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Lime Utilization in the Laboratory, Field, and Design of Pavement Layers

by

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16. Abstract

The objective of this study was to review and report the best practices of using lime (i.e., granulated lime, hydrated lime, and slurry lime) to dry soil, in working tables, and in pavement applications. The project also reviewed and documented the incorporation of lime in pavement design in other states as well as test methods, field application, and evaluation techniques to assess the quality of field construction.

Based on the results of the literature review and the survey questionnaire, it can be confidently stated that the overwhelming majority of laboratory and field studies involving lime-stabilization indicates that lime-stabilized subgrades perform better than non-stabilized subgrades, when due regard is given to materials design, structural design, durability, and construction. Enhanced performance is typically reported in terms of number of traffic loads to failure and strength properties of the subgrade soil and has been reported to be cost-effective. Furthermore, test results suggest that lime does not leach over time and remains in the subgrade after 5 to 11 years in service. With respect to consideration in the design, numerous states account for lime-stabilized subgrade in pavement design; yet, some states do not account for lime-stabilized subgrade in the design. For those states considering lime-stabilized subgrade in the design, a structural layer coefficient around 0.11 has been commonly used.

Since Louisiana typically uses lime concurrently with cement for subgrade stabilization, it is reasonable to account for the stabilized layer in the design. Subgrade may be dealt with in the design as a subbase layer such that a layer coefficient can be assigned. Concurrent to the recently-added UCS requirement, it is recommended to assign a layer coefficient of 0.05 in the design for lime and cement-stabilized subgrade. A concurrent study regarding an equivalent modulus for stabilized subgrade layers is also ongoing by LTRC.

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ABSTRACT

Poor quality soils are widely encountered in Louisiana during highway construction as most soils consist of soft and unconsolidated clay that is characterized with low bearing capacity and detrimental large deformation characteristics. This type of soil commonly exhibits undesirable engineering behavior during construction and service such as high shrink/swell potential and poor durability. Problematic organic soils are also often encountered in regular highway construction. Conventionally, modification and stabilization of the soil prior to construction of upper pavement layers with lime, cement, and fly ash have been used to allow for the construction process to advance and to enhance the mechanical properties of soil during service. Lime is typically used in Louisiana in road applications to construct a working table, to dry the natural soils, and to stabilize subgrade soil prior to cement stabilization (DOTD Specifications Section 305). Yet, no structural contribution is given to stabilized subgrade soils in pavement design.

The objective of this study was to review and report the best practices of using lime (i.e., granulated lime, hydrated lime, and slurry lime) to dry soil, in working tables, and in pavement applications. The project also reviewed and documented the incorporation of lime in pavement design in other states as well as test methods, field application, and evaluation techniques to assess the quality of field construction. Based on this review, this study provided a knowledge base that can be used by the Department to modify and improve current state specifications.

Based on the results of the literature review and the survey questionnaire, it can be confidently stated that the overwhelming majority of laboratory and field studies involving lime-stabilization indicates that lime-stabilized subgrades perform better than non-stabilized subgrades, when due regard is given to materials design, structural design, durability, and construction. Enhanced performance is typically reported in terms of number of traffic loads to failure and strength properties of the subgrade soil and has been reported to be cost-effective. Furthermore, test results suggest that lime does not leach over time and remains in the subgrade after 5 to 11 years in service. With respect to consideration in the design, numerous states account for lime-stabilized subgrade in pavement design; yet, some states do not account for lime-stabilized subgrade in the design. For those states considering lime-stabilized subgrade in the design, a structural layer coefficient around 0.11 has been commonly used.

Since Louisiana typically uses lime concurrently with cement for subgrade stabilization, it is reasonable to account for the stabilized layer in the design. Subgrade may be dealt within the

design as a subbase layer such that a layer coefficient can be assigned. A concurrent study regarding an equivalent modulus for stabilized subgrade layers is also ongoing by LTRC. The researchers recommend linking structural coefficients to the DOTD Specifications in Section 305.04.a.2. Unconfined compressive strengths (UCS) were recently added to this section; it is recommended that the layer coefficient of 0.05 should be associated with those strengths and added to the design. While lime-stabilization is not considered alone, it can be added in the future as a feasible alternative.

The researchers recommend that a follow-up study be conducted in order to evaluate the values recommended in this study using field testing such as Falling Weight Deflectometer (FWD), Dynamic Cone Penetrometer (DCP), and Pavement Management System (PMS) data of treated and untreated soil. The stability of soil properties over time should also be evaluated by testing soil conditions with different ages.

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IMPLEMENTATION STATEMENT

Based on the results of this study, the research team concluded that the existing Louisiana specifications may be modified to reflect the structural-contribution of stabilized subgrade soil. These changes will save funds, which may be used for other needs. Therefore, lime-stabilized layers should be considered in the pavement design, while lime modification, drying, and working table applications should not be considered in the pavement design.

Since Louisiana typically uses lime concurrently with cement for subgrade stabilization, it is reasonable to account for the stabilized layer in the design. Subgrade may be dealt with in the design as a subbase layer such that a layer coefficient can be assigned. The researchers recommend linking structural coefficients to the DOTD Specifications in Section 305.04.a.2. Unconfined compressive strengths (UCS) were recently added to this section; it is recommended that the layer coefficient of 0.05 should be associated with those strengths and added to the design.

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INTRODUCTION

Nearly two-thirds of highway construction projects in the US take place on poor, undesirable soils. These poor quality materials typically have the potential to demonstrate undesirable engineering behavior during construction and service such as low bearing capacity, high shrink/swell potential, and poor durability. Traditionally, modification and stabilization of the soil prior to construction with lime, cement, and fly ash have been used to allow for the construction process to advance and to enhance the mechanical properties of soil during service. For successful soil modification and stabilization, the selection of a suitable stabilizer and an optimum content is critical along with setting strength criteria; further, adequate mixing, curing, and compaction are important factors to achieve satisfactory field performance *[1]*. Lime modification and stabilization is generally more suited for treating plastic clays with high shrink/swell potential. The two main reactions taking place are cation exchange and flocculation-agglomeration; both of these reactions significantly improve soil properties and workability *[2]*.

Working tables, where the soil is dried and modified to an extent to facilitate construction, is a common practice in Louisiana. With lime working tables, performance has been generally adequate and is a time-tested practice in Louisiana; however, lime-treated soil is not assigned a structural coefficient value in the design *[3]*. Lime modification and stabilization may offer numerous advantages including improved soil properties especially for expansive soil, continuous strength gain with time and reduction in pavement thickness if incorporated in the design. The consideration of lime in the design may be justified given that laboratory and field studies show that lime-stabilized subgrades outperform soil that does not incorporate lime *[4]*.

OBJECTIVE

The objective of this study was to review and report the best practices of using lime (i.e., granulated lime, hydrated lime, and slurry lime) to dry soil, in working tables, and in pavement applications. The project also reviewed and documented the incorporation of lime in pavement design in other states as well as test methods, field application, and evaluation techniques to assess the quality of field construction. Based on this review, this study provided a knowledge base that can be used by the Department to modify and improve current state specifications.

SCOPE

To achieve the aforementioned objectives, a comprehensive review of previous research studies was conducted to investigate the current state of practices and studies that have evaluated the use of lime in drying soils, in working tables, and in pavement applications. A nationwide survey was conducted in order to identify current practices used by different state highway agencies. Collected information was used to conduct a comparative analysis to assess current Louisiana Department of Transportation and Development (DOTD) specifications and areas of improvement and modification that should be addressed by the Department. The gathered information was reviewed and summarized to provide recommendations to the Department to modify and improve existing state specifications and practices.

METHODOLOGY

The research approach adopted in this study consisted of collecting and reviewing pertinent literature that described current state practices and studies that have evaluated the use of lime in drying soils, in working tables, and in pavement applications. The literature search included, but was not limited to, standard methods such as TRIS, COPENDEX, and NTIS, as well as consulting with state practitioners.

The research team also conducted a comprehensive nationwide survey to gather information from highway agencies nationwide as related to the current practices and experiences with the use of lime in pavement layers. The survey gathered information from highway agencies as related to state's policy for using lime to stabilize and modify soils, quality assurance of lime construction in the field, percentage of lime used, cost-effectiveness, performance of lime-stabilization, incorporation of lime-stabilized layers in the design, and other factors related to the use of lime in pavement applications. Results of the survey were analyzed and reported through development of bar charts, pie charts, and tables developed using Microsoft Excel. These charts were used to demonstrate the current state of practices adopted by the different DOTs as well as the percentage of responses for each question in the survey.

LITERATURE REVIEW

Field and Laboratory Evaluation

Jung and Bobet conducted a comprehensive field and laboratory evaluation of lime-stabilized soils in Indiana on two Portland Cement Concrete (PCC) and four hot-mix asphalt (HMA) pavement sections *[1]*. The researchers utilized boring, Standard Penetration Test (SPT), Dynamic Cone Penetrometer (DCP) test, Falling Weight Deflectometer (FWD) test, soil characterization, X-ray Diffraction (XRD) test, and Thermogravimetric Analysis (TGA) to investigate the soil properties namely water content, soil index properties, stiffness, and lime content. Results from boring and SPT tests suggested that the addition of lime increased the granularity of the subgrade soil. However, no significant difference was observed in the water content of lime-stabilized and natural subgrade. Test results indicated a substantial increase in resilient modulus of the subgrade soil treated with lime. Although a correlation could not be established between the stiffness of the subgrade soil with depth and lime content, the results suggest a significant increase in California Bearing Ratio (CBR) values, by as much as 500% to 1500%, for the lime-stabilized subgrade. TGA and XRD tests on lime-treated subgrade soils measured the total mineral content and indicated that the lime content to be in the range of 5 to 7% by weight. Test results also suggested that the lime remained in the subgrade after 5 to 11 years in service and did not drain away from the subgrade soil. The results from field and laboratory tests are presented in Table 1.

