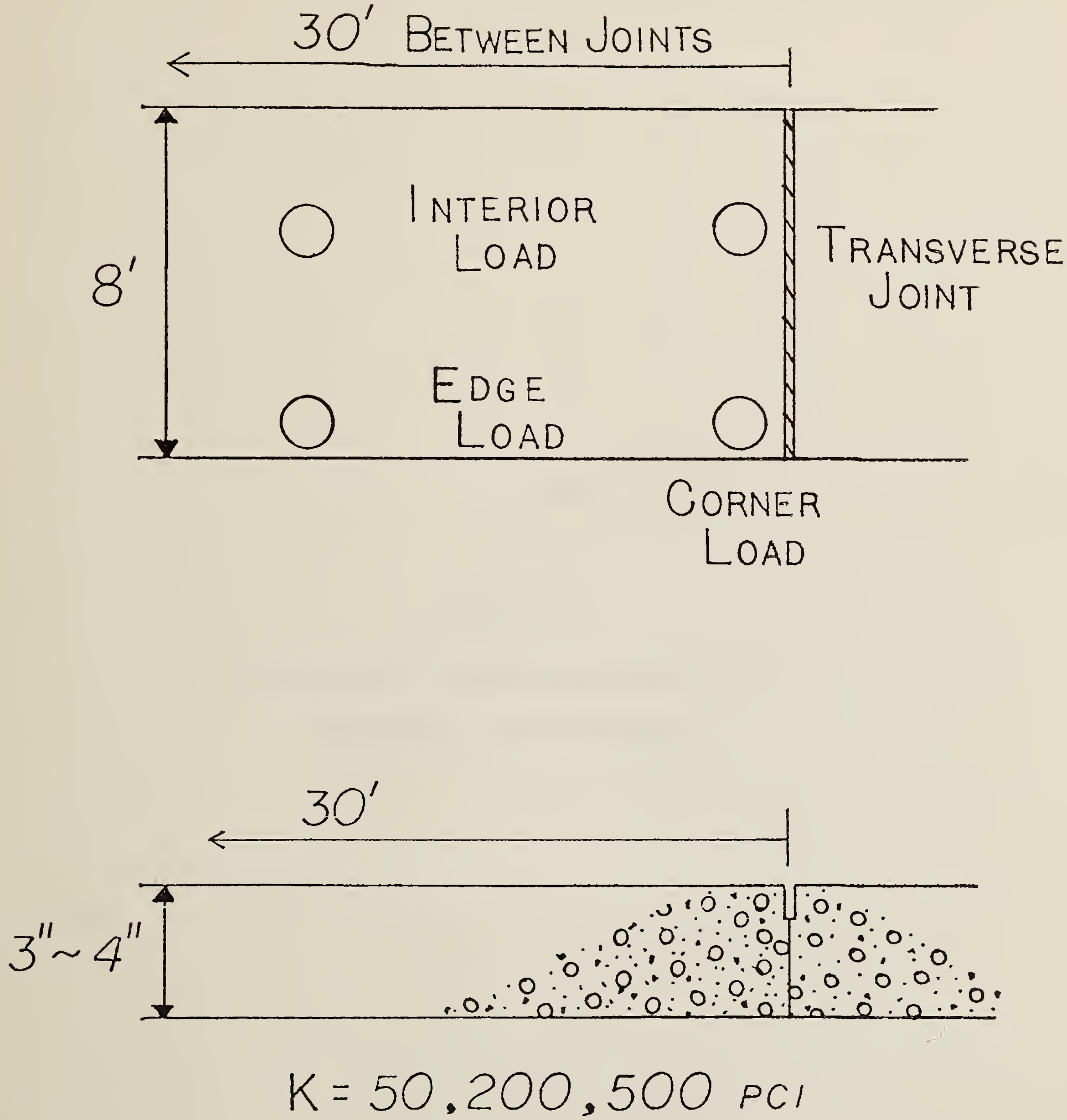

Fig. B-3. Position of Wheel Loads on Jointed Portland Cement Concrete Pavement.

APPENDIX C

EVALUATIONS OF MATERIAL PROPERTIES OF PEACHTREE BIKEPATH PAVEMENT

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EVALUATIONS OF MATERIAL PROPERTIES OF PEACHTREE BIKEPATH PAVEMENT

Eighteen 4"-diameter asphalt concrete samples and 6 disturbed soil samples were obtained from six sites in two locations, one location is under shade most of the time and the other location is more in open area. Three asphalt concrete samples were obtained from each site, one at about 2 ft. from each side of the edges and one at about the center of the pavement. The asphalt concrete samples were obtained by a trailer mounted portable coring drill. Disturbed soil samples, one from each site, were then obtained in the vicinity of the locations where asphalt concrete samples were taken. An attempt to obtain undisturbed soil samples using Shelby Tube was made. However, due to the sandy soil in the sites, undisturbed soil samples could not be obtained. A summary of the various testings on the soil and asphalt concrete samples for this study is shown in Table C-1. In the following, a brief description of each test and the results from the tests are presented.

Soil

(A) Atterberg Limits

Atterberg Limits, including liquid limit, plastic limit and plasticity index were determined following AASHTO T89-68 and AASHTO T90-70 standard testing methods. Results from the six soil samples are shown in Table C-2.

(B) Particle Size Analysis

Hydrometer analysis and siever analysis, according to AASHTO T88-72 standard testing method were conducted on the six soil samples. The gradation curves of the soil samples are shown in Figure C-1.

Based on AASHTO soil classification, soil sample 2,3,5 and 6 can be classified as A-3 (fine sand), and soil samples 1 and 4 as A-2-4 (silty

Table C-1. Summary of Material Testing

Material	Type of Test
1. Soil	Atterberg Limit Tests Particle Size Analysis Repeated Triaxial Load Test
2. Asphalt Concrete	Stability Flow Density Air Voids VMA % Asphalt
3. Asphalt (extracted from cores)	Penetration Ductility Viscosity

Table C-2. Atterberg's Limit Analysis of Soil Samples.

Soil Sample	Liquid Limit	Plastic Limit	Plasticity Index	AASHO Soil Classification
1	34.1	25.3	8.8	A-2-4
2	15.6	-	NP	A-3
3	17.1	-	NP	A-3
4	35	25	10	A-2-4
5	16.7	-	NP	A-3
6	15.7	-	NP	A-3

