White Paper

TRIAX GEOGRID BENEFITS IN PAVEMENT CONSTRUCTION

Developed for

Tensar®

Tensar International Corporation

By

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VOLUME 1

TRIAX GEOGRID BENEFITS IN PAVEMENT CONSTRUCTION

Table of Contents

VOLUME 2

DETAILED STUDIES ON TRIAX GEOGRID BENEFITS IN PAVEMENTS

1 INTRODUCTION

1.1 Purpose and Scope of the Evaluation

This white paper discusses the benefits of using TriAX® geogrids in the design of pavements. For evaluating the effectiveness of TriAX® geogrids in a pavement structure this paper reviewed the proof-of-concept from previous works that included:

- Laboratory-testing,
- Analytical analyses using numerical simulations,
- Heavy Vehicle Simulator Testing in accordance with NCHRP 512[1] and 325 [2], and
- Field testing in accordance with AASHTO R-50[3].

Incorporating geogrids for the stabilization of granular material layers within pavements has been accepted for many years. Geogrids have been found to be effective in base and subbase enhancement (stabilization); through aggregate interlock and confinement mechanisms. The aggregate interlock and confinement have been shown to be critical in providing long-term aggregate base layer stability and permanent deformation resistance. The Mechanically Stabilized Layer (MSL) resulting from the aggregate interlock and stiffening of the aggregate base matrix improves layer mechanical properties needed for long-term pavement performance. This paper discusses flexible, composite and rigid pavements. To provide a complete proof-of-concept for the effectiveness of the triaxial geogrids, the presentation in this paper has been structured to complete a full loop that includes:

- TriAx geogrid applications in pavements,
- Benefits of TriAx enhanced pavements, and
- The approval process with Caltrans.

1.2 Literature Review

This section provides a summary of studies using geogrids for stabilizing pavement structures. The presentation of these studies in this section has been organized into various areas:

- Laboratory testing (Volume 1.1),
- Numerical evaluation (Volume 1.2),
- Accelerated pavement testing (Volume 1.3), and

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[1] http://www.trb.org/Publications/Blurbs/153774.aspx

[2] http://www.trb.org/Publications/Blurbs/153349.aspx

[3] AASHTO R 50. Standard Practice for Geosynthetic Reinforcement of the Aggregate Base Course of Flexible Pavement Structures

- Field studies (Volume 1.4).

1.2.1 Laboratory Testing

Small Scale Box Testing

The Tensar Small Scale Trafficking Facility (shown in Figure 1) was built to investigate trafficking performance between different types of geogrids and the way in which the geogrids function in stabilization. The Tensar trafficking facility allows for the development of performance data for various geogrids before using larger and more costly accelerated trafficking facilities such as the US Army Corps facility in Vicksburg, Mississippi with the Heavy Vehicle Simulator (HVS).

Figure 1. The Tensar Small Scale Trafficking device in service, with pressure applied by the tire of ~600 kPa equivalent to that of conventionally loaded truck tire.

The test device and procedures are well-suited for quantifying levels of performance within geogrid families, and to understand how variations in product properties (i.e., rib height, aperture geometry, stiffness) influence performance. Results from this facility can be used to determine levels of performance for geogrids and can be combined with other full-scale tests of related products to reliably predict performance for design purposes. Volume 1.1 presents the detailed results of the small-scale box test used for testing geogrids effectiveness. The results presented in Figure 2 demonstrated about a 30% to 50% reduction in subgrade rut depth using TriAx geogrid and compared to a Bi-Axial geogrid and the control section (unreinforced).

Figure 2. Surface and subgrade rutting after trafficking. The top series shows the surface, and the bottom series shows subgrade rutting after removing the base and geogrid.

Large Scale Triaxial Compression Tests

Large scale triaxial compression tests (specimen size 0.5 m diameter × 1.0 m height) with a vacuum-applied confining stress were performed on crushed rock with and without TriAx geogrid; Figure 3. The TriAx geogrid was placed at the mid-height of the specimen. This test demonstrated the influence TriAx geogrid has on the material above and below the geogrid plane.

Figure 3. Large scale triaxial compression test on 1.0 m high and 0.5 m diameter specimen.

Figure 4 presents the typical plots of the deviatoric stress against the axial strain at 40 kPa confining stress with and without geogrid. The results demonstrate the enhanced shear strength that the TriAx geogrid provides. Additionally, the results show the increased ductility upon using TriAX geogrid.

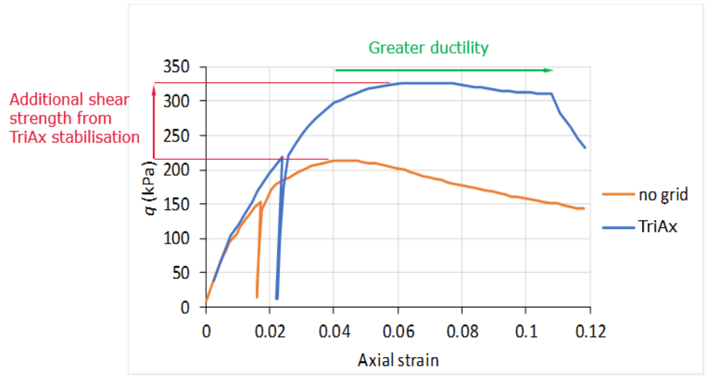

Figure 4. Results of large scale triaxial compression test showing shear strength as function of axial strain.

Volume 1.1 presents the published paper documenting these findings.

1.2.2 Numerical Evaluation

Numerical analysis of aggregate particle movements around geogrids can help explain the mechanisms involved in geogrid reinforcement and shed more light into the benefits of incorporating geogrids in aggregate base layers of pavement systems. For this purpose, the distinct element method (DEM) (Cundall and Strack 1979)[4] has often been used as a numerical technique for computing the motion of individual particles and the forces between particles within a system of geogrid-reinforced or unreinforced aggregate materials. The DEM applies Newton's laws of motion to the particles (Hart and Cundall 1992)[5]; so it differs from the finite element method (FEM) that models the continuum problem rather than simulating the interaction between distinct particles. In this regard, DEM offers an effective advanced numerical tool to quantify the interaction of the aggregate particles with the geogrid-

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[4] Cundall, P. and O. Strack, (1979), "A Discrete Numerical Model for Granular Assemblies," Geotechnique, 29(1):47-55.

[5] Hart, D. and P. Cundall, (1992), "Microcomputer Programs for Explicit Numerical Analysis in Geotechnical Engineering," International Seminar on Numerical Methods in Geomechanics, Moscow, Russia.

aggregate system. In the following, results from major numerical simulations of aggregate-geogrid interactions are presented as a proof of concept for aggregate reinforcement by geogrids.

Volume 1.2 presents a paper titled "*Discrete element modeling of trafficked sub-base stabilized with biaxial and multi-axial geogrids to compare stabilization mechanisms*".[6] This paper shows the benefits of a multi-axial geogrid under traffic loading as well as the benefit of TriAx geogrid over a Bi-Axial geogrid. Key findings from this numerical analysis include:

- Geogrids experience nominal (less than 0.7 kN/m) tensile and compression stresses when loaded; with the stresses on the TriAx being less.
- Strains experienced with TriAx system are less than 0.5%.
- The TriAx geogrid transfers forces from the granular particles in the near circular shape of the concentric hexagons formed in the geogrid, as schematically illustrated in Figure 5

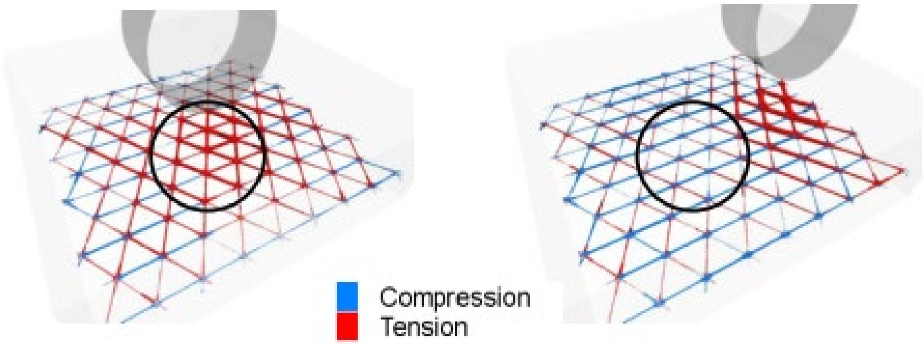

Figure 5. Compression and tension forces experienced by the TriAx geogrid.

Volume 1.2 also presents a paper that documents the benefits of TriAx Geogrid using FEM: "*Simulation of Geogrid Stabilisation by Finite Element Analysis"* [7]. A key finding of this research shows that TriAx stabilized materials exhibit higher shear strength than non-stabilized materials. Figure 4 above illustrates the increase in the shear strength and ductility of mechanically stabilized layer when TriAx geogrid is combined with aggregate base. The TriAx in the material restrains the soil particles against translation and rotation in and around the TriAx apertures; resulting in an increase in the shear strength of the stabilized gravel.

