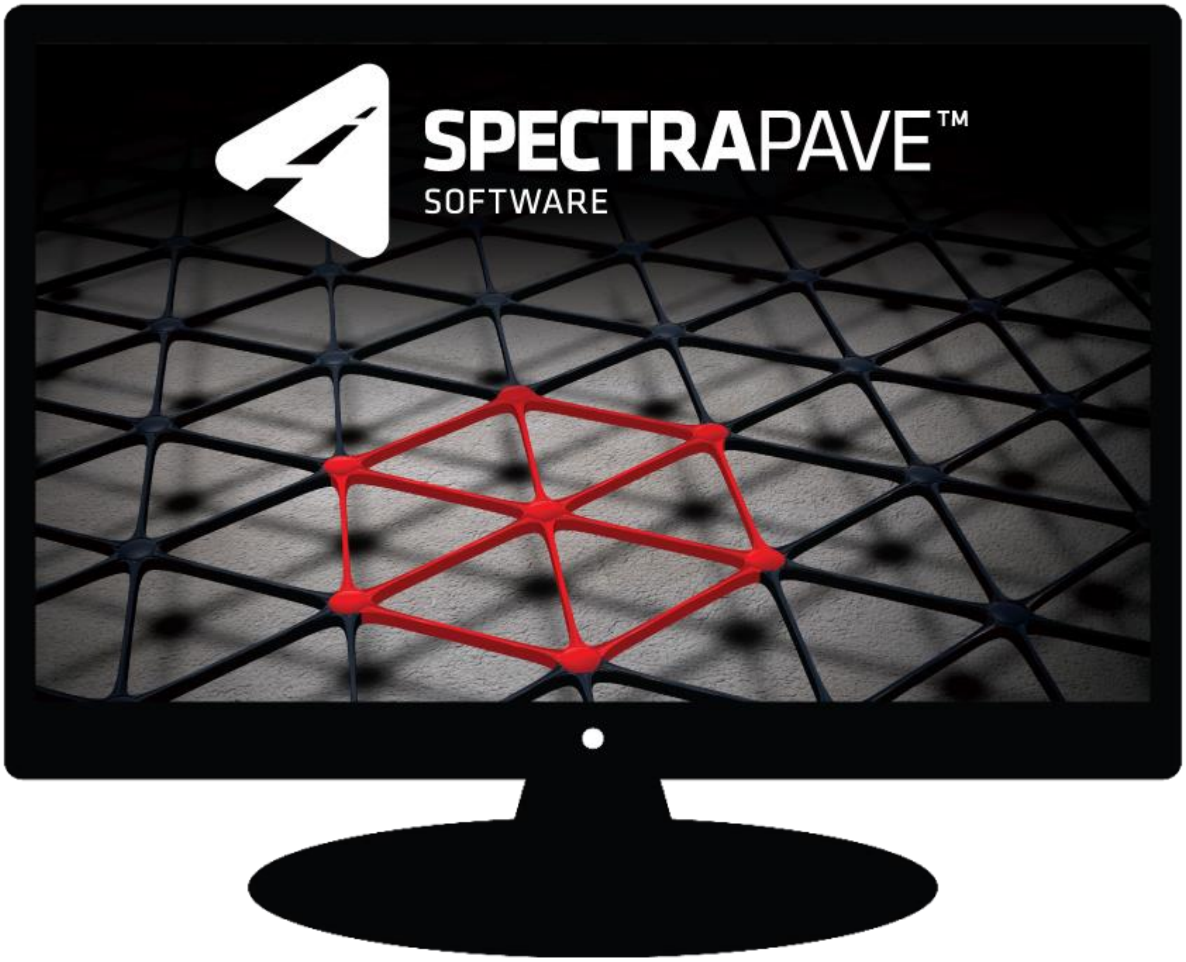

SpectraPave™ Software

User’s Manual –Version 4.7

February 2019

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SpectraPave™ Software - Version 4.7

Software for Subgrade Stabilization, Pavement Foundation Improvement, and Pavement Optimization Using Tensar TriAx® Geogrids

Overview

SpectraPave design software was developed by Tensar International Corporation, Inc. (TIC) for the analysis and design of unpaved and paved pavements, allowing for the consideration of a broad range of conditions. Besides, the design of temporary stone-surfaced haul and access roads, as well as permanent hard-surfaced highways and parking lots, can be investigated for various conditions using this software.

SpectraPave contains design modules for Subgrade Stabilization, Pavement Foundation Improvement and Pavement Optimization, along with a separate module for the input of user- and project-specific information. An overview of the software, its intended application and the operation of each module are outlined within this manual. Further details on the theoretical background of the software are available in the following sections.

Project Information Module

The Project Information module allows the user to input user- and project-specific information for individualized calculations. It is divided into Project name, Designer name and date. It can be activated at any time from the main menu (project info button) or, prior to printing designs and specifications, the user will be automatically prompted to enter the information. The users' company logo can be saved for future runs.

Subgrade Stabilization Module

The Subgrade Stabilization module is primarily intended for the design of both unpaved roads and working platforms atop underlying weak soils. It is also used in the design of lower sections of permanent roads, particularly where soft subgrades prevail, to assess constructability. The Subgrade Stabilization module consists of Design and Cost Analysis sub-modules.

Design Analysis Sub-Module

The Design Analysis sub-module for Subgrade Stabilization facilitates the design of unbound aggregate layers using the state-of-the-art Giroud-Han method (Giroud and Han, 2004a, b). The method determines the minimum aggregate thickness required to support wheel loads on the surface and prevent bearing failure and/or excessive deformation of the subgrade. It can be used to construct conventional unstabilized unpaved surfaces and those stabilized with TIC TriAx geogrids.

Cost Analysis Sub-Module

The Cost Analysis sub-module allows the user to investigate the benefits of different Subgrade Stabilization solutions utilizing TIC TriAx geogrids.

Pavement Foundation Improvement Module

The Pavement Foundation Improvement module is intended for the design of mechanically Stabilized Pavement Foundation layer for both flexible and rigid pavement. The benefit of using Tensar TriAx Geogrids to stabilize pavement foundation can be evaluated in terms of resulting resilient modulus of the stabilized foundation.

Pavement Optimization Module

The Pavement Optimization module is intended for the design of flexible pavements in accordance with AASHTO's Guide for Design of Pavement Structures and its Standard R50-09: "*Recommended Practice for Geosynthetic Reinforcement of the Aggregate Base Course of Flexible Pavement Structures"* (2010). The benefit of using Tensar TriAx Geogrids to stabilize unbound aggregate layers within flexible pavements is considered by incremental layer coefficients and extending pavement life and/or reducing aggregate base thickness. Further, the benefit can be evaluated in terms of cost savings, fuel saving, Dump Truck trip reduction, water savings and more.

Subgrade Stabilization Analysis

Theoretical Background

In Subgrade Stabilization where the subgrade is unable to adequately support traffic loads, geosynthetic reinforcement can be placed at the aggregate and subgrade interface to improve pavement performance by decreasing the load distributed on the subgrade. As a result, an equivalent stabilized road section thickness yields an increased allowable traffic load as compared to the unstabilized road section. The use of geogrid reinforcement allows a reduction in the aggregate layer thickness when compared to an unstabilized unpaved road. In some cases, the reinforcement is included in the pavement to permit the use of an inferior quality fill material (recycled fill, material containing excess fines, etc.) without a loss in performance.

Geogrids and geotextiles are geosynthetic materials that have been used successfully to improve the performance and increase the design life of unpaved roads and trafficked areas since the 1970s. Non-woven geotextiles have been efficient in applications that require the separation of aggregate layers from the underlying subgrade soil. Geogrids and woven geotextiles have been used as reinforcement tools to increase the resistance of road sections to traffic loading (Giroud and Noiray 1981). In laboratory and field studies, geogrids have consistently demonstrated superior performance. This performance is attributed to the efficient transfer mechanism of tensile stresses, because of the mechanical interlock between the geogrid and aggregate materials (Giroud et al. 1985; Fannin and Sigurdsson 1996).

For unpaved structures reinforced with geotextiles, Giroud and Noiray (1981) developed a design method using limited field data. Since it did not take into account the mechanism of interlocking aggregate particles within the geogrid apertures, it was not suitable for unpaved structures reinforced with geogrids. Later, Giroud et al. (1985) developed a design method for geogrid-reinforced unpaved structures with the aid of numerical elastic analyses. However, no field test data was available for verification at that time. Older methods such as the ‘US Forest Service Method’ (Steward et al. 1977), and adaptations thereafter, (see Tensar 1998) have also been used successfully in the past. These methods do not directly quantify the anticipated rut depth, difference in performance for various types of geosynthetics or changes in pavement performance for traffic loadings exceeding 1000 passes. In addition, the method prescribed by Steward et al. (1977), and subsequent methods based on the same general approach, involve the use of very high-quality aggregate (i.e. CBR not less than 80% after compaction). Achieving such a high CBR value over very soft soils is extremely difficult to achieve in the field.

Recent field and laboratory test data (Fannin and Sigurdsson 1996; Knapton and Austin 1996; Webster 2000; Gabr 2001) provided a basis for the development of the Giroud-Han method (Giroud and Han 2004) - a more rational design method for geogrid-stabilized unpaved structures. It enables the user to quantify key design parameters, specify lower quality fill material and consequently, the approach is more practical and provides the user with maximum flexibility in designing unpaved structures.

The Giroud-Han Method

The Giroud-Han (G-H) method (Giroud and Han 2004), utilized in SpectraPave, represents the next generation of the Subgrade Stabilization design methods. It supersedes previously developed methods by Giroud and Noiray (1981) and Giroud et al. (1985) for roads reinforced with geosynthetics. It was developed for geogrid-stabilized unpaved roads, but with appropriate values for relevant parameters, it can be used for the design of geosynthetic-reinforced or unreinforced unpaved roads.

A unique feature of the G-H method is its ability to take into account the effects of mechanical interlock of aggregate particles within geogrid apertures. A better understanding of the interaction between the geogrid and the aggregate layer material was gained through several significant research projects including some studies where geogrids were used for the reinforcement of paved roads (Webster 1992; Collin et al. 1996; Perkins 1999). These studies show significant differences in the performance of geosynthetics that have unique properties. For instance, the aperture stability modulus of Tensar Biaxial geogrids, in particular, has been shown to provide a good correlation with measured field performance (Webster 1992; Collin et al. 1996). The aperture stability modulus is measured using a test developed by Dr. Thomas A. Kinney for the U.S. Army Corps of Engineers Waterways Experiment Station (WES) on behalf of the U.S. Department of Transportation – Federal Aviation Administration (FAA). It is important to note that for valid use and to ensure reliable results; the Giroud-Han method requires proper calibration for each specific type of geogrid under consideration.

The Giroud-Han method (Giroud and Han 2004) is based on bearing capacity theory calibrated through direct reference to field and laboratory test data, arriving at a rational design method that predicts the performance of unpaved roads more accurately. Due to the relationship between the aperture stability modulus and the documented performance of geogrid-reinforced pavements described above, the method includes the aperture stability modulus as one of its design parameters. Compared to other methods, it also considers the quality of aggregate material, variation of the stress distribution angle with the number of load cycles and influence of the maximum allowable rut depth (Giroud and Han 2004).

Limitations of the Giroud-Han Method

In theory, the Giroud-Han method is applicable for all geosynthetics in Subgrade Stabilization. However, it is important to note that the method has been rigorously validated for use with geotextiles and Tensar Biaxial (BX) Geogrids, within the limitations noted by the authors. More recently additional testing has been performed to validate and calibrate the G-H model with Tensar TriAx (TX) geogrids. No such validation exists for other geogrids whose properties or characteristics differ from those manufactured by TIC (e.g. multi-layer geogrids, welded strip geogrids, woven geogrids, etc.). With the growing use of the method and the increasing number of geogrid materials available, it is important to recognize the limitations of the application of the G-H method for products that have not been calibrated. To date, it is the understanding of Tensar International Corporation, that the method has been calibrated only for the Tensar Type 1 and Type 2 biaxial geogrids using the aperture stability modulus as the characteristic property of the geogrids. More recently, calibrations have been performed for Tensar's new TriAx series of geogrids. Any additional calibrations of the G-H model must be specific to a given product or to different grades of geogrids within the same family of products from the same manufacturer and of the same manufacturing type (i.e. same polymer, process and equipment) that was actually calibrated to the G-H model.

TriAx Geogrid Technology

Geogrid usage has evolved steadily since the technology was first introduced in the early 1980s. Tensar biaxial geogrids have gained widespread acceptance in the Americas over the last 25 years primarily as a solution to problems associated with pavements, haul roads and working surfaces constructed on soft or problematic subgrades. By examining all the design characteristics of the biaxial geogrids, through independent testing and research, the TIC product development team identified the key product parameters that affect its performance. These include the profile of the rib section, rib thickness, junction efficiency, aperture size and in-plane stiffness. The development effort yielded a revolutionary change from a rectangular to a triangular grid aperture. This fundamental change to the grid structure, coupled with an increase in rib thickness and junction efficiency, gives significantly improved aggregate confinement and interaction, leading to the improved structural performance of the mechanically stabilized layer. The new TriAx Geogrid outperforms the biaxial geogrid for the following reasons:

Load Distribution

- Vehicle load distribution is 3-dimensional and conical and therefore acts radially throughout the aggregate.
- For a stabilized layer to be effective, it must have the ability to distribute load through 360 degrees within the plane of the geosynthetic. To ensure optimum performance, the geogrid reinforcement in a Mechanically Stabilized Layer (MSL) should have a high radial stiffness throughout the full 360 degrees.

Junction Integrity

- TriAx evolves from an extruded sheet of polypropylene. The unique TriAx structure is the result of punching an array of holes and stretching the sheet to its final geometry. This punched and drawn process, originally developed by Tensar, coupled with the design of the junctions, results in a product with high junction strength and stiffness.

Junction Efficiency

- Rigorous testing has been conducted in line with each of the three rib directions. In each direction tested, the junction strength was found to be essentially equal to the rib strength - giving junction efficiency greater than 90%.

Multi-Directional Properties

- As the name implies, biaxial geogrids have tensile stiffness predominantly in two directions. TriAx geogrids exhibit three principal directions of stiffness, which is further enhanced by their rigid triangular geometry. This produces a significantly different structure than any other geogrid available on the market today and provides high strength 360-degree stiffness. A truly multi-axial product with near isotropic properties and proven multi-directional performance.

Proving the importance of rib profile

- TriAx geogrids have greater rib depth compared with conventional biaxial geogrids.
- Trafficking tests and analytical modeling techniques were undertaken to compare performance advantages between the two forms of geogrid with various rib depths. The results were conclusive in confirming that a much-improved structural performance of a mechanically stabilized layer was achieved with the TriAx geogrid and its deeper rib depth. In addition, numerical modeling techniques have been utilized to confirm the importance of geogrid rib thickness on aggregate confinement and load dissipation.

Design of Subgrade Stabilization with SpectraPave Software

Two unpaved design options are analyzed in SpectraPave by default for a given set of traffic and soil conditions - an unstabilized pavement and Tensar TriAx geogrid-stabilized section. Analysis based on the Giroud-Han method is undertaken by selecting the ‘Results’ tab in the Subgrade Stabilization module.

Traffic and soil condition data are required for the analysis of the default options of, an unstabilized and stabilized road section with various Geosynthetics including Tensar TriAx Geogrids (Figure 1). Help is available in the ‘Data Input’ window by way of pop-up messages that appear beneath the pavement cross-section when the cursor moves over the edit box or text associated with a particular design parameter. Additional assistance is also available for estimation of the field subgrade CBR by clicking the icon next to Design Subgrade. When the information icon is selected, the help is shown in a chart displayed within a separate window.

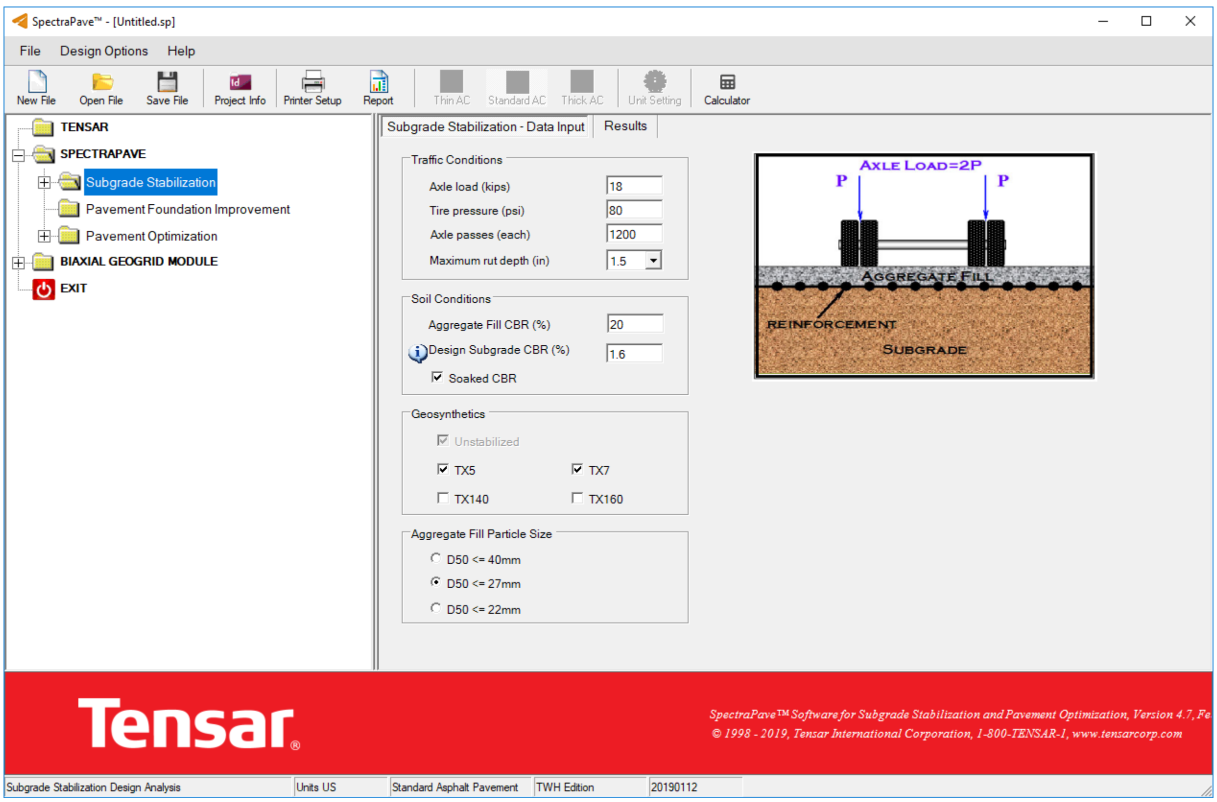


Figure 1: Subgrade Stabilization Analysis - Data Input Screen in SpectraPave Software

Mechanical Compatibility

When stabilizing aggregate layers, the FHWA (2008) recommends that the aperture size of the geogrid should be more than or equal to the average (D_{50}) particle size of the fill material placed in contact with the geogrid. SpectraPave takes this into consideration within the Data Input Screen, which is shown in Figure 1. The aggregate fill window is depicted as Figure 2. Within this window, the user is required to select grain size information regarding the aggregate placed on the geogrid. Once particle size is entered the software automatically selects a geogrid matching the D_{50} criteria.

