2002-17REV

Final Report

BEST PRACTICES FOR THE DESIGN AND CONSTRUCTION OF LOW VOLUME ROADS

REVISED

Research

Technical Report Documentation Page

1. Report No.	2.	3. Recipients Accession No.
MN/RC –2002-17REV		

4. Title and Subtitle	5. Report Date
BEST PRACTICES FOR THE DESIGN AND CONSTRUCTION OF LOW VOLUME ROADS REVISED	November 2003
	6.
7. Author(s)	8. Performing Organization Report No.
Eugene L. Skok, David H. Timm, Marcus L. Brown, Timothy R. Clyne and Eddie Johnson	
9. Performing Organization Name and Address	10. Project/Task/Work Unit No.
Department of Civil Engineering University of Minnesota 500 Pillsbury Drive SE Minneapolis, MN 55455	11. Contract (C) or Grant (G) No. (c) 74708 (wo) 123
12. Sponsoring Organization Name and Address	13. Type of Report and Period Covered
Minnesota Department of Transportation Research Services Section 395 John Ireland Boulevard Mail Stop 330 St. Paul, Minnesota 55155	Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

http://www.lrrb.org/PDF/200217REV.pdf This is a revised manual.

16. Abstract (Limit: 200 words)

This report presents information about the use of the mechanistic-empirical procedure (MnPAVE) in designing hot-mix asphalt pavements in Minnesota. Researchers developed the MnPAVE software program using information from the Minnesota Road Research Project (Mn/ROAD) test facility and from 40-year-old test sections around Minnesota. MnPAVE procedures use Equivalent Standard Axle Loads (ESALs) to evaluate traffic loading, and the report includes methods to estimate these values for design purposes over a 20-year design life, as well as a procedure to measure vehicle type distributions. In addition, the report presents an evaluation of subgrade soils for each thickness design procedure, summarizes Minnesota Department of Transportation specifications that relate to embankment soil construction and to construction of the pavement section materials, and recommends specific density or quality compaction using a control strip. It also includes best practices on setting up projects most effectively to follow specifications.

17. Document Analysis/Descriptors		18.Availability Statement
Mechanistic-Empirical Soil Factor Pavement Section Construction Specifications R-Value ESAL's	Resilient Modulus Subgrade Soil Granular Equivalent Flexible Pavement Thickness Design	No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161

19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	241	

BEST PRACTICES FOR THE DESIGN AND CONSTRUCTION OF LOW VOLUME ROADS-REVISED

Final Report

Prepared by:

Eugene L. Skok
Timothy R. Clyne
Eddie Johnson
David H. Timm
Marcus L. Brown

University of Minnesota
Department of Civil Engineering

November 2003

Published by:

Minnesota Department of Transportation
Research Services Section
MS 330
395 John Ireland Boulevard
St. Paul, MN 55155

TABLE OF CONTENTS

Chapter 2 THICKNESS DESIGN PROCEDURES

Chapter 3 TRAFFIC PREDICTIONS

Chapter 4 SUBGRADE (EMBANKMENT) SOIL DESIGN AND CONSTRUCTION

Chapter 5 PAVEMENT SECTION MATERIALS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION AND SUMMARY

1.1. Introduction

This manual has been developed to present methods of design and construction of Hot Mix Asphalt (HMA) pavements in Minnesota. Mn/DOT and the flexible pavement industry are now in a time of transition for thickness design and construction procedures. The MnPAVE thickness design procedure is a mechanistic-empirical computer software program that takes into account many variables that could not be considered previously. The MnPAVE procedure is based on work done at the University of Minnesota using an elastic layered system WESLEA developed at the Corps of Engineers (1). The University program called ROADENT used performance prediction equations for fatigue and subgrade rutting based on material properties and performance of test sections at MnROAD (2). This analysis with some updates has been used to develop MnPAVE. The performance of some 40-year old test sections has been used to check the performance prediction equations used in MnPAVE. Appendix A of this report is the report presenting the results of these comparisons. A big advantage of using a mechanistic-empirical design procedure is that the properties of various materials can be entered into the software to check what thicknesses would be predicted to perform well.

Chapter 2 reviews the three HMA thickness design procedures currently used in Minnesota – the Soil Factor, Stabilometer R-Value and MnPAVE methods. A survey of the city and county engineers in Minnesota indicated that both the Soil Factor and R-Value are being used throughout the state (3). About two-thirds of the counties use the soil factor and about two-thirds of the cities use the R-Value.

The Soil Factor Design Procedure is presented in the Mn/DOT State Aid Manual (4). The R-Value method is presented in the Mn/DOT Geotechnical and Pavement Design Manual (5). The MnPAVE software Beta Version 5.009 is now available. The draft of a MnPAVE Operating Manual gives instructions on how to set up and run the software (6). Each of the three design procedures is presented and summarized in Chapter 2.

The loading on a pavement, the traffic, is discussed for each of the three design procedures in Chapter 3. The two-way Annual Average Daily Traffic (AADT) and Heavy Commercial Daily Traffic (HCADT) predicted for the design year (usually 20 years in the future) are used for the Soil Factor Method. The R-Value and MnPAVE Procedures use Equivalent Single Axle Loads (ESALs) to predict the traffic effect. The ESAL concept equates the effect of these various weight and configurations of axle loads to the effect of an 80-kN (18,000-lb) single axle load. Eventually, the MnPAVE procedure will use the Load Spectra concept to evaluate traffic. Load Spectra gives a distribution of axle loads and types predicted to use that road over the design period (6).

The subgrade and embankment evaluation procedures for the three design procedures are presented in Chapter 4. These are the Soil Factor, R-Value and Resilient Modulus (M_r) determined for the soils to be used for a given project. The Soil Factor is based on the AASHTO Soil Classification and the R-Value can be measured in the laboratory or estimated from the soil classification. The Resilient Modulus can be estimated from either the R-Value or soil classification using relationships developed by Siekmeier and Davich (7). The resilient modulus of the soil can be varied throughout the year using variations at MnROAD defined by Ovik, et al using MnROAD soil stiffness variabilities measured (8). This work resulted in the definition of five (5) seasons for a given year in Minnesota. These are early spring, spring, summer, fall and winter.

The strength (stiffness) and variability of a given subgrade soil are very dependent on the construction procedures used for selecting, mixing, placing and compacting the soils. The procedures start with a good survey of what soils exist at the construction site and knowledge of how these materials will react under construction, environment and loading conditions. The construction procedures start with a good set of specifications. Mn/DOT Specifications 2105, 2111 and 2123 from the 2000 Mn/DOT Specifications for Construction book are recommended for the construction of subgrades in Minnesota (9). These specifications are summarized in Chapter 4.

Methods for carrying out the specifications from the Mn/DOT Grading and Base Manual (10) and the Geotechnical and Pavement Design Manual (5) are summarized.

General Design Considerations and notes from the Inspector’s Job Guide for Construction (11) published by the Office of Construction, Technical Certification Section is also presented to help show what procedures and documentation are recommended to result in successful construction of a subgrade. Various methods of subgrade enhancement are presented in Section 4.5.; Enhancement of in-place soils using proper design of drainage and good compaction, modification using lime, bituminous materials and chlorides, stabilization using fly ash., and use of geosynthetics for separation and reinforcement. General design considerations along with factors affecting of geosynthetic lifespan are also presented.

Substitution using various higher quality granular and lightweight materials is presented in Section 4.5.6. The granular materials are Select Granular and Breaker Run Limestone. Design and construction procedures along with specifications are presented. Design and construction of lightweight fills using Wood Chips, Shredded Tires and Geofoam are also covered.

Summaries using each of the materials and procedures are presented for design and construction control. Specifications for materials and procedures to use in Minnesota along with contacts for further information are presented.

Based on a review of the literature, questionnaires and interviews with Mn/DOT and county engineers and review of specific projects recommendations are made for when and how the various procedures should be used. The parameters used for the recommendations are "Grade above Water Table" and "Moisture Conditions". There are essentially no conditions recommended for soil enhancement for granular soils. Methods of Modification, Stabilization, Separation and Reinforcement are recommended for various conditions in the tables.

Table 4.17 lists the conditions including "Thickness of Peat" for which the various lightweight fills are recommended.

A database has been developed to document installations using the procedures listed. Projects were located during visits to the cities and counties during the summer, 2002. Sixty five projects have been identified. It recommended that the projects identified be reviewed about every three years and the location and parameters for additional projects be added to the database. In this way actual performance of the various methods of subgrade enhancement can be documented.

A subsequent study will look at the various methods of modification, stabilization and reinforcement as they can be used with the MnPAVE mechanistic-empirical design procedure.

The methods of evaluating the various layers of a pavement section are presented in Chapter 5. The materials discussed are Select Granular, Granular Subbases and Bases, Salvaged/Recycled Aggregates and Hot-Mix Asphalt Mixtures. The specifications used to define and construct these materials are MnDOT 3149, 3138, 2360/2350 respectively (9). The design parameters, which are recommended for each of the materials for each thickness design procedure, are presented.

Field control procedures needed to meet the specifications are also presented in Chapter 5.

The Inspector's Job Guide for Construction (11) sections for base and HMA construction are summarized to present items that will help field personnel to give them checklists to properly construct the pavement layers. Again, in order to realize the performance predicted by the respective design procedures both in terms of strength (stiffness) and durability the specifications must be followed carefully.

The remainder of Chapter 1 is a summary of Chapters 2, 3, 4, and 5. The chapters cover the following items: Chapter 2, the three design procedures, Chapter 3, the Traffic Factors definitions and determination, Chapter 4, Subgrade Design and Construction, and Chapter 5, Pavement Layer Design and Construction.

1.2. Minnesota Thickness Design

1.2.1. Soil Factor Design Procedure

The Soil Factor Design is shown in Figure 2.1. It is published in the MnDOT State Aid Manual (4). The chart uses seven categories of traffic based on the projected 20-year two-way Annual Average Daily Traffic (AADT) and Heavy Commercial Daily Traffic (HCADT). The procedures for predicting AADT and HCADT are presented in Sections 3.2 and 3.3. General flow maps are available for the entire state; however, it is recommended that a District Traffic Engineer or the Office of Transportation Data and Analysis be contacted to make the 20-year design predictions. These values will be dependent on future development planned for the area.

The soil is defined using the soil factor, which is dependent on the AASHTO Classification of the material represented on the particular project. Section 4.2 reviews methods for determining the appropriate soil that represents the embankment conditions on the project. The soil classification system is presented in Section 4.3.2.1. and the relationship between the soil class and soil factor is given in Section 4.3.4.2.

The thickness for the Soil Factor design is given in terms of the Granular Equivalent defined in Section 5.3.2.2. Granular Equivalency factors are assigned to materials based on the specification that they pass. For instance a Specification 3139 class 5 or 6 material has an equivalency factor of 1.0. A Class 4 material has a factor of 0.75 because it has a less restrictive gradation band. The relevant specifications for the other pavement materials are listed in Figure 2.1. Minimum bituminous and total granular equivalent are also shown for each traffic category. The thicknesses shown in Figure 2.1 represent a reduction in subbase thickness for granular type soils (soil factor less than 100%) and an increase in thickness for soil factors greater than 100% (heavy clay and some silty soils).

The soil factor recommended thicknesses have changed somewhat throughout the years because of changes in traffic levels and construction procedures.

The construction specifications and procedures presented in Chapters 4 and 5 for the soil and pavement section materials respectively must be followed to realize the design life predicted by the design procedures.

1.2.2. R-Value Procedure

Figure 2.2 is the R-Value design chart currently used by MnDOT for design of HMA pavement sections. The chart is in Reference 5. The embankment soil R-Value is determined by a standard laboratory test procedure that is run in the MnDOT Maplewood Laboratory. The procedure is outlined and discussed in Section 4.3.2.2.

The R-Value can also be predicted from the AASHTO Classification of the soil as shown in Table 4.5, which is in Section 4.3.4.3.

The traffic for the R-Value procedure is defined in terms of Equivalent 80-kN (18,000-lb) axle loads (ESALs). ESALs represent the effect of various axle loads and configurations on the performance of a pavement. Methods for estimating ESALs for a given location are presented in Section 3.4. ESALs are calculated from the total traffic predicted in a design lane (Section 3.4.1), the vehicle type distribution (Section 3.4.2.) and the average effect of each vehicle type in terms of ESALs per passage of that vehicle (Section 3.4.3.). Methods of taking into account predicted growth are given in Section 3.4.4. A spreadsheet to make the calculations is presented in Section 3.4.6.

The thickness for the R-Value procedure is given in terms of Granular Equivalent thickness using the same concepts as for the Soil Factor Design. The G.E. factors are listed in Section 5.3.2.2.

The three thicknesses obtained from Figure 2.2 are the total G.E., the bituminous plus base thickness G.E. and the minimum bituminous G.E.

An alternate R-Value Design in terms of full depth HMA is presented in Figure 5-3.7 of Reference 5. MnDOT no longer uses this "full depth" design chart unless a 1-m (30-in.) layer of select granular material is used under the surface layer. Some cities and counties use full depth design where there is limited vertical clearance or there is a severe aggregate shortage. If this procedure is used for design it is very important that the subgrade be compacted well and uniformly to adequately support construction equipment and the design traffic for the pavement.

1.2.3. MnPAVE Procedure

The Beta Version 5.009 of MnPAVE is now available (6). MnPAVE is a mechanistic-empirical based procedure, which uses relationships from MnROAD to predict the performance of a pavement. Elastic layer theory is used to calculate the critical strains in the system, which are correlated with fatigue cracking and development of rutting. In order to calculate strains, the resilient modulus of each layer including the subgrade must be determined and used along with the thicknesses of the pavement layers. The design then involves the determination of the thickness required to keep the strain low enough to withstand the calculated repetitions.

MnPAVE is set up so that the year can be divided into five seasons defined in Section 2.4.4.2. These can be adjusted for special situations. This makes MnPAVE much more versatile than the others.

Currently, MnPAVE uses ESALs as input for traffic. The ESALs are calculated using the procedure presented in Section 3.4 just as for the R-Value procedure. For the mechanistic calculations the traffic is defined using Load Spectra, which represents the distribution of loads on various axle configurations.

The subgrade is defined using the Resilient Modulus (M_r) as it is predicted to vary throughout the year. The resilient modulus can be determined in the laboratory with a repeated load triaxial test using the test conditions given in Section 4.3.2.3. However, laboratory triaxial testing has only been performed on a limited number Minnesota soils. The correlations given in Table 4.5 should be used to estimate the resilient modulus either from the R-Value or the AASHTO Classification. These correlations result in five moduli representing the five seasons defined at MnROAD.

The resilient moduli of the pavement layers are determined based on the specifications that the granular material or mixture passes. The moduli listed in Table 5.2 in Section 5.3.3. were measured from in-place testing at MnROAD. The high values for each layer in the winter represent frozen conditions and the other moduli represent the variations measured with the Falling Weight Deflectometer (FWD).

Section 2.4 summarizes the draft of an operating manual being developed for MnPAVE (6). The manual includes the Setup, Startup, Input and Output for the software. The results will give the operator the predicted life based on the design parameters assumed for a given pavement.

1.2.4. Procedure(s) to Use in 2001-03?

The three design procedures available in Minnesota have been summarized in Chapter 2. More complete descriptions of Soil Factor and R-Value procedures are given in References 4 and 5 respectively. These procedures have been used around Minnesota for the past 25 plus years on roads with all levels of traffic. The MnPAVE software is now being developed (6). The MnPAVE program makes it possible to account for many factors that could not be directly considered previously. The potential for improved design with MnPAVE is very great. However, it needs to be used for various design situations to develop confidence in the performance prediction equations. Designs with different types of materials such as stabilized or reinforced subgrades or bases should be tried to see what is predicted from MnPAVE compared to performance observed in the field. When new procedures or materials are used the resulting pavement section should be simulated with the MnPAVE model.

It is recommended that if a pavement is being designed with either the Soil Factor or R-Value procedures that a corresponding design be done with MnPAVE. A comparison between the two designs should be made. We ask that the Minnesota Road and Research Section be informed of the results of these comparisons. A form summarizing the comparisons of the designs should be completed so that the experience with MnPAVE relative to the current designs can be documented.

MnPAVE is very versatile and will become more useful as more people gain experience with it. Also, in the next year (we hope) the 2002 AASHTO Design Guide will be available. This program will need calibration for each state. As the engineers in Minnesota gain experience with MnPAVE they will be able to calibrate AASHTO 2002 to Minnesota climate, materials and traffic conditions effectively.

1.3. Traffic Estimates

The methods recommended for estimating traffic for the three design procedures have been summarized in Section 1.2. Chapter 3 presents the procedures, tables, procedures, and software available to make the estimates.

The Soil Factor Design requires an estimate of AADT and HCADT predicted for 20 years into the future, or whatever the design life is for the given roadway. To estimate current and future HCADT it is necessary to know the vehicle type distribution. The distribution can be estimated from a state HCADT map or measured on specific roadways using the procedure presented in Section 3.4.2.b. For many relatively low volume roads the value from the statewide map may be appropriate; however, in any special situations such as access routes for agriculture or manufacturing, a better estimate can be made using the field measurement procedure.

The R-Value and MnPAVE procedures currently use ESALs for traffic load evaluation. ESAL estimates require an estimate of AADT, vehicle type distribution, ESAL factors (the average effect of a given type of vehicle in terms of ESALs), a calculation or estimate of growth, and design lane distribution. Methods for predicting these factors and using them for predicting ESALs over the design life are presented in Section 3.4.

The MnPAVE design procedure uses the concept of Load Spectra to predict the life of a given pavement section. Load Spectra is a prediction is a measure of the load distribution within each axle configuration. The Load Spectra will be used for mechanistic design for the 2002 AASHTO Design Guide (12). MnDOT is working on procedures to help predict load spectra on Minnesota roadways.

1.4. Subgrade (Embankment) Soil

1.4.1. Background

The subgrade or embankment soil on which a pavement is built is the most important part of the pavement structure because:

- It is the layer on which the remainder of the structure is supported and helps resist the destructive effects of traffic and weather.
- It acts as a construction platform for building subsequent pavement layers.
- If there are embankment performance problems due to lack of strength or uniformity, the entire pavement section will have to be removed and replaced to correct the problem(s).

It is, therefore, imperative that the embankment be built as strong, durable and uniform and also economically as possible. The most economical embankment is one that will perform well for many years.

In Chapter 4 methods are presented to help achieve adequate STIFFNESS, STRENGTH and UNIFORMITY for a given embankment soil. This starts with a good soil survey at the location so that proper design and construction procedures can be designed into the project. Section 4.2, which is a summary of a more complete procedure for conducting a soil survey in Reference 5, presents some criteria for how to conduct a survey at a given location.

Section 4.3 presents the design factors used to evaluate the soil on a project to determine the appropriate thickness design for the three Minnesota procedures. These procedures have also been summarized in Section 1.2. Section 4.3.3. presents the Falling Weight Deflectometer (FWD) and Dynamic Cone Penetrometer (DCP) as methods to determine the stiffness or strength of the soils, subbase and base materials in place. The advantage of using field measurements is that the variability of the in-place materials can be determined. Variability will eventually be an input for the MnPAVE design procedure.

1.4.2. Drainage

Section 4.4 includes a discussion of the importance of drainage for a pavement section and most importantly the embankment soil. Specific design considerations to achieve adequate drainage are given in Reference 5. The most important design feature is to keep the final grade at least 1.7 m (5 ft) above the water table. This can be accomplished by either raising the grade or lowering the water table by dewatering.

Lateral drains can also be used in the pavement section. However, for them to work properly it is necessary to construct a drainable base and/or subbase [less than 7% passing the 0.075-mm (No. 200) sieve]. Proper drainage will not only help maintain the strength of the pavement section, but will also minimize the effect of frost heave.

1.4.3. Subgrade (Embankment) Soil Construction

1.4.3.1. General

To obtain the design values discussed above for the embankment soils in the field, proper construction practices must be followed. These start with specifications that will help assure good construction. In Chapter 4 the specifications that pertain to embankment soil construction, general construction design considerations and some field checklists are presented as suggestions on how best to build the embankment soil.

1.4.3.2. Specifications

MnDOT has three specifications that pertain to the construction of embankments. These are Specifications 2105, 2111, and 2123 (9). Specification 2105 is defined as a “Quality” specification for which two types of density control can be used. These are “Ordinary” and “Specified” compaction. The methods are similar because the specification states that compaction must be accomplished to the satisfaction of the Engineer. For ordinary compaction an experienced Engineer or Inspector must be on the project to make sure adequate compaction is achieved. For “specified” compaction the judgment of the Engineer is aided with the determination of a measured density. The density must be measured using an agreed upon test procedure and using the representative moisture-density test for the soil being constructed. Of these two alternatives in Specification 2105 the specified density is recommended.

Specification 2111 presents the test rolling method for density control. An experienced Inspector can determine where soft spots occur in the constructed subgrade and make sure measures are taken to correct these. This method of compaction control is recommended over Specification 2105 because more (almost total) coverage of the embankment grade construction is possible.

Specification 2123 lists the equipment and characteristics of the equipment required to carry out Specifications 2105 and 2111.

1.4.3.3. General Design Considerations

Based on the soil type and project conditions the structural design and appropriate specifications certain procedures need to be set up and followed to result in good soil construction. The goal is to provide a strong and uniform embankment for the pavement structure. Many of the procedures presented depend on the type of soil encountered on the project. As the project is started variations in the soils may be encountered and therefore the field Engineer and Inspector must be aware of the effect of these possible changes. The following considerations are presented in Section 4.5.3.

- Excavation and Embankment Construction: 1. The finished grade must be kept at least 1.7 m (5 ft) above the water table. 2. The finished grade should be at least the depth of frost penetration to minimize frost heave and 3. The existing soils or materials and their preparation including subgrade correction embankment placement and protection of the completed embankment need to be considered.
- Soils Evaluation: Soils must be evaluated based on whether they are, 1. Suitable or unsuitable, 2. Excavated soils, 3. Salvaged Materials, 4. Borrow,
- Soils Preparation: Proper preparation of the soils for good uniformity involves reworking and enhancing the existing materials and eliminating pockets of high moisture and unstable soils. Soil preparation must also include proper compaction using test rolling or specified densities, and possible lime treatment for moisture control.
- Subgrade Correction: Subcuts must be made in areas with pockets of high moisture, unstable materials or other non-uniform conditions. Subcuts must be used especially where there are silty type soils, which are particularly frost susceptible. Subcuts can vary from 0.3 m to 1.3 m (1 ft to 4 ft). Tapers must be provided with the subcuts.
- Placement of Embankment and Backfill Materials: As embankment materials are placed the same soil must be used for each layer. Specific design considerations to accomplish uniformity are listed in Section 4.5.3.6.
- Compaction: Compaction must be performed to MnDOT Specification 2105 and/or 2111 using the equipment specified in Specification 2123. These are Proof-Rolling, Specified Density and Quality/Ordinary Compaction. The situations where one method is appropriate relative to the others are listed in Section 4.5.3.7.

1.4.3.4. Construction Notes and Procedures

The MnDOT Office of Construction, Technical Certification Section has published an "Inspector's Job Guide for Construction" (11). This Guide gives the inspector a checklist that will help get a project started and document the parameters forms and procedures that need to be considered based on the specifications to be used. One of the items that will help keep a project under control is for the Inspector to keep a good diary. This will help all people involved make sure that work is progressing at an appropriate rate and that the inspection work is being accomplished.

1.4.3.5. Subgrade Enhancement

Various methods of subgrade enhancement are presented in Section 4.5.

- Enhancement of in-place soils using proper design of drainage and good compaction are summarized in Sections 4.5.2.
- Modification using lime, bituminous materials and chlorides (Sections 4.5.3.2., 4.5.3.3. and 4.5.3.4.)
- Stabilization using Fly Ash (Section 4.5.4.).
- Use of Geosynthetics
    - Separation (Section 4.5.5.3.2.)
    - Reinforcement (Section 4.5.5.3.)

    General design considerations along with factors affecting of geosynthetic lifespan are presented in Section 4.5.5.4.
- Substitution using higher quality granular and lightweight materials is presented in Section 4.5.6.
    - Higher quality granular materials presented are Select Granular (Section 4.5.6.2. and Breaker Run Limestone (Section 4.5.6.3.). Design and construction procedures along with specifications are presented.
    - Design and construction of lightweight fills using Wood Chips, Shredded Tires and Geofoam are covered in Sections 4.5.6.4.1., 4.5.6.4.2., and 4.5.6.4.3., respectively.

Summaries using each of the materials and procedures recommendations are summarized for design and construction control. Specifications for materials and procedures to use in Minnesota along with contacts for further information are presented.

Based on a review of the literature, questionnaires and interviews with Mn/DOT and county engineers and review of specific projects recommendations are made for when and how the various procedures should be used. Recommendations are presented in Tables 4.14, 4.15, and 4.16 for Granular, Semi-plastic and Plastic soils respectively. The parameters used for the recommendations are "Grade above Water Table" and "Moisture Conditions". There are essentially no conditions recommended for soil enhancement for granular soils. Methods of Modification, Stabilization, Separation and Reinforcement are recommended for various conditions in the tables.

Table 4.17 lists the conditions and including "Thickness of Peat" for which the various lightweight fills are recommended.

A database has been developed to document installations using the procedures listed. Projects were located during visits to the cities and counties during the Summer, 2002. Sixty five projects have been identified. It recommended that:

- The projects identified should be reviewed every three years or more often.
- The location and parameters for additional projects should be added to the database.

In this way actual performance of the various methods of subgrade enhancement can be documented.

1.5. Pavement Section Materials

1.5.1. General

Pavement section materials are all materials that are added above the subgrade soil to more effectively withstand the loads caused by the traffic. The materials must be stronger and more durable closer to the surface. All pavement section materials must be non-frost susceptible. Chapter 5 presents many different materials that are now used in pavement sections in Minnesota. There are others that are and will be tried in the future. With the MnPAVE program it will be possible to simulate the new materials as input for the software and make predictions of how the material will perform in a pavement.

Chapter 5 follows the same format as Chapter 4 for subgrade design and construction. Definitions of the various materials are first presented. The materials range from Select Granular to a high type Hot Mix Asphalt mixture.

The specifications that define each of these materials are listed in Section 5.4.1. The granular equivalency factors for the Soil Factor and R-Value design procedures are based on the specification that the material passes.

Section 5.3 summarizes how the specifications relate to the granular equivalent thickness factors. The moduli for the pavement layers that can be input for the MnPAVE software are also presented in Section 5.3.3. The pavement moduli are varied by season just as those of the subgrade soil. As the MnPAVE procedure and its input are developed further it will be possible to assign different moduli to various materials that pass a particular specification. For instance, a Specification 3138, Class 5 material with 10% passing the 0.075-mm (No. 200) sieve may have a different set of moduli than one with 5% passing the same sieve. Other variations in gradation and particle angularity may also result in different moduli. When a reliable laboratory test is finalized these moduli can be measured and then checked with back-calculated moduli from the falling weight deflectometer or other non-destructive field tests.

The design factor inputs for the two HMA mixes used by MnDOT are presented in Section 1.2.

1.5.2. Pavement Layer Construction

1.5.2.1. General

To obtain the design values discussed above for the granular, stabilized and HMA pavement materials in the field, proper construction practices must be followed. These start with specifications which when followed to assure good construction. Field control procedures to help meet the specifications are then presented in Section 5.4.2. This includes a summary of the Inspector's Job Guide for Construction (11). MnDOT has also published a "Materials Control Schedule" in the Grading and Base Manual (10), which summarizes the testing frequency and quantities of materials needed to conform to the respective specifications.

1.5.2.2. Specifications

In Section 5.4.1.the specifications pertaining to the construction of the pavement layers are summarized. These include:

- Select Granular (MnDOT Spec. 3149.2B2) Section 5.4.1.1.1.
- Granular Base and Subbase Materials Gradations (MnDOT Spec. 3138) Section 5.4.1.1.2.

- Salvaged/Recycled Materials Gradations (MnDOT Spec 3138, Class 7) Section 5.4.1.1.3.
- Aggregate Base/Subbase Construction (MnDOT Spec. 2211) Section 5.4.1.2.
- HMA Combined Mix Design (MnDOT Spec. 2350) Section 5.4.1.3.1.

The specifications are summarized in the indicated sections.

The specifications for Hot Mix Asphalt mixtures cover the materials, mixture design and construction of the mixtures. Currently, MnDOT uses the 2360/2350 specifications mixture designs. The 2350 mix design uses the gyratory or Marshall hammer for compaction for developing the Job Mix Formula and construction control. Both of the procedures use volumetrics including Voids in the Mineral Aggregate (VMA) and total air voids. Before the 2350 specification was adopted VMA was used in the design phase of the mixture, but not checked in the field. Some mixtures were experiencing “VMA collapse” in the field (13); therefore, the current specifications require that VMA be controlled in the final mixture. Ride (smoothness) requirements have also been added to the 2360/2350 specifications. Both incentives and disincentives are included for control of ride quality.

MnDOT also has Specifications 2331 and 2340 included in the 2000 Specification Book (9). Some of these mixtures are still being produced. The field control procedures for these mixtures also need to be followed carefully, especially for adequate compaction.

Currently, MnDOT uses the mixes only for Superpave (2360) for all new construction and mid and long life (> 5 years) overlays.

1.5.2.3. Field Control Procedures to Meet Specifications

1.5.2.3.1. General

Section 5.4.2. summarizes procedures presented in the MnDOT Grading and Base, Geotechnical and Bituminous Manuals (10)(5)(14). Checklists for field personnel from the Field Notes for Construction Engineers and Inspectors are also presented (11). Recommendations are made indicating which method is best for field control. Field control procedures for cold in-place recycling and full depth reclamation have not been finalized.

1.5.2.3.2. Granular Bases

The construction of granular bases and subbases involves the following procedures:

- Manufacture of the material from a gravel pit or quarry
- Storage of the materials
- Transport to the grade
- Placement
- Compaction

The material is initially tested for general quality and gradation and uniformity of these characteristics. Segregation must be minimized during the entire construction process.

The current Schedule of Materials Control must be followed for each project.

It is important that the Contractor use exactly the same procedures and the State when doing Quality Control and Quality Assurance companion testing is being done.

MnDOT specifications define three methods that can be used for compaction control:

- Specified Density
- Dynamic Cone Penetrometer (DCP)
- Quality (Ordinary) Compaction

The specified density is measured using the 150-mm (6-in.) Sand Cone Method (ASTM D 1556-90. Random sampling procedures should be followed to establish density test locations.

The DCP is a quick and easier test to run than the sand cone. It also gives a direct measure of stiffness. The DCP needs to be run using the prescribed procedure carefully and within 24 hours of compaction so that crusting does not occur.

Quality (Ordinary) Compaction should only be used if the equipment is not available to do either Specified or DCP testing. If quality compaction is used the Inspector and Engineer must be experienced in the construction of granular base and embankment materials. The compaction operation must be observed continuously. It generally is only appropriate for small areas where a limited amount of granular material is being placed.

The Field Notes for Construction Engineers and Inspectors (11) includes a section for inspection of granular base construction. This checklist will help the field personnel carry out the specifications well. Just as for the construction of embankment soils one of the most important items to maintain is a good diary which includes such things as hours, location, lift thickness, test results, quantity, yield and other events including weather which may have an effect on the work.

1.5.2.3.3. Hot Mix Asphalt Mixtures

The current Schedule of Materials Control should be reviewed and used for setting up the field control for each HMA construction project. That document will establish:

- The specification applicable for the project
- The minimum required field acceptance testing rate
- Form number to use
- Minimum required sampling rate for laboratory testing
- Sample size required for laboratory testing

The construction of an HMA pavement layer includes the following operations:

<u>Plant Operations</u>

- Materials delivery or manufacture and storage (asphalt and aggregate)
- Materials proportioning and mixing
- HMA storage and/or transfer to trucks
- Delivery to the construction project

<u>Paving Operations</u>

- Laydown
- Compaction

Each of these steps requires some Quality Control (QC) testing by the Contractor and the Quality Assurance (QA) testing by the Agency as spelled out in the Specification. The testing will help assure that the material is uniform (not segregated) is placed to specification density and that a surface is provided which passes the ride specifications.

It is very important that the same standard procedures be used for both QC and QA testing. The testing must also be done by certified technicians for both the Contractor and the Agency.

Section 5.4.2.3.3. includes a discussion on Methods of Compaction Control for HMA. Compaction is the most important part of construction of an HMA mixture. Inadequate compaction will result in a shorter life because of accelerated deterioration due to higher air voids resulting in more permeability and lower strength.

Three methods of compaction control are provided for in Specifications 2360/2350 (Gyratory/Marshall Design):

- Specified Density Method (2360.6-B2). The Bulk Specific Gravity of a field sample is compared to compaction obtained from the same material prior to compaction and compacted with a Marshall Hammer or gyratory compactor. The Maximum Theoretical Density is also determined to check the field compaction with the specified levels listed in Tables 2360.6 B-2 respectively. The frequency of and variations permitted between QC and QA testing are also listed.
- Ordinary Compaction. For Ordinary Compaction a control strip of at least 330 m^3 (395 yd^2) of the same material, on the same subgrade and base conditions shall be compacted to determine a proper roller pattern to achieve maximum density. A growth curve of density with roller passes must be used to determine when maximum density has been obtained. If materials or conditions change a new control strip must be constructed. A given control strip can only be used 10 days of construction.

The Specified Density Method should be used unless otherwise indicated.

Ordinary Compaction without a control strip should only be used for very small areas or thin lifts less than 39 mm (1.5 in.). For these areas the HMA should be compacted until there is no appreciable increase in density with each pass of the roller as defined by an experienced Engineer or Inspector.

The type and characteristics of the roller(s) to be used for Ordinary Compaction are presented in the Specifications.

The Inspector's Job Guide for Construction (11) includes sections on both the inspection of plant and paving operations.

The Guide assumes that the Inspector will not just be a data or sample taker. The Inspector should be aware of the whole operation to make sure that a consistent, uniform quality mixture is produced and constructed.

1.6. Summary and Recommendations.

Chapter 6 presents the summary and recommendations given in the manual. These deal with the thickness design procedure(s) to use now since the MnPAVE procedure is not documented fully across Minnesota especially for low volume roads. It is now recommended that either the Soil Factor or R-Value procedure be used and then the same roadway be designed using MnPAVE. Comparisons should be made and reported to the MnDOT Research Section. A form has been developed to report the comparisons.

Traffic is evaluated using 20-year projections of AADT and HCADT for the Soil Factor design procedure. Equivalent Standard Axle Loads (ESALs) are used for both the R-Value and MnPAVE design procedures. ESAL predictions over a 20-year design period require an estimate of AADT, vehicle type distribution, average effect of the various types of vehicles in terms of ESALs, a growth factor and lane distribution factor for the roadway. Tables and procedures are presented in Chapter 3 for determining these values both with estimates and using a field procedure for measuring vehicle type distribution.

The subgrade or embankment is the most important part of a pavement structure. Chapter presents the methods of evaluating the subgrade strength or stiffness for the three design procedures. To realize the design parameters obtained for a given soil good construction practices must be followed. Good construction starts with good specifications that define how the material is to be constructed and paid for. The MnDOT specifications that are used for subgrade construction are Nos. 2105, 2111 and 2123. Chapter 4 includes summaries of these specifications and the field procedures that will most effectively help carry them out. The importance of well-trained knowledgeable personnel is emphasized.

Chapter 5 presents how the materials used for the pavement section are evaluated for the three design procedures. The granular equivalent factors are used for the Soil Factor and the R-Value. The factors are dependent on the specifications which either a granular material or an asphalt mixture pass. The GE factors are presented in Chapter 5 and summarized in Chapter 6. The resilient moduli that are used for the MnPAVE procedure have been related to the other specification granular and hot mix asphalt materials. Eventually laboratory and non-destructive field tests (the FWD and DCP) will be used to relate the laboratory tests to the field values. One big advantage of the mechanistic-empirical design (MnPAVE) is that seasonal variations in resilient modulus for a material in the pavement section for a given year and from year to year can eventually be documented.

MnDOT combined 2360 and 2350 (Gyratory/Marshall Design) specifications are recommended for HMA construction on low volume roads in Minnesota. These specifications feature the use of volumetrics for field control and quality management (QM) of the team of the Contractor and the Agency. The Contractor is responsible for Quality Control QC) and the Agency, Quality Assurance (QA). The specifications include requirements for material quality, mixture design, mixture variability, density (voids), Voids in the Mineral Aggregate (VMA), moisture susceptibility, field density and smoothness of the finished surface. Construction procedures and a checklist for field engineers and inspectors are presented.

One of the major goals of the presentation of design and construction of the subgrade and pavement section materials is to obtain uniformity, which helps a great deal in the achievement of good performance.

CHAPTER 2

THICKNESS DESIGN PROCEDURES

2.1. Background and Introduction

There are three flexible pavement thickness design procedures now used in Minnesota. In addition some pavements, especially at the local level, are designed by experience based on what has worked in the past. The three formal thickness design procedures are the Soil Factor Design found in the MnDOT State Aid Manual (4), the Stabilometer R-Value Design found in the MnDOT Geotechnical and Design Manual (5) and MnPAVE, which is the mechanistic-empirical design procedure currently under development. The Soil Factor Procedure was developed in the 1950's and has been modified somewhat since then. MnDOT adopted the R-Value Procedure in the early 1970's. The MnPAVE Procedure is in software form and is being tested against the other procedures. The Beta version is now available (6). In this Chapter the procedures are presented along with the factors needed for thickness determination.

The traffic factor for each of the procedures is presented in Chapter 3. The embankment (subgrade) factors for design and construction specifications and recommended procedures are given in Chapter 4. The thickness of the pavement section is defined using the Granular Equivalent for the Soil Factor and R-value design procedures. The Resilient Modulus (M_r) and the thickness of the layers define the structure for the MnPAVE Procedure. The required specifications and recommended construction procedures to attain the respective pavement section factors are presented in Chapter 5.

2.2. Soil Factor Design

Since 1954 some pavements in Minnesota have been designed using a table similar to Figure 2.1. This is the 2001 version from the State Aid Manual which uses English and metric units (4). The chart uses seven traffic categories based on 20-year projected two-way AADT and HCADT and eight embankment types using the AASHTO classification system. Thickness in terms of Granular Equivalent (G.E.) is determined for each level of traffic and soil type. Each design also has a specified maximum spring axle load.

The traffic factors are Average Daily Traffic (ADT) and Heavy Commercial Average Daily Traffic (HCADT). The ADT and HCADT are both two-way values. The ADT includes all

FLEXIBLE PAVEMENT DESIGN USING SOIL FACTORS

Required Gravel Equivalency (G.E.) for various Soil Factors (S.F.)

For new construction or reconstruction use projected ADT. For resurfacing or reconditioning use present ADT.

All units of G.E. are in inches with millimeters (mm) in parenthesis.

7 TON @ LESS THAN 400 ADT		
S.F.	Minimum Bit. G.E.	Total G.E.
50	3.0 (75)	7.25 (180)
75	3.0 (75)	9.38 (235)
100	3.0 (75)	11.50 (290)
110	3.0 (75)	12.40 (310)
120	3.0 (75)	13.20 (330)
130	3.0 (75)	14.00 (350)

9 TON -150-300 HCADT		
S.F.	Minimum Bit. G.E.	Total G.E.
50	7.0 (175)	14.00 (350)
75	7.0 (175)	17.50 (440)
100	7.0 (175)	21.00 (525)
110	7.0 (175)	22.40 (560)
120	7.0 (175)	23.80 (595)
130	7.0 (175)	25.20 (630)

9 TON - MORE THAN 1100 HCADT		
S.F.	Minimum Bit. G.E.	Total G.E.
50	8.0 (200)	20.30 (510)
75	8.0 (200)	26.40 (660)
100	8.0 (200)	32.50 (815)
110	8.0 (200)	35.00 (875)
120	8.0 (200)	37.40 (935)
130	8.0 (200)	39.80 (995)

7 TON @ 400 - 1000 ADT		
S.F.	Minimum Bit. G.E.	Total G.E.
50	3.0 (75)	9.00 (225)
75	3.0 (75)	12.00 (300)
100	3.0 (75)	15.00 (375)
110	3.0 (75)	16.20 (405)
120	3.0 (75)	17.40 (435)
130	3.0 (75)	18.60 (465)

9 TON - 300-600 HCADT		
S.F.	Minimum Bit. G.E.	Total G.E.
50	7.0 (175)	16.00 (400)
75	7.0 (175)	20.50 (515)
100	7.0 (175)	25.00 (625)
110	7.0 (175)	26.80 (670)
120	7.0 (175)	28.60 (715)
130	7.0 (175)	30.40 (760)

MATERIAL	**TYPE OF MATERIAL**	**G.E. FACTOR***
Superpave Hot Mix	Spec. 2360	2.25
Plant Mix Asp Pave	Spec 2350	2.25/2.25/2.00
Plant-Mix Bit.	Type 41,61	2.25
Plant-Mix Bit.	Type 31	2
Aggregate Base	(Class 5 & 6) 3138	1
Aggregate Base	(Class 3 & 4) 3138	0.75
Select Granular	Spec 3149.2B	0.5

9 TON @ LESS THAN 150 HCADT		
S.F.	Minimum Bit. G.E.	Total G.E.
50	7.0 (175)	10.25 (255)
75	7.0 (175)	13.90 (350)
100	7.0 (175)	17.50 (440)
110	7.0 (175)	19.00 (475)
120	7.0 (175)	20.50 (515)
130	7.0 (175)	22.00 (550)

9 TON - 600 @ 1100 HCADT		
S.F.	Minimum Bit. G.E.	Total G.E.
50	8.0 (200)	18.50 (465)
75	8.0 (200)	23.70 (595)
100	8.0 (200)	29.00 (725)
110	8.0 (200)	31.10 (780)
120	8.0 (200)	33.20 (830)
130	8.0 (200)	35.30 (885)

AASHTO SOIL CLASS	**SOIL FACTOR (S.F.) %**	**ASSUMED R-VALUE**
A-1	50 - 75	70 - 75
A-2	50 - 75	30 - 70
A-3	50	70
A-4	100-130	20
A-5	130 +	-
A-6	100	12
A-7-5	120	12
A-7-6	130	10

NOTE: If 10 ton (9.1 t) design is to be used, see Road Design Manual 7-3.
For full depth bituminous pavements, see Road Design Manual 7-3.
* Granular Equivalent Factor per MnDOT Technical Memorandum 98-02-MRR-01.

Figure 2.1 Flexible Pavement Design Using Soil Factors

vehicles and the HCADT is defined as all trucks with six or more tires; thus HCADT does not include cars, small pickup and panel-type trucks. The ADT and HCADT normally used for design are values predicted for 20 years into the future. Local conditions must be considered and the projected value may either be increased or decreased based on the projected future use of the road. More specific methods of determining design values are presented in Chapter 3.

As noted in Figure 2.1 a soil factor of 100% represents an A-6 or A-4 soil. Stronger soils have soil factors less than 100% and weaker soils greater than 100%. The soil factor percentage represents the percent increase or decrease in the thickness of the subbase (D_3). There are ranges of percentages shown for A-1, A-2, A-4 and A-7 soils. Therefore, it is possible to use some judgment relative to the capabilities of the soils after evaluating drainage and other design considerations. Chapter 4 includes a discussion on the selection of these and other design parameters for the embankment soils.

The strength and stiffness of the soil supporting the pavement are very dependent on the density and moisture conditions of the constructed soil. **Uniformity** is also important to minimize differential heave during freeze up. The construction specifications and procedures presented in Chapter 4 must be followed to attain the strength and stiffnesses inferred in the given soil factors.

The Granular Equivalent (G.E.) defines a pavement section by equating the thickness of each aggregate or HMA layer to an equivalent thickness of granular base material. Equation 2.1 is used to calculate the Granular Equivalent. In Minnesota this is a Specification 3139 material, Class 5 or 6 (9). The relevant specifications for the other pavement materials are listed in Figure 2.1. Minimum bituminous and total granular equivalents are also shown for each traffic category. The total Granular Equivalent is defined using Equation 2.1.

$$\text{G.E.} = a_1D_1 + a_2D_2 + a_3D_3 + \ldots \qquad (2.1)$$

Where: D_1 = thickness of asphalt mix surface, in. (mm)
D_2 = thickness of granular base course, in. (mm)
D_3 = thickness of granular subbase course, in. (mm)
a_1, a_2, and a_3 = G.E. Factors listed in Figure 2.1.

The required design thicknesses are listed in two categories (minimum bituminous G.E. and total G.E.). The maximum granular base thickness can be calculated by subtracting the minimum bituminous G.E. from the total G.E. Other design combinations of bituminous and granular materials can be determined using the G.E. factors.

The respective specifications and construction procedures necessary to attain the material characteristics defined for the soil factor design are presented in Section 5.3.2.

2.3. Stabilometer R–Value Design

The Stabilometer R-Value is the current design procedure used by MnDOT to determine the design thickness of an HMA surfaced pavement. This procedure is based on research done in the 1960's using results from the AASHO Road Test. The basis of the design is limiting spring deflections by increasing the strength (stiffness) of the soil or by increasing the strength (stiffness) of the pavement layers for a given level of traffic.

Figure 2.2 is the R-Value design chart from the MnDOT Design and Geotechnical and Pavement Design Manual (5). The embankment R-Value can be measured with a standard laboratory test (ASTM D-2844) or estimated from the soil type or classification. The R-Value laboratory procedure used in Minnesota is presented in Chapter 4. An exudation pressure of 1655kPa (240 psi) is used for determining a design R-Value in Minnesota. Predictions of R-Value from soil classification are also presented in Table 4.5.