1.2.3 Accelerated Pavement Testing with a Heavy Vehicle Simulator

It is difficult to design laboratory evaluations that account for the real environmental, traffic, and subgrade soil capacity conditions that are normally experienced in actual pavement structures

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[6] Jas, H., M. Stahl, H. Konietzky, L. teKamp, and T. Oliver, (2015), "Discrete Element Modeling of a Trafficked Sub-Base Stabilized with Biaxial and Multi-Axial Geogrids to Compare Stabilization Mechanisms," Geosynthetics, Portland, OR.

[7] Lees, A.S. 2017. Simulation of geogrid stabilisation by finite element analysis. *19th Int. Conf. Soil Mech. Geotech. Engng., Seoul, 17–22 September*. Pp. 1377-1380. https://www.issmge.org/uploads/publications/1/45/06-technical-committee-08-tc202-13.pdf

and under field settings. Therefore, larger-scale studies become preferable when quantifying the actual benefits of geogrids for improving pavement performance. Additionally, scaling-up limitations can become critical in evaluations carried out in typical laboratory settings which rely on relatively small sample sizes. In contrast, accelerated pavement testing with a heavy vehicle simulator (HVS) in a large-scale setting can offer greater flexibility in designing experiments and can bring testing closer to a real field setting.

The TriAx geogrid-enhanced designs are validated in accordance with the Caltrans Accelerated Pavement Testing (CAL/APT) Validation Process illustrated in Figure 6. As shown in the diagram to the right, the TriAx NSSP geogrids were first evaluated with a significant amount of numerical analyses and laboratory tests as discussed in section 1.2.1 and 1.2.3 of this paper. Laboratory testing evaluated performance characteristics of reinforced and unreinforced unbound materials including small-scale testing (e.g., resilient modulus tests) or large-scale testing (e.g., using full-scale box testing). Several published papers demonstrating how Triaxial (hexagonally shaped aperture) geogrids perform superior to Biaxial (rectangular/square shaped aperture) geogrids, include (i) numerical analysis, and (ii) Discrete element modeling. The results from these laboratory tests were used to predict results for the HVS analyses. As a proof of concept, Accelerated Pavement Testing (APT) provides a practical understanding of long-term performance before installation in actual projects such as a state highway system. Tensar performed 3 phases of accelerated pavement testing using the HVS on flexible pavements with TriAx geogrid MSL's conducted at the U.S. Army Engineer Research and Development Center (ERDC) to study stiffness and permanent deformation. This research was in compliance with the National Cooperative Highway Research Program (NCHRP) Report 512 and Synthesis 325. Testing was

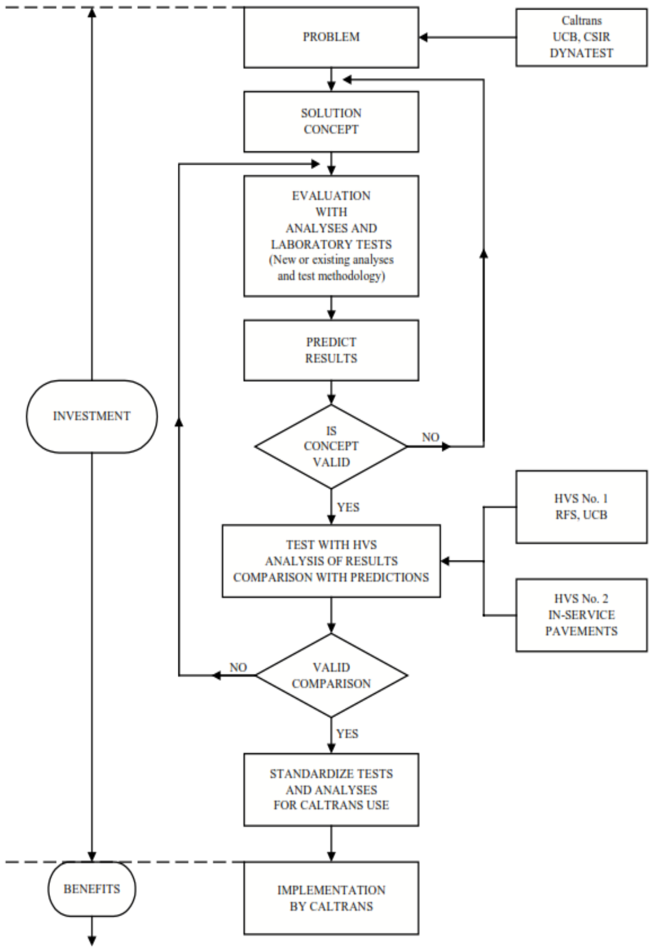

Figure 6. Flowchart illustrating the generalized concept of the Caltrans Accelerated Pavement Testing (CAL/APT) Validation Process.

performed on paved structures with varying subgrade strengths. Performance of pavement sections was evaluated with standard highway moving wheel loads. Geogrid reinforced sections with thinner asphalt and/or aggregate base sections were compared to a control (unrienforced) section with thicker asphalt and/or thicker aggregate base section.

The APT studies showed the superior performance of the TriAx geogrid reinforced pavements compared to the unreinforced pavements; resulting in enhanced aggregate base layer strength coefficients. Volume 1.3 presents summaries of the APTs.

The accelerated pavement testing results were used to predict field performance and develop design methods for incorporating geogrids into pavement sections. Additionally, enhanced pavement sections with geogrids have been compared to corresponding control sections in compliance with AASHTO R50, using Automated Plate Load Testing (APLT) to provide further validation of the effectiveness of the TriaAx geogrid-reinforced section.

1.2.4 Field Studies

In accordance with AASHTO R 50-09, the assumptions used in the pavement section designs are validated with field verification. TriAx designs are regularly validated using observational methods such as Pavement Condition Index (PCI) studies as well as field tests using Automated Plate Load Testing (APLT) equipment. APLT is a system developed to perform fully automated static and repetitive/cyclic plate load tests, per AASHTO and ASTM test methods to accurately measure the resilient modulus of each layer of the pavement structure. The resilient modulus (Mr) values are used in both rigid and flexible pavement design. Volume 1.4 presents results from Tensar's field validation studies.

Field studies confirm the finding from laboratory testing, numerical parametric analysis, and Accelerated Pavement Testing. Section 2.4 of this paper; Rigid Pavements, presents an example of this validation.

1.2.5 Bi-Axial Geogrid Compared to Tri-Axial Geogrid

The hexagonal confinement that is uniquely and exclusively achieved with a triangular geogrid offers the densest achievable arrangement of aggregate particles. The significantly denser arrangement, tighter confinement, stronger matrix, and more uniform support established by the TriAX®-MSL compared to conventional geogrid-aggregate layer offer all the key elements for the good and lasting performance of flexible, rigid and composite pavements.

Biaxial geogrids have been experimentally shown to be inadequate in transferring tensile strength benefits in the transverse direction of the load application direction. Only a very small fraction of strength was transferred. In contrast, the triaxial geogrid transferred; owing to the triangular apertures and hexagonal rib connectivity, as much tensile stiffness in the transverse direction of the geogrid as in the loading direction. Again, this demonstrates the triaxial geogrids superiority over biaxial geogrid in base layer reinforcement.

Axisymmetric (isotropic) aggregate confinement in an aggregate base or subbase layer is essential for providing multidirectional strength uniformity. Triaxial geogrids uniquely offer loading non-directionality benefits making them efficiently superior to conventional biaxial geogrids in responding to sudden random changes in loading directions.

2 TRIAX GEOGRID APPLICATION IN PAVEMENTS

2.1 Project Challenges

Many projects are confronted with challenges including:

- Constrained work areas that limit staging areas for storing roadway materials,
- Short working windows,
- Exporting material that contributes to traffic congestion, increased vehicle emissions and increased risk for project delays,
- Constructability issues with varying planned subgrade elevations, and
- Potential impacts to shallow utilities.

2.2 Enhanced Pavement Section Description

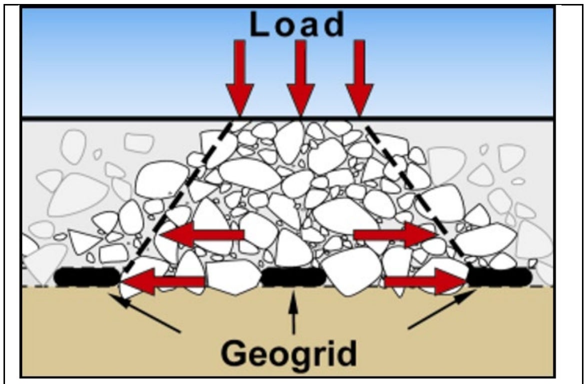

Figure 7. Schematic of geogrid confining aggregate base creating mechanically stabilized layer (MSL).