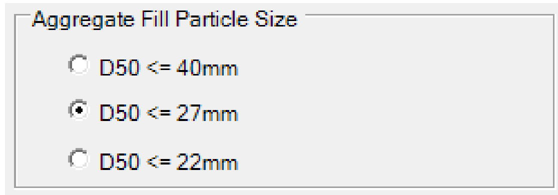


Figure 2: Aggregate Fill Particle Size Input Screen

Design Results

By selecting the ‘Results’ tab in the Subgrade Stabilization module, the aggregate thicknesses required for each of the pavement sections included in the analysis, along with the thickness savings relative to the unstabilized section, are calculated and presented in a table format within the ‘Results’ window (Figure 3). A graphic representation of the relation between the field subgrade CBR and required aggregate fill thickness for each design option is also provided for reference. Further analysis of the potential savings can be initiated by exporting the thickness data into the Cost Analysis sub-module using the button to the right of the table. Full details of this option are presented in the next section.

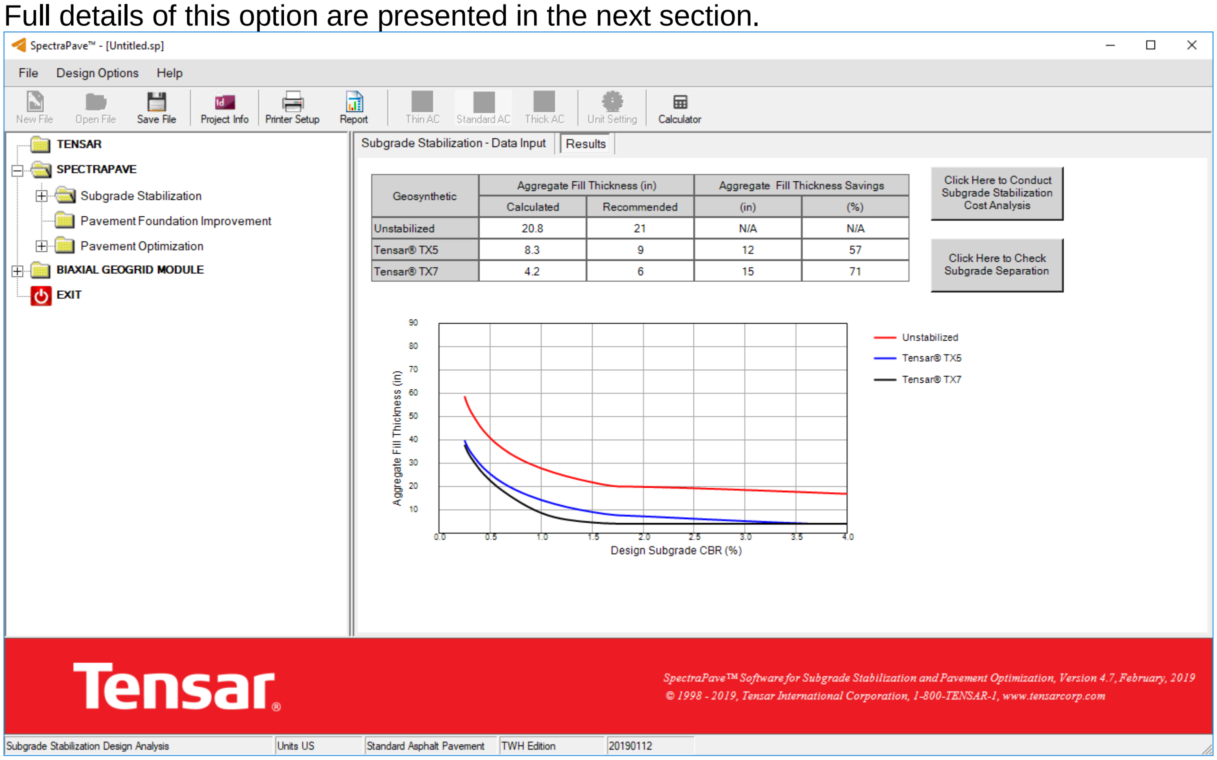


Figure 3: Subgrade Stabilization Analysis - Results Screen in SpectraPave Software

Subgrade Separation

As depicted within Figure 4 the user can also determine if a subgrade separation layer (filter) is required beneath the geogrid. The design of this layer is provided within the button on the right side of the Subgrade Stabilization Result window, which is shown in Figure 4. The filter analysis window is depicted as Figure 5. Within this window, the user is required to enter grain size information regarding the aggregate above and subgrade soils below the geogrid. Once entered the user must select the “Update Calculation” button to obtain results as to whether a geotextile is required in the design. Once updated the user needs to select the type of subgrade

(Clayey or Silty) within the Natural Filter Criteria box at the bottom of the screen. If a green check mark appears next to the subgrade type selected then a geotextile is not required for the design. If a red “x” is displayed the user either needs to input a different aggregate layer gradation (Natural filter design approach) or select the box the “Add Filter Fabric” to the design.

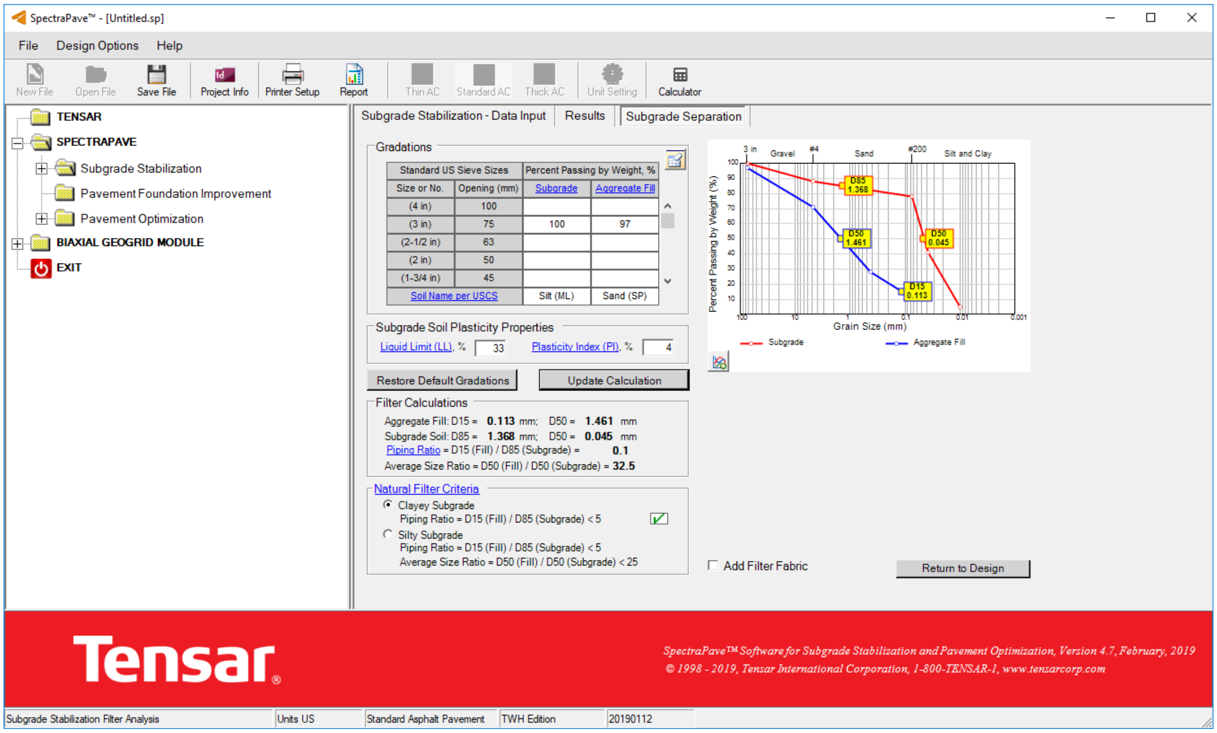


Figure 4: Subgrade Separation Module Analysis Screen

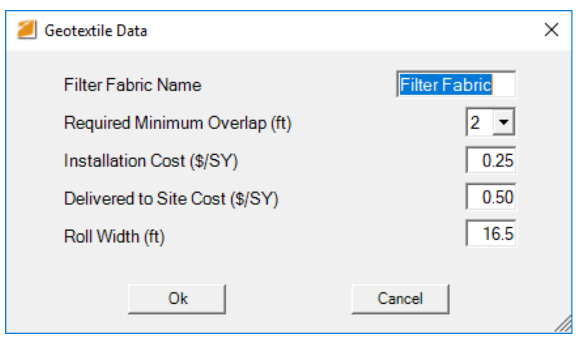


Figure 5: Geotextile Data Input Screen

If a geotextile is required the user needs to determine material costs and add those values to the geotextile data input screen, which is shown in Figure 5 so that this information can be added to the project cost as discussed in the Subgrade Stabilization Cost Analysis section of the manual.

Subgrade Stabilization Cost Analysis

The Cost Analysis feature in SpectraPave is available for use with the Subgrade Stabilization design (Figure 6). The Cost Analysis application can be accessed by selecting the Cost Analysis button on the ‘Results’ page in the Subgrade Stabilization module. The cost analysis input reflects the design results, by default. The existing thickness data for the unstabilized and Tensar TriAx geogrid-stabilized pavement sections are automatically transferred into the Cost Analysis Data Input window.

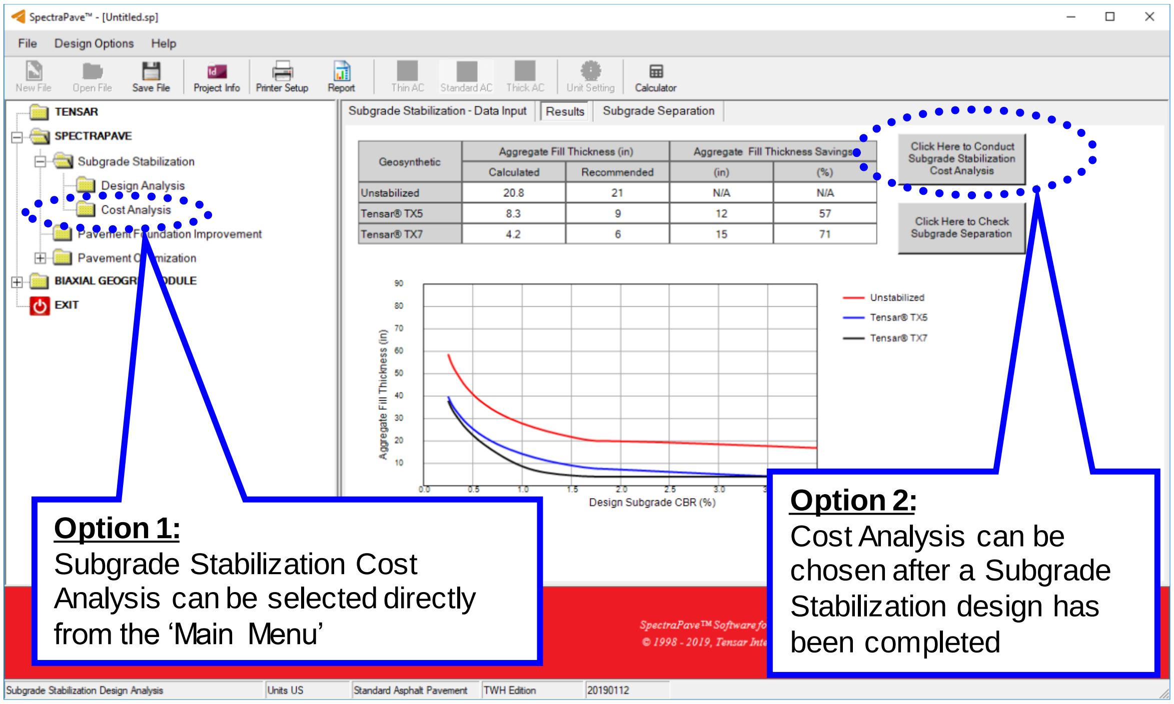


Figure 6: Subgrade Stabilization - Cost Analysis Options in SpectraPave Software

Cost Analysis Data Input

A series of panels for data entry in the Cost Analysis 'Data Input' window are briefly described below (Figure 7).

Project Size

The aggregate and geosynthetic quantities cost analysis is based on the overall project size defined by the length and width of the pavement being constructed.

Aggregate Fill Thickness

The 'Aggregate Fill Thickness' information is transferred automatically when the user selects the Cost Analysis button on the 'Results' page in the Subgrade Stabilization module. The user can change this thickness at any time, but then the cost analysis may not correspond to the Subgrade Stabilization design results. The user is cautioned against using a value lower than the design value transferred from the design section.

TriAx Geogrid Cost

Tensar TriAx geogrids cost varies on a regional basis depending on the quantities involved and other factors. For an accurate price estimate, it is recommended that the user contact their local Tensar geogrid supplier or Tensar representative. For information on Tensar geogrids and Tensar authorized distributors, please call 1-800-TENSAR-1.

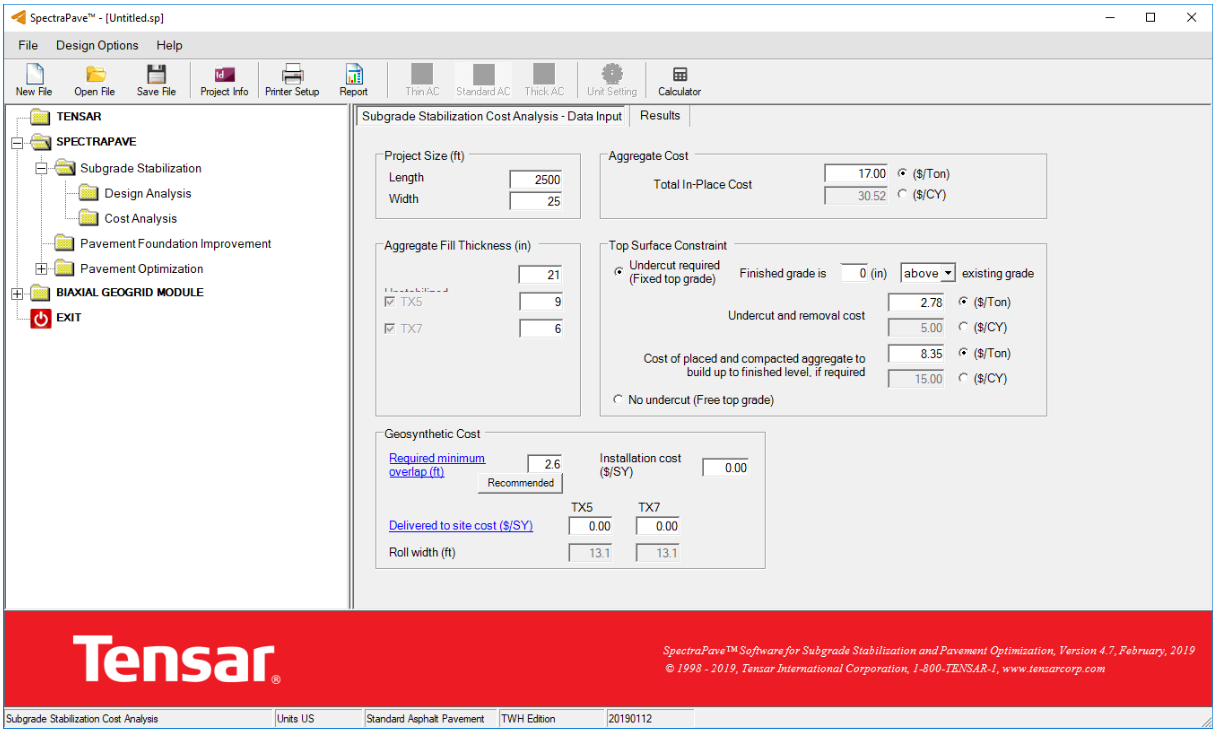


Figure 7: Subgrade Stabilization Cost Analysis - Data Input Screen in SpectraPave Software

In addition to the supply cost of the Tensar TriAx geogrids, the user is required to specify an installation cost. 'Required Minimum Overlap' is required to make an estimate of the material quantities. Tensar TriAx Geogrid is produced in 13.1 ft (4 m) wide rolls.