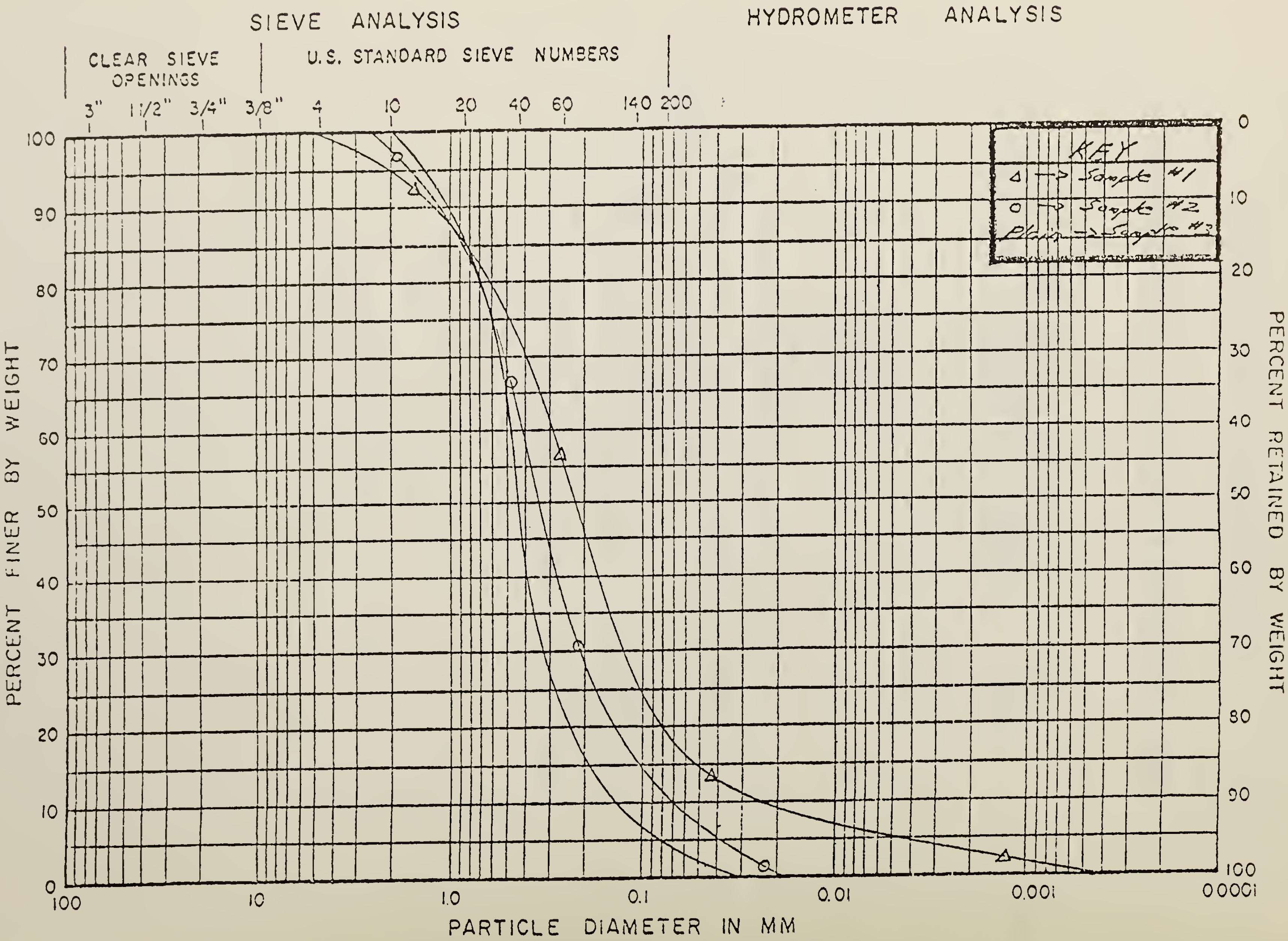


Figure C-1. Grain Size Distribution.

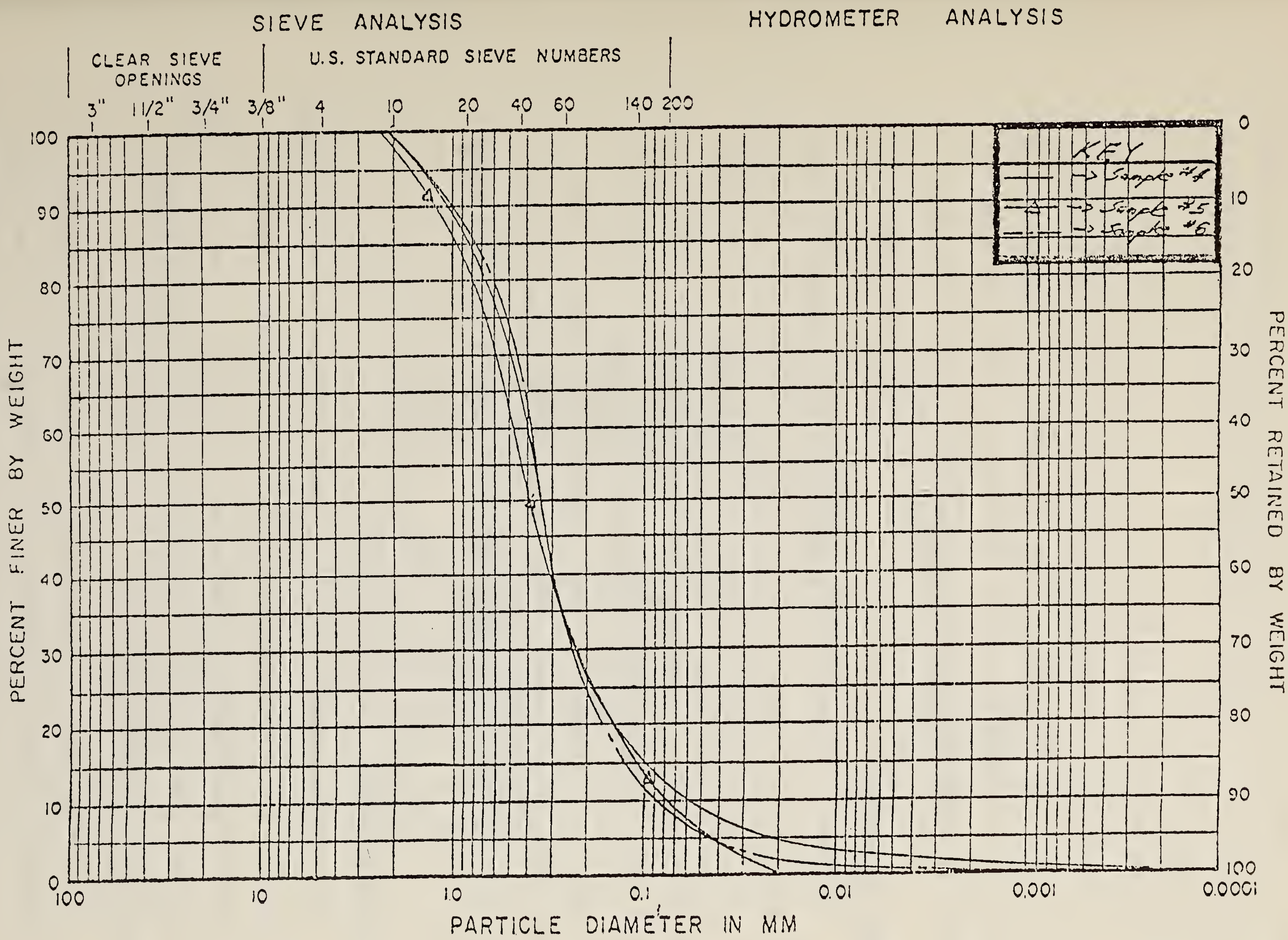


Figure C-1. Grain Size Distribution.

sand), according to the results of Atterberg's Limits and particle size distribution of the samples. In general, the soil is considered as a good subgrade material.