The purpose of an enhanced pavement section is to alleviate some of the project challenges and reduce the risk of the pavement's structural failure. The enhanced pavement sections consist of creating a Mechanically Stabilized Layer (MSL) below the wearing surface of the planned pavement sections. The MSL consists of the contractor installing geogrid at the subgrade elevation, as illustrated in Figure 7. The addition of geogrid interlocks and stiffens the aggregate base layer creating a an MSL that is resistant to rutting, aggregate base modulus degradation, and provides more uniformity than a pavement section without geogrid. The optimized Tensar geogrid sections will create an enhanced pavement that:

- Reduces roadway section thickness; thereby reducing export of on-site material and import of aggregate base,
- Improves pavement performance and longevity by providing more uniform pavement support characteristics, which reduce the potential for pavement distress, and
- Reduces environmental impact and construction time as an ancillary benefit of the items above.

2.3 Flexible Pavement and Composite

Tensar International Corporation (TIC) developed methods to design enhanced pavement sections using design methodologies prescribed in *Chapter 630*[8]*, Flexible Pavement* of the

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[8] http://www.dot.ca.gov/design/manuals/hdm/chp0630.pdf

California Department of Transportation’s *Highway Design Manual* as well as the AASHTO 93 Pavement Design Guide. Using geogrid to enhance the aggregate base layer within a flexible pavement provides performance advantages and[9]design options. The design of flexible pavement sections using geogrid is based on the increase in stiffness and reduced deformation of a mechanically stabilized aggregate layer, as compared to a conventional unbound aggregate base layer. This is accomplished by the geogrid interlocking with and confining the aggregate base. The performance of the aggregate base layer significantly affects the pavements performance. The aggregate base layer is a structural component that protects the subgrades from rutting and deformation; hence when adding TriAx to a pavement section the resulting performance improvement extends the service life of the pavement.

The United States Army Corps of Engineers (USACE) performed three phases of Accelerated Pavement Tests comparing a control section to an enhanced TriAx section. This is in accordance with NCHRP 512 *“Accelerated Pavement Testing: Data Guidelines.”* In general, the enhanced sections demonstrated less rutting. This is the result of increased stiffness of the aggregate base layer and reduced stress on the subgrade. Table 1 presents the results from Phase 3 of the USACE APT along with the enhanced gravel factors measured for the TriAx sections determined from the APT testing. Volume 1.3 presents the results of all 3 Phases of USACE Accelerated Pavement Tests.

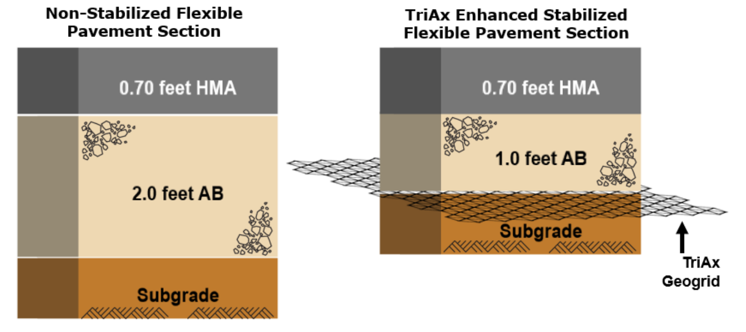
Table 1. Analysis of Phase 3 of the USACE APT

	Units	APT Phase 3		
Section Description	-	Control Section	Enhanced TriAx Section 1	Enhanced TriAx Section 2
Hot Mix Asphalt (HMA	inch	4.0	3.2	3.2
Aggregate Base (AB)	inch	7.7	5.8	5.9
TriAx Geogrid NSSP	-	None	TriAx	TriAx
Traffic Passes to Failure (At ½-inch rut depth)	ESAL	500,000	800,000 +	800,000 +
	Traffic Index[1]	8.29	8.78	8.78
Rut Depth	inch	0.50	0.25	
Subgrade[2]	CBR	5.9		
	R-value	32		
AB GE	Feet	0.71	0.94	0.94
Initial AB Gravel Factor (to account for section thickness reduction and improved traffic passes) [4]	Feet	1.10	1.94+	1.92+
25% Additional AB Gravel Factor (to account for 50% reduction in rut depth)[4]	Feet	-	0.48	0.46
Total: AB Gravel Factor	Feet		2.42	2.40
1-ESAL Equation 2-Correlations based on PCA Chart 3-GE=0.0032*TI*(100-R-Value) 4-AB Gravel Factor = AB Gravel Equivalent/ Thickness of AB (Feet)				

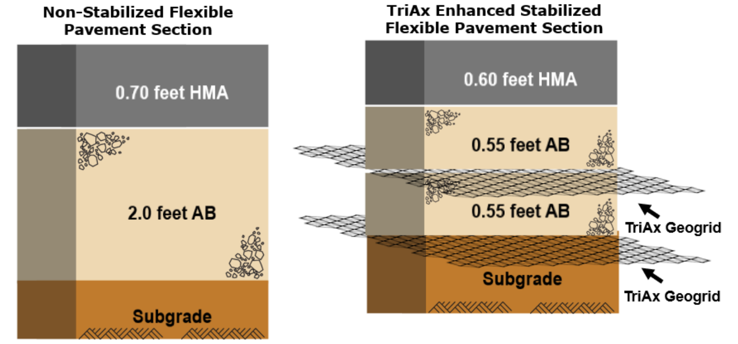
The steps to determine the appropriate gravel factors provided in Table 1 consist of the following:

1- Determining the ratio of the gravel equivalent (GE) required for the given load (ESAL,TI) compared to the actual GE of the tested section. This is necessary to verify that the enhanced sections are being compared to an equivalent control section.
2- Subtracting the GE of the AC from the total GE required to determine the GE of the AB layer
3- Dividing the GE of the AB layer by the thickness of the AB provides the appropriate AB gravel factor (G_f).
4- Improve the AB Gravel Factor by 25% to account for the 50% reduction in rut depth.

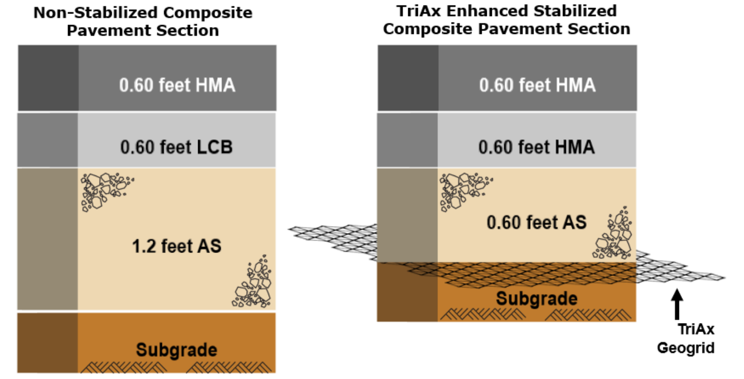
The analysis of the APT results shown in Table 1 demonstrate an enhanced aggregate base gravel factor greater of 2.40. Figure 8 (a, b, c, d) depicts typical sections for a Traffic Index (TI) of 13 and a subgrade soil of R-Value of 20 designed using the validated gravel factors.



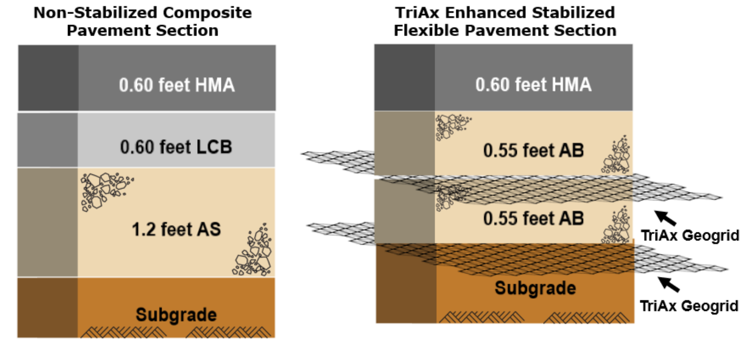
a. Flexible Pavement Section Alternate 1



b. Flexible Pavement Section Alternate 2



c. Composite Section Alternate 1



d. Composite Section Alternate 2

Figure 8. Non-stabilized and TriAX Enhanced Stabilized flexible pavements (a,b) and composite sections (c, d) designed with the Caltrans method using TI=13 and R-Value=20.

2.4 Rigid Pavement

In contrast to flexible pavements, the concrete structural layer of a rigid pavement is placed directly on prepared subgrade or on a layer of granular material. Historically, concrete slabs were placed directly on prepared subgrade, however, as axle loads became heavier and more frequent, pumping became a common distress, and the use of aggregate base became more popular. The use of base layer reduces the critical stresses in the concrete slab. Because concrete strength is significantly higher than that of aggregate base, increasing the concrete thickness by a very small amount can cause same effect as tremendously increasing base thickness. Hence, the use of an aggregate base beneath the concrete does not really benefit the pavement strength as much it does other benefits including: providing a working platform for heavy construction equipment and uniform support for the structural concrete layer. Additionally, in inclement weather the base can keep the surface clean and relatively dry and accessible to construction equipment.

Because fatigue cracking is very common in rigid pavements, structural layer design must analyze principal stresses and strains that develop in the concrete layer. Slab deflections (vertical displacements) above a yielding base greatly affects void development under slabs, and results in faulting, pumping and erosion leading to concrete edge cracking, corner breaks, and spalling. The rigid pavement design must analyze slab displacements and stresses in the supporting base to ensure that concrete thickness and strength are adequate, and the base layer is strong and stable enough to minimize the potential of these distresses.