No allowance for general site wastage is made in the SpectraPave material quantities estimate.

<u>Top Surface Restraint</u>

The position of the finished surface relative to the existing ground level affects the economy of a particular pavement section. Depending on the local topography, it may be necessary to undercut the existing soils or import and place additional fill to achieve the required finished surface. Thus, the user is asked to specify the position of the finished surface relative to the current ground level. Edit boxes are available for the user to enter the cost of these two potential requirements and this is taken into consideration in the final Cost Analysis.

Cost Analysis Results

The Cost Analysis results for all pavement options under consideration can be accessed by selecting the ‘Results’ tab (Figure 8). The total in-place costs for each design option are presented for different items in table format. For comparative purposes, the overall project savings are expressed in dollars and percent savings as compared to the unstabilized option. Note that by deselecting round results the costs are represented in dollars and cents.

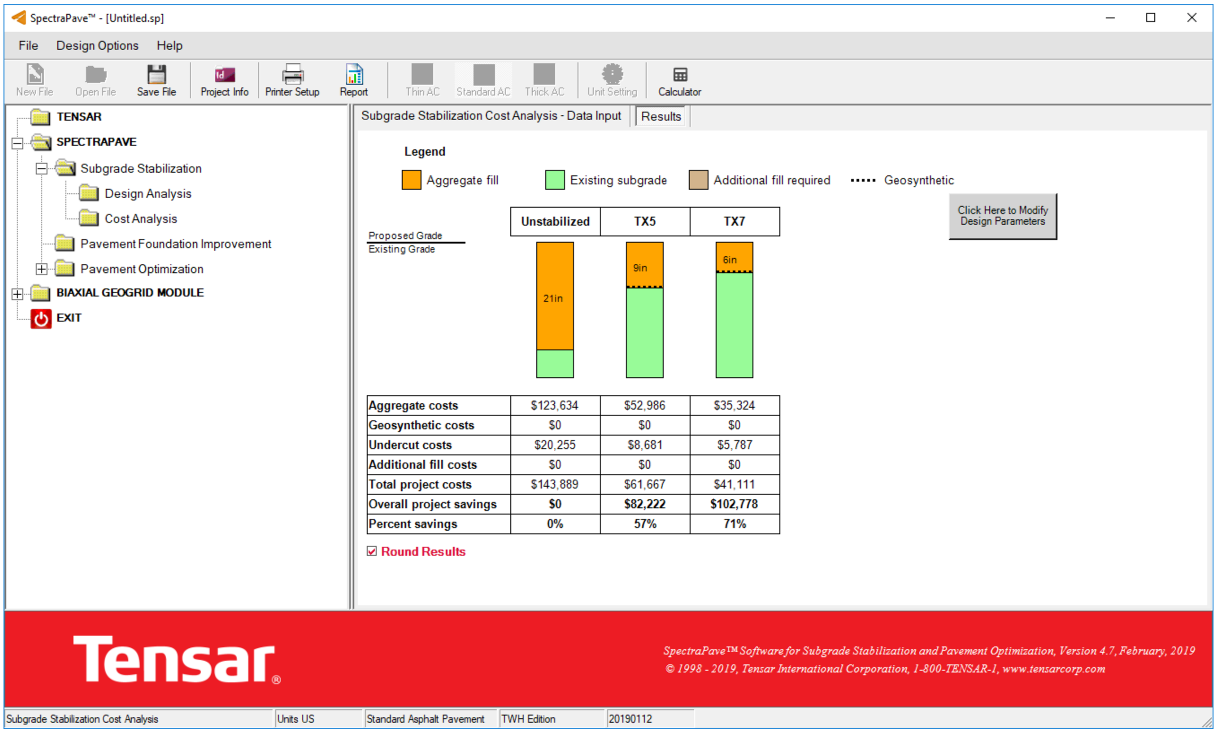


Figure 8: Subgrade Stabilization Cost Analysis - Results Screen in SpectraPave

Pavement Foundation Improvement Analysis

Theoretical Background

Tensar TriAx geogrid can improve the performance of the pavement foundation by mechanical stabilization of the overlying aggregate. The stabilized foundation serves as a new subgrade for overlying pavements. The resilient modulus of the MSL foundation can be determined based on the findings from large-scale cyclic plate loading tests and field automatic plate load tests. The resilient modulus of the stabilized foundation depends on the type of TriAx geogrid, thickness and quality of the granular material and the stress level applied to the MSL.

Design of Pavement Foundation Improvement Layer with SpectraPave Software

In the Pavement Foundation Improvement module, for a given set of design parameters, SpectraPave determines the resilient modulus of TriAx stabilized foundations. Design pavement section thickness and untreated soil condition data are required for the analysis (Figure 9). Help is available for estimation of the field subgrade CBR by clicking the icon next to Design Subgrade. When the information icon is selected, the help is shown in a chart displayed within a separate window.

Pavement Foundation Improvement Data Input

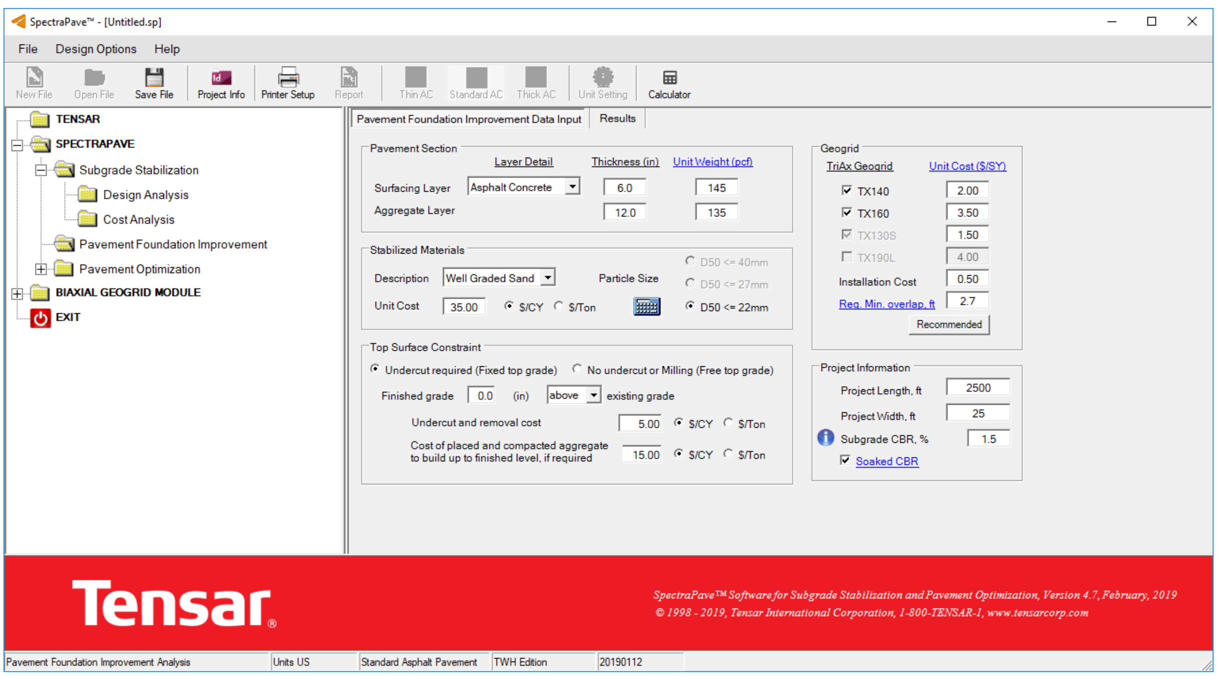


Figure 9: Pavement Foundation Improvement layer design - Data Input Screen in SpectraPave Software

Pavement Section

The user selects the appropriate surfacing layer detail and thickness information along with aggregate layer thickness information. Once this information is entered the software automatically calculates the stress level on the stabilized foundation based on the unit weight of overlying materials.

Stabilized Materials

Within the data input tab, the user is required to select the appropriate stabilized material grain size information. Once the particle size is entered, the software automatically selects a geogrid matching the D_{50} criteria.

Cost Analysis

The following information is required to determine the total project cost. Descriptions of information listed below are found in this manual.

- Project size
- Stabilized material cost
- TriAx Geogrid Cost
- Top surface restraint

Design Results

By selecting the 'Results' tab in the Pavement Foundation Improvement module, the required aggregate thicknesses for the pavement foundation, along with the resilient modulus of the new pavement foundation, are calculated and presented in a table format within the 'Results' window (Figure 10).

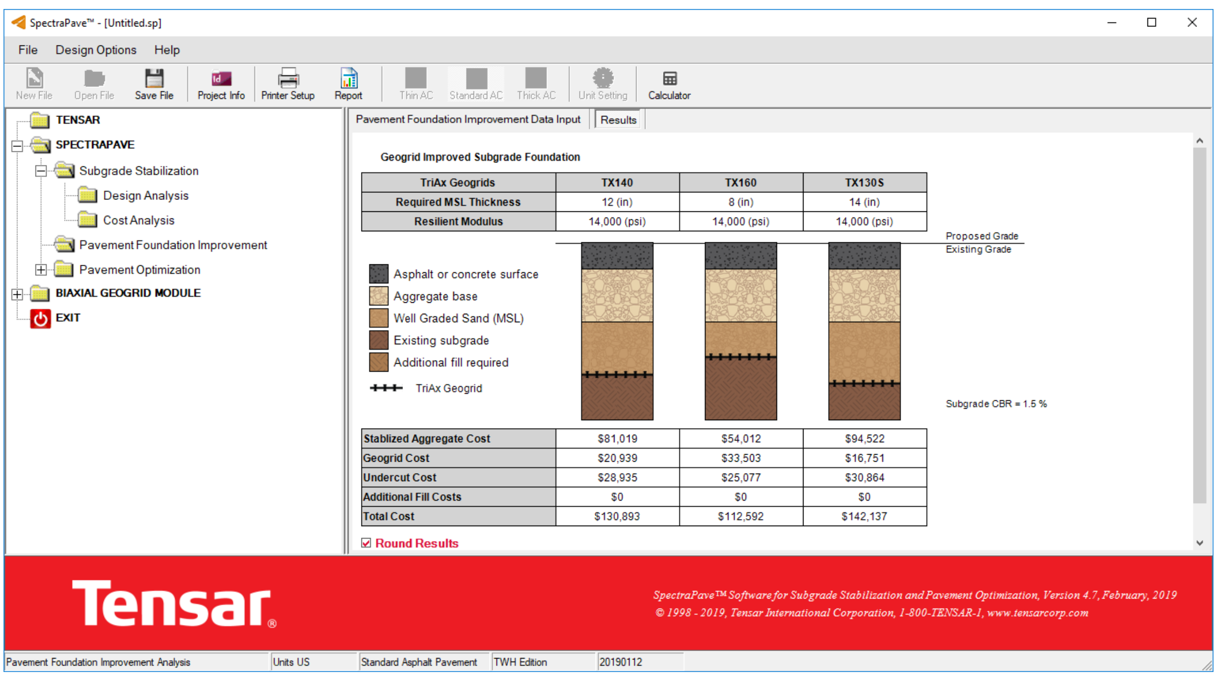


Figure 10: Pavement Foundation Improvement Layer Design - Results Screen in SpectraPave Software

Pavement Optimization Analysis

Theoretical Background

The Pavement Optimization module facilitates analysis and design of flexible pavements in accordance with the AASHTO Guide for Design of Pavement Structures (1993). The AASHTO (1993) method is empirically based and models a flexible pavement as a series of layers which have a combined structural capacity to carry a certain number of traffic loads (ESAL's) with pre-determined minimum levels of serviceability and statistical confidence.

Traditionally, geosynthetic reinforcement of pavements has concentrated more on projects involving unpaved roads. However, the rising cost of aggregates and increasing environmental pressure have caused government agencies and road builders worldwide to focus their attention on using similar techniques for permanent, surfaced pavements. To illustrate the level of acceptance within the pavement engineering community for this type of technology, the United States currently has a majority of State Departments of Transportation with published specifications for the use of geogrid reinforcement in roads.

Geosynthetics improve the performance of the pavement and are often placed within the aggregate base layer and/or at the aggregate base-subgrade interface. For a given base thickness and allowable surface rut depth, the traffic carrying capacity can be increased through the use of geogrids, compared to a similar pavement with the same thickness of unreinforced aggregate base. Additionally, with a given base layer thickness and trafficking, rutting is significantly less for the reinforced pavement. Another alternative involves a reduction in the quantity of base material used in construction of the pavement, to the extent that for the same trafficking, the performance of a thicker unreinforced pavement and a thinner geosynthetic-reinforced pavement are the same.

Geosynthetic Materials Used for Paved Applications

Evaluation of the effects associated with the use of geosynthetics in paved applications is based on pavement trials undertaken in both small-scale laboratories and full-scale field-testing. An extensive list of research projects is reported by Perkins and Ismeik (1997) and the GMA White Paper II (2000). The available research suggests that the two main types of geosynthetic reinforcement, geogrids and geotextiles, perform differently due to a different set of inherent properties that become mobilized under vehicular traffic. A brief overview of the improvement mechanisms for geogrids and geotextiles is presented below.

Geogrid reinforcement provides an improvement to roadways through four primary mechanisms:

- Interlock - Geogrid interlocks with aggregate at its subgrade interface and prevents lateral movement of the aggregate
- Reinforcement – Inclusion of a geogrid delivers tensile strength to the pavement, with a high modulus in the tensioned zone of the aggregate base course.
- Confinement - Geogrids provide a uniform confinement plane below the aggregate and limits the amount of rutting and upheaval of the subgrade into the aggregate base

- Separation – Geogrids prevent the aggregate base course from punching downward into the subgrade, thus maintaining a consistent aggregate thickness

In addition, **geogrid** reinforcement provides the following benefits:

- Filtration – Water draining from the separated subgrade and confined aggregate will not transport fines if the aggregate meets soil filter gradation requirements for the subgrade
- Tensioned Membrane Support – Mobilizes at very low strains if a thin aggregate section is used and deep rutting of subgrade occurs.

The improvement mechanisms of a **geotextile** are:

- Separation – A geotextile prevents subgrade and aggregate base course materials from mixing, thus maintaining effective aggregate thickness (primary mechanism);
- Filtration – A geotextile prevents subgrade water, draining to the aggregate base, from transporting fines provided that the aggregate meets soil filter gradation requirements
- Reinforcement Due to Tension Membrane Support – A geotextile may provide support through a deflected membrane if deep ruts develop in the subgrade
- Drainage – A non-woven geotextile provides lateral in-plane drainage

The overview of the improvement mechanisms shows that geotextiles do not employ the same reinforcement mechanisms as geogrids, and their application in Flexible pavements is not recommended (unless separation and filtration are the primary functional requirements for the geosynthetic). The 'mechanical interlock' is vital for the performance of any geosynthetic in stabilized pavements. It is a typical property of geogrids, occurring when properly sized well graded granular fill is compacted on top of a geogrid, letting the coarser particles partially strike through the geogrid apertures, achieving confinement of the aggregate base layer.

The mechanical interlock and resulting lateral restraint of the base course aggregate explain the superior performance provided by the Tensar TriAx Geogrids compared to geotextiles and other geogrids. TIC's patented manufacturing process produces a distinctive grid structure that consists of high strength junctions and stiff ribs which present a thick, high profile and squared leading edge to the aggregate, resulting in a positive 'mechanical interlock'. Tensar's TriAx Geogrids perform exceptionally well within pavement structures.

Traffic Improvement Factor (TIF) Concept in the Pavement Optimization Module

The ratio of the number of load cycles causing a preset surface rut depth in a geosynthetic-reinforced pavement to the number of load cycles required to cause the same surface deformation in an unreinforced section is termed the Traffic Improvement Factor (TIF) and/or traffic benefit ratio (TBR). The potential benefit of geogrid reinforcement is manufacturer and product specific. As such, the engineer of record should ensure that field and full-scale laboratory studies are available, like those described in Perkins and Ismeik (1997) and the GMA White Paper II (2000), in order to justify the TIF value used for the particular geosynthetic considered in the analysis.

Layer Coefficient Concept in the Pavement Optimization Module

The Layer Coefficient is an index used to represent the material properties in the AASHTO Guide for Design of Pavement Structures (1993). The layer coefficient contributes to the calculation of the Structural Number (SN) of a pavement, which in turn is used within a performance equation to predict the traffic life of the pavement.

In a recent study at the University of Illinois - Urbana Champagne, the Tensar Geogrid was reported to increase the residual or confining stress within the overlying aggregate layer. This increase in the confining stress can be reflected in the AASHTO Guide for Design of Pavement Structures (1993) by increasing the layer coefficients.

Current pavement design methods, including the standard practice authored by the American Association of State Highway and Transportation Officials (AASHTO) R 50-09, offer a convenient method for designing geogrid-reinforced pavements. Improvement to the pavement systems provided by geogrid reinforcement is frequently quantified by traffic improvement factors (TIFs), traffic benefit ratios (TBRs), and base course reduction (BCR) based on direct comparisons of the performance of reinforced sections with identical unreinforced sections. However, they are limited and do not fully account for the reinforcement benefit for the full range of design conditions.

