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SUSTAINABLE STABILIZATION OF SULFATE-BEARING SOILS WITH EXPANSIVE SOIL-RUBBER TECHNOLOGY

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16. Abstract

The beneficial use of scrap tire rubber mixed with expansive soils is of interest to civil engineering applications since the swell percent and the swell pressure can be potentially reduced with no deleterious effect to the shear strength of the mixture. The two main objectives of this research were (1) to propose a new subgrade soil stabilization protocol to allow CDOT to rely upon an alternative stabilization method that is not subject to the typical problems associated with calcium-based stabilization of sulfate-rich soils, and (2) to develop a new database of MEPDG parameters for local soil samples obtained from CDOT and to provide advanced testing and analysis of the stiffness degradation of these materials.

Implementation

Add the alternative expansive soil stabilization protocol outlined in this study to CDOT’s pavement design guidelines. Apply the specific results of this study to the development and construction of pilot test sections at the test sites from which the local soil samples were collected. Pilot test sections could then be monitored to validate the field performance of such structures.

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EXECUTIVE SUMMARY

The two main objectives of this research were (1) to propose a new subgrade soil stabilization protocol to allow CDOT and other transportation agencies to rely upon an alternative stabilization method that is not subject to the typical problems associated with calcium-based stabilization of sulfate-rich soils (the proposed technology is also appropriate to stabilize sulfate-free subgrade soils), and (2) to develop a new database of MEPDG parameters for local soil samples obtained from CDOT and to provide advanced testing and analysis of the stiffness degradation of these materials.

The beneficial use of scrap tire rubber mixed with expansive soils is of interest to civil engineering applications since the swell percent and the swell pressure can be potentially reduced with no deleterious effect to the shear strength of the mixture. However, for applications whose design and analysis rely upon the stiffness characteristics of the materials used (e.g. roadways and foundations), stringent stiffness requirements may be in order as well. Consequently, one of the goals of this study was to investigate the degree to which the stiffness of expansive soil-rubber (ESR) mixtures changes due to rubber addition so that the final mixture can have acceptable stiffness, shear strength and swell potential characteristics, while, at the same time, be entirely developed using sustainable materials. Additionally, conventional chemical stabilization methods typically used to stabilize expansive soils may present additional difficulties associated with the generation of expansive minerals formed as a result of the chemical stabilization process. Thus an alternative stabilization method that does not rely upon chemical stabilization would be useful, particularly due to the very specific combination of geotechnical, environmental and waste management issues encountered along the Front Range in Colorado.

While most of the fundamental background and initial development on ESR technology has already been conducted by the PI’s research team, a direct emphasis to local pavement engineering applications were in order, particularly on the resilient modulus characterization of such materials produced using this novel technology. A rubber content of around 10% appears to be beneficial to both reduce the swell potential characterisitcs of a subgrade soil with high-sulfate content from Colorado while preserving minimum levels of its elastic and resilient parameters when compacted using the Modified compaction effort at a level of relative compaction typically adopted in the design of pavement structures in Colorado.

Based on the rigorous set of experimental data generated in this study, the following recommendations are made for CDOT practice:

1) CDOT should consider adding the alternative expansive soil stabilization protocol outlined in this study to its pavement design guidelines, particularly to increase the number of options available for pavement subgrade stabilization in expansive soils.
2) CDOT should consider applying the specific results of this study to the development and construction of pilot test sections at the test sites from which the local soil samples were collected. Pilot test sections could then be monitored for a certain period of time to validate the field performance of such structures.

As it is customary during the adoption of novel, alternative technologies, a trade off might exist between environmental, technical and financial requirements. The results generated by this study suggest waste materials widely available in Colorado may be used in a rational and scientific manner to mitigate some of the technical difficulties associated with the conventional design and construction of pavement structures in the area in a way that addresses both engineering and environmental needs.

Other than a specific recipe that can be applicable to the stabilization of other expansive soil deposits in Colorado, the present study provides a general framework for ESR stabilization that may be used as is or further developed and/or used in combination with other types of soil stabilization protocols. The general rationale behind this study is that it is possible to elevate engineering design to a level that takes into account environmental-friendly, technically-sound, and cost-effective alternatives to conventional design practices.

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CHAPTER 1: INTRODUCTION

1.1 Background

Pavement construction and maintenance problems due to the presence of sulfates in lime-stabilized subgrade soils have been widely reported in many transportation projects. In Colorado, problems associated with sulfate-induced distresses have been observed at the Denver International Airport and, more recently, at the U. S. Highway 287 Berthoud By-pass project. Although problems caused by conventional calcium-based stabilization of sulfate-bearing subgrade soils may be mitigated by carrying out preliminary tests to determine sulfate concentrations followed by additional, appropriate analyses (Little and Nair 2007), it would be desirable if CDOT engineers could count on alternative soil stabilization techniques that are not affected by the potential presence of sulfates.

On a different topic, approximately 4.6 million tons of scrap tires were generated in the United States in 2007 (Rubber Manufacturers Association 2009). During that year, about 89% of the generated scrap tires went to end use markets. In areas such as Colorado, about 55 million waste tires remain in storage at designated waste tire facilities (Colorado Department of Public Health and Environment 2009). This suggests there is an obvious advantage in discovering and implementing alternative uses to expand the end use markets for scrap tire rubber and reduce the excessive number of scrap tires remaining in these designated waste tire facilities. Currently, approximately 12% of the scrap tire rubber generated in the United States is beneficially used in end use markets in civil engineering projects (Rubber Manufacturers Association 2009). Beneficial use of scrap tire rubber in civil engineering applications is desirable not only from a sustainable point of view, but also since scrap tire rubber is a relatively light-weight material, which makes it an ideal candidate for use in embankment fills and retaining wall backfills. Early research on this topic investigated the use of scrap tire rubber as an alternative geomaterial in civil engineering applications (Humphrey et al. 1993). Later studies investigated the use of sand-rubber mixtures (Ahmed & Lovell 1993, Edil & Bosscher 1994, Lee et al. 1999, Youwai & Bergado 2003, Lee et al. 2007, Kim & Santamarina 2008), while other studies have focused on the use of clay-rubber mixtures (Ozkul & Baykal 2001, Cetin et al. 2006). None of the previous studies focused on the more specific case of expansive soil-rubber (ESR) mixtures. With expansive soils being a major cause of damage to structures each year (Puppala & Cerato 2009), additional mitigation techniques may be advantageous to reduce costly damages caused by heaving of expansive soil.

In an attempt to address the two seemingly unrelated topics mentioned previously, a sustainable and innovative stabilization technique was developed by the PI and his research team to mitigate the swell potential of expansive soils with rubber from scrap tires (Seda et al. 2007). As the practical outcome of this new technology results in the development of an engineered expansive soil-rubber (ESR) mixture, the technology is also referred to as ESR stabilization. The main goals of this new stabilization technique are two-fold: (1) reduce the swell potential of expansive soil (including soils containing significant concentrations of sulfates), and (2) maximize recycling of scrap tires in the state. As mentioned above, Colorado has currently about 55 million stockpiled scrap tires – the largest number in the entire country – but also one of the lowest recycling rates in the United States. The use of scrap tire rubber products in civil engineering applications in the state is virtually nonexistent (CDPHE 2009).