(C) Repeated Triaxial Load Test

The objective of this test is to determine the resilient modulus and the permanent deformation of the soil under repeated triaxial loads. The resilient modulus of the soil determined from this test will be used to determine the pavement response under bicycle wheel load.

Sample Preparation

Specimens measuring 2 inches in diameter and 4 inches in length were prepared in a special hollow cylindrical aluminum mold. Material for making the specimens was the mixture in equal parts of the soils from the six sites. A dynamic compaction was supplied by means of a hammer with a 4 pound weight falling 12 inches. The foot diameter of the hammer was slightly less than 2 inches. The specimens, six of them, were prepared at 100% AASHTO T-99 density at optimum moisture. Specimens were compacted in three layers with equal blows applied per layer.

Testing Equipment

The testing equipment utilized is shown in Figure C-2. Axial loading was applied by means of compressed air and a Bellofram Air Cylinder. The frequency and duration of loading was controlled by means of a three-way solenoid valve which was activated by a micro-switch-cam device operated by a variable speed motor.

The loading pulse was approximately triangular with a duration of approximately 0.5 sec. A frequency of 40 load applications per minute was used. This load duration would approximate the subgrade loading effect

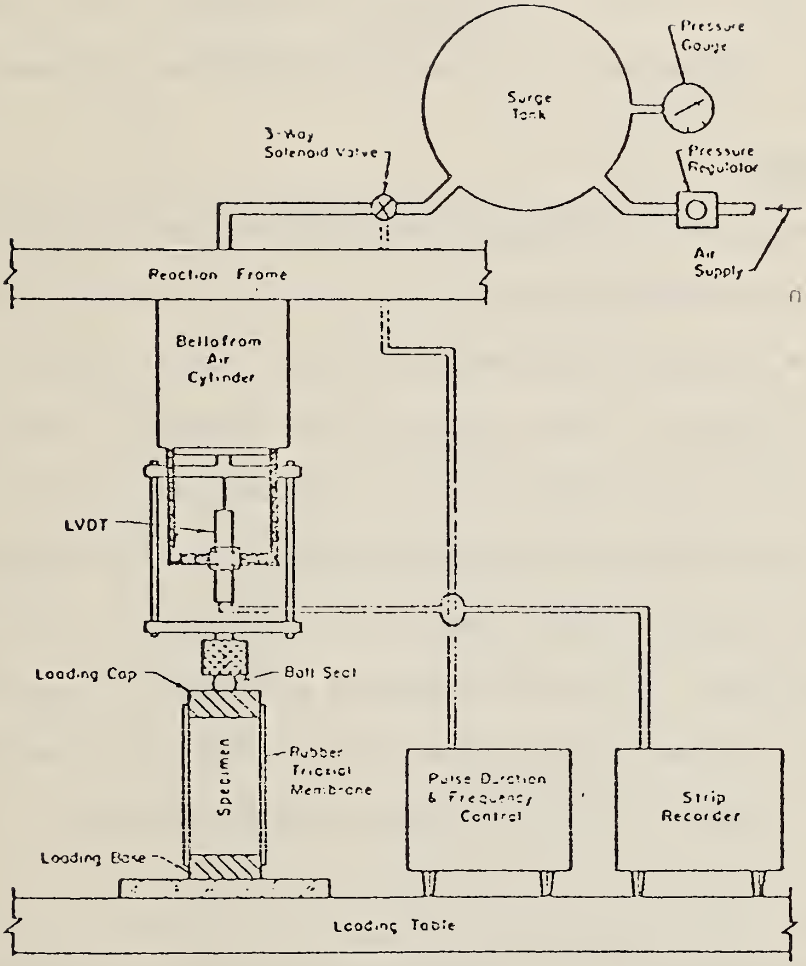


Figure C-2. Schematic Diagram of Testing Equipment for Repeated Triaxial Load Test.

of a wheel load traveling at about 5 mph.

The specimens were tested inside a conventional triaxial chamber so that confining pressure could be applied. Air was used for the confining pressure. Axial deformation of the specimens, both resilient and permanent, were measured by means of one centrally mounted linear variable displacement transducer (LVDT). A load cell was used to calibrate axial loading with a pressure gauge indicating pressure supplied to the air cylinder.

Testing Procedure

Three cyclic deviator stresses were used to load the specimens 3,6,9 psi. These three stress levels approximated the actual deviatoric stress exerted in the subgrade 1 inch below the top of the subgrade of the pavement model shown in Figure C-3. These ranges of the deviatoric stress and the confining pressure were estimated using this model and with the values of the resilient modulus of the asphalt concrete and the subgrade modulus chosen to represent the actual values in the field under different climatic conditions. A constant confining pressure of 3 psi was chosen for all the tests. At each of the three cyclic deviatoric stresses, two specimens were tested for up to 10,000 stress applications.

Test Results

Resilient modulus (E_R) is defined by the following expression:

$$E_R = \frac{\sigma_d}{\varepsilon_R}$$

where: E_R = resilient modulus

σ_d = cyclic deviatoric stress

ε_R = resilient axial strain at a certain number of stress applications and at a certain confining pressure.

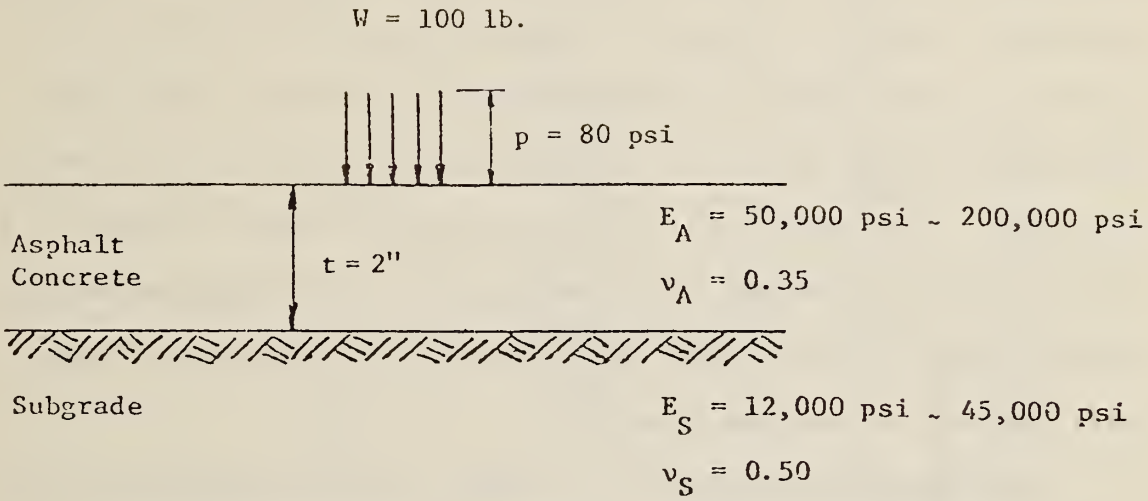


Figure C-3. Two-Layer Pavement System for Bicycle Path Pavement.

The amount of resilient axial strain in each loading cycle tends to decrease as the number of load applications increase. Consequently, the resilient modulus will be increased as the number of load application increased. However, the rate of change of the resilient axial strain decreases as the number of load applications increases. These have been shown by many previous investigations and have been confirmed by this study. The results of the resilient modulus shown in Figure C-4 were determined at 10,000 stress applications at the three deviatoric stress levels. It is evident that an increase of deviatoric stress will decrease the resilient modulus.