Extensive research and testing have been undertaken by independent researchers to determine appropriate TIF values for Tensar Geogrids. Recent research efforts at the University of Illinois and Itasca Consulting Group, Inc. contribute to the profession's understanding of how and why geogrids improve performance in flexible pavements. The governing reinforcement mechanism is identified as the geogrid aggregate interlock that causes local stiffness enhancement on both sides of the geogrid during compaction and traffic loading. Because of increased contact forces and stresses around the geogrid, the stiffness of the adjacent unbound aggregate increases significantly and improves overall pavement performance. These investigations demonstrated that confinement effects must be considered in designing with Tensar geogrids in flexible pavements (Kwon et al. 2008; Kwon and Tutumluer 2009).

The design approach employed in SpectraPave Software uses enhanced layer coefficients to account for initial confinement benefits of geogrids as well as retained stiffness, along with damage reduction or enhanced overall pavement performance. General trends relating geogrid benefits observed from previous studies indicate that the confinement effect to pavement performance increases with decreasing subgrade strength and is sensitive to pavement layer thickness.

Alternate Geogrid materials should not be considered as valid for acceptance based upon the design output generated through use of the SpectraPave paved applications module.

The FAA (1994) and AASHTO (2003), along with other agencies, recognize the importance of appropriate performance documentation. Caution on the part of the designer is warranted for road design applications. Research results to date demonstrate that one geogrid family cannot simply be substituted for another based on index property equivalence alone.

Optimization of Pavement with SpectraPave Software

In the Pavement Optimization module, for a given set of design parameters, SpectraPave will predict the allowable trafficking (ESAL's) for an unstabilized pavement using the AASHTO (1993) method. The equivalent stabilized structure is developed by inserting Tensar's TriAx Geogrid into the pavement section and then the overlying layer coefficients are increased and the pavement life is calculated.

Pavement Optimization Module Input Data (Thin, Standard and Thick AC Pavement)

Input data for Pavement Optimization design can be entered by using a series of text boxes, drop-down lists and control buttons in the 'Data Input' window shown in Figure 11. The user can select one of three options. These include the thin pavement design module (2" – 3"), Standard AC design module (3" – 6"), and thick AC (6" – 14"). Within each module, the user can adjust section thicknesses both on the input and results tabs. Observing pavement performance is similar to looking at a fingerprint for a pavement type in that each pavement type has a unique set of performance curves. In addition, the change in riding quality will be directly related to how well traffic loading is transferred to the road subgrade. It is important to acknowledge this because the design performance models serve to predict the service life of pavements based on expected performance. By applying a single traffic benefit ratio (TBR) value to pavement performance prediction for a variety of asphalt thicknesses the designer would be assuming that the geogrid is providing the same level of benefit in each case. Lastly, thin asphalt pavements are designed on a regional basis by engineers familiar with locally available materials and climatic conditions that permit the use of such a design section. Engineers not familiar with thin asphalt design should select the Standard Pavement AC design module. With these facts in mind, a series of panels for data entry is available in the 'Data Input' window, some are briefly described below.

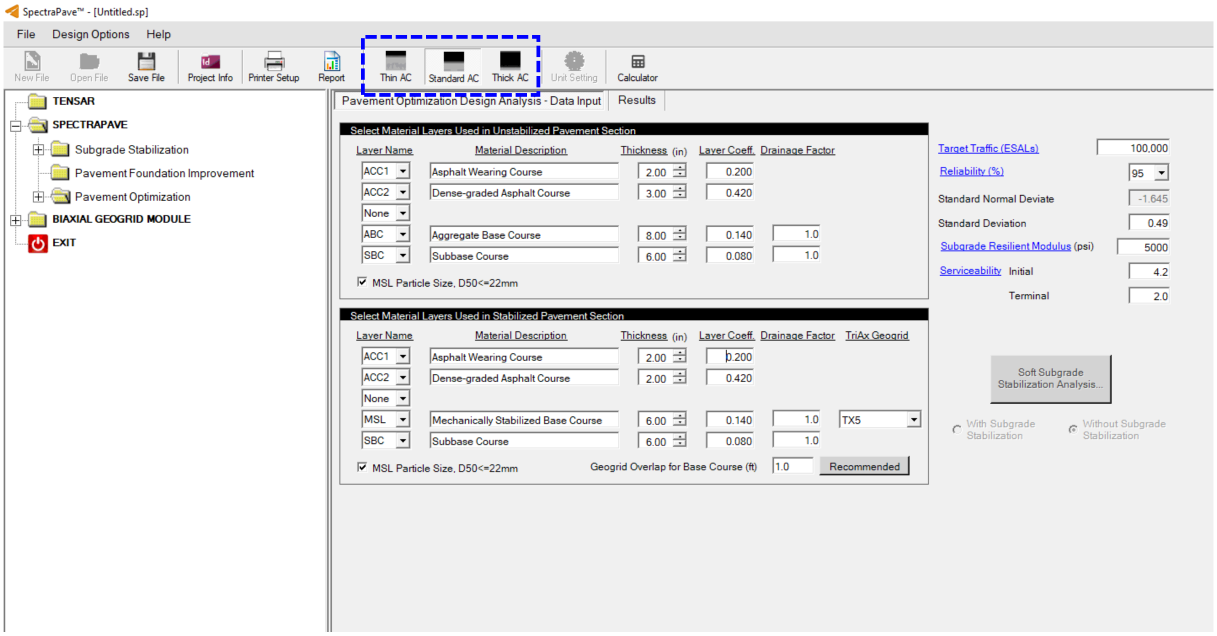


Figure 11: Pavement Optimization Input Screen

Number of Layers in the Pavement Structure

The following seven different types of pavement layers can be selected for developing a pavement structure on top of an existing subgrade material:

- surface layer (ACC1)
- asphalt intermediate layer (ACC2)
- asphalt base layer (ACC3)
- base course (ABC)
- sub-base course (SBC)
- chemical stabilized base course (CSL)
- mechanically stabilized layer (MSL)

The user can alter the selection of layers for the analysis, from a minimum of two to a maximum of five layers, using the check boxes adjacent to each layer in the 'Data Input' window.

Layer Coefficient Correlations for CSL

Table A. Correlations between structural layer coefficient a_2 and various strength and stiffness parameters for cement-treated granular bases (AASHTO, 1993).

Unconfined Compressive Strength (psi) 7 day break	Structural Coefficient
1000	0.250
800	0.220
600	0.190
400	0.155
200	0.125

Elastic Modulus (psi)	Structural Coefficient
1,000,000	0.265
900,000	0.240
800,000	0.215
700,000	0.190
600,000	0.150
500,000	0.115

NOTE: Soil properties values are approximate and estimated based on the scale for Structural Coefficient, a_2, from the original figure included in the FHWA 05-037, May 2006, NHI Course No. 132040, Geotechnical Aspects of Pavements Reference Manual/Participant Workbook

Table B. Correlations between structural layer coefficient a_2 and various strength and stiffness parameters for lime-treated granular sub-bases (FHWA-IP-80-2, 1980).

Lime Treated Subbase	Structural Coefficient
Lime-treated clay-gravel	0.14
Lime-treated soil	0.11

NOTE: NCHRP synthesis of Highway Practice. Issue No. 37 Lime-Fly Ash-Stabilized Bases and Sub-bases (1976)

OK

Figure 12: Chemically Stabilized Base Course Layer Coefficients

Pavement Structure Layer Properties

The layers of the specified pavement structure are characterized by:

- Layer Name/Material Type
- Elastic Modulus
- Layer Thickness
- Layer Coefficient
- Drainage Factor

The user can alter the default values by using a series of edit boxes, drop-down lists and pop-up help messages in the ‘Data Input’ window.

The relationship in the 1993 AASHTO Guide between the structural layer coefficient and 7-day unconfined compressive strength or elastic modulus is available for use with the Chemically Stabilized Layer (CSL). After selection of the CSL from the drop-down lists in the Input Screen, the layer coefficient correlation for CSL is displayed within the paved road module (Figure 12).

If the modulus of the subgrade drops below 5,000 psi (CBR < 3), then the software will warn you to check the constructability of the subbase or base course and recommend performing a Subgrade Stabilization analysis.

If the layer thickness of the base course on top of the Tensar TriAx geogrid is less than 6 inches, then the software will advise you that the minimum recommended lift on top of the geogrid should be 6 inches or more.

The software is only applicable for cases where the combined thickness of the asphalt course does not exceed 14 inches.

Design Traffic

The SpectraPave design section user input for should be input only after the planned service life of the road under consideration is calculated. This value will be used to check whether the predicted life exceeds (represented with a green box) or does not meet (represented with a pink box) the design traffic specified by the pavement designer (Figure 13).

Pavement Optimization Module Results

After the design inputs are specified, the results for an unstabilized pavement and a pavement stabilized with a Tensar TriAx Geogrid can be viewed by selecting the ‘Results’ tab. The results are presented in a table in the ‘Results’ window (Figure 13).

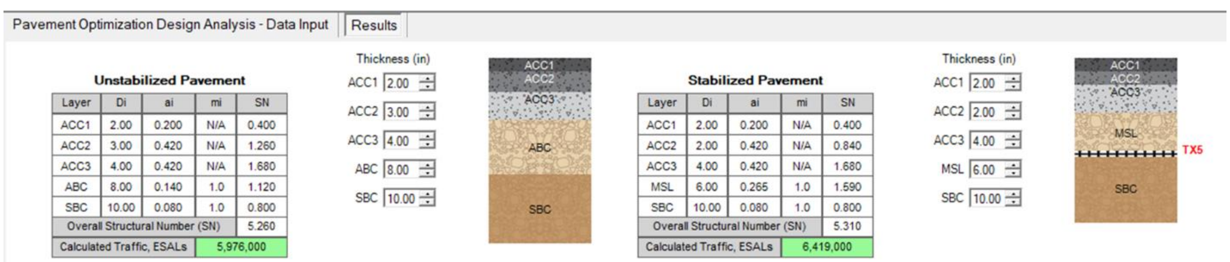
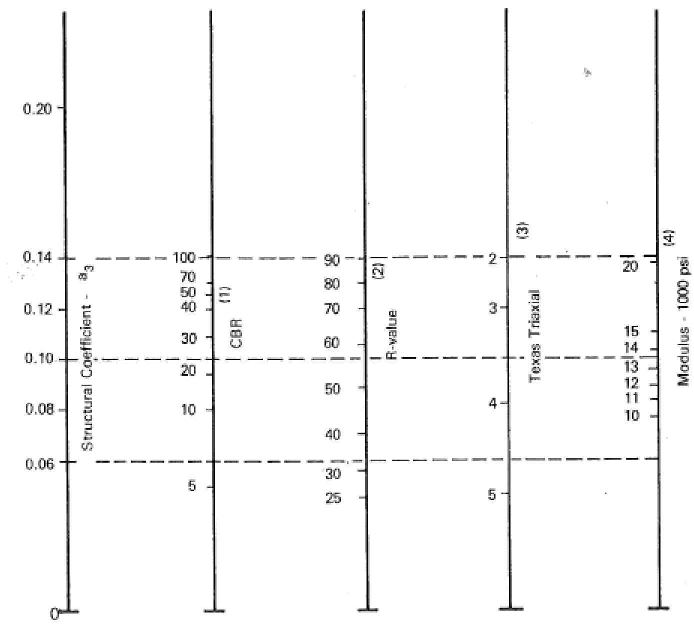


Figure 13: Pavement Optimization Results Screen

In Figure 13, the input parameters used to determine the overall Structural Number for both the unstabilized and TriAx Geogrid stabilized pavement sections. The calculated Structural Number is used in the main AASHTO equation to determine the allowable number of ESAL. For the stabilized pavement, the layer coefficients are automatically modified to reflect the confinement stress benefit of the geogrid and the Structural Number is then calculated. The calculated life (ESALs) for each unstabilized and stabilized pavement section are displayed in the boxes below the section diagrams. In all cases for the stabilized and unstabilized pavement sections, the overall Structural Number method per AASHTO (1993) is considered the basis for design.

A series of control buttons are available adjacent to the pavement cross-sections in the 'Results' window. These buttons allow the user to modify the thickness of the various layers and view the calculated traffic (ESALs).



(1) Scale derived from correlations from Illinois.

(2) Scale derived from correlations obtained from The Asphalt Institute, California, New Mexico and Wyoming.

(3) Scale derived from correlations obtained from Texas.

(4) Scale derived on NCHRP project *(3)*.

Figure 14 - Relationship Between CBR and Granular Subbase Strength

Design of Pavements on Soft Soil Subgrades

The design of a paved road over a soft subgrade is a two-step process. Based on Tensar International's experience, stabilization of the subgrade is required for soils exhibiting a resilient modulus of less than or equal to 5,000 psi (CBR of approximately 3). For these field conditions, the stabilization layer should be designed using the Giroud-Han method as incorporated within the subgrade stabilization module of the SpectraPave software. For stabilization of soft soil, the designer needs to consider axle load, tire pressure and the required maximum rut depth associated with placement of the aggregate stabilization layer. Site-specific soil strength conditions as a function of CBR as developed by AASHTO (1993) is presented in Figure 14. As indicated in Figure 14, a resilient modulus of 12,800 psi can be achieved when placed on a firm foundation. Field evidence for Tensar TriAx geogrid indicates that placement of the mechanically stabilized layer (MSL) over soft soil results in a recommendation to use resilient modulus of ranges from 9,000 psi to 15,000 psi at the top of the MSL. This value serves as the resilient modulus of subgrade for new pavement which is then used to undertake a conventional paved road design.

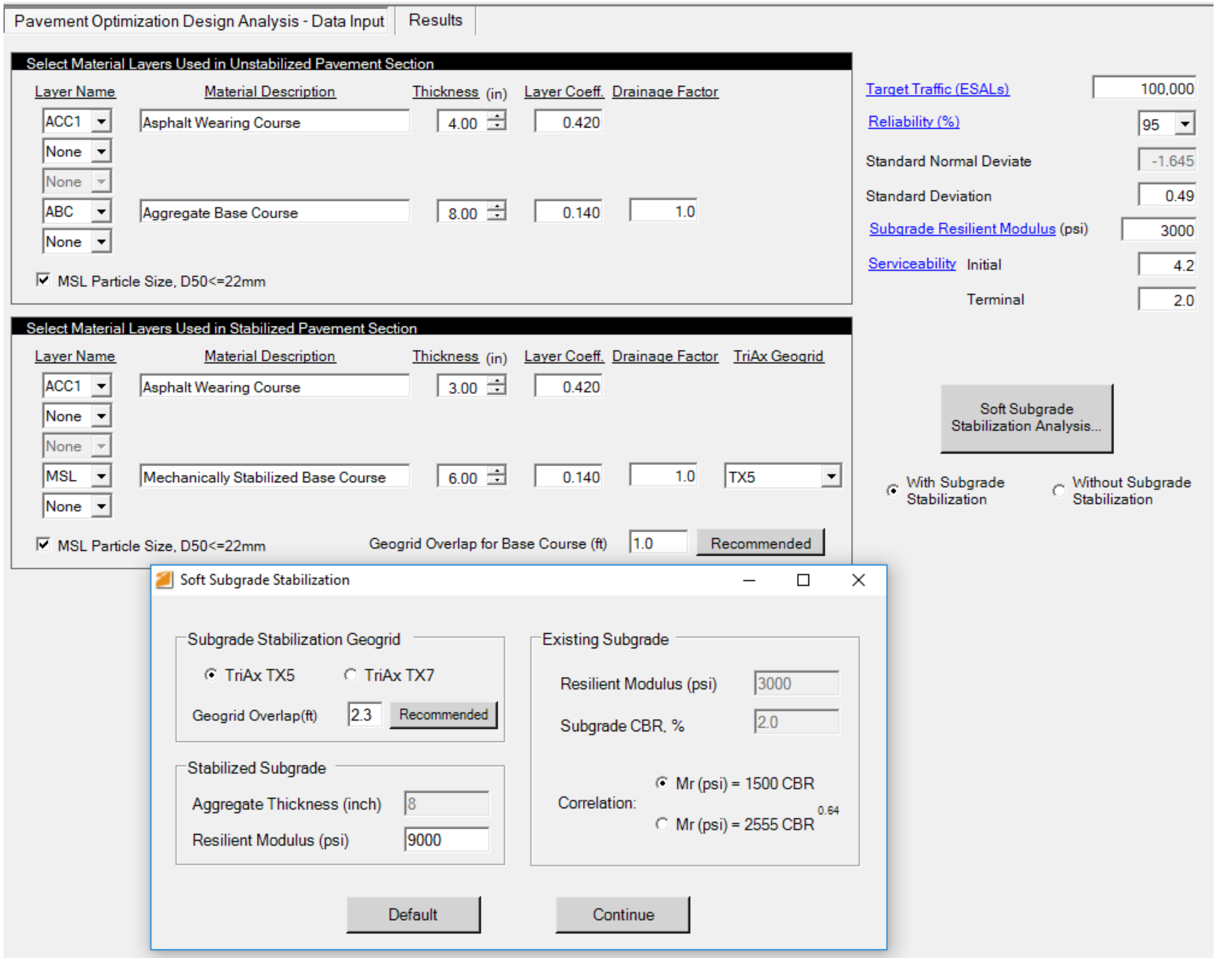


Figure 15: Design of Paved Roads Over Soft Soils

After completion of stabilization design, the paved road base course stabilization design can be performed using the AASHTO '93 design procedure with incorporation of an "improved" subgrade modulus that is deemed acceptable to the pavement design engineer. Again, based on TIC's experience this value would range from 9,000 psi to 15,000 psi for the conditions described above and the default values found within the subgrade stabilization module of the SpectraPave software. Keep in mind that base course stabilization will require a second layer of geogrid. As such, within SpectraPave software, the unstabilized paved module case represents use of one layer at the subgrade interface and the stabilized paved module design case represents one geogrid layer at the subgrade interface and one geogrid layer beneath the base course layer. To enforce this analysis approach, the user is asked if they want to design using this approach when they enter a subgrade resilient modulus value less than 5,000 psi. After selection of the yes button, Figure 15 is displayed within the paved road module. Within the new input section of the screen the user can select a stabilization geogrid, see the computed CBR based on two commonly used conversion equations and adjust the resilient modulus at the top of the stabilization MSL. Note that the enhanced modulus value depends on the stress level and type of geogrid used for stabilization. Using the default values found in the subgrade stabilization module the software uses the CBR from the existing subgrade to determine aggregate thickness requirements. This value is displayed for the MSL. The user can generate a "subgrade stabilization" specification to see the unbound aggregate requirements or run the subgrade stabilization module with their site CBR value (leaving all other default values the same). As depicted in Figure 16, the analysis compares the unstabilized pavement section (consisting of a stabilized subgrade) with the stabilized pavement section consisting of a stabilized subgrade. Figure 16 shows a layer of TX5 in the unstabilized pavement section which is used for stabilizing the subgrade. Similarly, two layers of TX5 are shown for the stabilized pavement. The upper TX5 is used for stabilizing the aggregate base and the lower TX is used for stabilizing the subgrade.