The alternative soil stabilization method developed by the PI and mentioned above was originally employed during a preliminary study that attempted to mitigate the swell potential of an expansive soil from Colorado with granulated rubber. Basic characterization, compaction and swell-consolidation tests on soil samples collected from the U. S. Highway 287 Berthoud By-Pass project were carried out for the first time in 2005 and 2006 using the newly proposed technology. Results of this preliminary study indicated that both the swell percent and the swell pressure of ESR mixtures prepared with this technology were significantly lower than the swell percent and swell pressure of the untreated natural soil (Seda et al. 2007).

A subsequent comprehensive research study supervised by the PI indicated that the shear strength of ESR mixtures may be slightly higher than the shear strength of the untreated expansive soil (Dunham-Friel 2009). However, this same study showed that a significant reduction in stiffness might also take place due to scrap tire rubber addition (Dunham-Friel 2009).

These groundbreaking original results (both encouraging and challenging) eventually led to additional, more comprehensive research programs, but they also promptly suggested the proposed ESR technology could be considered and possibly used to reduce the swell potential of expansive soil layers in a variety of geotechnical and highway projects including (but not limited to) stabilization of subgrade soils and bridge abutment embankments. Since this novel stabilization technology does not rely upon conventional calcium-based stabilization mechanisms, it may be particularly suitable for projects where local soil deposits are rich in sulfates and traditional chemical stabilization techniques are either unsuitable or require additional mitigation efforts to be implemented. ESR technology may be particularly useful in engineering projects associated with expansive soil stabilization problems (e.g. formation of ettringite and thaumasite minerals) and availability of a near source or a stockpile of scrap tires.

As it has been pointed out previously, the beneficial use of scrap tire rubber mixed to expansive soils is of interest to civil engineering applications since the swell percent and the swell pressure can be potentially reduced with no deleterious effect to the shear strength of the mixture (Seda et al. 2007, Dunham-Friel 2009). However, for applications whose design and analysis rely upon the stiffness characteristics of the materials used (e.g. roadways and foundations), a more stringent stiffness assessment may be in order. Consequently, one of the objectives of this study was to investigate the degree to which the stiffness of ESR mixtures changes due to rubber addition so that the final mixture can have acceptable stiffness, shear strength, and swell potential characteristics, and, at the same time, be developed using sustainable materials only.

The ability to extend and apply this novel technology to transportation and other large-scale infrastructure applications would not only require development of an appropriate database of mechanistic-empirical pavement design guidelines (MEPDG) parameters including resilient modulus and Poisson’s ratio for local soils in Colorado but also allow for a significant assessment of current stiffness testing and analysis to be conducted that may help clarify some of the inconsistencies related to the use of the current resilient modulus testing protocol, for example.

1.2 Objectives of This Study

1) To develop a new soil stabilization method to allow CDOT and other state, federal and local government transportation agencies to rely upon an alternative tool for expansive soil subgrade stabilization that is not subject to the typical issues associated with calcium-based stabilization of sulfate-rich soils (the proposed technology is also appropriate to stabilize sulfate-free subgrade soils).

2) To build a new database of MEPDG parameters for local soil samples obtained from CDOT and to provide advanced testing and analysis of the stiffness degradation of these materials.

CHAPTER 2: RESEARCH METHODS AND RESULTS

2.1 Materials

The soil and rubber samples used in this study were selected based on CDOT suggestions regarding sulfate-bearing soil sources and the PI’s previous experience with local scrap tire rubber manufacturers. The map developed by Carraro et al. (2008) showing the location of rubber suppliers in Colorado was also taken into account for the selection of scrap tire rubber materials. Due to the large number of variables affecting various aspects of the mechanical response of expansive soils and ESR mixtures (e.g. soil type, rubber content, rubber size, relative compaction (C_R), water content (w), mean effective stress, etc.), only two types of expansive soils were used in this study. Basic characteristics of the materials tested are presented in the next section.

2.1.1 Index Tests and Particle Size Distribution

The particle size distribution curves for the two soils (ASTM D422) and the granulated rubber tested in this study are presented in Figure 1. The particle size distribution curve shown for the 6.7-mm granulated rubber material represents the average of two determinations. The granulated rubber tested in this study is consistent with that of poorly-graded (SP) sands and identical to the particle size distribution obtained for granulated rubber materials tested in previous studies by Seda et al. (2007) and Dunham-Friel (2009).

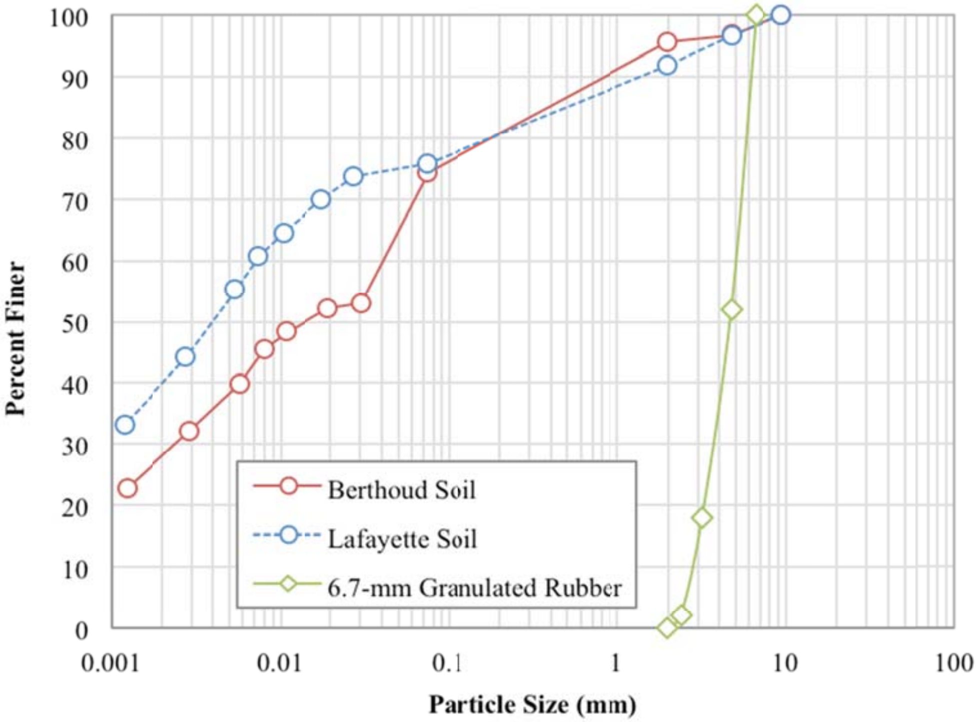

Figure 1. Particle size distributions of the materials tested

The specific gravity (ASTM D854) of the materials tested is presented in Table 1 along with results from Atterberg limits (ASTM D4318) and sulfate tests (CP-L 2103) for the two soils.