Table 1
Summary of laboratory and field test results *[1]*

		Site (1)	Site (2)	Site (3)	Site (4)	Site (5)	Site (6)
Year of Lime Treatment		1997	2002	1999	2002	1996	2002
Soil Type	Natural	CL / A-7-5	SM / A-4	CL / A-7-6	ML / A-6	CL / A-6	ML / A-6
	Treated	SM / A-1-b	SM / A-2-4	SM / A-2-4	SM / A-1-b	ML / A-4	SM / A-4
Increase of CBR (%)	“Effective” Thickness	0 ~ 1500	150 ~ 810	0 ~ 630.	210 ~ 740	100 ~ 350	250 ~ 1500
	16-in Thickness	0 ~ 450	150 ~ 660	0 ~ 280	100 ~ 740	0 ~ 180	130 ~ 880
Increase of MR (%)		200	530	100	400	190	320
Content of CaCO3		2 ~ 7	7 ~ 10	7 ~ 11	8 ~ 17.5	1.4 ~ 2	1.2 ~ 2

[1] M_R: Modulus of Resilience

Puppala et al. conducted a study to evaluate the engineering properties of lime-treated subgrade soil in Louisiana *[2]*. Laboratory tests such as Unconfined Compressive Strength (UCS) and CBR tests were conducted at different moisture contents and density levels to compare the structural characteristics of raw (silty clay) and lime-stabilized subgrades. The fundamental properties of soil such as liquid limit (LL) and plasticity index (PI) were observed to decrease with the addition of lime. A lime content of 4% by dry weight was selected for this study; at this lime content, the soil exhibited an approximate PI of 15. The standard procedure of lime application, mixing, and mellowing was followed to prepare the samples for laboratory testing. The subgrade soil mixed with 4% lime by weight was allowed to mellow for 3 days before it was dried and pulverized to prepare the samples. The laboratory specimens exhibited a maximum dry density of 102 lb. /ft^3 and an optimum moisture content of 17% as determined from the standard proctor test. The specimens were then tested for strength and resiliency using UCS, CBR, and repeated load triaxial tests. The UCS of lime-treated soil was observed to be greater than that of the raw soil and was highest at the optimum moisture content; additional improvements in strength were observed with the increase in curing period. The observed increase in modulus of resilience (M_R) values with the addition of lime suggested an increase in resistance to rutting and plastic deformation. The M_R was observed to increase with the increase in confining pressure and to decrease with the increase in moisture content.

Gautreau et al. conducted field and laboratory testing of chemically-stabilized subgrade soils. Results were used to develop a systematic methodology to modify and stabilize natural subgrade at various moisture contents and to obtain a layer that can contribute to the overall structural capacity of the pavement *[3]*. A high-plasticity clay soil (PI > 25) was selected to derive the correlation among moisture content, lime content, and the strength of the subgrade soils. The moisture content increased while the dry unit weight decreased with the increase in additive percentage. The UCS of the soil increased with the addition of lime while it decreased as the molding moisture content deviated from the optimum moisture content during curing. The LL and PI for the untreated soils were observed to be in the range of 31 to 153% and 10 to 125% while the clay content was in the range of 23 to 80%. The researchers also utilized the Eades & Grim (E&G) test and the PI-Wet test methods to determine the percentage of lime required for saturation as illustrated in Figure 1. The resilient modulus of lime-stabilized soils was observed to increase from 225 to 325% as compared to the natural soils. A significant decrease in permanent deformation with the increase in load repetitions was observed with the addition of lime as indicated by accelerated loading test results. Field testing also indicated that the strength for lime-treated soil increased from 24 psi to 35 psi over 28 days with a peak value of 42 psi in one of the samples.

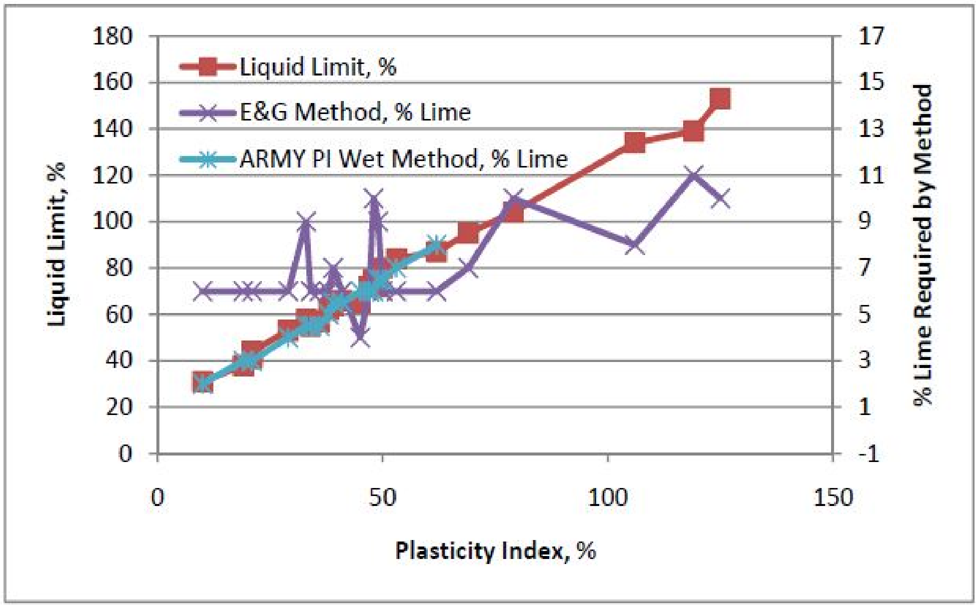


Figure 1
Lime percentage methods *[3]*

Generally, most of the field-studies involving lime-stabilization indicate that lime-stabilized subgrades perform better than non-stabilized subgrades, when due regard is given to materials design, structural design, durability, and construction. Enhanced performance is typically reported in terms of number of traffic loads to failure and strength properties of the subgrade soil *[4]*. Post-construction tests on lime-treated subgrade are necessary to evaluate the long-term performance of these soils. In 1996, a field study was conducted to evaluate the long-term performance of lime-stabilized subgrades using FWD and DCP *[5]*. Results indicated that the stiffness of the treated subgrade increased to more than 300% of that of the natural subgrade. In 2001, a study was conducted in Mississippi to evaluate the performance of in-service lime-stabilized subgrades *[6]*. The ratio of the stiffness of the treated subgrade and the natural subgrade was reported to be in a range between 12 and 33 from the DCP test, and between 4 and 20 from the FWD test.

Between 2009 and 2012, the Department of Transport and Main Roads (TMR) in Australia conducted field testing on several projects with lime-stabilized subgrades *[7]*. The purpose of the study was to develop a systematic procedure for the structural design of pavements constructed on lime-stabilized subgrade. Sample cores were extracted from lime-stabilized subgrades and used to conduct UCS and capillary rise tests. The selected projects were Cunningham Highway, constructed in 1997, Warrego Highway, constructed in 2009, and Leichhardt Highway, constructed in 2002. Based on the results of the study, the lime content required to achieve an UCS of 218 psi at 28 days was recommended as the lime content required for soil stabilization. The lime-stabilized layer shall be a single layer with a minimum thickness of 250 mm, and a preferable thickness of 300 mm. The stabilized layer shall be modeled as a cross-anisotropic layer with a Poisson's ratio of 0.45 and a modulus of 29 ksi. The steps for pavement design with lime-stabilized subgrade are as follows:

- A trial design is developed, which includes thickness and modulus of unbound granular materials, minimum thickness of the lime-stabilized layer, and design subgrade CBR for semi-infinite layer.
- The subgrade underneath the lime-stabilized layer is characterized with CBR, vertical and horizontal moduli, shear modulus, and Poisson's ratio.
- The lime-stabilized layer is characterized with CBR, vertical and horizontal moduli, shear modulus, and Poisson's ratio. The maximum modulus of the top sublayer of the subgrade layer stabilized with lime is assumed to be 29 ksi.
- The total depth of the lime-stabilized layer is divided into sublayers. For each layer, the ratio of moduli is calculated as $R = E_{top}$ (stabilized subgrade layer) / E_{top} (non-stabilized layer).
- The total depth of unbound granular base layer above the lime-stabilized layer is divided into sublayers. For each layer, the ratio of moduli is calculated as $R = E_{top}$ (granular layer)/E (lime-stabilized layer).
- The allowable loading is calculated using CIRCLY (pavement design software) based on the assumed thicknesses and moduli.
- If required, the aforementioned steps are repeated to arrive to the final design.