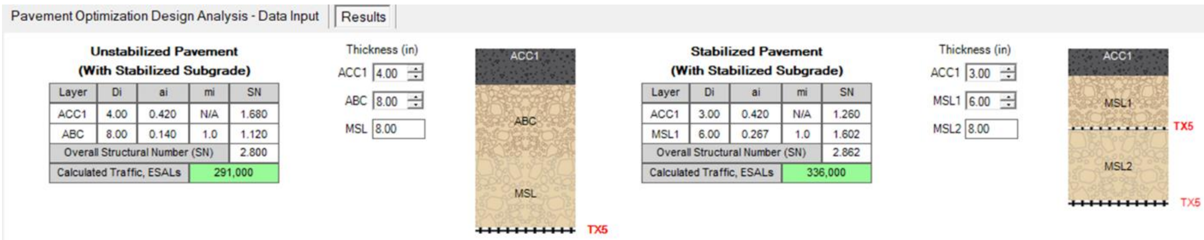


Figure 16: Analysis for Pavement Section with Subgrade Stabilization MSL

Benefits of Pavement Optimization

As the Pavement Optimization module allows users to design stabilized pavements with an extended pavement life and/or a reduced aggregate base course thickness, the Tensar TriAx geogrids have direct benefits in saving construction cost and/or enhancing pavement performance. Based on our experiences, the benefits are not only limited to cost and performance. The other benefits of using stabilized pavements include the reduction in Dump Truck trips for construction, reduction in water to build unbound aggregate layers, reduction in construction time and more. Figure 17 provides an overview of the benefits using Tensar TriAx geogrids. The following sub-sections discuss those benefits.

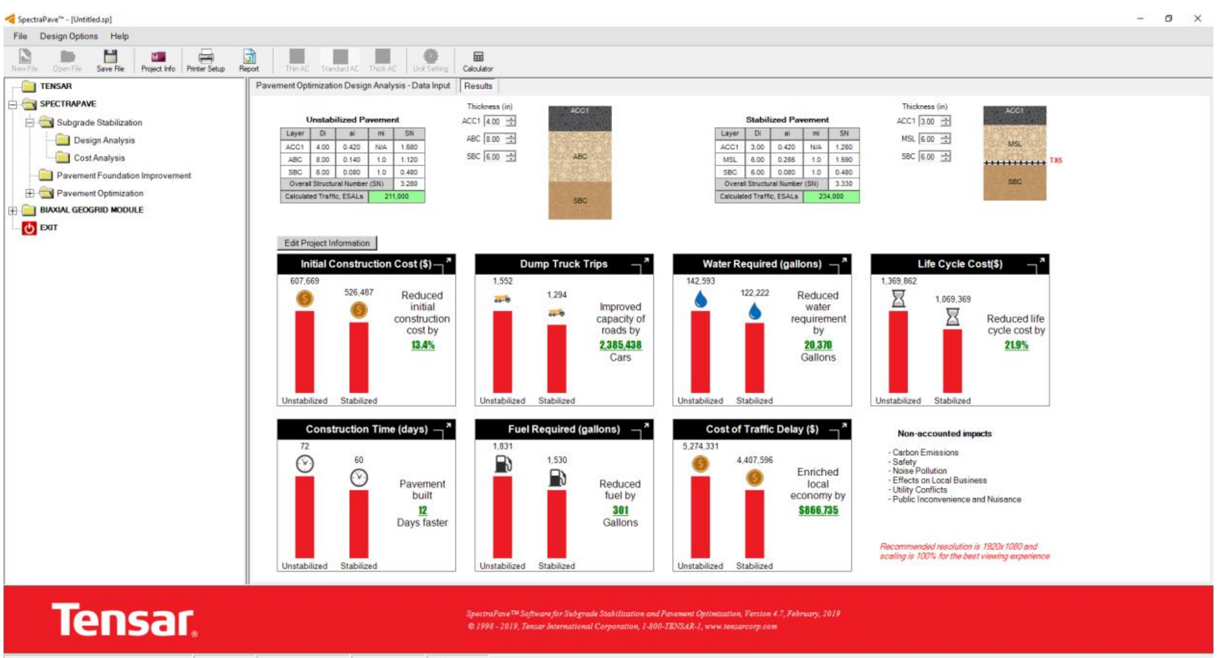


Figure 17: An Overview of Benefits

Initial Construction Cost

The initial construction cost analysis module compares the construction costs for unstabilized and stabilized pavements. The total initial construction cost is related to material, labor, equipment and other costs. SpectraPave has a provision to consider “material cost” and/or “labor and equipment cost”.

The material cost depends on the thickness of pavement layers, surface area of pavement, type of TriAx geogrid, material unit cost and other factors. Users can modify these inputs by clicking “Edit Project Information” (see Figure 18). Users are advised to use the appropriate cost for Tensar TriAx Geogrid based on the rate provided by the distribution. If the geogrid cost is not available, please call Tensar International Corporation at 1-800-TENSAR-1 for getting information about a local stocking distributor for relevant unit price estimates.

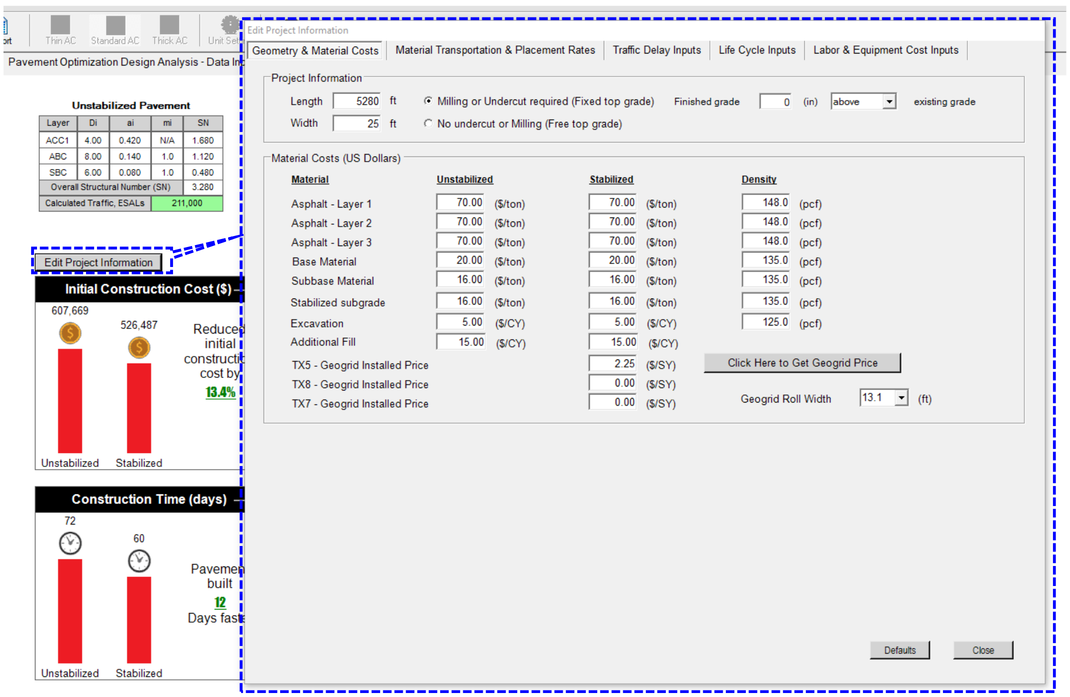


Figure 18: Geometry and Material Cost Inputs

The labor and equipment costs vary depending upon the site condition, construction method and contractor. User-specific labor and equipment cost can be assigned to different pavement layers (see Figure 19). The default data for the labor and equipment cost is adopted from National Construction Estimator Book, 65th edition (Pray 2017). Users can disregard using labor and equipment cost by checking “*Do not consider variable labor and equipment costs when calculating initial construction cost*” (see Figure 19).

The top surface constraints allow the user to also consider the cost implications of various cut or fill scenarios on the overall application cost. The top grade needs to be defined as either fixed or free, and the associated costs need to be entered to accurately determine the influence on the overall costs. The conditions of top surface constraints can be changed from “Edit Project information”>”Geometry & Material Costs”> “Project Information” (See Figure 18). Figure 20 describes different cases of the top surface constraints.

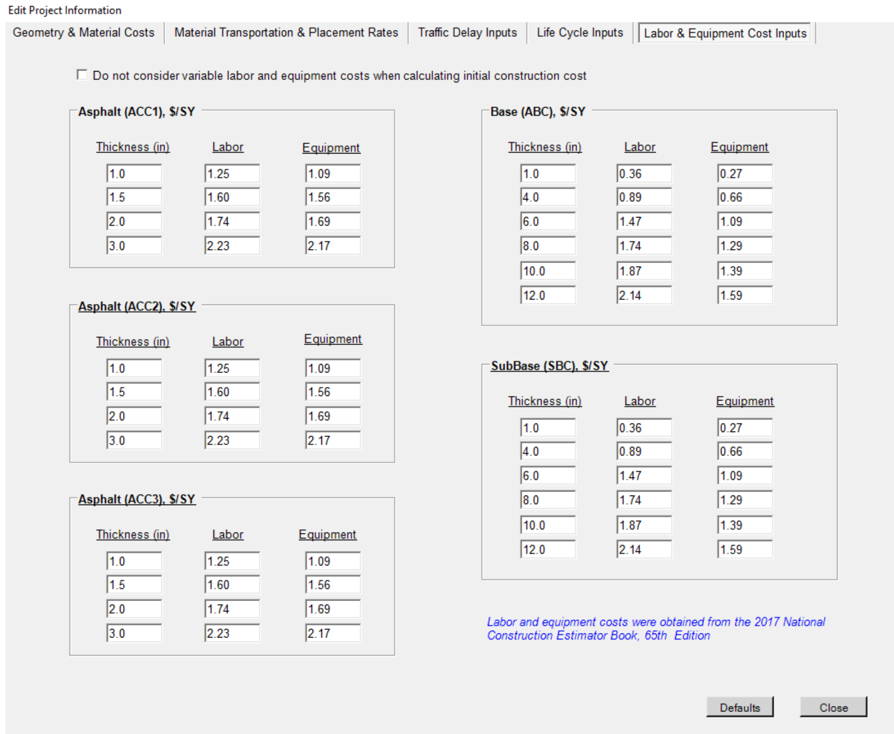


Figure 19: Labor and Equipment Cost Inputs

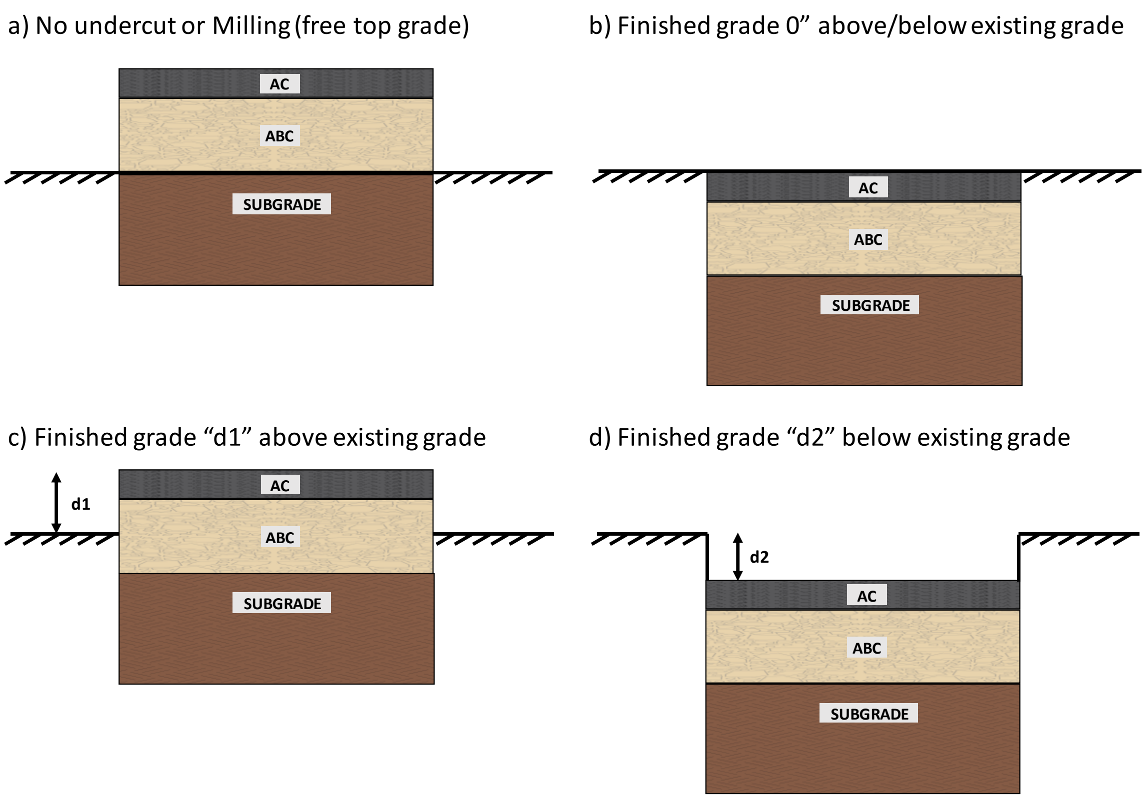


Figure 20: Top Surface Constraints

Figure 21 shows an example of an initial construction cost analysis. Each figure showing the benefit can be expanded to view the detailed calculation as shown in Figure 21. The unit cost of material ($/SY) for each pavement layer is calculated from the material, labor and equipment cost. The initial construction cost can be compared either in terms of the unit cost ($/SY) or the total cost. Further, the efficiency comparison provides the percentage cost savings and pavement life extension.

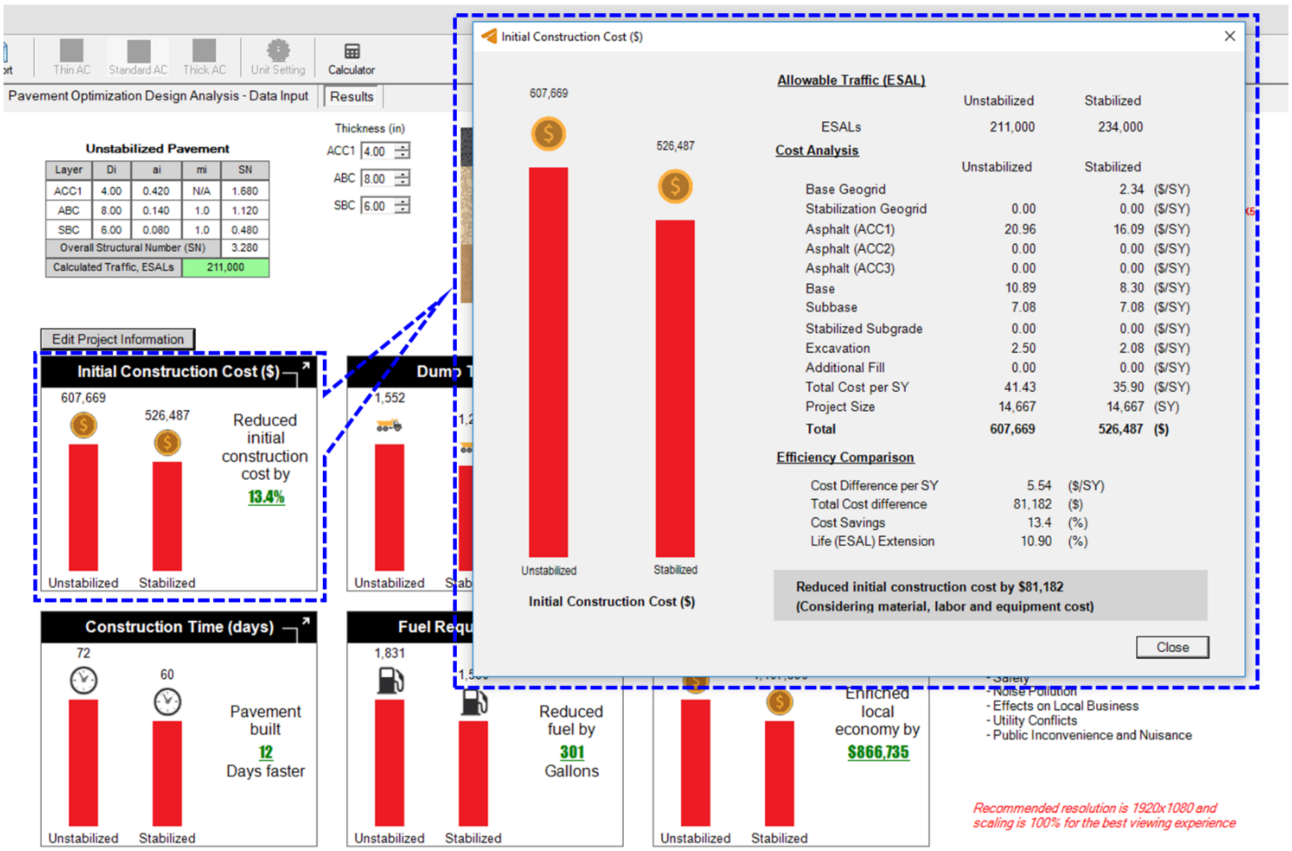


Figure 21: Initial Construction Cost Analysis

Dump Truck Trips

The Dump Truck Trips analysis module compares the truck trips required to build the unstabilized and stabilized pavements. This analysis requires the quantity of pavement material, the quantity of excavation, the material transportation rate and other inputs. The input required for this analysis can be accessed by clicking “Edit Project Information” (See Figure 22). When a pavement is stabilized with TriAx geogrids, it results in the need of less material (aggregate) for construction. This ultimately results in the reduction of Dump Truck Trips in the job sites. As a result, the damage of the existing roadway is minimized, and the chances of traffic congestion are also reduced.