Table 1. Index parameters and classification of materials tested

	Berthoud soil	Lafayette soil	Rubber
Specific Gravity	2.79	2.78	1.16*
Liquid Limit (%)	37	41	-
Plasticity Index (%)	9	13	-
Sulfate Concentration (mg/l)	8000	300	-
USCS Classification	CH	CH	SP
AASHTO Classification	A-7-6	A-7-6	-

* Seda et al. (2007), Dunham-Friel (2009)

Both soils classify as fat or highly plastic inorganic clay (CH) according to the Unified Soil Classification System and as A-7-6 materials according to the AASHTO classification system. The specific gravity of the rubber material tested is consistent with values reported by other researchers (Heyer 2012, Manion and Humphrey 1992). Results from sulfate tests suggest the Berthoud soil may contain enough water-soluble sulfates to potentially pose problems if stabilized with chemical stabilizers as its sulfate concentration is greater than 2000 to 3000mg/L (Little and Nair 2007).

2.1.2 Compaction

Systematic characterization of the water content-dry unit weight relationships and determination of the compaction parameters of all soils and ESR mixtures tested were conducted for both the standard (ASTM D698) and modified (ASTM D1557) compaction efforts. A total of 12 compaction curves were determined and the systematic variation of both maximum dry unit weight and optimum water content with soil type, compaction effort and rubber content is summarized in Table 2. A third-order polynomial was used to fit the data from each compaction test for each material tested. This also allows the optimum water content and maximum dry unit weight of each material to be determined in a consistent manner (Howell et al. 1997).

Table 2. Compaction parameters for all soils and ESR mixtures tested

Soil	**Compaction Effort**	**Rubber Content** *RC* (%)	**Maximum Dry Unit Weight** $\gamma_{d\,max}$ (kN/m^3)	**Optimum Water Content** w_{opt} (%)
Berthoud	Standard	0	18.3	14.0
		10	16.3	15.7
		20	15.1	16.1
	Modified	0	19.1	13.0
		10	17.4	13.8
		20	16.2	14.5
Lafayette	Standard	0	17.1	18.4
		10	16.0	18.6
		20	15.0	19.5
	Modified	0	19.4	12.3
		10	17.4	14.5
		20	16.2	14.5

For the two compaction efforts (standard and modified) and range of rubber contents used in this study, the maximum dry unit weight of ESR mixtures decreases linearly with increasing rubber content. Figure 2 shows the variation of maximum dry unit weight ratio with increasing rubber content, where the maximum dry unit weight ratio is defined as the ratio of maximum dry unit weight of soil (or ESR mixture) normalized by the maximum dry unit weight of the soil (or ESR mixture) alone determined for a given compaction effort. An increase in rubber content of 20% leads to a maximum decrease in maximum dry unit weight of about 16% for both soils and compaction efforts used. This trend of decreasing unit weight with increasing rubber content for a given compaction effort is consistent with previous research studies conducted by the PI's research team. Briefly, it is due to two mechanisms: (1) replacement of a reference volume of compacted soil by an equivalent volume of rubber, and (2) loss of compaction efficiency due to the elastic response of rubber during compaction (i.e., energy that otherwise would be employed to compact a certain volume of soil is lost through elastic deformation of rubber particles), so the resulting compacted soil matrix in an ESR mixture is not as well compacted as it would be if no rubber had been added to the soil.

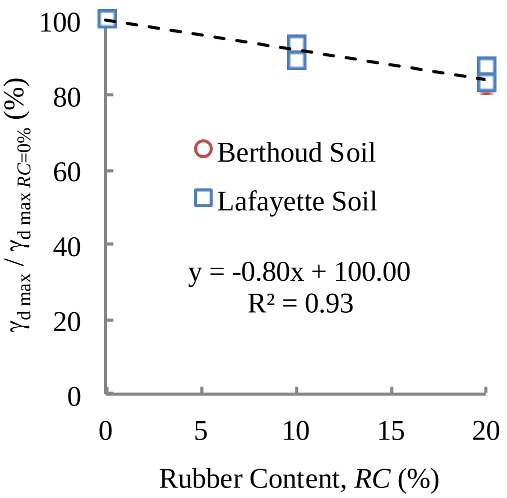

Figure 2. Variation of maximum dry unit weight ratio with rubber content for all materials tested and compaction efforts used in the tests

The optimum water content increased by no more than about 2% for rubber contents increasing from 0 to 20% (Table 2). A clear trend on the effect of rubber addition on the optimum water content of compacted ESR mixtures has not been identified from other previous systematic studies conducted by the PI's research team (Seda et al. 2007, Dunham-Friel 2009, Heyer 2012). In general, a slight increase in optimum water content with rubber addition (for $0\% \leq RC \leq 20\%$) has been observed for the modified compaction effort, with the standard compaction effort typically leading to either slight decreases or no changes in the optimum water content of ESR mixtures (Seda et al. 2007, Dunham-Friel 2009, Heyer 2012).

2.1.3 Resilient Modulus

The material stiffness at relatively small strains induced by cyclic loading (resilient modulus) was evaluated in general accordance with AASHTO T307. Testing was conducted using a state-of-the-art cyclic triaxial apparatus with capabilities to test either solid or hollow cylindrical specimens. Detailed discussions on the specimen preparation and testing equipment and methods used are provided by Dunham-Friel (2009) and Budagher (2012).

2.1.3.1 Effects of Rubber Content and Compaction Effort

The main objective of this stage of the research was to assess the influence of rubber addition and compaction effort on the resilient modulus of the soils and ESR mixtures tested. Thus, all specimens tested at this stage were intended to be compacted at optimum water content and at 95% relative compaction (please note target compaction parameters were specifically defined for each mixture, according to values summarized in Table 2). Table 3 summarizes the range of resilient modulus results obtained for each specimen tested as well as details associated with specimen compaction parameters (target and actual values). Maximum absolute variations between target and actual (as-compacted) compaction parameters for water content and relative compaction were always less than ±0.3% and ±0.5%, respectively, which indicates the high degree of control obtained during specimen preparation.