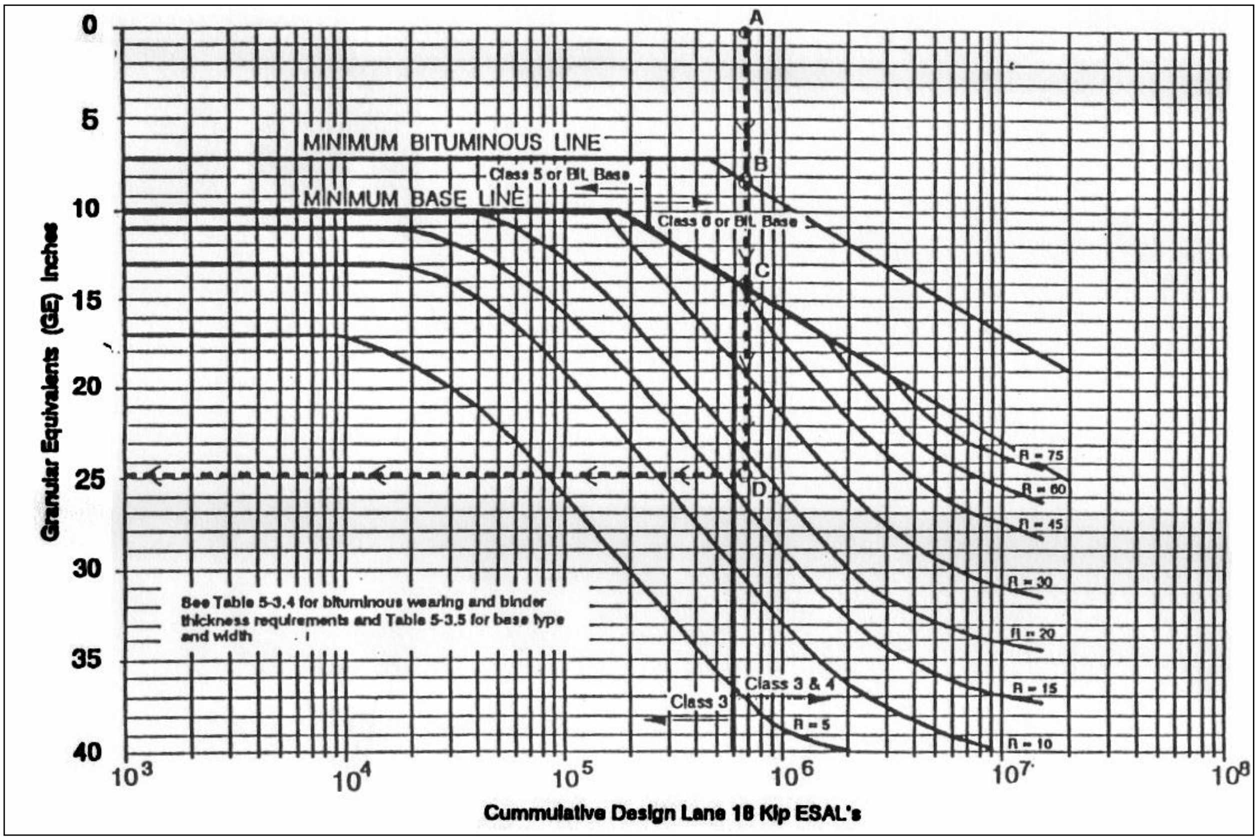


Figure 2.2 R-Value Design Chart

The traffic is evaluated in terms of 80-kN (18,000-lb) equivalent standard axle loads (ESAL's). For a particular road being designed the ESAL's are estimated for a design lane in one direction. Calculated ESAL's will be different for flexible and rigid pavements for the same traffic mix. Chapter 3 presents methods for estimating design ESAL's for flexible pavements in Minnesota.

The thickness is defined in terms of Granular Equivalent in inches. Granular equivalent factors (a_1, a_2, and a_3) for the R-Value design are listed in Section 5.3.2. Equation 2-1 is used to calculate the total granular equivalent in the same way as for the soil factor design. In addition to the lines for specific R-Values showing the required GE for a given number of ESAL's, lines on the R-Value design chart represent:

1. The minimum bituminous thickness GE and
2. Bituminous plus base thickness GE.

The actual thicknesses represented can be calculated using the appropriate G.E. factors.

Examples of designs using the R-Value design chart with minimum thicknesses of surface and base, plus other combinations are given in Reference 5.

2.4. MnPAVE Design

2.4.1. General

The Minnesota Department of Transportation and the University of Minnesota have developed a mechanistic-empirical (M-E) design method for flexible pavements. The procedure has been developed as a software package (MnPAVE) because of the great quantities of data and analyses used for the design. A Beta Version of the software is now available. It is still being fine-tuned somewhat.

MnPAVE predicts the structural performance of pavement sections using calculated strains in a simulated elastic layered system. To use the elastic layered system moduli and the thickness of each pavement layer must be determined for the pavement. Up to five (5) layers can be used for the calculations of:

- The tensile strain in the bottom of the surface layer and
- The compressive strain on the top of the subgrade, which is assumed to be infinite in depth.

Various combinations of material properties (moduli) are used to simulate the seasons throughout the year. Currently, five seasons are used (winter, early spring, late spring, summer and fall). MnPAVE calculates the percent of damage that occurs in each season, maximum stress, strain and displacement at the critical locations, the allowable axle load repetitions and reliability percentages. The life in years is then predicted using the predicted traffic in ESAL's or load spectra.

Fatigue cracking has been correlated with the tensile strain in the HMA surface layer and embankment rutting has been correlated with the compressive strain on the embankment. The performance equations are derived from the development of fatigue cracking and rut depth on the MnROAD test sections. Moduli of the layers have been measured throughout the year using backcalculated Falling Weight Deflectometer (FWD) data or estimated from the Dynamic Cone Penetrometer (DCP) or other standard tests.

The performance equations were also checked using the performance of a number of 40-year old test sections from Investigation 183 (15). The research to develop the information to check the performance of these sections was done as part of this project and reported in Appendix A of this report.

Variability can also be incorporated into MnPAVE. Variations in the following parameters contribute to the overall variation of the pavement section.

- Layer Moduli
  - HMA Surface
  - Granular base and subbase
  - Subgrade Soil
- Layer Thicknesses
- Load Predictions
  - Vehicle class predictions
  - Vehicle weight estimates
  - Total number of vehicles

The variability of these parameters is used with the predictions equations to calculate the reliability of the performance predictions. A Monte Carlo simulation is used to calculate the reliability of the performance predictions (16). With this type of analysis it is possible to relate the variability of the thickness, material properties and traffic predictions to required thickness. More uniform construction can therefore be translated into thickness saved or increased life predictions.

MnPAVE requires that the materials be described by their stiffness (modulus) for the seasons defined. This requires that the modulus be defined for these seasons either directly or backcalculated using the FWD or DCP. Correlations with other standard tests as shown in Table 4.5 can also be used.

At this time MnPAVE should be used in conjunction with one or both of the current methods. In this way a city or county can develop confidence in the results of the MnPAVE design. Without the MnPAVE software it has not been possible to take into account the many variables that affect the performance of a pavement section.

MnPAVE has the following features:

- Three design levels based on input data quality
- Material properties adjusted seasonally
- Traffic quantified using either ESAL's or load spectra
- English or System International (S.I.) Units
- HMA modulus temperature adjustment equations that can be modified
- Reliability estimates using Monte Carlo simulations

2.4.2. Set Up

MnPAVE is designed for Windows 95/98/NT operating systems and requires 2 MB of hard drive space and a 200 MHz processor or higher.

Installation can be accomplished using the following procedure:

1. Create a new folder on the hard drive called "MnPAVE"
2. Copy the *.exe file from the floppy disk to the MnPAVE folder.
3. Run the program.

2.4.3. Start Up

2.4.3.1. Control Panel

The "Control Panel" is the first window to appear when MnPAVE is started. The control panel includes areas for input data which includes "Climate, Structure and Traffic" A button to display "Output" also appears on the window. The input must be entered in order beginning with **"Climate"** and ending with **"Traffic"**, because the seasonal factors used in **"Structure"** depend on Climate and some of the ESAL calculations in Traffic depend on Structure. Changes can be made in these input windows at any time. However, for a given design check, all inputs must be completed before **"Output"** can be selected.

2.4.3.2. General Operation

MnPAVE uses the pull-down menu and window selection structures common to most software packages. The pull-down menu at the top of the screen includes, "File, Edit, Record, View, Window and Help." The **Output** will provide damage factors for asphalt fatigue, rutting and the percent of damage for each season. It also displays the maximum stress, strain and displacements at the critical locations, the allowable load repetitions and reliability percentages.

2.4.4. Inputs

2.4.4.1. General

MnPAVE can be operated using either S.I. or the English system of units, sometimes called Customary units. The system of units can be selected separately for the Climate, Structure and Traffic data. However, is recommended to use the same System for a given design application.

The data for each of the input parameters, Climate, Structure and Traffic are defined using three design levels, **"Basic, Intermediate or Advanced"**.

- The **Basic Level** requires the least amount of data and is intended for many low volume roads. It may also be used for preliminary design for higher volume roads.
- The **Intermediate Level** requires more specific information for a given project and is similar to the information required for that of the Soil Factor or R-Value design procedures.
- The **Advanced Level** requires detailed traffic and material property information and is intended for high volume trunk and interstate highways. It is possible for the designer to use a different design level for each type of input data.

For this manual only input for the **Basic Level** and **Intermediate Level** are considered. At this time the procedures for obtaining and using the data for the **Advanced Level** have not been developed. However, the actual moduli and other values that are used for the stress and strain calculations are shown in the **Advanced Level** window.

2.4.4.2. Climate Inputs (Seasonal Design)

The material properties used for the design levels are adjusted for seasonal changes in temperature and moisture. For example, typically the HMA modulus will be lower during the warm summer season and higher during the cooler seasons. Also, the modulus of an aggregate base will be lower during the wet spring periods. These variables cannot be taken into account with the Soil Factor and R-Value Design Procedures.

For the current version of MnPAVE the year is divided into five seasons, which reflect the major periods influencing pavement behavior as observed at MnROAD. The seasons are **"Early Spring, Late Spring, Summer, Fall (standard), and Winter"**.

- **Early Spring** is defined as the period when the aggregate base or subbase is thawed, but the subgrade is still frozen.
- **Late Spring** is the period when the aggregate base has drained, but the subgrade is thawed, saturated and weak.
- During **Summer** the aggregate base has fully recovered its strength and the subgrade has only partially regained its strength.
- By **Fall**, both aggregate base and the subgrade have recovered their strength. **Fall** is considered the standard season for estimating stiffness (modulus) variations throughout the year.
- **Winter** is the season for which all the pavement layers are frozen.

The duration of the seasons will vary somewhat for different locations around the State and from year to year. A study by Ovik, et al (8) using moduli calculated at MnROAD indicated that the season durations were respectively, 4, 7, 13, 13, and 15 weeks for Early Spring, Late Spring, Summer, Fall, and Winter respectively. These must always total 52 weeks and could be redistributed as more specific data are obtained for other locations. For the Advanced Level of Climatic data in MnPAVE any combination of duration and material properties during the various defined periods of the year could be used.

To estimate the seasonal modulus for the HMA the temperature at one-third the depth can be entered directly or estimated using seasonal average daily air temperatures and predictive equation developed by Witczak (17).

2.4.4.3. Structural Inputs

The structural inputs required for the MnPAVE software include the number, thickness and elastic properties (moduli) of each layer. The number and thicknesses are the design values being tried for that trial.

The moduli can be directly input if laboratory testing of the materials have been measured. If the project-specific materials have been tested, this would be considered an "advanced" determination of the moduli.

If the correlations shown in Chapter 4 for subgrade materials or Chapter 5 for the pavement section materials are used, then these would be considered Basic or Intermediate Levels of Input.

Layer 1, the surface layer can be either HMA or “Other”. The “Other” option is used to allow the designer to use materials that have moduli value outside the HMA range allowed by MnPAVE.

The **lower layers** may include “Aggregate Base, Subbase, Engineered Soil, Undisturbed Soil, Groundwater and Bedrock”.

The **Aggregate Base and Subbase** are to be constructed stiff enough to enhance HMA compaction as well as provide long term support for the HMA and help protect the subgrade.

The **Engineered Soil** is located directly below the base and/or subbase. This is the layer of soil that is excavated, blended, shaped and compacted to result in the most efficient use of that material. The construction specifications and procedures outlined in Chapter 4 must be followed to achieve the properties predicted for these materials.

The **Undisturbed Soil** is the material in-place that existed along the road alignment prior to construction. The modulus of the undisturbed soil is assumed to be one half of that of the same soil if it has been “engineered”.

The **Bedrock** and **Groundwater** layers must be included if either occurs within 2 m (6 ft) of the surface. MnPAVE uses a constant modulus of 350 MPa (50,000 psi) for both the bedrock and soil below the groundwater table because both materials behave rigidly under dynamic loads. The ditch bottom is usually assumed to be the depth of the water table. Poisson’s Ratio is assumed to be 0.15 for bedrock and 0.5 for the groundwater table. The bottom layer of the pavement structure is to be of infinite depth.

After the basic structure has been defined, a **trial thickness** for each pavement layer is entered into the boxes next to the “Materials”. The variability of thickness allowed in the respective specifications should be considered for prediction of variability of the design life. Several different materials and thicknesses can be input to develop a variety of preliminary pavement design structures.

For the **Intermediate Design Level** the structure is entered in the “Edit Structure” section of the window. The number of layers is selected by the “Material” and

“Thickness”. At the Intermediate Level a single design value of the modulus for each unbound material is used to estimate the seasonal moduli. These are listed in Table 5-2 and are backcalculated values from FWD tests at MnROAD. The HMA moduli are also listed in Chapter 5.

The laboratory moduli for each material can either be entered directly or the “design” modulus can be estimated using correlations presented in Chapters 4 or 5. Currently, it is not possible to directly measure the moduli with a laboratory test. However, correlations with modulus have been made with the laboratory R-Value, or soil classification as shown in Table 4.2. The moduli determined from the correlations will appear on the **Advanced Level** screen.

Damage equations are used by MnPAVE to convert the calculated strain values from each loading into the number of allowable load applications. The allowable load applications are compared to the estimated traffic to calculate the damage factor and/or design life. The coefficients in and the format of the damage equations will be changed periodically as more performance information becomes available.

2.4.4.4. Traffic Inputs

The traffic input is quantified by selecting either **“ESAL”** or **“Load Spectra”** above the **“Traffic”** button on the **Control Panel**. At this time only ESAL’s can be used for the Traffic Input. The definition of ESAL’s and methods for predicting and calculating ESAL’s are presented in Chapter 3.

For the **Basic Design Level** the designer can obtain an estimate of ESAL’s by entering Average Annual Daily Traffic (AADT), Direction Factor, Lane Factor, and Annual Growth Rate and then can select from a number of typical Vehicle Type Distributions that have been obtained from around Minnesota.

For the **Intermediate Design Level** the AADT, Direction Factor, and Annual Growth Rate are entered along with a Vehicle Type Distribution determined for that specific location. This value may be obtained from a road with similar traffic, or be a measured distribution using the procedure presented in Chapter 3.

The **Advanced Design Level** allows the designer to enter the number of axles expected in each load class in addition to tire pressure for some special design situations.

At this time this sophistication is not recommended except for very special design situations.

It is necessary to enter information into each of the Input Windows **(Climate, Structure and Traffic)** to obtain an estimate of the life and/or damage factors for that design.

2.4.5. Outputs

The **Output** can be viewed either in a "Seasons" or "Reliability" format. Seasons output includes **Damage Factors** which are the inverse of the number of times the predicted traffic volume can be supported by the pavement before failing due to either fatigue cracking or rutting. The input traffic divided by the **Fatigue Damage Factor** gives the number of ESAL's the pavement is able to withstand before developing fatigue failure. Fatigue failure is defined as 20% of the total lane cracked. The **Rutting Damage Factor** gives the same type of prediction for a rutting failure criteria based on a 12-mm (0.5-in.) rut depth. A damage factor of 1.00 over 20 years would be the goal for most designs.

MnPAVE provides an option for the quick recalculation of damage factors as different layer thicknesses are considered. The layer thicknesses can be altered individually or as a group until **Damage Factors** of 1.0 are obtained for both rutting and fatigue cracking.

2.5. Which Procedure Should be Used in 2001-02?

Three design procedures have been presented and summarized in this chapter. These are the Soil Factor, Stabilometer R-Value and the Mechanistic-Empirical (MnPAVE) designs. The Soil Factor and R-Value procedures are published in the MnDOT manuals (4)(5). They have been used for the past 25 plus years for the design of many low, medium and high volume roads. The MnPAVE procedure has been developed initially at the University of Minnesota and now is being put into useable form by MnDOT.

At this time it is recommended that either the Soil Factor or the R-Value Design continue to be used and that the resulting design be checked with the MnPAVE Design. The MnPAVE design takes into account many variables that the other two procedures cannot. For instance the variation of material properties for different seasons can be input to determine which is the most critical season and what effect heavier or limited loads will be. Tire pressure, different types of stabilization or other construction techniques can also be simulated.

If all of the parameters necessary to use the MnPAVE procedure are not available then the values can either be assumed for estimated from the correlations given in the respective chapters. MnPAVE is versatile and will be improved as more people use the software and compare performance predictions from the software program with field experience and designs determined from the currently used procedures. Also, in the next year (or so) nationally, the AASHTO 2002 Design Guide will be available (12). The experience with MnPAVE will make it possible for MnDOT and other agencies in Minnesota to calibrate the AASHTO 2002 Procedure to Minnesota climate, materials, and traffic conditions more easily.

CHAPTER 3
TRAFFIC PREDICTIONS

3.1. Background and Definitions

For design, rehabilitation and maintenance of pavement structures traffic characterization plays a crucial role. Estimation of the amount and type of traffic that the roadway will be expected to carry over the design life will affect the types of materials chosen for the pavement, the thickness design of the pavement structure and the predicted pavement performance. Traffic analysis is also an essential part of project feasibility studies, project selection, project path analysis and sizing of facilities. Therefore, it is critical that the traffic be accurately characterized so that engineers may optimize designs for the expected traffic.

Most pavement design procedures either rely on estimates of heavy commercial average daily traffic (HCADT) or equivalent single axle loads (ESAL's) for traffic loading characterization. This chapter outlines the best practices regarding calculation of these two traffic parameters. Prior to describing the various aspects of traffic characterization, it is important to define a number of terms often used in traffic data collection and analysis:

1. Average Annual Daily Traffic (AADT): The estimate of daily two-way traffic on a road segment representing the total traffic on the segment that occurs in one year divided by 365. It is important to note that AADT is a volume that *may* never actually occur, but represents the average daily traffic on that segment throughout the year.
2. Average Daily Traffic (ADT): A 24-hour two-way traffic volume that must be qualified by stating a time period (e.g., average summer weekday).
3. Automated Traffic Recorder (ATR): A permanent device that continually collects and stores traffic data.
4. Axle Load: The total load transmitted by all wheels in a single, tandem or tridem axle configuration. A single axle is defined as one axle with two sets of dual tires; a super-single is one axle with two single tires. A tandem axle has two axles spaced less than 1.7 m (5 ft) apart with two sets of dual tires on each axle. A tridem axle has three axles spaced less than 1.7 m (5ft) apart each with two sets of dual tires on each side. Both tandem and tridem axles can have single tires if they are wide enough to decrease the load to 200 kg (450 lb) per 25 mm (1 in.).

5. Average Daily Load (ADL): The estimate of a daily load on a roadway segment calculated from the daily vehicle types multiplied by their appropriate ESAL factors.
6. Annual Design Lane ESAL: The estimate of total ESAL damage a roadway segment will experience in one year.
7. Equivalent Single Axle Load (ESAL): The relative amount of damage imparted to a pavement structure by the passage of a standard single axle load, with dual tires. The ESAL standard is typically an 80-kN (18,000-lb) single axle and all other axle configurations and weights are equilibrated to the standard.
8. ESAL Factor: The average effect of a given vehicle type on a pavement, in terms of Equivalent Standard Axle Loads (ESAL's).
9. Heavy Commercial Traffic: All vehicles two or more axles and a minimum of six tires.
10. Heavy Commercial Annual Average Daily Traffic (HCADT): The estimate of heavy commercial daily two-way traffic on a road segment representing the total traffic on the segment that occurs in one year divided by 365. It is important to note that HCADT is a volume that *may* never actually occur, but represents the average heavy commercial daily traffic on that segment of road
11. Weigh-In-Motion (WIM): A permanent device that continually collects and stores axle weight data. This device also collects the total number of vehicles, axle spacing, length, speed and vehicle type data.
12. Vehicle Classification: The classification of traffic by vehicle type (i.e., cars, pickups, 3-axle semis, etc.)

3.2. Determination of AADT

For the Soil Factor Pavement Thickness Design Procedure described in Chapter 2 design (20-year projected, usually) AADT is one of the parameters used to categorize traffic. The design AADT can be calculated using the current value and increasing it by a growth factor depending on the projected use of that roadway. MnDOT maintains AADT flow maps for the County State Aid Highway (CSAH) system. These maps, which are up-dated about every two years are available on CDROM and may be obtained by contacting either the Traffic Forecast and Analysis Section or the District Traffic Engineer of MnDOT.

AADT can also be measured by conducting a vehicle count at the location of, or similar location to the proposed roadway.

3.3. Determination of HCADT

The other factor used to categorize traffic for the Soil Factor Pavement Thickness Design Procedure is the two-way Heavy Commercial Traffic (HCADT). The design HCADT is the value projected for the last year of the design life, which is usually 20 years. The current HCADT can be determined by:

- Estimating HCAADT from Mn/DOT flow maps maintained throughout Minnesota.. The HCAADT flow maps for trunk highways in each county are available on the Mn/DOT Traffic and Data Analysis web site and may be obtained by contacting the MnDOT Traffic Forecast and Analysis Section. Thedefault HCAADT value found in the Mn/DOT Geotechnical and Pavement Design Manual (5) and in Table 3.1 is 5.9 percent.
- Conduct a vehicle-type distribution study as outlined in Appendix 3.1. The current HCADT can be measured and the projected design value can be calculated. Again, the HCADT includes all vehicles having six or more tires, which includes all vehicles except passenger cars and pickup trucks.

3.4. ESAL Calculations

The number of Equivalent Standard Axle Loads (ESAL's) is used to define the traffic effect for the R-Value (5) and MnPAVE Design Procedures (6). The following parameters must be determined to calculate predicted ESAL's. The ESAL concept equates the damage of the measured number of various axle loads to an 80-kN (18,000-lb) axle load. The following steps outline the data collection procedure and the ESAL calculation. Determine:

3.4.1. AADT for project location. (Section 3.2)

3.4.2. Vehicle Type Distribution for the location.

3.4.3. ESAL factors by vehicle type.

3.4.4. Traffic growth factor(s).

3.4.5. Design lane traffic percentage.

3.4.6. Calculate ESALs.

3.4.1. Estimate AADT

The determination of AADT is presented in **Section 3.2**.

3.4.2. Vehicle Type Distribution

Vehicle type distribution is very important in calculating ESAL's because the axle load weights and configurations greatly affect the damage effect on the pavement. The most practical method of estimating the load effect is to determine the current vehicle type distribution and project that into the future. Two methods are available to predict current vehicle type distribution for a given roadway:

- Use statewide average distribution for an estimate. The statewide average for Rural CSAH and county roads for eight vehicle types are listed in Table 3.1.
- Measure the distribution at a given location using the dual hose technique developed by MnDOT.

Because the distribution presented in Table 3.1 represents a statewide average distribution from the 1994 Geotechnical and Pavement Manual (5) it may not be directly applicable for a given location and type of road. A comparison between the assumed and measured distributions made in 1998 and 1999 on roads in three counties indicated that significant errors could be made by using the assumed distribution. The complete study is presented in Reference 18.

Table 3.1. Vehicle Classification Percentages – Rural CSAH or County Road

Vehicle Type	Percentage in Traffic Stream
Cars and Pickups	94.1
2 Axle, 6 Tire - Single Unit	2.6
3+ Axle - Single Unit	1.7
3 Axle Semi	0.0
4 Axle Semi	0.1
5+ Axle Semi	0.5
Bus/Truck Trailers	1.0
Twin Trailers	0.0

Ref: Mn/DOT - Geotechnical and Pavement Manual, 1994 (5)

A better approach, given the deficiencies of Table 3.1, is to conduct a vehicle classification field study on the actual roadway, or similar roadway being evaluated. In doing so, many of the errors introduced by assuming a vehicle type distribution can be eliminated. Appendix B contains a field guide for conducting such a field study.

3.4.3. Determination of ESAL Factors by Vehicle Type

Each of the vehicle types specified above will impart a different amount of damage per vehicle, expressed in terms of ESAL factors. While the ESAL factors are dependent upon the type and thickness of the pavement, the default values listed in Table 3.2 may be used. A range of ESAL factors for various traffic conditions can be found in Appendix H.2 of the MnDOT Geotechnical and Pavement Design Manual (5).

Table 3.2. Average ESAL Factors by Vehicle Type

Vehicle Type	ESAL Factor
Cars and Pickups	.0007
2 Axle, 6 Tire - Single Unit	.25
3+ Axle - Single Unit	.58
3 Axle Semi	.39
4 Axle Semi	.51
5+ Axle Semi	1.13
Bus/Truck Trailers	.57
Twin Trailers	2.40

Ref: Mn/DOT - Geotechnical and Pavement Manual, 1994 (5).

In cases where axle weight data for a particular vehicle are available and the size and cost of the project warrant better traffic information, it is possible to calculate the ESAL factors for particular vehicles. In fact, the values shown in Table 3.2 were obtained through a method similar to that described in the 1993 AASHTO Guide (19) and requires axle weight data, an estimate of the structural number (SN) of the pavement and an estimated terminal serviceability level (p_t). Reference 19 recommends the following:

SN = 5.0

$p_t = 2.5$

Table 3.3 illustrates the method to calculate an ESAL factor for a hypothetical 5-axle truck with corresponding weight data from a study including 165 vehicles. The load equivalency factors were obtained from Reference 19 and are dependent upon SN and p_t. The equation at the bottom of the table demonstrates that an average ESAL factor (2.078) is calculated by dividing the total equivalent axle loads (ESAL's) by the total number of vehicles weighed. In this case the ESAL factor for these 5-axle trucks, which is somewhat higher than the value shown in Table 3.2. If a distribution of axle weights can be determined for a given truck type the blank Table 3.3 in the appendix can be used to calculate the appropriate ESAL factor.

Table 3.3. Sample Computation of ESAL Factor

Axle Load, kips	Traffic Equivalency Factor		Number of Axles		18 Kip ESAL's
Singles					
3-5	0.002	x	1	=	0.002
5-7	0.01	x	5	=	0.05
7-9	0.034	x	15	=	0.51
9-11	0.088	x	57	=	5.016
11-13	0.189	x	63	=	11.907
13-15	0.36	x	17	=	6.12
23-25	3.03	x	3	=	9.09
Tandems					
27-29	0.495	x	50	=	24.75
29-31	0.658	x	72	=	47.376
31-33	0.857	x	85	=	72.845
33-35	1.09	x	120	=	130.8
35-37	1.38	x	25	=	34.5
			Total 18 kip ESAL's	=	342.966
ESAL Vehicle Factor =	Total 18 kip ESAL's / Number of Trucks Weighed	=	342.966 / 165	=	2.078

3.4.4. Determination of Growth Factor

The growth factor is key in determining how traffic volume will change over the life of the pavement. Two methods are available for calculating anticipated growth.

- A method is presented in the MnDOT Geotechnical and Pavement Design Manual (5). This method is illustrated with ESAL calculation spreadsheet (Table 3.6). This method assumes the volume of traffic will increase based on the AADT history. It is assumed the weight of trucks will increase by about 12% over 20 years based on historical increases.
- A growth factor table is presented in Reference 19. Table 3.4 lists these factors for 10 and 20-year lives with growth rates of 1, 2, and 4%. Growth rates are rarely greater than 4%.

These factors when multiplied by the current year estimated ESAL's yields the total ESAL's predicted for the given roadway.

Table 3.4. Growth Factors

	Assumed Growth Rate, %		
Design Life, Years	**1**	**2**	**3**
10	10.46	10.95	12.01
20	22.02	24.30	29.78

3.4.5. Design Lane Distribution

The "Design" ESAL's for a given roadway are the number calculated for the lane that is expected to have the greatest loading. Lane distribution depends on the total number of lanes and traffic characteristics based on road usage. If trucks are loaded in one direction and not the other the loading distribution will be skewed.

Table 3.5 is a list of distribution factors assuming uniform directional traffic for 1, 2 and 3 lanes in each direction. Special attention must be made for turning lanes and other variations.

Table 3.5. Lane Distribution Factors

	Lane Distribution Factor	
Number of Lanes in One Direction	Single-Direction Traffic Data	Two-Direction Traffic Data
1	1	0.5
2	0.9	0.45
3	0.7	0.35

3.4.6. ESAL Calculation Spreadsheet

Once all the data have been determined as specified above, the ESALs may be determined. Mn/DOT uses a spreadsheet program, MNESALS (20). It is strongly recommended that the program be used for all ESAL calculations. The MNESAL2003 Program is available from the Traffic Forecast and Analysis Section of Mn/DOT. However, to demonstrate the essence of the program and how the above data are used, Table 3.6 illustrates an example ESAL calculation.

The second column in Table 3.6 shows the total AADT in the base year and the AADT by vehicle type. For example, cars and pickups comprise 80.47 percent of the traffic stream

(1207/1500). The fifth column also shows AADT, but it has been increased by approximately 40 percent for all vehicle types to account for an increase in traffic volume over the life of the pavement. The base and design year average daily loads are simply calculated by multiplying the ESAL factors by the AADT and summing all the vehicle classifications together.

Table 3.6. ESAL Calculation Worksheet

Vehicle Classes	Base Year AADT (two-way)		ESAL Factors		Base Year ADL	Design Year AADT (two-way)	Design Year ADL
Cars and Pickups	1207	x	.0007	=	.8	1690	1.2
2 Axle, 6 Tire - Single Unit	98	x	.25	=	24.5	137	34.2
3+ Axle - Single Unit	34	x	.58	=	19.7	48	27.8
3 Axle Semi	6	x	.39	=	2.3	8	3.1
4 Axle Semi	8	x	.51	=	4.1	11	5.6
5+ Axle Semi	120	x	1.13	=	135.6	168	189.8
Bus/Truck Trailers	25	x	.57	=	14.2	35	20.0
Twin Trailers	2	x	2.40	=	4.8	3	7.2
Total	1500				206	2100	288.9

The worksheet in Table 3.6 only yields the ADL in the base and design years. Additional calculations must be done to determine the design ESALs. The following steps must be completed to determine the total ESALs over the design life and take into account the growth of ESAL's from the initial year.

1. Determine average ADL over life.

   Average ADL = (Base ADL + Design ADL) / 2 =

   (206 + 288.9) / 2 = 247 (rounded)

2. Determine total ESALs over life.

   Total ESALs = Days in N years (assume N = 20 for this example) * Average ADL =

   20*365*247 = 1,803,100

3. Apply design lane factor to calculate total ESALs in design lane. (Table 3.4)

   Total ESALs in Design Lane = Total ESALs * Design Lane Factor (assume 4-lane in this example) =

   1,803,100 * .45 = 811,951

4. Build in a 12% safety factor for the possibility of increased loads during the design.

   Adjusted ESALs = 12% increase factor * Total ESALs in Design Lane =

   1.12*811,951 = 909,385

5. Round off to the nearest thousand for design.

   ESALs = 909,000

3.5. Summary and Conclusions

In this chapter the traffic factors needed to design an asphalt pavement have been defined and procedures have been presented for estimating the traffic factors used from the three current Minnesota Design Procedures.

For pavement thickness design the traffic factor should consider

1. The total volume of traffic,
2. The distribution of axle weights and types,
3. The distribution of vehicles and axle weights and types by lane and
4. The traffic growth at the given location.

The three Minnesota design procedures are the Soil Factor, the R-Value and the Mechanistic-Empirical (MnPAVE).

The Soil Factor Procedure uses the design year AADT and HCADT to categorize traffic as shown in Chapter 2. The methods for determining these factors are presented in Sections 3-2 and 3-3.

The R-value and MnPAVE procedures both use the summation of ESAL's over the design period for the facility. The estimation of ESAL's requires the following parameters, which are presented in Section 3.4:

• AADT	Section 3.4.1
• Vehicle Type Distribution	Section 3.4.2 assumed (Table 3.1) measured (Appendix 3.1)
• ESAL Vehicle Factors	Section 3.4.3. average for local roads(Table 3.2) sample calculations (Table 3.3)
• Growth Factors	Section 3.4.4. (Table 3.4)
• Design Lane Distribution	Section 3.4.5. (Table 3.5)
• Sample ESAL Calculations	Section 3.4.6. (Table 3.6)

A more comprehensive procedure for estimating ESAL's is available in a software package MNESAL2003 (20). MNESAL2003 considers the current and past characteristics of the traffic and predicts future trends from the recent past. MNESAL's is available from the MnDOT Office of Transportation Data and Analysis or the District Traffic Engineer.

It is recommended that county and city engineers estimate ESAL factors and Vehicle Type distributions for typical roads in their jurisdiction. Annual ESAL calculations can then be made for the traffic distributions experienced at specific locations.

A study was made to determine the effect of using statewide average vehicle type distributions for city and county roads rather than measuring the distribution using the procedure presented in Appendix B. Based on the comparisons of thicknesses determined with assumed distributions versus measured distributions at specific locations. Based on the thickness variations represented by the differences in traffic prediction the following recommendations are made:

1. For the Soil Factor Design:

a. If the AADT is 1500 or less the minimum design can be used without considering HCAADT and therefore not vehicle type distribution. If it is known that the heavy commercial traffic is very high because of a specific industry then provisions should be made.

b. The vehicle type distribution should be measured for a specific project if the AADT is greater than 1500.

2. For the R-Value design procedure:

a. There is essentially no relationship between AADT and ESALs. Therefore, either assumed or measured distributions can be used for a given project. Statewide averages are generally not appropriate.

b. Distributions at a given location can be estimated with the help of a Mn/DOT traffic engineer or using the procedure presented in Appendix B. The measurements should be carried out for a minimum of one week in the summer **and** one week in the fall.

3. When vehicle type distributions are measured or estimated the results should be reported to the Mn/DOT Office of Transportation and Data Analysis at Mn/DOT Mailstop 450 or e-mailing the information to

Melissa,thomatz@dot.state.mn.us

The coding for a given county or city should be used so that the data from around Minnesota can be coordinated to establish realistic distributions for various areas of the State.

In this way the information can be used to develop a database of vehicle type distributions throughout Minnesota.

4.Design calculations should continue to be made so that better relationships can be established between designs from "assumed" versus "measured" distributions.

5.Weigh-in-motion data should continue to be collected and analyzed to improve the ESAL factors for specific vehicle types in the traffic mix. The factors can be made more industry and location specific.

The Mn/DOT Procedure Manual for Forecasting Traffic on Minnesota's Highway Systems", (figures 27 and 28) present measured distributions on many roads throughout Minnesota. The manual was written by Mr. Mark Levenson of the Mn/DOT Office of Transporation Data and Analysis. For specific distributions measured around the State, he may be reached at: Mark.Levenson@dot.state.mn.us

As experience and technology in the measurement of traffic factors improves and more data are accumulated the procedures and factors presented in this chapter should continue to be up-dated.

CHAPTER 4
SUBGRADE (EMBANKMENT) SOIL DESIGN AND CONSTRUCTION

4.1. Background

Subgrade conditions are an influential factor on pavement performance. A stronger and stiffer subgrade will provide a more effective base for the pavement material. By improving the *in situ* soil conditions to approach more optimal characteristics, the pavement will be more resistant to repeated loading and environmental stresses. The *in situ* conditions must be considered carefully, and if there is a problem with frost-susceptible or variable soils, appropriate changes should be made. The subgrade must be strong enough to resist shear failure, while having adequate stiffness to limit significant deflection. To accomplish this effectively adequate drainage is necessary. The necessary amount of support must be well understood in order to design a subgrade that will withstand the expected traffic volume and loads. Modification of the soil may be necessary depending on the *in situ* soil and local moisture conditions. The subgrade design should allow for construction processes with local resources that can achieve the desired support and maintain that condition for the life of the road.

The embankment soil on which a pavement is built is the most important part of the structure because:

- It is the layer on which the remainder of the structure is supported and helps resist the destructive effects of traffic and weather.
- It acts as a construction platform for building subsequent pavement layers.
- If there are embankment performance problems due to lack of strength or uniformity, the entire pavement structure will have to be removed and replaced.

It is, therefore, imperative that the embankment be built as strong, durable, uniform, and also as economically as possible. The most economical embankment is one that will perform well for many years. Because of the many different soil and moisture conditions, which can occur along the grade on any project in Minnesota, the balance between these items is critical.

The following steps need to be followed so that adequate stiffness, strength and uniformity can be achieved most economically:

- Perform soil survey and sampling
- Determine representative design factor(s)
- Setup appropriate specifications
- Carry out construction details according to specifications

Based on the characteristics of the soil sampled on the given project, a representative design value for the soil must be established. For current pavement design methods in Minnesota this will be the Soil Factor, R-value and/or the Resilient Modulus (M_r). These design values can be measured in the field, the laboratory, or estimated from soil classification tests and calibrations.

4.2 Soil Surveys and Sampling

A good soil survey and sampling program will provide essential information on the TYPE and EXTENT of soils to be encountered on a project. Three methods are available to conduct soil surveys:

- Local soil maps,
- Previous records of soil surveys on the same grade,
- Auger borings using techniques recommended in the MnDOT Geotechnical and Pavement Design Manual (5).

The soil survey will help establish where there are changes in soils especially at transitions from one soil type to another. The different soil types may require different moisture-density and field control criteria. Standard methods should be used for classification of the soils so that meaningful decisions can be made with respect to design and construction procedures. Borehole samples should be taken, where the grade changes from cut to fill or fill to cut, a change in soil type, or a change is drainage conditions. Boreholes should be placed every 150 m (500 ft). Modification of the interval will be necessary for individual locations depending on the complexity of the in situ soil conditions.

Generally, soils are field classified using the Triangular Textural Classification system or the AASHTO Classification presented in the MnDOT Geotechnical and Pavement Design Manual (5). Use of this procedure for classifying and sampling the soils can give the design staff the information needed for preliminary thickness design and design of the grade. Sufficient quantities of each soil type from a project need to be obtained for laboratory testing of the material to determine AASHTO Classification, R-Value (measured or predicted) and Resilient Modulus (M_r) (measured or predicted).

The number of samples taken over the length of the project must be sufficient to determine the amount and extent of improvement necessary to ensure uniformity throughout the project. The sampling rates (Table 4.1) given are estimates and more frequent sampling in soil type transition zones is suggested to ensure maximum uniformity is reached (5).

Table 4.1 Sampling Rates (5)

Major Soil Texture	Recommended Minimum Sampling Rate	Minimum Number of Samples
Sands	0 (assume an R-value of 70 or 75)	0
Clays, Clay Loams	1 every 3 km	3
Sandy Loams (nonplastic to slighty plastic)	2 per km	5
Silt Loams	2 per km	5
Silty Clay Loams	2 per km	5
Plastic Sandy Loams	2 per km	5

4.3 Subgrade Soil Design Factors

4.3.1 General

Each of the Minnesota Flexible Pavement Design procedures classify subgrade soils in a different way:

- The Soil Factor Design uses the AASHTO Classification of the soil to select the appropriate Soil Factor (4).
- The R-value design uses the Stabilometer R-value laboratory test to determine a laboratory-measured stiffness. A higher R-value indicates a higher stiffness, which will, generally require less thickness.
- The Resilient Modulus (M_r) is the soil input for MnPAVE. Currently, there is not a standard laboratory test for measuring resilient modulus; however, it has been correlated with R-value and AASHTO Classification (7). The results now being finalized are summarized in Section 4.3.2.3.

The correlations between Soil Factor and R-value are based on testing and experience in Minnesota over the past 30 years. The relationships used for R-value and Resilient Modulus is presented in the 1993 AASHTO Pavement Design Guide (19). In this section the relationships between soil classification, Soil Factor, R-value and Resilient Modulus are presented. These relationships have been summarized in table form by Siekmeier and Davich (7) and also partially listed in Table 4.4.

4.3.2 Laboratory Testing

Soil tests such as resilient modulus an R-value are used to estimate the properties of the soil and may be used to estimate other parameters. The MnDOT Road Research Section has developed a comprehensive correlation table relating soil classification, soil strength tests, to seasonally varying design moduli. The seasonal factor (SF), which relates the moduli throughout the five seasons as defined in MnPAVE (6), is determined by the change in average FWD results collected at the MnROAD test site. This table has been developed to help predict appropriate resilient modulus input values for MnPAVE, for a given soil. These important design moduli for subgrade design are given in Table 4.4.

4.3.2.1 The AASHTO Soil Classification System:

The AASHTO Soil Classification System was developed in the 1920's and is used to give a general idea of how well a soil will perform in a pavement system. Soils are classified based on gradation and Atterberg Limits. The classes range from A-1 through A-7. A-1 soils are very good materials for highway construction and A-7 soils are poor. Table 4.2 shows the gradation and Atterberg Limits for the various soil classes.

- Gradation for the AASHTO soil classification using the 0.425-mm (No. 40) and 0.075-mm (No. 200) sieves needs to be determined, using a washed sieve analysis as described in the AASHTO T-27 Procedure.
- Atterberg Limits – The Plastic Limit and Liquid Limit are used to define the characteristics of fine-grained soils.
- The Plastic Limit is defined as the moisture content at which the soil transforms from a friable state to a plastic state. It is determined using the AASHTO Method T-90 for which a small sample of the soil is rolled into a 3 mm (1/8 in.) diameter ribbon.
- The Liquid Limit is defined as the moisture content of a fine-grained soil at which it transforms from a plastic state to a liquid state. It is determined using AASHTO Method T-89 for which a sample of soil about 25 mm (1 in.) thick is

placed in a bronze dish, a groove is put in the sample and the number of drops of the cup is counted until the groove closes about 25 mm (1 in.) The Liquid Limit is the moisture content that requires 25 drops of the cup.

- The Plasticity Index (PI) is defined as the difference between the Liquid Limit and the Plastic Limit. The PI gives an indication of how much and how active the clay in the sample is.
- When run according with the standard AASHTO or ASTM Procedures the Plastic Limit and Liquid Limits are quite repeatable tests.
- Table 4.3 shows the conversion of AASHTO Classifications to Soil Factors according to the State Aid Manual (4).

Textural Class	Identification by "Feel"	Ribbon Length	AASHTO Group (H.R.B. Class)	Group Index	Rating For Upper Emb.
Gravel (G)	Stones: Pass 3" sieve, Retained on #10	0	A−1−a	0	Excellent
Fine Gravel (FG)	Stones: Pass 3/8" sieve, Retained on #10	0	A−1−a	0	Excellent
Sand (S)	100% pass #10. Less than 10% silt & clay.	0	A−1−a	0	Excellent
Coarse Sand (CS)	Pass #10, Retained on #40	0	A−1−a or A−1−b	0	Excellent
Fine Sand (FS)	Most will pass #40. Gritty−non plastic	0	A−1−b or A−3	0	Excellent to Good
Loamy Sand (LS)	Grains can be felt, Forms a cast.	0	A−2−4 or A−2−5	0	Excellent to Good
Sandy Loam (SL)					
a. slightly plastic	0−10% clay. Gritty	0−1/2"	A−2−6 or A−2−7	0	Excellent to Good
b. Plastic	10−20% clay. Gritty	1/2"−1"	A−4	0−4	Excellent to Good
Loam (L)	Gritty, but smoother than SL.	1/4"−1"	A−4	0−4	Excellent to Good
Silt Loam (SiL)	Smooth, slippery or velvety. Little resistance.	0−1"	A−4	0−4	Fair to Poor
Clay Loam (CL)	Smooth, Shiny, considerable resistance.	1"−2"	A−6	0−16	Good to Fair
Silty Clay Loam (SiCL)	Dull appearance, slippery, less resistance.	1"−2"	A−6 or A−5	0−16	Fair to Poor
Sandy Clay Loam (SCL)	Some what gritty. Considerable resistance.	1"−2"	A−6 or A−5	0−16	Good to Fair
Clay (C)	Smooth, shiny, long thin ribbon.	2"+	A−7	0−20	Fair to Poor
Silty Clay (SiC)	Buttery, smooth, slippery.	2"+	A−7 or A−7−5	0−20	Poor
Sandy Clay (SC)	Very plastic but gritty. Long thin ribbon.	2"+	A−7 or A−7−6	0−20	Fair to Poor

Note: Where the group index is expressed as a range, such as 0−16, the lower values are the better foundation soils.

Table 4.2 AASHTO Soil Classification (5)

Table 4.3 AASHTO-Soil Factor Correlation (4)

AASHTO Classification	Soil Factor
A-1-b, A-2-4, A-3	50 – 75
A-4, A-6	100
A-7-5	120
A-7-6	130
A-5*	130+

*an A-5 soil occurs very rarely in Minnesota

An A-1-b soil can have a range of soil factors from 50-75 depending on other conditions such as drainage or other environmental factors.

4.3.2.2. Stabilometer R-Value

The Stabilometer R-value has been used in Minnesota since 1970 to measure the stiffness of embankment soils. The laboratory procedure generally follows AASHTO-T-190. The procedure includes the use of a kneading compactor. The sample is then subjected to a final static compaction to compress the soil to the point water is exuded; called the exudation pressure. In Minnesota an exudation pressure of 1.65 MPA (240 psi) is used. This compaction has been correlated best with field conditions. Compacted specimens are then put in a device to measure swell pressure while being soaked over night.

The Stabilometer R-value is then measured by placing the compacted sample in a device, which measures horizontal pressure (p_h) when a given vertical pressure is applied. A lower horizontal pressure results in a higher R-value. Equation 4.1 is used to calculate the R-value (21).

$$R = 100 - \frac{100}{\frac{2.5}{D} * \left(\frac{p_v}{p_h} - 1 \right) + 1} \tag{4.1}$$

Where: D = Turns displacement (Fig. 4.1)

p_h = Horizontal pressure (stabilometer gauge reading at 1103 kPa (160 psi) vertical pressure p_v)

Over the years MnDOT and others have conducted stabilometer tests on soils throughout Minnesota. The R-value can be either used as input for the R-value (G.E.) thickness design procedure or as a method to predict the Resilient Modulus (M_r) of the soil as input for the MnPAVE method.

The R-Value has been correlated with AASHTO Soil Type in Table 5-3.2(a) of the MnDOT Geotechnical and Pavement Manual (5). A general correlation with Textural Class is also shown. Table 5-3.2(b) lists assumed R-Values for granular subgrade, subbase, and base courses. This table is for properly constructed AASHTO Soil Types A-1-a, A-1-b and A-3 soils.