Toohey et al. performed a laboratory study to compare the stress-strain-strength behavior of four lime-stabilized soils (see Table 2) under two different curing conditions: (1) 2 to 8 days at 41°C accelerated curing and (2) 0 to 28 days at 23°C normal curing *[8]*. The stress-strain behavior was observed to be similar for normal and accelerated curing indicating that no influential chemical reaction occurred during the accelerated curing (see Figure 2). The unconfined compressive strength for the specimens cured at 41°C was equivalent to the UCS for the specimens cured under normal conditions in just 1.8 to 5.9 days. Table 3 presents the comparison of UCS gain for the specimens under accelerated and normal curing. It was concluded that the accelerated curing (7 days at 41°C) proposed by the National Lime Association (NLA) and AASHTO overestimates the normal curing (28 days at 23°C) UCS by 13 to 256%. Five days at 41°C accelerated curing was reported to be reasonable as it yielded similar UCS values (within 0.90 -1.94) of the 28 days at 23°C UCS.

Table 2
Untreated and treated soil properties for soils 1, 2, 3, and 4 *[8]*

Soil		Untreated					Treated	
	AASHTO classification	% clay	% silt	LL	PL	PI	OMC (%)	Density (kg/m^3)
1	A-6	8	29	39	26	13	28	1490
2	A-6	28	35	39	15	24	25	1506
3	A-7-6	29	50	41	15	26	26	1538
4	A-7-6	29	19	55	18	37	29	1394

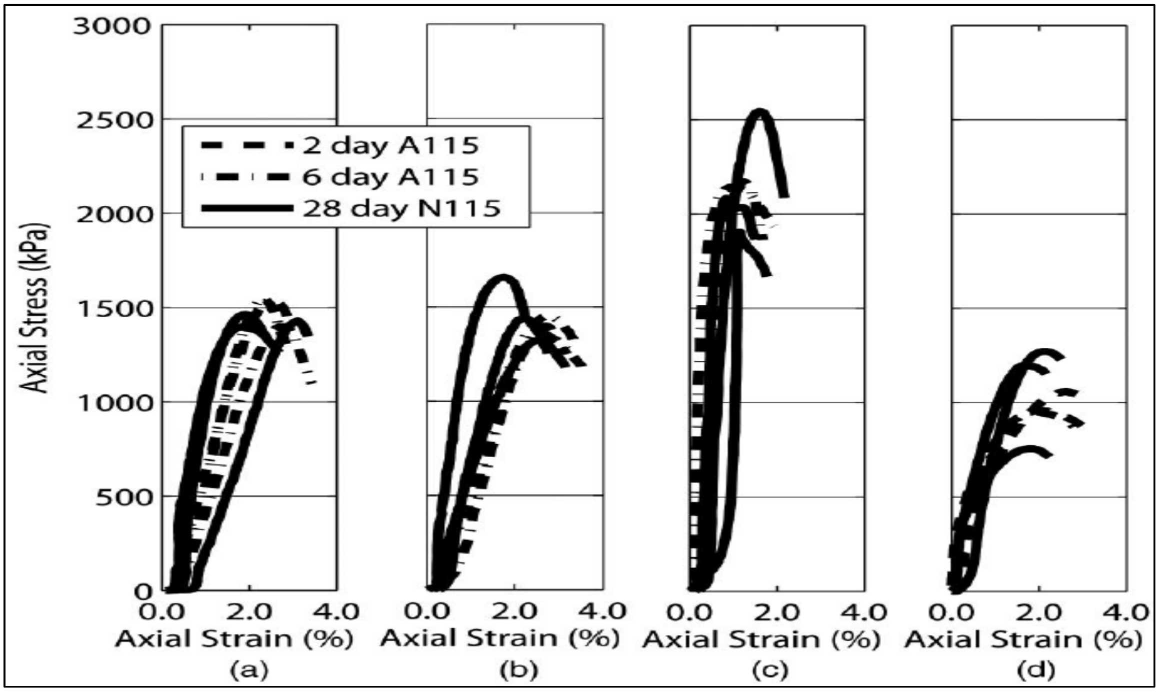


Figure 2
Comparison of 6-day accelerated and 28-day normal curing axial stress-strain behavior for soil: (a) 1; (b) 2; (c) 3; and (d) 2-day accelerated and 28-day normal curing axial stress-strain behavior for soil 4 *[8]*

Table 3
Comparison of q_u gain with time for normal and accelerated curing *[8]*

Soil	PI	% clay	m_N (normal) (kPa/day)	m_A (accelerated) (kPa/day)	m_A/m_N	Equivalent accelerated curing time (days)
1	13	8	34.5	230	6.7	5.4
2	24	28	15.9	126	8	4.6
3	26	29	59.3	328	5.5	5.9
4	37	29	24.8	356	14.4	1.8

$m=\Delta q_u/\Delta t$; A= accelerated curing; N= normal curing

Talluri et al. studied the effectiveness of pre-compaction mellowing of lime-stabilization on high-sulfate soils that causes heaving and premature failures of the subgrade *[9]*. Six different types of soils were tested for sulfate content using the Texas Department of Transportation (TxDOT) method; three soil samples were reported to have a sulfate content less than 8,000 ppm and the remaining three samples to have a sulfate content greater than 20,000 ppm. Optimum moisture content test and compaction tests were conducted to classify the soil according to the basic fundamental properties. Three-dimensional (3D) volumetric swell, shrinkage, and UCS tests were conducted at two different moisture levels (OMC, and wet of OMC [WOMC]; WOMC was 3 to 6% higher than OMC) to assess the swelling, shrinkage, and strength characteristics of the soil samples. Soil samples were mixed with 6% lime by weight and allowed to mellow for 0, 3, and 7 days in a moisture-controlled environment. A double inundation technique that represents a maximum heave was utilized to determine the maximum volumetric swell. Three-dimensional swell was observed to increase for all soil samples that did not undergo any mellowing except for two soil samples, for which the swell decreased from 16.6 to 8.8%. The swell decreased for four samples that received 3 days of mellowing while it increased for two samples (Austin, Childress) with sulfate content greater than 20,000 ppm. Shrinkage tests indicated a higher volumetric shrinkage at WOMC than at OMC. The authors concluded that mellowing had a minimal impact on shrinkage though a higher shrinkage was associated with longer time of mellowing. Compressive strength of lime-treated soils was observed to be 2 to 5 times greater than that of the natural soils.

It was concluded that the mellowing period had an insignificant effect on the compressive strength of the samples, though the samples that mellowed for a short duration were observed to have a slightly higher UCS. Inductively Coupled Plasma (ICP) analysis was conducted to test soils samples for reactive alumina and silica. Though the Austin (high-plasticity clay) and Childress (high-plasticity silt) soils were observed to contain lower alumina and silica, the higher sulfate content and the available reactive minerals on these soils resulted in higher swelling. Comparison of the results showed the opposite results in terms of strength and mineral content; the soil with high alumina and silica content (Riverside) was observed to have a lower strength compared to the soil with low alumina and silica content (Childress). The authors suggested that higher plasticity index of the Childress soil (PI = 35) than that of Riverside soil (PI = 24) to be the reason for increased compressive strength. Table 4 presents the UCS of natural and lime-stabilized soils at different moisture contents. The volumetric swelling for two soil samples under different mellowing periods is presented in Figure 3.

Table 4
UCS values of natural and 6% lime-treated soils *[9]*

Soil	UCS Strength (psi)					
	Natural		**0 Days Mellowing**		**3 Days Mellowing**	
	OMC	WOMC	OMC	WOMC	OMC	WOMC
Austin	28	21	88	53	84	56
Childress	23	16	108	78	103	56
Dallas	16	10	92	56	73	63
FM-1417	33	19	81	60	70	46
Riverside	30	18	63	52	47	37
US-82	31	18	73	45	52	38

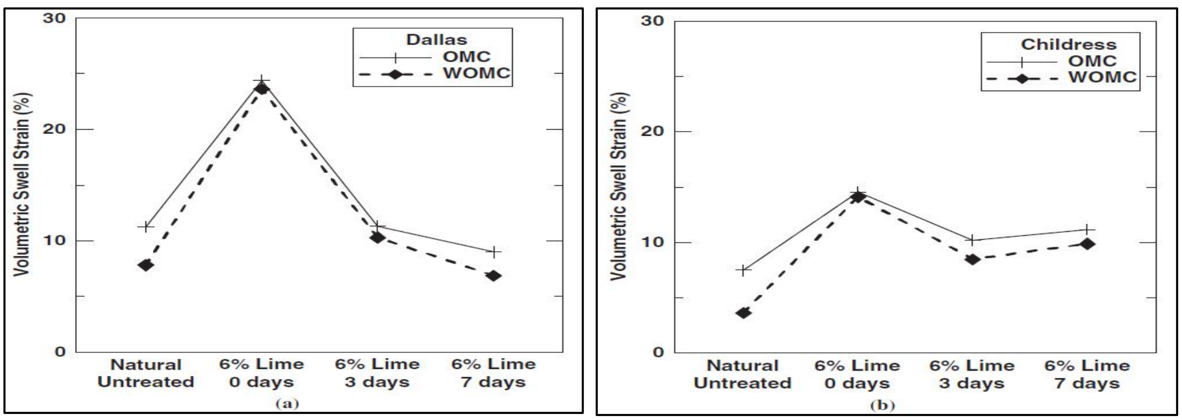


Figure 3
Variation of volumetric strain at different mellowing periods: (a) Dallas soil and (b) Childress soil *[9]*