Table 3. Compaction parameters and resilient moduli of specimens tested

Soil Type	Compaction Effort	Rubber Content	Water Content		Relative Compaction		Resilient Modulus
		RC	w		C_R		M_r
		(%)					(MPa)
Berthoud	Standard	0	14.0	13.9	95.0	94.8	75-105
		10	15.7	15.7		95.2	7-37
		20	16.1	16.0		94.9	3-6
Lafayette		0	18.4	18.2		94.6	42-69
		10	18.6	18.8		95.3	5-11
		20	19.5	19.7		94.5	6-14
Berthoud	Modified	0	13.0	13.3		95.1	106-190
		10	13.8	14.1		94.8	15-58
		20	14.5	14.6		94.6	5-19
Lafayette		0	12.3	12.3		94.5	120-173
		10	14.5	14.6		94.5	13-18
		20	14.5	14.6		95.1	10-33
			Target	Actual	Target	Actual	

As it would be expected for most soils, an increase in compaction effort leads to an increase in the density of the compacted specimen. In turn, this leads to an increase in stiffness (or resilient modulus) of the material, all other factors being kept the same. Incidentally, it might be worth mentioning that while the relative compaction has been kept constant and equal to around 95% in this phase of the research, the actual dry unit weight of specimens compacted using the modified compaction effort is always higher than the dry unit weight of specimens compacted using the standard compaction effort (i.e., relative compaction values are the same for all specimens as the γ_{dmax} value used for relative compaction normalization was always obtained from a given compaction curve determined for a given compaction effort, but the actual dry unit weights will vary accordingly for the various materials and compaction efforts used).

As it has been shown by previous research studies conducted by the PI’s research team, addition of rubber to a compacted expansive soil reduces both the swell potential (Seda et al. 2007, Heyer 2012) as well as the stiffness (Dunham-Friel and Carraro 2011) of the mixtures (compared to the reference response of the original untreated expansive soil at similar stress states and levels of relative compaction). An alternative, sutainable stabilization method to restore the stiffness of ESR mixtures to levels compatible to those obtained for the untreated expansive soil has been proposed by Carraro et al. (2011) and Wiechert et al. (2011).

2.1.3.2 Effect of Compaction Water Content and Relative Compaction

Since the Berthoud soil had the highest sulfate content between the two soils tested in this study (making it less suitable to other soil stabilization methods such as chemical stabilization), an additional analysis was conducted on compacted specimens of this soil to assess its sensitivity to systematic variations in compaction water content and relative compaction. Even though it is widely known that soil behavior is significantly affected by changes in soil state (in the case of this study, soil state might be simply envisioned as systematic variations in water content, relative compaction and confining stress, for example) no clear guidelines are available on how to handle these variations for pavement design purposes in Colorado (particularly in terms of systematic variations of the first two factors). Thus, three levels of compaction water content were adopted (i.e., w_{opt}, $w_{opt} + 1\%$, and $w_{opt} - 1\%$). Likewise, three levels of relative compaction were used, representing namely 95, 100 and 105% of the maximum dry unit weight obtained for the Berthoud soil using the standard compaction effort. This allowed evaluation of the resilient modulus of the compacted Berthoud soil under nine different soil states.

Table 4 summarizes the range of resilient modulus results obtained for each specimen tested as well as details associated with specimen compaction parameters (target and actual values). Maximum absolute variations between the target and actual (as-compacted) compaction parameters for both water content and relative compaction were always less than ±0.5%, which once again reflects the high degree of control obtained during specimen preparation.

Table 4. Compaction parameters and resilient moduli of Berthoud soil specimens

Water Content		**Relative Compaction**		**Resilient Modulus**
w		C_R		M_r
(%)				(MPa)
13.0	13.0	95.0	94.9	89-139
14.0	14.0		94.5	79-136
15.0	14.8		95.2	75-127
13.0	12.7	100.0	99.5	100-156
14.0	13.9		99.5	96-145
15.0	14.9		99.5	87-142
13.0	12.9	105.0	104.5	107-172
14.0	13.6		104.5	111-163
15.0	14.5		104.5	89-136
Target	Actual	Target	Actual	

As the resilient modulus is simply a characterization of the stiffness of the soil following a specific type of cyclic loading protocol, it should not come as a surprise the resilient modulus is actually controlled by the same fundamental state parameters affecting all other aspects of the mechanical behavior of geomaterials. In the case of this study, such parameters would include: relative compaction (or some alternative representation of soil density) and water content (or some alternative representation of soil suction, neglecting any potential histherysis variations possibly induced by drying-wetting cycles). The upper and lower bounds for the resilient modulus values presented in Table 4 are also displayed in Fig. 3. Soil stiffness systematically increases with increasing relative compaction (or density, as shown in Fig. 3a) and decreasing compaction water content (or soil suction, as shown in Fig. 3b).

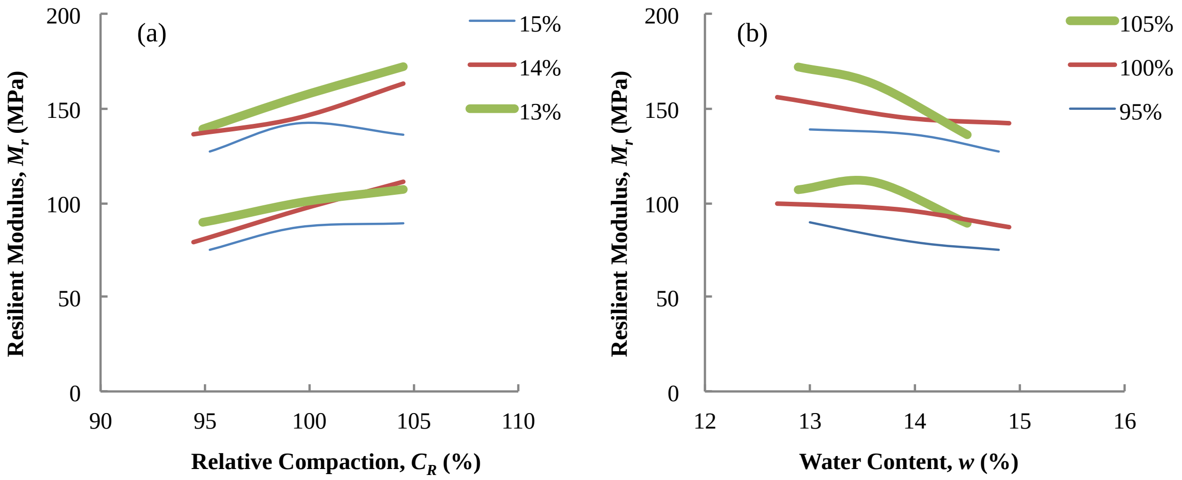

Figure 3. Upper and lower bounds of resilient moduli of compacted Berthoud soil specimens (reference relative compaction of 100% defined for standard compaction effort) as a function of: (a) relative compaction (for water contents of 13, 14 and 15%), and (b) water content (for relative compactions of 95, 100 and 105%)

While the compacted soil will present a relatively higher stiffness at lower compaction water contents, from a practical point of view it is important to appreciate this is just a temporary feature related to the current unsaturated state of the soil. If the soil water content increases due to infiltration of rain water, poor drainage in the subgrade, or any other practical reason, the soil stiffness will eventually decrease accordingly. This aspect may be even much more critical in expansive soils due to the corresponding volumetric strains that will incur as a result of water content changes in the soil.