Correlations between Soil Classification(s), R-Value and the sets of seasonal moduli are presented in Table 4.5. This is a portion of the comprehensive table and correlations used in the MnPAVE software described in Chapter 2 (7).

The NOTES accompanying the tables in the Geotechnical and Pavement Manual are very important. To attain the stiffness indicated by the R-value or any other procedure the soil must be constructed in a uniform manner with proper density and moisture control. Section 4.5 covers construction control and recommended procedures more completely.

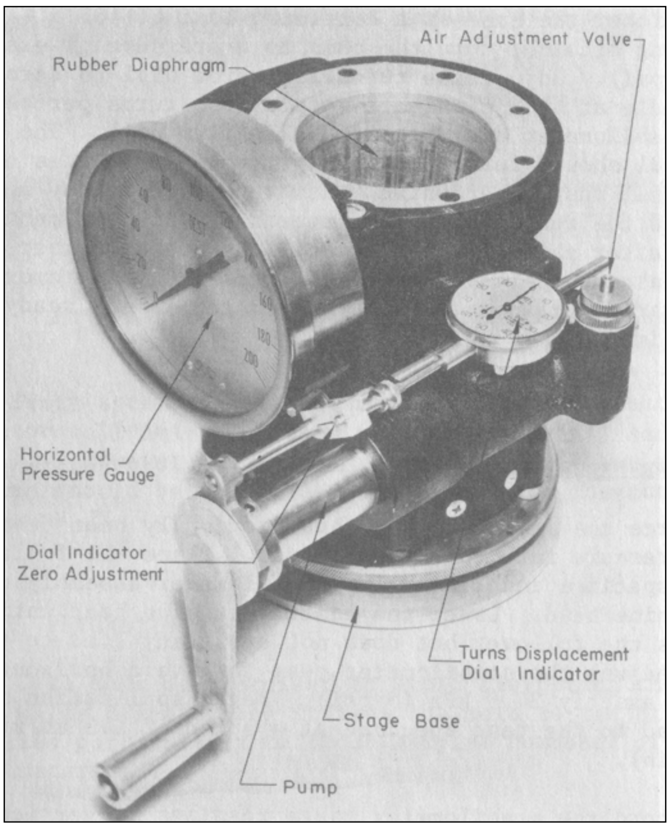


Figure 4.1 Stabilometer R-value Testing Apparatus (22)

4.3.2.3 Resilient Modulus

The Resilient Modulus (M_r) is used to indicate the stiffness of the pavement materials including the subgrade. M_r is analogous to Young's modulus, in that it is the measurement of the recoverable elastic strain of the soil. The M_r values are used for mechanistic-empirical design procedures including MnPAVE. The M_r varies with density, moisture content, age, and position. During the SHRP Program a standard procedure, now AASHTO P46 was developed to measure M_r (22). This procedure is now being modified to more accurately measure the loading and deformation to which the sample is subjected.

The response of the *in situ* soil to repeated loadings will change throughout the year. The reason for this variation is the changing moisture and freeze-thaw conditions. When the soil mass is frozen throughout the entire embankment, the response of the soil to loading will be almost entirely recovered. This can be represented by a very high M_r value.

AASHTO P46 is a repeated load triaxial test for which a confining stress is applied and the deformation under a repeated vertical haversine stress is measured (22). The modified procedure includes a load cell and strain measurement devices inside the triaxial cell as indicated in Figure 4.2. A 0.1-sec load is applied after which a 0.9-sec rest period is used, illustrated in Figure 4.3. The recovered deformation is used for calculating the M_r.

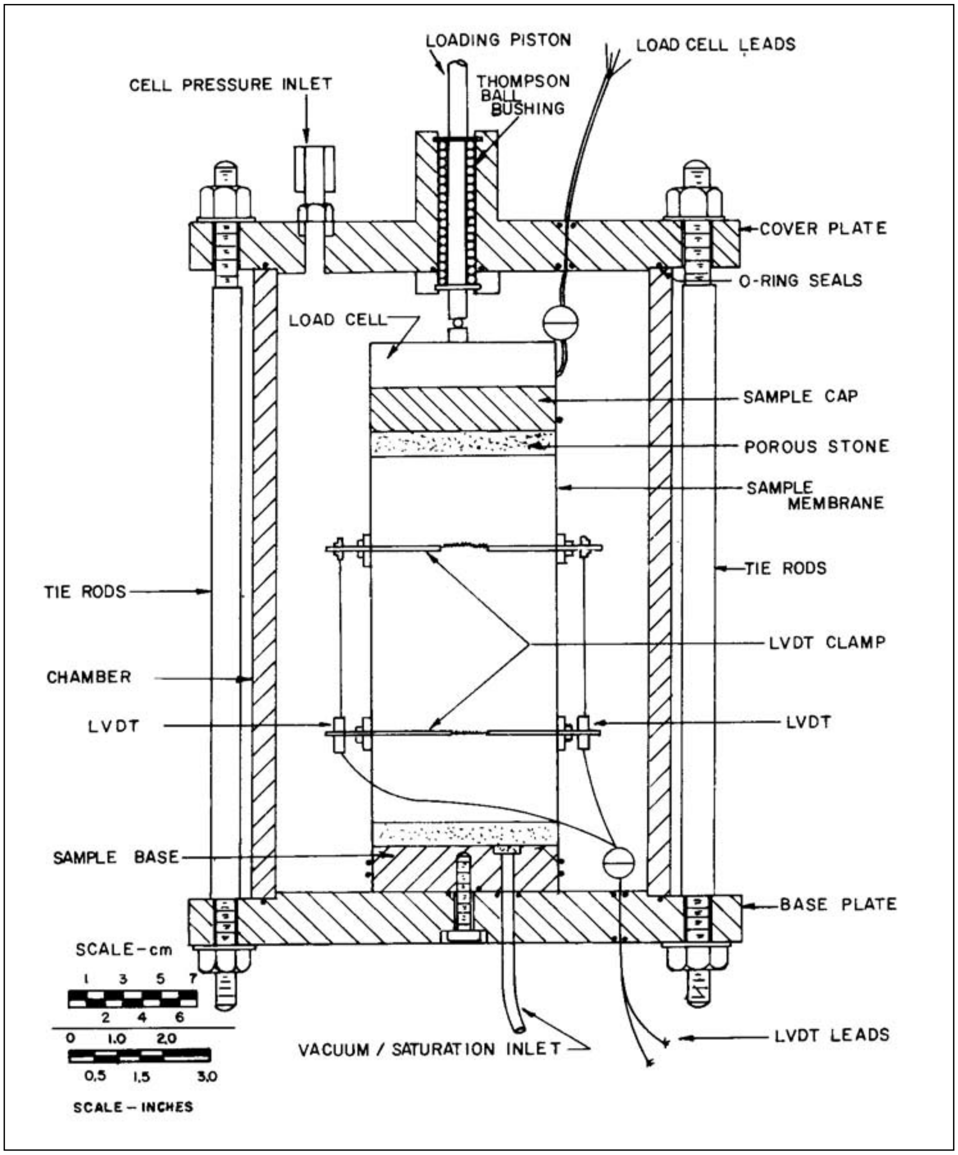


Figure 4.2 Resilient Modulus Testing Apparatus (22)

The deviatoric stress is applied for 200 cycles, with the displacements and recovered strains recorded for the last 50 cycles. The recovered strains from the last 50 loadings are then averaged to determine the resilient modulus. The confining and deviatoric stress should be selected to reflect the expected field conditions. A confining pressure of 14 kPa (2 psi) and a deviatoric stress of 41 kPa (6 psi) are used for AASHTO P-46 (23). It is anticipated that the modified P46 Procedure will be used for the modulus testing for the 2002 AASHTO Design Guide (12). MnDOT and one consultant laboratory, in Minnesota are currently setup to run the Mn/DOT modified AASHTO P46 test.

When running AASHTO P-46 the materials are defined as Material Type 1 and Material Type 2. Material Type 1 includes all unbound granular material used as subbase and base and untreated subgrade soils which meet the criteria of less than 70% passing the 2.00 mm (No.10) sieve and less than 20% passing the 0.075 mm (No. 200) sieve. Material Type 1 soils are run using a 150-mm (6 in.) diameter sample (5).

Material Type 2 includes all unbound granular base/subbase and untreated subgrade soils not meeting the Type 1 criteria. Remolded Type 2 materials are to be tested using a 71-mm (2.8-in) diameter specimen (5).

The resilient modulus (M_r) (Eq. 4.2) is the ratio of the amplitude of the cyclical deviatoric stress (σ) to the amplitude of the resultant recoverable axial strain (ε), which is illustrated in Figure 4.3.

$$M_r = \frac{\Delta\sigma_{axial}}{\varepsilon_{axial}^{recov}} \tag{4.2}$$

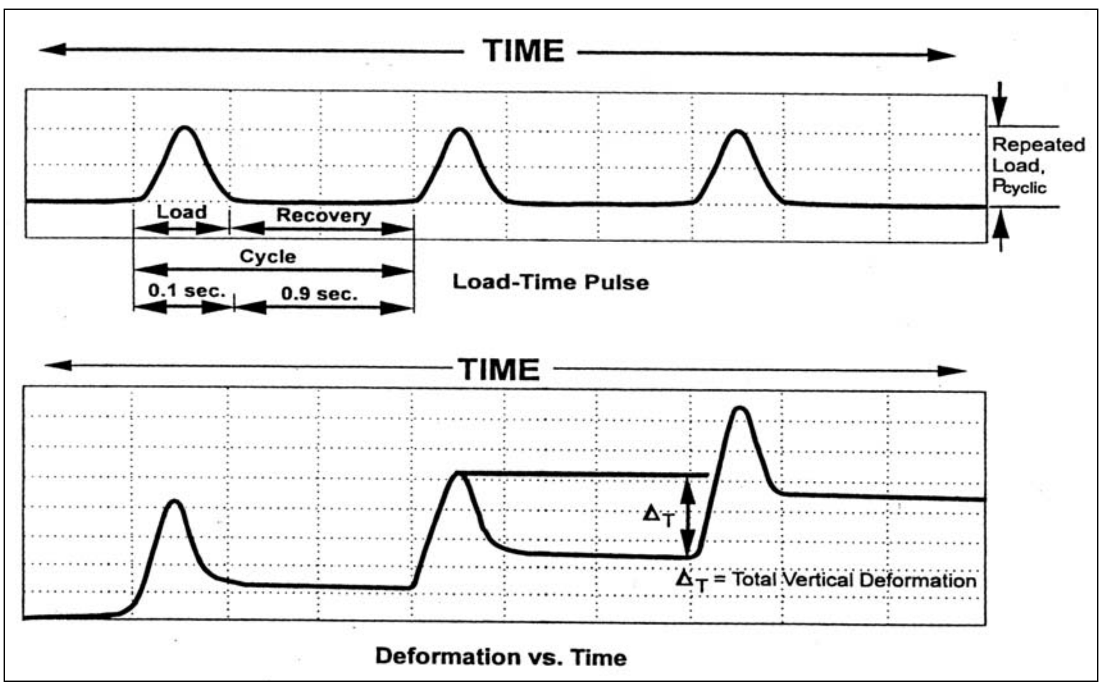


Figure 4.3 Load and Deformation vs. Time for Resilient Modulus Test (5)

4.3.3. Field Measurements of Subgrade Stiffness

4.3.3.1 General

Resilient modulus can be determined in the field, by many different methods. The original method for determining the modulus of the pavement and soils was the Plate Load Test (15). The primary drawback to this device is that each layer must be removed in order to test the layer below. The Falling Weight Deflectometer (FWD) and other surface devices are major improvements over the Plate Load Test because they are non-destructive, and are able to determine the moduli for the layers below the surface with a single test. They can test the same location more than once in order to monitor change over time. One of the advantages over the plate load test is that multiple tests at different locations can be run in a short period of time, in order to determine the changing conditions along the road. The Dynamic Cone Penetrometer (DCP) is a destructive device that is used to test soil (24). The limit of the soil disturbance is small, approximately 100 mm (4 in.). As with the FWD, the DCP can be run at many locations in a short period of time, making it very useful for determining the variation along the embankment during construction. These testing mechanisms allow the collection of large quantities of data, over a large area, in a short period of time. The ability to collect data quickly allows for seasonal variations to be measured and understood because the test is non-destructive. The changing characteristics at a particular location can be accounted for in the design procedure.

4.3.3.2 Falling Weight Deflectometer

The Falling Weight Deflectometer (FWD) is a device designed to measure the deflections produced by a dynamic (falling) load. The device may be hand operated or mounted in a vehicle. Mounting the FWD to a vehicle allows for rapid data collection by decreasing the time between measurement sites. The basic idea is to measure the deflection caused by loading. The load in this case is a falling mass; the means of measurement is dependant on design and extent of data that are to be collected. The FWD measures the deflection at a distance of 0 to 1.5 m (0-5 ft) at 0.3 m (1 ft) intervals (25). The locations of measurements are shown in Figures 4.4. The shape of the deflection basin is indicative of the modulus of the layers (Figure 4.4). The deflection near the load plate is representative of the modulus of the upper layers, and the deflections measured further away represent the modulus of the lower layers.

The primary deflection measured is due to a static load, where only the only the peak value of the deflection in recorded. The loading is interpreted as a single mass placed on the material being tested. Another method is with a dynamic approach, measuring the entire impact-deflection relation. This procedure will lead to a more thorough understanding of the elastic properties of the underlying materials. The dynamic approach should be used if the bedrock is within 6 m (18 ft) (26). However, it is thought that the static method of measurement yielding the maximum deflection will give adequate information for proper subgrade design, when the bedrock is deeper than 6 m (18 ft).

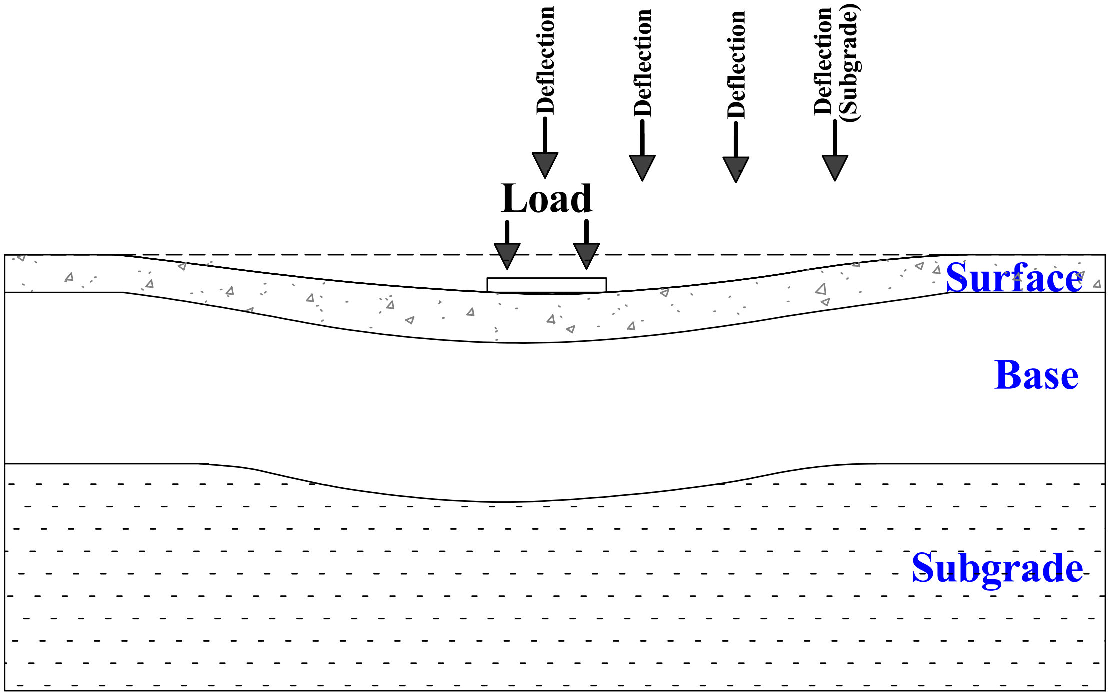
The modulus of the soil is then backcalculated for the measured deflection basin. There are many algorithms commercially available, such as, EVERCALC, WESTEV, and the HOGG model. The following information must also be known about the pavement section to obtain a good estimate of the pavement moduli:

a. Accurate determination of pavement and embankment layer thickness

b. Determine presence and location of relatively stiff layer

c .Reasonably accurate initial estimate of the moduli

Ground penetrating radar has been used successfully to determine layer thickness and the depth of the bedrock (26).



Deflection Basin Shape is a Function of:

1. Thickness of Layers
2. Elastic Modulus of Layers

Figure 4.4 Falling Weight Deflectometer Deflection Basin

4.3.3.3. Dynamic Cone Penetrometer

The Dynamic Cone Penetrometer (DCP) has been in use for the past 20 years. The test consists of a falling mass that forces a standard cone with a diameter of 20 mm (0.8 in) and an angle of 60° into the soil being tested. The MnDOT design DCP is illustrated in Figure 4.5. The amount of penetration is recorded after each blow from the hammer (24). The test is usually run until a penetration of 0.75-1.0 m (2-3 ft) is achieved. A cone with an angle of 30° can also be used for stiffer soil. The hammer has a mass of 8 kg (17 lb) and a drop distance of 575 mm (23 in.). The rate of movement into the soil with each blow is called the Penetration Index (PI), expressed in mm per blow. The PI has been correlated to the California Bearing Ratio, unconfined compressive strength, elastic modulus, and shear strength of cohesionless granular soils (7). With this correlation the design parameters that are desired can be determined, from the DCP data. This test is useful because the information can be easily converted into the form that is most useful to work with for a specific project. Another similar machine is the instrumented DCP (iDCP). The iDCP is capable of collecting the same information as both the DCP and FWD, however the drawback to the iDCP over the FWD is that it is a destructive test (27).

Table 4.4 General Correlations for Strength and Stiffness Tests

Soil Type	CBR Range	FWD MPa	DCP mm/blow	R-value 240 psi exudation pressure
Clay (CL)	< 15	27-31	30+	10-40
Sand (S-W)	5– 40	70	14-30	N/D
Gravel (G-W)	20–80	70	14	N/D

4.3.3.4. Additional *In Situ* Factors

There are many other parameters that can be examined. Density and moisture content are two of the most common and well understood. Increasing the soil density is one of the easiest ways to improve strength and stiffness, therefore limiting response to loading. If this is done with optimum water content (AASHTO T-99) the maximum density can be achieved, yielding the stiffest condition for the material. The water content that will be achieved in the future due to precipitation and runoff must also be considered in order to limit possible degradation from pumping or excessive soil creep.

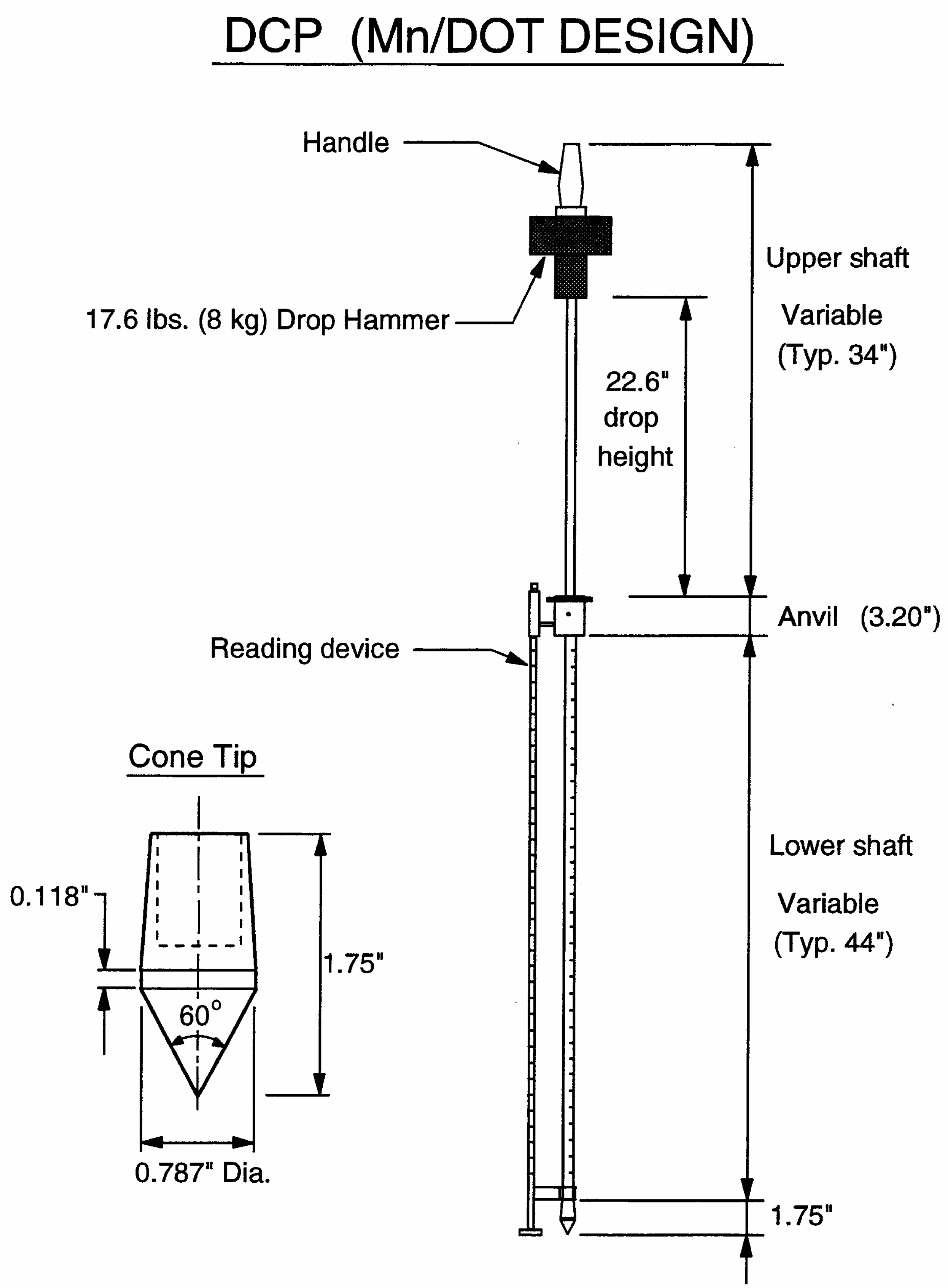


Figure 4.5 Mn/DOT Dynamic Cone Penetrometer

4.3.4. Use of Subgrade Design Factors

4.3.4.1. General

The Minnesota DOT currently has three methods of asphalt (flexible) pavement design.

- The Soil Factor
- The R-Value (Granular Equivalent)
- The Mechanistic Empirical (MnPAVE)

The embankment characterization depends on the design procedure selected. Proper subcutting and mixing will limit the variation of soil characteristics that have to be overcome in order to achieve a more uniform embankment. Compaction to AASHTO T-99 density will increase strength. Constructions specifications are summarized in Section 4.5. Other methods of embankment stabilization can be employed to increase strength, such as the addition of lime, portland cement, or various bituminous materials. Subgrade enhancement is covered in Section 4.6.

4.3.4.2. Soil Factor

The Soil Factor design procedure is dependant on the AASHTO classification system. The construction process to be used for a soil depends on the soil class. If the soil varies over the project area then embankment construction should be specified in relation to the most critical soil type. More information can be found in the State Aid Manual (4).

4.3.4.3. R-Value

The R-Value is preferred over the Soil Factor, because it provides a measure of the strength and stiffness of the soil. The current MnDOT design procedure is presented in the Geotechnical and Pavement Design Manual (5). The existing information for this design factor is extensive, covering most of the soil types encountered in Minnesota. A correlation has been made between Soil Factor and AASHTO classification system. The R-Value can be correlated with resilient modulus for use in the MnPAVE program (7).

4.3.4.4. MnPAVE

MnPAVE is a computer program available through MnDOT for thickness design of the HMA surface, base, and subbase for a given subgrade. MnPAVE has the ability to account for seasonally changing water conditions with the use of seasonal factors (Table 4.5). The Resilient Modulus is varied using the seasonal factor determined at MnROAD in order to account for the amount and state of water present (8). Winter and early spring are given a default resilient modulus of 350 MPa (50 ksi) for the subgrade; this is because the water in the soil is frozen creating a very stiff material. In contrast, the base is given a seasonal factor of 0.3 for the early spring verses the summer value of 1. This very low seasonal factor is used because the base and subbase are thawed and saturated, while the subgrade is frozen prohibiting the water from draining. The thawed base causes the strain on the thawed layers to increase during the early spring. This change in stress conditions cannot be accounted for by other design factors. The application of this change in seasonal conditions to design criteria is a significant advance in embankment design. MnPAVE is currently under development by MnDOT and is available on the Mn/DOT website. Table 4.5 shows the correlations developed by Siekmeier and Davich (7) relating soil classification, R-Value, and Resilient Modulus. In this way the stiffness characteristics of a soil can be estimated from the soil classification or stabilometer R-Value.

Table 4.5 MnPAVE Design Moduli Correlations (7)

Soil Classification			Strength Tests				MnPAVE Design Moduli							
Textural Class	AASHTO	MnDOT Soil Factor	R-Value (240 psi Exudation Pressure)		CBR Percentage	DCP mm/blow	Winter & Early Spring		Late Spring		Summer		Fall	
			Estimated	Measured	Estimated	Estimated	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
Gravel (G)	A-1	50-75	70	ND	21	12	350	50	62	9.0	78	11	78	11
Sand (Sa)	A-1 A-3	50-75	70	ND	21	12	350	50	62	9.0	78	11	78	11
Loamy Sand (LSa)	A-2	50-75	30	46 - 74	6.2	22	350	50	33	4.8	41	6.0	41	6.0
Sandy Loam (SaL)	A-2 A-4	100-130	30	17 - 49	4.4	27	340	50	27	4.0	34	5.0	34	5.0
Loam (L)	A-4	100-130	15	14 - 26	4.2	27	330	48	27	3.9	33	4.8	33	4.8
Silt Loam (SiL)	A-4	100-130	12	10 - 40	3.9	28	320	46	26	3.7	32	4.6	32	4.6
Sandy Clay Loam (SaCL)	A-6	100-130	17	14 - 27	4.5	26	350	50	28	4.0	35	5.0	35	5.0
Clay Loam (CL)	A-6	100-130	13	13 - 21	4.1	28	330	48	26	3.8	33	4.8	33	4.8
Silty Clay Loam (SiCL)	A-6	120-130	10	11 - 21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Sandy Clay (SaC)	A-7	120-130	14	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Silty Clay (SiC)	A-7	120-130	8	ND	3.4	30	300	43	24	3.5	30	4.3	30	4.3
Clay (C)	A-7	120-130	12	10 - 17	3.9	28	320	47	26	3.7	32	4.7	32	4.7

4.4. Subgrade (Embankment) Soil Construction

4.4.1. General

To achieve the design values estimated for the actual embankment soils in the field, proper construction practices must be followed. These start with specifications that help define good construction. The specifications that pertain to embankment soil construction, general construction design considerations and some field checklists are presented.

4.4.2. Specifications

Mn/DOT has three specifications that pertain to the construction of embankments. These are Specifications 2105, 2111, and 2123. Specification 2105 "Excavation and Embankment" includes two types of density control. These are "Specified" (sand cone) and "Quality" (visual) compaction (9). Both methods state that compaction must be accomplished to the satisfaction of the engineer. For "Quality" compaction an experienced engineer or inspector must be on the project to judge if adequate compaction is achieved. For "Specified" compaction the judgment of the engineer is aided by the determination of a measured density. The density must be measured using the representative moisture-density test for the soil being constructed. The **Specified Density Method** is recommended by Mn/DOT (11).

Specification 2111 presents the test rolling method for subgrade acceptance. Test rolling is a supplement to Specification 2105. Test rolling evaluates uniformity and consistency of subgrade support relative to rutting. Test rolling will detect weak/unstable areas due to inadequate compaction or high moisture content. Failed areas will require corrective measures which could include removing the unstable/unsuitable materials, reducing moisture content and recompaction of the soils.

Test rolling is <u>not</u> recommended for the following situations:

- Areas having less than 0.75 m (30 in.) subcut backfill in depth. These areas would probably not pass 2111 requirements.
- Areas having shallow underground utilities or structures.
- Areas having closely spaced bridges.
- Areas where geosynthetics are placed within the upper 1.7 m (5 ft) of the subgrade (10).

An experienced inspector can determine where soft spots occur in the constructed subgrade and make sure measures are taken to correct these. The test roller method of compaction control is recommended along with Specification 2105 because almost total coverage of the embankment grade construction is possible.

Specification 2123 lists the equipment and characteristics of the equipment required to carry out recommendations.

- Excavation and Embankment Construction

  1. Ideally, the finished grade should be kept at least 1.7 m (5 ft) above the water table in order to reduce capillary moisture and should be at least equal to the depth of frost penetration in order to minimize frost heave. A minimum height of 1 m (3 ft) should be maintained.

  2. The existing soils and their preparation; including subgrade correction, embankment placement, and protection of the completed embankment need to be considered.
- Soils Evaluation: Soils must be evaluated based on whether they are suitable or unsuitable, excavated soils, salvaged materials or borrow.
- Soils Preparation: Proper preparation of the soils for good uniformity involves reworking, blending, mixing, and enhancing the existing materials. The mixing of existing soils will help eliminate pockets of high moisture and unstable soils. Subcutting, and/or mixing and proper compaction will help provide a uniform subgrade. Proper compaction can be verified with specified densities and test rolling. Lime or other treatments for moisture control may be considered.
- Subgrade Correction: Subcuts must be made to ensure uniformity of material and stability in the upper portion of the embankment. Subcuts are used to reduce or eliminate differential or pocketed high-moisture conditions, unstable materials, frost heave potential and non-uniform subgrade conditions. Typical subcut depths range from 0.6 to 1.2 m (2 to 4 ft) with a 0.3 m (1 ft) minimum. Subcuts must be used especially where there are silty type soils, which are particularly frost susceptible. In areas of the embankment that may generate frost heaves the subcut depth must extend below the frost line. The subcut should be backfilled with select granular material. If it is not practical to use select granular, then the existing soil should be mixed uniformly to a moisture content appropriate for good compaction. Drains may be needed in the bottom of the subcut to assure that water does not collect in the subcut.
- Placement of Embankment and Backfill Materials: As embankment materials are placed, the same soil should be used throughout each layer to prevent non uniform moisture and drainage conditions.

- Compaction: Compaction must be performed in accordance with Mn/DOT Specification 2105 supplemented with 2111 using the equipment specified in Specification 2123.

4.4.3. General Design Considerations

Based on the soil type, project conditions, structural design and specifications, certain procedures need to be established and followed to achieve good embankment construction. The goal is to provide a strong and uniform embankment for the pavement structure. Many of the procedures presented depend on the type of soil encountered on the project. As the project is started variations in the soils may be encountered and therefore the field engineer and inspector must be aware of the effect of these changes.

4.4.4. Construction Notes and Procedures

The Mn/DOT Office of Construction, Technical Certification Section has published an "Inspector's Job Guide for Construction" (11). This Guide gives the inspector a checklist that will help get a project started and document the parameters and procedures that need to be considered based on the specifications. One item in particular that will help keep a project under control is for the inspector to keep a good daily diary. This will help all people involved with the project feel confident that work is progressing at an appropriate rate and that the inspection work is being accomplished (11).

4.5. Subgrade Enhancement

4.5.1. General

Many different procedures have been used to enhance the performance of a subgrade. The methods that have been used with varying degrees of success are the following:

- Improvement of existing materials using density and moisture control (Section 4.4).
- Modification of existing materials; lime
- Stabilization;
  fly ash, lime-fly ash, bituminous emulsions

- Separation using geofabrics to keep fine-grained saturated soils from infiltrating into granular base/subbase materials
- Reinforcement using geogrids to support subgrade over soft areas
- Substitution with more suitable or lighter weight and/or more uniform materials; examples are select granular, shredded tires, wood chips, geofoam

Some of the procedures have been tried by Mn/DOT and others by cities and counties. Minnesota Local Road Research Project 772 is a study of the use of various methods of modification, stabilization and reinforcement in Minnesota and surrounding states.

4.5.2. Enhancement Summary of Existing Soils on Grade

The following parameters are considered to enhance on-site soils.

- drainage
- compaction
- moisture content adjustment

Drainage commonly refers to the removal of surface and/or subsurface water. **Surface drainage** is the removal of watershed runoff and is accomplished through using storm sewers, ditches, culverts or bridges.

Subsurface drainage is the removal of infiltrated water in the pavement and is accomplished through the use of impermeable barriers, pipes, drains and geosynthetics (36).

Compaction is the most common method of enhancement. Compaction refers to increasing the soil density by mechanical means, such as the use of heavy equipment (37). Higher soil density for the same moisture content will result in a stiffer and/or stronger subgrade soil.

Moisture content adjustment refers to either the removal of moisture by mechanical or chemical methods (10).

4.5.2.1. Drainage

General

The Mn/DOT Geotechnical and Pavement Manual, 1994 (5) notes that the performance of a base (or subgrade) will be proportional to its degree of saturation. Drainage systems may be utilized to prevent decreased strength from frost heave from volume changes below the surface and lower inter-particle friction resulting from increased pore water pressure (5).

Two common types of drainage systems are longitudinal edge drains and permeable base layers. Longitudinal drains can be built-in or retrofitted. Filter materials and pipes are used to enhance the effectiveness of longitudinal drains. Permeable base layers utilize gradations having a large top size and few fines (5). The quality of subsurface drainage is dependent on soil permeability, location of seepage within the system, the type of filter material and the type or size of the underdrain pipe (5).

Design Factors

There are three drainage options for reconstruction projects:

- design a permeable base with edge drains
- daylight the base
- use longitudinal edge drains only.

Note that daylighted bases are prone to clogging and are not recommended and the effectiveness of longitudinal edge drains is limited if the base is not permeable (5).

Permeable bases may be treated with asphalt (2-5% by weight) or Portland cement (2-3 bags/cubic yard) for strength in construction. A separator layer should be installed a minimum depth of 4 in. (102 mm) below the permeable base to prevent the migration of fine aggregate particles. Aggregate should have a dense gradation meeting the following uniformity requirements:

- $\frac{D15}{D85} \text{ of } \frac{\text{filter}}{\text{subgrade}} \text{ and } \frac{\text{base}}{\text{filter}} \leq 5$
- $\frac{D50}{D50} \text{ of } \frac{\text{filter}}{\text{subgrade}} \text{ and } \frac{\text{base}}{\text{filter}} \leq 25$
- $20 \leq \frac{D60}{D10} \leq 40$

Where:

D15 = Maximum particle size at which 15 percent of the aggregate is finer.

D50 = Maximum particle size at which 50 percent of the aggregate is finer.

D85 = Maximum particle size at which 85 percent of the aggregate is finer. These specifications will minimize the infiltration of one layer into a neighboring upper or lower layer.

Subsurface Hydrology

Drainage systems typically remove water from infiltration and groundwater sources. Darcy's Law characterizes water movement for saturated conditions. In order to calculate the quantity of water in the pavement system the designer must estimate the permeability coefficient and the hydraulic head in the system. Permeability may be measured with field methods, lab permeability tests or estimates from a soil grading analysis. Hydraulic head data may be collected from observing the location of wet stratum when collecting soil borings (5).

A drainage system should maintain adequate capacity since it may be used to drawdown the water table, intercept lateral seepage above an impervious pavement layer, drain infiltrating surface water, prevent capillary rise or collect discharge from other drainage systems. It is important to use an analysis for determining the design requirements. The analysis must include:

- location of seepage areas
- maximum rate of flow into the pavement structure
- type of filter material for drains
- type of drain rock for below-pavement use (single sized material)
- data on the local climate including expected frost heave (5).

Drainage Analysis

There are two commonly used analysis methods. (i.) Time-to-Drain and (ii.) Inflow-Outflow estimates.

i. Time-To-Drain

A **Time-to-Drain** analysis considers the damage that is likely to occur at an 85 percent saturation level. This method of analysis should be used with caution since it does not consider rainfall. Since dense soil gradations will generally not have enough permeability to comply with the FHWA recommendation of 50 percent drainage in 1 to 2 hours (for Interstates and freeways) they must often be improved. The choices for improvement are:

- increase the permeability of the base
- increase the cross slope
- decrease the length of the flow path (5).

ii. Inflow-Outflow

Inflow-Outflow analysis uses a calculated Qin (a representative value is approximately 0.23 m^3/day/m (2.4 ft^3/day/ft) to design drainage that removes infiltrated water under fully saturated conditions and limits the time of saturation to a short duration after rain stops. This method usually requires a base permeability that is higher than the Time-to-Drain method.

Drainage during Construction

Some common approaches to drainage enhancement during construction are to:

- Make wet cuts in stratified material and install toe drains and cross-drains.
- Alter the pavement permeability by installing an "impermeable" asphalt pavement.
- When the ground water table is high, place deep trenches on the sides of the road, raise the grade of the road or use a full depth asphalt pavement (1). (Mn/DOT does not recommend full depth pavement designs.)

Beware of frost heave due to ice lenses. Frost heave damages the pavement and the drainage structure. To prevent frost heave, remove material to ¾ depth of frost penetration or mix the soil to prevent differential heaving (5).

Effectiveness of Drainage

Permeable Asphalt Stabilized Base (PASB) - the material is coated with asphalt but the voids between grains are not filled. The coefficient of permeability is approximately 300m (1,000 ft)/day (5, 10).

Class 5 Dense Graded Base – (Mn/DOT) the material has a coefficient of permeability of 1.1 m (0.4 ft)/day (10).

Pavement drainage systems were evaluated in a 1995 Mn/DOT report (38). The study evaluated pavement drainage systems under Jointed Plain Concrete Pavement (JPCP) and focused on four types of drainage systems having longitudinal edge drains. Drainage flow, percent rainfall drained, time to drain, base and subgrade moisture content and joint durability was evaluated. The systems included a Mn/DOT standard dense graded base, two dense graded bases with transverse drains under the transverse joints (geo-composite fins and drainage pipe) and a Permeable Asphalt Stabilized Base.

The pavement in test section 1 was designed with a 280-mm (11-in.) PCC pavement, a 100-mm (4-in.) Permeable Asphalt Stabilized Base and a 75-mm (3-in.) Class 5 dense graded base. Transverse joint spacing was equal to 8.2 m (27 ft). Sections were sealed but were intentionally interspersed with joints left unsealed.

Cost differentials for Test Sections 2, 3 and 4 were provided for each type of drainage design in terms of savings over the PASB design in test section 1.

The study concluded that all of the designs were functional but the PASB drained the most water within 2 hours of the end of rainfall. PASB provided the driest pavement foundation and the least early distress. Sealing joints temporarily reduced all inflow but within 2 weeks the inflow resumed, regardless of the apparent excellent condition of the joint seals. The authors recommend that all concrete pavements need some type of positive subsurface drainage system (38).

4.5.2.2. Compaction

General

Higher strength, stiffness and lower permeability will generally result from higher compaction.

Compaction is the densification of soil by mechanical manipulation. The effectiveness of the compaction process is dependent on the soil type, moisture content and method of compaction. Densification is achieved in 102 to 305-mm (4 to 12-in.) lifts as heavy equipment reduces voids in the soil mass. Density is measured in terms of the dry unit weight of the soil. The amount of compaction varies depending on the proposed use of the soil. Compaction is usually accomplished in 6 to 10 equipment passes. The use of more passes is usually uneconomical (39).

Methods and Equipment

Table 4.6. Methods for Incorporating Water Prior to Compaction (39)

Generalized correlation of soil classification and equipment	
Type of Soil	Equipment and Methods
Heavy clays	Difficult to work and to incorporate water. Best results usually obtained by sprinkling followed by mixing on grade. Break clods and cut in water with disc harrows then use heavy-duty cultivators and rotary speed mixers. Lift thickness in excess of 6 in. loose measure is difficult to work. Time is needed to obtain uniform moisture distribution. Sheepsfoot and pneumatic-tires rollers work well for cohesive soils.
Medium clayey soils	Can be worked in pit or on grade. Sprinkle then use cultivators and rotary speed mixers. Use sheepsfoot and pneumatic-tire roller.
Friable silty and sandy soils	These soils may also be handled by sprinkling and mixing. Mixing can be done with cultivators and rotary speed mixers to depths of 8 to 10 in. .. Silty soils may also be compacted efficiently with sheepsfoot and pneumatic wheeled rollers or smooth-wheeled rollers may be used.
Granular soils	Use vibratory rollers.

The State of Minnesota specifies minimum equipment and construction standards. Compaction may be controlled with one of three methods (10):

- Specified Density, (Compact to 100% AASHTO T-99 maximum density). Mn/DOT specification 2105 for soils and Mn/DOT specification 2211 for bases and subbases.

- Quality (Ordinary Compaction using steel-wheeled or pneumatic-tired rollers), and the
- Penetration Index Method (The Dynamic Cone Penetrometer gives a direct measure of soil strength and uniformity. Uniformity is especially important in Minnesota because of the effect of frost heave.) At this time (2002) the Penetration Index Method is only used for granular bases and subbases.

Moisture Content Adjustment

Laboratory tests using standard methods, such as the AASHTO T 99-90 standard moisture-density test, are used for setting limits on construction conditions. Moisture-density tests are used when constructing with specified density methods (Mn/DOT Specifications 2105 and 2211).

The Mn/DOT Geotechnical and Pavement Manual Section 5-2.01.04 3 (5) states that compaction moisture control must comply with Mn/DOT spec. 2105.3F. Embankment moisture content should be less than 115% of optimum when 95% maximum density is specified and should be 65% - 102% of optimum when 100% maximum density is specified. There are special moisture restrictions for problem soils. Restrictions for expansive soils state the moisture content should be 90-115% of optimum for material below the top 1 m (3 ft). of fill and 90-102% within the top 1 m (3 ft). Restrictions for red drift soils state the compaction moisture content should be 65 – 95% of optimum. (5).

4.5.3. Enhancement using Soil Modification

4.5.3.1. General

Subgrade modification is the improvement of subgrade materials workability, stiffness or plasticity resulting from the use of additives such as cementing or waterproofing agents. The extent of improvement required from modification is greater than ordinary mechanical methods alone but less than that required for full subgrade stabilization.

There are various materials used as cementing agents for modification of soils. When selecting a modifier type it is important to use field tests to show types and properties of the subgrade and borrow materials. It is also important to use lab tests to learn the engineering properties of mechanically modified and chemically modified soils and borrow material (40). The use of trial mixes is recommended with cement, lime and asphalt modifying agents (5).

4.5.3.2. Use of Lime for Modification

The discussion of materials for modification will be limited to lime.

Lime reacts with medium, moderately fine and fine soils to produce decreased elasticity, increased workability, decreased swell and increased strength. Lime may be effective for soils with clay content as low as 7% (40). Lime also works well when stabilizing (modifying) granular materials and lean clays. Cationic exchange and flocculation-agglomeration changes the texture of clay soils (called lime modification). This flocculation process causes a short-term increase in strength. Also, pozzolanic reactions occur when lime, water, soil and silica react to form various cementing compounds. This process causes a long term strength gain that may be as high as 100 psi 690 kPa (100 psi) at 28 days, 4.3 MPa (625 psi) at 56 days, and 10.9 MPa (1580 psi) at 75 days cured at 49C (120 F) with 5% lime). Soil properties including optimum pH (about 12.4, where the solubility of silica and alumina increase) influence the lime reactivity of a soil (41).

Lime is used to treat fine-grained soils that have a plasticity index > 10 and a clay content > 10%. Mn/DOT cautions that the use of lime may increase frost susceptibility, pavement roughness and cracking (5).

Construction of lime modified subgrades is usually done by end-dumping the ash on the subgrade, then spreading and mixing. Mn/DOT notes that lime is a very fine material and the construction process would be enhanced by controlling dust during the dumping and spreading process. Moisture content should be monitored before and after application of lime and at the rotary mixer (42).

- All compaction should be completed within two hours using pad-foot vibratory compaction, pneumatic-tire compaction, or smooth-drum compaction (42).
- Compact the soil. Most projects require 95% of AASHTO T-99 for sub-bases and usually 98% for base courses. The compactive effort may be applied with a sheepsfoot roller followed by a multiple wheeled pneumatic

roller. (A flat wheel may be used for finishing). Note that single lift compaction may be done with a vibratory roller or pneumatic roller followed by a light pneumatic or steel roller to finish.

- Cure the mix. Temperatures should be above 5-10 C (40-50 F). Moisture content should be kept close to optimum to aid compaction and curing. Curing may be done with moist cure techniques or asphaltic membrane cure techniques (41).

4.5.3.3. Use of Bituminous Materials for Modification

4.5.3.3.1. General

Asphalt can be used with soils that meet the following requirements;

- maximum percent passing the 0.075- mm (No. 200) sieve is less than 25 %,
- PI less than 6,
- sand equivalent less than 30 and,
- (PI × percent passing 0.075-mm (No. 200 sieve) less than 72.

In general asphalt modification techniques may be used with A-1-a, A-1-b, A-2-4, A-2-6, A-3, A-4, and low-PI A-6 soils (40).

4.5..3.3.2. Asphalt Materials

Asphalt is a product of the petroleum industry. Asphalt cement is available in standard binder form with properties varying according to performance grade (PG). Asphalt is also available in emulsified form where droplets are held in suspension by anionic or cationic conditions. Currently, only asphalt emulsions are used for soil modification.

4.5.3.3.3. Design Factors

Key points:

Determine the desired depth of modified subgrade [upper 200 mm (4 in.), etc.] or the total amount of bituminous treatment (plant mix aggregate asphalt, plant mix sand emulsion base or emulsion treated subgrade (43).

Table 4.7. Limitations and Safety Precautions for Asphalt Treatment (44)

Modification Type	Climatic Limitations	Construction Safety Precautions
Asphalt Emulsion	• Air temp above 0C (32F) when using emulsions. • Air temperatures 5C (40°F) and rising when placing thin lifts 25.5 mm(1 in) of hot mixed asphalt concrete. • Hot – dry weather is preferred	• Some emulsions have flash and fire points below 40C (100F). • Hot mix asphalt cement temperatures may be as high as 175C (350F).