The permanent axial strain vs. number of stress applications for the three deviatoric stress levels is shown in Figure C-5. It is evident that a linear relationship exists between permanent strain and number of stress applications on log-log plots. This implies that the following relationship exists:

$$\varepsilon_p = a N^b$$

where: ε_p = permanent axial strain

N = number of stress applications

a,b = experimentally determined coefficients.

Fig. C-5 also indicates that an increase of deviatoric stress results in higher permanent axial strain.

Asphalt Concrete and Asphalt

The test program for the eighteen asphalt concrete cores obtained from the 2 locations is shown in Figure C-6.

(A) Stability, Flow and Density and Voids Analyses

Determinations of the unit weight, stability and flow values of the 4 inches diameter cores were conducted according to ASTM-D 1559

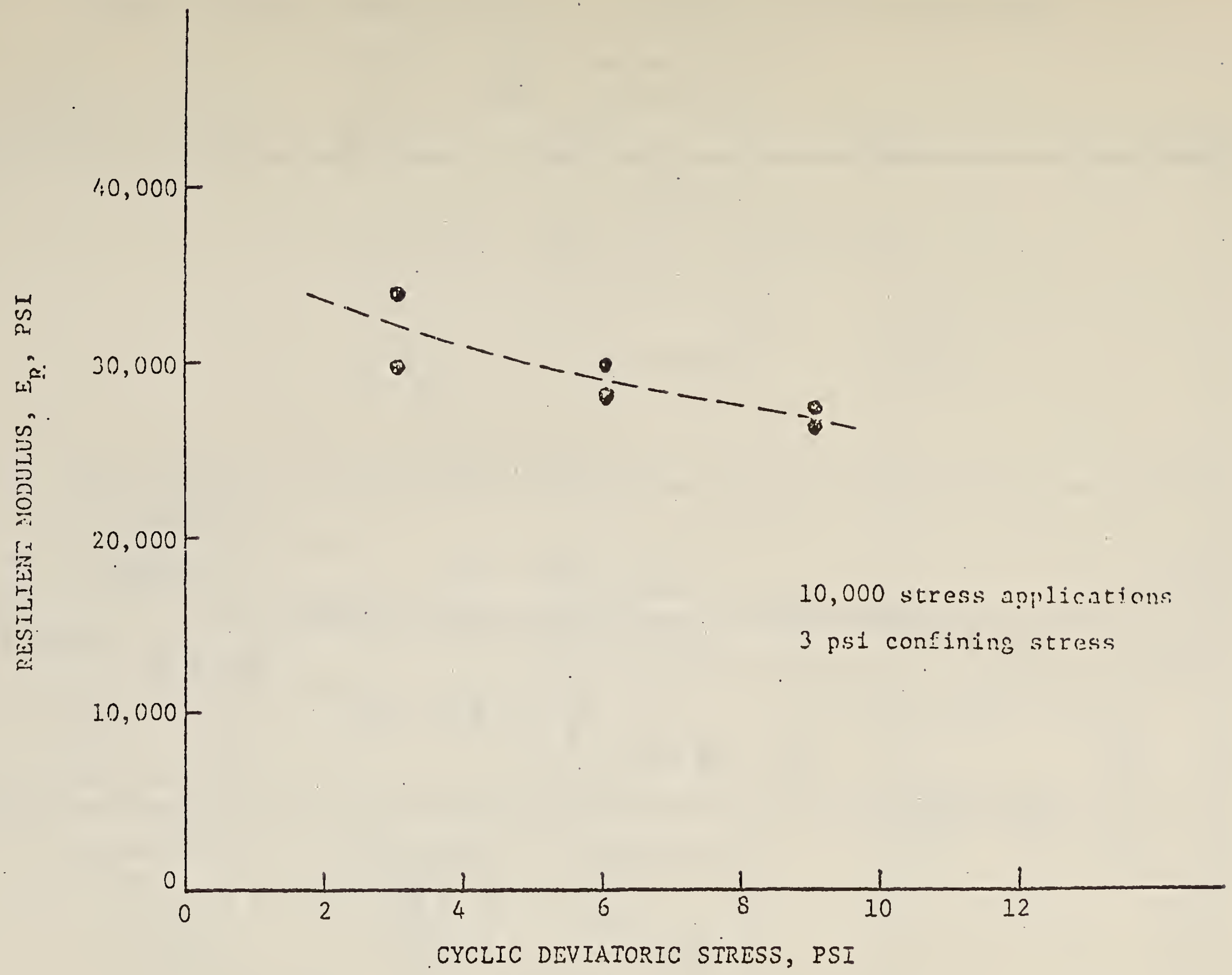


Figure C-4. Effect of Deviatoric Stress on the Resilient Modulus.