2.1.4 Poisson's Ratio

In some special tests, local axial and radial displacement transducers were used inside the triaxial cell to measure the axial and radial strains of unsaturated soil specimens prepared in the same way as those subjected to resilient modulus testing, as described previously. Typical values of the Poisson's ratio of the materials tested are summarized in Table 5. Poisson's ratio tends to increase slightly with increasing rubber content, although the relatively minor variations observed are likely not sufficient to cause any substantial changes to the design of pavement structures. Poisson's ratio values within the 0.10-0.35 range have been reported for materials similar to the ones tested in the present study (Budagher 2012).

Table 5. Poisson's Ratio of materials tested

Rubber Content	**Poisson's Ratio**
RC (%)	ν
0	0.10-0.19
10	0.10-0.25
20	0.15-0.25

2.1.5 One-Dimensional Swell-Compression

In this phase of the research, the one-dimensional swell-compression response of compacted specimens of soil and/or ESR mixtures was evaluated in accordance to ASTM D4546. The swell percent of the materials tested was assessed under a vertical effective stress that is equivalent to the lowest value of vertical stress imposed during resilient modulus testing (13.8 kPa). A summary of the swell-compression test results and parameters is provided in Table 6. Maximum absolute variations between the target and actual (as-compacted) compaction parameters for both water content and relative compaction were always less than ±0.5%, reflecting the high degree of control obtained during specimen preparation.

Summary of individual plots of the swell-compression response of the Berthoud soil and its corresponding ESR mixtures compacted using both the standard and modified efforts are presented in Figure 4. Figure 5 shows similar results obtained for the Lafayette soil and its corresponding ESR mixtures. Similarly to what has been observed in previous systematic studies, addition of rubber to an expansive soil reduces its swell percent, swell pressure and one-dimensional stiffness (Seda et al. 2007, Heyer 2012, Budagher 2012).

Table 6. Summary of one-dimensional swell-compression test results and parameters

Soil Type	**Compaction Effort**	**Rubber Content**	**Water Content**		**Relative Compaction**		**Swell Percent**	**Swell Pressure**
		RC	w		C_R		$\Delta\varepsilon_z$	σ'_z
		%						kPa
			Target	Actual	Target	Actual		
Berthoud	Standard	0	14.0	14.5	95.0	94.7	6.6	245
		10	15.7	16.1		94.8	0.9	22
		20	16.1	16.2		94.8	0.9	19
Lafayette		0	18.4	18.3		95.0	3.1	75
		10	18.6	18.1		95.4	2.6	45
		20	19.5	19.9		94.5	0.6	21
Berthoud	Modified	0	13.0	13.0		94.8	7.7	255
		10	13.8	13.9		95.0	2.6	32
		20	14.5	14.6		94.5	1.6	24
Lafayette		0	12.3	12.5		94.8	8.4	280
		10	14.5	14.3		95.0	3.5	55
		20	14.5	14.9		94.8	1.0	24

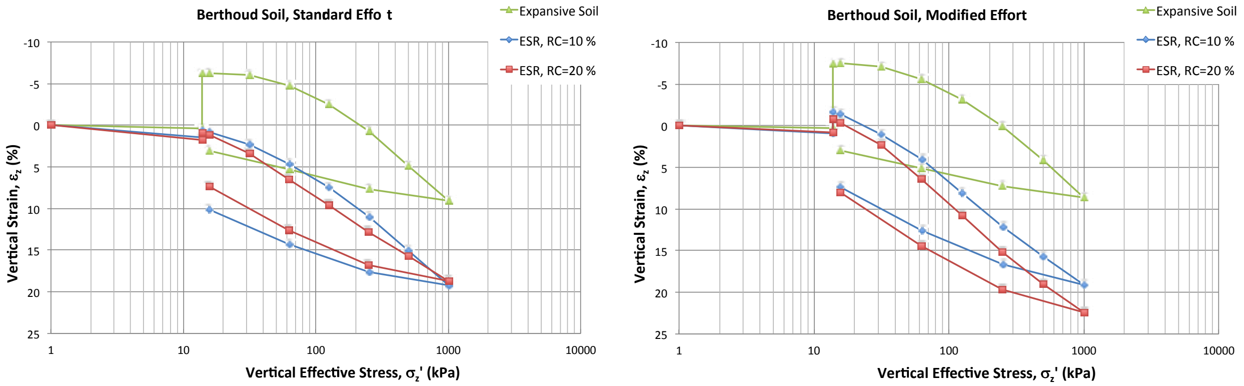

Figure 4. One-dimensional swell-compression response of Berthoud soil and ESR mixtures

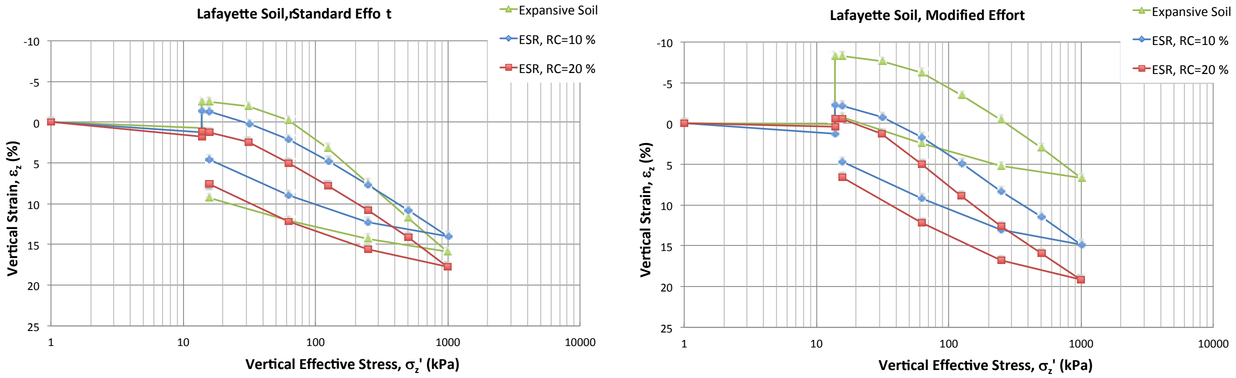

Figure 5. One-dimensional swell-compression response of Lafayette soil and ESR mixtures

2.1.6 Undrained Axisymmetric Compression

Additional undrained axisymmetric (or triaxial) compression testing was conducted on back-pressure saturated, isotropically-consolidated compacted specimens of the Berthoud soil to completely characterize the stiffness degradation response of the soil over the entire strain range, as well as the evolution of shear strength and excess pore pressure during undrained shearing. The mean effective stress (p') levels used at this stage were consistent with the three levels required by the resilient modulus protocol, with the main difference being that specimens tested at this stage were back-pressure saturated prior to being isotropically-consolidated and subjected to undrained triaxial compression. Thus, the triaxial specimen states could be explicitly defined in terms of w and C_R. Any discrepancies among stiffness indices obtained through the two different types of protocols must therefore be solely associated with the strain levels induced by the testing protocol adopted and/or changes in p' due to the differences in initial degree of saturation (or soil suction) of the specimens. All triaxial specimens were compacted to a target relative compaction of 95% and at the target optimum water content obtained for a particular compaction effort (i.e., standard or modified). Maximum absolute variations between the target and actual (as-compacted) compaction parameters for both water content and relative compaction of the specimens were less than ±0.8% and ±0.1%, respectively.