4.5.3.3.4. Construction General

See the Mn/DOT Standard Specifications for Construction No. 2207 for asphalt base stabilization (9).

According to The Asphalt Handbook (44), asphalt may be applied by four methods, blade mixing, rotary mixing, travel plant mixing and stationary mixing facilities.

Blade Mixing uses multiple drag blades to blend the asphalt and aggregate together. Spread the material out with a grader so the moisture content is 3% or less and asphalt is applied from a distributor in two to three passes. The asphalt is partially mixed in after each pass.

Rotary Mixing uses a machine to cut through the grade to a specified depth and then applies asphalt. This method is also commonly used for cold recycle construction.

Travel Plant Mixing uses a self-propelled pugmill that can use recycled, virgin or a blend of materials.

Stationary Mixing Facilities have some advantages. The weather is less of a factor, aggregates may be heated (dried) prior to mixing and there is good control over proportions (this may be more important for pavement layers than subgrade).

Aeration

In the case of sands and sandy soils (base material) volatile components should be reduced by at least 2/3. The material can be placed to one side in windrows. Blade spreading is done in several layers. Note that emulsified asphalt should not be placed if the temperature is less than 10C (50F).

Rolling

If rolling is done prematurely the evaporation process is retarded, thereby increasing the time needed to attain density and cohesion. Roller selection may include:

- Open grade: steel wheel followed by vibratory roller
- Dense grade: steel wheel or pneumatic followed by vibratory roller

If there is any sign of rutting during compaction the rolling should stop. Wait until the moisture content is reduced to resume rolling (44).

Techniques used in Minnesota:

- Compact subgrade to 100% max AASHTO A-99 density and apply 2 gallons per square yard dilute emulsion. (30% SS-1 and 70% water) and mix full depth of treatment with rotary mixers.
- Compact with pneumatic tired rollers and apply a dilute application of emulsion (0.7 gallon per square yard) to prevent raveling.
- Construct the base.
- Cure (43).

Performance of bituminous subgrade modification

In the past, data show the outer wheel path was weaker than the inner wheel path. Tests on the stabilized subgrade (plate bearing) show progressively higher values up to 49 days but only equal to non-emulsified sand. (Finished Road Deflections).

Lower base cures at 24 to 43 days. A 25-mm (1-in.) crust formed with softer material below. The conditions show that curing time is needed for a sand-ashpalt-stabilized base. Benkelman beam data showed that the 6-in. stabilized base needed at least 2 weeks for satisfactory curing (43).

4.5.3.4. Embankment Modification Using Chlorides

General

Calcium chloride and sodium chloride material have been used for modification of embankment soils in Minnesota and elsewhere.

Illinois permits sodium chloride treatment when modifying the shoulders and bases of secondary roads but now excludes the use of calcium chloride as a stabilizing agent because of performance-cost shortcomings (45).

Minnesota Test Sections

A number of Minnesota agencies have arrived at similar conclusions. A 1960 Minnesota study (Nobles County) compared the effectiveness of sodium chloride, calcium chloride and cutback asphalt. It was found that chlorides tend to rapidly migrate out of the roadway structure. After a five-year period the embankment chloride levels were approximately zero. Use of chlorides did not increase construction efficiency or improve performance in test sections (46). The treatment rate for NaCl was 2.4 lb. per square yard (0.8% by weight MHD spec 3910 rock salt). Treatment rate for $CaCl_2$ was 1.3 lb. per square yard (0.42% by weight). Surface construction was bituminous.

4.5.4. Subgrade Soil Enhancement using Stabilization

4.5.4.1. General

Subgrade stabilization is high-level subgrade improvement through the use of Portland cement, lime, fly ash, asphalt. The only material currently used successfully in Minnesota is fly ash. Fly ash is being used by a number of agencies and shows promise (42). The design and construction of fly ash stabilized soils is covered in this section. Portland cement has also been used in some other states. It is therefore also covered briefly.

4.5.4.2. Stabilization Materials

Portland cement may be used to stabilize sandy soils and lean clays. Cement stabilization guidelines given by the FHWA(40,47). AASHTO says soil classes A4 to A7 are suitable for lime and fly ash stabilization (40).

Fly ash has been used most recently for subgrade stabilization in Minnesota.

4.5.4.3. Application to Soils

Soils Suitable for Cement Stabilization:

Cement stabilization is economical with sands, sandy and silty soils, and clayey soils of low to medium plasticity (PI < 30 %) since it is difficult to mix into a soils having a PI > 30 % . If the pH of a 10:1 soil cement mix after 15 minutes is at least 12.1 it is improbable that organic substances will interfere with strength development (47).

Portland cement has not been used in Minnesota over the past 20 years because of previous poor performance primarily due to shrinkage cracking.

4.5.4.4. Soil Stabilization Using Fly Ash

4.5.4.4.1. General

Fly ash has been used for many of the same soil stabilization applications as lime and Portland cement. These include:

- Drying Agent – the reduction of soil moisture content to facilitate mechanical compaction.
- Reduction of Shrink-Swell properties of clay soils.
- Stabilization to increase Strength – CBR values have been shown to increase from 2-3 up to 25-30 for a clay stabilized soil allowing a corresponding decrease in pavement thickness requirements.

Conditions: A clay-type soil especially if above optimum moisture conditions in the field or an existing pavement in poor condition.

4.5.4.4.2. Laboratory Mixture Design

Since most stabilization applications with fly ash rely on the ash as the stabilizing agent, the test and design procedures must address the rapid rate of hydration when the ash is exposed to water. Ash hydration alters the soil compaction characteristics because soil particles become bonded together in a loose state. A portion of the compactive energy is lost in disrupting these bonds. Maximum density achieved therefore decreases as the hydration reaction progresses after blending of the soil, fly ash and water.

Self-cementing fly ash hydrates more rapidly than Portland cement; therefore, a 2-hour delay in compaction can result in a decrease in maximum density of up to 1.6 kN/m^3 (10 pcf) or more. Usually a 2-hour delay time can be achieved even with rudimentary equipment. When pulvamixers are used with experienced personnel a 1-hour compaction time can be readily achieved.

The allowable range in moisture content must be specified and be monitored during construction to ensure that moisture contents of the stabilized section are near the optimum for maximum strength. If the actual compaction in the field will be completed within the specified 2-hour delay period, actual strengths achieved in the field would be between the laboratory test results with 0 and 2 hour compaction delay.

No standard methods have been adopted for the design of materials stabilized with fly ash. (ASTM C-593 and ASTM D-1633). Depending upon the application either standard or modified Proctor compactive energy may be used. For most county road application, standard Proctor compaction should be adequate.

For cohesive soils, the moisture content should be up to 10 percent below optimum moisture content for maximum density. Test specimens should be cured for 7 days at 38C (100F) in accordance with C-593 after which compressive strength should be determined. The optimum moisture content for maximum strength has been shown to be consistent for cure periods of 7, 28, and 56 days. Therefore, optimum moisture content can be determined using 7-day strengths.

The reduction of PI for clay soils will be less for fly ash compared to lime.

4.5.4.4.3. Construction Procedures and Concerns

The laboratory mix design is usually conducted to establish the optimum ash and moisture contents. Maximum dry density and strength gain for design and construction testing are determined. A general construction specification is presented in Reference 38.

The following goals must be achieved to result in a good project:

- Uniform distribution of the fly ash
- Proper pulverization and thorough mixing of the fly ash with the material to be stabilized

- Control of moisture content for maximum density and strength
- Final compaction within the prescribed time frame (usually 2 hours)

Typical design specifications call for fly ash contents of 1 to 2 percent greater than optimum contents determined in the laboratory. Pneumatic tankers or bottom dump trailers are used to transport fly ash to the project. Careful blading of the fly ash over the exposed grade from uniform windrows deposited by the transports is the best way to obtain uniformity of application. The quantity of ash can be calculated knowing the depth, width, length and design percent of fly ash. Uniform distribution can be accomplished using metered gates on the transport of direct metering of the ash into the mixing drum of a mobile mixer.

Construction discs can effectively blend the ash with cohesive soils. The depth the disc is cutting must be closely monitored. Where higher degrees of stabilization are required the use of a self-propelled mixer (pulvamixer) is required to ensure adequate pulverization and uniform distribution of moisture and fly ash. One or two passes of a mixer can be used to obtain good mixing.

Moisture Content

Control of moisture content is both critical and difficult. Strengths of the stabilized materials decrease significantly as the moisture increases above the optimum moisture for maximum strength. Strength also decreases on the dry side of optimum moisture and increased compactive effort is required.

Maintaining moisture contents within a range of 0 to 4 percent above optimum moisture content for maximum compressive strength is typically recommended and is readily achieved with proper equipment.

Significant quantities of water may be required to bring the moisture to the design level. The following aspects of moisture control must be considered.

If water is added after the fly ash is blended the final strength of the stabilized material will be reduced due to hydration of the ash before compaction is completed.

- Adding sufficient water to the pulverized material prior to distribution of the ash may make the untreated material unstable, hampering distribution and operation of construction equipment.
- Applying water directly onto the fly ash distributed on the surface in not

advisable since this increases the rate of hydration.

- Water can be added after the fly ash has been incorporated; however, additional passes with the mixing equipment will be required to achieve uniform mixing.
- Introducing water directly into the drum of a rotary mixer is the most effective procedure in controlling moisture content so it falls within the desired range and providing the most uniform mixing without additional delay in compaction.

Moisture contents can be monitored using a nuclear density gauge. The nuclear gauge may not give an accurate moisture measurement; however, it can give a good indication of uniformity.

Field Compaction

Compaction of the mixture must be accomplished as soon as possible following the final pass of the mixing equipment. Using paving train type operations initial compaction can easily be achieved within 15 minutes of the final pass of the mixing equipment.

Initial compaction is most often accomplished using a vibratory padfoot or a self propelled padfoot roller operated immediately behind the mixing equipment. The padfoot provides good compaction from the bottom of the stabilized layer and imparts a kneading action which can give some additional mixing.

After initial compaction the materials should be shaped to final grade by blading and final compaction done using a self-propelled, pneumatic-tired roller. Shaping should not be delayed.

Curing

The surface of the stabilized lift should be maintained in a moist condition to help hydration of the fly ash. Curing can be accomplished through periodic application of water on the surface until the nest lift or a wearing surface is constructed over the stabilized material.

Temperature Effects

Stabilization with fly ash can be performed satisfactorily down to temperatures of 10C (50F). Construction can be accomplished at cooler temperatures with modified procedures. At cooler temperatures two passes of a pulvamixer may be required to reduce the maximum size of the material to less than 25 mm (1 in.). Cooler temperatures may be beneficial apparently because the cooler temperature retards hydration. However, cooler temperatures also result in decreased density for the same compactive effort. With additional compactive effort, and in-place densities are adequate, the strength of the compacted section can be near design strength when constructed below 4.5C (40F).

Cooler temperatures have greater impact on soil pulverization and compaction than on ash hydration. Soil temperatures below 10C (50F) help retard ash hydration which increases long-term strength of the stabilized material. Multiple passes of the pulvamixer may be required to achieve pulverization and mixing with the ash. Additional compactive effort may also be required to obtain specified density.

Effective stabilization of clay soils as long as soil temperature is above 0C and construction procedures are modified to attain proper mixing and compaction of the stabilized materials (47).

4.5.4.4.4. Concerns when Using Fly Ash for Soil Stabilization

High-Sulfate Ashes

There are two common high-sulfate content ashes: fluidized bed combustion **(FBC)** and flue gas desulfurization **(FGD)** ash. These materials can exhibit self-cementing properties similar to subbituminous coal ashes**. These materials may cause serious expansion characteristics when hydrated.** Therefore, the following should be considered when evaluating the sulfate content of an ash.

- Ash with SO_2 contents of 5 to 10 percent should be considered potentially expansive until laboratory testing indicates otherwise
- Ash with SO_2 contents greater than 10 percent should not be used for stabilization applications
- Soluble sulfates in the soil or groundwater can influence swell potential and be considered in addition to the amount of sulfate in the ash

The relative damage/deterioration of a high-sulfate ash-stabilized material can be categorized based on combined clay and colloid content as follows:

Relative Damage	Clay and Colloids Content
Minor	5-10%
Moderate	10-30%
Major/Severe	Greater than 30%

The availability of free moisture in the stabilized material is critical to long term performance. With saturated or near-saturated conditions, sulfate, silica and alumina ions within the fluid are mobile and free to react (47).

Environmental Concerns

The primary environmental concern when using self-cementing ashes is the migration of metals. Data from four roadbases and one embankment suggested that very localized migration of ash derived metals had occurred into the underlying soils. Depth of migration was less than 0.7 m (2 ft) below the stabilized section on two study projects.

Most applications of fly ash stabilized soils or bases would be designed such that the material would be above the water table and water flow through the material would be minimal. This is necessary to maintain the structural integrity of the stabilized and layers of the pavement section. If there is a groundwater associated problem, the stabilized section is encapsulated in a geofabric.

To evaluate the potential of leaching particular materials the specific metals in a given ash should be determined. The source of coal for a given generating plant the coal source is usually the same because the burning system is setup for that coal source.

An EPRI Demonstration Project was conducted in Kansas to assess the migration of metals from the stabilized section in to the underlying subgrade. Of the 23 metals evaluated only one was present in a higher concentration in the fly ash than in the soil below the section to be fly ash-stabilized. Barium was the only metal that was present in significantly higher concentrations than in the soil.

The Toxicity Characteristic Leaching Procedure (TCLP) has been used by a number of agencies to what and how much of various metals are leached from various situations and environments. Studies at specific locations showed that the metals leached from the ash were a small percentage of the total metals present in the existing soils. Overall, it was found that the hydration and solidification of the ash in addition to the natural soil attenuation characteristics caused a reduction in leachable barium.

Fugitive Dust can be a problem just as for any other construction process. Maximum dust is generated at the time the ash is discharged from the tankers or end dump trailers onto the pavement subgrade. Construction activity will generally minimize fugitive dust. When a rotary mixer is used, water is added in the mixer, which minimizes fugitive dust. This is the procedure that also is most effective in constructing a good stabilized soil subgrade (47).

4.5.4.4.5. Summary of Fly Ash Soil Stabilization Procedures

Weather

a. Best

- Damp or dry
- Little or no wind
- Temperature above 40F (4.5C)

b. Worst

- Saturated
- Windy
- Temperature below 40F (4.5C)

Transportation

- Fly ash is delivered to The the project either in tarped trucks or tanker trucks with pressurized pumping systems

Measurement of Quantities

- Fly ash either metered from the truck and trucks counted.
- Moisture added to grade as needed.
- Disking may be sued to decrease moisture content.

Method(s) of Mixing

a. Trucks dump fly ash in uniform windrow (if no wind);
b. Spread laterally across the embankment with a bulldozer
c. Mix with a recycler (BOMAG) traveling at 20-30 ft/min or disked to design or lift depth.
d. If water needed, the truck is pulled through the grade with a bulldozer
e. Shape the grade with a bulldozer

Compaction Procedures

a. Initial compaction - pad roller or sheepsfoot roller
b. Final compaction – steel wheeled roller to provide smooth surface and help shed water
c. Compaction control – Mn/DOT Specification 2105 allows for specified density based on a Procter with the given percent fly ash or quality compaction with proofrolling
d. **Compaction must be accomplished within two (2) hours because working of the mixture after that may break up the products of hydration which stabilize the soil.**

Curing of a Soil-Fly Ash Mixture

When self cementing fly ash is mixed with water, hydration of the material creates the gel which binds (stabilizes) the soil and results in the stronger more uniform lower permeability material. The hydration requires water. Therefore, the surface of the grade should be kept damp.

Construction Rate

About 0.4 to 0.6 km (¾ to 1 mi) of stabilized grade can be constructed in one day.

PRECAUTIONS:

1. **Wind:** watch out for windy conditions if fly ash laid out on the grade.
2. **Mixing:** mix in fly ash as soon as possible.

3. **Protection:** Workers should wear protective equipment to avoid burning skin, eyes, nose and mouth

Value

Life: With proper mix design and construction it is expected the grade would last at least 50 years.

Contacts: Jeff Blue, Waseca County, John Seikmeir, Mn/DOT

4.5.5. Subgrade Soil Enhancement using Geosynthetics

4.5.5.1. General

Geosynthetics are a class of textile materials that are extruded petroleum polymer-based thin pliable sheets of varying permeability. There are many different varieties, such as geotextiles, geogrids, geonets, geocells, and geomembranes. One difference is the size of the aperture, with geogrids having the largest aperture. Most varieties of geosynthetics used for pavement applications in Minnesota are of Mn/DOT Type V and VI (Spec 3733.1) classification.

Table 4.8 Mn/DOT Geosynthetic Classifications (Mn/DOT Spec 3733.1)

Class	Description
Type I	For use in wrapping subsurface drain pipe or for other specified drainage applications.
Type II	For use in wrapping joints of concrete pipe culvert and as a cover over drain field aggregate.
Type III	For use under Classes I and II random riprap, gabions, and revet mattresses.
Type IV	For use under class III and IV random riprap, hand-placed riprap, and quarry-run riprap.
Type V	For use in separating materials (stabilization).
Type VI	For use in earth reinforcement and Class V random riprap.

Geosynthetics are used in many areas of ground construction. Common highway applications include separation, reinforcement, drainage and filtration. The usefulness and effectiveness are directly dependent on the application, the type of geosynthetic, and the design in which the geosynthetic is incorporated.

Interpretation of the benefits associated with geosynthetics can be difficult. Some of the most common benefits are cost savings, longer life, and improved performance. Obtaining quantifiable improvement using geosynthetics requires careful design along with correct and careful installation procedures.

Proper design procedure requires more information than what is presented in this report. The purpose of this overview is to provide an introduction to geosynthetic applications and construction procedures. This information can be used to facilitate the decision whether geosynthetics are appropriate for specific pavement design applications.

4.5.5.2. Types of Geosynthetics

4.5.5.2.1. Geotextiles

Geotextiles are permeable textile-like materials most commonly composed of a polymer like polypropylene and polyester (48). The two most common geotextile varieties are woven and non-woven. The woven varieties are made from both monofilament and multifilament fibers. The non-woven (multifilament) varieties are bonded together after extrusion by one of three processes: melt-bonding, needle-punching, or resin-bonding. The spectrum of geotextile variations is vast, providing flexibility for design.

Applications

Geotextiles are used in three major categories of pavement system improvement:

- Separation
- Reinforcement
- Filtration

The most common pavement application for geotextiles is **separation** of dissimilar materials (49). Separation between an underlying fine-grained soil and an aggregate base or granular subbase to prevent contamination of the base material has been used for many applications. Separation is mostly needed for grades that will be saturated or close to saturation.

Reinforcement of weak soils is another application for geotextiles. Reinforcement applications require tensioning of the geotextile and achieving sufficient tension throughout the entire fabric is difficult. Tension may also be developed after construction is complete if larger strains and deflections are tolerable. Current research suggests that the use of geotextile-geogrid composites is more effective than geotextiles for reinforcement applications.

Filtration within drainage systems is also a major application of geotextiles (48). The small aperture size will keep large particles from entering the drainage layer or pipe, while allowing some of the small suspended particles to pass without clogging the filter.

Geotextiles are also used as a protective outer layer of geocomposites.

4.5.5.2.2. Geogrids

Geogrids, a stiff structure, differ from geotextiles in that they have large apertures, typically 10-100 mm between ribs (50). The primary use of geogrids is soil reinforcement. Some geogrids begin as a geomembrane with holes punched through it. The geogrids may be run through rollers with different rotational speeds or placed in a stretcher to elongate the polymers. Both uniaxial and biaxial elongation versions are commercially available. The benefit of polymer elongation is that the polymer goes into a post-yield state which increases the material strength, modulus, and resistance to creep (50). Elongation should be in the direction of the major principal stress. If the direction of the primary stress is unknown, it is recommended to use a biaxial grid. Many variations of geogrids are commercially available. Choice of an appropriate type is a function of the application and manufacturers' specifications.

Applications

Geogrids are commonly used to improve the modulus of a granular base, by providing lateral confinement and reducing "walk out" of the base material. Haas (50), showed that the use of geogrids can significantly reduce deformation and improve the durability and lifespan of paved roads. The greater resistance to failure is due primarily to an increase in stiffness and the load spreading ability of geogrids. The increase in stiffness suggests that a decrease in the thickness of base material or HMA is possible for some situations (51, 52, 53). A more common approach is to consider that the increased stiffness of the standard base and HMA thickness translates into a longer lifespan. It has been shown that the placement of geogrids at mid-depth of a base course dissipates the magnitude of the stress transferred through the geogrid (50). The dissipation effect of the geogrid may allow for a reduced base thickness. Tension will need to be developed in order to realize the full capacity of the system. This can be accomplished in two ways.

- Pre-tensioning and anchoring
- Developing tension by overburden after installation

4.5.5.2.3. Geonets

Geonets are primarily used for drainage applications and are similar to geogrids except that the aperture is usually about 12 x 8 mm (0.5 x 0.3 in.) (53). They are manufactured from polyethylene. The ribs are manufactured at angles of 70° and 110°. This diamond shaped pattern changes the amount of vertical loading that the geonet can support. Thickness is the most influential factor on the drainage performance of a geonet, and should be determined using ASTM D1777. A thicker net will allow better drainage. Greater thickness can be achieved by adding a foaming agent during manufacture, which increases the thickness up to 5-7 mm (0.2-0.3 in.) and sometimes up to 13 mm (0.5 in.). The hydraulic properties of a geonet should be determined using ASTM D4716

Geonets are usually separated from the in situ soil, both below and above, by another geosynthetic, such as a geotextile in pavement applications.

The long-term conditions surrounding the geonet also need to be assessed in order to design a system that will not degrade over time. Soil may block the openings of the geonet. Temperature can also be destructive to these systems, because the polymers will creep faster at high temperatures. The design must account for the maximum temperature expected. Subsurface chemicals being transported, which can damage the geonet, must be determined. Composition of the water therefore, is important. The amount of a dissolved chemical that the geonet and separation layers will be exposed to is much greater than in most reinforcing situations, due to the increase flow rate of geonet systems. A high flow-rate factor of safety must be used in order to ensure a long performance life.

Applications

These materials are almost exclusively used for drainage applications. They are separated from the in situ soil by another geosynthetic placed on both sides of the geonet. This separation allows for lateral drainage in embankment applications, or vertical drainage in retaining walls.

4.5.5.2.4. Geomembranes

Geomembranes are relatively impermeable barriers used for complete separation (53). The term impermeable layer is used because the permeability of water vapor for the material is between 5 x 10^{-11} and 5 x 10^{-14} cm/s (1.9 x 10^{-17} and 1.9 x 10^{-20} ft/day). This type of geosynthetic consists of two major categories:

- Modified
- Waterproof

Modified geomembranes are impregnated with bitumen, or elastomeric materials in the field.

The second geomembrane type is manufactured to be waterproof. For this class of geosynthetics, tensile strength, tear resistance, puncture resistance, and seam behavior are more important than in other geosynthetic applications because failure or deterioration of any type that allows increased permeability will compromise the entire system. Resistance to chemicals must also be considered, as it may reduce the effective life of the material. To reduce the possibility of failure, other types of geosynthetics are often used to add a protective barrier on both sides of the geomembrane (53).

Applications

Geomembranes are used in transportation applications to stop intrusion of water into expansive soils. This application has two variations, horizontal and vertical depending on the direction of fluid flow. Determining if one or both are necessary depends on groundwater flow and surface infiltration. Horizontally-installed geomembranes vary in width depending on the application. Vertically-installed geomembranes typically are placed to a depth of 1.5 to 2.5 m (5 to 8 ft), such as for cut off wall applications. They must be wide enough to prevent water from vertically infiltrating and to isolate the overlying material. In frost sensitive soils, geomembranes will allow for the control of moisture content, reducing the effects of differential frost heave. Geomembranes are also used for containment of runoff and contaminated fluids as well as for waterproofing foundations, walls, and bridge abutments.

4.5.5.2.5. Geocells

Geocells are another type of geosynthetic sometimes installed as a geocomposite. Geocells are composed of polymer strips that are arranged to form vertical boxes, which are then filled with sand. This soil-containment system is able to distribute large vertical forces and compensate for weak soils. The geocell is sometimes installed with a protective geotextile above and below (53).

Applications

Geocells are typically used for reinforcement or containment, installed in or below the base course.

4.5.5.2.6. Geocomposites

Geocomposites are a combination of two or more types of geosynthetics (53). A geonet or geogrid with another geosynthetic on either side is a common example of a geocomposite. A geomembrane reinforced with geotextiles is also an example of a geocomposite. Geocomposites are often used to enhance the performance of the primary synthetic chosen.

Strip or wick drains are composites that use a large aperture geogrid or geonet middle layer and fine aperture geotextile as a filter sandwiching the middle layer. There are many different arrangements that can be made for various purposes. The properties of each system are dependent on the components chosen and their interactions.

Applications

A composite is intended to create a synergistic effect where the performance of the entire system is greater than its individual components. The primary factors in composite selection are cost and the results achieved The construction of a temporary access road over wetland soils was facilitated by the use of a geofabric-geogrid combination (53). The purpose of this design was to minimize the impact on local vegetation. The use of geosynthetics allowed for minimal disturbance to the subgrade. The use of geofabrics for separation and geogrids to increase the friction between dissimilar layers has been effective in many situations such as subgrade reinforcement and pavement overlays.

4.5.5.3. Applications of Geosynthetics in Minnesota

4.5.5.3.1. General

In Minnesota geosynthetics have been used primarily as separation layers between fine-grained soils and granular bases or subbases or a geogrid reinforcement between the embankment soil and the subbase. In this section the best practices for separation and reinforcement applications are presented.

4.5.5.3.2. Geosyntethics as a Separation Layer

Soil separation is a primary concern for pavement sections with wet or saturated fine-grained plastic soils. The small grain size of some soils allows the subgrade soil to infiltrate the granular base, or the granular base to migrate into the subgrade. This mixing of subgrade and base course material will result in contamination of the base and a decrease in stiffness and strength of the pavement system, allowing excess deformation of the HMA surface. Installing a separation layer will help retain the design stiffness which will help increase the pavement life. Installation of a geosynthetic (geotextile) has been proven to be a successful method to limit soil intrusion into a coarse aggregate (48, 49). Selection of a suitable separation layer is dependent on the grain size of the soil. The aperture of the geosynthetic should be smaller the smallest grains. If there is material smaller than the aperture, migration will occur. The migration of the fines is facilitated by water and the pumping effect caused by repeated loading.

The following section is a summary of the application of the use of geofabrics as separation layers in Minnesota:

Purpose: Separate wet silt or clay soils from granular subbase or base materials

Conditions: Areas with high moisture content fine-grained soils near the water table and/or where pumping action may cause infiltration of the soil into the upper layers.

Materials:

- Mn/DOT Specification 3733 Type V; this is usually a slit film geofabric with a minimum grab tensile strength of 140 MPa (200 psi).
- Mn/DOT Type VI with a minimum bi-directional strength of 210 MPa (300 psi) is recommended for weaker, wetter conditions; Type VI is usually a woven fabric.

- Water Conductivity – minimum of 400 liters/sq m/minute (10 gal/ft^2/min)
- Manufacturer certification of geofabric must be received from contractor.

Design Considerations:

- Geotextiles used under granular materials over soft wet clays can provide separation and eliminate contamination of the granular material however,
- A geotextile needs to be placed within 0.3 m (12 in.) of the surface to mobilize tension under wheel loads at the surface.

The key to getting a good bid price on placement of a geotextile is to allow placement in such a way as to not significantly delay the contractor's normal operations

- **Quantities**

  Geofabrics come in standard widths, typically 4, 5 and 6 m (12, 15, and 18 ft). By specifying an overall width that fits some combination of these widths and allowing about 0.2 m (0.5 ft) for sewing material waste will be minimized.
- **Recommended Width**

  The recommended width of geofabric is the width of the driving surface plus about 0.7 m (2 ft) on each side.
  - Gravel Surface, an 24-ft (8-m) width would require fabric at least 28-ft (9.1-m) wide. Two 15-ft (5-m) rolls sewn together in the factory would produce a width a little over 29 ft (9.2 m). On gravel surface roads, the width should be as close as possible to the shoulder-to-shoulder width.
  - Bituminous Surface, for 24-ft (8-m) lanes and 4-ft (1.3-m) shoulders a fabric width would be 32 ft (10.9 m). A combination of a 18-ft (6-m) and 15-ft (5-m) or three 12-ft (4-m) rolls would be appropriate. If the width is too great pre-sewing is not practical and field sewing is required.
- **Recommended Length**

  By specifying bi-directional grab strength, the fabric can be placed in the long direction typically in lengths of 200 to 300 ft (60 to 100 m). This will minimize delay.
- **Area**

The area of geofabric to be used for design and bidding should be the area of the embankment covered. Overlap and the amount of fabric allowed for proper sewing should not be used for calculating area of coverage.

- **Stitching/Overlap**

  The geofabric should be laid out parallel to the centerline if field stitching if required, using a 3-ft (1-m) overlap. Use a J-stitch with a double stitch, not more than ½ in. (12 mm) apart (Figure 4.6).

  If prayer stitches are used then two lines of sewing should be used. A 401 stitch is best. All seams should be sewn “face up” for inspection.

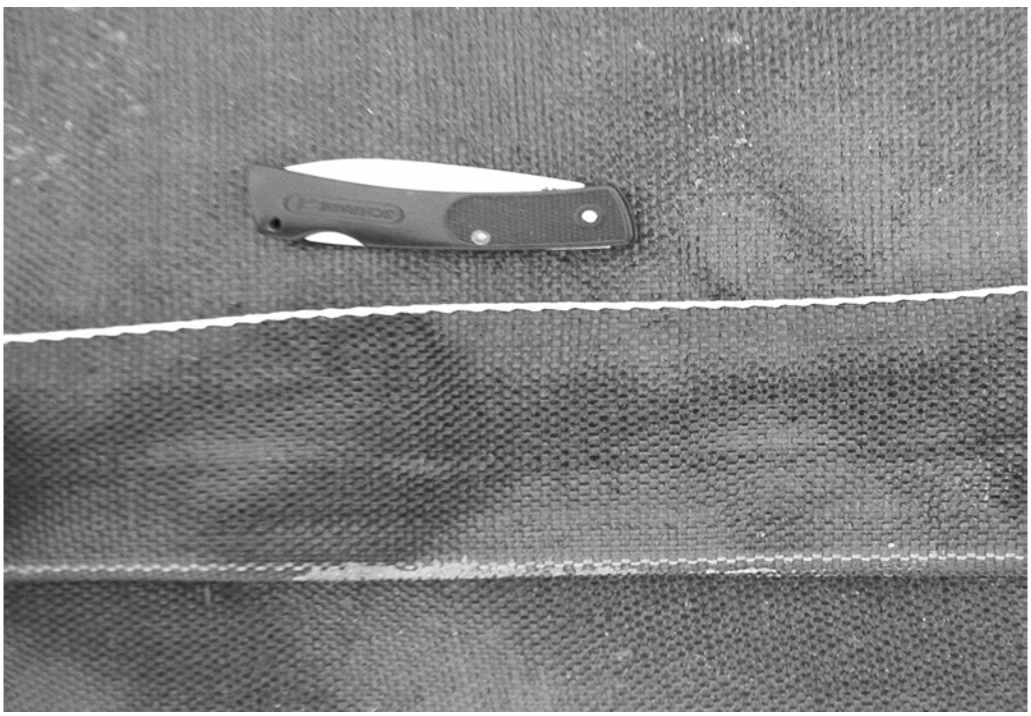


Figure 4.6 Type V Woven Geofabric Connected Using a “Prayer seam” with 75-mm (3-in.) Overlap and 401 Stitch.

Construction:

- Weather

  Best: No wind, dry, warm

  Okay, Slight wind, some precipitation, cool

  Worst: Windy, wet, cold

- Placement **Proper placement is critical**

  Subgrade must be stable:

  1. For normal hauling operations geofabric will not substitute for poor subgrade preparation

  Geofabric Placement

  1. Roll out and stretch out over subgrade
  2. Provide some anchor on edges (small shovels of soil)
  3. Minimize wrinkles (Fabric should be "Stretched" across subgrade)
  4. Transverse Continuity (joints): near end of roll
     a. Place next roll like shingles with 2-m (6-ft) overlap or
     b. Sew the connection; (double or triple stitch)

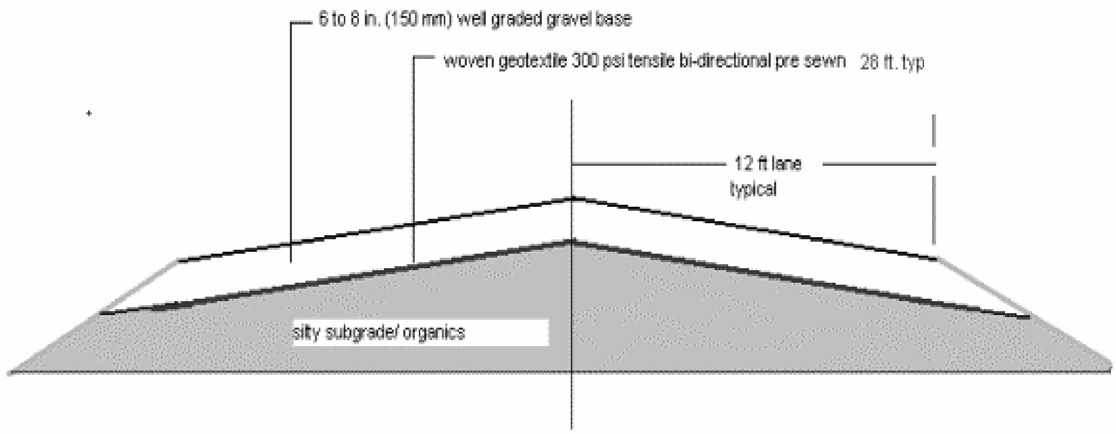
Placement of Granular Material over Geofabric

1. Trucks (belly dumps) can travel directly on geofabric if extremely careful. **No turns, braking or spinning tires**
2. Place material down center in a windrow
3. Spread material forward and to the sides (stretch fabric to remove wrinkles in this way).
4. Cover middle portion of the fabric first with a 75 to 100-mm (3 to 4-in.) layer of granular material. This may require one or two truck dumps side by side between 20 and 30 m (70 to 100 ft) long to get the proper sized windrow. A shorter distance may result in a windrow too high and cause the trailer to ride up on the windrow and spin the wheels.

At the end of a workday the contractor should place an additional. 75 to 100-mm (3 to 4-in.) layer of granular over the fabric and complete the spreading operations over the entire fabric width.

Typically, 1.6 km (1 mi) of roadway can be placed in this way in one working day.

Figure 4.7 Granular Material placed on Overlapped Geofabric



1. SHAPE EXISTING ROADBED ONCE DRY AND STABLE, WITH 3 PERCENT CROWN, SMALL SIDE WINDROW OF MATERIAL
2. ROLL OUT PRESEWN GEOTEXTILE AND ANCHOR LIGHTLY WITH WINDROW MATERIAL, WORK WITH THE WIND
3. SMOOTH FABRIC ON SUBGRADE AND ANCHOR OTHER SIDE WITH WINDROW MATERIAL
4. BOTTOM DUMP AGGREGATE TRUCK SPREADS WINDROW OF GRAVEL DOWN CENTER
5. MOTORGRADER SPREADS MATERIAL FORWARD AND OUT FOR AN INITIAL 3 TO 4 INCH LIFT, 20 FT. WIDE
6. THIS METHOD, IF DONE CORRECTLY, STRETCHES THE GEOTEXTILE AND GIVE IT AN INITIAL PRESTRESS.

Figure 4.8 Typical Section Using Geofabric.

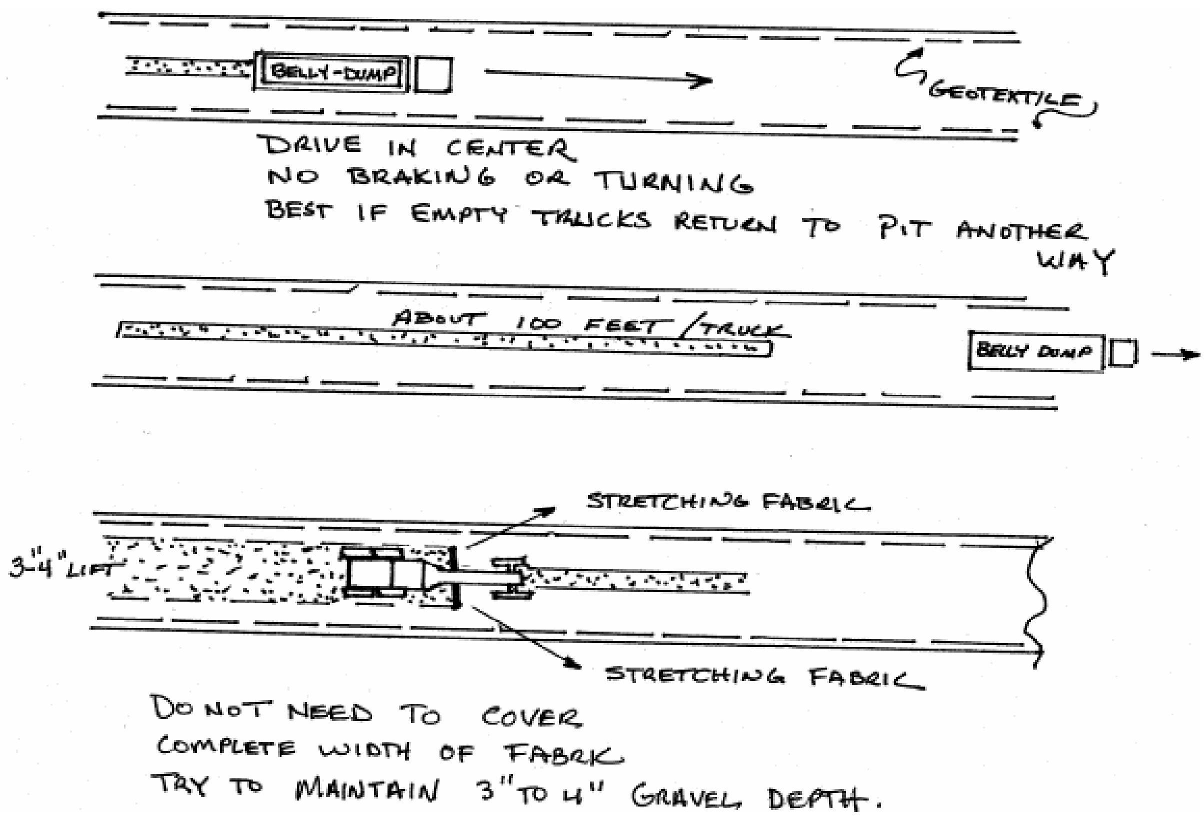


Figure 4.9 Geofabric Construction with Belly Dump and Motorgrader (courtesy of Walter Leu and Lou Tasa)

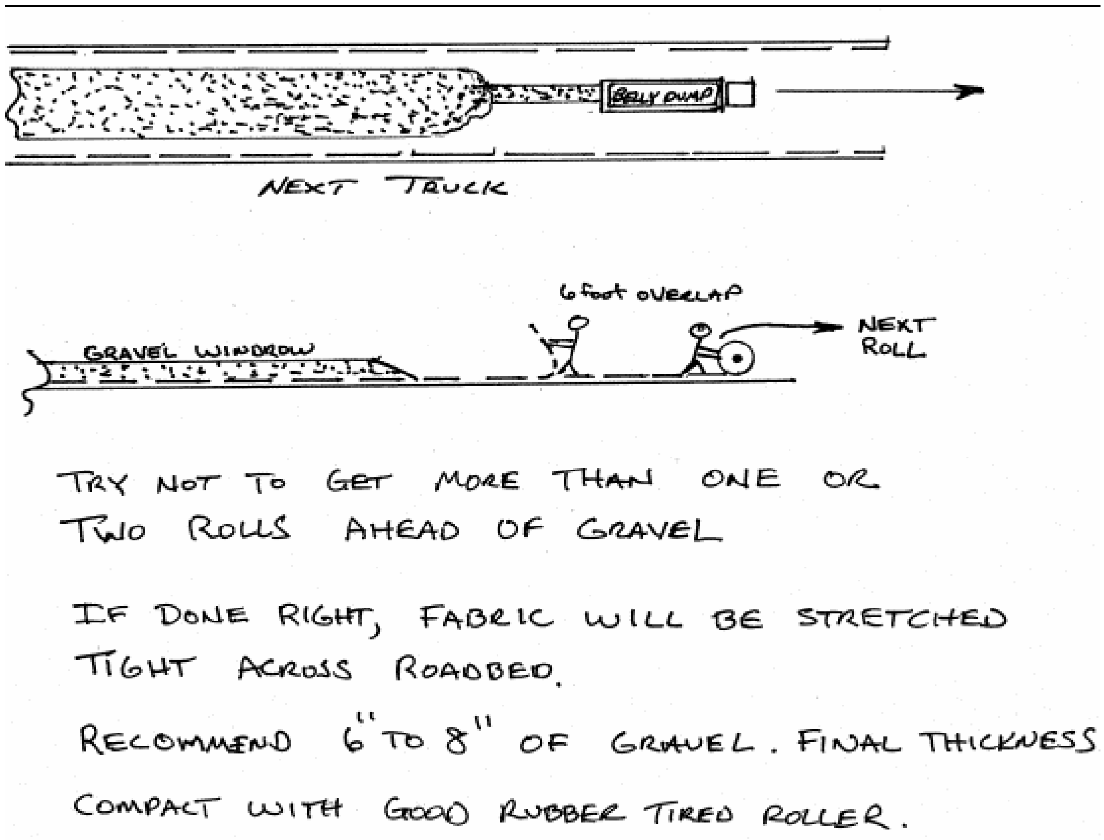


Figure 4.10 Geofabric Construction (cont.). (courtesy of Walter Leu and Lou Tasa)

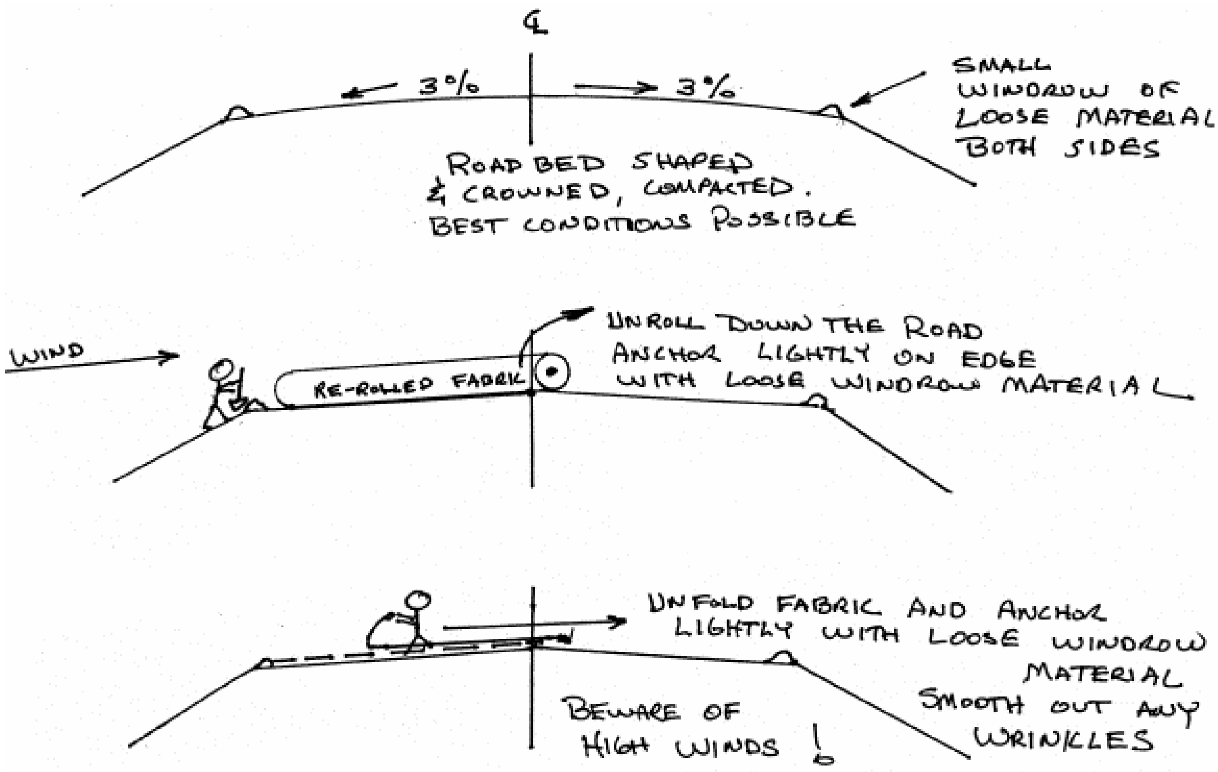


Figure 4.11 Geofabric Construction (Transverse Placement) (courtesy of Walter Leu and Lou Tasa).

Value:

a. Cost:

$0.90 to $1.50/ m² ($0.75 to $1.25/yd²) for Type V

$1.20 to $2.40/ m² ($1.00 to $2.00/yd²) for Type VI

for a width of 30 feet (10 m) this equivalent to

- $13,200 to $22,000 per mile ($7,920 to $13,200 per km) for Type V
- $17,600 to $35,200 per mile ($10,560 to $21,120 per km) for Type VI

b. Expected Life: 50 years with proper design and installation (see Section 4.5.5.4. for factors which effect longevity of geofabrics).

c. Comments: Proper materials and construction procedures are necessary to obtain good performance

The following are some of the contacts who have designed and constructed embankments with geofabrics used as separation layers.

James Mehle, City of Albert Lea, Alan Forsberg, Blue Earth County, Stephen Gale, Gale-Tec Engineering, Inc., David Olsonowski, Hubbard County, Richard Sanders, Polk County, Joel Uhlring, St. Louis County, Daniel Jobe, Scott County, Virgil Hawkins, Wright County, Walter Leu and Lou Tasa, Mn/DOT

4.5.5.3.3. Geosynthetics (Geogrids) used for Reinforcement of Embankments

4.5.5.3.3.1. General

Geogrids have many reinforcement applications. Installation of load distributing geosynthetics can have a significant effect on the strength parameters of the embankment system. Because soils fail in shear, a high tensile strength material compliments the low shear strength of soils, and is able to dissipate the shear stress, resulting in an increased load carrying ability of the subgrade (53). It is common not to decrease the thickness of the base but rather to provide more stability and stiffness, thereby increasing pavement life (56, 57).