Performance models that relate concrete pavement distresses to design variables and primary responses are computed from mechanistic models; however, plate theory rather than multilayer elastic theory (MLET) is used (Huang 2003)[10]. In plate theory, the concrete layer is modeled as slab on a Winkler foundation in which the slab is modeled as a plate resting on springs each with a spring constant k represented by the subgrade k-value (also called modulus of subgrade reaction). The k-value is determined with plate loading test. In a multilayered rigid pavement structure, the structure is replaced with an equivalent two-layer (slab and base) pavement section resting on a Winkler foundation having a stiffness characterized by an “effective k-value” which is back-calculated by fitting actual deflections estimated for the actual multilayered structure against the modeled two-layer structure. Distress and performance models are developed with effective k-value as the foundation strength parameter and other design variables including the concrete strength properties. The mechanistic-empirical (ME) process for rigid pavement design uses both the mechanistic models for calculating primary responses (stress, strains, displacements) and performance models to determine required thickness of concrete surface layer. The concrete and base thicknesses are determined in the ME process through iterative procedure until performances at end of design period match a set of selected performance thresholds.

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[10] Huang, Y. H. (2003). Pavement analysis and design, 2nd ed., Pearson Education, Inc., Upper Saddle River, NJ.

As discussed above the concrete layer provides most of the support for the traffic loading and the concrete’s strength minimizes the stresses on the foundation structure below the rigid wearing surface. We understand the California Department of Transportation (Caltrans) as well as many concrete pavement designers consider the planned aggregate base below the rigid section as a working platform and not a structural component:

- In accordance with the Caltrans Highway Design Manual when the underlying subgrade consists of Type II Soils, Subgrade R-Values ranging between 10 to 40 (3,500 psi ≤ Resilient Modulus ≤ 9,500 psi), an aggregate subbase section is recommended to provide:
  - Uniform support, and
  - Additional load distribution.
- When the underlying subgrade consists of Type I Soils, Subgrade R-Values > 40 (Resilient Modulus > 9,500 psi), the aggregate subbase section is not required.

Table 2 provides a summary of a typical section and how TriAx is applied to rigid pavement design.

Table 2. Summary of typical sections of rigid pavements designed with TriAX geogrid.

Approval Status		**Standard**	**Standard**	**Non-Standard Alternative 1**	**Non-Standard Alternative 2**
Pavement Structural Section		JPCP or CRCP	JPCP or CRCP	JPCP or CRCP	JPCP or CRCP
Construction Platform: Bond Breaker (BB) /Lean Concrete Base (LCB) or HMA		BB placed on 0.35 feet LCB or 0.25 feet HMA	BB placed on 0.35 feet LCB or 0.25 feet HMA	BB placed on 0.35 feet LCB or 0.25 feet HMA	BB placed on 0.35 feet LCB or 0.15 feet HMA
Construction Platform: Aggregate Subbase (AS)		None	0.70 Feet	0.35 Feet/ TriAx Geogrid	0.50 Feet/ TriAx Geogrid
Caltrans HDM Subgrade (Table 623.1A)	**Type**	I	II	II	II
	California R-value (R)	R > 40	10 ≤ R ≤ 40	10 ≤ R ≤ 40	10 ≤ R ≤ 40
	Resilient Modulus (Mr)	Mr > 9,500 psi	3,500 ≤ Mr ≤ 9,500	3,500 ≤ Mr ≤ 9,500	3,500 ≤ Mr ≤ 9,500
	Field Trafficking	Subgrade is Firm and Unyielding			

NOTE: Geogrid is only applicable for Type II and III soils only

The increase in the design resilient modulus (Mr) from a Type II material (3,500 ≤ Mr ≤ 9,500) to a Type I material (Mr > 9,500 psi) is accomplished through the increased resilient modulus of the aggregate base/subbase layer with the TriAx geogrid. An example of this research was demonstrated with a test section located along Interstate 5 (Caltrans District 7) in Santa Clarita, California. A contractor constructed the test section within the limits of project area. Figure 9 presents the test sections the contractor constructed to demonstrate the improved Mr of the aggregate base.

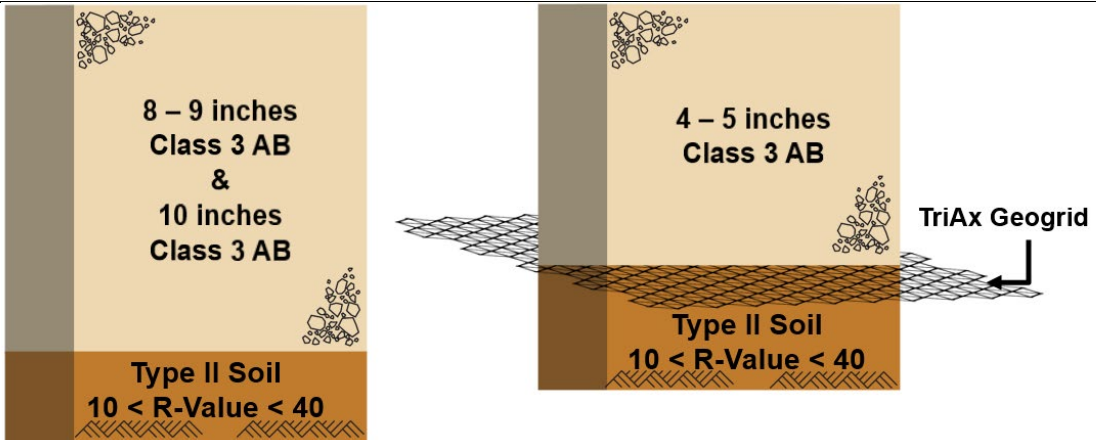

Figure 9. Interstate 5 (Caltrans District 7) Test Sections.

Ingios® performed a series of Automated Plate Load Test's (APLTs) at the subject I-5 site. APLT is a system developed to perform fully automated static and repetitive/cyclic plate load tests, per AASHTO and ASTM test methods. Figure 10 below shows the resilient modulus of the aggregate base versus the applied stress using the 12-inch diameter plate. The results demonstrate how the resilient modulus of the 0.35 feet Class 3 AB section underlain by TriAx geogrid is two times stronger (twice the resilient modulus) as the stress and loading increments increase as compared to the control sections with 0.70 feet Class 3 AB and 0.85 feet Class 3 AB.

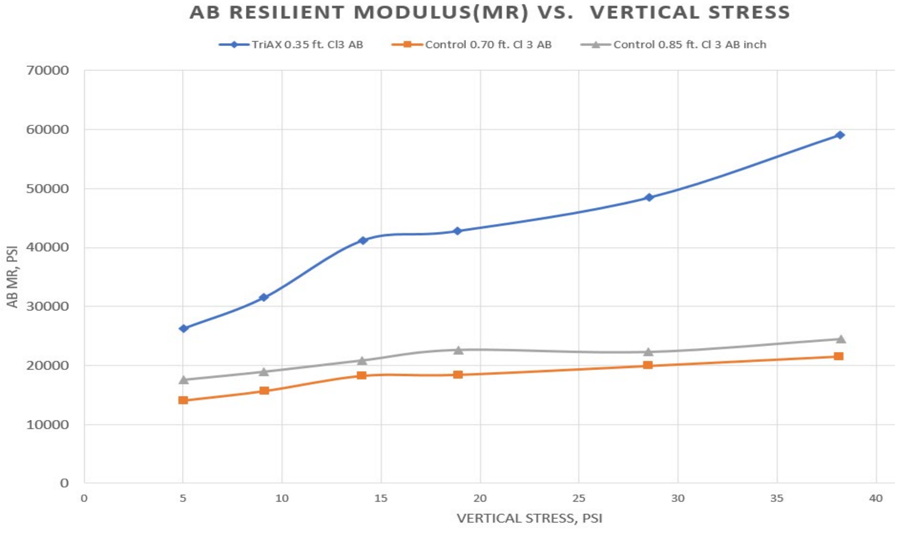

Figure 10. Aggregate base resilient modulus versus applied stress using the 12-inch diameter plate

Figure 11 shows the permanent and recoverable (elastic) deformation measured with a 10,000 cycle plate load test at 15 psi. <u>The 0.35 feet AB TriAx section (Figure 11-right) deformed about</u>

1/3 of the deformation measured within the 0.70 feet AB control section (Figure 11-left) over the 10,000 cycles.