Figure 7 shows the typical stress-strain-pore pressure change responses of the Berthoud specimens tested for the three levels of *p'* used, namely 13.8, 27.6 and 41.4 kPa. The specimens tested at this stage were compacted to a relative compaction of 95% according to the maximum dry unit weight obtained with either the standard or modified compaction efforts.

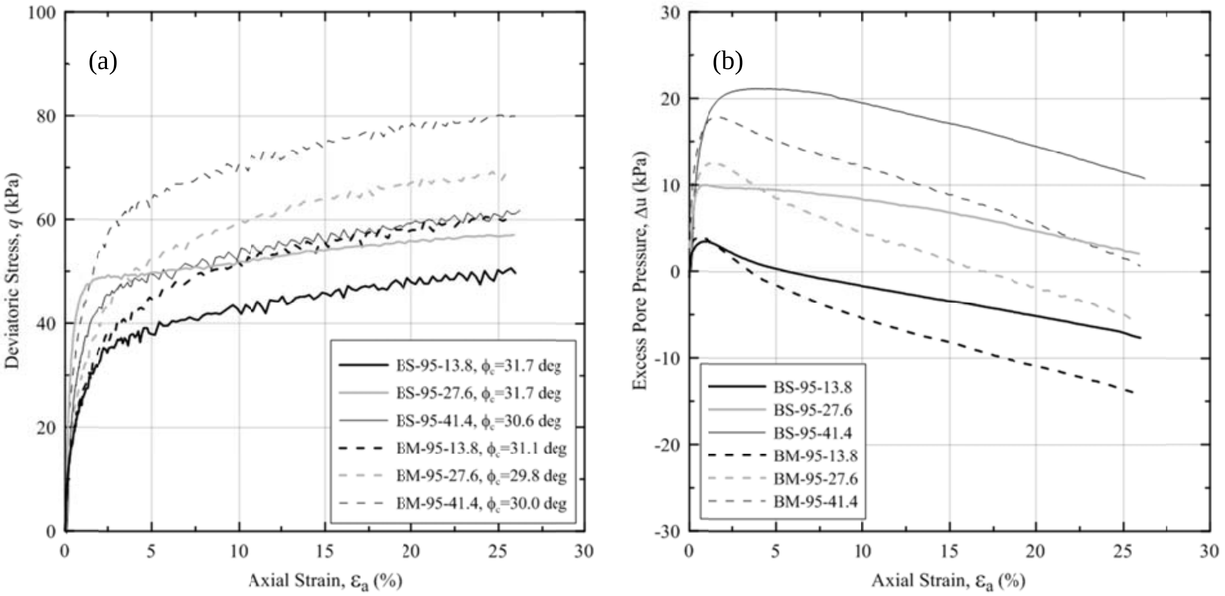

Figure 6. Variation of (a) deviatoric stress and (b) excess pore pressure with axial strain during undrained triaxial compression of Berthoud soil specimens compacted to 95% of the maximum dry unit weights obtained with either the standard or modified efforts for *p'* = 13.8, 27.6 or 41.4 kPa.

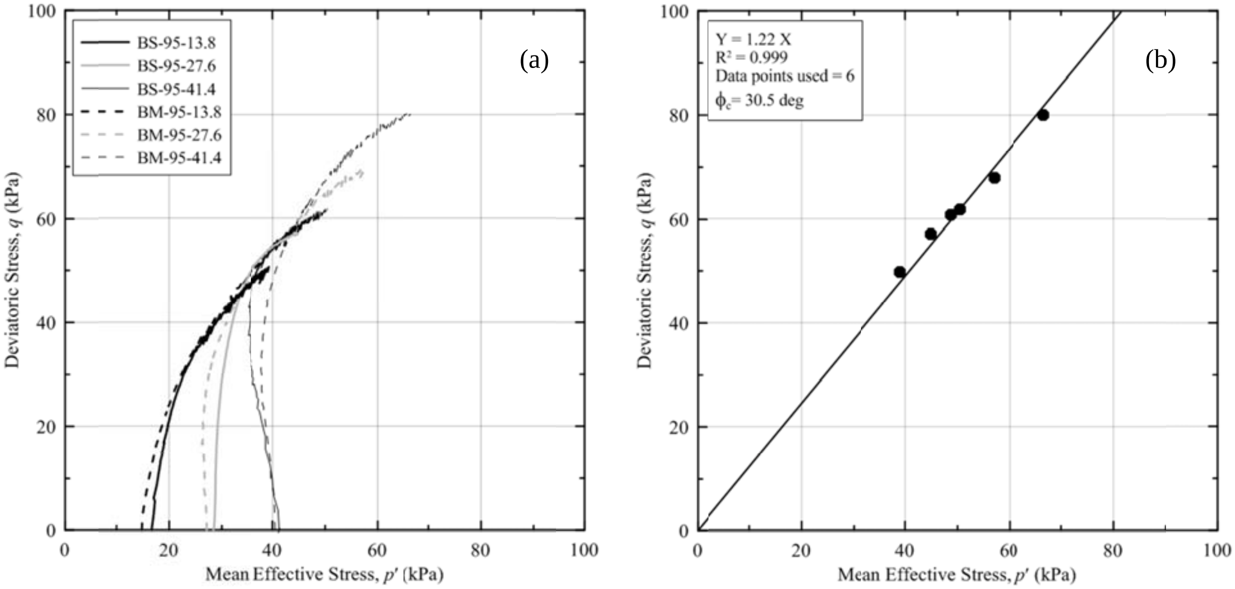

Figure 7. (a) Stress paths during undrained triaxial compression tests with *p'* = 13.8, 27.6 or 41.4 kPa, and (b) critical state line of Berthoud soil specimens compacted to 95% of the maximum dry unit weights obtained with either the standard or modified efforts

Stress paths observed during undrained triaxial compression are shown in Figure 7a for all specimens tested. The critical-state friction angle of the soil is equal to 30.5° (Fig. 7b) with specific values determined for each test also provided in the legend of Fig. 6a.

Results presented in Fig. 6 and 7 are typical of compacted specimens that are overconsolidated due to the nature of the compaction process employed during specimen preparation (i.e., stresses used to compact the specimens according to the AASHTO T307 mold are typically high enough to impart a stiff response to the triaxial specimens when tested under the relatively low mean stress levels recommended by AASHTO T307).