Geogrids are able to distribute wheel loads when placed within the base course layer. This is due to the greater amount of friction developed between the geogrid and the granular material. This friction is much greater than between geotextiles and granular materials. The tension necessary to increase structural support is not immediately developed; the amount of time necessary for the tensile stress to develop is a function of the properties of the soils, geosynthetic, and loading.

4.5.5.3.3.2. Summary of Design and Construction using Geogrids for Embankment Reinforcement in Minnesota

Purpose : Geogrids have been used to reinforce and stabilize a fill in a swamp area where the fill itself does not have the strength to stand up.

Conditions: Over a swamp where geofabrics are used to stabilize poor soils especially by limiting shear strain and increasing shear strength at the location of a failure plane. Reinforcement may needed particularly for relatively high fills over poor soils.

Material(s)

Specifications:

Best: Biaxial Grid – polypropylene geogrid (BX 1200) or

Approved equal with the following properties:

1. Tensile Strength @ 5% strain (MD/XD)
   >810/1360 lb/ft.
2. Junction Strength (MD/XD) > 1180/1778 lb/ft
3. Flexural Stiffness > 750,000 mg-cm
4. Torsional Stiffness > 6.5 kg-cm/deg

   Uniaxial Geogrid – The Uniaxial Geogrid shall be a uniaxial polypropylene geogrid (UX 1600) or approved equal with the following properties:

1. Initial Modulus in use (MD) > 144,620 lb/ft
2. Longterm Allowable Load (MD) > 3,771 lb/ft
3. Junction Strength > 8,865 lb/ft
4. Flexural Stiffness > 6,000,000 mg-cm

Not Appropriate: Some geogrids that are not as stiff and are more brittle.

A sample of the geogrid should be supplied, along with its test results for the design requirements to the Agency, for approval, prior to placement on the job **or** Manufacturer certification of geogrid must be received from contractor

Special Considerations:

- Wider rolls are better because the material is easier to place.
- Tension in the geogrid is not developed immediately; therefore, some type of anchorages (pins) will provide necessary reinforcement
- Ductility will be needed as strains get higher.

Construction

Weather:

- Best: Any time not frozen
- Worst: Frozen subgrade

Transportation/Storage: Must keep geogrid covered as indicated in Mn/DOT specifications

A sample of the geogrid shall be supplied, along with its test results for the design requirements to the Agency, for approval, prior to placement on the job.

Measurement of Quantities: The quantity of geogrid shall be measured in place by the square yard actually covered. No allowance shall be made for laps and seams.

The geogrid shall be installed per the manufacturer's recommendation with the approval of the Engineer.

Criteria for connecting geogrids:

- Biaxial geogrid shall be shingled or overlapped in the direction of fill placement, a minimum of 0.7 m (2 ft) and tie as per manufacturer's recommendations. Because the geogrid has a tendency to bulge, it may be essential to cut and retie the fasteners.
- Adjacent rolls of Biaxial geogrid shall be overlapped 0.3 m (1 ft) to obtain the road covering width shown in the plans.
- Uniaxial geogrid shall be cut to length and rolled perpendicular to the roadway.
- No overlap of the Uniaxial geogrid is necessary.

Construction Procedures: (see **Figures 4.9, 4.10, and 4.11** for sequencing of construction of geogrids which is basically the same as for geofabrics).

- Best Practices
    - Use geogrid on top of base to reduce cracking
    - For fill on top of geogrid dump in the middle and work toward the edges.

- End or belly dump and push with a bulldozer

- Precautions
  - Keep constant speed when spreading
  - No turning movements and no braking

Value

a. Typical Cost (2002):: Geogrid – UX, $9.00/sq yd

BS, $3.65/sq yd

Typically, $30,000 / mi for a good road

The contract price paid for a square yard of the geogrid shall include full compensation for furnishing all labor, equipment, materials, tools and incidentals necessary to place the geogrid as shown on the plans.

b. Expected Life: with good design and construction practices should last 50 years+.

c. Comments – Geogrids have retarded longitudinal cracking by dissipating the wheel loads when grid placed between the subgrade and the base course or within the base course layer. Friction and interlock occur between the geogrid and the granular material.

Contacts:

Dan Suave, Clearwater County, Joel Ulring, St. Louis County, Walter Leu, Mn/DOT Duluth District, Graig Gilbertson and Lou Tasa, NW District, Mn/DOT, James Mehle, City of Albert Lea, Richard Sanders, Polk County,

4.5.5.4. Factors Affecting the Lifespan of Geosynthetics

4.5.5.4.1. Factors Reducing Effective Life Span

The effective life of a geosynthetic is a function of many factors. Solar radiation, heat, ozone, and acid rain, all begin to degrade the polymer before the geosynthetic is in service. For this reason, proper transportation and on-site storage must be carefully considered. Ultraviolet radiation, specifically UV-B, will cause severe polymer damage. The chemical bonds of the polymer structure are broken. Heat from solar radiation may cause some damage to the geosynthetic, and placing the geosynthetic in close proximity to hot materials such as asphalt or joint compound may compromise strength and longevity of the geosynthetic. To prevent heat damage, design specifications should provide adequate insulation between the geosynthetic and the hot material. Excess temperature should be avoided because polypropylene melts at 165C and polyester melts at 250C. On the opposite side of the spectrum, low temperatures can cause the materials to become brittle and decrease workability.

Appropriate procedures must be implemented in order to insure that damage is minimized during construction. The stresses endured during construction may be significantly greater than those expected during service. This is due to the limited amount of material present above the geosynthetic during construction available to distribute the stresses. Construction equipment should never contact the geosynthetic directly. It may cause failure during construction, because the equipment is often heavier than the calculated loads developed by the traffic after construction.

After installation is complete, other degradation processes take over. Acidity or alkalinity of the groundwater may cause a decrease in strength. The groundwater composition and pH should be tested and used during design to select a geosynthetic that will minimize the effect of the groundwater. Physical damage can still occur, though not likely from human interaction. Plant roots as well as insects and burrowing rodents may create holes that will decrease the strength and effectiveness of the geosynthetic (54). Chemical degradation is likely the primary concern after installation.

The effective longevity will vary depending on the in situ conditions and the intended applications. Properties of installed geosynthetics have been shown to be stable for over 20 years (55). Geosynthetics used for filtration and drainage have been shown to assist in the development of an internal soil filter based on a bridging network.

4.5.5.4.2. Creep Degradation

The value for the strength reduction factor is based on the inverse percentage of thestatic strength at which no creep occurs. The reduction factor will be a product of the polymer, manufacturing process, and type of geosynthetic. ASTM D5262 is the procedure used to measure the rate of creep under tensile load.

4.5.5.4.3. Installation Damage

Damage of geosynthetics during installation and compaction can be a major component of the decrease in tensile strength over the life of the material (56). The average diameter of the granular backfill material will significantly influence the amount of damage. The amount of installation damage may be assessed using ASTM D5818

4.5.5.4.4. Chemical and Biological Degradation

Chemical and biologic degradation are environmentally dependant factors (56). Chemical degradation is directly related to the composition and pH of the soil and groundwater. These parameters can be determined by analyzing the conditions near the construction site. Biologic degradation is more difficult to estimate because it is not a true deterioration of the material. It however, increases deterioration of material properties such as permeability and local tear resistance. Two types of biologic deterioration are commonly encountered:

- clogging of the apertures by bacteria or other small organisms,
- holes created by rodents
- flow may be restricted by precipitation of solids resulting from high concentrations of chemicals in solution

4.5.5.4.5. Polymeric Aging

Polymeric aging is the gradual process that brings the polymer into a state of equilibrium. The equilibrium state can be maintained unless a degradation process occurs. Degradation may be associated with exposure to many different compounds. The two simplest are;

- oxidative degradation and
- degradation caused by exposure to a strong acid or base.

The extent of the degradation effect is dependant on concentration and the amount of time in contact. Studies by Elias have shown that polyester geosynthetics degrade in the presence of strong acid and alkaline solutions. This degradation is associated with a decrease in tensile strength. Polyester geosynthetics with a low molecular weight and high carboxyl end group (CEG) will provide more resistance to high levels of acidity and alkalinity.

4.5.5.4.6 Summary of effects on Lifespan

The effectiveness of a system using geosynthetics is different for every situation (51, 52, 58). It has been shown that geosynthetics distribute shear stress over a greater area when the geosynthetic is in tension. The result will be different for each application depending on type of geosynthetic used, soil and granular material both above and below the geosynthetic, as well as the load and distance from the load. Isolating the effects of a geosynthetic is difficult because it is dependant on the application, in situ conditions, time in use, and the installation process. These parameters cannot be simulated easily in the laboratory and a conservative design approach must be taken until the effects of geosynthetic are better understood in field applications. FHWA (53), AASHTO, and ASTM have recommended design parameters for specified geosynthetic applications.

The effectiveness of geosynthetics will be greater for poor quality in situ conditions. The greatest improvement may be associated with one or more of the following: (53).

- Weak soil subgrades with CBR of 3 or less
    - R-Value < 15
- Poor quality aggregate base materials
- Low structural number of the pavement (approx. 3 or less). G.E. < 10.

Geosynthetics can be used between different materials to provide separation or within a granular layer to provide reinforcement and confinement. Initial tension also increases the amount of initial support. However, some geosynthetic materials are susceptible to creep therefore reducing the externally applied tension. The internal tension will increase over time after load is applied.

Geosynthetics used to reinforce extremely weak soils provide a greater amount of support than a geosynthetic used to reinforce moderate soils. The type of geosynthetic chosen will also greatly impact the performance of the pavement. Careful evaluation of the geosynthetic properties and the in situ conditions will provide the best results. Geocomposites are often able to provide better results than a single material. Geogrid/geotextile composites have been shown to provide better results than the components individually (26, 50, 53).

4.5.5.5. General Construction Considerations

Success with geosynthetics begins with choosing the right material for a given application. Knowledge of the conditions the geosynthetic will be exposed to, along with the desired properties of the geosynthetic, will lead to a successful project. Considering the properties

The construction area must be cleared of debris that may cause damage to the geosynthetic. As the geosynthetic is laid in place, care should be taken to check orientation and also prevent overexposure to sunlight. After the material is put in place seams may need to be secured. Keeping the geosynthetic in place during construction may be difficult; as some materials may curl or slip as the aggregate is placed.

Table 4.9 Geosynthetic Property Testing Methods

Property	Test Method
Apparent Opening Size	ASTM D4751
Water Permittivity	ASTM D4491
Tensile Strength	ASTM D4595
Geosynthetic Durability	ASTM D5819
Secant Modulus at 5% strain	ASTM D4595
Seam Breaking Strength	ASTM D4884
Puncture Resistance	ASTM D4833
Tear Strength	ASTM D4533
Ultraviolet Radiation Stability	ASTM D4355
Burst Strength	ASTM D5617
Hydraulic Conductivity Ratio	ASTM D5567
Biological Clogging	ASTM D1987
Temperature Stability	ASTM D4594
Clogging Potential	ASTM D5101

Coefficient of Friction	**ASTM D5321**
Chemical Resistance	**ASTM D5322**
Installation Damage	**ASTM D5818**
Creep Resistance	**ASTM D5262**
Multi-Axial Tension	**ASTM D5617**
Geogrid Chem. Resistance	**ASTM D6213**
Geotextile Chem. Resistance	**ASTM D6389**

After the geosynthetic is installed, the granular base course should be put in place such that material is not dumped directly on the geosynthetic, and a minimum of 150 mm (3 in.) is in place before any equipment is driven over the geosynthetic. Lightweight dozers and front-end loaders should be used to spread the aggregate. A complete construction sequence for soft and firm subgrade conditions is given as modified from Holtz 1998 (53).

Subgrade Preparation for Soft Foundations

1. Cut tree stumps flush with the ground surface.
2. Do not remove or disturb root mat.
3. Leave vegetative cover, such as grass and reeds, in place.
4. For undulating sites or areas where there are many stumps and fallen trees, construct a working table before placement of the embankment reinforcement. In this case, a lower strength sacrificial geosynthetic can be used to construct and the support the working table.

Geosynthetic Placement Procedures

1. Orient the geosynthetic correctly with the machine. This depends on the type of geosynthetic and the intended design objectives. In general for uniaxial geosynthetics:
    - no seams should be parallel to the embankment alignment.
    - these widths should be factory-sewn to provide the largest width compatible with shipping and field handling.

2. Unroll the geosynthetic as smooth as possible transverse to the alignment. **Do not drag it.**
3. Geotextiles should be sewn as required with all seams up and every stitch inspected. Clamps, cables, pipes, etc. should positively join geogrids. The following criteria should be used to evaluate sewing;
   - The seams should be sewn J-seam style (a prayer-seam is also permissible).
   - One row of sewing is required when using two spools of thread to give a 401-stitch.
   - If the stitching is "untested" two rows are needed not more than 13 mm (0.5-in). apart.
   - Need 4 –7 stitches per inch.

Fill Placement, Spreading and Compaction Procedures

- End-dump fill along edges of geosynthetics to form toe berms or access roads.
- Use trucks and equipment compatible with constructability design assumptions (Table 4.9).
- End-dump on the previously placed fill; do not dump directly on the geosynthetic.
- Limit height of dumped piles, e.g., to less than 1m above the geosynthetic layer, to avoid local bearing failure. Spread piles immediately to avoid local depressions.
- Use lightweight dozers and/or front-end loaders to spread the fill.
- Toe berms should extend one to two panel widths ahead of the remainder of the embankment fill placement.
- After constructing the toe berms, spread fill in the area between the toe berms.
  1. Placement should be parallel to the alignment and symmetrical from the toe berm inward toward the center to maintain a U-

shaped leading edge (concave outward) to contain the mud wave.

- Traffic on the first lift should be parallel to the embankment alignment; no turning of construction equipment should be allowed.
- Construction vehicles should be limited in size and weight to limit initial lift rutting to 75 mm (3 in.). If rut depth exceeds 75 mm (3 in.), decrease the construction vehicle size and/or weight.
- The first lift should be compacted only by tracking in place with dozers and end-loaders.
- Once the embankment is at least 0.6 m (2 ft) above the original ground, subsequent lifts can be compacted with a smooth drum vibratory roller or other suitable compactor. If local liquefied soil conditions occur, any vibration should be turned off and the weight of the drum alone should be used for compaction. Other types of compaction equipment also can be used for nongranular fill.
- After placement, the geosynthetic should be covered within 48 hours.
- **For less severe conditions (i.e., when no mudwave forms):**
    - Place the geosynthetic with no wrinkles or folds; if necessary, manually pull it taut prior to fill placement.
- Place fill symmetrically from the center outward in an inverted U (convex outward) construction process. Use fill placement to maintain tension in the geosynthetic.
- Minimize pile heights to avoid localized depressions.
- Limit construction vehicle size and weight so initial lift rutting is no greater than 75mm (3 in.)
- Smooth-drum or rubber-tired rollers may be considered for compaction of the first lift; however, do not over compact. If weaving or localized quick conditions are observed, the first lift should be compacted by tracking with construction equipment.

Construction Monitoring

c. Monitoring should include piezometers to indicate the magnitude of excess pore pressure developed during construction. If excessive pore pressures are observed, construction should be halted until the pressure drops to a predetermined safe value.
d. Settlement plates should be installed at the geosynthetic level to monitor settlement during construction and to adjust fill requirements appropriately.

Benefits/Cost

Benefits can be realized in two ways. Adding a geosynthetic to a standard pavement system design may increase the stiffness of the system, increasing the stability. This method does not quantify the mechanistic properties of geosynthetics during the design by reducing other material requirements. An alternative to this approach is to modify the design using the properties of geosynthetics. Savings associated with geosynthetic designs are realized by decreasing the thickness of granular material required to protect a soft subgrade and create a construction platform. A cost savings of more than 15% has been realized for geogrid stabilization of soft subgrades in Pennsylvania (59). The cost savings are commonly a function of the haul distance for the granular material.

4.5.6. Subgrade Enhancement using Substitution

4.5.6.1. General

Substitution is a method that directly enhances the subgrade by removing unstable or unsuitable soil and replacing or covering it with other suitable material.

If the use of in situ soil or available borrow is not practical from an engineering or financial standpoint then substitution with lightweight fill materials may be a solution. The following materials have been used in Minnesota to replace unstable subgrade materials. Select granular and/or Breaker Run Limestone have been used where the weight of the fill is not a concern. Wood fibers, shredded tires, or geofoam have been used in areas where the weight of the fill can cause consolidation of a submerged layer of peat or other compressible material.

Each section summaries the use of these materials. References and contacts for more detailed information are included in each of the summaries.

4.5.6.2. Substitution Using Select Granular Materials

Purpose: Select Granular has been used as a substitute subgrade material for regions having poor soils.

Conditions: Areas with high moisture content fine-grained soils near the water table.

Materials: Mn/DOT specification 3149.2 identifies Select Granular borrow is either pit-run or crushed material graded from coarse to fine, having:

$$\frac{\text{Mass passing } 0.075\,\text{mm}\,(\text{No. }200)}{\text{Mass passing } 25\,\text{mm}\,(1\text{in.})} \leq 0.12.$$

"The material shall not contain oversize salvaged bituminous particles or stone, rock or concrete fragments in excess of the quantity or size permissible for placement as specified. This is a very open gradation specification. The material should not be very frost or moisture susceptible. To minimize frost and moisture susceptibility there should be less than seven percent passing the 0.075-mm (No. 200) sieve (4)."

Design Considerations: Reported practice is to subcut and then fill with 0.6 m (24 in.) of select granular followed by 0.3 m (12 in.) of Mn/DOT Class 5 material. Depending on the existing soil it may be desirable to use a geofabric separation layer between soft, wet soils and the granular material.

Construction: Construction with Select Granular material should be governed by the standard practices given in Mn/DOT 2105 and 2112.

Contacts: Mn/DOT District Materials Engineer

4.5.6.3. Substitution using Breaker Run Limestone

Purpose:

Breaker run limestone has been used in Minnesota as a substitute for undesirable subgrade materials, particularly where fine grained, wet soils occur. Satisfactory compaction is achieved using the Quality Compaction Method given by 2211.3C2 in the *Minnesota Standard Specifications for Construction* (9) After compaction and grading the embankment is ready for placement of granular base materials (Class 5 or 6 recommended) and bituminous surfacing.

Description:

The term breaker run limestone shall refer to a limestone/dolostone material that has been run through a crusher one time and then screened for maximum size. The material has a maximum particle size of 150 mm (6 in.) and is well graded from the top size down to the 0.075-mm (No. 200) sieve. Item S-4.1 from the specifications for S.A.P. 20-625-01 states that 100% breaker run limestone material shall be graded from coarse to fine and pass the 150-mm (6 in.) sieve. Column (A) of Table 4.10 shows the results of sieve analyses performed on breaker run samples collected from a construction site. Column (B) contains the same information but with some interpolated values. Column (C) is the gradation band for MnDOT Class 5 aggregate containing more than 60 percent crushed quarry rock.

Table 4.10 Breaker-Run Limestone and MnDOT Class 5 Gradations

	Breaker Run		MnDot Class 5 (+ 60% crushed)
Sieve	A	B	C
6 inch	100	100	-
3 inch	-	90	-
2 inch	-	82	-
1.5 inch	80	80	-
1.0 inch	72	72	100
3/4 inch	67	67	90 – 100
3/8 inch	56	56	50 – 90
#4	43	43	35 – 70
#10	-	22	20 – 55
#30	10	10	-
#40	-	8	10 – 35
#200	0.3	0.3	3 – 10

Breaker run material may contain amounts of magnesium. Materials normally used for this type of backfill will not meet the insoluble residue requirements given in Minnesota specification 3138.2A3.

Construction

Sunny and dry weather conditions are best when constructing with breaker run limestone. The worst weather conditions would be overcast/misty or frozen.

Recommended practice is to end dump the breaker run material then spread it with a bulldozer. Compacted lift thickness should not exceed 225 mm (9 in.). The lift moisture content should be adjusted to 4 to 5 percent then followed by compaction. Compaction is carried out using a vibratory steel-wheeled roller.

In cases where the design includes geofabric there is a danger of the coarse breaker run material causing tears or otherwise damaging the geofabric. To prevent this damage a 150-mm (6-in.) separation layer of granular material (Class 5 recommended) should be included. In keeping with good construction practice the geofabric should be sewn or overlapped. Sewing shall be J-seam or prayer-seam according to Minnesota specification 3733.2B(D). An overlap of 0.3 to 1 m (1 to 3 ft) is adequate. Granular separation material should be initially spread along the centerline. This keeps the geofabric taut and wrinkle free. The construction sequencing and procedures presented in Section 4.5.5. should be followed.

Costs in 2002.

Breaker run limestone has been priced at $8.39 per ton from the Mantorville quarry. This bid was contingent upon the purchase of 14,000 cubic yards.

For more information on breaker run limestone contact Guy Kohlnhofer, Dodge County Engineer at guy.kohlnhofer@co.dodge.mn.us.

Figure 4.12 Overlapping Layers of Type V Nonwoven Geofabric Separate Granular Material from Wet, Fine Soil. 150-mm (6-in.) of Class 5 Granular Material Protects the Geofabric from the Breaker Run Material.

Figure 4.13 Steel-wheeled Roller Applies Compactive Effort to a 225-mm (9-in.) Lift of Breaker Run Limestone.

4.5.6.4. Lightweight Fills

Wood chip, shredded tires and geofoam have been used as lightweight fills to decrease the weight on in areas where the lower layers can consolidate or are otherwise unstable. Table 4.11 lists some of the factors used to help design an embankment using wood chips or shredded tires. A summary of the use of wood chips is presented in Section 4.5.6.4.1., shredded tires in Section 4.5.6.4.2. and geofoam in Section 4.5.6.4.3. Each of the summaries include 1. Purpose, 2. Conditions, 3. Materials, 4. Construction specifications and procedures, 5. Value, and 6. Contacts which includes people who have had experience with the given material.

Table 4.11 Characteristics of Common Lightweight Fill Materials (52)

Material	Expected Compacted Density [lbs/ft^3]	Comments
Wood Products (Chips)	24 – 36	Readily available, renewable. Easily placed with standard construction equipment. Should remain saturated at all times. Sawdust form is a relatively inexpensive byproduct of lumber industry. No formal design parameters, based on field experiments.
Shredded Tires	20 – 45	Readily available. Considered a by-product, relatively inexpensive. Easily placed by standard construction equipment. Design parameters are based on field experiments. Use restricted to above the water table by MPCA regulations.

4.5.6.4.1. Use of Wood Chips for Lightweight Fill

General

Wood Chips have been used in Minnesota as a lightweight substitute for undesirable subgrade materials. Wood chips have a unit weight of approximately 30 pcf and are particularly suited to swamp-like conditions where the water table is close to the surface. Wood chip construction can be combined with the use of other lightweight fills and the use of geotextiles.

Mn/DOT conducted a 1976 study that included log and wood chip construction. The methods were described as corduroy and wood chip and were used to widen sections of road over a swamp (60).

- Corduroy – Place tied logs perpendicular to the road. The corduroy creates a working platform for further construction.
- Wood chip working platform – Create a working platform using a layer of wood chips. Place a 0.7-m (2-ft) thickness then cover with a minimum of 150 mm (6 in.) of clay to reduce exposure to air.

- Wood chip embankment – Use of wood chips to reduce weight on soft subgrade materials, especially for sites requiring large amounts of fill material. Cover with a 0.7-m (2-ft) thickness of clay to reduce exposure to air.
- Keyed widening - Peat, muck or poor quality soils are dug out.

Observations and conclusions from the study:

- Wood will not displace in front of machinery but running water may easily displace wood chips.
- Disturbance of the existing vegetation mat (drainage ditches) can cause longitudinal cracking in adjacent lanes. Locate the ditches far enough away from the road so as to prevent transverse movement.
- The construction costs of floated widenings are much less than the keying method. Floating widenings are also much quicker to construct than keyed widenings.

Methods of controlling bio-degradation in embankments containing wood products (60):

- Construct so as to make sure the wood stays below the water table.
- Seal wood with chemicals (may be an environmental issue). Emulsified asphalt may be an option. Chemical treatment may be expensive and difficult to apply.
- Use a geotextile or a plastic soil to restrict/reduce the exposure to air.

Wood and wood chips may be used in construction without the need of special equipment.

See also "Wood Chips as a Lightweight Fill", Mn/DOT technical report December, 1996 (60).

Materials and Specifications

The term wood chips shall refer to byproduct materials having a relatively uniform size and obtainable by volume (yd^3 placed) from various wood industry sources. The term shall not refer to bark, leaves, twigs or stumps.

- Wood chips having a uniform gradation and an average size of approximately 75 mm (3 in.) may be available in some locations. Chips having a maximum size of

50 to 75 mm (2 to 3 in.) and semi-cubic shape can be produced from a pallet recycler.

- Lumber mill sawdust (Figure 4.14) is a material having a maximum size of approximately 50 mm (2 in.). The shape of lumber mill sawdust varies from flat and elongated particles to semi-cubic shapes. Wood chips of other sizes may be available locally from a variety of sources such as municipalities but they may have greater variation than that from wood industry sources.

Figure 4.14 Lumber Mill Sawdust

Construction

Wood chip construction is best when done under warm, dry conditions. The most unfavorable construction conditions would be frozen or moist (wet).
Standard use: In Minnesota the most common method of preventing decay is to keep the wood chip layer below the water table elevation. For some conditions it may be reasonable to partially or fully encapsulate the wood chips with geofabric and soil.

Alternate use:Use above the water table elevation is possible if the entire layer of wood chips is protected from moisture. Service conditions should be high and dry. The wood chip material should be dry when installed. The wood layer should be encapsulated in geofabric to prevent loss of material.

The geofabric may be Type V or VI, woven or nonwoven material. Whenever possible the geofabric should be placed on compacted soil. In keeping with good construction practice the geofabric should be sewn or overlapped. Sewing shall be J-seam or prayer-seam according to Minnesota specification 3733.2B(D) (9). An overlap of 0.3 to 1.0 m (1 to 3 ft) is usually adequate but depends on in-situ moisture conditions.

Wood chip construction does not require special equipment. End dump the wood chips and place them in 0.3 to 0.7 m (1 to 2 ft) lifts using dozers (Figure 4.15). The chips should next be covered with a minimum of 150 mm (6 in.) of plastic soil to reduce exposure to air. Proceed with compaction after placement of plastic soil.

Figure 4.15 Bulldozer Spreading Lumber Mill Sawdust

Precautions

- Poorly graded chips or non-uniform chips (sticks with organic debris) will not compact adequately.
- Moving water may easily displace wood chips.
- Beware of transverse movement that may cause longitudinal cracking.
- Fungi are the most common wood destroyers and causes significant strength loss for small weight loss. Fungi need air and moisture to be effective. Applications using continuous total submersion in fresh water will prevent fungal destruction.

- Help ensure the uniformity of wood material by obtaining wood from a single source per fill project.

Settlements of approximately 0.7 m (2 ft) [for 7-m (20-ft) excavations] have been observed over a 10-year period in swamp excavation projects that utilize sawdust as a fill material. However, there have been excellent results when using wood chips for fill and floated widening projects in swampy areas. When using wood chips in this manner the 20-year settlement is limited to that associated with initial construction.

Figure 4.16 Wood Chips Placed on Geofabric

Costs

Wood chips have traditionally been very inexpensive however the paper industry has recently emphasized use of these types of byproducts.

Table 4.12 Typical costs of Wood Chips

Material type	Cost
Coarser than sawdust	$7.62 / cu yd
Recycled chips	$5-6 /cu yd

Contacts

Dan Suave, Clearwater County, Richard Larson, Mille Lacs County, Robert Paine, Ramsey County, Jeff Blue, Waseca County.

4.5.6.5.2. Use of Shredded Tires for Lightweight Fill

Background and General Design Considerations

Shredded tires have also been used as a lightweight fill by a number of agencies in Minnesota. Table 4.13 lists a number of advantages, disadvantages and uses of shredded tires as lightweight fill.

Table 4.13 Advantages / Disadvantages and Practical Use of Waste Tires (52)

Material	Advantages	Disadvantages	Practical Areas of Use
Waste Tires	Inexpensive. Easily placed. Non-biodegradable.	Must be kept above water table. May leach toxins. Minimal design parameter available.	Bogs/wetlands when water table is not near the surface.

Mn/DOT has sponsored research on the use of shredded tires reported in Development of Design Guidelines for Use of Shredded Tires as a Lightweight fill in Road Subgrade and Retaining Walls (61).

Design Factors

Waste tires are an inexpensive source of lightweight fill but the MPCA has found they may also be a source of potential environmental problems when used in construction projects.

MPCA Guidelines (52)

Toxic metals (barium, cadmium, chromium, lead, selenium, and zinc) are leached from the tires under acidic conditions. Soils in northeastern Minnesota may be acidic.

Polynuclear Aromatic Hydrocarbons (PAHs) and total petroleum hydrocarbons are leached from tire materials in the highest concentration under alkaline conditions. Soils in southwestern Minnesota may tend to be alkaline.

Asphalt materials may leach higher concentrations of contaminants of concern than tire materials under some conditions.

Drinking water Recommended Allowable Limits (RALs) set by the Minnesota Department of Health may be exceeded under “worst-case” conditions for arsenic, barium, cadmium, chromium, lead, selenium, and carcinogenic and non-carcinogenic PAHs. "Worst-case" case conditions for metals appear to occur at low pH (acid) conditions. "worst-case" conditions for organics appear to occur at high pH (basic) conditions.

Environmental impacts from the use of waste tires can be minimized by placement of tire materials only in the unsaturated zone (above the water table) of the roadway subgrade. Place alternative materials, such as wood chips or soil, below the water table.

Methods and Equipment

In 1986 the Hedbom Forest Road in Floodwood, MN was constructed using waste tires below the base material. Methods used varied from connecting whole tires to spreading shredded tires as a base material. As of 1989 all of the sections were performing well.

MPCA Guidelines for Construction (52):

Road Repair and Construction

- Shredded waste tires can be used in road construction or repair if the tire shreds will be above the water table and not in contact with ground water. Tire shreds cannot be used below the water table.
- Design slopes to reduce water infiltration and drain surface water away from shredded tires.

General Construction (Applies to all construction projects)

The most common method is encapsulation within geotextile materials.

- A synthetic geotextile fabric is recommended above and below the areas where shredded waste tires are used. The fabric will prevent movement of soil into and within the tire shreds, and will hold the tire shreds in place.
- Tire shreds must be covered by a low-permeability surface (soil) to reduce seepage of surface water.
- Lift thickness of shredded tires may be up to 1 m (3 ft).

Interim Design Guidelines (52)

This interim report was generated from data from a private access road constructed with shredded tire thickness of 1 to 2 m (3 to 6 ft):

1. The rate and effectiveness of compaction are similar to sawdust fills.
2. Approximately 99 percent of maximum compaction can be achieved with about 24 passes of a D7 caterpillar.
3. The maximum bulk unit weight of tire shreds with an average particle area of 0.1m^2 (1 ft^2) is approximately 20 to 23 pcf.

Summary of Design and Construction Procedures for Shredded Tire use in Minnesota Embankment Installations

Purpose

Shredded tires have been used as a lightweight fill and drainage layer(s). They can replace common borrow and use discarded tires which would otherwise need to be wasted in landfills.

The **compacted dry density** of tire shreds is about one-third to one-half of the compacted dry density of typical soil. They are therefore attractive lightweight fill for construction on weak, compressible soils where slope stability or excessive settlement are a concern.

The **thermal conductivity** of tire shreds is about eight times greater than typical granular materials and therefore they can be used as an insulating layer 150 mm (6 in.) to 450 mm (18 in.) thick.

The high **hydraulic conductivity** of tire shreds which is generally greater than 1 cm/sec makes them suitable for many drainage applications.

Conditions: An area which has a poor wet soil and will settle significantly under normal aggregate or soil fills.

Materials and Specifications: ASTM 6270 defines the following materials and quantities related to scrap tires:

Definitions:

Shredded tire: a size reduced scrap tire where reduction is accomplished with a "shredder"

Tire chips: pieces of scrap shredded tire that have a basic geometric shape and are generally between 12 mm (0.5 in.) and 50 mm (2 in.) in size and have most of the wire removed (also called chipped tires).

Tire shreds: pieces of scrap tire that have a basic geometric shape and are generally between 50 mm (2 in.) and 305 mm (12 in.) in size.

Whole tire: scrap tire that has been removed from the rim, but has not been processed.

Figure 4.17 Tire Shreds

Design Quantities for use of tire shreds:

Gradation: The materials should be chunky tire shreds with a minimum size of 150 mm (6 in.) and maximum size of 300 mm (12 in.). They should not include any ½ tires.

Depth: The Tire Shreds should be placed initially about 5 m (15 ft) loose and then compacted to 3+m (10+ft).

Thickness Design Elements: The soil on which the fill is to placed should be smoothed and covered with a Type V non-woven geofabric to prevent infiltration of soil into the tire shreds. A 0.7-m (2-ft) layer of soil or granular material is placed over the Tire Shreds and used as a separation layer during compaction. The shredded tire layer should be wrapped completely in a layer of woven or unwoven geofabric.

Compaction: Compaction is accomplished similar to quality compaction procedures, i.e. until no further consolidation of the embankment is observed. This can be accomplished with four or five passes of a bulldozer operating on top of the soil or granular layer. The inspector can usually tell when the system is solid/compacted.

Construction

Weather: Weather is not a big factor. The only problems would be if the grade was frozen or 100 percent saturated.

Transportation can be by dump truck or any other over-the-road vehicle. In Carlton County a system was set up whereby the supplier advertised that transportation would be available to remove used tires from the county. When shredded tires were brought to the job site the same live-bottom trucks (Figure 4.18) picked up scrap tires for transport back to the manufacturing site.

Shredded tires were moved around and from the storage area adjacent to the project using a "**thumb probe" device** pictured in Figure 4.19 attached to a front end loader. This device expedited the transfer of shredded tires around and to the project site. The quantity of shredded tires was measured in truckloads.

If more than a compacted 3-m (10-ft) lift of tires is specified a minimum of 0.7-m (2 ft) of clay separation is necessary.

Construction Control

Materials-uniformity can be attained by having a constant gradation

Procedures-use the probe device to place the shredded tires in a consistent horizontal orientation.

Measurements-thickness of the layers should be monitored using survey levels.

Best Practices

Use the **"Thumb Probe"** to move the tires into a uniform horizontal configuration.

Totally wrap shredded tires in fabric.

Figure 4.18 Live-Bottom Truck Delivering Tire Shreds

Figure 4.19 Placing Tire Shreds with “Thumb-Like Attachment

Figure 4.20 Tire Shreds Placed on Geofabric

Figure 4.21 Geofabric and Fill being Placed over Tire Shreds

Precautions

- Tires can burn and therefore the shredded tire storage area and fill should be protected form accidental causes of fire or arson until properly covered.
- The fill needs to be designed to minimize the possibility of an internal heating reaction (fire). Heating and eventually fire can be caused by oxidation of the steel belts or rubber.
- Minimize free access to **air and water**
- Use relatively large size shreds to minimize surface area.
- **Type I and Type II** fills with tire shreds should be free of all contaminants such as oil, grease, gasoline that could be a fire hazard.
- **For a Class I fill (less than 1 m deep)** a maximum of 50% should pass the 38-mm (1 ½-in.) sieve and 5% pass the 4.75-mm (No. 4) sieve. No special design considerations to minimize heating would then be needed for Class I fills.

- **For Class II fills (1-3 m deep)** a maximum of 25% should pass the 38-mm (1 ½-in.) sieve and 1% pass the 4.75-mm (No. 4) sieve. There should also be less than 1% metal fragments exposed.
- **Class II fills** should be constructed to minimize infiltration of water and air into the system. There also should be no direct contact between topsoil and the shreds.
- The top and sides of the fill should be covered with a 0.5-m (2 ft) thick layer of compacted soil with more than 30% fines.
- The grade should be built so that water will drain away from the shreds.
- The pavement and soil should be extended to the shoulder so that water will drain to the ditch.
- The thickness of the drainage layer where it is daylighted should be minimized.
- The granular base should be separated from the tire shreds with a non-woven geofabric.
- The shredded tire fill will be softer (less stiff) than most other fill materials. The overlying pavement must be designed for the design traffic considering this condition.

Minnesota Pollution Control Agency (MPCA) Guidelines

The Minnesota Pollution Control Agency has developed the following guidelines for use when using shredded tires as a lightweight fill material in construction:

- Shredded waste tires can be used in road construction or repair if the shreds will be above the water table and not in contact with ground water. Tire shreds cannot be used below the water table.
- Roads and road slopes must be designed and constructed to reduce water infiltration and to promote surface water drainage away from the road bed, which will reduce the amount of surface water seeping through the shredded tires.
- A geofabric is recommended above and below the area where shredded waste tires are used. The fabric will prevent movement of soil into the layer of tire shreds and will hold the tire shreds in place.

- Tire shreds must be covered by a low-permeability surface to reduce seepage of surface water.
- The **leachate** from shredded tire installations was studied by MPCA and reported in 1992 (52). The laboratory test results showed leaching of heavy metals and PAHs as follows:

  - Tire shreds leach heavy metals at significant concentrations in highly acidic (low pH) solutions.
  - Tire shreds leach polynuclear aromatic hydrocarbons (PAHs) at significant concentrations in highly basic (high pH) solutions.
  - Tire shreds *did not* leach contaminants of concern in neutral pH solutions (pH of about 7.0).

  Vehicle tires contain metal additives, metal belts and bead wire, plus petroleum is used to make rubber. These materials can account for the heavy metals as well as the PAHs (Compounds found in petroleum).
- A proposal should be submitted to MPCA for technical review, including on methods of construction, number and type of tires to be used, depth to ground water table and soil data. Also required are maps, diagrams and cross-sections to show construction detail.
- **More information** is available from MPCA. Fact sheets are available outlining the major components of the waste tire management program by calling (651)-296-6300 in the Twin Cities area, or 1-800-657-3864 in Greater Minnesota.

Contacts: Wayne Olson or Randy McCusky, Carlton County, Blake Nelson or John Seikmeier, Mn/DOT, Steve O'Brien, First State Tire Recycling, Joseph Otte, Wenck Associates, Inc.

4.5.6.6.3. Use of Geofoam for Lightweight Fill

General

The foam products discussed in this report are of the type "Expanded Polystyrene" (EPS), also referred to as "geofoam". Historically the use of this product has been less common in the United States than in northern Europe.

No special equipment is required for placing EPS. In most cases slabs of EPS may be placed by hand. If needed, makeshift handles can be created by inserting screwdrivers into a slab of EPS to help maintain stability in windy conditions.

Purpose

Geofoam is useful as a low-density, lightweight fill material when use of in situ soil or available borrow is impractical from an engineering or financial standpoint. Geofoam is useful near structures that cannot tolerate high lateral forces.

Materials

Geofoam (EPS) has a density of approximately 1% of soil or granular fill materials and is therefore attractive lightweight fill for construction on weak, compressible soils where slope stability or excessive settlement is a concern. Manufacturers sell a variety of sizes on request. Geofoam blocks are available in 1.3-m (4-ft) widths, thicknesses variable from 0.1 to 1.0 m (3 - 30-in.), and 2.7 to 5.5 m (8 to 16-ft) lengths (52).

EPS can be manufactured to various densities and strengths. Therefore cost is dependent on the strength specifications and the amount needed. The benefits of using EPS are realized in the analysis of load reduction and excavation costs compared to those of standard fill materials. In some cases the use of protective concrete slabs or fabrics will add additional cost (52).

Geofoam is a cellular material made of expanded polystyrene

Flexural strength ranges from 70 to 344 kPa (10 to 50 psi) and compressive resistance at 10% deformation ranges from 40 to 200 kPa (5.8 to 29 psi) (52). Studies have found that the compressive strength of the expanded polystyrene remains constant in use. Although some compressive strengths have shown increases; this is thought to occur because of an increase in the moisture content over time.

Geofoam

- has been shown to be moisture resistant when submerged after nine years,
- dissolves when exposed to petroleum products,
- is flammable and care must be taken with any high temperature work near EPS, and
- is available in a more expensive, self-extinguishing version (52).

Design Factors

- The thermal properties of geofoam are of concern in cold regions due to differential surface icing. 0.7 to 1.0 m (20–30-in.) of granular material placed above the geofoam is recommended to reduce icing.
- Water absorption of geofoam may be 32 to 81 kg/m^3 (2 to5 pcf).
- With respect to other materials has the lowest available density for the strength it supplies. Compacted density of approximately 48 kg/m^3 (3 pcf).
- Geofoam is easily placed, no need for additional equipment.
- Little effect from environmental conditions such as submersion.
- Requires the least amount of soil replacement for given load reduction.
- Geofoam has a high unit cost and may not be readily available.

Construction

- **Weather**: Best when atmospheric conditions are calm and the grade is neither frozen nor saturated.
- **Transportation** can be accomplished with trucks.
- **Level the subgrade.** Supplement with geotextiles and granular materials as necessary.
- Blocks should be placed squarely and touch each other. Use staggered placement techniques to interlock geofoam blocks. Stagger lifts of geofoam blocks to prevent "seams" (Figure 4.22).

Figure 4.22 Placing Geofoam (EPS) Blocks (52).

Construction Control

- **Materials**-variety of strengths, sizes may be specified.
- **Procedures**- place on level ground during calm conditions. Hand placement is possible.
- **Measurements**-thickness of the layers should be monitored.

Best Practices

- Place on blanket of sand, geotextile.
- **Cap with impermeable layer to prevent infiltration of petroleum products.**

Precautions

- It is recommended that **in-service deflections** should be offset either by either a 100-mm (4-in.) slab of concrete or increasing the bituminous surface by 300 to 400 mm (12 to 16 in.).
- EPS foam can **degrade** when exposed to petroleum based chemicals so some design situations may require protection.

Protect EPS with either a **concrete covering or a petroleum resistant geotextile.**

- **EPS can insulate pavement surfaces** from radiant heat in the embankment. This is of concern during winter when ice buildup can cause hazardous driving conditions (52).
- Long term exposure to sunlight will cause geofoam to yellow.

Value

- value – EPS geofoam has a high unit cost but savings is derived from comparing load reduction and excavation costs to those of standard fill materials.
- expected life-50 years

Contacts: Robert Paine, Ramsey County and R-Control Building Systems, Excelsior, MN 55331, www.r-control.com and www.geofoam.syr.edu

4.5.7. Recommendations for Use of the Various Subgrade Enhancement Methods in Minnesota

4.5.7.1. General

Procedures to use for special subgrade conditions have been presented in this Chapter. Most projects can be designed with the grade at least 1.7 m (5 ft) above the water table with adequate drainage provided to result in a good uniform well compacted subgrade. However, if the grade must be built closer to the water table and/or peat or other undesirable materials exist in the grade then special procedures such as those presented here can be used.

The subgrade soil design and construction procedures presented are based on the review of literature, responses to questionnaires sent to Minnesota cities and counties, and discussions and review of specific projects with city, county, and Mn/DOT engineers and suppliers. Recommendations for when and how to use the procedures are presented in Tables 4.14, 4.15, 4.16 and 4.17. The first three tables are based on soil type:

Table 4.14 Granular

Table 4.15 Semi-plastic

Table 4.16 Plastic

The soil types are defined using categories from the MnPAVE design soil parameters. The moisture conditions estimated for the grade are estimated using

- height of the final grade above the water table and
- drainage provided for the pavement section.

The height of the final grade above the water table is sometimes limited by the presence of peat or some other compressible material in the grade. Table 4.17 applies to layers of peat or other unstable materials occurring in the grade.

Mn/DOT recommends that the grade be designed at least 1.7 m (5 ft). If a peat or other compressible layer exists along the alignment regular aggregate may be too heavy, causing the material to displace. One remedy would be to replace (substitute) a portion of all of the compressible material.

Table 4.17 includes the recommended procedures of various thicknesses of peat, drainage, and moisture content.

The moisture conditions of the subgrade soil are estimated using:

- the height of the grade above the water table and
- drainage designed into the pavement section.

The height above grade is measured at the centerline. It is assumed the side slope is sufficient for runoff. It is also assumed that the surface is sealed enough to promote runoff.

4.5.7.2. Summary of Subgrade Soil Enhancement Procedures

The listed procedures have been presented and described for subgrade enhancement.

1. Modification/Stabilization with Lime
2. Stabilization with Fly Ash
3. Separation with Geofabrics
4. Reinforcement with Geogrids
5. Substitution
   a. Select Granular
   b. Breaker Run Limestone
   c. Wood Chips

d. Shredded Tires

e. Geofoam

Table 4.14 Subgrade Soil Enhancement – Granular Soils

Soil Type	**Grade above Water Table**	**Drainage***	**Moisture** Conditions**	**Special Subgrade Soil Enhancement**
Granular, gravel, sand, loamy sand	>2 meters (6 feet)	Good	Dry/damp	None
		Fair	Dry/damp	None
		Poor	Wet	None
	1 – 2 meters (3 – 6 feet)	Good	Dry/damp	None
		Fair	Wet	None
		Poor	Wet	None
	0.3 – 1 meter (1 – 3 feet)	Good	Dry/damp	None
		Fair	Wet	None
		Poor	Saturated	3

* Good – longitudinal and transverse drainage with free draining base daylighted.

Fair – longitudinal and transverse drainage **without** free draining base or not daylighted.

Poor – drainage not provided and no free draining base.