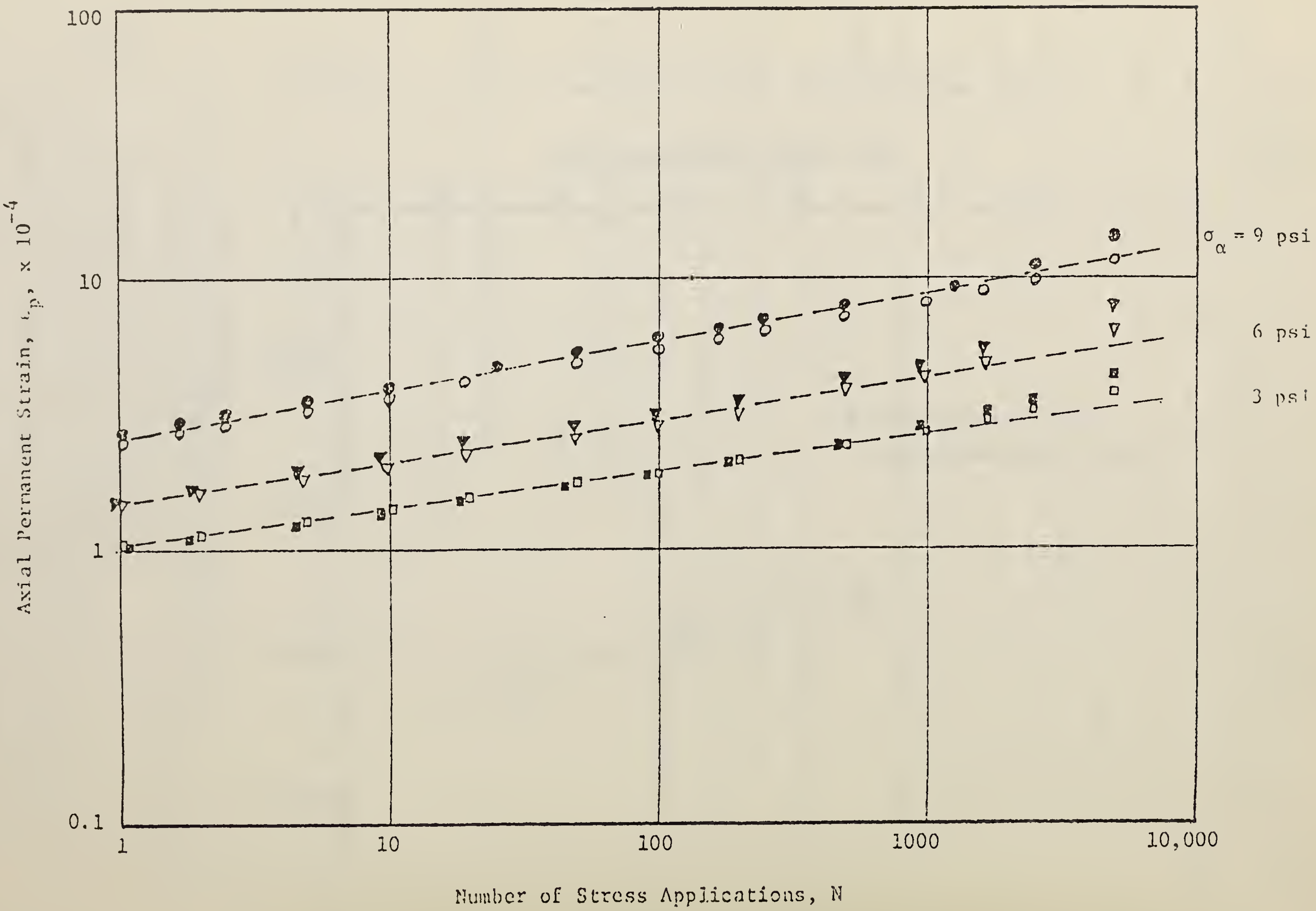
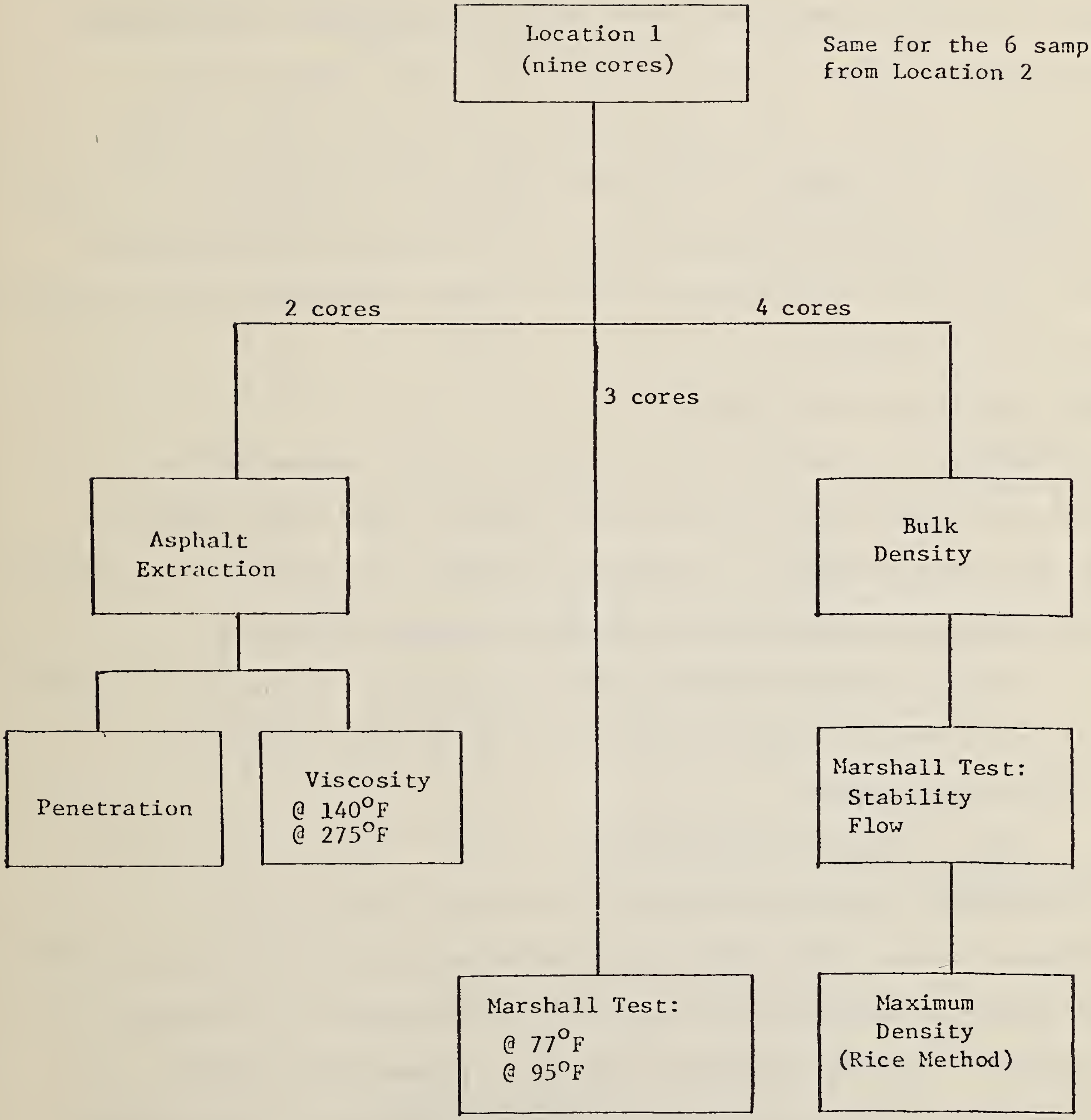


Figure C-5.Axial Permanent Strain vs. Number of Stress Applications.



Same for the 6 samples
from Location 2

Figure C-6. Test Program for Asphalt Concrete Cores.

method. After the stability and flow values were obtained from each sample, the sample was carefully separated when the sample was still soft. The asphalt concrete particles from all four samples were combined and thoroughly mixed. Using quartering method, about 2000 grams of sample was obtained. The maximum specific gravity of asphalt concrete was determined according to ASTM-D 2041 method. Results of the bulk density and the maximum specific gravity were used to determine the air void content of the asphalt concrete. Results from these tests are shown in Table C-3.

(B) Asphalt Extraction Tests

Extraction of asphalt from the asphalt concrete samples and the penetration and viscosity tests on the recovered asphalt were conducted by the Asphalt Institute. The results are shown in Table C-4.

(C) Determination of Resilient Modulus of the Asphalt Concrete

There are several approaches that can be used to estimate the resilient modulus of asphalt concrete from the 4 inches diameter by 2 inches high samples:

(C-1). Diametral Resilient Test.

This test method was developed by Schmidt * of the Chevron Research Company. The method uses a loading apparatus that is capable of applying a repeated load across the vertical diameter of a Marshall specimen. This pulsating load results in a corresponding pulsating deformation across the horizontal and vertical diameters of the specimen. The results of these horizontal and vertical pulsating deformations can be used to determine the resilient modulus of the asphalt concrete.

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* Schmidt, R. J., "A Practical Method for Measuring the Resilient Modulus of Asphalt Concrete Mixes", Highway Research Record Number 404, Highway Research Board, 1972.

Table C-3. Summary of the Test Results of Asphalt Concrete Samples.