2.1.7 Stiffness

Bender element testing was carried out to assess the shear wave velocity and shear stiffness in the very small-strain range (G_{max}) of the Berthoud soil compacted to a relative compaction level of 95% of the maximum dry unit weight obtained for both the standard and modified compaction efforts. Corresponding maximum values of the secant modulus of elasticity of the specimens tested in the bender element protocol are derived by assuming a Poisson's ratio of 0.5 for consistency with the undrained secant moduli measured during undrained triaxial compression. The entire stiffness degradation response of the select specimens of Berthoud soil is presented for its entire (i.e., very-small, small, and large) strain range in Figure 8.

The range of values shown in Fig. 8 is substantially lower than the lower bound resilient modulus values obtained for this soil (equal to 75 and 106 kPa, respectively, for the standard and modified compaction efforts) under similar compaction conditions (C_R=95% and optimum water content). As previously discussed, this discrepancy may be due to the unsaturated conditions prevailing during resilient modulus testing, whereby the soil suction effectively increases the actual mean effective stress in the specimens thus increasing their stiffness.

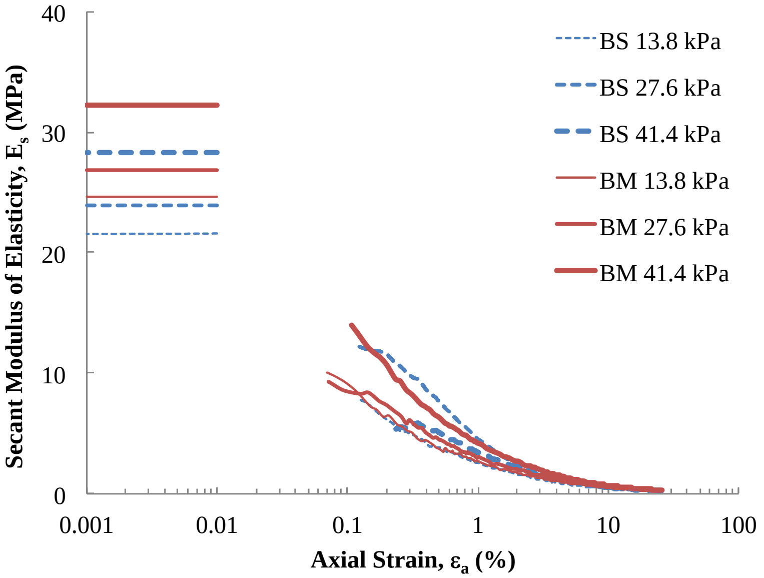

Figure 8. Variation of secant modulus of elasticity with axial strain in undrained triaxial compression – stiffness values at very small strains were determined from bender element tests

CHAPTER 3: MEPDG DATABASE

Results from the systematic experimental program presented in Chapter 2, particularly those conducted for the select expansive soil used in the experiments (Berthoud soil) allowed for a rigorous and fundamental characterization of the elastic parameters of the two compacted expansive soils from Colorado tested in this study. Such parameters are typically required in MEPDG analyses.

A summary of such parameters was assembled and is presented in Table 7 to provide designers with reliable ranges for both the resilient modulus and Poisson's ratio parameters of compacted expansive soils from the Berthoud and Lafayette areas in Colorado.

Table 7. Resilient moduli and Poisson's ratios of two compacted expansive soils from Colorado

Compaction Water Content	**Relative Compaction, C_R (%)**	**Compaction Effort**	**Resilient Modulus, M_r (MPa)**			**Poisson's Ratio, ν**
			Berthoud soil	Lafayette soil	AASHTO[1]	
Optimum	95	Standard	75-105 [2,3]	42-69	-	0.1-0.2
		Modified	106-190	120-173	-	
	100		-	-	55-90	Default values[1]

[1] Input Level 3 from AASHTO (2008) "Mechanistic-Empirical Pavement Design Guide - A Manual of Practice" (compaction parameters from AASHTO T180)

[2] Increase in relative compaction from 95 to 105% may increase M_r values by about 40%

[3] Increase in compaction water content from optimum to 1% above optimum may decrease M_r values by about 10%

It should be noted that additional analyses such as those described in section 2.1.3.2, which are usually neglected by conventional design guidelines, were also taken into account during database development and creation of Table 7.

CHAPTER 4: ESR DESIGN PROTOCOL AND FIELD CONSTRUCTION

A systematic process should be followed to assess the appropriate amount of rubber that can be added to an expansive soil to improve its mechanical response. In applications where the overall goal is to reduce the swell potential of a soil to be used as a stabilized road subgrade, for example, not only the swell characteristics of the soil must be assessed but also the impact the stabilization protocol will have on its stiffness. Once such a general assessment is carried out, proper values for the amount and range of materials to be used can be determined. In the specific case of ESR mixtures, the following guidelines would consititute a minimum set of steps to be considered:

1) Assess the sulfate content of potential soil(s) to be used. For soils from Colorado, the Colorado Procedure CP-L 2103 may be used at this stage. ESR and/or other conventional mechanical stabilization methods may be particularly useful for soils with medium to high sulfate content, even though ESR stabilization can be used with any soil, in principle. For soils with relatively low sulfate content, other soil stabilization protocols might also be available. Thus, preliminary information on the sulfate content of a soil may help compare all stabilization options potentially available.
2) Select the type of scrap tire rubber material to be used. In Colorado, the majority of scrap tire rubber suppliers are located along the Front Range (Carraro et al. 2008). The Colorado Department of Public Health and Environment may be a good reference for an up-to-date list of suppliers currently operating in Colorado. In other states, similar lists may be obtained by contacting the state's department of transportation and/or environmental/health authorities. Guidelines on expected technical performance of ESR mixtures including either granulated rubber or tire chips have been provided by Heyer (2012), which indicate tire chip-ESR mixtures may perform quite similarly to ESR mixtures stabilized with granulated rubber. Generally, the smaller the scrap tire rubber material, the more expensive it will be. As a rule of thumb and based on the PI's experience during the course of this research program in Colorado (between around 2005 and 2011), the unit cost (by weight) of tire chips would tend to be about ten times lower than the corresponding cost of granulated rubber materials.
3) For soil(s) and ESR mixture(s) of interest:
    a. Determine appropriate compaction parameters. As discussed in previous sections, rubber addition alters the compaction characteristics of the compacted expansive soil. Therefore, each ESR mixture created by a given combination of soil and scrap tire rubber should be treated as a different material. Specific compaction characterization may also help understand the link between changes in soil state (i.e., density and water content) and engineering performance.
    b. Evaluate swell percent and swell pressure. Similarly to the procedures used in this study, which have been reported in detail in previous sections, the typical approaches used to assess the swell percent and swell pressure of expansive soils can be adopted for ESR mixtures. This will allow a rational assessment of the degree of improvement (or reduction of swell potential, in this case) imparted by ESR stabilization. Recent, systematic research suggests a preliminary assessment conducted via relatively standard swell-compression testing

    protocols may provide reasonable insight into the behavior of ESR mixtures including larger particle sizes such as tire chips (Heyer 2012).
    c. Measure resilient modulus. Stiffness characterization under repeated cyclic loading procedures that may be representative of traffic loading scenarios should be conducted at this stage. Similarly to the approach employed in this study, it is recommended that additional factors that are well-known to impact the mechanical response of geomaterials such as water content and density be taken into account, if possible. This will allow a more comprehensive evaluation of the relative impact of the main factors affecting the mechanical response of ESR mixtures, namely: rubber content, compaction water content and relative compaction, which are not specifically bounded by current resilient modulus testing protocols.
4) Select final rubber content and compaction characteristics of selected ESR mixture(s) based on the combined effect of rubber addition and compaction parameters on both the swell and stiffness characteristics of the material to be used as a potential stabilized subgrade layer and/or in some other role within the pavement structure.