** Dry/damp – maximum strength attainable

Wet – reduced strength

Saturated – reduced strength and pumping can occur

Table 4.15 Subgrade Soil Enhancement - Semi Plastic Soils

Soil Type	**Grade above Water Table**	**Drainage***	**Moisture** Conditions**	**Special Subgrade Soil Enhancement**
Semi Plastic, pl SL, L, SiL, SCL, CL, SiCL	>6 feet (2 meters)	Good	Dry/damp	None
		Fair	Dry/damp	3
		Poor	Wet	1,2,3
	3 – 6 feet (1 – 2 meters)	Good	Dry/damp	None
		Fair	Wet	1,2,3
		Poor	Wet	1,2,3
	1 – 3 feet (0.3 – 1 meter)	Good	Dry/damp	None
		Fair	Wet	1,2,3
		Poor	Saturated	1,2,3,4,5

Table 4.16 Subgrade Soil Enhancement - Plastic Soils

Soil Type	**Grade above Water Table**	**Draina ge***	**Moisture** Conditions**	**Special Subgrade Soil Enhancement**
Plastic, SC, SiC, Clay, Peat	>2 meters (6 feet)	Good	Dry/damp	None
		Fair	Dry/damp	None
		Poor	Wet	1,2,3
	1 – 2 meters (3 – 6 feet)	Good	Dry/damp	None
		Fair	Wet	1,2,3
		Poor	Wet	1,2,3
	0.3 – 1 meter (1 – 3 feet)	Good	Dry/damp	1,2,3
		Fair	Wet	1,2,3
		Poor	Saturated	1,2,3,4

Table 4.17 Subgrade Soil Enhancment Recommendations for Peat and/or Swamp Areas

Thickness of Peat	Drainage*	Moisture** Conditions	Special Subgrade Soil Enhancement
< 6 feet (2 meters)	Good	Dry/damp	5a, 5b, 3
	Fair	Dry/damp	5a, 5b, 3
	Poor	Wet	5a, 3
6 – 12 feet (2 – 4 meters)	Good	Dry/damp	5a
	Fair	Wet	5a, 5b, 5c, 5d 5e
	Poor	Wet	5a, 5b, 5c, 5e, 3, 4
> 12 feet *** (4 meters)	Good	Dry/damp	5c, 5d 5e, 5f
	Fair	Wet	5c, 5d 5e, 5f, 3, 4
	Poor	Saturated	5c, 5d 5e, 5f, 3, 4

*** Peat quality varies with the amount of natural fibers present and the level of decomposition. When peat thickness > 12 ft (4 m) consult a geotechnical engineer. Note: If the grade is being constructed at 1 m (3 ft) above the water table or less, special precautions must be made so that the construction equipment does not sink into the grade.

CHAPTER 5
PAVEMENT SECTION MATERIALS

5.1. Background

Pavement section materials are defined as all the layers overlying the subgrade soil and can be of many different types and properties. They can vary from a granular subbase material that will enhance the properties of the subgrade soil, to a 100-percent crushed aggregate base, to a high quality asphalt mixture that can withstand many applications of very high stresses due to loading and weather. Generally, the closer to the surface a layer is located the higher the load and environmental stresses it must withstand. Therefore, layers closer to the surface must be stronger and more durable. In Chapter 4 soil characteristics and embankment design are presented. The purpose of the procedures presented was to provide a uniform and stiff foundation with the existing soils. In some cases this will require stabilization and/or reinforcement. These same principles must be applied to the pavement materials so that a strong durable pavement will result.

Definitions of the various materials used are given for the three design procedures currently used in Minnesota [Soil Factor, R-Value and mechanistic-empirical design (MnPAVE)].

The material must meet Mn/DOT specifications in order for the pavement section materials to achieve the properties assumed for design the specifications must be carried out in the field. The specifications must be implemented by knowledgeable people with proper equipment.

Section 5.2 presents definitions of materials used in the layers of a pavement section and the specifications used for construction of the materials.

Section 5.3 presents the properties used to define how the materials are input for the design procedures. In order for these properties to be obtained the section must be built according to the specifications,

Section 5.4 lists field control procedures that should be followed to meet the specifications and result in a well-constructed project.

5.2. Definitions

5.2.1. Granular Subbase and Select Granular (Mn/DOT Specification 3149-B2)

5.2.1.1 Granular

Aggregate on crushed rock primarily retained on the 0.075 mm (No. 200) sieve.

5.2.1.2. Select Granular

For special use in embankment or backfill construction Select Granular may be any pit-run or crusher-run material that is so graded from coarse to fine that the ratio of the percent passing the 0.075-mm (No. 200) sieve divided by the portion passing the 25-mm (1-in.) sieve does not exceed 12 percent by mass.

5.2.1.3 Subbase Course (Mn/DOT Specification 3138, Class 4)

The subbase course will consist of a pit run or crushed aggregate that meets the gradation specifications in Table 3138-1 of the Mn/DOT 2000 Specifications (9).

5.2.2. Aggregate Base Course

5.2.2.1. Granular (Mn/DOT Specification 3138, Class 3, 5, and 6)

A granular base course consists of any combination of screened pit-run and crushed aggregates that meet the gradation specifications of the respective columns in Table 3138-1 of the Mn/DOT 2000 Specifications (9).

5.2.2.2. Salvage Materials (Mn/DOT Specification 3138, Class 7)

- **Salvaged Concrete (C)**: Crushed concrete processed to meet Class 4, 5, or 6 gradation specifications listed in Table 3138-1 when being used to substitute for Class 4, 5, or 6 materials respectively.
- **Salvaged Bituminous (B)**: Crushed bituminous mixtures processed to meet Class 4, 5, or 6 gradation specifications listed in Table 3138-1 when used to substitute for Class 4, 5, or 6 materials respectively. The maximum percent residual asphalt permitted is 3 %.
- **Reclaimed Glass (G)**: Up to 10 % by weight of reclaimed glass may be mixed/blended with virgin or salvaged/recycled aggregates during the crushing operation. Restrictions on sources, composition, debris content and storage are included in Specification 3138 A2. A certification procedure is also required.

5.2.3. Stabilized Base Materials.

Many materials have been used for stabilizing base courses with varied success in Minnesota. When using a stabilizing agent it is necessary to use a mix design procedure that will result in an optimum material content. The material must then be mixed with the aggregate or salvage material uniformly to provide a consistent product.

5.2.3.1. Portland Cement, lime and/or fly ash have been used in many combinations to provide a stabilized base. Mix design is very important to provide a material that will be strong and durable without excessive brittleness.

5.2.3.2. Asphalt cement, asphalt emulsions and cutbacks have been used for many years to stabilize and waterproof granular bases. Mix designs must efficiently use these materials and result in a strong durable mix. Mn/DOT Specification 2204 covers the requirements for these mixtures (9).

5.2.4. Recycling and Reclaiming

5.2.4.1. Cold In-Place Recycling: This process involves the grinding of an existing HMA surface, mixing asphalt and/or aggregate and compacting the final mixture. Mn/DOT is developing a specification for the process.

5.2.4.2. Full Depth Reclamation: This process involves the grinding and mixing of the full pavement section and compacting it in place. A Mn/DOT Specification is being developed for the use of this process.

5.2.5. Hot Mix Asphalt (HMA)

Currently, there are two types of mixtures (designs) used by Mn/DOT. The Mn/DOT 2360 Combined 2360/2350 (Gyratory/Marshall Design) Specification includes Marshall Mix Design Procedure (2350) and Superpave Mix Design Procedure (2360). The Superpave mix design is used on State Highways for all new construction and mid and long life overlays and the Marshall mix design is used on State Highways for short life overlays (<5 years) and/or small quantities (<5,000 tons).

5.3. Pavement Design Factors

5.3.1. General

The design factors for the Soil Factor and R-Value Design procedures are the Granular Equivalent Factors used to build up the pavement section in terms of factors a_1, a_2 and a_3 which are for the surface, base and subbase respectively. The factors depend only on the specification which the material or mixture meets. Based on decades of experience, the relative values of these factors reflect the contribution that layer provides to the performance of the pavement structure.

The design factors for MnPAVE are the effective moduli of the respective materials.. Resilient Modulus tests are now being run by Mn/DOT to develop a catalogue of moduli to use for the various combinations of materials used. For MnPAVE five moduli are used to represent the five seasons defined at Mn/ROAD (6).

5.3.2. Granular Equivalency Factors

Table 5.1 lists the Granular Equivalency Factors used for calculating the Granular Equivalent Thickness. The factors a_1, a_2, and a_3 relate to the surface, base and subbase respectively.

Table 5.1 Granular Equivalent (G.E.) Factors

Material	Specification	G.E. Factor
Hot-Mix Asphalt	2360/2350	2.25
	2331, 2340 Type 41, 47, 61	2.25
	2331 Type 31	2.00
Road-mix Surface (base)	2321	1.50
Bituminous-treated Base	2204 (rich)	1.50
	2204 (lean)	1.25
Aggregate Base	Class 5 or 6, 3138	1.00
Aggregate Base	Class 3, 4, 7, 3138	0.75
Select Granular	3149.2C	0.50

Other materials and procedures do not have published factors. For procedures such as cold in-place recycling and reclamation contact the Mn/DOT Pavement Design Engineer.

5.3.3. Resilient Modulus for Pavement Materials

For MnPAVE, resilient moduli must be determined for each material for each of the five seasons. The default values listed in Table 5.2 should be used unless a Mn/DOT District Materials Engineer or the State Pavement Design Engineer has been consulted.

Table 5.2. Default Resilient Modulus Values to Use in MnPAVE

Hot Mix Asphalt Properties	Hot Mix Asphalt (HMA) Surface	MnPAVE Design Moduli									
		Early Spring		Late Spring		Summer		Fall		Winter	
		4 weeks		varied length		varied length		varied length		varied length	
		MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
	2350 Mixture* (MnDOT Spec. 2350)	11,900	1730	5000	725	1850	268	7860	1140	15,200	2200
	2360 Mixture* (MnDOT Spec. 2360)	11,900	1730	5000	725	1850	268	7860	1140	15,200	2200

*Assume PG 58-28 asphalt binder

Aggregate Base Properties	MnDOT Aggregate Base Classification	MnPAVE Design Moduli									
		Early Spring		Late Spring		Summer		Fall		Winter	
		4 weeks		varied length		varied length		varied length		varied length	
		SF = 0.5		SF = 0.5		SF = 1.0		SF = 1.0		Frozen	
		MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
	Class 7 (MnDOT Spec. 3138)	39	5.6	39	5.6	78	11	78	11	350	50
	Class 6 (MnDOT Spec. 3138)	39	5.6	39	5.6	78	11	78	11	350	50
	Class 5 (MnDOT Spec. 3138)	39	5.6	39	5.6	78	11	78	11	350	50

Granular Subbase Properties	MnDOT Granular Subbase Classification	MnPAVE Design Moduli									
		Early Spring		Late Spring		Summer		Fall		Winter	
		4 weeks		varied length		varied length		varied length		varied length	
		SF = 0.5		SF = 0.5		SF = 1.0		SF = 1.0		Frozen	
		MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
	Class 4 (MnDOT Spec. 3138)	39	5.6	39	5.6	78	11	78	11	350	50
	Class 3 (MnDOT Spec. 3138)	39	5.6	39	5.6	78	11	78	11	350	50
	Select Granular (MnDOT Spec. 3149.2B2)	39	5.6	39	5.6	78	11	78	11	350	50
	Granular (MnDOT Spec. 3149.2B1)	21	3.0	21	3.0	41	6.0	41	6.0	350	50

5.4. Construction of the Pavement Layers

5.4.1. Specification Review

5.4.1.1. Granular Materials Properties and Gradations

5.4.1.1.1. Granular Subbase (Specification 3149.2B2)

Granular material may be any pit-run or crusher-run material that is graded from coarse to fine whose ratio of the portion passing the 0.075-mm (No. 200) sieve divided by the portion passing the 25-mm (1 in.) sieve may not exceed 12 percent by mass. The material shall not contain oversize salvaged bituminous particles or stone, rock or concrete fragments in excess of the quantity or size permissible for placement as specified. This is a very open gradation specification. However, the material should not be very frost or moisture susceptible. To minimize frost and moisture susceptibility there should be less than seven percent passing the 0.075-mm (No. 200) sieve.

5.4.1.1.2. Aggregate Base and Subbase Materials (Mn/DOT Specification 3138)

Specification 3138 covers the gradation of surface gravel (Class 1 and 2), subbase granular materials (Class 3 and 4), and granular base materials (Class 5 and 6). The following requirements are listed:

- All unsuitable and weathered materials shall be removed from the face of the pit.
- The mixture must contain 100 percent virgin aggregate and shall consist of sound durable particles or fragments of gravel and sand except Class 2, which shall consist of 100 percent crushed quarry or mine rock. The materials should be free of sod, roots, plants and other organic matter and lumps of clay.
- The insoluble portion of carbonate rock passing the 0.075-mm (No. 200) sieve shall not exceed 10 percent. This requirement applies to materials from Anoka, Carver, Dakota, Hennepin, Ramsey, Scott, Washington and all counties in Mn/DOT District 6.
- The gradations for each of the Classes of materials are listed in Table 3138-1.
- Crushing will be required for Class 5 and 6 aggregates for materials larger than the maximum size and smaller than a 200-mm (8-in.) grizzly. If crushing causes a poor gradation it must be adjusted or some material will need to be stockpiled.
- The Los Angeles Abrasion Loss should be no more than 35 percent for Class 6 material and no more than 40 percent for all other Classes; Class 3, 4 and 5

aggregate shall contain no more than 10 percent shale as defined in the Mn/DOT Grading and Base Manual (10).

5.4.1.1.3. Stabilized Base

5.4.1.1.4. Recycled and Reclaimed Materials may be used or blended with a combination of virgin aggregates in any percentage if the resulting material meets the requirements of the base or subbase layer being designed. These materials are covered under Specification 3138, Class 7. Three types of salvaged/recycled materials are covered:

- Salvaged Bituminous Aggregate Mixtures can be used alone or in combination with virgin aggregates such that the final mixture meets the gradation and quality requirements for the Class aggregate for which it is being substituted.
- Salvaged Crushed Concrete Aggregate has the same requirements as Salvaged Bituminous.
- Reclaimed Glass can be incorporated up to 10 percent in a granular base. Restrictions are put on the sources and types of reclaimed glass that can be used. These are listed under "composition" in Specification 3138. Restrictions on debris content and storage are also given. The source of the glass must also be certified.

5.4.1.1.5. Sampling and Testing

Specification 3138 requires the following criteria with respect to Sampling and Testing:

- All sampling of Class 1, 2 and 7 materials can be done in the stockpile.
- All other sampling for testing Class 3, 4, 5 and 6 materials should be done during placement to make sure segregation has not occurred.
- If additives such as lime or bituminous materials are being used, the sampling should be done before they are incorporated into the aggregate.
- Six test procedures are listed in Specification 3138 to be used for evaluating the aggregates. See page 827 of Mn/DOT Standard Specifications for Construction, 2000 Edition (9).

5.4.1.2. Construction of Aggregate Base (Mn/DOT Specification 2211)

The work covered under this specification includes the construction of one or more courses of aggregate base on a prepared subgrade or another base. The base will consist of granular materials graded to Specification 3138 Classes 1, 2, 3, 4, 5, 6 or 7. The gradation shall be uniform and checked with random field gradations tests as outlined in Specification 2211.3F (9).

5.4.1.2.1. Construction Requirements

5.4.1.2.1.1. General

- If the aggregate is mined from under water, it shall be stockpiled for 24 hours so as not to saturate the subgrade.
- Individual layers shall be 75 mm (3 in.) or less. Layers up to 150 mm (6 in.) with proper equipment such as heavy rollers and/or relatively clean aggregate materials can be used.
- Vibratory rollers can be used in compaction if shown to be effective.
- Higher quality material than specified can be used. However, payment will be based on the material specified.

5.4.1.2.1.2. Placing and Mixing

- Material can only be placed or windrowed on the grade a maximum of 3 km (2 mi.) in advance of construction.
- Multiple layers can be placed a maximum of 5 km (3 mi.) in advance of construction.
- A single class of aggregate must be placed and compacted along the project before another class of aggregate is placed.
- The subgrade shall be so dry during aggregate placement that no rutting will occur.
- Calcium chloride and/or water should be added for proper compaction.
- Material contaminated with subgrade material shall be replaced.
- If a surface course is in the plans the base must be covered with at least one layer of HMA over the winter. A bituminous penetration coat is not a substitute for an HMA.

5.4.1.2.1.3. Spreading

- The material must be uniformly spread so as to pass gradation specifications.
- Each layer must be completed and compacted before the next layer is spread.
- Each layer must be maintained with the surface aggregate keyed in place until the next layer is applied.

5.4.1.2.1.4. Compaction

Compaction shall be controlled using one of three methods:

- Specified Density – A full layer 75 mm (3 in.) thick shall be compacted to 100% AASHTO T-99 maximum density. The compaction moisture content shall not be less than 65% of optimum moisture content.
- Quality (Ordinary Compaction) – The material will be compacted until no further evidence of consolidation occurs under a steel-wheeled or pneumatic-tired roller defined in Specification 2123 (9). A vibratory roller may be used if approved by the Engineer. Water should be applied during compaction as needed.
- Penetration Index Method Class 5, 6, 7 shall be compacted to achieve a Penetration Index less than or equal to 10 mm (0.4 in.) per blow using a calibrated Mn/DOT Dynamic Cone Penetrometer (DCP) (24).

A layer is considered to be 75 mm (3 in.) thick unless a vibratory roller is used; then layers up to 150 mm (6 in.) can be used.

Two passing DCP tests must be obtained for each 800 cubic meters (1000 cubic yards).

If a test fails the material must be reworked compacted and retested.

The DCP testing must be completed within 24 hours of when the placing and compacting is completed. After 24 hours, the specified compaction method must be used.

Water must be applied as necessary for proper compaction.

The Penetration Index will be determined using the Mn/DOT Dynamic Cone Penetrometer (DCP) following the User Guide (24) available at the Mn/DOT Grading and Base Office (651-779-5564).

If no method of compaction is indicated, then the SPECIFIED DENSITY method shall be used. For Class 7 material only the Quality or Penetration Index Method can be used.

5.4.1.2.1.5. Workmanship and Quality

- The aggregate shall be placed to the cross-sectional dimensions shown on the plans
- The grade shall not vary by more than 15 mm (0.05 ft) from the staked grades.
- Contaminated material shall be replaced.

5.4.1.2.1.6. Aggregate in Stockpiles

When stockpile aggregate is included in the proposal the contract shall, in addition to the aggregate required for the project, stockpile aggregate of the class specified at the designated sites as directed by the Engineer.

5.4.1.2.1.7. Random Sampling Gradation Acceptance Method

- The contractor and/or producer must maintain a gradation quality control program using a random sampling acceptance procedure outlined in the Mn/DOT Grading and Base Manual (10).
- Form 24346 can be used by the contractor to certify that the material conforms to specification requirements.
- The contractor shall assume full responsibility for the production and placement of uniform and acceptable materials.
- Aggregate gradation compliance will be determined in accordance with Table 2211-A (9). Materials and workmanship shall be uniform and within the prescribed target values.
- Eleven provisions are listed in Specification 2211-F for the obtaining and testing of aggregate samples for compliance with Specification 2211 (9).

5.4.1.2.1.8. Payment

Table 2211-B lists the Aggregate Base Payment Schedule using four sublots and four samples. Table 2211-C lists the Aggregate Base Payment Schedule using individual tests.

Section 2211.4 presents the Method of Measurement for Aggregate Base placed (A) and Stockpiled Aggregate (B).

The Basis of Payment for accepted materials is presented in Section 2211.5

5.4.1.3. Hot Asphalt (HMA) Mixtures

5.4.1.3.1. General

The specifications for Hot Mix Asphalt materials cover the materials, mixture design and construction of the mixtures. The current Mn/DOT Specification is 2360 Plant Mixed Asphalt Pavement Combined 2360/2350 (Gyratory/Marshall Design) Specification . The 2350 mix design uses the Marshall hammer for the laboratory compaction for initial design and construction control. The 2360 mix design is the Minnesota application of the Superpave mix design that uses the gyratory compactor for compaction both for design and field control. Both of the procedures use volumetrics including Voids in the Mineral Aggregate (VMA) for design and control of the mixes. In the 2340 specification, VMA was used only in the design phase; however, it was found that lower VMA's were encountered in the field in some cases. Therefore, a requirement was placed on the field-manufactured mix. Mn/DOT currently uses Superpave (2360) mixtures on State Highways for all new construction and mid and long life (>5 years) overlays.

In this section, a brief review of the Mn/DOT 2360 Plant Mixed Asphalt Pavement Combined 2360/2350 (Gyratory/Marshall Design) Specification is given.. The complete specification is available on the Mn/DOT Bituminous Web Page, www.mrr.dot.state.mn.us/pavement/bituminous/bituminous.asp. The numbering in this section is the same as in Mn/DOT Specification 2360 Plant Mixed Asphalt Pavement Combined 2360/2350 (Gyratory/Marshall Design).

5.4.1.3.2. Mn/DOT 2360 Plant Mixed Asphalt Pavement Combined 2360/2350 (Gyratory/Marshall Design) Specification

0.1 Description

The specification is for Hot Mix Asphalt on a prepared foundation, base course or existing surface. It is to be placed in accordance with prescribed plans or as established by the Engineer.

For Marshall design, the Specification describes mixtures appropriate for two levels of traffic (Type LV and MV). The levels are defined as:

LV	Low Volume	Less than 1 million ESALs (AADT < 2300)
MV	Medium Volume	From 1 to 3 million ESALs (2300 < AADT < 6000)

For Superpave design, the Specification describes mixtures appropriate for five levels of traffic that are based on the 20-year design traffic level (ESAL). The levels are defined as:

Traffic Level	20 Year Design ESALs (1 x 10^6 ESALs)
2[1]	< 1
3[2]	1 to < 3
4	3 to < 10
5	10 to ≤ 30
6	SMA

1 -- (AADT # 2300)
2 -- (2300< AADT <6000)

A. Aggregate Gradation

The aggregates for mixtures produced under Mn/DOT 2360 Plant Mixed Asphalt Pavement Combined 2360/2350 (Gyratory/Marshall Design) Specification shall comply with the following gradation requirements.

Sieve Size (mm [**inch**])	A or 4*	B or 3*	C or 2*	5*	E (SMA)
25.0 [**1 inch**]			100		See SMA Provisions
19.0 [**3/4 inch**]		100	85-100		
12.5 [**1/2 inch**]	100	85-100	45-90		
9.5 [**3/8 inch**]	85-100	35-90	-	100	
4.75 [**#4**]	25-90	20-80	20-75	65-95	
2.36 [**#8**]	20-70	15-65	15-60	45-80	
0.075 [**#200**]	2.0-7.0	2.0-7.0	2.0-7.0	2.0-7.0	

* Marshall DesignationGradation size is indicated by letter for Superpave design and number for Marshall design. The letter or number indicates the maximum aggregate size as follows:

A or 4 = 12.5mm [**1/2 inch**], SP 9.5 mm [**3/8 inch**]**
B or 3 = 19.0mm [**3/4 inch**], SP 12.5 mm [**1/2 inch**]**
C or 2 = 25.0mm [**1 inch**], SP 19.0 mm [**3/4 inch**]**
5 = 9.5mm [**3/8 inch**], 4.75 mm [**#4**] nominal size (Marshall design only)

B. Minimum Lift Thickness

The following minimum lift thickness applies to the designated aggregate size.

Aggregate Size A, 4*; B, 3*: Minimum Lift thickness = 40 mm [**1 ½ inch**]
Aggregate Size 5*: Minimum Lift thickness = 20 mm [**3/4 inch**]
Aggregate Size C, 2* (for non-wear only): Minimum Lift thickness = 65 mm [**2 ½ inch**]

* Marshall designation

0.2 Materials

-
- Recycled Asphalt Pavement (RAP) can be used in all wearing courses and non-wear courses. Requirements and methods for estimating the percent crushed for the RAP are presented. Adjustments in the PG grade to use with RAP if more than 20% is used are listed in the specification. [See 2360.2 G1.]
- Crushed Concrete and Salvaged Aggregate. Crushed concrete can only be used for up to 50% of the aggregate in non-wear courses.
- Salvaged Aggregate can be used for up to 100% of the mixture aggregate if it meets the requirements of the mixture aggregate and is stored and proportioned into the mixture as specified.

- Scrap Shingles can be used in the mixture. The percent of shingles will be included in the percent RAP in the mixture.

Additives requirements are listed. These include mineral filler, hydrated lime, liquid anti-stripping materials and coating and anti-stripping material covered under Specification 3161 (9). These can be part of the original mix design as approved by the Bituminous Engineer or by the Construction Engineer.

The asphalt binder must meet all of the requirements laid out in AASHTO M - 320. The grade to be used on Minnesota projects should be established using the most current Mn/DOT Memorandum "Inspection, Sampling and Acceptance of Bituminous Materials"(33). It is important that fuel oils or other distillates not be used in the tanks used for storage of the asphalt materials. Asphalt materials are usually certified for use by the supplier. The supplier should also provide a memo indicating appropriate mixing and compaction temperatures in the laboratory and field.

- Aggregate quality requirements are listed in Table 2360.3-B2a and described below:
- Los Angeles Abrasion (Toughness Test) AASHTO T-96
- Magnesium Sulfate (Soundness Test) AASHTO T-104. Maximum loss percentages are given for specific sieve sizes. An aggregate proportion that passes the 4.75-mm (No. 4) sieve and exceeds the loss requirements listed above on the coarse aggregate fraction cannot be used in the mixture.
- Total Spall and Lumps (Deleterious Materials Test), Mn/DOT Manual No. 1209. Spall is defined as shale, iron oxide, unsound cherts, pyrite, and other similar materials.
- Insoluble Residue (Soundness Test), Mn/DOT Laboratory Manual 1221. The maximum percent insoluble residue must not exceed 10%.
- Aggregate Specific Gravity shall be run on all aggregates used in the mixtures. AASHTO T-84 and T-85 as modified by Mn/DOT are to be used.

- Class B Carbonate Restrictions- Limits the amount of +4 sieve and –4 sieve carbonate material allowed in mixtures depending on traffic level.
- Other aggregate requirements included in Table 2360.3-B2a and described below are:
- Coarse Aggregate Angularity (ASTM D 5821)
- Fine Aggregate Angularity (ASTM C 1252)
- Flat and Elongated Particles (ASTM D 4791) The maximum number of flat and elongated particles is 10 percent by mass for traffic Class 3 and above. The ratio of length to width used is 3:1. (Superpave only)
- The clay content is measured using the Sand Equivalent Test (AASHTO T-176). Higher percentages indicate a cleaner material. (Superpave only)
- Asphalt Mixture Requirements: Table 2360.3-B2b lists the requirements for Superpave and Marshall mixtures. Some requirements are described below:
- Gyratory Compaction - Table 2360.3-B2b lists the Superpave Design Gyratory Compactive Effort for three levels of gyrations: $N_{initial}$, N_{design} and $N_{maximum}$ at different traffic levels. The design criteria in terms of percent of maximum density for the three levels of gyrations are shown in the table. The criteria are listed for mixes within 100 mm (4 in.) of the surface and for those greater than that depth. The table shows that initial compaction is defined at 89 to 90 percent of maximum density (10 to 11 percent air voids). The number of gyrations at design level relates to 96 to 97 percent of maximum density and the maximum levels correspond to 98 to 99 percent maximum density. These criteria would help make sure the aggregate structure is strong enough to keep the mix from densifying too much under traffic.
- Marshall Compaction – The compactive effort for both LV and MV mixtures is 50 Marshall blows.
- Volumetric Criteria for Superpave - The design air void content is 4.0 percent for mixes to be placed in the upper 100 mm (4 in.) of the surface and 3.0 percent for those at greater depths.

- Voumetric Criteria for Marshall – The design air void content for all MV mixtures is 3.5 percent and 3.0 percent for all LV mixtures.
- Voids Filled with Asphalt (VFA) – The voids filled with asphalt criteria are listed in Table 2360.3-B2b. The criteria are also listed for mixes within the top 100 mm (4 in.) and those at greater depths. The values for Traffic levels 4 –5 have been increased slightly (Superpave only).
- Fines to Effective Asphalt Ratio – The effective asphalt content is to be estimated using the Asphalt Institute Method presented in MS-2 (34).
- Moisture Damage Susceptibility – The retained tensile strength (TSR) of the mixture shall be determined by ASTM D-4867, Mn/DOT modified. The DOT will test the submitted mixture once unless anti-strip or a different aggregate composition is submitted.
- Voids in the Mineral Aggregate (VMA) - The VMA criteria for Superpave and Marshall mixtures are given in Table 2360.3-B2c. The values are given for coarse and fine mixes that have the same nominal maximum size. The criteria are slightly lower as the aggregate generally gets coarser. The VMA criteria are used to make sure the mix is open enough to hold enough asphalt for a good durable mixture.

0.3 Mixture Design

A. General - Two types of mixture design are presented. The asphalt mixture designs are to be carried out by the Contractor and reviewed by Mn/DOT. A review is done by either the District Materials or Central Office Laboratory, depending on where the Project is located. Once a mix design is completed the addition of other aggregates and materials is prohibited. If any changes in proportions exceed 10% a new mix design must be done.

It is the Contractor's responsibility to design a Marshall mixture in accordance with the most current AASHTO T-245, the Asphalt Institute's Mix Design Methods for Asphalt Concrete MS-2, and the Mn/DOT Laboratory Manual.

It is the Contractor's responsibility to design a gyratory mixture in accordance with the most current AASHTO T-312, the Asphalt Institute's Superpave Mix Design Manual SP-2 (2-hour short term aging period is used for volumetric), and the Mn/DOT Laboratory Manual.

- Laboratory Mixture Design (Option 1): At least 15 days prior to the start of paving materials and a Laboratory Mixture Design are submitted to the District Materials Lab where the project is located. Mn/DOT will evaluate the materials. Then a minimum of 7 days before paving is scheduled the Contractor will submit a Job Mix Formula. Samples of the mixture will also be submitted 7 days before paving for Mn/DOT to check Tensile Strength Ratios for the mixture. No materials in addition to those can be used in the mix. If the mix proportions change by more than 10% a new mix design must be performed. Materials to be used in the proposed mix must be submitted at least 15 working days before paving is planned.
- Modified Mixture Design (Option 2): This option may be used if, the aggregates in the proposed Mix Design have been used in part in other Mix Designs, and the Level II mix designer has a minimum of 2 years experience in mixture design, and the Contractor and his representative have not violated 1512 unacceptable and unauthorized work in the last 12 month period.
- At least 2 days prior to the start of asphalt production, the Contractor shall submit a proposed JMF for review.

B. Documentation - Each proposed mix design Job Mix Formula shall include the documentation items listed in Section2360.3C.

C. Mix Design Report– A Mixture Design Report includes a job-mix formula (JMF) from the composite gradation, aggregate component proportions and asphalt content of the mixture. Design air voids, VMA and aggregate bulk specific gravity values are also indicated on the Mixture Design Report. JMF limits will be shown for gradation control sieves, percent asphalt binder content, air voids and VMA.

A Mix Design Report is required for all paving except small quantities. All materials must meet specifications before an MDR is issued. Mn/DOT will verify two trial mix designs per mix designated in the plan, per contract at no cost to the Contractor. Additional mix designs will be verified for $2000 per design.

For city, county and other agency projects that have no federal or state-aid funding, the Contractor shall provide to the District Materials Laboratory a complete project proposal including typical sections, addenda, supplemental agreements and change orders that affect mix design. All test procedures and required forms are on file with the Mn/DOT Bituminous Engineer.

0.4 Mixture Quality Management

A. Quality Control (QC) – The Contractor must provide and maintain a quality control program. This includes all activities and documentation including mix design, process control inspection, sampling and testing, and necessary adjustments in the process that are related to the HMA pavement which meets the requirements of the specification. This also includes the development and maintenance of a certification plan.

   The Contractor is required to provide qualified personnel, a laboratory with calibrated equipment, and sampling and testing using specific procedures as listed. The test results will be documented using control charts, control limits, JMF adjustments, corrective actions and failing materials. A Payment Schedule is included in the specification for the various production failures.

B. Quality Assurance (QA) – Mn/DOT will perform QA testing as part of the acceptance process. The Engineer is responsible for QA testing, records and acceptance. Specific operations for QC and QA are laid out in the specification.

   As part of QA the Engineer will periodically witness the sampling performed by the Contractor. If the Engineer observes that the sampling and QC are not being performed properly or tests are not being done correctly the Engineer may stop production until corrective action is taken. All sampling and testing must be performed by a Certified Bituminous (QM) Technician. The Engineer shall calibrate and correlate all laboratory equipment in accordance with the latest version of the Mn/DOT Bituminous Manual (14).

C. Verification Testing – Verification testing of the Contractor's results shall be performed daily. Verification testing is to be conducted as part of QA. This testing includes one set of production tests and the taking of a companion sample once per day. Test result tolerances are listed in Table 2360.4-M for the various items used for QC/QA. Verification testing is very important to make sure the Contractor and Agency technicians are running the QC/QA tests using the procedures within acceptable limits. Resolution procedures are also laid out.

D. Sampling and Testing

Sampling is to be at the prescribed rate using random numbers to determine the location of the samples.

E. Production Tests

Specific tests are listed for determining asphalt binder content, Bulk Specific Gravity, Maximum Specific Gravity, Air Voids-Individual and Isolated, Voids in the Mineral Aggregate (VMA), Gradation of the blended aggregate, Field Moisture Damage, Aggregate Specific Gravity, Coarse Aggregate Angularity, Fine Aggregate Angularity, and Moisture Content. Asphalt Binder Samples must also be taken in the amount of 1 liter (1 quart) for every one million liters (250,000 gallons).

F. Documentation (Records)

The Contractor shall maintain control charts and records on an on-going basis. Diaries should be kept and filed as directed and become the property of Mn/DOT.

G. Documentation (Control Charts)

The following data are to be recorded on standard control charts:

1. Blended aggregate gradation with specification sieves.
2. Percent asphalt binder content
3. Maximum mixture specific gravity
4. Production air voids, percent
5. VMA

Both individual values and moving average of four are plotted.

H. JMF Adjustment

Procedures for adjusting the JMF during construction are presented.

I. Corrective Action

The procedures for taking corrective action when the mix goes out of the specified limits are given. Testing rates are increased and if the problem is not solved production is to stop.

J. Failing Materials

This section lays out how to handle failing materials, which are defined as materials outside of the control limits. The following situations are covered:

- Moving Average Failure – Production Air Voids
- Moving Average Failure – Percent Asphalt Binder Content, VMA and Gradation
- Individual Failure – Production Air Voids, Percent Asphalt Content, and VMA
- Individual Failure – Gradation

Coarse and Fine Aggregate Crushing Failure

0.5 Construction Requirements

A. General – The construction requirements listed in the Specification provide for the construction of all courses.

B. Restrictions – Work can only proceed after load restrictions have been lifted in the spring. No paving can proceed if the Engineer feels damage will be caused to the subgrade or the HMA. Generally, no paving should be done after October 15 north of Browns Valley to Holyoke or after November 1 south of that line.

C. Equipment – The Specification lays out requirements for asphalt mixing plants and placement and hauling equipment, including asphalt pavers, trucks and motor graders.
D. Treatment of the Surface – An asphalt tack coat shall be applied to existing asphalt and concrete and all surfaces of each course or lift constructed except for the final course or lift according to Mn/DOT Specification 2357 (9).
E. Compaction Operations – Compaction shall be accomplished with continuous operation so that all areas are compacted uniformly to the required density. Rolling with steel-wheeled rollers will not be continued if crushing of aggregates results. To secure a true surface, variations such as depressions or high areas that may develop during rolling operations and lean fat or segregated areas shall be corrected or removed.
F. Construction Joints – Joints must be thoroughly compacted to produce a neat tightly bonded joint that meets surface tolerances. Both transverse and longitudinal joints are subject to specified density requirements. Randomly selected core locations may fall on the joint in which case the cores will be taken tangent to the joint.
G. Asphalt Mixture Production – Mixture as produced is to be provided to Mn/DOT for check testing.

0.6 Pavement Density

A. General – For the 2360 Plant Mixed Asphalt Pavement Combined 2360/2350 (Gyratory/Marshall Design) all mixtures are to be compacted using the Maximum Density Method unless otherwise indicated. Some mixes that would not require maximum density are lifts less than 39 mm (1.5 in.) wedge sections, patching, driveways or non-traffic areas, excluding shoulders. These exceptions will be compacted using the "Ordinary" Compaction Procedure.
B. Maximum Density Determination – For the Maximum Density Method all courses and layers will be compacted to the values listed in **Table**

2360.6-B2,. The mixture used for calculation of densities shall be a field-manufactured mixture. The requirement may be reduced by 1% if the first lift of a mix is to be placed on an unstable base. Such cases would be the first lift on a cold recycled base, aggregate base or on a PCC slab that is faulted or has mid-panel cracks or other problems. The payment schedule for Maximum Density is presented in **Table 2360.6-B4**. The Table shows that incentives can be obtained for higher densities. The payments for density are based on cores. A lot is defined as about one day's production. The payment schedule is set up by lot. The density is a percent of the Maximum Theoretical Density. The density of the cores is to be determined using AASHTO Method T-166. Compaction must be accomplished by eight (8) hours after the mixture is laid. Coring and traffic control during the coring operation is the Contractor's responsibility.

Density and the resulting voids are very important to the performance of an asphalt mixture. It is therefore important that specified density be used to obtain a high quality mix.

C. Ordinary Compaction Method – In areas where the specified density method is not required, then the Ordinary Compaction Method is used. For this method a control strip is used to establish how much compaction effort is needed to densify the mixture. Construction of the control strip will be directed by the Engineer. It is to commence as soon as possible in the job. It shall be on the same base conditions and HMA layer thickness as planned for that section of the project. A growth curve of density versus roller passes shall be used to establish when no more density can be achieved. A portable nuclear density device calibrated properly can be used to establish the growth curves. Specifications for steel-wheeled and pneumatic-tired rollers to be used for Ordinary Compaction are given.

D. Mixture temperature requirements are listed when compaction is by the Ordinary compaction method. The limits are based on the thickness of the lift and the air temperature. Unless allowed by the Engineer, no paving is allowed under the Ordinary Compaction Method when the air temperature is below 32F.

0.7 Thickness and Surface Smoothness Requirements

The final thickness and smoothness of the HMA surface will affect the performance of the pavement quite significantly.

A. Thickness – After compaction the thickness of each course shall be within 6 mm (0.25 in.) of the thickness shown in the plan unless automatic screed controls are used on the first course placed. If the thickness is less than the minimum specified, that course shall be replaced. If it is greater than the plans then the excess will not be included in the payment.

B. Surface Requirements – After compaction, the finished surface shall be free of open and torn sections and true to grade and cross sections shown on the Plans using the following definitions:
   - For leveling courses a tolerance of 15 mm (1/2 in.) shall be used.
   - The surface of the non-wear and the wear course shall show no variation greater than 3 mm (1/8 in.) from the edge of a 3 m (10 ft) straightedge.
   - The transverse slope shall not vary from the planned slope by more than 0.4 percent.
   - The distance to the edge of each course and the centerline shall not be more than 75 mm (3 in.).

C. Pavement Smoothness
   - General - Pavement smoothness is evaluated on the final mainline pavement surface because it has been shown to affect the overall performance of the pavement. Exceptions such as turn lanes, shoulders, intersections, etc are listed in the specification .
   - Smoothness Requirements – The smoothness requirements are based on the type of original surface, base and timing of the project. The limiting profiles are listed on three different tables within the specification and show the levels of incentive and disincentive.

- Measurement – Smoothness will be measured with a 7.62 m [**25 foot**] California type profilograph or an Inertial Profiler (IP), which produces a profilogram (profile trace of the surface tested). One pass is made 2.74 m (9 ft) from the centerline. The profilograph shall be equipped with automatic data reduction capabilities. Segments of roadway are defined in the Specification.
- Profile Index – The profile index is calculated for each defined segment. A blanking band of 5 mm (0.2 in.) is used for the profile. Bumps and dips equal to or exceeding 10.2 mm in 7.62 m (0.4 in. in 25 ft) are treated separately. Bump, dip and smoothness corrections shall be done across the full width of the pavement. All corrective work shall be made by diamond grinding or approved equivalent, overlaying the area, by replacing or by inlaying.
- Payment – The cost of the smoothness testing and associated traffic control will be incidental to the cost of the wear course.

  The contractor can receive incentives and disincentives for each segment. However, the total ride incentive for the surface cannot exceed 15% of the total mix price. Also, the contractor cannot receive an incentive for ride if more than 25% of all density lots fail to meet minimum density requirements.

5.4.2. Field Control Procedures to Meet Specifications

5.4.2.1. General

The section procedures in the Mn/DOT Grading and Base, Geotechnical and Bituminous Manuals (10, 5, 14) are presented. Checklists developed by the laboratory and field staff are also summarized in the Field Notes for Construction Engineers and Inspectors (11). Some discussion is also made as to which methods are the best to use for field control of either granular or HMA materials. Field control procedures for cold in-place recycling and full depth reclamation have not been finalized.

The next section reviews the procedures recommended for the QC/QA of granular bases and the following will review those considered best practices for HMA materials. As with other procedures for design and control of pavements, it is anticipated that the procedures presented here will be improved over the years and therefore, the methods presented should be up-dated periodically.

5.4.2.2. Granular Subbases and Aggregate Bases

5.4.2.2.1. General

The construction of granular subbases and aggregate bases involves the following procedures:

- Manufacture of the material from a gravel pit or quarry.
- Storage of the materials (stockpiling)
- Transport to the grade
- Placing of the material
- Compaction

The specifications require that the material be tested initially for general quality, gradation and compaction. It must be determined that the material being tested is uniform meaning that very little segregation has occurred. It is also important to make sure the material being constructed is represented by the correct moisture-density test if specified density is being used.

5.4.2.2.2. Schedule of Materials Control

A current schedule of materials control should be reviewed before each project to establish:

- The specification applicable for that project
- The minimum required acceptance testing rate
- Form No.
- Minimum required sampling rate for laboratory testing
- Sample size required for laboratory testing

These requirements are listed for gradation, one-point density, Moisture-density, relative density, relative moisture content, pulverization testing, percent crushing, and aggregate quality testing.

The Schedule of Materials Control is Tab. A 5-692.100 in the Grading and Base Manual (10).

A standard sample identification card is also presented in the Grading and Base Manual Fig. 1 5-692.101 (10).

Standard forms to use for Independent Assurance Sampling and Testing are also presented.

5.4.2.2.3. Standard Methods of Testing

Standard methods of testing and procedures to be used by the contractor and Mn/DOT for QC and QA are presented in Section 5-296.200 of the Grading and Base Manual. It is very important that exactly the same procedures be used by both groups when quality assurance and verification testing are performed.

Methods to correctly sample and test for statistically based specifications are presented in Chapter 5-692.700 of the Grading and Base Manual. It is very important to use the principles of statistics because all pavement construction materials are variable. When a material is designed the variability is considered. Then in the field the constructed material must be placed as uniformly as possible and within the variability assumed during design. The MnPAVE Design procedure will include variability as one of the conditions to consider in thickness design and generally will show that a thinner pavement can be designed where less variability can be measured.

5.4.2.2.4. Methods of Compaction Control for Aggregate Bases

Three methods are included for Compaction Control of aggregate bases in the Mn/DOT specifications:

- Specified Density
- Dynamic Cone Penetrometer
- Quality Compaction

Specified density is usually measured using the 150-mm (6-in.) Sand Cone Method, ASTM D 1556-90. The larger cone is used to minimize side effects of the hole. It is important to make sure that random sampling procedures are used for selecting sample locations, that the material being tested has been moisture-density tested and that the standard test procedure is used for the sand cone test.

The Dynamic Cone Penetrometer (DCP) has recently been added as a test procedure for aggregate base construction control. This procedure is quicker and easier to run than the sand cone density. Also, it gives a direct measure of the material stiffness modulus. It is important to follow the test procedure carefully and to conduct the test within 24 hours of compaction so that crusting does not occur. Statistical procedures should again be used to establish the test location and analyze the data. Quality Compaction should only be used if the equipment is not available to do either Specified or DCP testing. If quality compaction is used, the inspector and engineer should be experienced in the construction of aggregate base and embankment materials. They must also observe the compaction operation continuously. This method of compaction is appropriate only for very small areas where a limited amount of material is being placed.

5.4.2.2.5. Job Guide for Aggregate Base Construction

The Mn/DOT Office of Construction, Technical Certification Section has published Field Notes for Construction Engineers and Inspectors (11). This booklet presents many items that an inspector should use to do a quality job of construction control. The following are a portion of the checklist items presented for aggregate base construction:

1. Review the contractor/producer QC procedures and test results. Obtain the completed Certification of Aggregates (form #24346) from the contractor.

2. Review any certification of crushed glass.
3. Perform the necessary inspection and testing (bitumen content, crushing, abrasion testing, shale, etc.) before delivery of any materials.
4. Prior to placing the base, verify that the subgrade is true to required grade and cross-section. Subgrade must be free of ruts, soft spots, large stones and excess dust.
5. Monitor placement operation. Lift should not exceed 75 mm (3 in.) of thickness unless approved by the Engineer.
6. Check depth and yield (tons per station) to ensure uniform construction.
7. Obtain samples for testing gradation, moisture-density, etc. according to the Schedule of Materials Control.
8. Ensure that compaction of each lift is completed satisfactorily to required density and cross-section before starting placement of the next lift.
9. When weight tickets are required, collect, check, and initial them for each load as they arrive.
10. Maintain records (Diary) that should include such things as hours, location, lift thickness, test results, quantity, yield and other events that may have an effect on the work.

5.4.2.3. Hot Mix Asphalt (HMA) Construction

5.4.2.3.1. General

A current Schedule of Materials Control should be reviewed and used for setting up the field control for each HMA construction project. That document will establish:

- The specifications applicable for the project
- The minimum required acceptance testing rate
- Form number to use
- Minimum required sampling rate for laboratory testing
- Sample size required for laboratory testing

The construction of an HMA pavement layer can be summarized as follows:

<u>Plant Operations</u>

- Materials delivery or manufacture and storage (asphalt and aggregate)
- Materials proportioning and mixing

- HMA storage and transfer to trucks
- Delivery to construction project

Paving Operations

- Laydown
- Compaction

Each of these steps requires Quality Control (QC) testing by the Contractor and Quality Assurance (QA) testing by Agency as spelled out in the Specifications. The purpose of this testing is to establish that the material is uniform (no segregation) and is placed to specification density so that the mixture will perform well. The ride is also now checked after construction. Penalties are assessed if specifications are not met and incentives make it possible to earn bonuses if specifications are exceeded.