White et al. evaluated the performance of lime and fly ash stabilized subgrades in Iowa. Laboratory tests (Moisture, pH, unconsolidated-undrained triaxial compression, Scanning Electron Microscopic [SEM] analysis) and field investigation (DCP, FWD, Light-Weight Deflectometer [LWD], Plate Load Test [PLT], and boring and sampling) was conducted to evaluate the engineering and mineralogical properties of lime-stabilized subgrades in six different sections *[10]*. The surface deflections, which are influenced by the CBR profile of underlying subgrade as determined by the FWD test, were observed to be non-uniform with coefficients varying from 10 to 30%. The modulus of elasticity of subgrade varied with the test methods; the elastic moduli determined from LWD and FWD were about 0.7 times and 8.3 times the PLT modulus. Two out of six subgrade soils were observed to have an elastic modulus less than 15,000 psi, which was not in agreement with the Mechanistic Empirical Pavement Design Guide (MEPDG) recommendation. The CBR values of the stabilized soil was higher than those of the normal soil with a ratio ranging from 2.2 to 7.4 depending upon the thickness of stabilization. Pavement performance was observed to be improved with the improved strength after stabilization lasting for several years after construction. Further evaluation was recommended as the researchers observed the top layer to be weaker than the center of the stabilized layer.

The addition of a small amount of lime (from 1 to 3%) causes change in the plasticity of clayey soil. Expansive clay minerals such as montmorillonite exhibit substantial reduction in the PI when treated with lime and thus the soil becomes more workable and consistent. On the other hand, non-expansive clay minerals such as kaolinite exhibit a slight increase in the plasticity when treated with lime *[11]*. The addition of lime reduces the swelling potential of expansive clay soils. The shrinkage properties of expansive soils were also found to be improved significantly. In all clayey soils, lime-addition increases the optimum moisture content and decreases the maximum dry density at the same compaction effort *[12]*. Higher maximum dry density is achieved in kaolinite than in montmorillonite *[13]*. Moreover, the CBR of both types of clayey soils is increased with lime-stabilization when compared with non-stabilized soils. The increase in strength depends on the length of curing time and the curing temperature. Kaolinite clays were observed to respond slower to lime-stabilization when compared to montmorillonite, and thus gain strength latter than do montmorillonite clays *[11]*. Table 5 depicts the changes in optimum moisture content, maximum dry density, and CBR associated with lime addition to kaolinite and montmorillonite *[11]*.

Table 5
Comparison of the results of compaction and CBR tests carried out on kaolinite and montmorillonite with those obtained when these materials were treated with optimum lime contents *[11]*

Material	Optimum lime content by weight (%)	Optimum moisture content (%)	Maximum dry density (Mg/m^3)	CBR (%)
Kaolinite	0	29	1.4	1
	6	31	1.33	14
Montmorillonite	0	20	1.29	9
	4	25	1.15	18

In 2015, research studies were conducted to evaluate the impact of lime-stabilized subgrades on the induced fatigue and rutting strains using MEPDG (Mechanistic Empirical Pavement Design Guide) analysis *[14]*. Results indicated that the compressive strain on the top of lime-stabilized subgrades decreased significantly. Furthermore, it was reported that the tensile strain at the bottom of the asphalt layers was below the critical tensile strain suggested by Asphalt Institute *[145]*. Similarly, the horizontal tensile strain at the bottom of the lime-stabilized subgrade layer was below the critical tensile strain suggested by Austroads *[16]*.

Results also showed significant improvement in rutting performance with lime-stabilization. Figure 4 demonstrates a wet soft clay subgrade before and after lime-stabilization.

Figure 4
Untreated soft clay subgrade showing highly wet condition (on the left) vs. the same subgrade after lime-stabilization (on the right)

Bell reported that the optimum lime content ranges between 1 and 3% lime by weight of dry soil *[11]*. Further addition of lime will not affect the plastic limit but will increase soil strength. Other studies suggested that the optimum lime to be added to stabilize expansive clays ranges between 2 and 8% by weight *[17]*. Studies in Al-Khoud, Oman, concluded that the addition of 6% lime decreases the swell pressure and swell percentage to zero in expansive clay soils *[18]*. Other studies reported that soil stabilization using lime may be effective in soils having plasticity indices below 10 and in soils having clay contents as low as 7% *[19]*. Soil types A-4, A-5, A-6, A-7 and some soils classified as A-2-6 and A-2-7; based on AASHTO classification, are appropriate for lime-stabilization *[20]*. Soils with PI greater than or equal 12 is recommended by the U.S Army Corps of Engineers for lime-stabilization, while the NLA suggests the soils to have a plasticity index equal or greater than 10 for lime to be used as a potential stabilizer *[21, 22]*.

Laboratory Evaluation of Threshold Sulfate Content for Soil Stabilization

In Louisiana, sulfate bearing soils generally occur in two places: (1) naturally occurring gypsum “winrock” from around Winn Parish and (2) from blended calcium sulfate (BCS), an air stripping byproduct that has occasionally been used as a base course. Harris et al. conducted laboratory soil tests to develop lime-stabilization construction practices to reduce volumetric swelling of high-sulfate soils *[23]*. Results from traditional lime-stabilization indicated an increase in subgrade swell with the increase in sulfate content. In one of the test sites, a soil with no sulfate and stabilized with 6% lime by weight was observed to swell by about 3% while the swelling reached up to 30% for the non-stabilized soil. The soils with sulfate content less than 3,000 ppm are subjected to less risk of swelling while the soils with sulfate content greater than 8,000 ppm have higher risk of swelling as ranked by TxDOT and the NLA. The method of injection of sulfate into the stabilized layer had an impact on swelling; greater swell was observed in the samples with dissolved sulfate than the coarse-graded gypsum for same percent lime and sulfate amount. Results from the laboratory tests indicated that a moisture content of 2% above optimum and a single application of lime reduced swelling in the subgrade. Improved results were observed when the soils with a sulfate content of about 7,000 ppm were subjected to 6% lime-stabilization by weight with 3 days of mellowing. The swell was higher for soils with 10,000 ppm sulfate content for similar conditions of stabilization. The effect of mellowing time and lime application on swelling is presented in Figure 5.

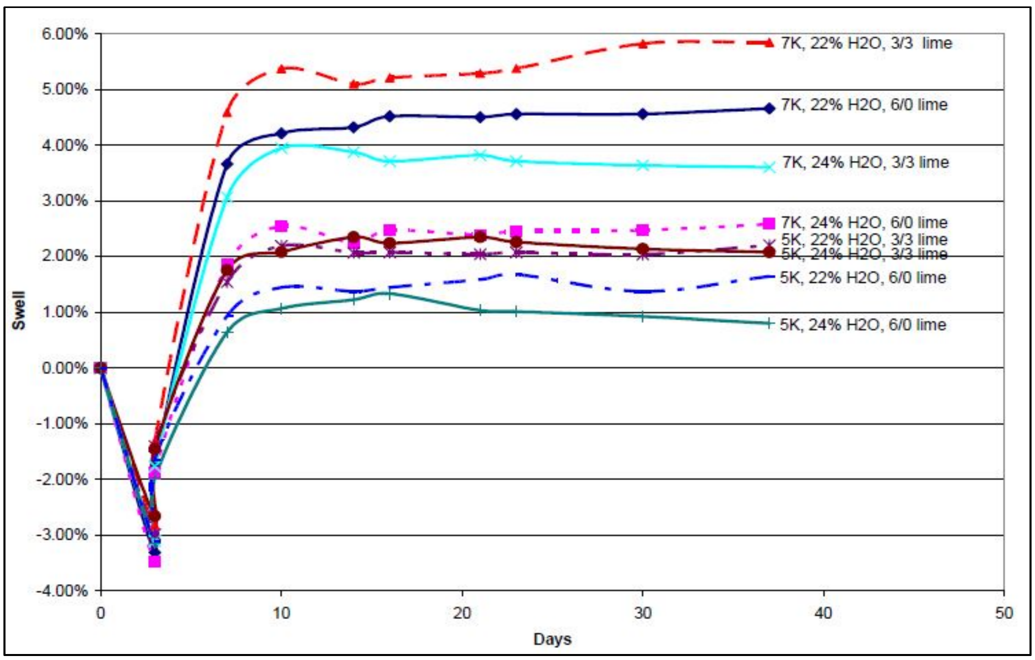
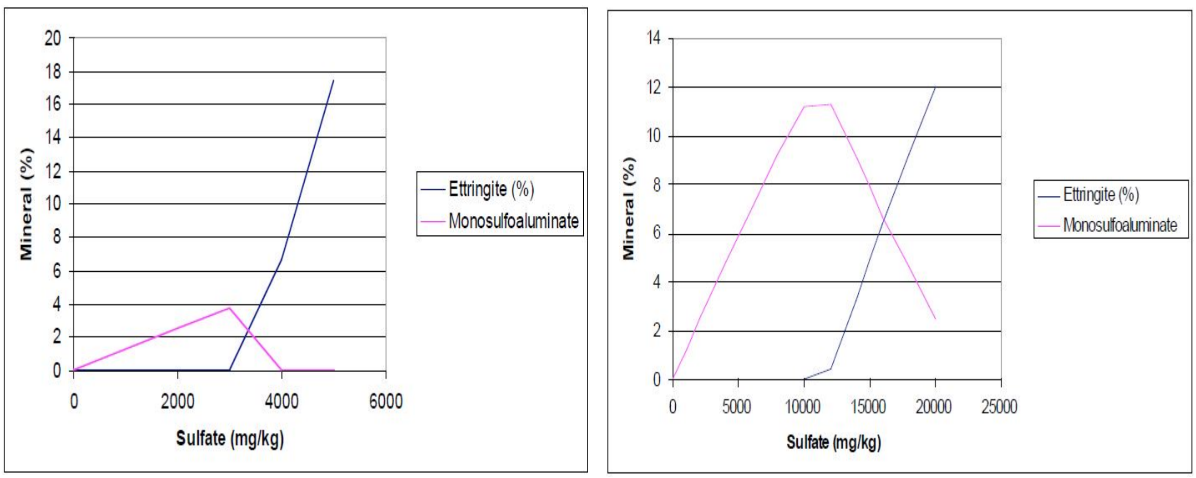