As a specific example and based on the rigorous set of experimental data generated in this study, it would appear that a rubber content of 10% and modified compaction effort used to achieve a relative compaction of 95% would be most beneficial for the stabilization of the Berthoud soil, which has a relatively high sulfate content and may not be easily stabilized using other conventional methods of stabilization. While the reduction in swell potential of the 10% Berthoud ESR mixture is not as high as that obtained with a rubber content of 20%, it would still allow the resilient modulus characteristics of such stabilized layer to be within an operational range typically allowed for similar types of soils (CH), as per AASHTO (2008) without having to address any of the issues typically associated with alternative chemical stabilization processes in high-sulfate soils.

Construction of actual layers of compacted ESR mixtures in the field can be conducted using field compaction equipment typically used for road construction of regular and/or stabilized soil layers. Based on various research studies conducted by the PI since the creation of this research program in 2005, the following general guidelines and compaction parameters are suggested for future studies involving field construction of ESR mixtures:

- Rubber content: between 0 and 20%
- Compacted lift thickness: ≤ 200 mm
- Compaction roller: 73.4-kN, single-drum
- Number of roller passes: ≥ 7
- Compaction water content: -1% > w_{opt} > 1% (for w_{opt} determined as per ASTM D698)

The general guidelines and compaction parameters listed above have allowed successful construction of compacted ESR layers in the field with final relative compaction values equal to or greater than 95% of the maximum dry unit weight obtained in the laboratory using the standard compaction effort (ASTM D698). Additional details about field compaction procedures and equipment are described by Carraro et al. (2011) and Heyer (2012).

Previous field research studies conducted by the PI's team on compacted ESR mixtures also suggest that a combination of rotary tiller (Fig. 9) and regular single drum compaction roller (Fig. 10) can be used to optimize the mixing and compaction stages, respectively, of large stabilized subgrade pavement sections (Carraro et al. 2011). While smaller, manual rotary tillers can be used for relatively small volumes of ESR mixtures (Carraro et al. 2011), automated rotary tillers such as those commonly used for lime/fly ash stabilization of soils may proof more cost efficient – an example of the use of such equipment during field mixing of a ESR layers is shown in Fig. 9. An important aspect of field construction of compacted ESR mixtures requires that procedures used in a particular project ensure mixture uniformity and mitigate segregation during mixing and compaction. By paying attention to detail and articulating the main objectives of the field compaction procedures among the field crew, it is possible to obtain uniform layers of compacted ESR mixtures in the field using relatively conventional compaction equipment (Figure 11) such as the ones described previously.

Figure 9. Rotary tiller typically used in lime/fly ash stabilization employed during field construction of an tire chip-ESR stabilized subgrade layer

Figure 10. Single drum roller (73-kN) used to compact ESR layers in the field

Figure 11. Inspection borehole in a 300-mm-thick ESR layer compacted with regular field equipment (Rubber content: 20%, Target relative compaction: 95% of maximum dry unit weight obtained with standard compaction effort)

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

A new stabilization protocol has been proposed and assessed in this study to mitigate the deleterious effects of water content changes on the performance of expansive soil subgrade layers as well as issues arising from calcium-based stabilization in high-sulfate content soils. Briefly, the proposed protocol is based on the addition of scrap tire rubber material(s) to expansive soils. The material resulting from this alternative stabilization method is referred to as an ESR mixture, which needs to be properly designed and engineered according to fundamental geomechanics principles in order for it to perform properly as a potential stabilized subgrade layer. ESR technology might be particularly advantageous in Colorado due to the large presence of both expansive soil deposits and scrap tires along the Front Range, where most of the state's population reside. Since ESR technology does not rely on chemical stabilization processes, it might be specially useful for the stabilization of expansive soils with high sulfate content, although its use is applicable to any type of expansive soil.

The systematic, rigorous analyses and experimental procedures employed in this study outline a framework that can be used in the future to develop a new mechanistically-focused database of relevant pavement design parameters that are directly applicable to Colorado soils.

Specifically, the following conclusions can be drawn from the results of this study:

1) For the two compaction efforts (standard and modified) and range of rubber contents used in this study, the maximum dry unit weight of ESR mixtures decreases linearly with increasing rubber content. An increase in rubber content of 20% leads to a maximum decrease in maximum dry unit weight of about 16% for all soils and compaction efforts used.
2) The optimum water content increased by no more than about 2% for rubber contents increasing from 0 to 20%. In general, a slight increase in optimum water content with rubber addition (for $0\% \leq RC \leq 20\%$) has been observed for the modified compaction effort, with the standard compaction effort typically leading to either slight decreases or no changes in the optimum water content of ESR mixtures.
3) An increase in compaction effort leads to an increase in the density of the compacted specimen, which, in turn, leads to an increase in stiffness (or resilient modulus) of the material (all other factors being kept the same), as expected. Addition of rubber to a compacted expansive soil reduces the stiffness of the resulting ESR mixtures (compared to the reference response of the original untreated expansive soil at similar stress states and levels of relative compaction).
4) Soil stiffness systematically increases with increasing relative compaction (or density) and decreasing compaction water content (or soil suction). While compacted soil will present a relatively higher stiffness at lower water contents, it is important to appreciate this is just a temporary feature related to the current unsaturated state of the soil. If the soil water content increases due to infiltration of rain water, poor drainage in the subgrade, or any other reason, soil stiffness will decrease accordingly. This may be even more critical in expansive soils due to the corresponding volumetric changes that will incur as a result of water content changes.

5) Poisson's ratio of the materials tested ranged from 0.10 to 0.25 and tend to increase slightly with increasing rubber content. The relatively minor variations observed may not be sufficient, however, to cause any substantial changes to the design of pavement structures.
6) Addition of rubber to an expansive soil reduces its swell percent, swell pressure and one-dimensional stiffness.
7) Stiffness values derived from bender elements and triaxial tests on saturated specimens are substantially lower than the lower bound resilient modulus values under similar initial compaction conditions (C_R=95% and optimum water content). This difference may be due to the unsaturated conditions prevailing during resilient modulus testing, whereby soil suction effectively increases the actual mean effective stress in the specimens thus increasing their stiffness.
8) Field equipment typically used in conventional mechanical and/or chemical soil stabilization projects can be used to compact ESR layers in the field with final compaction parameters consistent with those established by standard laboratory compaction procedures.

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