5.4.2.3.2. Standard Methods of Testing

Standard testing methods to be used by the Contractor and Mn/DOT for QC and QA are presented in 2360 Plant Mixed Asphalt Pavement Combined 2360/2350 (Gyratory/Marshall Design) Specification. It is very important that exactly the same procedures be used by both groups when QC, QA and verification testing are performed.

Procedures to correctly sample and test for statistically based specifications are presented in Chapter 5-692.700 of the Grading and Base Manual. It is very important to use the principles of statistics because all construction materials are variable. When a pavement structure is designed the variability should be considered. Then in the field the constructed material must be placed as uniformly as possible and within the variability assumed during design MnPAVE uses variability as one of the conditions to consider in thickness design.

5.4.2.3.3. Methods of Compaction Control for HMA

Section 5-3.10 of the Geotechnical and Pavement Manual (5) presents Bituminous Mixture Compaction Guidelines. Compaction is the final stage in the placement of a bituminous mixture during the paving operation. At this stage it is possible to develop or not develop the full potential strength and durability of the mixture. Inadequate compaction of the mixture will result in a shorter pavement life because of accelerated deterioration due to load and/or environment.

The engineer has a choice of two different compaction control methods to select from based on the 2360 Plant Mixed Asphalt Pavement Combined 2360/2350 (Gyratory/Marshall Design) Specification for a given project. The various methods are presented in detail in the Mn/DOT Bituminous Manual. A brief description of each and when to use them are given.

- Maximum Density Method. This process involves comparing the Bulk Specific Gravity of a core sample obtained from the roadway with the maximum specific gravity of the mixture. The frequency of and variation between QC and verification testing are also presented.
- Ordinary Compaction For the Ordinary Compaction Method a control strip of at least 330 m^2 (395 yd^2) of the same material, subgrade and base conditions shall be compacted to determine a proper roller pattern to achieve maximum density. A growth curve of density with passes must be used to determine when maximum density is obtained. If materials or conditions change a new control strip must be constructed. A given control strip can only be used for 10 days of construction.

The Maximum Density Method should be used unless otherwise indicated.

Ordinary Compaction can be used without a control strip for very small areas or thin lifts less than 39 mm (1.5 in.). For these cases the HMA should be compacted until there is no appreciable increase in density with each pass of the roller as defined by the engineer.

The type and characteristics of the roller(s) to be used for Ordinary Compaction are presented in the given sections of the 2360 Plant Mixed Asphalt Pavement Combined 2360/2350 (Gyratory/Marshall Design) Specification.

5.4.2.3.4. Job Guide for Plant Mix Bituminous Paving

The Mn/DOT Office of Construction, Technical Certification Section has published Field Notes for Construction Engineers and Inspectors (11). This booklet presents many items that will help an inspector be ready for working with a contractor to construct a high quality project. The quality of construction affects the performance of the pavement more than the thickness design. The items listed are for mixing plant inspection and then the paving operation. The list presented here is a selected group of items that influence the performance of the pavement most.

The development of this Guide is set on the principle that the Inspector should not just be a data and sample taker. The inspector should be aware of the whole operation to make sure that a consistent, uniform quality mixture is produced and constructed.

<u>Plant</u>

1. Determine under which specification the mixture(s) are to be produced and review any special provisions.
2. Review the plant certification along with the schematic of the plant. If the plant is not certified go through the procedure for certification. Have the plant inspector and Plant Authorized Agent complete and sign the Asphalt Plant Inspection Report (TP 02142-02, TP 021143-02). By signing the Asphalt Plant Inspection Report, the plant-authorized agent agrees to maintain all plant and laboratory equipment within allowable tolerances set forth in the respective specification and the Bituminous Manual.
3. Identify items to be sampled, rates of sampling and testing using the Materials Control Schedule. Determine source or access for securing samples.
4. Determine material flow controls and settings to comply with the design mixture. Review the Mix Design Report.
5. Monitor calibration of plant equipment (pumps, aggregate bins, feeders, etc.).
6. Check that appropriate QC samples are being taken and tested.
7. Check that contractor is monitoring asphalt content through required spot checks.
8. Make sure that the HMA is being mixed at the temperature recommended by the asphalt supplier.

9. Watch mixture appearance to ensure uniformity and look for any indication of plant malfunctions such as sticky feeders or other operations.
10. Watch stockpile operations so that contaminated materials are not entered into the cold feed bins.
11. Ensure that truck boxes are clean and protected against buildup and also free of excessive cleaning agents. Fuel oil or other distillates must not be used to clean the truck beds.
12. Make sure segregation is not occurring during the loading operation. Also make sure trucks are covered when necessary.
13. Weigh tickets are to be completely and properly filled out and automatic scale printer operations are to be monitored. Make sure scale calibration is being performed.
14. Monitor asphalt shipments and make sure Contractor is taking necessary asphalt samples.
15. Monitor Contractor's testing to ensure that the required number and type of tests are done and that proper procedures with calibrated equipment are being followed:
    a. Review Contactor's on-site QC records and charts for accuracy and completeness.
    b. Monitor agency tests and confirm that they are within allowable tolerances for Contractor and Agency checks.
16. Check that Contractor is maintaining plant diary and daily records that include hours of operation, production, asphalt delivered, shutdowns (why?), mix adjustments, temperature and any other significant events.
17. Take or observe the taking of verification samples (one per mix per day).
    a. Retain one half of sample for Verification testing.
    b. Provide Contractor with companion sample.
    c. Deliver Verification sample to the Agency lab.
    d. The Contractor must test the Verification sample(s).

<u>Paving</u>

1. Check paving and compaction equipment for compliance with specifications. Get acquainted with the equipment operation.
2. Check adjustments available on the paver including flow gates, auger control, tamper bar, screed angle, vibration and crown.
3. Check grade for smoothness, compactness, cross slope, grade and alignment. Make sure the surface is free of gravel, loose patches or excessive patch and joint material.
4. Identify areas of instability that require repair.
5. Establish the paving and rolling sequence with the Contractor.
6. Observe the tacking operation. It needs to be uniform and not too thick or thin.
7. Collect, check, and initial each delivery ticket.
8. Check material in each load for problems such as segregation or contamination. Check in truck and as the load is dumped.
9. Watch the paver operation for:
    a. Maintaining of grade
    b. Incorrect line
    c. Malfunctioning automatic screed control
    d. Too much starting and stopping
10. Monitor laydown temperature to make sure it is consistent and within the range recommended by the Supplier.
11. Observe the mat surface for uniformity of texture, presence of spot segregation, proper thickness, width and yield.
12. Observe breakdown roller operation for uniformity and continuity of operation with attention to speed, pattern, location of drive wheel and vibration (if used).
13. Continue observation of roller operations to ensure timely performance geared to removal of roller marks and bumps.
14. Check surface for compliance with smoothness requirements. If a profilograph is being used, make sure the settings are correct and the profilograph is calibrated.

15. Cores are to be taken and tested by the Contractor. Core locations are to be determined and marked by the Agency. Take possession of the companion cores. Monitor density tests for compliance with proper equipment and test procedure. The Contractor will schedule testing so that it can be observed by the Inspector.
16. Maintain daily records that include such things as:
    a. Hours of operation
    b. Stations paved
    c. Course paved
    d. Depth, width, tonnage and yield
    e. Measured delivered temperature
    f. Weather
    g. Other events which could affect the quality and quantity of work
17. Take or observe the taking of verification samples (one per mix per day).
    a. Retain one half the sample for Agency testing.
    b. Provide the Verification companion sample to the Contractor for testing.
    c. Deliver Verification sample to Agency lab.
    d. Verification companion samples must be tested by the Contractor.

18. Obtain Summary Sheets:
    a. Contractor Density Core Worksheets
    b. Agency Core Worksheets
    c. Agency's Verification results
    d. Tonnages represented by the respective worksheets to establish density incentives and disincentives.

If there are any questions about the frequency or amount of material to sample, refer to the Materials Control Schedule.

CHAPTER 6

SUMMARY AND RECOMMENDATIONS

6.1. General

This manual presents design and construction methods recommended for Hot Mix Asphalt (HMA) pavements in Minnesota. MnDOT and the asphalt pavement industry are in a time of transition both for pavement thickness design construction procedures.

6.2. Thickness Design Procedures

Three procedures are now available for use in Minnesota: the Soil Factor Procedure, the Stabilometer R-Value, and the mechanistic-empirical procedure (MnPAVE). The Soil Factor Design Procedure is presented in the MnDOT State Aid Manual (4) and the R-Value method is presented in the MnDOT Geotechnical and Pavement Manual (5). The MnPAVE software Beta Version 5.009 is also available (6). A summary of the procedures is presented in Chapter 2. Currently, both the Soil Factor and R-Value procedures are being used for city and county roads. A summary of the operating manual for MnPAVE is included in Chapter 2. The manual includes a summary of Setup, Startup, Input and Output for the software.

The current procedures have been used over the past 25 plus years. It is recommended that:

- The current procedure of choice (Soil Factor or R-Value) be used to establish a thickness design or alternative designs.
- The MnPAVE software be used to establish alternate design(s).
- Send comparisons to the MnDOT Road Research Section using the form provided.
- If new materials or existing materials are used in a different way, set up designs using MnPAVE and report the results.

6.3. Traffic

The methods recommended for estimating traffic for the three design procedures are presented in Chapter 3.

The Soil Factor Design requires an estimate of AADT and HCADT predicted for 20 years into the future or other design life. The HCADT prediction requires an estimate of vehicle type distribution. The distribution can be estimated from a statewide HCADT map or measured on specific roadways using the procedure presented in the appendix.

When predicting traffic for the Soil Factor Procedure, the design AADT and HCADT should be determined using:

- An estimate current AADT by conducting a vehicle count at the location of, or similar location to the roadway being designed.
- An estimate current HCADT using the field procedure with two pneumatic tubes conducted by the MnDOT Traffic Forecast and Analysis Section and given in the Appendix B.
- As an alternate, the current ADT and HCADT are estimated from current statewide AADT and HCADT maps, which are maintained for State Highways and County State Aid Highways (CSAH) system. The statewide AADT maps are up-dated about every two years are available on CDROM and may be obtained by contacting either the MnDOT Traffic Forecast and Analysis Section or the MnDOT District Traffic Engineer.
- The future AADT and HCADT predicted using the appropriate growth factor determined as presented in Section 3.4.4.

The R-Value and MnPAVE Design procedures currently use ESAL's for traffic load evaluations. ESAL (Equivalent Standard Axle Loads) estimates require a determination of current AADT, vehicle type distribution, ESAL factors (the average effect of a given type of vehicle in terms of ESAL's), a calculation or estimate of growth, and design lane distribution. The procedures and tables recommended for these calculations are presented in Chapter 3. The MnESALS software will result in the best estimate of ESAL's for a particular design situation. The procedure(s) are presented in Section 3.4. The procedure requires the following:

- Estimate of AADT as indicated above and in Section 3.4

Estimate Vehicle Distribution; the procedure recommended is the method presented in Appendix B. The length of the study depends on the volume of traffic on the roadway. As an alternate the statewide average for Rural CSAH and county roads for the eight vehicle types listed in Table 3.1. If at all possible the vehicle type distribution should be measured for a given location because of the significance of the vehicle distribution shown in calculating ESAL's in Reference 18. . Based on the thickness variations represented by the differences in traffic prediction the following recommendations are made:

1. For the Soil Factor Design:

a. If the AADT is 1500 or less the minimum design can be used without considering HCAADT and therefore not vehicle type distribution. If it is known that the heavy commercial traffic is very high because of a specific industry then provisions should be made.

b. The vehicle type distribution should be measured for a specific project if the AADT is greater than 1500.

2. For the R-Value design procedure:

a. There is essentially no relationship between AADT and ESAL's. Therefore, either assumed or measured distributions can be used for a given project. Statewide averages are generally not appropriate.

b. Distributions at a given location can be estimated with the help of a Mn/DOT traffic engineer or using the procedure presented in Appendix B. The measurements should be carried out for a minimum of one week in the summer **and** one week in the fall.

3. When vehicle type distributions are measured or estimated the results should be reported to the Mn/DOT Office of Transportation and Data Analysis at Mn/DOT Mailstop 450 or e-mailing the information to

Melissa,thomatz@dot.state.mn.us

The coding for a given county or city should be used so that the data from around Minnesota can be coordinated to establish realistic distributions for various areas of the State.

In this way the information can be used to develop a database of vehicle type distributions throughout Minnesota.

- Estimate ESAL Factors by vehicle type; Table 3.2 shows a list of ESAL factors for CSAH and other low volume roads. Other distributions can be assumed based on loadings determined from knowledge of the usage for the design roadway. Table 3.3 illustrates a method of estimating ESAL effect for a given vehicle type.
- Growth Factor; The growth factor to be used can be estimated using the procedure presented in Table 3.6 or the factors listed in Table 3.4.
- The Design Lane distribution for 1, 2 and 3 lanes in one direction are listed in Table 3.5.
- An ESAL calculation spreadsheet is presented in Table 3.6. This spreadsheet should be used if the MNESALS Software is not available.

Eventually, the MnPAVE procedure will use the estimated Load Spectra concept to evaluate traffic. Load Spectra yields a distribution of axle loads for various configurations of axles. For the next few years the same type of data will be required to predict Load Spectra as has been used to predict ESAL's. Therefore, it is recommended that data and information continue to be obtained as has been listed herein.

6.4. Subgrade (Embankment) Soil

6.4.1. Subgrade Soil Design Parameters

For the Soil Factor Design procedure the subgrade soil is evaluated using the soil factor, which is dependent on the AASHTO classification. The AASHTO classification should be determined by testing the soil "representative" of the project being designed. The "representative" soil can only be determined using a soil survey with the procedure(s) given in Section 4.2. To determine the AASHTO classification the gradation uses a sieve analysis and hydrometer analysis for the fine-grained material. The Atterberg Limits (Plastic Limit and Liquid Limit) must be run and used for the classification.

The R-Value can be measured directly in the laboratory, or can be estimated from the AASHTO Classification. It is recommended that the R-Value for the "representative" be measured directly using the procedure as modified by MnDOT (5). A second choice is to estimate the R-Value using the correlated values from Reference 7.

The resilient modulus (M_r) can be estimated from either the R-Value or AASHTO soil classification using relationships developed by Siekmeier and Davich (7). A laboratory test is now being developed to measure the resilient modulus directly in the laboratory (23). Until this test is developed, the resilient modulus must be determined preferably using the R-Value correlation or else with the AASHTO classification correlation.

The resilient modulus should be varied throughout the year using the seasonal factors given in Section 4.3.4.4. More research needs to be conducted to determine how the five seasonal factors determined from Reference 8 vary with soil type.

6.4.2. Construction Specifications and Construction for Subgrade Soils

MnDOT Specifications 2105, 2111 and 2123 should be used for construction of subgrades in Minnesota (9). Test rolling (2111), specified density and quality compaction are the three methods of compaction control included in these specifications. Proof rolling, which is covered in Specification 2111, is recommended. Proof rolling requires an experienced inspector for observation. Specified density as presented in Specification 2105 is the second choice. Quality compaction is recommended only if an experienced inspector is available and/or for relatively small areas. The situations where one method is appropriate relative to the others are listed in Section 4.4.4. The six items listed in Section 4.4.4 must also be followed to result in a well-constructed subgrade.

The MnDOT Office of Construction, Technical Certification Section has published as "Inspector's Job Guide for Construction" (11). This guide should be used so that the Inspector has a checklist which will help start and keep the project well organized and follow the specifications set up for the project.

6.4.3. Subgrade Soil Enhancement Procedures in Minnesota

Various methods of subgrade enhancement are presented in Section 4.5.

- Enhancement of in-place soils using proper design of drainage and good compaction are summarized in Sections 4.5.2.
- Modification using lime, bituminous materials and chlorides (Sections 4.5.3.2., 4.5.3.3. and 4.5.3.4.)
- Stabilization using Fly Ash (Section 4.5.4.).
- Use of Geosynthetics
    - Separation (Section 4.5.5.3.2.)
    - Reinforcement (Section 4.5.5.3.)

  General design considerations along with factors affecting of geosynthetic lifespan are presented in Section 4.5.5.4.
- Substitution using higher quality granular and lightweight materials are presented in Section 4.5.6.
    - Higher quality granular materials presented are Select Granular (Section 4.5.6.2. and Breaker Run Limestone (Section 4.5.6.3.). Design and construction procedures along with specifications are presented.
    - Design and construction of lightweight fills using Wood Chips, Shredded Tires and Geofoam are covered in Sections 4.5.6.4.1., 4.5.6.4.2., and 4.5.6.4.3., respectively.

Summaries using each of the materials and procedures recommendations are summarized for design and construction control. Specifications for materials and procedures to use in Minnesota along with contacts for further information are presented.

6.4.4. Recommended Enhancement Procedures for Specific Conditions

Based on a review of the literature, questionnaires and interviews with Mn/DOT and county engineers and review of specific projects recommendations are made for when and how the various procedures should be used. Recommendations are presented in Tables 4.14, 4.15, and 4.16 for Granular, Semi-plastic and Plastic soils respectively. The parameters used for the recommendations are “Grade above Water Table” and “Moisture Conditions”. There are essentially no conditions recommended for soil enhancement for granular soils. Methods of Modification, Stabilization, Separation and Reinforcement are recommended for various conditions in the tables.

Table 4.17 lists the conditions and including “Thickness of Peat” for which the various lightweight fills are recommended.

6.4.5. Documentation of In-Place Projects Using Soil Enhancement

A database has been developed to document installations using the procedures listed. Projects were located during visits to the cities and counties during the Summer, 2002. Sixty five projects have been identified. It recommended that:

- The projects identified should be reviewed every three years or more often.
- The location and parameters for additional projects should be added to the database.

In this way actual performance of the various methods of subgrade enhancement can be documented.

6.5. Pavement Section Materials

6.5.1. General

The materials used for pavement sections range from select granular materials to high type Hot Mix Asphalt materials. Each of these materials or combination of materials is defined by specification for the Soil Factor and R-Value design procedures. Granular Equivalent factors are assigned to each specification material. These factors are considered constant throughout the year. The MnPAVE procedure requires that Resilient

Modulus values be assigned to each of the materials. The resilient modulus has been found to vary throughout the year (8) and within specifications. At this time moduli values are being used based on laboratory and field testing of MnROAD materials (7). The recommendations in this section are for the specifications to use, the design factors, construction procedures and specific procedures within the specifications that will result in a good performing pavement.

6.5.2. Specifications and Design Factors

The following granular equivalent factors are recommended for materials that pass the respective specifications:

Material	G.E. Factor	MnDOT Specifications
Select Granular	0.50	3149-2, 2211
Subbase	0.75	3138 (Class 3 & 4), 2211
Granular Base	1.00	3138 (Class 5 & 6), 2211
Plant Mix Bituminous	2.00	2331
Plant Mix Bituminous	2.25	2360/2350

Various other G.E. factors have been applied to some stabilized bases. However, the MnDOT District Materials Engineer or Pavement Section should be contacted for advice on these materials.

For MnPAVE default seasonal moduli have been developed based on in-place non-destructive and laboratory testing of the MnROAD materials. The moduli have been related to the specifications used at MnROAD and the temperature and moisture conditions measured. Table 5.2 lists the default moduli used now in MnPAVE. The variation of modulus throughout the year for pavement materials in other locations must be monitored for MnPAVE input. Documentation of these values must be an on-going project for the next few years. At this time the correlation of moduli to specifications shown in Section 5.3 should be used.

6.5.3. Construction of Granular Bases

For aggregate base and subbase materials construction should follow the procedures and criteria listed in Specification 2111. The construction requirements for placing and mixing, spreading, and compaction must be followed. Three methods of compaction control are listed; specified density, quality (ordinary) compaction and penetration index using the DCP. The recommended procedures are:

1. Use of the penetration index with the DCP.
2. Specified density.

These procedures indicate that the granular material has been compacted to a level where the construction of the next layers can be accomplished and that the material has the strength needed to support the design traffic.

Quality or ordinary compaction should only be used for small areas and/or an experienced Inspector is available to observe the construction continuously.

The "Schedule for Materials Control" must be setup and followed for each project so that the required sampling and testing are accomplished.

Standard methods of testing whether it be for density or DCP testing must be followed. The Inspector's Guide for Construction (11) should be used as a checklist to determine what materials and procedures will help the Engineer, Inspector and Contractor efficiently carry out the project specifications.

6.5.4. Construction of Hot Mix Asphalt Materials

Specification 2360/2350 should be followed for construction of HMA surface mixtures. All HMA mixtures in Minnesota use PG graded asphalts. The cities and counties should use the PG graded asphalt specified for their region. Laboratory compaction is accomplished with a standard Marshall hammer that applies blows to each side of the specimen.

The 2360/2350 LV and MV mixtures are based on strength criteria measured with the Marshall Stability test and design air voids which are listed in Table 2360/2350-2. Moisture susceptibility as measured with the modified Lottman test strength ratios is also specified along with the coarse and fine aggregate angularity.

The Superpave part of the specification does not have a strength or stiffness requirement. The primary difference in the two specifications is the method of compaction. The Superpave specification uses the gyratory compactor both in the lab and in the field.

Table 2360-3 lists the minimum VMA for the mixture as compacted in the field. Also the compaction percent of maximum theoretical density is listed in Table 2350/2360-8.

The mixture design for both procedures is accomplished using Quality Management procedures; that is the Contractor provides the mix design and Quality Control and the Agency does check testing or Quality Assurance testing to check the work done by the Contractor. The procedures laid out in Specification 2360/2350 should be followed carefully to result in a good stable and durable mixture. Section 5.4.1.3.2.6 presents the methods of compaction control available. These are:

1. Specified Density – Measurement of density for comparison with maximum theoretical density.
2. Quality compaction with a control strip
3. Quality compaction without a control strip.

Specified density should be used unless otherwise indicated. The only reasons would be lack of equipment or people to run the tests. The second option is Quality compaction with a control strip. The control strip indicates when maximum compaction was achieved and gives a measure of consistency. The roller requirements for use with ordinary compaction are given in Section 2350-6 and 2360-5. Quality compaction without a control strip should only be used for very small areas and when an experienced Inspector is on the job to observe the operations continuously. The incentives and disincentives listed for density control in Table 2360.6-B4 should be used.

Also, the incentives and disincentives for ride in 2360.6-B4 should also be followed. A road built smoother will perform better than one using the mixture and pavement section built rougher.

The Schedule for Materials Control should be setup and followed for the specifications on the given project. The listings are for both plant and paving operations. Each of these requires Contractor (QC) testing and Agency (QA) testing. The specifications lays out the differences allowable between the tests.

The Inspector's Job Guide for Plant Mix Bituminous Paving (11) should also be consulted to help setup and run the project efficiently.

A good diary will help all people involved with the project maintain a good schedule of construction and field control.

One of the major goals of presenting the specifications and recommended field procedures for constructing the subgrade and pavement section materials is so that the available materials are used as effectively as possible. The procedures should also result in the construction of the materials so that a uniform product will be obtained. The most uniformly constructed materials will perform the best.

REFERENCES

1. Van Cauwelaert, F.J., Alexander, D.R., White, T.D., and Barker, W.R., “Multilayer Elastic Program for Backcalculating Layer Moduli in Pavement Evaluation”, Nondestructive Testing of Pavements and Backcalculation of Moduli, ASTM STP 1026, A.J. Bush, III and G.Y. Baladi, Editors, American Society for Testing Materials, Philadelphia, PA., 1989, pp. 171-188.

2. Roadent Reference

3. Skok, Eugene L., Newcomb, David E., Timm, David H., “Minnesota Low Volume Road Design – 1998”, MnDOT Project 74708, TOC#55, Report No. 1999-34

4. MnDOT State Aid Manual, MnDOT Division of State Aid for Local Transportaton, July, 1998.

5. MnDOT Geotechnical and Pavement Manual, April, 1994.

6. Chadbourn, Bruce A., Dai, Shongtau, Davich, Peter A., Siekmeier, John A., Van Deusen, David A., “Pavement Designer’s Guide for MnDOT Flexible Pavement Design, MnPAVE Beta Version 5.0, DRAFT, MnDOT Office of Materials and Road Research, July, 2001.

7. Siekmeier, John A., and Davich, Peter A., “Correlation Table for Predicting Resilient Modulus from other Soils and Aggregate Characteristics”, DRAFT, 2001.

8. Ovik, Jill M., Birgisson, and Newcomb, David E., “Characterizating Seasonal Variations in Pavement Material Properties for Use in a Mechanistic-Empirical Design Procedure”, Final Report, MnDOT Report 2000-35.

9. Standard Specifications for Construction – 2000 Edition, MnDOT

10. MnDOT Grading and Base Manual, June, 1998.

11. "Inspector's Guide for Construction", MnDOT Office of Construction Technical Certification Section, 2001.

12. "AASHTO Guide for Design of Pavement Structures – 2002", American Association of State Highway and Transportation Officials, NCHRP Project

13. Chadbourn, Bruce A., Skok, Jr.,Eugene L., Newcomb, David E., Crow, Benita L., and Spindler, Samantha, "The Effect of Voids in the Mineral Aggregate (VMA) on Hot-Mix Asphalt Pavements", MnDOT Contract 74581, W.O. 202, MnDOT Report 2000-13.

14. MnDOT Bituminous Manual, March, 1935.

15. Kersten, Miles S., Skok, Eugene L., "Application of AASHO Road Test Results to the Design of Flexible Pavements in Minnesota", Final Report, Minnesota Department of Highways Investigation 183, Final Report, 1968.

16. Timm, David A., Newcomb, David E., and Birgisson, Bjorn, "Mechanistic-Empirical Flexible Pavement Thickness Design: The Minnesota Method", MnDOT Report No. MN/RC – P99-10, January 1999.

17. Witczak, M.W., "Temperature Distribution Prediction Equations."

18. Skok, Eugene L., Timm, David A., Clyne, Timothy, "Traffic Supplement to Low Volume Road Best Practices Manual", MnDOT Project 74708, Work Order No. 180, Final Report Draft, 2001.

19. AASHTO Pavement Design Guide, American Association of State Highway and Transportation Officials, 1993.

20. MnESAL's Manual, MnDOT Traffic Data Collection and Analysis Section.

21. Soils Manual, The Asphalt Institute, Manual Series No. 10, Fourth Edition, USA, 1986.

22. Kupferman, M., Pinciotti, R.D., "Use of a Micro-Computer for Control, Data Acquisition and Evaluation of the Resilient Modulus Test, Resilient Modulus of Soils: Laboratory Conditions, Elton, D.J., Ray, R.P., Geotechnical Special Publication No. 24, American Society of Civil Engineers, New York, NY, October, 1989.

23. Brodsky, Nancy S., Resilient Modulus Measurements of Cohesive Soils: Laboratory Conditions", Elton, D.J., Rat, R.P., Geotechnical Special Publicaton No. 24, American Society of Civil Engineers, New York, NY, October, 1989.

24. User Guide for the Dynamic Cone Penetrometer (DCP), Minnesota Department of Transportation, 1999.

25. Uzan, J., "Dynamic Linear Backcalculation of Pavement Material Parameters, Journal of Transportation Engineering, Vol. 120, No. 1, American Society Of Civil Engineers, January/February, 1994.

26. Uzan, J., "Advanced Backcalculation Techniques, Nondestructive Testing of Pavements and Backcalculation of Moduli", Second Volume ASTM STP 1198, Harold L.VonQuintos, Albert Bush, III, and Gilbert Baladi, Editors, ASTM, Philadelphia, PA, 1994.

27. Nazarian, S., Tandon, V., Crain, K., and Yuan, D., "Use of Instrumented Dynamic Cone Penetrometer in Pavement Characterization, Nondestructive Testing of Pavements and Backcalculation of Moduli", Third Volume, ASTM STP 1375, S.D. Tayabji, S., Lukanen, E.O., Editors, ASTM, West Conshohocken, PA, 2000.

28. Yoder, E.J., Witczak, M.W., "Principles of Pavement Design", Second Edition, 1975, John Wiley & Sons, Inc., New York, NY,

29. Bearden, J.B., and Labuz, J.F., "Fabric Reinorcement and Separation in Unpaved Roads", MnDOT Report No. MN/RC-1994-04, St, Paul, MN December, 1998.

30. Huntington, G., and Ksaibati, K., "Evaluation of Geogrid-Reinforced Granular Base, Recent Advances in the Characterizaton of Transportation Geo-Materials" Tutumluer, E., and Papagiannakis, A.T., Geotechnical Special Publication No. 89, American Society for Civil Engineers, Virginia, 1999.

31. MnDOT Technical Memo on the use of PG graded asphalt in Minnesota., 2001.

32. "Superpave Asphalt Mixture Design", AASHTO Method MP-1, 1997.

33. MnDOT Technical Memo on Inspection Sampling and Acceptance of Bituminous Mixtures, 2000

34. Asphalt Mixture Design Manual, The Asphalt Institute Manual Series No. 2 (MS-2)

35. Asphalt Superpave Mixture Design Manual, The Asphalt Institute Special Publication Series No. 2 (SP-2), 1999.

36. The Asphalt Institute, *Drainage of Asphalt Pavement Structures MS-15*. The Asphalt Institute, Research Park Drive, Lexington, KY. September 1984.

37. The Asphalt Institute, *Soils Manual 5th Edition.* Manual Series No. 10 (MS-10). The Asphalt Institute, Research Park Drive, Lexington, KY. 1997.

38. Hagen, Mark G. and Cochran, George R., *Comparison of Pavement Drainage Systems Research Report Number Mn/RD – 95/28.* Minnesota Department of Transportation, 395 John Ireland Blvd., St. Paul, MN. November 1995.

39. *Compaction of Roadway Soils.* Transportation Research Board Commission on Sociotechnical Systems National Research Council, National Academy of Sciences Washington D.C. 1979.

40. Krebs, Robert D. and Walker, Richard D., *Highway Materials*. McGraw-Hill 1971

41. Terrel, Ronald L., et al., *Soil Stabilization in Pavement Structures A Users Manual Volume 1 Pavement Design and Construction Considerations. FHWA-IP-80-2.* U. S. Department of Transportation Office of Development Implementation Division. October 1979.

42. Siekmeier, John and Blue, Jeff , *Fly Ash Soil Stabilization on Waseca CSAH 8, LRRB Project. Draft Executive Summary.* Mn/DOT Office of Materials and Road Research and Waseca County Highway Department. October 2000.

43. Velz, Paul G., Special Study No. 266 Asphalt Emulsion Stabilized Base Construction T.H. 65, S.P. 0208-18 Near Johnsonville. State of Minnesota Department of Highways Materials And Research Section. December , 1960.

44. The Asphalt Institute, *The Asphalt Handbook.* Manual Series No. 4 (MS-4). The Asphalt Institute, Research Park Drive, Lexington, KY. 1989.

45. AASHTO-FHWA, *Special Product Evaluation List FHWA/RD-83/093*. U. S. Department of Transportation, Federal Highway Administration. August 1983.

46. Korfhage, G. R., *Base Stabilization With Cut-Back Asphalt and Chlorides – Nobles County. Investigation No. 607, Final Report.* Office of Materials Minnesota Department of Highways in cooperation with U. S. Department of Transportation Bureau of Public Roads and Minnesota Local Road Research Board. 1967.

47. Terrel, Ronald L., et al., *Soil Stabilization in Pavement Structures, A Users Manual. Volume 2, Mixture Design Considerations FHWA-IP-80-2.* U. S. Department of Transportation Office of Development Implementation Division. October 1979.

48. Koerner, Robert M., *Designing with Geosynthetics*, Second Edition, Prentice Hall, Englewood Cliffs, NJ. 1990.

49. Rowe, R. Kerry and Badv, K., "Use of a Geotextile Separator to Minimize Intrusion of Clay into a Coarse Stone Layer", *Geotextiles and Geomembranes,* No. 14, Elsevier Science Ltd, Ireland, 1996, pp. 73-93.

50. Haas, R., "Structural Behavior of Tensar Reinforced Pavements and Some Field Applications", *Proc. Symp. Polymer Grid Reinforcement in Civil Engineering,* London: ICE, 1984, pp. 166-170.

51. Jung, F.W. *Interpretation of Deflection Basin for Real-World Layer Materials of Flexible Pavements*, Ontario Ministry of Transport, Downsview, Ontario. December 1989.

52. Kohlnhofer, Guy W., Marti, Michael M., Braun Intertec Pavement, Inc., *Lightweight Fill Materials for Road Construction*, Mn/DOT MN/RC – 92/06 Local Road Research Board

Report No. 9LRR645. Minnesota Department of Transportation, 395 John Ireland Blvd., St. Paul, MN. March 1992.

53. Holtz, Robert D., Christopher, Barry R. and Berg, Ryan R., *Geosynthetic Design and Construction Guidelines*, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C. April 1998.
54. Ionescu, A. et al., “Methods Used for Testing the Bio-Colmatation and Degradation of Geotextiles Manufactured in Romania”, *Proc. 2nd Infl. Conf. Geotextiles*, St. Paul, MN: IFAI, 1982, pp. 547-552.

55. Faure, Y.H., et al., “Analysis of Geotextile Filter Behavior After 21 Years in Valcros Dam”, *Geotextiles and Geomembranes*, No. 17, Elsevier Science Ltd, Ireland. 1999.

56. Geotechnology Outreach Team, *Degradation Reduction Factors for Geosynthetics*, Federal Highway Administration Geotechnology Technical Note, http://www.geocouncil.org/Geo_Council_News/fhwa_tech_note/fhwa_tech_note. html. May 1997.

57. Narayan, S., Bhatia, S.K., Corcoran, B.W., and Nabavi, T.R., “Analysis of a Failed Basal Reinforced Embankment”, *Geotechnical Special Publication.* No. 103, 2000. ASCE, Reston, VA, USA. pp. 398-417.

58. Loulizi, A., Al-Qadi, I.L., Bhutta, S.A., Flintsch, G.W., “Evaluation of Geosynthetics Used as Separators”, *Transportation Research Record,* No.1687, 1999, pp. 104-111.

59. Clark, Ronald J., *Subgrade Stabilization Using Geogrids*, Commonwealth of Pennsylvania Department of Transportation, Project number 89-54A, October 1995

60. Braun Intertec, Inc., *Mn/DOT Technical Report 1998-05U, Wood Chips as a Lightweight Fill*. Minnesota Department of Transportation, 395 John Ireland Blvd., St. Paul, MN. December 1996.

61. Drescher, Andrew and Newcomb, David E., *Development of Design Guidelines for Use of Shredded Tires as a Lightweight Fill in road Subgrade and Retaining Walls*, Mn/DOT Report Number 94-04. January 1994.

APPENDIX A

USE OF INVESTIGATION 183 AND 195 TEST SECTIONS AS A LONG TERM PERFORMANCE COMPARISON WITH THE MINNESOTA M-E DESIGN PROCEDURE

INTRODUCTION

A mechanistic-empirical design procedure (ROADENT) has been developed to determine appropriate design thicknesses of hot-mix asphalt pavements in Minnesota (1,2). Calculated strains in the pavement section are used with transfer functions to predict the amount of traffic, in ESALs, the section will support before deterioration in the form of fatigue cracking or critical rut depth. To make these predictions, field performance must be observed and related to measured or calculated strains in the pavement. The first performance prediction equations were developed based on performance of sections at the Minnesota Road Research Project (Mn/ROAD) after four years of service (3,4).

Since the Mn/ROAD project represents only a portion of conditions encountered in Minnesota, it is necessary to expand the calibration data set to a wider range of conditions. To validate and/or calibrate the performance equations for other traffic levels, soil types and pavement sections, performance records of some of the Investigation 183 and 195 test sections (5,6) were reviewed, some of which are over 40 years old. The properties of the soils and pavement layers were measured during the course of the research studies and included in References (5) and (6). Strain levels for the pavements were simulated mechanistically and damage factors were calculated for each season and totaled for each of the years to rehabilitation for the test sections and observed performance was compared to the predicted performance.

Mr. Tom Nelson and Mr. Mark Levenson of the Mn/DOT Data Management Services Section made the traffic predictions necessary for comparison. The condition of the 50 test sections from 1964 through 1977 was reported by Lukanen (7). The Mn/DOT Pavement Management Section provided information on conditions from 1977 to the present. The conditions of the sections were observed on videos from 1992 to the present. Elaine Miron and Erland Lukanen located the sections using the video station at Mn/DOT and it was necessary to locate the original test sections using historical stationing and current reference points. This information was retrieved from historical records and files that had been stored for the past 25 years. The locations using current reference points were determined using logbooks provided by the Mn/DOT Pavement Design and Management Sections.

The construction histories of the 10 Investigation 183 test sections were used to relate the observed performance with the predicted damage ratios calculated from the computer simulated pavement and empirical transfer functions. The predictions were then compared to the observed performance and determined to be conservative or not conservative. This information was used to judge if the current performance prediction equations should be modified.

MINNESOTA FLEXIBLE PAVEMENT DESIGN TEST SECTIONS

In 1963 and 1964, 50 flexible pavement design test sections were established to help evaluate flexible pavements in Minnesota using the concepts and results from the AASHO Road Test. In addition the stabilometer, R-Value was introduced as a strength test to evaluate subgrade soils and granular bases. Each test section consisted of two 500-ft test or evaluation sections separated by a 200-ft sampling and destructive testing segment. The evaluation of the 1200-ft test sections was made using the following methods:

1. Sampling and testing of each layer was performed with plate load testing. Thickness measurements of each layer were also made as trenches were dug.
2. Condition surveys were conducted each year to document the type, severity and amount of cracking. Alligator cracking was measured in square feet per 1000 square feet as defined at the AASHO Road Test. Cold temperature cracks were counted periodically, but not always recorded because they were not considered part of a structural evaluation.
3. Longitudinal profile was measured using the Bureau of Public Roads (BPR) roughometer in units of inches per mile and was called the Roughness Index. The Roughness Index was correlated with Present Serviceability Rating (PSR). Later the PSR was also correlated with the PCA roadmeter and the Maysmeter.
4. Traffic was measured using load and vehicle type distribution studies conducted in 1964 and 1969 at each test section along with statewide data for other years. This information was used to calculate equivalent loads in ESALs for each year from the time of construction.
5. Performance was defined as the number of ESALs the pavement withstood or was predicted to withstand before the serviceability was reduced to 2.5.

6. The structural capacity of the sections was measured using the plate bearing test and the Benkelman beam test.

The information from the study of these test sections was used to develop the current Mn/DOT R-value design procedure, which has been in use since about 1971. A report summarizing the performance of the original 50 test sections was written in 1980 (7). The distress and rideability conditions, applied traffic and strength summaries of each section were presented through 1977.

SELECTION OF PILOT TEST SECTIONS

With the advent of mechanistic-empirical (M-E) flexible pavement design and the need for a well-calibrated design system, it was decided to calibrate the mechanistic-empirical design procedure developed at the University of Minnesota using the performance and construction histories of the Investigation 183 test sections. The steps required to accomplish this were the following:

1. Locate the test sections on the trunk highway system, which required determining the reference points and stationing of the sections. These were obtained from original project files and Mn/DOT log books in the Mn/DOT design and pavement management sections.
2. Request traffic predictions for each of the test sections' reference points from original construction through the year 2000.
3. Obtain pavement condition data. The condition of each section was summarized in Reference (7) from original construction through 1977. Conditions were observed using the Pavement Management video station from 1992 to the present. Rut depths on each section were also measured.
4. Determine structural profile histories of the sections by examining pavement management records. These records were used to establish when reconstruction or significant maintenance was performed, changes in thickness were also noted.

5. Resilient moduli of each layer were estimated using the stabilometer R-value of the soils and granular materials for each test section. The moduli of the asphalt concrete layers were estimated from backcalculated moduli at the Mn/ROAD project. The moduli along with

thicknesses were used to calculate strains for each of five seasons. Using these strain calculations and the traffic estimates damage factors were determined using the existing performance equations for fatigue and rut depth. Comparisons of predicted and measured performance were made to check if the predictions were less or more conservative than the observed performance over the 40-year period.

Selection of Pilot Study Test Sections

As a pilot study to evaluate whether data could be generated to review the 40-year old test sections, it was decided to develop information from nine of the Investigation 183 test sections. The fifty Investigation 183 test sections were categorized by soil type using Table 1 and by traffic using Table 2. Table 3 lists the sections along with the district, soil type and traffic level for each. Table 3 shows that there were five sections with granular subgrades, 23 semi-plastic and 22 plastic subgrades. There are 24 sections with low traffic, 17 medium and 8 high traffic sections. The following criteria were used to select the pilot test sections:

1. At least one test section from each Mn/DOT district.
2. Some test sections with Plastic, Semi-Plastic, and Granular subgrade soils using the definitions as in Table 1.

Table 1. Soil Classifications for Pilot Project.

Soil Type (Abbreviation)	AASHTO Classification
Plastic (P)	A-6, A-7
Semi-Plastic (SP)	A-4, A-5
Granular (G)	A-1, A-2, A-3

3. Test sections which had Low, Medium and High traffic. The traffic categories were based on the calculated 1966 annual ESALs using the levels as in Table 2:

Table 2. Traffic Classifications for Pilot Project.

Traffic Category (Abbreviation)	Annual ESAL Level in 1966
Low (L)	< 20,000
Medium (M)	20,000 to 100,000
High (H)	> 100,000

Table 3. Investigation 183 Pavement Sections.

		Soil Category			Traffic Category		
Test Section	District	GR	SP	P	L	M	H
1	4	X					X
2	2			X		X	
3	2			X		X	
4	1			X	X		
5	1		X		X		
6	1		X				X
7	1			X	X		
8	1			X		X	
9	1		X			X	
10	3		X		X		
11	3	X			X		
12	3			X	X		
13	3		X			X	
14	3		X			X	
15	3	X					X
16	3		X			X	
17	5		X			X	
18	5	X				X	
19	5		X				X
20	5		X			X	
21	5			X		X	
22	5		X			X	
23	9		X				X
24	6			X	X		
25	6			X	X		
26	6		X		X		
27	6		X		X		
28	6			X	X		
29	6			X	X		
30	7		X				X
31	7		X		X		
32	7			X	X		
33	8			X		X	
34	8			X			X

35	8			X	X		
36	8		X			X	
37	8			X		X	
38	8			X		X	
39	8		X		X		
40	8	X			X		
41	6		X				X
42	4		X		X		
43	4			X	X		
44	4			X	X		
45	2		X		X		
46	2		X		X		
47	7			X	X		
48	7			X	Unknown		
49	7		X			X	
50	8			X	X		

Table 4 lists the test sections selected for the pilot study to establish whether the pavement management system along with traffic and materials characterization could be used to trace performance history. One section was selected from each Mn/DOT district and a variety of soil types and traffic levels. There are four each of semi-plastic and plastic soils and one with a granular subgrade. There are four sections with low, two medium and three high traffic levels.

Table 4. Investigation 183 Sections Selected for Pilot Study of 40-Year Performance.

District	Test Section	Soil Type	Traffic
1	183-6	SP	H
2	183-3	P	M
3	183-11	G	L
4	183-43	P	L
5	183-22	SP	M
6	183-26	SP	L
7	183-47	P	L
8	183-34	P	H
9	183-23	SP	H

Location

Table 5 lists the Trunk Highway, Lane, Reference Marker (Mile Post) and stationing for the nine pilot test sections. The information was obtained from the Investigation 183 files and was necessary for locating the sections using the current referencing system in the Mn/DOT Pavement Management System. It was also necessary to establish the locations for traffic requests.

Table 5. Pilot Section Locations.

Test Section	District	Trunk Highway	Lane*	Mile Post (Mile Post Stationing)	Test Section Station Limits
6	1	2	EB	250 - 251 (372+43.7 - 424+82.3)	372 - 384
3	2	59	SB	363 - 362 (4099+52 – 4155+54)	4140 - 4152
11	3	371	SB	43 - 44 (555+92-608+63)	565-577
43	4	54	NB	4 - 5 (211+22 - 264+20)	227 - 239
22	5	55	EB	179 - 180 (1322+12 – 1374+72)	1335 -1347
26	6	76	SB	30 - 29 (682+50 - 734+79)	693-700
47	7	19	EB	121 - 122 (117+68 - 170+41)	129-141
34	8	7	EB	(116 - 117) (456+62 - 509+52)	465-477
23	9	36	EB	(13 - 14) (141+89 - 196+73)	171-183

*Lane: The direction of traffic over the test section (EB = Eastbound, WB = Westbound, NB = Northbound and SB = Southbound)

The nine test sections selected for this study were subjected to a mechanistic-empirical (M-E) analysis to assess whether the current performance transfer functions accurately predict observed pavement performance. The following subsections detail the process and findings of the M-E analysis.

PILOT TEST SECTION DATA

Prior to performing the M-E analysis it was necessary to gather information regarding the structural profiles of the sections, seasonal layer moduli, traffic and performance data. Each of these is described below.

Structural Profiles

Records from the pavement management office of Mn/DOT were examined to obtain the dates of maintenance; rehabilitation or reconstruction activities performed on each of the test sections. Of interest in this study were changes made to the structural profile of the sections. Tables 6 through 14 detail the construction histories of the test sections. It is important to note that, in some cases, sections were milled and overlaid. However, in the tables, simply total thicknesses are given since only these were needed in the M-E analysis. Additionally, except where noted, the granular base layers were constructed of Mn/DOT Class 5 material and subbase layers of Mn/DOT Class 4 material. Finally, the subgrade soil types are specified according to the AASHTO soil classification system.

Table 6. Section 183-3 Structural Profile History.

Year	Asphalt Concrete Thickness (in)	Granular Base Thickness (in)	Subgrade Soil Type
1961	2.0	15.5	A-7-6
1969	6.5		
1987	8.0		
1999	10.0		

Table 7. Section 183-6 Structural Profile History.

Year	Asphalt Concrete Thickness (in)	Granular Base Thickness (in)	Granular Subbase Thickness (in)	Subgrade Soil Type
1959	1.5	5.0	11.0	A-2-4
1960	6.0			
1981	7.5			

Table 8. Section 183-11 Structural Profile History.

Year	Asphalt Concrete Thickness (in)	Granular Base Thickness (in)	Granular Subbase Thickness (in)	Subgrade Soil Type
1960	2.0	5.0	4.0	A-1-b
1961	5.5			
1986	4.5			

Table 9. Section 183-22 Structural Profile History.