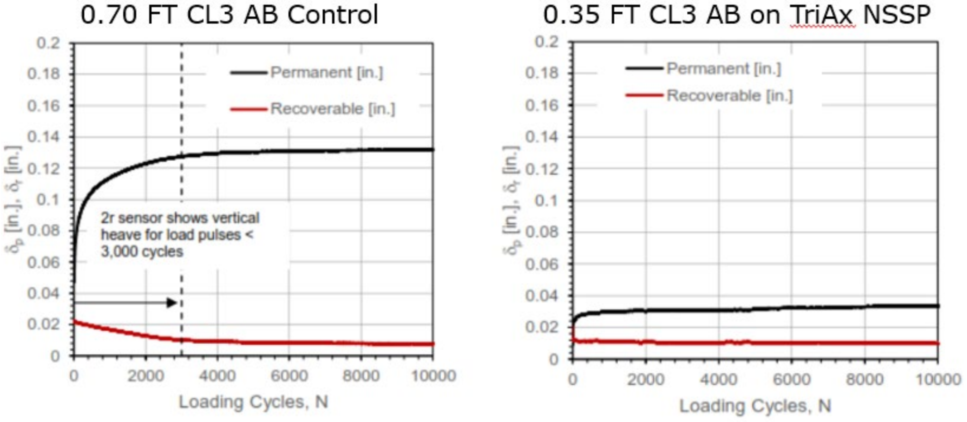

Figure 11. Permanent and recoverable strains with loading cycles. (left) Control section, and (right) TriAx reinforced section.

With less deformation a more uniform surface is created. This uniform surface provides for a non-yielding platform for paving and ultimately provides a better foundation for the rigid pavement.

Another benefit the TriAx provides is the reduced potential of deformation and development of voids below the concrete layer. By controlling permanent deformation, the bending stresses developed within the concrete will be significantly lower.

Ingios® performed finite element analyses (FEA) using the KENSLAB software (Huang 2003). Another example study compared the principal stresses developed in a 10-inch concrete slab underlain by 8 inches (Figure 12) of aggregate base compared to a 10-inch concrete slab underlain by 4 inches (Figure 13) of aggregate base enhanced with TriAx geogrid. As shown in Figure 13, stresses are much lower in the TriAX reinforced section compared to the unreinforced section which contains 4 inches more aggregate base than the geogrid reinforced section. This is clearly observed regardless of the degree of support beneath the slabs characterized by level of support (LOS).

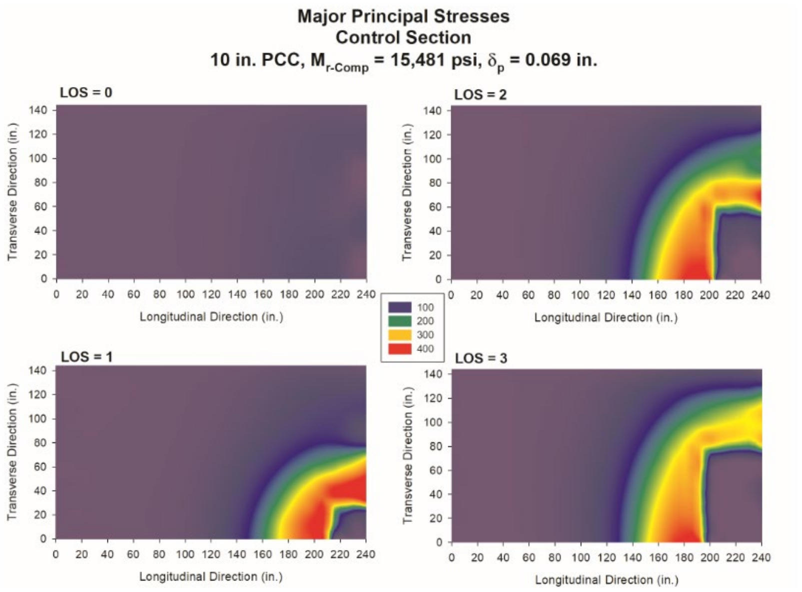

Figure 12. Major principal stresses in control section with 10 inch PCC over 8 inch AB.

3 ESTIMATED BENEFITS OF TRIAX ENHANCED PAVEMENT SECTIONS

The benefits of the geogrid-enhanced pavement sections can be categorized into 3 areas:

- Cost benefits affect initial cost of the project,
- Technical benefits affect long-term performance/service life of the pavements, and
- Construction, operation and maintenance benefits affect construction efficiencies that impact safety and the environment during construction and after construction is complete.

In the following, a brief description of the benefits in all various areas is given.

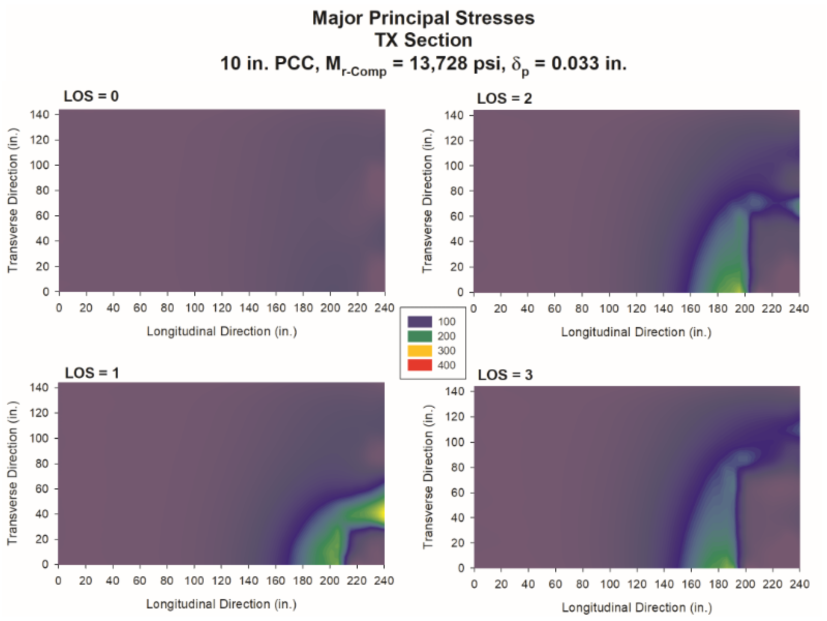

Figure 13. Major principal stresses in TriAX section with 10 inch PCC over 4 inch AB.

3.1 Cost Benefits

Constructing a TriAX-enhanced pavement sections offers immediate cost savings. Tables 3, 4, and 5 summarize cost and materials quantities saved in constructing one lane mile of flexible, composite, and rigid pavements, respectively.

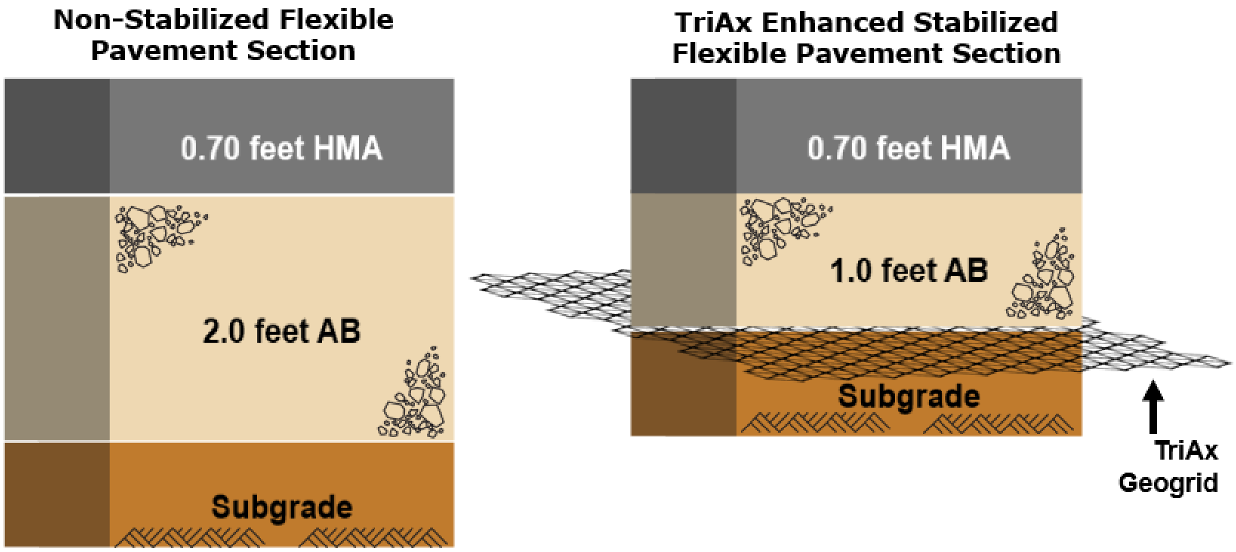

Table 3. Estimated cost and material saving per lane mile of flexible pavement.

Description	Units	TriAx Reduction	Assumptions
Cost	$	*-$150,000 per lane mile*	Installed Costs: $35/CY for export, $25/Ton for Class 2 AB, $3/SY for TriAx Geogrid
Aggregate Base (AB) Import	Cubic Yards	*-2,500*	TriAx Geogrid reduced 1.0 Feet Class 2 AB thickness
Excavation Export	Cubic Yards	*-2,500*	TriAx Geogrid reduced 1.0 Feet Roadway Excavation
Truck Loads	Number	*-420*	Truck Storage Capacity is 10 Cubic Yards per Load
Water	Gallons	*-63,000*	25 Gallons of water per Cubic Yard of Class 2 AB required
Fuel	Gallons	*-1,450*	30 min per truck load at 7 Gallons per Hour
Carbon Output Emissions	Tonnes of CO_2	300	Varies depending on aggregate and export transportation distances.