Figure 5
3D swell with sulfate dissolved in molding water and one-day mellowing *[23]*

Little et al. studied the thermodynamic geochemical models of lime-treated soil to determine the sulfate level that leads to the formation of minerals called ettringite and thaumasite, which result in expansion and strength loss in soil *[24]*. Two different soils were modeled with two different approaches (a reaction path approach and a predominance approach) to study various factors that leads to the formation of ettringite. The first soil was from Frisco, Texas, with the Eagle Ford formation, which was highly responsive to ettringite formation due to high pyretic content and pedological effects, while the second soil was from the

Taylor formation and was less susceptible to ettringite formation. In the reaction path approach, the reactive minerals were allowed to react to completion with reactive ions that were extracted at a pH of 7, while in the predominance approach, a selected percentage of lime was allowed to react in an aqueous environment with the ions that were extracted at a pH of 12. The phase diagram at sulfate concentrations of 3,000 ppm and 10,000 ppm indicated that the soil from the Eagle Ford formation was more susceptible to ettringite formation even at a lower sulfate content (3,000 ppm) than the soil from Taylor formation (10,000 ppm). The same soil when tested with different percentages of lime at the same sulfate content of 20,000 ppm provided different results; the chance of ettringite formation was much higher for soil with higher percentages of lime. The authors concluded that the stability models can be of high importance to determine the threshold sulfate content and the effect of additives to control the formation of ettringite. The mineral precipitation threshold for two types of soils is presented in Figure 6.



(a) **(b)**

Figure 6
Minerals precipitation threshold in soils with (a) Eagles Ford formation and (b) Taylor formation *[24]*

Adams et al. evaluated the threshold sulfate level that prevents ettringite formation in Oklahoma soil *[25]*. Atterberg limits performed in three soil samples determined that all three soils were low plasticity clays, with liquid limit less than 50%. Standard proctor tests conducted on soil samples consistently showed higher optimum water content and lower maximum densities for the soil sample mixed with 5% lime by weight. The sulfate levels were observed to be in the range of 194 to 84,000 ppm depending upon the test method (Colorimetry and Ion Chromatography) used. The odometer free swell test was conducted for both raw samples and soil samples treated with 5% lime by weight. The increase in swell was 1% and 3.5% for two of the soil samples with high sulfate levels while the third soil sample with a soluble sulfate of 200 ppm showed a decrease in swell by 2.3% after the addition of lime. The second soil sample was observed to have higher swell than the first sample though the measured sulfate content was 10 times less (approximately 8,500 ppm); the authors attributed these results to the higher clay content (Δ =17%), additional Specific Surface Area (SSA) available (Δ=26m^2/g), and the difference in Cation Exchange Capacity (CEC) value (-Δ=89.5 meq/100g), which increased the swelling potential. The authors concluded that the exact threshold sulfate level cannot be determined due to the large variation in sulfate level in natural soils; all the behavior and physiochemical soil properties must be studied in order to determine the exact threshold value of sulfate content for possible soil stabilization.

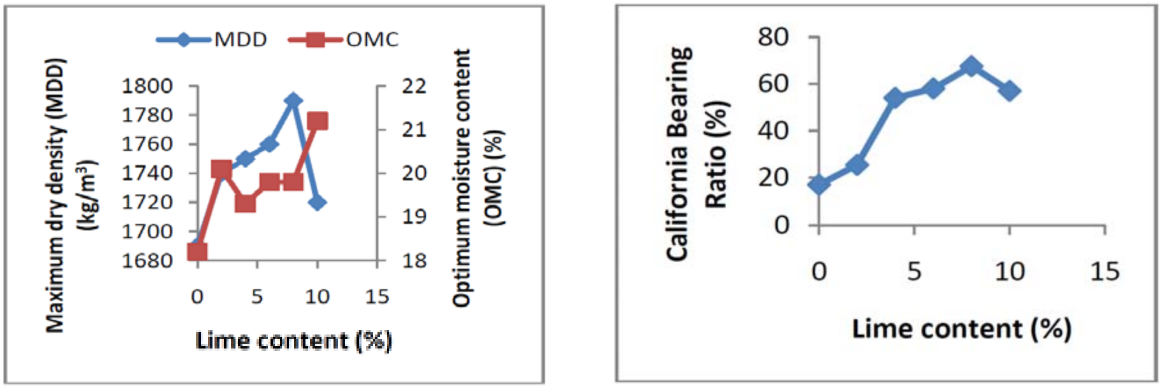
Laboratory Mix Design

Celaya et al. evaluated several methods to attain a faster mix-design for lime-stabilization of subgrade soils in Texas *[26]*. Laboratory specimens of various soil types (Bryan, El Paso, Fort Worth, and Paris) that were acceptable for lime-stabilization were tested using several accelerated testing methods that could minimize the time for specimen preparation, curing, conditioning, and testing in order to complete the mix design. The moisture-conditioning processes (i.e., standard Texas DOT protocol), dry protocol, tube suction test protocol, back-pressure conditioning method, submergence method, and vacuum method were characterized and evaluated using UCS strength test, dielectric constant test, the Free-Free Resonant Column (FFRC) test, and moisture content test. The amount of lime required for stabilization for each sample was determined from Eades and Grim (E&G) method and then tested for UCS, moisture content, modulus, and dielectric constant after a given number of days of curing. The initial moisture content for all specimens after compaction was similar while the final moisture content after conditioning was observed to be 1% higher than the initial for all methods except for the back pressure method, which was 0.6% lower than the initial. Different curing times were applied in the TxDOT protocol method for which the final moisture content was observed to be 2% lower than the initial. The specimen conditioned based on the TxDOT protocol was observed to have the highest strength while the lowest strength was associated with the 4-hr. submergence method. The moduli of all specimens increased during curing, and decreased after conditioning except for the TxDOT protocol, for which the final moduli was greater than the moduli during curing. The final dielectric constants of all specimens were observed to be greater than the dielectric values after drying except for the 4-hr. submergence method. The back pressure method provided similar results in terms of strength with the Tube Suction Test (TST) method while the strength of vacuum-conditioned specimens was lower than the TST specimens and much lower for the submerged specimens. Similar results were observed for the final moduli of the specimens.

Little and Nair presented a systematic methodology for the selection of the stabilizers for different soil types *[27]*. For lime-stabilized soil, they started with the protocol developed and recommended by the National Lime Association (NLA) to obtain a high strength and durable soil. According to the NLA, soils with a PI of 10 or above and a minimum of 25% passing No. 200 are suitable candidates for lime-stabilization. Additional tests are recommended by AASHTO for soils with sulfate content greater than 3,000 ppm. The E&G pH test method is recommended to select the optimum lime content required to achieve a pH of about 12.45 at 25°C, which is an important criterion to sustain long-term pozzolanic reaction. The change in the moisture-density relationship with soil stabilization shall be determined in accordance to AASHTO T 99. ASTM D 3551 shall be followed to determine the compressive strength of the stabilized soil samples in order to ensure satisfactory field performance. A maximum mellowing period of 24 hours is recommended to simulate field condition. Additional samples with lime content higher than the optimal lime content determined by E&G method should be prepared and tested for compressive strength to verify the optimal lime content required for a specific compressive strength. The compacted specimens are cured at 40°C for 7 days and then soaked for a minimum period of 24 hours before compressive testing. A three-dimensional expansion in volume of 2% is acceptable for dry and soaked samples. ASTM D 5102 procedure B shall be followed to test the samples for compressive strength. The lowest lime concentration to achieve a standard compressive strength is selected. The process should be repeated with different lime contents if the criterion for compressive strength is not met with the selected lime content.