Figure 23 provides an example of a Dump Truck Trips analysis. The software also estimates the total number of passenger cars by assuming “one fully loaded Dump Truck is equivalent to 9245 passenger cars”.

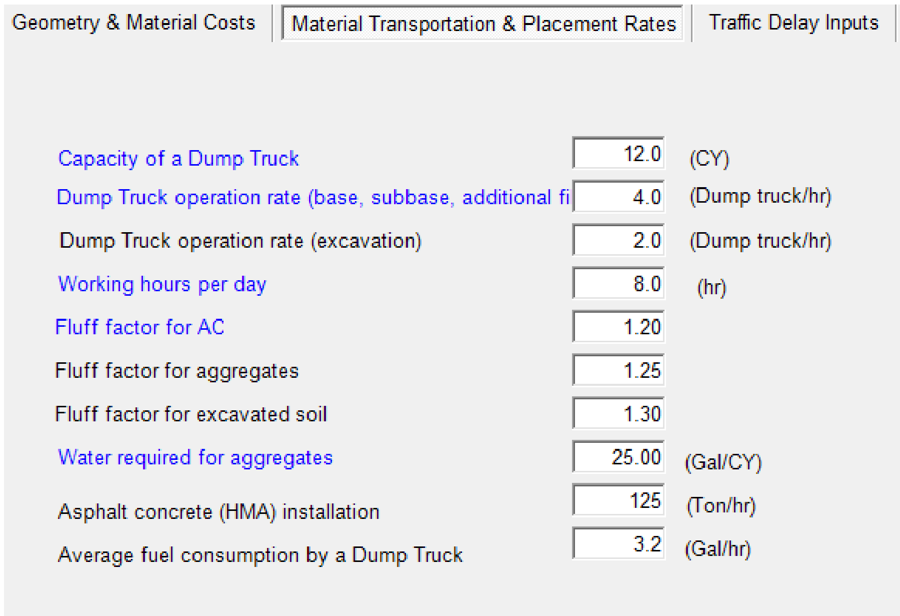


Figure 22: Material Transportation and Placement Rates Inputs

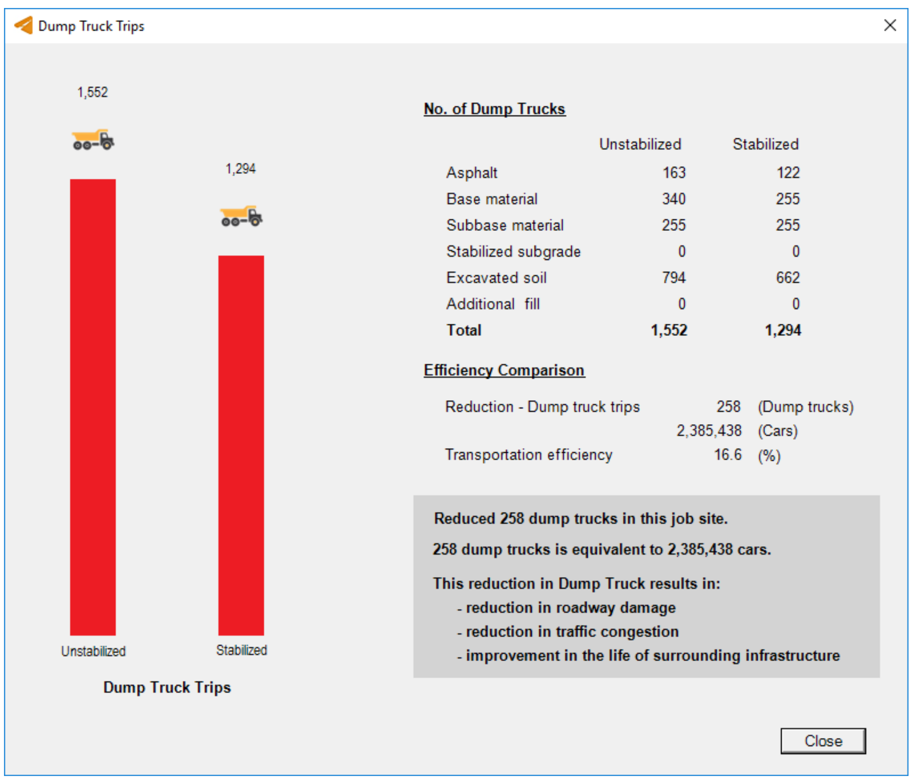


Figure 23: Dump Truck Trips Analysis

Water Required

The Water Required analysis module compares the quantity of water required to build unbound pavement layers of the unstabilized and stabilized pavements. The unbound pavement layers are aggregate base, subbase and additional fill. The input required for this analysis can be accessed by clicking "Edit Project Information" (See Figure 22). Using the input "Water required for aggregates" and the quantity of unbound aggregates, the total quantity of water required is calculated. Figure 24 shows an example of a Water Required analysis.

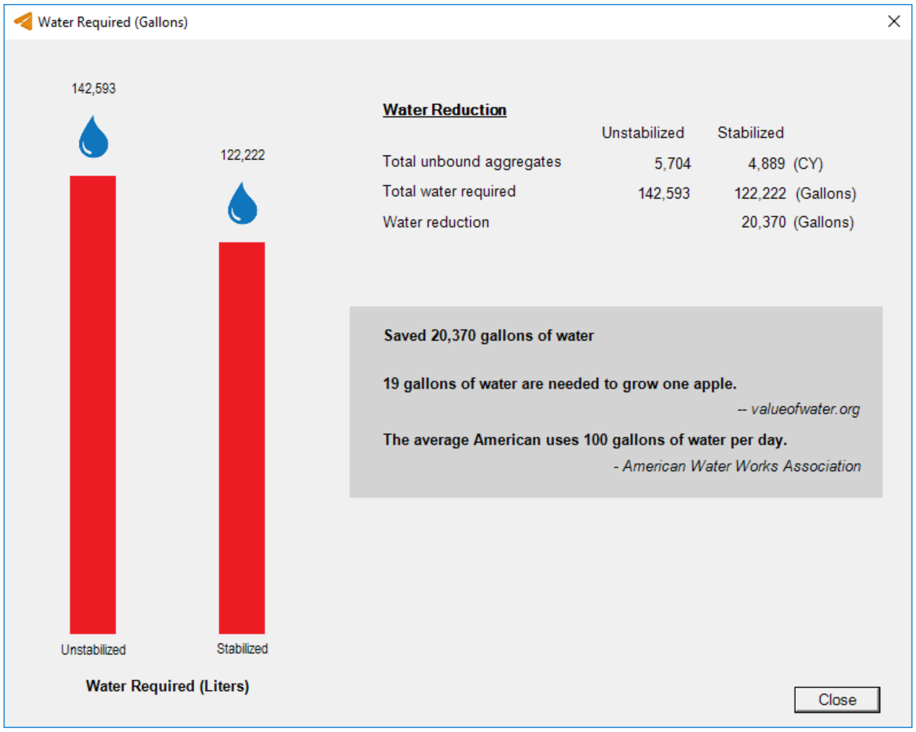


Figure 24: Water Required Analysis

Life Cycle Cost Input and Results

When two design alternatives have different initial costs and different predicted performance lives, then the initial cost benefit comparison is not appropriate to make an informed decision. Pavement engineers are faced with comparing design sections that comprise different material types, component thicknesses and predicted service lives (AASHTO 1993 Ch3; FHWA 1998). The Life Cycle Cost Analysis (LCCA) is currently required by the FHWA for federally funded projects in most states. To properly evaluate these sections, the LCCA is performed to develop an equivalent selection criterion by which the best design can be adopted. The utilization of Tensar TriAx geogrid in a design section offers a thickness reduction of the unstabilized section where the resulting predicted life of both section alternatives are equivalent. This feature results in an initial cost benefit as calculated in the Advanced Cost module. However, when the thickness reduction is limited by minimum thickness constraints for example, then the two sections will have different predicted lives and different initial costs, which will require a life cycle cost analysis to make an objective decision.

The Life Cycle Cost Analysis considers the costs associated with each design:

- Initial Cost
- Rehabilitation Cost
- Maintenance Costs

The analysis is done using a common evaluation or design period for both pavement structures. If a pavement structure does not reach the end of the service life by the end of the design period, the remaining life is accommodated by using a Salvage Value, or a negative cost at the end of the design period. All the costs and salvage value are then converted and combined in Equation 1 to generate a Present Worth of Cost (PWOC) for both pavements as shown in Figure 25. The solution with the lowest PWOC is the optimum solution in terms of performance and cost.

$$PWOC = IC + \sum_{i=1}^{4} PW(MC) + \sum_{i=1}^{2} PW(RC) - PW(SV) \qquad \text{(Equation 1)}$$

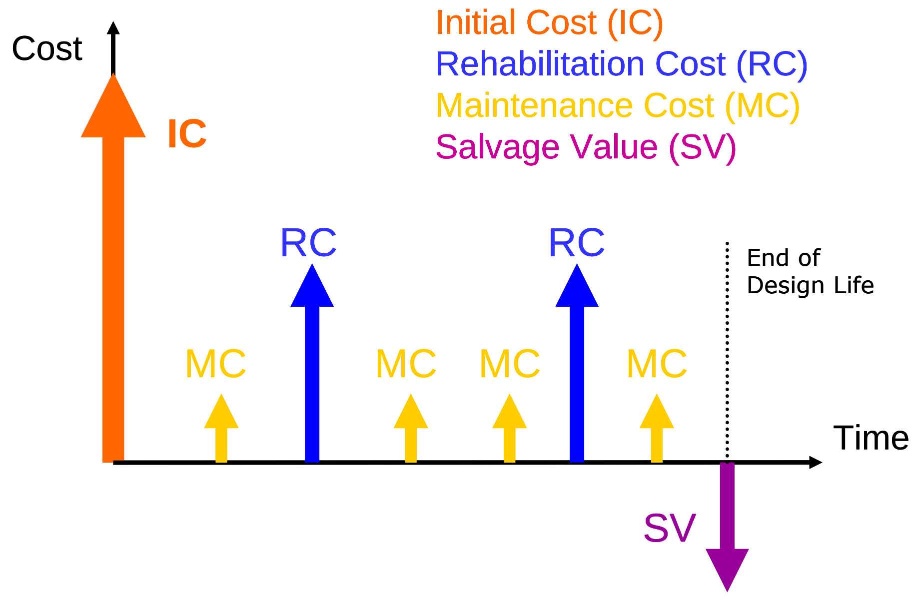


Figure 25: Life Cycle Cost Components over the Design Life of a Pavement

Each of the components in Figure 25 can be defined as follows:

- **IC Initial Cost** (Costs associated with the construction of a new section of pavement)
- **MC Maintenance Cost** (Costs of future major interventions to maintain or restore riding quality)
- **RC Rehabilitation Cost** (Costs necessary to maintain a pavement at or above some predetermined performance level)
- **SV Salvage Value** (Salvage (or Residual) value is the value of reusable materials, and/or extended performance at the end of the design period)

Each of these components is normalized to a present worth of cost, which means that we convert the cost of certain future activities into today's money. The analysis of all the components is done using Equation 1.

The user has two choices available for analysis. The top button, "Use Design Analysis" allows for a cost-neutral evaluation. This means that the reduced cross-section can be adjusted by the user to account for geogrid costs through an iterative process. The second button "Maximum Savings" can be used to demonstrate the LCCA for equivalent sections using the geogrid to extend the life of the pavement. To perform a Life Cycle Cost Analysis, adjust the values as found in Figure 25 then click on the 'Results" tab located on the tab below the toolbar as shown in Figure 26.

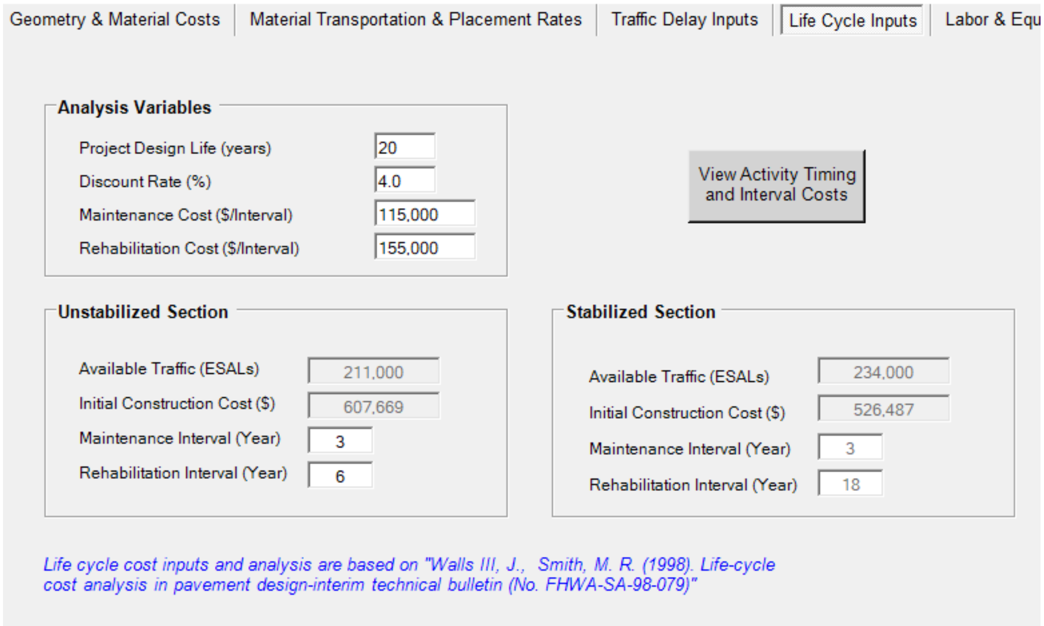


Figure 26: Life Cycle Cost Analysis Inputs

Figure 27 shows the cycle cost savings for the unstabilized and stabilized pavement sections. By clicking "View Detail Costs", the activity timing and interval costs can be viewed (see Figure 28).