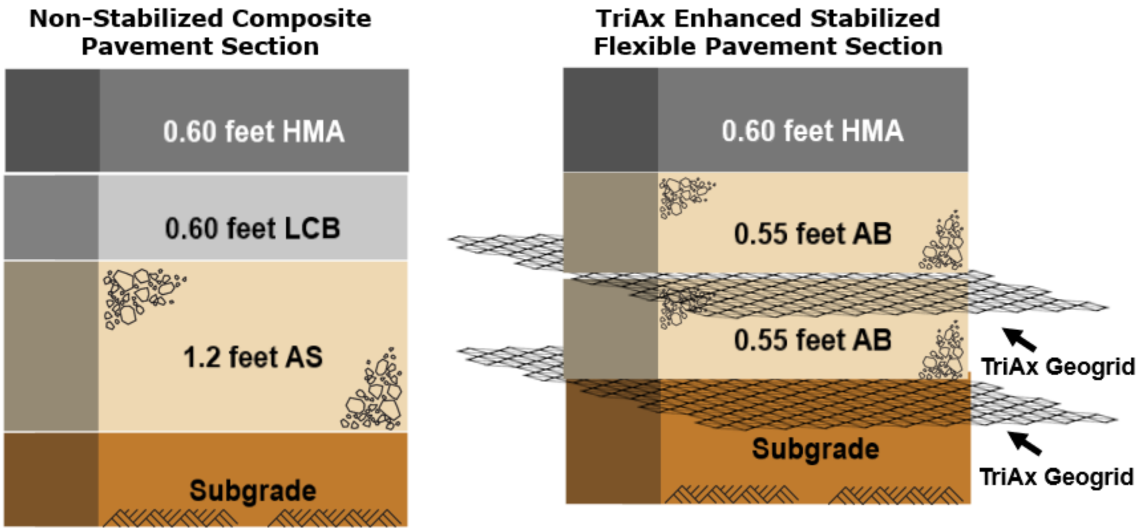

Table 3. Estimated cost and material saving per lane mile of composite pavement.

Description	Units	TriAx Reduction	Assumptions
Cost	$	*-$210,000 per lane mile*	Installed Costs: $120/CY for LCB, $100/Ton for HMA, $35/CY for export, $25/Ton for Class 2 AB, $3/SY for TriAx Geogrid
Learn Concrete Base (LCB)	Cubic Yards	*-1,500*	TriAx Geogrid reduced 0.60 Feet Class 2 AB thickness
Aggregate Base (AB) Import	Cubic Yards	*-250*	TriAx Geogrid reduced 0.10 Feet Class 2 AB thickness
Excavation Export	Cubic Yards	*-1,800*	TriAx Geogrid reduced 0.70 Feet Roadway Excavation
Truck Loads	Number	*-350*	Truck Storage Capacity is 10 Cubic Yards per Load
Water	Gallons	*-44,000*	25 Gallons of water per Cubic Yard of Class 2 AB required
Fuel	Gallons	*-1,000*	30 min per truck load at 7 Gallons per Hour
Carbon Output Emissions	Tonnes of CO_2	150	Varies depending on aggregate and export transportation distances.

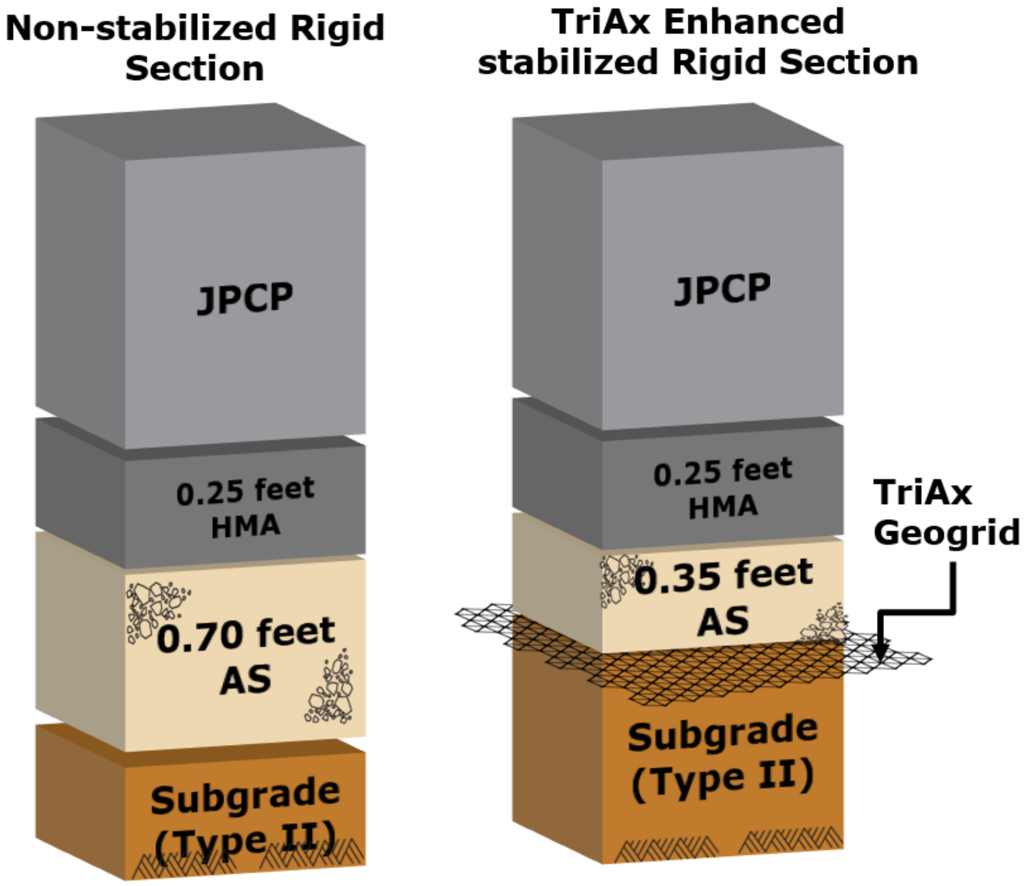

Table 4. Estimated cost and material saving per lane mile of rigid pavement.

Description	Units	TriAx Reduction (Sustainability Enhancement)	Assumptions
Cost	$	-$25,000	Installed Costs: $35/CY for export, $25/Ton for Class 2 AS, $3/SY for TriAx Geogrid
Aggregate Base (AB) Import	Cubic Yards	-890	TriAx Geogrid reduced 0.35 Feet AB/AS thickness
Excavation Export	Cubic Yards	-890	TriAx Geogrid reduced 0.35 Feet Roadway Excavation
Truck Loads	Number	-150	Truck Storage Capacity is 10 Cubic Yards per Load
Water	Gallons	-22,244	25 Gallons of water per Cubic Yard of Class 2 AB required
Fuel	Gallons	-500	30 min per truck load at 7 Gallons per Hour
Carbon Output Emissions	Tonnes of CO_2	85	Varies depending on aggregate and export transportation distances.

3.2 Construction Benefits

Constructing a thinner enhanced pavement section underlain by TriAx Geogrid results in the following benefits:

- *Safety*
  - By minimizing the amount of trucks entering and exiting the construction site,
  - By reducing traffic congestion during construction that can lead to accidents along dedicated haul routes, and
  - By improving work zone safety by reducing time spent during temporary closures for night work and along the traveled way. This is very critical during temporary closures when construction time is limited.

- *Environment*
  - By reducing carbon emissions from all construction vehicles on-site as well as those traveling to and from the site,
  - By reducing water usage due to less earthen materials that will need to be moisture conditioned,
  - By controlling dust control and tracking with fewer trucks and less material being used, and
  - By minimizes tracking of soil on dedicated haul routes.

- *Construction efficiencies*
  - Because aggregate base sections will be underlain by geogrid, compaction of the aggregate base will be achieved faster with more uniformity. This can expedite construction.
  - Because the sections will already be underlain by geogrid, the influence of yielding areas caused by inclement weather can quickly be mitigated without significant construction design changes.

3.3 Operation and Maintenance Benefits

By constructing an enhanced pavement section, the uniformity of the foundation below the pavement wearing surface is improved. This maximizes investments on pavements keeping them in a good working condition.

3.4 Technical Benefits

Constructing enhanced pavement sections stabilized with geogrid create a better pavement by:

- Providing a better performance through:
  - Mechanical interlocking and restraining of the aggregate base,
  - Increased stiffness and stiffness retention of the aggregate base, and
  - Less deformation.
- Reducing risk
  - The stabilized geogrid designs will reduce risk by providing uniform pavement support characteristics minimizing potential for pavement distress.