Ogundipe performed laboratory tests, namely the mechanical sieve analysis and hydrometer test, specific gravity, moisture content, Atterberg limit test, compaction test, and CBR test to determine the optimum lime content required to stabilize clayey soils *[28]*. The soil was classified as A-7-5 with an average moisture content of 20.2%, Liquid Limit (LL) of 63.9, specific gravity of 2.48, and CBR of 17%. The LL of the soil decreased steadily with the increase in lime content from 2 to 8% by weight, indicating the reduction in plasticity of the soil. However, the LL was observed to increase for 10% lime content. The PI of the soil increased with 2%, 4%, and 6% lime content by weight and decreased with 8% and 10% lime content by weight. The shrinkage limit decreased with the increase in lime content, which indicates the susceptibility of the soil to volume change with the addition of lime. The maximum dry density (MDD) of the soil increased for 0 to 8% lime content while it decreased for 10% lime content. The CBR of the soil was observed to increase with a lime content of 2 to 8% with a maximum value at 8% while it decreased with 10% lime content. The reduction in MDD and CBR values at 10% lime content was attributed to the excess of lime not required for cation exchange. Best results were observed at 8% lime content by weight, which was recommended for the stabilization of the considered natural clay soil.

Figure 7 presents the effect of lime content on MDD, optimum moisture content (OMC), and CBR of the clayey soil.



(a) (b)

Figure 7
Laboratory test results: (a) MDD and OMC versus lime content and (b) CBR versus lime content *[28]*

NCHRP 20-07 outlined the procedure and guidelines for mix design in lime-stabilized subgrade and base layers *[29]*. The mix design guidelines for lime-stabilized soils are based on the NLA protocol *[30]*. The NLA recommends soils used in lime-stabilization to have at least 25% passing No. 200 sieve and a minimum PI of 10. Moreover, the NLA recommends an increased lime content when the organic content of the soil is higher than 1%. Consequently, screening for organic contents above 1% is required in the soil evaluation process, following ASTM D 2974. The NLA recommends to perform swell tests when the soluble sulfate content is more than 3,000 ppm to consider the anticipated expansion degree of the soil. The NLA determines the optimum lime content to be used through two steps. The first step is to perform the E&G pH test as highlighted in ASTM D 6276. This test selects the amount of lime needed to achieve the design pH at 25°C. In the second step, strength testing is essential to validate the optimum lime content in soil stabilization. The NLA recommends the moisture density relationship of the lime-stabilized soil mixture to be verified when the optimum lime content is added following AASHTO T 99. The NLA describes in details the fabrication and curing procedure of lime-soil mixture for compressive strength testing. Finally, the unconfined compression strength testing should be performed in accordance with ASTM D 5102 procedure B to evaluate the compressive strength of lime-stabilized soil. Table 6 illustrates the suggested minimum compressive strength for lime-stabilized soils. The samples used for compression testing can be used to take different measurements between the dry and soaked conditions. These measurements would assist to evaluate the swelling characteristics of lime-stabilized expansive soils. A maximum three-dimensional volumetric expansion of 2% is considered acceptable *[31]*.

Table 6
Compressive strength recommendations for lime-stabilized sections *[32]*

Anticipated use of stabilized layer	Compressive strength recommendations for different anticipated conditions (psi)			
	Extended soaking for 8 days	Cyclic Freeze- Thaw		
		3 cycles	7 cycles	10 cycles
Subbase material				
Flexible pavement (>10 in.)	60	60	100	130
Flexible pavement (8 in.-10 in.)	70	70	100	140
Flexible pavement (5 in.-8in.)	90	90	130	160
Base material				
	130	130	170	200
For cycling moisture conditioning the samples should be made to reach 80% saturation upon "wetting" followed by 50% saturation upon "drying." This is satisfactory to represent the damaging cyclic environment				

NCHRP 20-07 also summarized the different steps for lime-stabilization of base layers *[29]*. First, different lime percentages are added to the mixture, starting with 1% by weight of the mixture and increasing to 4% by weight. Then for each aggregate-lime mixture, the moisture density relationships are determined according to agency requirements following AASHTO T 99 or AASHTO T 180. Finally, the unconfined compressive strength of the different soil blends is determined and compared with the specifications defined by the user agency.

Lime Consideration in Pavement Design

Subgrade stabilization is a fundamental factor that has a noticeable impact on pavement performance and design. Lime-stabilization is one of several methods used to improve the properties of subgrade soils, which in turn will enhance pavement performance. The change in properties of lime-stabilized soil is dependent upon the type of clay soil, length of curing, lime content, and the quality of construction *[11]*.

In 1972, NCHRP conducted a survey to collect information about the layer coefficients adopted by different states in the AASHTO design procedure *[33]*. Table 7 illustrates the layer coefficients for lime-treated soil adopted by different states.

Table 7
Results of the 1972 NCHRP survey of layer coefficients for lime-treated soil *[33]*

State	Montana	New Mexico	Pennsylvania	South Dakota	Wisconsin	Wyoming
Layer Coefficient	0.15-0.20	0.05-0.10	0.20	0.15	0.15-0.30	0.07-0.12

In 2000, Little examined the long-term performance of lime-stabilized subgrade *[30, 34]*. FWD testing was conducted on non-stabilized subgrade soil and lime-stabilized subgrade soil to backcalculate the resilient modulus of both soils. Results indicated that the resilient modulus of lime-stabilized soils was on the order of 1000% higher than the resilient modulus of untreated soils. These results could be correlated to the layer coefficient of lime-treated soils to be considered in flexible pavement design.

In 2002, research was initiated by the Kentucky Transportation Cabinet (KYTC) in collaboration with the University of Kentucky Transportation Center (UKTC) to assess the structural benefits of lime-stabilized subgrade soils *[35]*. Among the objectives of this research was to determine the structural credit that should be assigned to lime-treated subgrade soil. The FWD test was performed before coring and laboratory tests were performed on samples of untreated subgrade and lime-stabilized subgrade. Results indicated that the CBR value of lime-treated subgrade was about 13.5 times more than the CBR value of untreated subgrade. Furthermore, backcalculation of layer moduli indicated that the elastic modulus of lime-stabilized subgrade is about two times the modulus of untreated subgrade. The research utilized the AASHTO published relationship, which relates CBR and the structural layer coefficient (a_3), along with CBR values of lime-stabilized subgrades to arrive at a reported structural layer coefficient (a_3) of 0.106 for lime-stabilized subgrades.

In 2004, Chou et al. suggested a design procedure that considers the improvements of lime-stabilized subgrades in the AASHTO 1993 flexible pavement design procedure *[34, 36]*. This method incorporates a combined overall subgrade modulus (B), which represents the lime-stabilized subgrade and the non-stabilized subgrade. The ratio (B) is calculated from the following equation:

$$B = 1 + (A - 1)\left[1 - \exp\left(-\left(0.000225D_1{}^2 - 0.00991D_1 + 0.106\right)D_3{}^{1.3}\right)\right] \quad (1)$$

where,

D_1 = the thickness of asphalt layer,

D_3 = the thickness of the lime-stabilized layer, and

A = the ratio of lime-stabilized layer modulus and non-stabilized layer modulus.

The value of A ranges between 1.5 and 3; however, if no laboratory testing is performed, the value of A is recommended to be assumed as 1.5. Chou et al. utilized the overall subgrade modulus (B) instead of the non-stabilized subgrade modulus in the AASHTO design equation. Consequently, the design modulus used in the AASHTO design equation is equal to the non-stabilized subgrade modulus multiplied by the ratio B.

Qubain et al. presented the benefits of incorporating lime-stabilized subgrade into pavement design in Pennsylvania *[37]*. The project consisted of widening and reconstruction of a 21-km long pavement section in Pennsylvania. The subgrade was traditionally stabilized using lime to prevent the softening due to rain; however, it was not incorporated in the design. The subgrade soil was a homogeneous medium to stiff clay with an average LL and PI of 34 and 13, respectively. The optimum lime content required for saturation of the subgrade soil for the selected project was 5% by weight as determined by the Virginia Test Method (VTM). The resilient modulus (M_R) and CBR values were higher while PI, LL, and swell decreased for the lime-treated subgrade. To incorporate the lime-stabilized subgrade into the design, three different methods incorporating M_R, CBR, and structural layer coefficient were evaluated. The respective serviceability loss of 0.6 and 0.3 were assigned for natural and lime-treated soils as suggested by the AASTHO Design Guide. The M_R design approach predicted a reduction in pavement thickness of 9.4 in. for the lime-stabilized pavement while the CBR approach predicted the pavement thickness to be ¾ in. more than the M_R approach. For the layer structural coefficient approach, the subgrade was counted as a subbase and a structural coefficient of 0.11 was assigned based on AASTHO correlation of structural number with strength parameters (CBR and M_R). This approach predicted a total thickness of 21.6 in., which was 7.1 in. and 5.1 in. less than the thickness suggested by the M_R and CBR approaches. The estimated cost for the different design approaches are presented in Table 8. Based on these results, the authors predicted a savings of $7.7 million, if lime-stabilized soil is considered in the design.

Table 8
Estimated costs for different design approaches in Pennsylvania *[37]*

Design Approach	Total Cost in Millions	
	Natural Subgrade [a]	Lime-stabilized Subgrade [b]
Preliminary, CBR=5	29.3	
MR (treated=165Mpa, untreated=60Mpa)	28.2	21.6
CBR (treated=15, untreated=8)	26.1	22.1
Structural Coefficient (treated=0.11)		23.7

[a] Includes $2.3 million for removal of existing pavement.
[b] Includes $2.3 million for removal of existing pavement and 2.3$ million for lime-stabilization.