Samples	Bulk Sp. Gravity	Stability	Flow	Max. Sp. Gravity	Remarks
Location 1					
1	2.12	550	13		
2	2.08	620	15		
3	-	-	-		A large crack in the sample
4	2.07	650	14		
Average	2.09	630	14	2.30	
Location 2					
1	2.11	570	12		
2	2.13	550	14		
3	2.13	510	14		
4	-	-	-		A large crack in the sample
Average	2.12	543	13	2.31	

$$\text{Air Void (\%)} = 100 - \frac{\text{Bulk Sp. Gravity}}{\text{Max. Sp. Gravity}} \times 100$$

Average air void for Location 1 = 9.1%

" " " for Location 2 = 8.2%

Table C-4. Summary of Extraction Test Data on Asphalt Concrete Cores (Averaged Values)

Asphalt Content, % = 6.10

Properties of Recovered Asphalt

Viscosity

140°F, poises	10098
275°F, CS	622

Penetration

(77°F, 5 sec., 100 gr.)

Table C-5. Estimation of Dynamic Modulus of Asphalt Concrete from Marshall Test.

	Marshall Tests		Dynamic Modulus 10^5 psi
	Stability (lb)	Flow (0.01 in.)	
Temp. = 77°F	4650	17	2.655
	5580	21	2.560
Ave.	5115	19	2.601
Temp. = 95°F	1150	15	0.538
	1400	17	0.589
Ave.	1275	16	0.564

(C-2). Stiffness According to Van der Poel Method

From both creep and dynamic tests, Van der Poel * developed data indicating that, in the case of mixtures containing dense-graded aggregates and asphalt cements and which were well compacted, the stiffness of a mixture is dependent on the stiffness of the asphalt which it contains and the volume concentration C_V, of the aggregates. The stiffness of asphalt cement can be estimated from the penetration and ring and ball softening point of the recovered asphalt.

(C-3). Dynamic Modulus from Marshall Test Results

Based on correlation studies between the dynamic modulus of asphalt concrete vs. each of the routine tests for the mechanical properties of asphalt concrete, a very good correlation was found by Shook and Kallas ** between the dynamic modulus and the Marshall stability-flow ratio. This relationship is:

$$\mathrm{Log}_{10}E = -0.124262 + 1.25469\ (K) - 0.0616215\ (V)$$

$$R^2 = 0.900$$

where E = dynamic modulus

K = Log_{10} (Marshall stability (lb)/100X Marshall Flow)

V = percent air voids for the modulus specimen minus percent air voids for the Marshall test specimen.

Considering the relative simplicity of the equation and the availability of Marshall test equipment, this method was used to determine the modulus of asphalt concrete. Thus, among six asphalt concrete cores remaining from the 18 cores taken from the bikepath, four cores were chosen and the Marshall tests were conducted on those cores, two at room temperature (about 77°F) and two at 95°F. The results as well as the corresponding dynamic modulus calculated based on the formulas given above are shown in Table C-5. In calculating E from the equation, V in the equation was assumed zero.

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* Van der Poel, C., "A general System Describing the Viscoelastic Properties of Bituminous and its Relation to Routine Test Data", J. App. Chem., May, 1954.

** Shook, J. F., and Kallas, B. F., "Factors Influencing Dynamic Modulus of Asphalt Concrete", Proceedings of the Association of Asphalt Paving Technologists, Vol. 38, 1969.

APPENDIX D

SOIL STABILIZATION FOR BIKEPATH PAVEMENTS

APPENDIX D

SOIL STABILIZATION FOR BIKEPATH PAVEMENTS

Soil stabilization using different stabilization agents will be discussed separately in the following.

Soil Stabilization Using Lime [21,25]

Lime

There are various types of lime commercially available. Calcitic Quicklime (C_a0) and Dolomitic Quicklime ($C_a0 + M_g0$) are produced by calcining Calcitic and Dolomitic Limestone respectively. There are three types of hydrated lime that can be produced by the controlled addition of water to quicklime: high calcium, $C_a(OH)_2$; Monohydrated Dolomitic, $C_a(OH)_2 + M_g0$; and Dihydrated Dolomitic, $C_a(OH)_2 + M_g(OH)_2$.

Waste lime, a by-product of various manufacturing processes, is often suitable for use in soil stabilization. There are two types available, (1) collected from the draft of the calcining process in lime production, and (2) the by-product of various manufacturing processes. The by-product limes are very economical; however, they are often non-uniform in quality and should be used with discretion.

Mechanisms of Stabilization

There are several reactions that take place when lime is added to a reactive soil (soils that develop significant strength increases with addition of lime). These reactions are referred to as lime-soil reactions and consist of the following:

1. Cation Exchange, Flocculation, and Agglomeration of the soil clay particles which result in reduced plasticity and increased workability or friability.
2. Carbonation of the lime by carbon dioxide which produces a very weak cementing agent.

3. Pozzolanic reaction between the soil particles and lime which results in the production of hydrated calcium silicate and aluminate cementing agents.

The addition of lime to the soil increases the PH to approximately 12.3 which increases the solubility of the silica and alumina thus aiding in the pozzolanic reaction.

Soils Amenable to Stabilization

To utilize soil stabilization successfully it becomes necessary to define the particular types of soils which can most readily be stabilized by the various stabilizing agents.

Soils are generally classified for engineering purposes by either the unified soil classification system (USCS) or the AASHTO Soil Classification System. Soils can also be classified utilizing the Pedological Soil Classification System.

Experience has indicated that lime will react with medium to fine grained soils [25]. Generally, soils classified by AASHTO as A-4, A-5, A-6, A-7, and some of the A-2-7 and A-2-6 are most amenable to lime stabilization. Soils classified as per the USCS Classification as CH, CL, MH, ML, SC, SM, GC, GM, SW-SC, SP-SC, SM-SC, GW, GC, GP, GC, and GM-GC (soils containing clay) can be considered potentially capable of lime stabilization.

Typical Lime Content Requirements

When considering typical content requirements of stabilizers it becomes necessary to point out that the values mentioned in this report are only rough estimates. The quantity of stabilizer needed for satisfactory results should be determined by laboratory studies. Mixture design criteria is outlined in the handbook.

As a rough guide, 2-4%, 5-10% and 3-8% of lime are needed for clayey gravels, silty clays and clays respectively.

Typical Properties of Lime Stabilized Materials

In general, when lime is mixed with fine-grained soils, they exhibit improved plasticity, workability, volume change characteristics, and increased strength. The properties of lime-soil mixtures depend on numerous variables, the most important being soil type, lime type, lime percentage, and curing conditions including time, temperature and moisture.

Compressive strength has traditionally been the most popular method of determining the relative quality of stabilized materials. In general, as the quality of the lime-soil mixture increases, the compressive strength increases. The two most common procedures used to determine the compressive strength are:

(1) Unconfined compression strength after 27 days curing at 70°F and 90-100 percent relative humidity, plus 24 hours of water immersion prior to testing, and

(2) Unconfined compression test after accelerated curing of 7 days at 140°F.

Typical compressive strength of 200 - 500 psi can be obtained.

Factors Affecting Properties of Stabilized Materials

The quantity of lime used affects both strength and durability and is dependent upon (1) the amount of clay and silt present, (2) the quality of the lime. Generally as the clay and silt content increase, so does the lime content.

The moisture content generally preferred is that which produces the maximum density with a particular compactive effort. Generally, the moisture content that produces maximum density usually produces maximum strength.