- Additionally, the risk of lost time from developing methods to mitigate areas such as yielding subgrades are reduces since geogrid will already be on-site and part of the planned pavement section.
- The stabilized geogrid pavement creates a perpetual pavement. A perpetual pavement is a pavement design that begins with a strong, yet flexible bottom layer that resists deformation caused by traffic. This stops cracks from forming in the bottom of the pavement and forces pavement failure to the surface where maintenance can be done. Geogrid creates a strong, yet flexible bottom layer that resists deformation by interlocking the aggregate base material during construction and for the duration of the project. This interlocking of the aggregate base and the geogrid creates what is known as an MSL. The MSL forces the critical component of the pavement structural section to be the wearing surface. This facilitates pavement maintenance and the ability to have a perpetual pavement.

4 APPROVAL PROCESS

4.1 FHWA

4.1.1 Repeal of CFR 635.411 (the “proprietary product rule”) by Federal Highway Administration

The FHWA is revising its regulations at 23 CFR 635.411 to provide greater flexibility for States to use patented or proprietary materials in Federal-aid highway projects. Based on a century-old Federal requirement, the outdated requirements in 23 CFR 635.411(a)-(e) are being rescinded to encourage innovation in the development of highway transportation technology and methods. As a result, State Departments of Transportation (State DOTs) will no longer be required to provide certifications, make public interest findings, or develop research or experimental work plans to use patented or proprietary products in Federal-aid projects. Federal funds participation will no longer be restricted when State DOTs specify a trade name for approval in Federal-aid contracts. In addition, Federal-aid participation will no longer be restricted when a State DOT specifies patented or proprietary materials in design-build RFP documents.

4.1.2 What has changed?

Even though state DOTs typically design and implement road projects, most of the time the majority of the funding (up to 90 percent) comes from the federal government. Because of the patented and proprietary products rule, states almost always avoided the use of patented or proprietary products, due to the additional work required for approval and the fear of losing the federal portion of the project funding. State DOTs can now use patented or proprietary products, reference single trade names in specifications and plans, and specify proprietary products in design-build RFP document, without fear of losing project funding. This provides the opportunity to improve the performance and/or lower the total cost of their projects by using innovative solutions they may have avoided in the past.

4.1.3 Who is affected?

The rule change directly affects state DOTs. Since many local agencies rely on state specifications and guidelines, the rule will also affect practices at the local level. It will be up to the individual states and local agencies how and when they implement this change in their own specifications.

4.1.4 *Additional information: https://www.fhwa.dot.gov/construction/cqit/propriet.cfm*

4.2 Specifications and Project Types

4.2.1 Caltrans non-standard special provision (nSSP)

The TriAX® geogrid has been placed on several Caltrans projects, Volume 2. However, as a non-standard product, the triaxial geogrid placed on Caltrans construction projects uses the established non-Standard Special Provision (nSSP). nSSPs are developed to address site-specific issues that the standards do not adequately cover; or when a technology or product that does not have an approved standard is decided to be used on a project. For Caltrans projects, an nSSP for TriAx geogrid has been frequently used on numerous projects (500+ lane miles) on Caltrans highway system. A copy of the nSSP used on most recent project is included in Volume 3. Comparing index properties for different family types of geogrids (i.e., multi-axial geogrid, biaxial geogrid, uniaxial geogrid) does not correlate to accurate performance comparison. In ground performance studies correlate to accurate performance. Therefore, the specification describes the performance testing validation requirements of Accelerated Pavement Testing (APT) and in-ground performance plate load tests within the state of California. By writing these requirements within the specification, it provides assurance for the designer that the TriAx geogrid has already met the performance requirements to validate the design.

4.2 Using Triaxial Geogrid Reinforced MSL on Caltrans Projects

The use of triaxial geogrid-reinforced MSL system on Caltrans pavement projects may be performed with value engineering change proposal, CCO, and alternative project delivery/contracting methods. These will be discussed below.

4.2.1 Value Engineering Change Proposal (VECP)

Caltrans encourages contractors to develop and implement innovative approaches to construction projects. The Contractor may submit a proposal to Caltrans to reduce any of the following: (1) construction cost savings, (2) reduction in construction activity duration, or (3) reduction in traffic congestion. Section 4-1.07 “Value Engineering”, page 6-14, of the Caltrans’ 2015 Standard Specifications[11] identifies the method and procedure for sharing construction cost savings. A contractor’s proposal made in accordance with this section of the Standard Specifications is called a Value Engineering Change Proposal (VECP). Therefore, the VECP is a post-award value engineering proposal made by construction contractors during the course of construction under a value engineering clause in the contract. The term VECP has a wider scope than the term used previously for such changes, i.e., Cost Reduction Incentive Proposal (CRIP) which is no longer used in contracts or as an industry standard. When new approaches result in construction cost savings, Caltrans and the contractor may share the savings in construction cost.

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[11] http://ppmoe.dot.ca.gov/hq/esc/oe/construction_contract_standards/std_specs/2015_StdSpecs/2015_StdSpecs.pdf

The Contractor’s VECP must include as a minimum the following: (1) Description of the Contract specifications and drawing details, (2) Itemization of Contract specifications and plan details that would be changed, (3) Detailed cost estimate for performing the work under the existing Contract and under the proposed change, and (4) Deadline for the Engineer to decide on the changes, and (5) Bid items affected and resulting quantity changes. Caltrans requires that their project Resident Engineer (RE) provide all communication and written correspondences regarding the VECP, except denials, to the contractor in a timely manner. Based on the 2015 Standard Specifications, if Caltrans accepts the VECP or parts of it, it issues a Change Order that: (1) Incorporates changes in the Contract necessary to implement the VECP or the parts adopted, (2) Includes the Department's acceptance conditions, (3) States the estimated net construction-cost savings resulting from the VECP, and (4) Obligates the Department to pay the Contractor 50 percent of the estimated net savings. If the Caltrans-accepted VECP provides for a reduction in traffic congestion or avoiding traffic congestion, Caltrans will pay 60 percent of the estimated net savings in construction costs attributable to the VECP. Some deductions may apply such as Contractor’s VECP preparation cost and Caltrans’ VECP investigation and administrative costs.

4.2.2 Contract Change Order

A Contract Change Order (CCO) changes the requirements of construction contracts that were previously reviewed and approved through the project development stages of projects. CCOs are required for changing any part of the original contract. The Caltrans Construction Manual[12] lists reasons for which a CCO must be written, including when a change is proposed for contract plans, specifications, or both. The use of triaxial geogrids, if it was not part of the contract in the form of nSSP, will require a CCO written during or before starting construction. Additionally, because the use of triaxial geogrids can reduce project construction costs, expedite construction, and reduce traffic congestion as a result, its use on a contract being executed will most likely be accompanied by a previously approved VECP. In this case, a CCO would be required to implement the VECP or a construction evaluated research proposal. Refer to Section 3-5, “Control of Work,” of the Caltrans Construction Manual for a discussion of VECPs. If the Caltrans Resident Engineer (RE) believes that his/her Department will benefit as much or more by adopting the modifications proposed in the VECP, the Contractor’s VECP will be approved, and subsequently the Contractor’s plan is implemented with a CCO requested by the contractor.

4.2.3 Design Build (DB)

Design-Build (DB) is as an alternative project delivery method that is different from the traditional design-bid-build (DBB) method. Under this method, the project owner executes a single contract for both architectural/engineering services and construction. Both the design and construction of a project are awarded to a single entity. Unlike DBB, DB projects are awarded to either lowest responsible proposer or best value proposer. One of the benefits of DB method is the close contractor-designer relationship; therefore, design changes are made easier and changes are

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[12] http://www.dot.ca.gov/hq/construc/constmanual/

implemented (constructed) faster than if they were attempted under traditional method. Easier and more direct communication between the contractor and designer allows the contractor to have a better control over the project schedule.

Caltrans established a Design-Build Demonstration Program that resides in the HQ Division of Design to help assess the effectiveness of the DB method as a means of delivering Caltrans projects. In early 2009, the state authorized a demonstration program of up to 15 State-funded DB transportation projects. The Caltrans DB process is described in the flowchart at this link http://www.dot.ca.gov/design/idd/db/Proposed-RFQ-RFP-Process-Flowchart.pdf. The process involves the design that has to be fully completed (100% complete), then PS&E is developed, advertised, awarded, then constructed. The use of TriAX®-MSLs offers an opportunity to District engineers to consider this type of contracting because of the nonstandard design of the pavement structure involving this enhanced system. At this time, the Caltrans Geogrid Guide [13]allows up to 20% reduction in aggregate base layer thickness and considers only the use of a biaxial geogrid. Because triaxial geogrids offer greater benefits than the biaxial geogrids, the DB contracting method in which the designer and builder are the same entity can be very helpful in realizing the greater benefits/savings and increased cost-effectiveness of projects involving MSLs.

4.2.4 Construction Manager General Contractor (CMGC)

The CMGC is another alternative contracting method. It allows the project owner to engage a construction manager to provide input during the design process. At some design completion percentage, both the owner and construction manager negotiate a price for construction of the project, and once an agreement reached, the construction manager becomes the general contractor. The use of the CMGC contracting method was authorized by MAP-21 for delivering Federal-aid projects. The California Legislature passed, and the Governor signed into law, Assembly Bill 2498 (Gordon) in 2012 authorizing Caltrans to use CMGC delivery method. As a pilot program, the law authorized Caltrans to use CMGC on up to six projects, and a subsequent legislation provided authority for more projects.