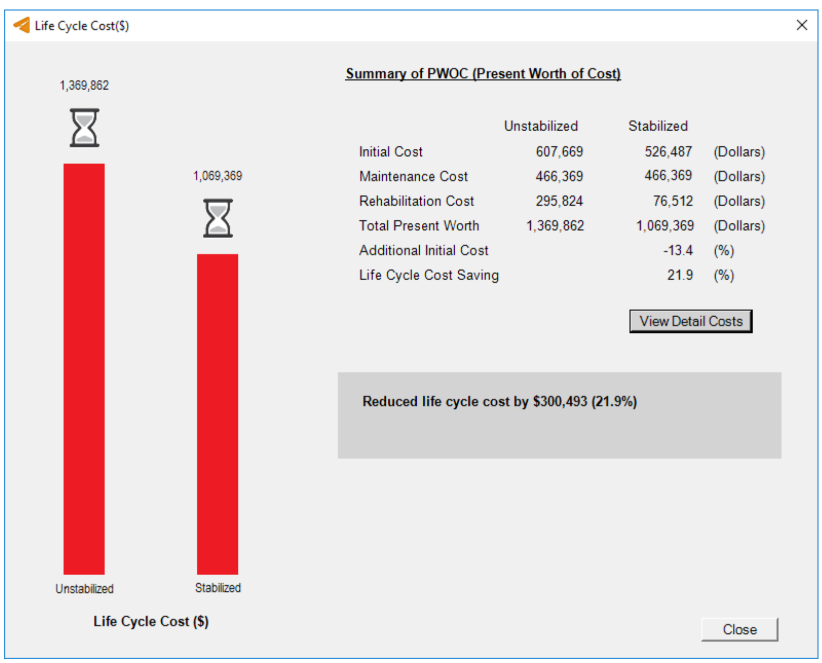
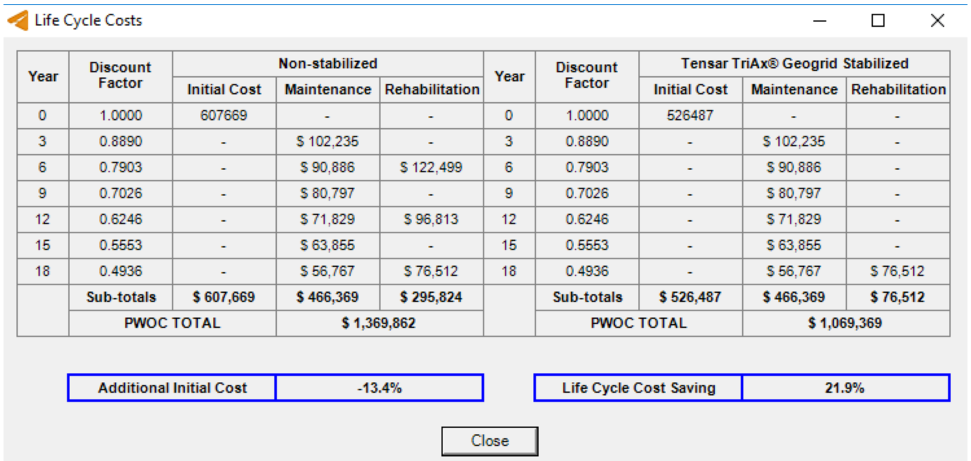


Figure 27: Life Cycle Cost Analysis (LCCA) Analysis



Life Cycle Costs

Year	Discount Factor	Non-stabilized			Year	Discount Factor	Tensar TriAx® Geogrid Stabilized		
		Initial Cost	Maintenance	Rehabilitation			Initial Cost	Maintenance	Rehabilitation
0	1.0000	607669	-	-	0	1.0000	526487	-	-
3	0.8890	-	$ 102,235	-	3	0.8890	-	$ 102,235	-
6	0.7903	-	$ 90,886	$ 122,499	6	0.7903	-	$ 90,886	-
9	0.7026	-	$ 80,797	-	9	0.7026	-	$ 80,797	-
12	0.6246	-	$ 71,829	$ 96,813	12	0.6246	-	$ 71,829	-
15	0.5553	-	$ 63,855	-	15	0.5553	-	$ 63,855	-
18	0.4936	-	$ 56,767	$ 76,512	18	0.4936	-	$ 56,767	$ 76,512
	Sub-totals	$ 607,669	$ 466,369	$ 295,824		Sub-totals	$ 526,487	$ 466,369	$ 76,512
	PWOC TOTAL		$ 1,369,862			PWOC TOTAL		$ 1,069,369	

Additional Initial Cost	-13.4%	Life Cycle Cost Saving	21.9%

Close

Figure 28: Activity Timing and Interval Costs of LCCA

Construction Time

The Construction Time analysis module compares the total number of days required for constructing the unstabilized and stabilized pavements. This includes building pavement layers and excavating existing ground. The input required for this analysis can be accessed by clicking “Edit Project Information” (See Figure 22). To compute the construction time for asphalt layers, the input “Asphalt Concrete (HMA) Installation” is used. For unbound layers, the input “Dump Truck operation rate (base, subbase, additional fill)” is used. Similarly, “Dump Truck operation rate (excavation)” input is used for estimating excavation time.

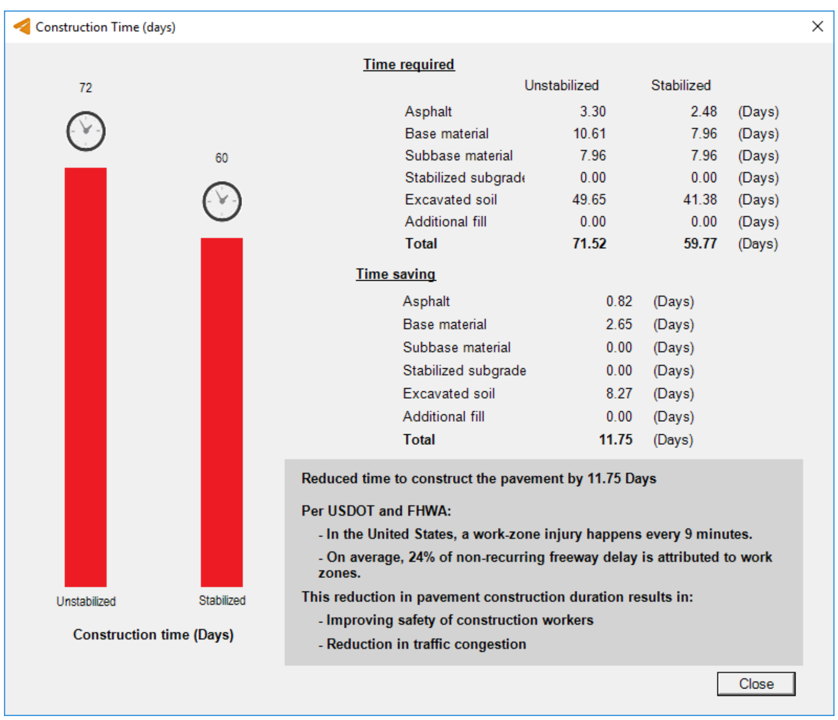


Figure 29: Construction Time Analysis

Figure 29 shows an example of a construction time analysis. For unstabilized and stabilized pavements, the construction time for each pavement layers and the overall excavation time are shown under “Time required”. “Time saving” provides the difference in time for each item and the total time difference.

Fuel Required

The Fuel Required analysis compares the total amount of fuel needed to operate Dump trucks on the job sites. Based on the total quantity of pavement materials and the total quantity of excavation, the total number of Dump trucks is computed. And, the fuel required for those trucks used for constructing unstabilized and stabilized pavements is estimated. The input “Average fuel consumption by a Dump Truck” is needed for this analysis (See Figure 22). Figure 30 shows an example of a Fuel Required analysis.

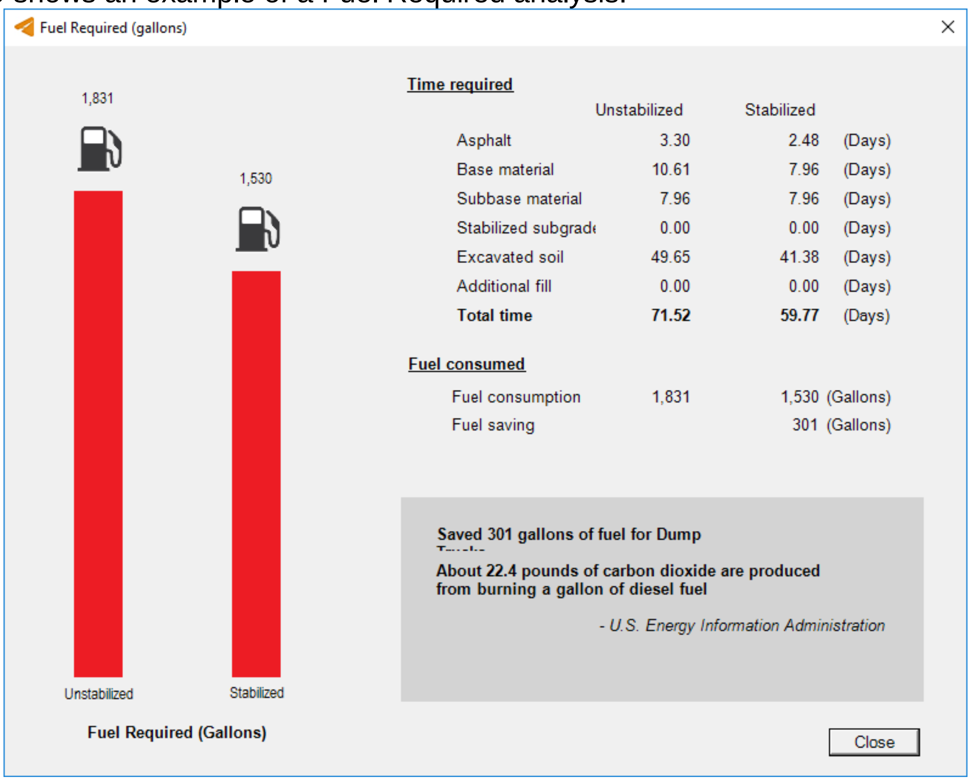


Figure 30: Fuel Required Analysis

Cost of Traffic Delay

Due to the presence of roadway work zones, the road users face serious consequences of traffic congestions and traffic delays. It is always challenging to quantify the cost associated with those traffic delays. Several researchers have proposed different methods of computing traffic delay cost. In SpectraPave, the cost of traffic delay analysis is a two-step process based on Jiang (2001) and Mallela and Sadavisam (2011). In the first step, an average traffic delay time is estimated by using the method proposed by Jiang (2001). In the second step, an average traffic delay cost per day is estimated by using the method proposed by Mallela and Sadavisam (2011). Then, using the “average traffic cost per day” and total duration for pavement construction, the total traffic delay cost is computed. The inputs needed for this analysis are shown in Figure 31. Figure 32 shows an example of a Cost of Traffic Delay analysis.

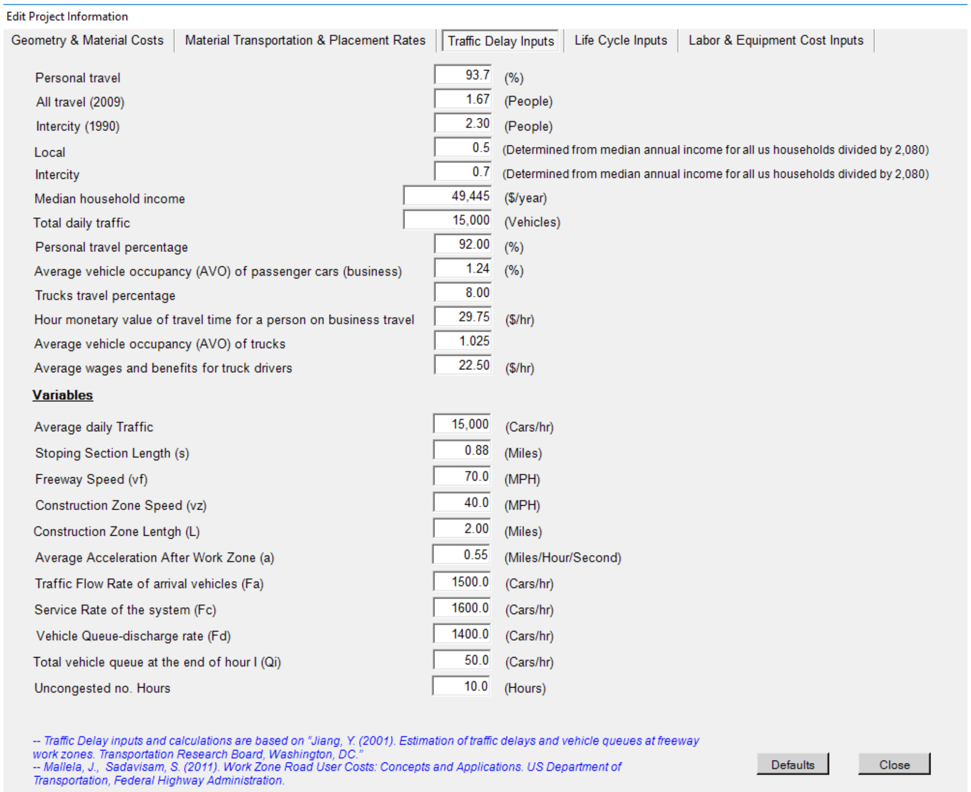


Figure 31: Traffic Delay Inputs

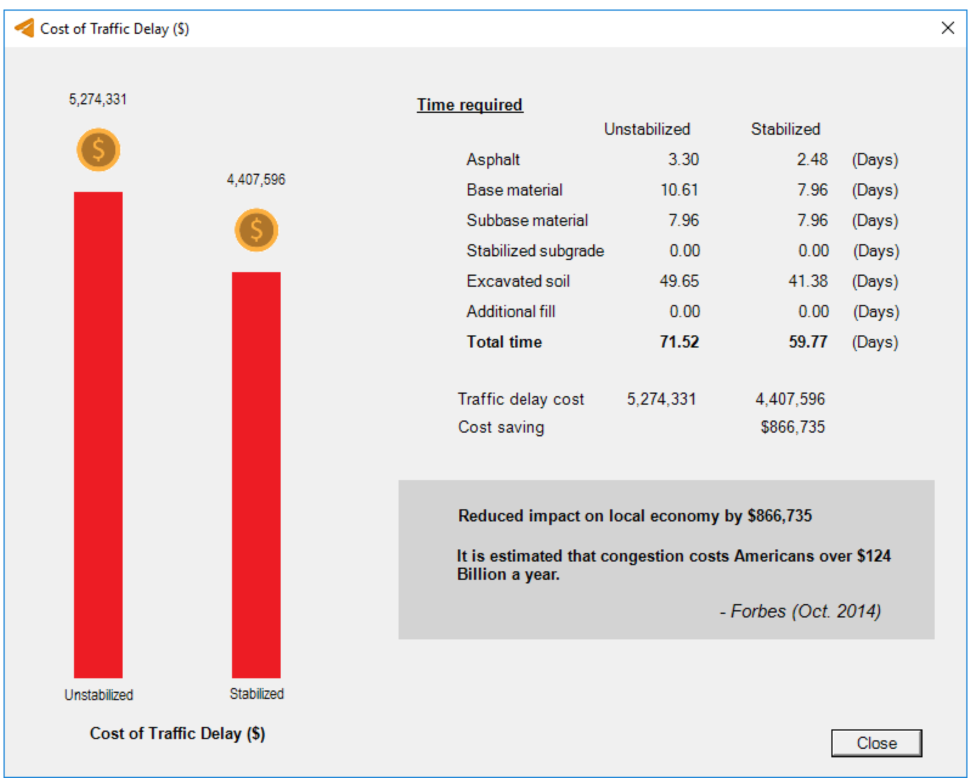


Figure 32: Cost of Traffic Delay Analysis

Flexible Pavement Analysis

The Flexible Pavement Analysis module facilitates analysis and design of flexible pavements with TriAx and biaxial geogrids. The design for biaxial geogrids follows CALTRANS Guide for Design of Pavement (Caltrans 2012). The guide recommends using a layer of biaxial geogrid for the base course thickness less than equal to 18”. The maximum allowable subgrade stiffness is R-Value of 40 which is equivalent to the modulus of 8800 psi. Christopher et al. (2010) provided a chart to convert R-Value (California) to modulus.

In this Flexible Pavement Analysis module, the base course thickness for the stabilized section is reduced in such a way that the stabilized section and the unstabilized section have the same traffic life (ESALs). The thickness reduction is based on the subgrade stiffness and type of geogrid. Examples of inputs and outputs for flexible pavement analysis are shown in Figure 33 and Figure 34.

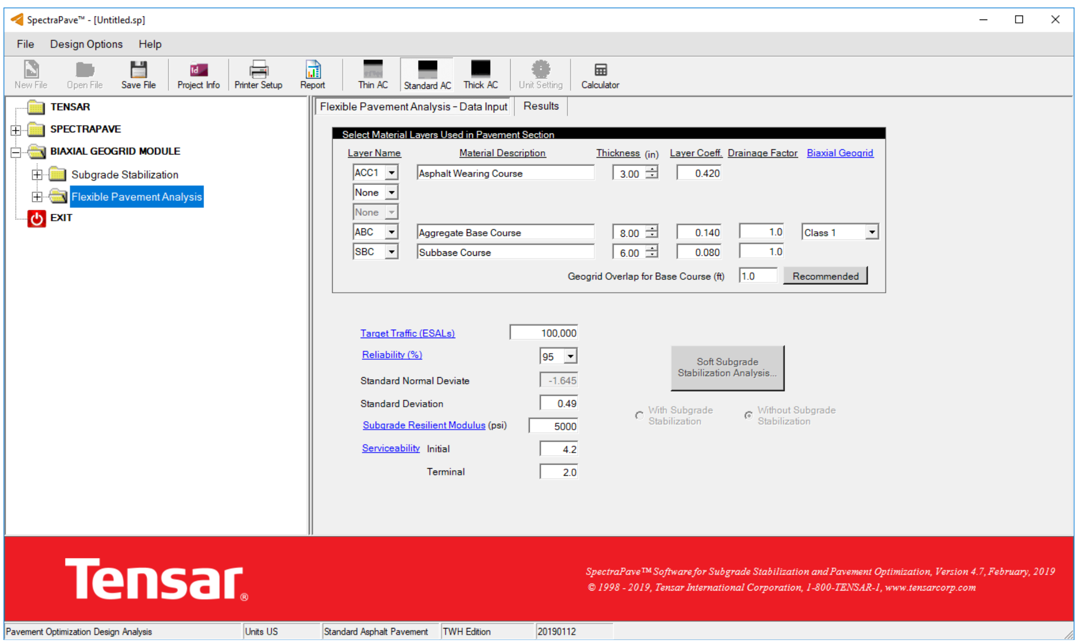


Figure 33: Flexible Pavement Analysis Inputs

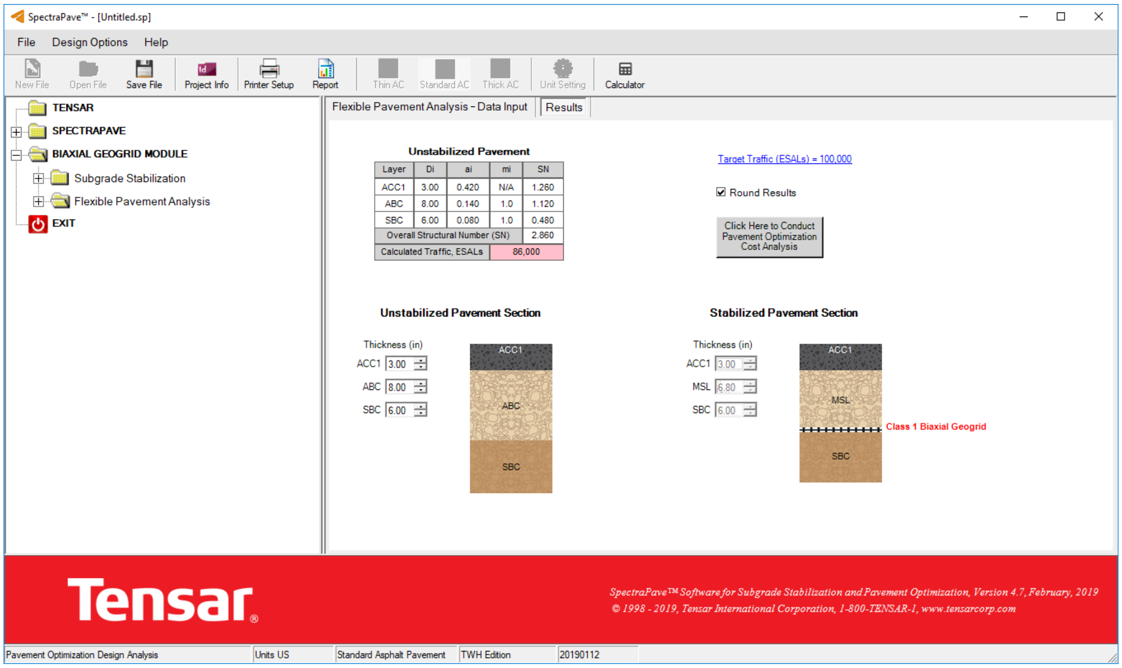


Figure 34: Flexible Pavement Analysis Results

Other Features

Update Facility

The “Updates” feature is devised to allow users to make sure that the most recent version of SpectraPave is in use. The user can activate it by pressing the “Updates” button, located at startup of the software (see Figure 35). The update occurs automatically as long as the computer is connected to the internet.