Year	Asphalt Concrete Thickness (in)	Granular Base Thickness (in)	Granular Subbase Thickness (in)	Subgrade Soil Type
1961	7.0	6.0	16.0	A-4
1973	8.5			

Table 10. Section 183-23 Structural Profile History.

Year	Asphalt Concrete Thickness (in)	Granular Base Thickness (in)	Granular Subbase Thickness (in)	Subgrade Soil Type
1960	7.0	9.0	12.0	A-2-4
1987	11.75			

Table 11. Section 183-26 Structural Profile History.

Year	Asphalt Concrete Thickness (in)	Granular Base* Thickness (in)	Subgrade Soil Type
1961	3.0	14	A-4
1988	7.5		

*Mn/DOT Class 3 Material

Table 12. Section 183-34 Structural Profile History.

Year	Asphalt Concrete Thickness (in)	Granular Base Thickness (in)	Granular Subbase Thickness (in)	Subgrade Soil Type
1959	9.5	3.5	4.5	A-6
1986	12.5			

Table 13. Section 183-43 Structural Profile History.

Year	Asphalt Concrete Thickness (in)	Granular Base Thickness (in)	Granular Subbase Thickness (in)	Subgrade Soil Type
1959	2.0	7.0	8.0	A-6
1968	4.0			
1989	7.5			

Table 14. Section 183-47 Structural Profile History.

Year	Asphalt Concrete Thickness (in)	Granular Base* Thickness (in)	Granular Subbase Thickness (in)	Subgrade Soil Type
1954	2.0	4.0	8.0	A-6
1973	4.5			

*Asphalt stabilized base

Seasonal Layer Moduli

Asphalt Concrete

Based upon previous research at Mn/ROAD (8), the asphalt concrete layers were assigned seasonal moduli as shown in Table 15.

Table 15. Asphalt Concrete Seasonal Moduli.

Season	Modulus, psi
I (Winter)	1,987,433
II (Spring Thaw)	1,528,794
III (Spring Recovery)	993,717
IV (Summer)	290,471
V (Fall)	764,397

Granular Base and Subbase

Tests to determine the R-value of the granular bases and subbases were done in the original 183 investigation (5,7). The data were used in this project to determine the normal or summer modulus using the following relationships (9):

$M_R = 1000 + 555 * \text{R-value}$ (R-value ≤ 20)

$M_R = 1000 + 250 * \text{R-value}$ (R-value > 20)

Seasonal multipliers, obtained from Mn/ROAD (8), were used to determine the moduli in the other four seasonas as shown in Table 16.

Table 16. Seasonal Base and Subbase Moduli.

Season	I*	II	III	IV	V
Test Cell and Layer	Modulus, psi				
183-3 Base	40,000	19,200	24,100	28,650	28,940
183-6 Base	40,000	19,665	24,650	29,350	29,650
183-6 Subbase	40,000	14,070	17,600	21,000	21,200
183-11 Base	40,000	19,900	24,950	29,700	30,000
183-11 Subbase	40,000	8,880	11,100	13,250	13,380
183-22 Base	40,000	19,665	24,700	29,350	29,650
183-22 Subbase	40,000	13,400	16,800	20,000	20,200
183-23 Base	40,000	18,730	23,480	27,950	28,200
183-23 Subbase	40,000	11,200	14,100	16,750	16,900
183-26 Base	40,000	20,600	25,800	30,750	31,100
183-34 Base	40,000	13,800	17,300	20,600	20,800

183-34 Subbase	40,000	11,900	14,900	17,750	17,900
183-43 Base	40,000	18,960	23,770	28,300	28,600
183-43 Subbase	40,000	12,900	16,200	19,250	19,400
183-47 Base	40,000	19,900	24,950	29,700	30,000
183-47 Subbase	40,000	18,730	23,500	27,950	28,200

*Winter modulus assigned a maximum value of 40,000 psi.

Subgrade

Previously measured R-values, as with the base and subbase layers, were used to determine the moduli for the subgrade soils in the summer condition. The following equations converted R-value to resilient modulus (9):

$M_R = 1000 + 555*\text{R-value}$ (R-value ≤ 20)

$M_R = 1000 + 250*\text{R-value}$ (R-value > 20)

Seasonal multipliers obtained from Mn/ROAD (8) were used to adjust the moduli for seasonal effects. Table 17 lists the seasonal subgrade moduli by test section. It is important to point out that soils having the same AASHTO classification typically had somewhat different R-values resulting in different seasonal moduli.

Table 17. Seasonal Subgrade Moduli.

Season	I	II	III	IV	V
Test Cell (Soil Type)	Modulus, psi				
183-3 (A-7-6)	40,000	19,020	5,740	5,550	7,760
183-6 (A-2-4)	40,000	20,800	16,000	16,000	14,550
183-11 (A-1-b)	40,000	23,400	18,000	18,000	16,360
183-22 (A-4)	40,000	31,950	9,650	9,325	13,040
183-23 (A-2-4)	40,000	15,925	12,250	12,250	11,140
183-26 (A-4)	40,000	29,980	9,055	8,750	12,236
183-34 (A-6)	40,000	28,150	8,500	8,215	11,500
183-43 (A-6)	40,000	26,250	7,930	7,660	10,700
183-47 (A-6)	40,000	29,126	8,797	8,500	11,888

Traffic Data

The test section locations were provided to the Management Data Services Section of Mn/DOT where estimates of accumulated ESALs over the 40 years were made. Original estimates were made from the initial date of construction through 1980 and then from 1980-2000. The estimates are based on weight and vehicle type distributions made periodically at the specific test section location throughout these time periods. Accumulated and yearly total ESAL values were tabulated so that accumulated ESALs could be noted at the time of rehabilitation or reconstruction. The total number of ESALs were then determined for each of the structural cross sections shown in Tables 6 through 14. Table 18 lists the relevant ESALs for each structural profile.

Table 18. ESALs by Test Section During Each Time Span.

Years	ESALs
Section 183-3	
1961-1968	109,073
1969-1986	458,126
1987-1998	504,711
1999-2001	100,858
Section 183-6	
1959	0
1960-1980	3,241,078
1981-2001	3,705,513
Section 183-11	
1960	13,463
1961-1985	477,568
1986-2001	655,432
Section 183-22	
1961-1972	258,706
1973-2001	1,771,782
Section 183-23	

1960-2001	3,833,503
Section 183-26	
1961-1987	126,198
1988-1998	113,450
Section 183-34	
1959-1985	1,541,977
1986-2001	1,139,912
Section 183-43	
1959-1967	31,730
1968-1988	112,630
1989-2001	69,730
Section 183-47	
1954-1972	565,554
1973-2001	1,422,364

Performance Data

In the original 183 study, yearly measurements of rut depth and amount of cracking were recorded; however, measurements were taken only through 1977. More recently, video records of the test sections were evaluated to assess the rutting and cracking performance of the test sections. These records were available for the years of 1996 to 1998. These two sources of data were merged to give a more complete sectional history of pavement performance. Figures A1 through A18, in Appendix A, illustrate the rutting and cracking performance of each section by year. Additionally, the total surface thickness was plotted on the graphs to give an indication of when the structural profile changed during the life of the section. It is important to note that years in which there is a profile change and zero rut depth or cracking corresponds to no performance data available for that year.

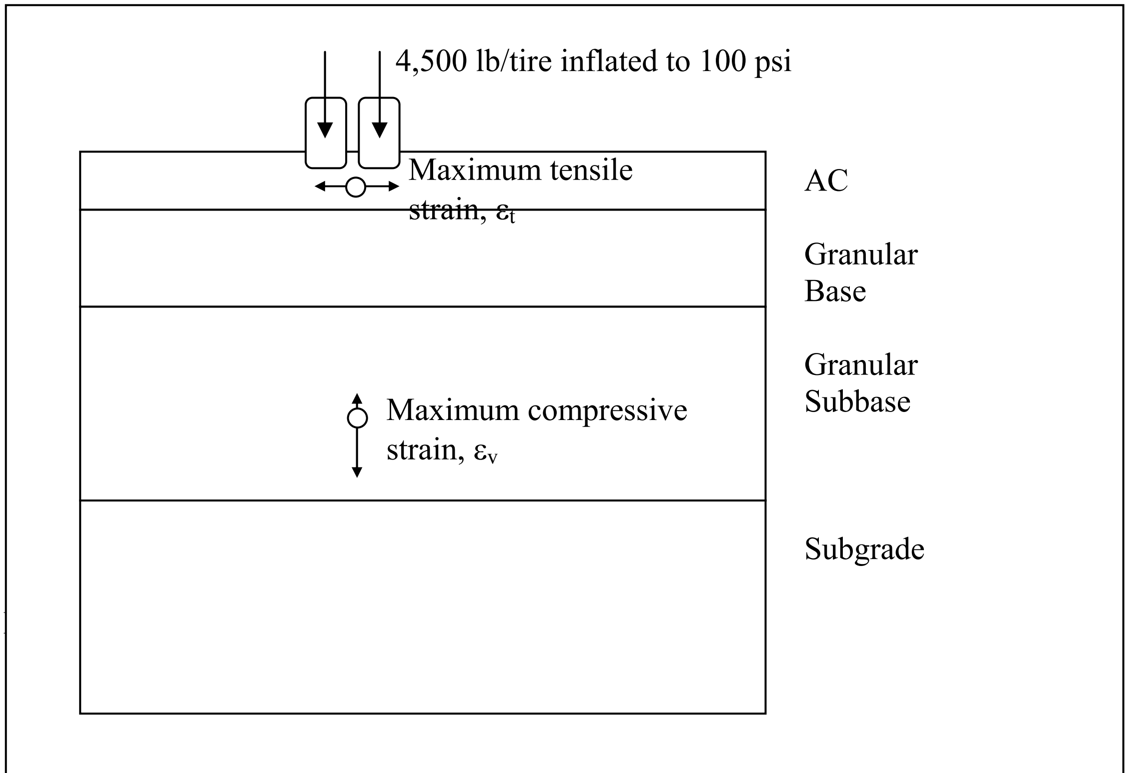
MECHANISTIC-EMPIRICAL ANALYSIS

Once all the necessary inputs had been obtained as specified above, it was possible to proceed with the M-E analysis of the test sections. The procedure consisted of four steps, detailed below:

1. Calculate strains for each pavement cross section.
2. Calculate seasonal traffic volumes.
3. Calculate seasonal expected number of allowable loads.
4. Calculate damage factors using Miner's Hypothesis.

Calculate Strains for Each Pavement Cross Section

The program, WESLEA for Windows, was used to perform the mechanistic simulation necessary to determine strains in the pavement structures. The structural inputs, specified above, were input and an 18-kip single axle load with dual tires inflated to 100 psi was applied to the pavement surface. The maximum tensile strain (ε_t) at the bottom of the asphalt concrete layer and the maximum compressive strain (ε_v) at the top of the subgrade were recorded as illustrated in Figure 1. This was done on a seasonal basis to account for changes in layer stiffnesses due to temperature and moisture changes in the different layers. The strain data may be found in Appendix B.



Calculate Seasonal Traffic Volumes

To accommodate a seasonal evaluation in Miner's hypothesis, it was necessary to distribute the ESALs over the five seasons of the analysis. The percentages shown in Table 19 were used to distribute the traffic to each season. The seasonal traffic data for each section are in Appendix B.

Table 19. Seasonal Traffic Multipliers.

Season	% of ESALs In Each Season
I - Winter	23%
II - Spring Thaw	5.8%
III - Spring Recovery	5.8%
IV - Summer	50%
V - Fall (Normal)	15.4%

Calculate Seasonal Expected Number of Allowable Loads

Transfer functions developed at the Minnesota Road Research Project (Mn/ROAD) were used to estimate the number of allowable loads for each structural cross section based on the strain data obtained from WESLEA for Windows. The number of allowable loads, by test section, season and year are listed in Appendix A. The transfer functions for fatigue and rutting life are as follows:

$$N_f = 2.83 \cdot 10^{-6} \left(\frac{10^6}{\varepsilon_t} \right)^{3.206} \tag{1}$$

$$N_r = 5.5 \cdot 10^{15} \left(\frac{1}{\varepsilon_v} \right)^{3.929} \tag{2}$$

where: N_f = number of allowable load repetitions until fatigue failure (approximately 10% of area fatigue cracked)

N_r = number of allowable load repetitions until rutting failure (0.5 inch rut depth)

ε_t = maximum tensile microstrain at bottom of asphalt concrete layer

ε_v = maximum compressive microstrain at top of subgrade layer

Calculate Damage Factors Using Miner's Hypothesis

Using Miner's hypothesis, which is a damage function that accounts for the cumulative effects of traffic-related pavement damage, it was possible to determine damage factors for each structural profile. The equation representing Miner's hypothesis is:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \tag{3}$$

where: D = damage factor

n_i = number of actual repeated loads in season i

N_i = number of allowable loads before fatigue or rutting failure in season i

i = Season, 1 through 5

By definition, when D exceeds unity, failure has occurred. When D is less than unity, then the pavement structure has sufficient capacity to withstand the given traffic level. The damage factors for each test section, by season and year, are listed in Appendix A.

M-E AND OBSERVED PERFORMANCE COMPARISON

A primary objective of this study was to assess whether the current pavement performance models accurately predict field performance. To this end, the damage factors obtained in the M-E analysis were compared to measured distress on the nine test sections. The comparison process and results are presented below for rutting and fatigue cracking performance, respectively.

Rutting Performance

Rut depth measurements from the nine sections were used to classify rutting distress as low, medium or high severity with corresponding rankings of 1, 2 or 3, respectively. Rutting damage factors, as calculated in the M-E analysis, were classified in the same manner. Table 20 lists the classification system.

Table 20. Rutting Classifications.

Severity	Rank	Measured Rut Depth (in.)	Simulated Damage Factor
Low	1	< 0.25	< 0.5
Medium	2	0.25 - 0.5	0.5-1.0
High	3	> 0.5	> 1.0

For each pavement profile, the rut depth and damage factors were determined and assigned a rank according to Table 20. The *measured* rank was then subtracted from the *predicted* rank to give an indication of the conservative or un-conservative nature of the M-E simulation. For example, if a section had a measured rut depth of 0.2 inches (Rank=1) and the simulated damage factor was 0.65 (Rank 2), the result would be +1.0, or a conservative prediction. In other words, the M-E simulation predicted more rutting than was observed. Table 21 lists the possible outcomes of this ranking system and their interpretations.

Table 21. Possible Comparison Outcomes and Interpretation.

Outcome	Interpretation
+2.0	Very Conservative Prediction
+1.0	Conservative Prediction
0	Accurate Prediction
-1.0	Un-conservative Prediction
-2.0	Very Un-conservative Prediction

Figure 2 illustrates the rutting comparisons for all of the test sections. The following observations are made with respect to the graph:

1. Most predictions were on the conservative side, only one prediction was un-conservative.
2. Only four of the seventeen predictions were very conservative, while six were rated as accurate.
3. The majority of predictions were either off by a ranking of one or were rated as accurate.

Based on these observations, it may be stated that the rutting performance transfer function provides somewhat conservative estimates of rutting, yet not excessively so.

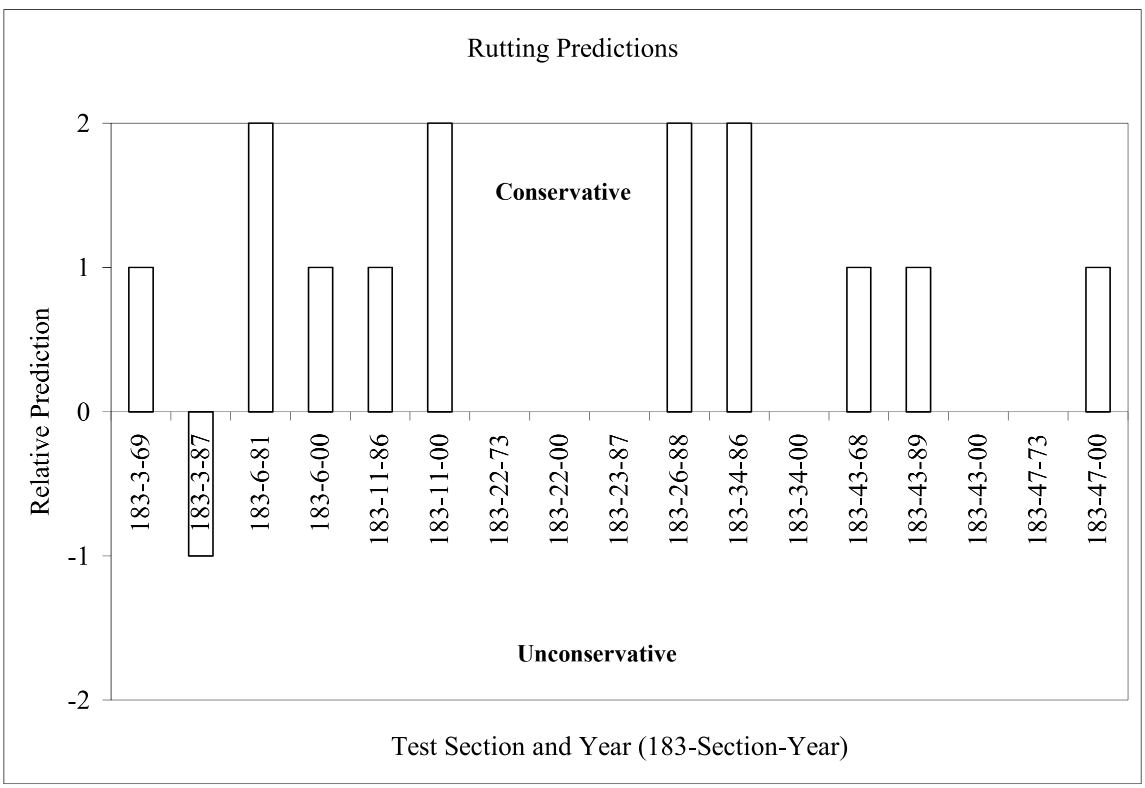


Figure 2. Rutting Performance Comparison.

Fatigue Performance

A similar procedure was used in comparing measured fatigue performance to that predicted in the M-E analysis. Table 22 lists the relative rankings for fatigue performance. Figure 3 illustrates the relative outcome and Table 21 may be used to interpret the results.

Table 22. Fatigue Cracking Classifications.

Severity	Rank	Measured Cracking ($ft^2/1000ft^2$)	Simulated Damage Factor
Low	1	< 50	< 0.5
Medium	2	50 - 100	0.5-1.0
High	3	> 100	> 1.0

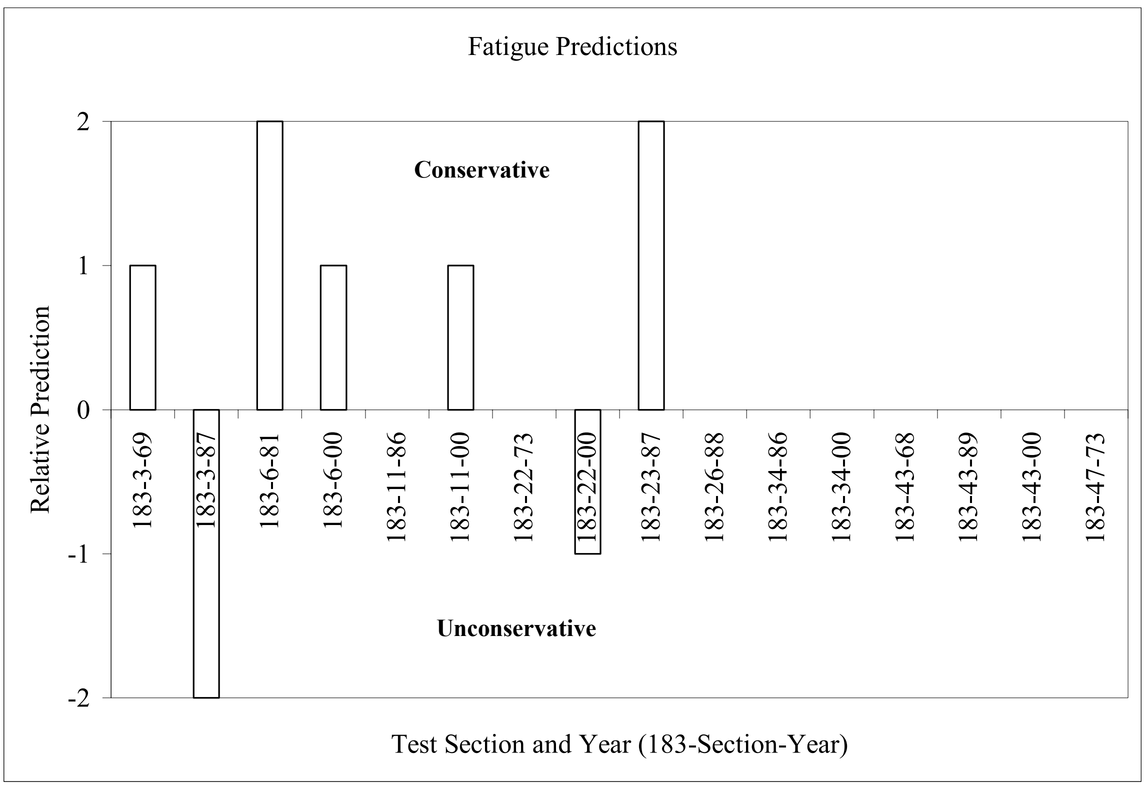


Figure 3. Fatigue Performance Comparison.

With respect to Figure 3, the following observations may be made:

1. Nine of the sixteen predictions were found to be accurate.
2. The remaining predictions tended to the conservative side, with two very conservative predictions.

3. Only two un-conservative predictions were made, one being very un-conservative.

Based on these observations it may be stated that the current fatigue prediction equation provides reasonable estimates with respect to fatigue performance.

CONCLUSIONS AND RECOMMENDATIONS

Based on the data presented in this investigation, the following conclusions may be drawn:

1. The data from Investigation 183 and 195 are sufficient and accessible enough to execute an M-E validation/calibration procedure as described in this report. As there are 41 additional sections, it is recommended that the validation/calibration procedure continue to widen the data set even further.
2. The comparison between predicted and observed rutting performance did not indicate a need to alter the rutting performance equation at this time. However, as more test sections are added to the calibration database, a modification may be necessary.
3. Likewise, the comparison between predicted and observed fatigue cracking did not warrant a change to the current transfer function. As more sections are added, it may need to be modified.

REFERENCES

1. Timm, D.H., David E. Newcomb and Theodore V. Galambos, "Incorporation of Reliability into Mechanistic-Empirical Pavement Design," Transportation Research Record, Transportation Research Board, Washington, D.C., 2000 (in press).
2. Timm, D.H., David E. Newcomb and Theodore V. Galambos, "Incorporation of Reliability into the Minnesota Mechanistic-Empirical Pavement Design Method," Final Report, MN/RC-1999-35, Minnesota Department of Transportation, St. Paul, MN, 1999.
3. Timm, D.H., David E. Newcomb and Bjorn Birgisson, "Development of Mechanistic-Empirical Design for Minnesota," Transportation Research Record No. 1629, Transportation Research Board, Washington, D.C., 1998, pp. 181-188.
4. Timm, D.H., D.E. Newcomb and B. Birgisson, "Mechanistic-Empirical Flexible Pavement Thickness Design: The Minnesota Method," Staff Paper, MN/RC-P99-10, Minnesota Department of Transportation, St. Paul, MN, 1999.
5. Kersten, M.S. and Skok, E.L., "Application of AASHO Road Test Results to Design of Flexible Pavements in Minnesota," MHD Investigation 183, Interim Report, University of Minnesota, 1968.
6. Lukanen, E.O., "Evaluation of Full-Depth Asphalt Pavements," Investigation No. 195, Interim Report, Minnesota Department of Transportation, 1977.
7. Lukanen, E.O., "Application of AASHO Road Test Results to Design of Flexible Pavements in Minnesota," Investigation No. 183, Report No. FHWA-MN-80-09, Minnesota Department of Transportation, 1980.
8. Ovik, J.M., "Characterizing Seasonal Variations in Pavement Material Properties for Use in a Mechanistic-Empirical Design Procedure," M.S. Thesis, University of Minnesota, 1998.
9. AASHTO Guide for Design of Pavement Structures, American Association of State Highway and Transportation Officials, Washington, D.C., 1993.

APPENDIX B

VEHICLE CLASSIFICATION FIELD GUIDE FOR LOW VOLUME ROADS

Task 2

Traffic Supplement to the Low Volume Road Best Practices Manual

INTRODUCTION

The purpose of this field guide is to give specific directions in setting up and performing a vehicle classification study on low volume roads. This guide is limited to setting up a study on a two-lane, two-direction roadway. The instructions contain provisions for a one or two data collection unit study, depending on traffic volume.

EQUIPMENT LIST

- 1 or 2 Timemark Lambda vehicle classification data collection unit (sometimes referred to as “boxes”), depending on traffic volume
- 2 pneumatic air tubes capable of spanning entire pavement width and connecting to the data collection unit.
- 4 metal stakes
- 4 anchoring brackets
- Chain(s) and lock(s)
- Sidewalk chalk
- Tape measure (capable of measuring 16 ft)
- Mallet
- Gloves to protect hands during installation and removal of equipment
- Asphalt backed roofing tape, 2” or 4” wide, available from Mn/DOT district traffic engineers

EQUIPMENT POSITIONING

Once a roadway has been selected for a classification study, it is important to consider the following factors in placing the air tubes:

- Vehicles should cross tubes in a perpendicular fashion. Avoid placing tubes on curves or in turns.
- Vehicles should cross the tubes at uniform speeds. Avoid placing tubes in zones where acceleration or deceleration is common (e.g., near stop signs or turns).
- The tubes should be placed flat against the pavement. Avoid placing tubes where curbs will prevent tubes from lying flat.
- The data collection unit should be locked to a signpost or other roadside stationary object.
- When traffic volumes exceed 3,000 AADT, it is recommended that a two-box setup be used. Otherwise one box will suffice.

EQUIPMENT SET UP

CAUTION: When working in an area that is under live traffic, exercise extreme caution. Flashing lights on vehicles, fluorescent vests and hats are required.

1. Cut eight 10” strips of roofing tape.

2. Warm up the roofing tape. On a warm day (above 55^{o}F), this may not be necessary. Otherwise, place the tape near a car heater.

3. Unravel the pneumatic hoses and lay them side by side parallel to the roadway.
   A. One-box setup: 60-ft hoses are used. These hoses are clamped at one end.
   B. Two-box setup: 75-ft hose are used. These hoses are free at both ends and have a stopper in the middle so that data may be collected independently in each lane.

4. Check the hoses for any obvious holes or splits which could affect the ability to collect data.

5. Anchor one end of hose.
   It is important that the hoses be of identical length so that the air pulse takes the same amount of time to travel down both tubes to the data collection box. The length can be adjusted by moving the anchor at the free end so that the hoses have equivalent length.
   A. <u>One-box setup</u>: Using mallet and stake, anchor the clamped end of one tube to the side of the roadway opposite from where the data collection unit will be placed.
   B. <u>Two-box setup</u>: Anchor one end of one tube to the side of the roadway near an anchoring device where the box will be placed.

6. Stretch the staked hose, perpendicular to the centerline, to the other side of the roadway. Stretch the hose about 10% of its length. For example, a 40-foot section of hose, unstretched, should be stretched about 4 ft.

7. Anchor other end of hose.
   A. <u>One-box setup</u>: Using mallet and stake, anchor the free end of the stretched tube.
   B. <u>Two-box setup</u>: Using mallet and stake, anchor the other end of the stretched tube. Be sure that the stopper in the hose is near the centerline of the pavement.

8. Check that the staked tube is perpendicular to the centerline.

9. Using the chalk, make three marks adjacent to the staked tube. These marks should be spaced evenly across the pavement.

10. Using the tape measure and chalk, make three parallel marks 16 ft from the first set of marks.

11. Place the second hose on top of the second set of marks.
    A. One-box setup: Stake the clamped end on the same side of the roadway as the first tube.
    B. Two-box setup: Stake one of the free ends on the side of the roadway.
12. Stretch the second hose about 10% (see step 2) and stake to the other side of the road.

13. Place the data collection unit(s).
    A. One-box setup: Place the data collection unit near the anchoring device (e.g., signpost).
    B. Two-box setup: Place the data collection units near the anchoring devices (e.g., signposts).

14. Connect the tubes to the data collection unit.
    A. One-box setup: Tube A should be the most northbound or eastbound direction. Tube B should be the most southbound or westbound direction.
    B. Two-box setup: Tube A should be the tube that is hit first by oncoming traffic. Tube B should be the tube hit second by oncoming traffic.

15. Continue with software setup.

SOFTWARE SETUP

Figure 1 illustrates the inside of the Timemark Lambda data collection unit. Note that the [Select] button will move between different options (indicated by flashing text) in a particular menu, while the [Enter] button will choose the option and go on to the next menu.

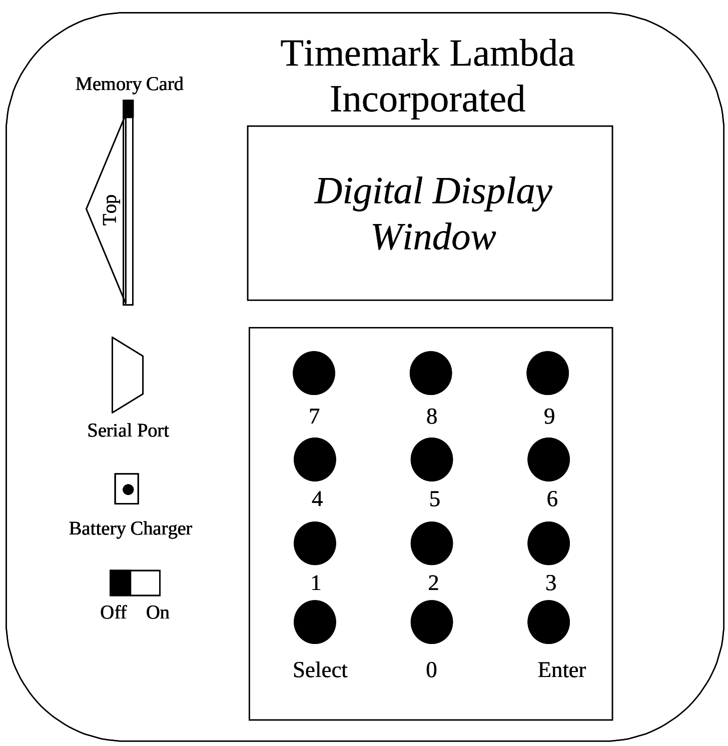


Figure 1 Data Collection Unit Controls and Display

For a one-box setup, follow these instruction exactly. For a two-box setup, follow the directions for each box.

1. Decide on Data Storage: Decide whether to use the data collection unit's internal memory or a data card to record the vehicle hits during the study. If the study will not exceed 25,000 vehicles, then the data collection unit's internal memory is sufficient. If the study will exceed 25,000 vehicles, then a data card should be used. If you decide to use a data card, insert one into the memory card slot as shown in Figure 1.

2. Turn on the data collection unit: An introductory screen will appear displaying the software version number. The screen will then proceed to *Main Menu* automatically.

3. Choose *Memory Manager*: Under the *Main Menu*, the following options appear:
   Record a New Study
   Monitor Traffic
   Memory Manager
   Use the [Select] button, if necessary, to make *Memory Manager* flash. Then press [Enter]. Select the option to clear the memory and return to the main menu. **NOTE:** Clearing the memory will erase all previously recorded data. Be sure that previously recorded data has been saved elsewhere or has already been processed.

4. Choose *Record a New Study*: Under the *Main Menu*, the following options appear:
   Record a New Study
   Monitor Traffic
   Memory Manager
   Use the [Select] button, if necessary, to make *Record a New Study* flash. Then press [Enter]. The *Tubes: Raw Data* menu will now appear.

5. Choose *Select a New Study*: Under the *Tubes: Raw Data* menu, the following options appear:
   Start Recording Now
   Set Start/Stop Times
   Select a New Study
   Use the [Select] button, if necessary, to make *Select a New Study* flash. Then press [Enter]. The *Enter Site Code* screen will now appear.

6. Enter the 12-digit filename using the following guide:
   Digits 1-4 = site number (each county has been assigned a range of numbers, refer to the end of the field guide for the appropriate number)
   Digit 5 = number of boxes used in study (typically 1 or 2)
   Digit 6 = direction of traffic in primary direction. This is the direction of traffic crossing Tube A first. Refer to Figure 2 for directional numbers.
   Digit 7 = lane number for primary direction (1 = Driving, 2 = Passing)
   Digits 8-9 = route system
   01=Interstate

02=US Hwy
03=MNTH
04=CSAH
05=MASS
07=County Road
08=Township Road
09=Unorganized Township Road
10=City St.

Digits 10-12 = route number

Once the data filename has been input, press [Enter] and the *Study Type Menu* will appear.

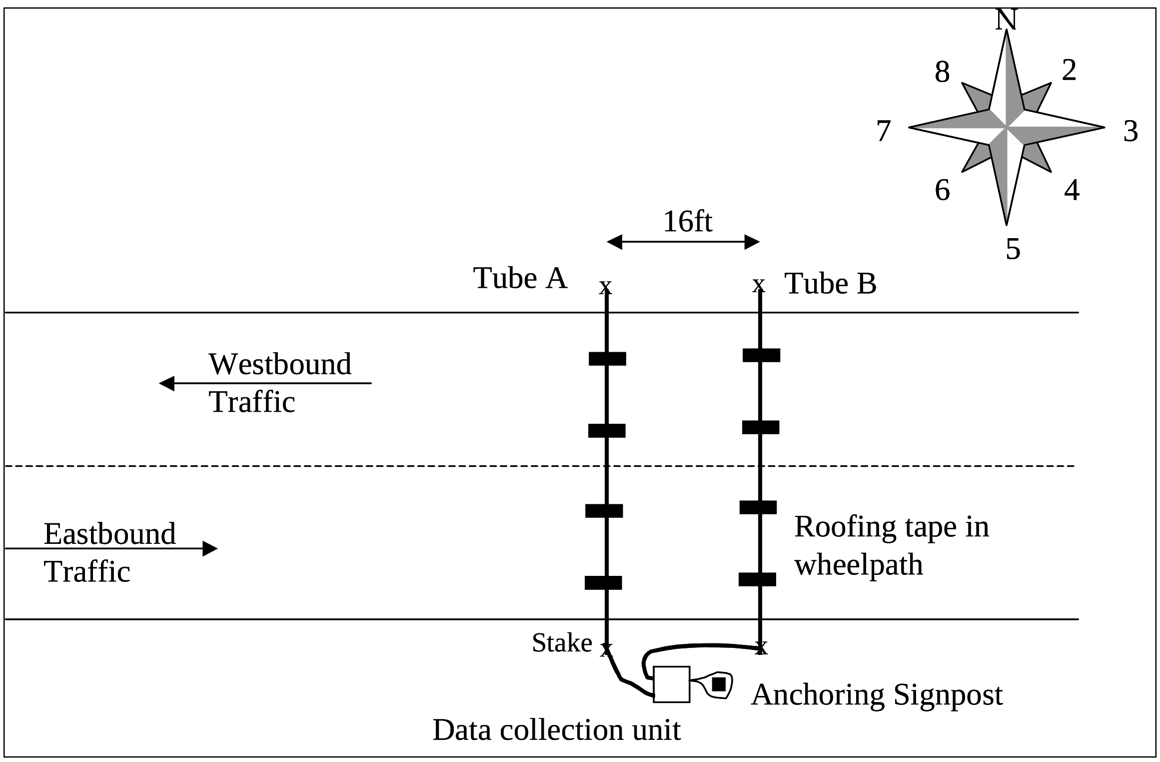


Figure 2 Final Setup (One-Box)

7. Choose *Raw Data*: Under the *Study Type Menu* the following options appear:
   Raw Data
   Volume
   Speed
   Use the [Select] button, if necessary, to make *Raw Data* flash. Then press [Enter]. The *Sensor Type Menu* will appear.

8. Choose *Road Tubes*: Under the *Sensor Type Menu* the following options appear:
   Road Tubes

Piezos Only
Loops Only
Use the [Select] button, if necessary, to make *Road Tubes* flash. Then press [Enter]. The *Sensor Layout Menu* will appear.

9. Choose *A/B, C/D Spaced*: Under the *Sensor Layout Menu* the following options appear:
   A,B,C,D
   A/B, C/D Spaced
   Use the [Select] button, if necessary, to make *A/B, C/D Spaced* flash. Then press [Enter]. The *Select Spacing Type* menu will appear.

10. Choose *Set Universal Value*: Under the *Select Spacing Type* menu the following options appear:
    Set Universal Value
    Set Individual Lanes
    Use the [Select] button, if necessary, to make *Set Universal Value* flash. Then press [Enter]. The *Enter Sensor Spacing* screen will appear.

11. Enter 16-ft Spacing: On the *Enter Sensor Spacing* screen input 16-ft sensor spacing, this value will usually be there by default. Once '16' has been input, press [Enter]. The *Tubes: Raw Data* menu will appear.

12. Choose *Start Recording Now*: Under the *Tubes: Raw Data* menu, the following options appear:
    Start Recording Now
    Set Start/Stop Times
    Select a New Study
    Use the [Select] button, if necessary, to make *Start Recording Now* flash. Then press [Enter]. The data collection screen will now appear. The data collection screen contains a table as shown below:

Raw Tube	Time	Lane: 1
A:	0	TA
B:	0	TB

The middle column contains the number of total hits on each of the two tubes, A and B.

13. Verify that the System is Operational: Check that the tubes are recording hits, either by vehicles or by stepping forcefully on one of the tubes. If hits are not being recorded, there may be a problem with the connection of the tubes to the data collection unit or a tube may be damaged. The equipment and connections may need to be inspected. If hits are being recorded, continue with final setup.

FINAL SETUP

1. Make sure tubes are aligned with chalk marks. Adjust if necessary.
2. Using pre-cut, warm strips of tape, secure tubes in each of the wheelpaths.
3. Check that collection unit is still registering hits. If necessary, even the number of hits between each tube.
4. Close box and chain to anchoring device.

The final one-box setup is pictured in Figure 2. A two-box setup is shown in Figure 3.

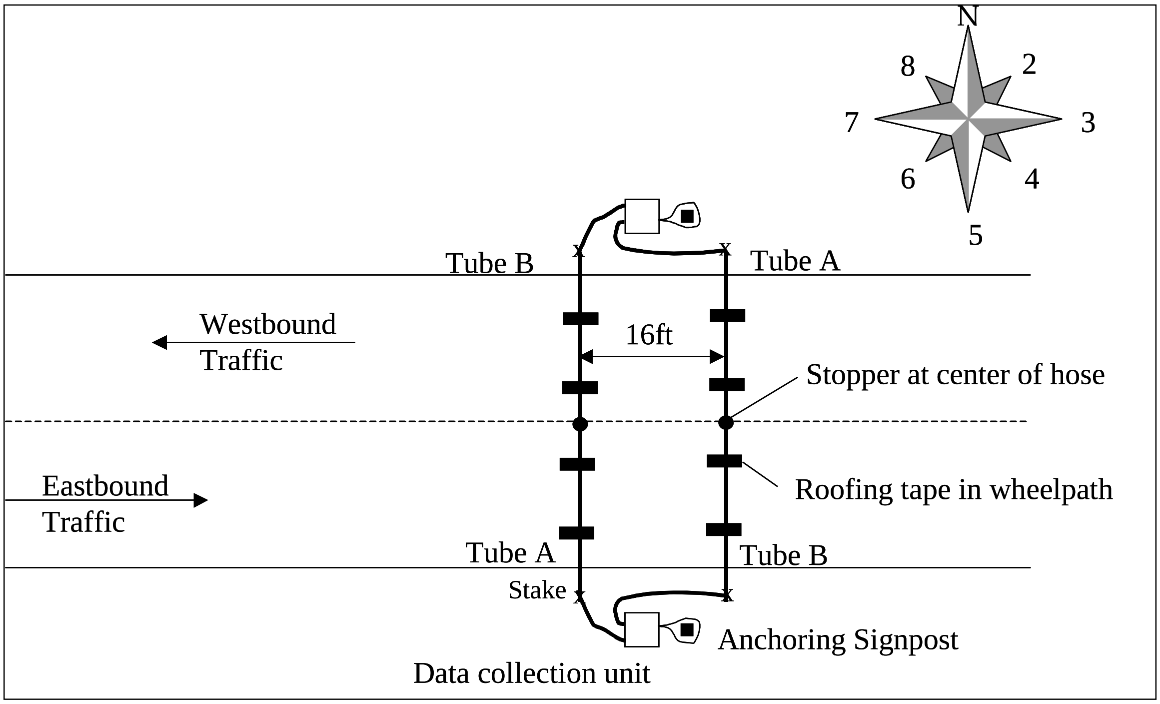


Figure 3 Final Setup (Two-Box)

LENGTH OF STUDY

The duration of the study is influenced by several factors.

1. <u>Capacity of data collection unit:</u> Each unit may store up to 25,000 vehicles over the duration of the study. In most low volume road cases, this number will not be exceeded. For higher volume (>3,000 AADT) two boxes or data cards should be used to handle the increased traffic volume.

2. <u>Traffic Volume:</u> To get an accurate classification of vehicles, it is important to collect enough data. A minimum of 48 hours should be collected. However, on lower volume roads it may be necessary to collect up to a week's worth of data. Judgement should be exercised in deciding on the length of the study. A Mn/DOT traffic engineer may be contacted for further guidance.

AFTER THE STUDY

1. Open the data collection unit and verify that data were collected and that it is still operating.
2. Manually record the number of hits on each tube. This serves as a crude backup in case the data are lost.
3. Shut off the unit.
4. If a flash card was used to record data during the study, the data have already been saved to the disk. The disk can now be removed for analysis later. If not, insert a flash card in the disk drive of the data collection unit.
5. Turn on the data collection unit and the new study will automatically be transferred to disk. After data have been transferred, remove the disk for analysis later.
6. Label the disk with the 12-digit number used to specify the study.
7. Remove equipment from roadside and roadway.
   CAUTION: When working in an area that is under live traffic, exercise extreme caution. Flashing lights on vehicles, fluorescent vests and hats are required.

8. The labeled disks may be sent to the Traffic Division of Mn/DOT's Office of Data Management Services for analysis. Send to:

   Melissa Thomatz
   Transportation Data Section
   Office of Transportation Data and Analysis
   Mailstop 450
   Minnesota Department of Transportation
   395 John Ireland Blvd.
   St Paul, MN 55155

   Alternatively, the data files may be emailed to Melissa Thomatz at:
   melissa.thomatz@dot.state.mn.us

IMPORTANT NOTES

1. The air hoses have an approximate life span of 2 years. They will not collect data if punctured.
2. The batteries in the data collection units typically last one month without recharging. They can be recharged overnight.
3. On the newer Timemark units, there is a power saver feature that shuts off the screen if no buttons are pushed after a period of time. However, the unit will still collect data. To reactivate the screen, press [Enter]. The screens on the older units will remain on as long as the unit is on.
4. For further assistance on running a vehicle classification study, the following people are available for contact:

Rod Heuer: rod.heuer@dot.state.mn.us
Tom Nelson: tom.nelson@dot.state.mn.us
651-297-1194

ASSIGNED COUNTY COUNT NUMBERS

COUNTY	SITE CODES	COUNTY	SITE CODES
AITKIN	4001-4025	MARSHALL	5451-5475
ANOKA	4026-4075	MARTIN	5476-5500
BECKER	4076-4110	MEEKER	5501-5525
BELTRAMI	4111-4150	MILLE LACS	5526-5550
BENTON	4151-4200	MORRISON	5551-5600
BIG STONE	4201-4225	MOWER	5601-5650
BLUE EARTH	4226-4275	MURRAY	5651-5675
BROWN	4276-4300	NICOLLET	5676-5700
CARLTON	4301-4325	NOBLES	5701-5725
CARVER	4326-4375	NORMAN	5726-5750
CASS	4376-4400	OLMSTED	5751-5800
CHIPPEWA	4401-4425	OTTER TAIL	5801-5850
CHISAGO	4426-4475	PENNINGTON	5851-5875
CLAY	4476-4525	PINE	5876-5900
CLEARWATER	4526-4550	PIPESTONE	5901-5925
COOK	4551-4575	POLK	5926-5975
COTTONWOOD	4576-4600	POPE	5976-6000
CROW WING	4601-4650	RAMSEY	6001-6025
DAKOTA	4651-4700	RED LAKE	6026-6050
DODGE	4701-4725	REDWOOD	6051-6075
DOUGLAS	4726-4750	RENVILLE	6076-6100
FARIBAULT	4751-4775	RICE	6101-6125
FILLMORE	4776-4800	ROCK	6126-6150
FREEBORN	4801-4825	ROSEAU	6151-6175
GOODHUE	4826-4875	ST. LOUIS	6176-6225
GRANT	4876-4900	SCOTT	6226-6275
HENNEPIN	4900-4925	SHERBURNE	6276-6300
HOUSTON	4926-4950	SIBLEY	6301-6325
HUBBARD	4951-4975	STEARNS	6326-6375
ISANTI	4976-5000	STEELE	6376-6400
ITASCA	5001-5050	STEVENS	6401-6425
JACKSON	5051-5075	SWIFT	6425-6450
KANABEC	5076-5100	TODD	6451-6475
KANDIYOHI	5101-5150	TRAVERSE	6476-6500
KITTSON	5151-5175	WABASHA	6501-6525
KOOCHICHING	5176-5225	WADENA	6526-6550
LAC QUI PARLE	5226-5250	WASECA	6551-6575
LAKE	5251-5275	WASHINGTON	6576-6625
LAKE OF THE WOODS	5276-5300	WATONWAN	6626-6650
LeSUEUR	5301-5325	WILKIN	6651-6675
LINCOLN	5326-5350	WINONA	6676-6725
LYON	5351-5400	WRIGHT	6726-6800
McLEOD	5401-5425	YELLOW MEDICINE	6801-6825
MAHNOMEN	5426-5450		

Note: If the numbers for your county are insufficient, contact Tom Nelson or Rod Heuer at Mn/DOT for additional site codes.