The CMGC project delivery method allows Caltrans to select a contractor early in the project development process to act in an advisory role (e.g., provides constructability reviews, value engineering suggestions, construction estimates, and other construction-related recommendations). At 90 to 95 percent design completion, the CMGC Contractor provides a price to construct the project. If the price is acceptable, the CMGC Contractor becomes the general contractor who will be assigned to construct the project. The Caltrans CMGC procedures for conducting CMGC pilot projects is described at this link: http://www.dot.ca.gov/design/idd/cmgc/Caltrans%20CMGC%20Procedures.pdf. The CMGC Program under the Division of Design is responsible for maintaining these procedures with collaboration with the FHWA California Division. The District identifies and nominates projects

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[13] http://www.dot.ca.gov/hq/maint/Pavement/Offices/Pavement_Engineering/PDF/Aggregate_Base_Enhancement_with_Biaxial_Geogrids_for_Flexible_Pavements_Design_Guide.docx

that would benefit from this alternative project delivery method. The District submits the nominated projects to the Office of Innovative Design and Delivery under HQ Division of Design for assessment and approval. After the assessment is completed and CMGC is found to be appropriate, the project is presented to the Caltrans Alternative Contracting Steering Committee for approval. The CMGC method is still a pilot program but it has been evolving over the last a few years thanks to lessons learned and experiences gained from pilot projects. The districts may consider this type of project delivery method on projects involving the use of triaxial geogrid MSLs as means to reduce long-life cycle cost. This type of contracting methods offers the districts who are unfamiliar with designing and constructing pavements with triaxial geogrid-MSLs access to external expertise who can aid in both design and construction activities.

5 Summary, Conclusions and Recommendations

This paper provided a comprehensive review of geogrids use in pavement construction, with emphasis on the use of the innovative TriAx® geogrid as a critical element for the structural reinforcement of the aggregate base in flexible, rigid, and composite pavements, as well as for addressing yielding subgrade conditions. The inadequacy of the aggregate base layer in a pavement can be detrimental to the pavement performance. Pavement design should direct more attention to the lower (foundation) layers (base, subbase, and subgrade) because any failures can be confined to the surface structural layer that can be repaired and replaced more expediently and at lower cost than trying to address deep layer structural deterioration issues. The benefits of using a TriAX® geogrids in base/subbase layers draw from the equilateral triangular geometry of the geogrid's apertures which offers the geogrid-aggregate system a myriad of structural and stability benefits.

Incorporating a TriAx® geogrid in an aggregate base layer creates a Mechanically Stabilized Layer (MSL) comprised of the monolithic system combining both the aggregate and geogrid components. The TriAx®- MSL established with the use of the combination of properly selected aggregate base and TriAx® geogrid have been shown throughout the paper to provide for numerous benefits. A summary of these benefits is given below. These should be considered by the pavement engineer when designing a new pavement structure (flexible, rigid, composite):

1. Due to perfectly designed aperture and rib geometry (besides strength), TriAx® geogrids deliver a near-optimal confinement to the aggregate particles in the aggregate base or subbase layer. The strong and stable confinement has been observed in extensive research experimental studies (lab-scale, accelerated testing, field scale), and advanced theoretical simulations, to outperform any confinement that could be achieved with conventional biaxial geogrids.
2. The hexagonal confinement that is uniquely and exclusively achieved with a triangular geogrid offers the densest practically achievable arrangement of aggregate particles. The significantly denser arrangement, tighter confinement, stronger matrix, and more uniform support established by the TriAx®-MSL compared to conventional geogrid-aggregate

systems offer all the key elements for the good and lasting performance of flexible, rigid and composite pavements.

3. Besides the confinement and reinforcement superiority of the TriAx® geogrid that delivers the highest possible strength/stiffness benefits, the TriAx® geogrid also offers a strong junction stability that is critical for resistance against in-plane rotational distortion. Advanced simulations have demonstrated that the triaxial geogrid remains almost intact under high shear stresses (ribs did bend and junctions hardly twisted).
4. Axisymmetric (isotropic) aggregate confinement in an aggregate base or subbase layer is essential for providing multidirectional strength uniformity. Triaxial geogrids uniquely offer loading non-directionality benefits making them efficiently superior to conventional biaxial geogrids in responding to sudden random changes in loading directions.
5. Biaxial geogrids have been experimentally shown to be inadequate in transferring tensile strength benefits in the transverse direction of the load application direction. Only a very small fraction of strength was transferred. In contrast, the triaxial geogrid transferred; owing to the triangular apertures and hexagonal rib connectivity, as much tensile stiffness in the transverse direction of the geogrid as in the loading direction. Again, this demonstrates the triaxial geogrids superiority over biaxial geogrid in base layer reinforcement.
6. In a flexible pavement, a TriAx®-MSL provides for a more uniform support and higher resistance to rutting and degradation of aggregate base modulus with time than a pavement section without geogrid. This translates into a better control in the occurrence of local permanent deformations in the form of bumps, corrugations, and depressions that typically occur with non-uniform base support. TriAx®-MSLs can ensure a longitudinal (i.e., along the pavement profile) support uniformity beneath the asphalt concrete layer; thus controlling the occurrence of localized fatigue cracking, voids, local zones of low stiffness material, etc. During construction, the improved aggregate interlock with the TriAx® geogrids can be especially helpful in expediting aggregate compaction and achieving the required (as specified or better) levels of density and stiffness.
7. In a rigid pavement where the base layer does not essentially contribute directly to the pavement load carrying capacity, a TriAx®-MSL ensures long-term performance benefits including integrity and sustained intimate contact between the aggregate base or subbase and the concrete surface layer. This reduces the potential of base erosion beneath the transverse and longitudinal joints in jointed plain concrete pavements (JPCPs) that often contributes to fines pumping and development of voids under JPCP joints. As such, the potential of concrete spalling, joint faulting, loss of load transfer across joints, and longitudinal roughness can be reduced.
8. The non-uniformity of base layer stiffness along the pavement profile is a major contributor to surface roughness and poor ride quality. The isotropic (all around, radial) confinement of the aggregate base achieved through the installation of a TriAx®-MSL system significantly reduces stiffness non-uniformity; thus maintaining ride quality and pavement smoothness.
9. TriAX®-MSL can achieve a fully confined zone at the bottom of the base layer that can simulate an effective separation function that helps prevent materials intermixing at the soft subgrade-base interface. In other words, a TriAx®-MSL can essentially offer the dual function of reinforcement and separation.

10. Owing to the superior near-optimal hexagonal confinement and strength improvement offered by the TriAX®-MSL system, lesser-quality granular materials such as recycled and crushed HMA and/or Portland cement concrete could be used in base layer construction; thus providing for both environmental and economic benefits.
11. In pavement construction projects, utilizing TriAx®-MSLs can offer many advantages to project economic and environmental feasibility, including:
    - Reduced roadway structural sections through reduced aggregate base and/or asphalt concrete layer thicknesses. This has been demonstrated by many projects built on the CA state highway system where tremendous cost saving was realized.
    - Improved pavement performance and longevity.
    - Reduced environmental impact and time savings.
    - Improved safety during construction due to minimizing the number of trucks entering and exiting the construction site, relieving traffic congestion during construction, and improving work zone safety.
    - Improved construction efficiencies due to ability to achieve compaction levels and stabilizing yielding subgrades faster.

The following are some of the recommendations that could be made:

1. The State (Caltrans) should promote increased utilization of triaxial geogrids in aggregate base/subbase reinforcement on their projects to reduce pavement costs (both initial and life-cycle) and gain additional benefits through implementation of the TriAx®-MSL proven technology.

2. Caltrans and Industry should work together to revise the current geogrid Guide that limits the use of geogrids to the conventional biaxial geogrids as a standard product. Many projects were built with the TriAx®-MSL technology on the CA highway systems as was shown in the paper; totaling a minimum of 17,000,000 square foot of TriAx® geogrid installed (~272 lane-miles). Caltrans should benefit from the available experience obtained thus far from these projects and expand the use of this technology throughout the State.

3. The TriAx® geogrid allows for greater reductions in aggregate base layer thickness for an equal performance. Many studies have shown the increased reductions over those allowed at this time with the biaxial geogrids. It is recommended that Caltrans and Industry cooperatively revisit performance studies results and derive fair and reasonable reduction factors for the triaxial geogrids. Applying on triaxial geogrids the same standard aggregate base reduction factors currently allowed for biaxial geogrids does not do the CA taxpayers any good when there is substantial evidence that the triaxial geogrid are capable of delivering much greater structural benefits to the pavement structure than the conventional biaxial geogrid.

Caltrans can benefit from alternative contracting and project delivery methods (such as those currently allowed in pilot programs) in efforts to increase the State's utilization of triaxial geogrids on highway projects. This type of contracting will help enrich Caltrans' familiarity with triaxial geogrids by benefitting from external partner's experiences (in areas of pavement design and construction), while achieving economic, environmental, and traffic congestion relief benefits, and minimizing risk associated with using relatively newer pavement products.