In 2014, research was carried out by the Ohio Research Institute for Transportation and the Environment in cooperation with the Ohio Department of Transportation, to evaluate the increase in stiffness of lime-stabilized subgrade and its consideration in flexible pavement design *[34]*. The main objective of the research was to develop input values for the design of flexible pavements with lime-stabilized subgrade in both the AASHTO 1993 flexible pavement design and the MEPDG. Field measurements were obtained from various selected sites in Ohio that included lime-stabilized subgrades using the Portable Seismic Pavement Analyzer (PSPA), coring, FWD, and dynamic cone penetrometer. The results of this research indicated the following:

1. In flexible pavement design and using the AASHTO 1993 procedure, the lime-stabilized subgrade should be considered in the thickness design procedure by allocating a new layer coefficient. It is suggested that the designer selects a layer coefficient using the cumulative frequency chart (Figure 8) with a proper level of confidence for the pavement structure being designed.

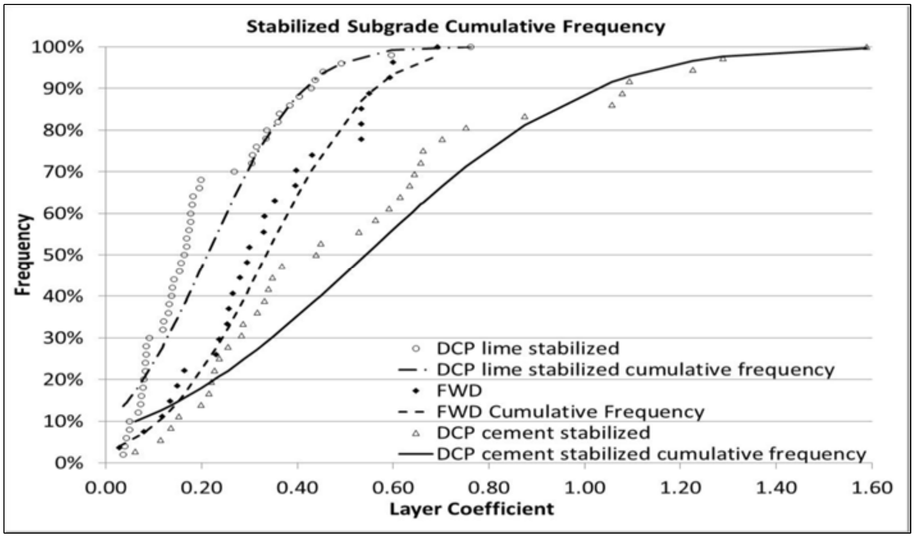


Figure 8
Cumulative frequency of stabilized subgrade layer coefficients—FWD vs. DCP *[34]*

2. Lime-stabilized subgrades increase the stiffness of the aggregate base layer. This increase must be considered when using the AASHTO 1993 in flexible pavement design. This could be achieved by increasing the layer coefficient of the base layer used in the design procedure. It is recommended that the designer select a layer coefficient using the cumulative frequency chart in Figure 9 with an appropriate level of confidence for the pavement structure being designed.

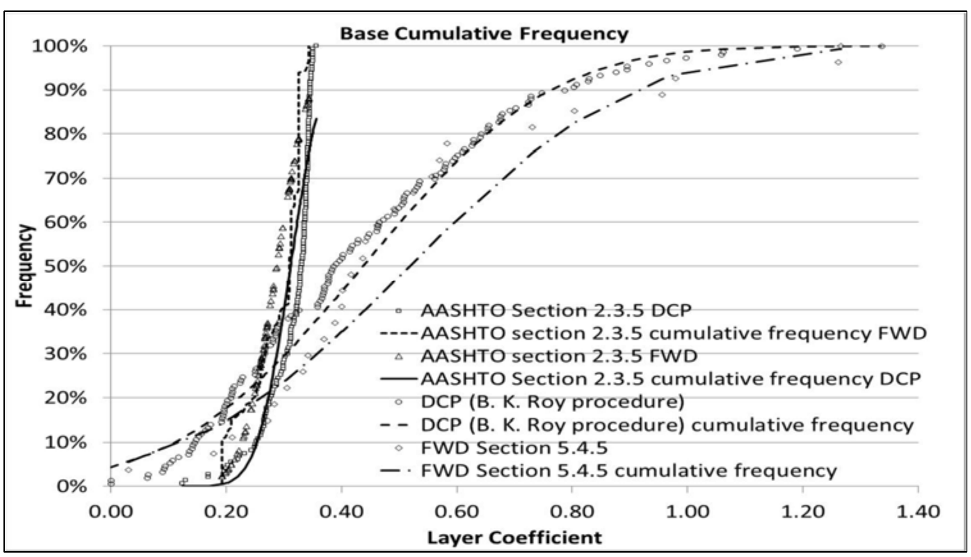


Figure 9
Cumulative frequency of granular base layer coefficients-various approaches compared *[34]*

3. It is recommended to use a minimum lime-stabilized subgrade thickness of 16 in. (41 cm) in the design procedure.

In 2015, Selvi conducted a research study to evaluate the impact of lime-stabilized subgrades on the MEPDG design procedure *[14]*. Selvi utilized KENLAYER and the MEPDG analysis to develop a pavement design catalogue for lime-stabilized subgrade soils having virgin subgrade CBR values of 2, 3, and 4% and subjected to traffic intensities of 1, 5, 10, 20, and 30 million standard axle (msa). The design catalogue considered both fatigue and rutting failure criteria *[14]*.

Virginia DOT incorporated the use of lime-stabilized subgrade in their pavement design guide. Virginia DOT assigned a thickness equivalency value of 0.4 to subgrade soils stabilized with 5% lime by weight. This corresponds to a structural layer coefficient of 0.18 *[7, 37]*. AASHTO introduced a correlation between structural coefficient and different subgrade strength parameters and obtained a structural layer coefficient of 0.11 *[37, 38]*.

Solanki et al. studied the effects of lime, fly ash, and cement kiln dust stabilization on the resilient modulus of different pavement subgrade soils, namely, Port series (p-soil), Vernon series (V-soil), Carnasaw series (C-soil), and Kingfisher series (K-soil) *[38]*. The resilient modulus of the subgrade soil was observed to be higher with lime-stabilization, which was dependent upon the type of soil and lime content. An increase in resilient modulus by approximately 642%, 750%, and 311% was observed with 6% lime content by weight for P, V, and C soil, while 6 to 9% lime content decreased the resilient modulus of P and V soil types, and 3 to 6% lime content decreased the resilient modulus of V soil type. The increase in resilient modulus with lime-stabilization was higher in V-soil (Clay). Four models were evaluated using standard deviation of error, square of correlation coefficient, and visual examination of the predicted versus measured M_R and validated using the M_R values of a lean clay (K-soil) stabilized with 3, 6, and 9% lime by weight. The best performing model was then incorporated in the mechanistic empirical pavement design procedure. The stabilized subgrade was treated as a subbase and assigned a structural number using the AASTHO equation for granular subbase, i.e., $a = 0.227 (\log M_R) – 0.839$. Compared with the thickness computed using the measured value of K-soil, the stabilized soil layer with 3 and 6% lime over predicted the required asphalt thickness by 8.4% and 7%, respectively, while the stabilized soil with 9% lime under predicted the layer thickness by 1.4%. It was concluded that the pavement design could be conducted with the predicted M_R values with certain degree of certainty. The results of the study are presented in Table 9.

Table 9
Pavement design comparisons for actual and predicted M_R values (K-soil) ***[39]***

Additive (by weight)	Actual Mr (MPa)	a(mm^{-1})	D (mm)	Predicted Mr (MPa)	a (mm^{-1})	D (mm)	Percent Difference
Raw Soil	56	—	—	—	—	—	—
3% lime	1,017	0.0132	97	844	0.0124	105	8.4
6% lime	1,081	0.0134	94	938	0.0128	101	7
9% lime	719	0.0118	113	746	0.012	111	-1.4

Cost-Effectiveness and Cost-Benefit of Using Lime in Pavement Applications

Weak and expansive soil subgrade is a serious problem in flexible pavement applications. In different seasons, the moisture content varies in the subgrade. These variations cause volumetric changes in expansive soils due to their swelling/shrinkage characteristics, which in turn cause differential settlement and cracking. Accordingly, the use of lime-stabilized soils offers a feasible solution to address poor soil conditions during construction. Cost-effectiveness of lime-stabilization was investigated by a number of research studies.

Research was conducted in India to assess the cost effectiveness of using lime to stabilize expansive soils in pavement design *[40]*. Test specimens of a lime-soil mixture were prepared with different percentages of lime content, and the CBR was calculated along with the maximum dry density. The study indicated that the addition of 5% lime to expansive soils is regarded as the optimum content considering both, the CBR and maximum dry density. Further research was conducted, where two pavement cross sections were analyzed in accordance with IRC: 37, a section with non-stabilized subgrade and another section with lime-stabilized subgrade (5% lime content by weight) *[41]*. It was reported that the stabilized-subgrade pavement section saved about 32.5% of the total cost when compared to the non-stabilized subgrade pavement section.