Figure 35: Updating SpectraPave

When the “Updates” button is selected by the user, SpectraPave automatically compares the version on Tensar’s web site (www.tensarcorp.com) to the one in use. If there is a newer version available, the user will be prompted to download the latest files for an upgrade and is then guided through the process by a set of dialog boxes.

Save File Feature

By selecting the appropriate icon on the toolbar or choosing the save option on the File menu, the user can either create, revise or over-write an existing file. To open a previously saved file or create a new file the user will need to select the home button. Once selected the user has access to these buttons.

Printing

By selecting the appropriate icon on the toolbar (see Figure 36) or choosing the print option on the File menu, printing of the design and/or analysis output can be performed at any point within the design process. If the user- and project-specific information has not been entered in the software, the user will be prompted to do so and will then select the required set of analyses for printing.

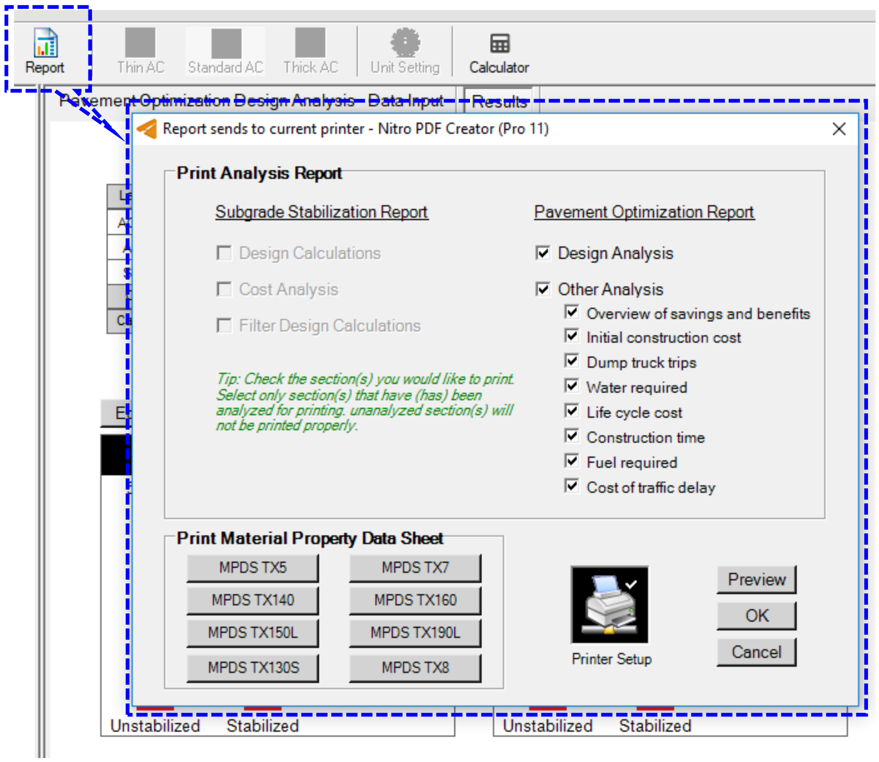


Figure 36: Printing Reports

Help Section

The Help section provides access to resources related to the theoretical background and operation of SpectraPave. Case studies and additional technical information can be downloaded from the TIC web site, *www.tensarcorp.com*, or by calling TIC at 800-TENSAR-1.

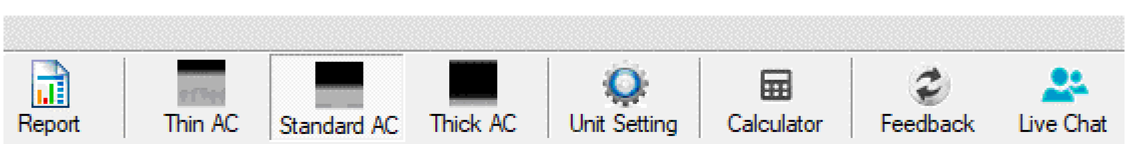


Figure 37. Feedback and Live Chat Tools

Feedback

New to SpectraPave is our "Feedback" feature introduced under the Help Section and in the toolbar (see Figure 37). The feedback feature enables users to provide comments or questions regarding SpectraPave. Upon clicking "Feedback", the software will redirect you to a weblink hosted by Tensar. This feature can also be used to report issues or problems related to the SpectraPave software.

Live Chat

Live Chat (see Figure 37) allow SpectraPave users to instantaneously interact with the Tensar representative and get additional information about the software. If the request of Live Chat is made after regular business hours, the user will be asked to leave a message and the Tensar representative will respond the next business day.

Layout

The recommended screen resolution is 1920x1080 and "scale and layout" of 100% (see Figure 38) for the best viewing experience. This feature can be accessed from computer's display setting (Windows Setting>System>Display).

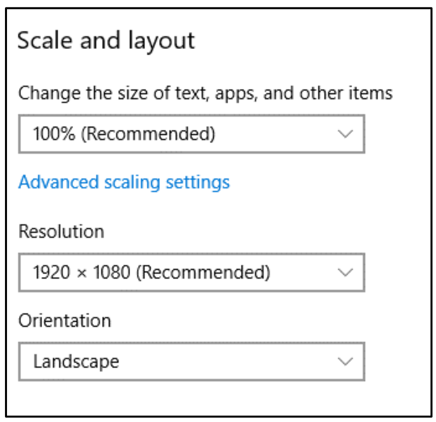


Figure 38: Recommended Screen Resolution and "Scale and Layout"

Unit Setting

SpectraPave can be used either in "English" or in "Metric" units. The selection of "Unit" should be done before starting any module (see Figure 39).

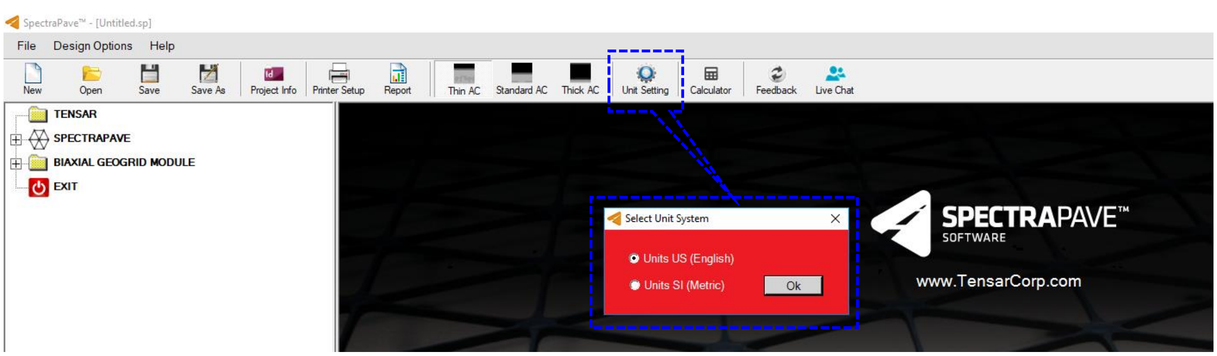


Figure 39: Unit Selection

For additional SpectraPave support, please contact:

Tensar International Corporation
2500 Northwinds Pkwy, Suite 500
Alpharetta, GA 30009
1-800-TENSAR-1

http://www.tensarcorp.com

References

AASHTO, (1993), AASHTO Guide for Design of Pavement Structures; Part I, Chapter 3: Economic Evaluation of Alternative Pavement Design Strategies,

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

AASHTO. (2010)."Recommended Practice for Geosynthetic Reinforcement of the Aggregate Base Course of Flexible Pavement Structures." AASHTO Publication R50-09. American Association of State Highway and Transportation Officials, Washington, D.C.

Al-Qadi, I. L., Dessouky, S. H., Kwon, J. and Tutumluer, E. (2008). "Geogrid in Flexible Pavements: Validated Mechanism," Transportation Research Record 2045, TRB, National Research Council, Washington, DC, USA, pp. 102-109.

Barksdale, R.D., Brown, S.F. & Chan, F. (1989). "Potential Benefits of Geosynthetics in Flexible Pavement Systems." National Cooperative Highway Research Program Report 315. Transportation Research Board, Washington, D.C.

Brown, S.F., Jones, C.P.D. & Brodrick, B.V. (1983). "Use of Non-Woven Fabrics in Permanent Road Pavements." Proceedings of the Institution of Civil Engineers, Part 2, Volume 73, pp. 541-563. London, England, United Kingdom.

Caltrans (2012). "Aggregate Base Enhancement with Biaxial Geogrids for Flexible Pavements Guidelines for Project Selection and Design". California Department of Transportation, Pavement Program, Office of Concrete Pavements and Pavement Foundations

Collin, J.G., Kinney, T.C. & Fu, X. (1996). "Full Scale Highway Load Test of Flexible Pavement Systems with Geogrid Reinforced Base Courses." *Geosynthetics International* , Vol. 3, No. 4, pp. 537-549.

Christopher, B. R., Schwartz, C. W., & Boudreau, R. L. (2010). *Geotechnical aspects of pavements: Reference manual*. US Department of Transportation, Federal Highway Administration.

Fannin, R.J. & Sigurdsson, O. (1996). "Field Observations on Stabilization of Unpaved Roads with Geosynthetics." *Journal of Geotechnical Engineering,* Vol. 122, No. 7, pp. 544-553. American Society of Civil Engineers.

FHWA, (1998), Life Cycle Cost Analysis in Pavement Design, Publication No. FHWA-SA-98-079.

FHWA, (2008) Geosynthetic Design & Construction Guidelines, Publication No. FHWA NHI-07-092.

Gabr, M. (2001). "Cyclic Plate Loading Tests on Geogrid Reinforced Roads." Research Report to Tensar International Corporation., NC State University.

Giroud, J.P. & Han, J. (2004a). "Design Method for Geosynthetic-Reinforced Unpaved Roads: Part I – Development of Design Method." *Journal of Geotechnical and Geoenvironmental Engineering*, in press. American Society of Civil Engineers.

Giroud, J.P. & J. Han. (2004b). “Design Method for Geosynthetic-Reinforced Unpaved Roads: Part II – Calibration and Applications.” *Journal of Geotechnical and Geoenvironmental Engineering*, in press. American Society of Civil Engineers.

Giroud, J.P. & L. Noiray. (1981). “Geotextiles-Reinforced Unpaved Road Design,” *Journal of Geotechnical Engineering*, Vol. 107, No. 9, pp. 1233-1253. American Society of Civil Engineers.

Giroud, J.P., Ah-Line, C. & Bonaparte, R. (1985). “Design of Unpaved Roads and Trafficking Areas with Geogrids.” Proceedings of Polymer Grid Reinforcement Conference, pp. 116-127. Thomas Telford Ltd., London, England, United Kingdom,.

GMA (2000). GMA White Paper II: Geosynthetic Reinforcement of the Aggregate Base/Subbase Courses of Pavement Structures. Geosynthetic Materials Association, Industrial Fabrics Association International.

J. Han, J. (2013). “Experimental Study of Innovative Geogrid Products for Subgrade Improvement,” Research Report to Tensar International Corporation., University of Kansas.

Jiang, Y. (2001). Estimation of traffic delays and vehicle queues at freeway work zones. In 80th Annual Meeting of the Transportation Research Board, Washington, DC.

Knapton, J. & Austin, R.A. (1996). “Laboratory Testing of Reinforced Unpaved Roads,” *Earth Reinforcement*. Ochiai, Yasufuku, and Omine (eds). Balkema, Rotterdam.

Kwon, J. and Tutumluer, E. (2009). “Geogrid Paved Applications with Aggregate Interlock and Modeling of the Associated Stiffness Enhancement in Mechanistic Pavement Analysis,” Presented at the 88th Annual Meeting of Transportation Research Board (TRB), accepted for publication in the Transportation Research Record.

Kwon, J., Tutumluer, E., and Konietzky, H., (2008). “Aggregate Base Residual Stresses Affecting Geogrid Reinforced Flexible Pavement Response,” International Journal of Pavement Engineering, Volume 9, Issue 4, pages 275-285.

Mallela, J., & Sadavisam, S. (2011). Work Zone Road User Costs: Concepts and Applications. US Department of Transportation, Federal Highway Administration.

Perkins, S.W. & Ismeik, M. (1997). “A Synthesis and Evaluation of Geosynthetic-Reinforced Base Layers in Flexible Pavements: Part I.” *Geosynthetics International*, Vol. 4, No. 6, pp. 549-604.

Perkins, S.W. (1999). “Geosynthetic Reinforcement of Flexible Pavements: Laboratory Based Pavement Test Sections.” Final Report, FHWA/MT-99-001/8138. United States Department of Transportation, Federal Highway Administration, Washington, D.C.

Pray, R. (2017). National Construction Estimator 2017, 65th Edition. Craftsman Book Company.

Steward, J., Williamson, R. & Mohney, J. (1977). “Guidelines for Use of Fabrics in Construction and Maintenance of Low-volume Roads.” Report FHWA-TS-78-205. United States Department of Transportation, Federal Highway Administration, Washington, D.C.

Tensar (1996). “Design Guideline for Flexible Pavements with Tensar Geogrid Base Layers.” Tensar Technical Note, TTN: BR96, p. 77. The Tensar Corporation, Atlanta, Georgia.

Tensar (1998). “Design Guideline for Unpaved Applications under Dynamic Loading with Tensar Geogrids.” Tensar Technical Note, TTN:BR5, p. 30. The Tensar Corporation, Atlanta, Georgia.

Watts G.R.A., Blackman, D.I. & Jenner, C.G. (2004). “The Performance of Reinforced Unpaved Sub-bases Subjected to Trafficking.” Proceedings of the Third European Geosynthetics Conference. Munich, Germany.

Wayne, M.H., Boudreau, R.L., and Kwon, J. (2011b). “Characterization of a mechanically stabilized layer using resilient modulus and permanent deformation testing,” *10th International Conference on Low-Volume Roads*, Lake Buena Vista, Florida**.**

Wayne, M.H., Kwon, J. and Boudreau, R.L. (2011c). “Resilient Modulus, Repeated Load Permanent Deformation and Plate Load Testing of a Mechanically Stabilized Crushed Miscellaneous Base material,” Transportation Research Board, 90th Annual Meeting, Washington, D.C.

Wayne, M.H., White D.J., and Kwon, J. (2011a). “Field and Laboratory Evaluation of a Mechanically Stabilized Salvaged Base Course Used in the Construction of US 12 Marmarth, North Dakota,”, 2011 Mid-Continent Transportation Research Symposium, Iowa State University, Ames, Iowa.

Webster, S.L. (1992). “Geogrid Reinforced Base Course for Flexible Pavements for Light Aircraft: Test Section Construction, Laboratory Tests and Design Criteria.” US Army Corps of Engineers Report No. DOT/FAA/RD-92-25. United States Army Corps of Engineers, Washington, D.C.

Webster, S.L. (2000). Personal Communication with Mr. Robert B. Anderson. Tensar International Corporation.

White, D.J., Vennapusa, P.K.R., Gieselman, H.H., Douglas, S.C., Zhang, J. and Wayne, M.H. (2011). “In-Ground Dynamic Stress Measurements for Geosynthetic Reinforced Subgrade/Subbase,” Geo-Frontiers, Dallas, Texas.

White, D.W. (1990). “Literature Review of Geotextiles to Improve Pavements for General Aviation Airports.” US Army Corps of Engineers Report No. DOT/FAA/RD-90/26. United States Army Corps of Engineers, Washington, D.C.