The type and quality of processing (pulverizing) also affects the resulting properties of lime stabilized materials. In general, as the uniformity of the mixture increases, so do the strength and durability of the mixture.

The degree of compaction obtained is one of the most important factors in the stabilizing process. In general, as the density is increased, the strength and durability also increase.

Proper curing is extremely important in the development of strength and durability. The most important aspects of the curing process are curing time, temperature, and moisture regime. In general, higher curing temperatures and longer curing periods result in higher strengths. At temperatures below 40^{o} - 50^{o}F, strength development ceases. Optimum compaction moisture will provide sufficient moisture for the pozzolanic reaction. However, during the curing process it becomes necessary to reduce evaporation by sealing the surface with liquid bituminous material, plastic, or some suitable means.

Construction Constraints

1. Climatological - Use only when ground temperature is 50^{o}F and rising (strength gain not rapid in low temp.). Also if numerous freeze-thaw cycles are expected, construct when temperature is such that sufficient durability will be gained to resist freeze-thaw cycles.
2. Construction - Do not traffic with vehicles having gross loads > 5000# for 10-14 days after construction.
3. Site Limitations - Areas where obstructions (culverts, large tree roots, pipes, buried cables) may be encountered. Rotary pulverization not recommended.

Construction Factors

An overall simplifying approach to construction may be summarized as follows:

A. Initial Site Preparation
   1. Shape the designated area to the desired crown and grade.
   2. Scarify, pulverize, and prewet soil as needed.
   3. Reshape crown and grade.

B. Processing
   1. Spread stabilizer (field mix method)
   2. Add water as needed
   3. Mix
   4. Compact
   5. Finish
   6. Cure as required

Essentially all the stabilizers mentioned in this chapter using other stabilizing agents are constructed in much the same way and thus follow the above simplified procedure.

In the site preparation portion of the field construction process it is imperative that all organic material and vegetation be removed. The exposed surface must then be pulverized. This can be accomplished by utilizing motor patrols, rotary mixers (pulverizers), discs, harrows, or other suitable scarifying and pulverizing equipment. This is an important step in the success of the stabilized materials and should not be slighted.

Processing and placement of the stabilized mixture can be accomplished by field mixing (inplace) or central batch plant processing operations.

The type of process used is usually based on economics and/or the engineers discretion. Both methods will produce satisfactory results when used correctly.

The inplace stabilization equipment can be classified into several groups with certain features common to each. These are briefly: 1) windrow-type traveling plants, 2) flat-type traveling plants, 3) multiple-pass rotary mixers, and 4) others. Various construction equipment manufacturers can provide details on such equipment.

Distribution equipment (spreaders) especially designed for certain stabilizers are available for bulk distribution. In the cases of lime and cement manual labor can be used to spread the stabilizer if desired.

Compaction can be applied by a number of methods:

1. Sheeps foot rollers used until the feet walk out of the soil with final compaction applied by rubber tired rollers. (Primarily for fine-grained soils).
2. Utilize rubber tired rollers exclusively.

If the central mix plant operation is chosen the field mixing operation is eliminated. In this instance placement or distribution of the mixture becomes important. Placement should be accomplished with placer-spreader-trimmer. Tailgate dumping and grader spreading should be eliminated since they reduce mix uniformity and moisture content.

Common to both central mix and inplace stabilization is the need for a good curing environment, thus sealing the surface to prevent evaporation is vital.

Soil Stabilization Using Portland Cement

Portland Cement [22]

There are various types of portland cement available for commercial use. Of these, Types I and II portland cement are most commonly used in soil stabilization.

Mechanisms of Stabilization

The stabilizing effect due to the addition of cements to the soil is primarily due to cement hydration. The hydration effect results in the formation of calcium aluminate and silicate bonding agents, and the production of free-lime. Cation exchange and flocculation reactions also occur with the fine grained soil fraction.

Soils for Cement Stabilization

Essentially all soils are amenable to cement stabilization. However, the fine grained soils (cohesive) are not usually stabilized with cement due to the difficulties in pulverization and mixing associated with field construction. The well-graded granular materials provide the best results in cement stabilization.

Typical Cement Content Requirements

The Portland Cement Association has performed numerous tests to determine an estimate of cement contents for various soils. Their results are published in the Soil-Cement Laboratory Handbook[22].

Typical Properties

The influence of cement on plasticity is quite significant. Cement has its greatest affect at low cement contents. The cation exchange and flocculation that result from the addition of cement, cause an increase in the plastic limit, thus decreasing the plasticity index.

Strength and durability of cement-treated soils are determined much the same as lime-treated soils. It has been found that the most severe deterioration forces are those resulting from wetting and drying and/or freezing and thawing. Typical values of unconfined compressive strength for durable mixes of various soils range from 200 to 1000 psi.

Drying shrinkage of soil-cement is often considered a drawback. This shrinkage is due to loss of moisture from evaporation and cement hydration. Fine-grained (clayey) soils generally exhibit higher shrinkage than do granular soils. The granular soils, however, usually have wider and less frequently occurring cracks.

Factors Affecting Properties of Stabilized Materials

Various soil properties influence the engineering properties of cement stabilized materials. Some of the major factors are:

(1) Plasticity and clay content

(2) Gradation

(3) Organic matter, and

(4) Soil pH

Pulverization, mixing and the amount and type of cement also affect the engineering properties of cement-treated materials.

Uniformity in mixing is essential. Generally, an increase in uniformity usually results in an increase in strength and durability.

Generally, as the relative proportion of cement in a mix increases, the plasticity index, volume-change characteristics, and frost susceptibility characteristics decrease while the elastic, strength and durability properties increase.

The moisture-density relations of a cement-treated soil also affect the end results. Optimum moisture content provides sufficient moisture for hydration. Variations from optimum affect results adversely. Generally, maximum compressive strengths occur at optimum moisture. Increased density results in increased strength and a reduction in shrinkage characteristics.

Similar to lime-treated soils, cement-treated soils require proper curing. Retention of compaction moisture is essential, and thus, it becomes imperative to seal the compacted material to prevent evaporation.

Construction Constraints

1. Climatological - Do not place unless temperature is $50^{\circ}F$ and rising; if numerous freeze-thaw cycles expected, construct when temperature is such that sufficient durability will be gained to resist freeze-thaw cycles. Do not use when excess rainfall liable to prevent compaction within 2 hours after spreading and mixing.
2. Construction - Do not traffic during initial curing period; only light vehicular loads allowed during first 28 days.
3. Site Limitations - Same as for lime.

Construction Factors

Same as that of lime stabilization discussed in Section 1.

Soil Stabilization Using Lime-Flyash [24,26]

Lime and Flyash

The properties of the lime are the same as those for Section 1.

The flyash is a by-product material of burning powdered coal. The major source of flyash is from coal powdered steam generated electric power plants. The flyash is collected from the flue gases by either mechanical or electrostatic precipitators. The color of flyash is usually black to gray depending on the amount of carbon present. The quantity of unburned carbon present depends on the efficiency of the precipitators, but should be less than 10 percent for a good quality flyash.

Mechanisms of Stabilization

In general, there are two groups of reactions that take place when lime and flyash are added to a soil.

One group of reactions is caused by the reaction of the soil with the lime. The second group of reactions is caused by the reaction of the lime with the flyash. This is a complex mechanism and basically achieves stabilization through the formation of hydrated calcium silicates and aluminates. As with lime-soil mixtures, the cementing agents are formed due to the solubility of the silica and alumina in the flyash with the increase in PH caused by the addition of the lime.

Soils for Lime-Flyash Stabilization

Generally, the more granular materials such as sands, gravels, crushed stones, and slag are best suited for lime-flyash stabilization. Soil classification of suitable soils would include: (AASHTO) A-1, A-2 and A-3 (USCS) GW, GP, GM, GC, SW, SP, SM. Certain A-4, A-5, A-6 and A-7 soils can also be stabilized using lime-flyash.

Typical Lime-Flyash Content Requirements

Both lime and flyash contents will influence the properties of the final mix. The quantities of lime and flyash necessary must be determined in the laboratory. Mixtures have been prepared with lime contents as low as 2 percent and as high as 8 percent. Flyash contents have varied from 8 to 36 percent. Typical proportions are 2-1/2 to 4 percent lime and 10 to 15 percent flyash.

Typical Properties

In general, compressive strength and durability are considered the chief properties of lime-flyash stabilized soils. These properties are examined similarly to those of lime-treated soils.

Factors Affecting Properties of Stabilized Materials

Laboratory testing may indicate that effectiveness of the lime used, but it is important to realize that the quality of the flyash has a much greater affect on the pozzolanic reaction than does the lime. As mentioned previously, flyash is a by-product material, and thus the quality of the flyash can be quite variable. ASTM C593-66T provides a procedure that deals with the requirements of quality flyash for nonplastic mixtures.

The quality of the stabilized produce is also dependent on the type of material being stabilized. Stabilization of plastic fine-grained soils with lime-flyash is seldom used due to difficulty in proportioning the lime and flyash with these soils. Best results are obtained on well-graded aggregates.

The quantity of lime affects the strength and durability of the produce and is dependent on (1) the amount of clay and silt present, (2) the total quantity and quality of the flyash, and (3) as mentioned previously, the quality of the lime. Generally, as the clay and silt content increases, so does the lime content. Also, as the quantity and quality of the flyash increases, the quantity of lime required increases.

The ratio of lime to flyash affects strength and durability also. In general, there is an optimum lime-flyash ratio that will result in economical savings and required strength.

The total amount of lime and flyash also influences the strength and durability of the product. In general, the compressive strength increases as the total amount of lime and flyash increases.

The most desirable moisture content is that which produced maximum density under a certain compactive effort. This moisture is usually sufficient to produce a good pozzolanic reaction resulting in maximum strength.

The decrease of compaction is extremely influential on the strength and durability of the stabilized material. As the density of the material is increased, the strength and durability increase.

Proper curing is important in the development of the strength and durability of the stabilized material. Curing time, temperature, and moisture are probably the most important variables. In general, higher curing temperatures and longer curing periods result in higher strength and durability. At temperatures below 40° - 50°F, strength development ceases.

Construction Constraints and Construction Factors

Same as lime stabilization discussed in Section 1, except compaction is done by the use of rubber tired rollers or vibratory steel wheel on vibratory rubber tired rollers.

Soil Stabilization Using Asphalt [23].

Asphalt

The common types of bituminous materials considered in bituminous stabilization are: asphalt cements, cutback asphalts, and emulsions. Generally, asphalt cements are used for higher type pavement construction, and cutback liquid asphalts and emulsions are used for bituminous stabilizing agents. For details concerning the characteristics of asphalt cements, cutback asphalts, and emulsions refer to reference [23].

Mechanisms of Stabilization

The mechanisms involved in bituminous stabilization are primarily mechanical. Basically bituminous materials provide stability through cementing and/or waterproofing characteristics.

Soils for Bituminous Stabilization

The most desirable materials for bituminous stabilization are well-graded crushed stones, gravels, and sands with non-plastic to slightly plastic fines. The fine-grained cohesive soils are generally not used in bituminous stabilization mainly because of the inability to properly pulverize, mix, and compact these mixtures.

General Atterberg Limits for suitable soils require the plasticity index to be less than 12-15. Thus, in general, only A-1-a, A-1-b, A-2-4, A-2-6, A-3 (in some cases fines must be added) A-4 soils and possibly A-6 soils are suitable for bituminous stabilization.

Typical Asphalt Content Requirements

The selection of a bituminous type depends on many variables, such as: climate, temperature, gradation, amount of fines, desired engineering properties of the mixture, and construction equipment.

In general, the bitumen requirement is that amount which yields suitable strength, durability and economy, which can only be determined by appropriate testing and design procedures.

Typical bitumen contents range from 4-10%.

Typical Properties

Again, strength and durability are considered to be of prime importance in bituminous stabilized materials. The strength can be determined by a number of methods, such as:

1. Marshall stability (granular materials)
2. CBR
3. Unconfined Compressive Strength (fine-grained soils)
4. Hveem Stability
5. Hubrard-Field Stability
6. Extrusion Value
7. Standard and Modified Florida Bearing
8. Iowa Bearing Value

Factors Affecting Properties of Stabilized Materials

There are numerous factors that affect the strength and durability of bituminous stabilized materials. This subsection will present only the most important factors.

For coarse textured soils and aggregates, gradation is an important factor. As gradation is improved, the contact area between particles increases, thus leading to a higher frictional resistance and higher strength. Another important property of coarse aggregates is the affinity for bitumen. The mixture must have a higher affinity for bitumen than water or else stripping will occur resulting in loss of strength.

Fine-grained soils exhibit some important properties that affect the stabilization process. They are: clay content, plasticity and volume change characteristics. High clay content and volume change soils typically result in poor waterproof mixtures due to the inability of the bitumen to coat the soil particles and also the inability to pulverize the soil creates a non-homogeneous mixture.

The filler content (fines) can be a very influential factor. Filler content is defined as that material which passes the No. 40 sieve and affects the total surface area, the strength and the final compacted air void content of the mixture. Generally, the more angular the filler material, the higher the strength.

The type and amount of bituminous material used as a stabilizing agent can affect the final engineering properties of the material. When selecting the bituminous material, three characteristics should be considered: (1) workability, (2) curing characteristics, and (3) the nature of the residue.

The workability and curing characteristics of the bituminous material also affect the properties of the stabilized mixture. A primary requirement of the bituminous-treated soil is that it remain workable until proper mixing, placing and compaction is completed. If it does not, the following effects may result: (1) poor distribution of bitumen, (2) inadequate coating of the bitumen, (3) high air void content and permeability, (4) low density, (5) low stability, and (6) reduced water proofing.

Generally, for increased construction manipulation time, a lower grade cutback with a low volaticity solvent or an emulsion with a slow setting time should be used.

Construction Constraints

1. Climatological
    - a. Asphalt Cements - For thin lifts, temperature should be 33°F and rising; temperature usually not important for thick lifts.
    - b. Cutbacks and Emulsions - Temperature should be 33°F and rising.
    - c. Bituminous material should completely coat mineral matter before rainfall stops construction.
2. Site Limitations - Same as for lime.

Compaction is accomplished by means of rubber tired rollers and vibratory rollers.

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