In 2005, the Michigan Department of Transportation (MDOT) faced the challenge of reconstructing a major interstate highway (I-96) in a congested urban area with low performance underlying subgrade soil *[42]*. MDOT evaluated the cost effectiveness of using lime to stabilize the weak subgrade soil versus the "remove and replace technique." MDOT adopted the mix design protocol developed by Little in order to verify that the soil could be stabilized using lime *[35]*. Testing indicated that a minimum of 3.5% lime by dry weight of soil is required to increase the soil loading capacity and to meet the required specifications. Based on these results, MDOT compared between the bid costs of two alternatives; the first alternative was stabilizing the weak soil using 5% quicklime by dry weight of soil, while the other alternative was the "remove and replace" technique. MDOT indicated that the cost of "remove and replace" technique was about $8.81 per square yard. On the other hand, the cost of lime-stabilization was about $3.70 per square yard, which is less than half the cost of the "remove and replace" alternative. Based on these estimations; MDOT stabilized 424,255 square yards of the project and saved about $2 million, in addition to completing the project ahead of schedule *[42]*.

In 2008, a similar project was conducted by North Carolina State University (NCSU) and was sponsored by the North Carolina Department of Transportation, in order to evaluate the cost-effectiveness of lime-stabilized subgrade soils, when compared with the "cut-and-fill" alternative. The results indicated that lime-stabilization of subgrade test section experienced less rutting and thus performed better than the "cut-and-fill" alternative. In addition, the lime-treated test section saved about half the costs associated with the "cut-and-fill" alternative *[43]*.

A study was conducted in Pennsylvania to evaluate the cost-effectiveness of lime-stabilized subgrade soils *[37]*. In this study, two pavement cross sections were designed using the AASHTO guidelines. One section included lime-stabilized subgrade and the other section had no stabilization. Results indicated that lime-stabilization improved the subgrade strength along with other desirable properties. Consequently, the flexible pavement cross section including the lime-stabilized subgrade was thinner than the section with no stabilization. This reduction in thickness was associated with a reduction in initial cost of about 20%. In 2015, Selvi utilized the MEPDG software to assess the economic benefits of lime-stabilization of subgrades *[14]*. Selvi reported that pavement thickness could be reduced with lime-stabilized subgrades without affecting the performance of the pavement. Eventually, lower pavement thickness means lower costs.

Mishra et al. performed an experimental investigation and life-cycle cost analysis of lime-stabilization of clayey subgrade *[44]*. Light compaction and CBR tests were conducted on non-stabilized soil and soils stabilized with 1.5, 2.5, 3.5, and 5% lime content by dry weight of the soil. The soil samples were cured and soaked for 4 days (4 days soaking), 7 days (3 days air curing and 4 days soaking), and 14 days (10 days air curing and 4 days soaking) and were tested for CBR. The CBR values for soil was observed to increase from 2.7% to 10.4% and 37.1% with stabilization by 1.5% and 2.5% lime content, respectively. For 2.5% lime content, the CBR value was observed to increase to 37.1%, 37.7%, and 53.2% for 4, 7, and 14 days of curing and soaking period, respectively. A considerable reduction in pavement thickness due to lime-stabilization was observed; the reduction in pavement thickness was a function of the optimum lime percentage and the design traffic. For 2.5% lime content, the total cost of flexible pavement construction was estimated to decrease by 9.4%, 6.8%, 9.1%, and 12.4%, respectively for design traffic intensity (ESALs) of 60,000-100,000, 100,000-200,000, 300,000-600,000, and 600,000-1,000,000, respectively. However, a slight increase in cost of 0.44% was estimated for a traffic intensity of 200,000 to 300,000. For the same lime content, the total cost for rigid pavement was calculated to decrease by 10.8%. The cost comparison for stabilized and non-stabilized flexible pavement is presented in Figure 10.

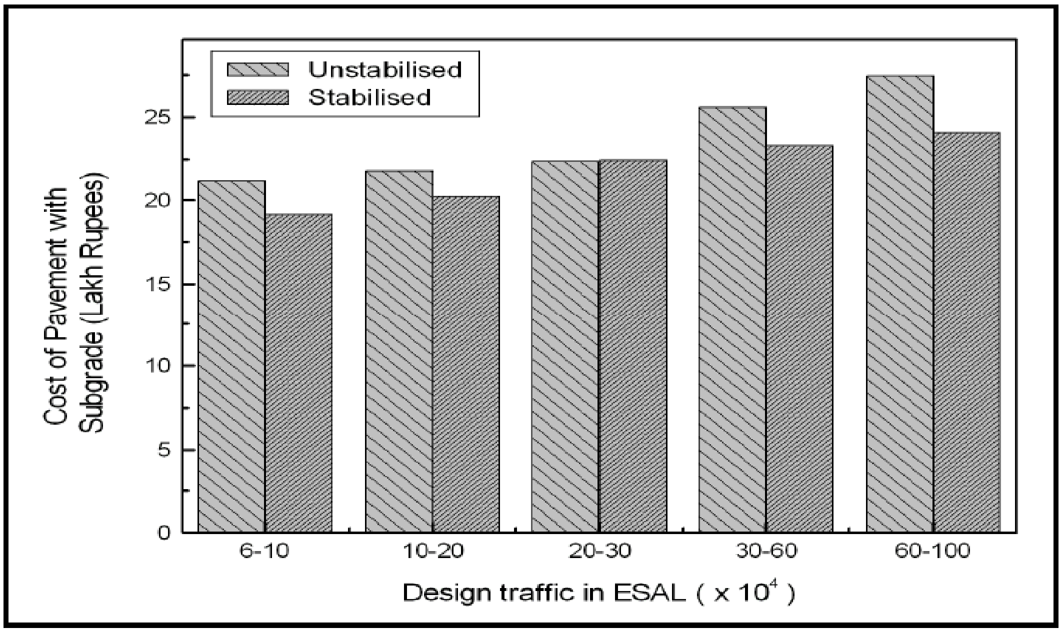


Figure 10
Cost comparison between un-stabilized and stabilized flexible pavement *[44]*

Leaching and Loss of Lime after Construction

In lime-stabilization, the permanency of lime has been studied. The leaching of lime-stabilized soil is a major concern facing the durability of these soils *[45]*. In 1960, Eades and Grim suggested that, in lime-soil stabilization, permanent reaction products are formed *[46]*. These products include silicate and aluminate hydrates and are not liable to leaching. In 1988, it was reported that in the stabilization process, once calcium silicate hydrates are formed, they never revert *[47]*. In 1990, McCallister and Petry conducted a research to evaluate the impact of leaching on lime-stabilized soils *[48]*. The research concluded that the lime content in the soil mixture is the fundamental factor that determines the magnitude of changes in chemical and physical characteristics of the soil mixture subjected to leaching. Soils stabilized with 6 to 7% lime experienced minimal or even negligible changes in their chemical and physical characteristics when subjected to leaching. Whereas, soil stabilized with lower lime content (3 to 4%) experienced significant changes in their physical and chemical properties. This difference between lime-stabilized mixtures with high and low lime content occurred due to the pozzolanic effect. In other words, mixtures with low lime content usually do not develop the pozzolanic reaction and thus are unable to resist leachate and moisture damage. In conclusion, McCallister and Petry recommended the use of the optimum lime content to achieve maximum strength in the lime-stabilized soils; this would in turn protect the soil mixture from leachate and moisture damage *[48]*.

A comprehensive field study was conducted in Indiana in cooperation with the Indiana Department of Transportation for post construction assessment of lime-treated soils in in-service roads *[1]*. One of the main objectives of this research was to measure the remaining lime content in the treated soils and to detect any leaching effect. Results of the field study indicated that the lime remains in the soil after 11 years of service after construction *[1]*.

The pore structure and tensile strength of material have major influence on durability of lime-stabilized soils on repeated wetting and drying *[49]*. Inter-particle friction and cohesion may also influence the material loss in the process. Stabilized soils suffered from small to significant material loss, and disintegrated in many cases prior to completion of 12 cycles during the wet-dry testing of the lime-stabilized samples. The soils stabilized with cement were observed to have a better performance compared to the soils stabilized with lime. Figure 11 presents the weight loss of cement and lime-stabilized soils compacted at OMC using standard compaction effort.

The hydraulic conductivity of cement and lime treated soils was measured on three soils (see Table 10) by analyzing the pH and water-soluble calcium, sodium, potassium, and sulfate ions *[49]*. The permeability of cement stabilized California (Cal) soils was observed to be lower than the permeability of lime-stabilized Cal soils over a length of time. The permeability of 6% lime-stabilized sample and 9% lime-stabilized sample by weight was observed to be similar after 40 days, which might be the result of adequate pozzolanic reaction in the 6% lime-stabilized sample. The permeability of Texas 1 soil was observed to be similar for both cement and lime-stabilization at 3% and 6% dosage levels; the conductivity being less at 6% dosage level. Similar results were observed for Texas 2 (clay, A-7-6) soil at 3% dosage level; however, the lime-stabilized soil was observed to be less permeable compared to cement stabilized soil at 6% dosage level. The change in hydraulic conductivity with time for Cal and Texas 1 soils is presented in Figure 12.

Table 10
Classification, Atterberg limits, OMC, and strength of the as-received soils *[49]*

Soil ID	Textural Classification	Atterberg limits			OMC (%)	Strength (psi)
		Liquid Limit	Plastic Limit	Plasticity Index		
Cal	Sandy Clay	43	18	25	17	60
Texas 1	Clay	63	21	42	25	54
Texas 2	Clay	61	24	37	23	57

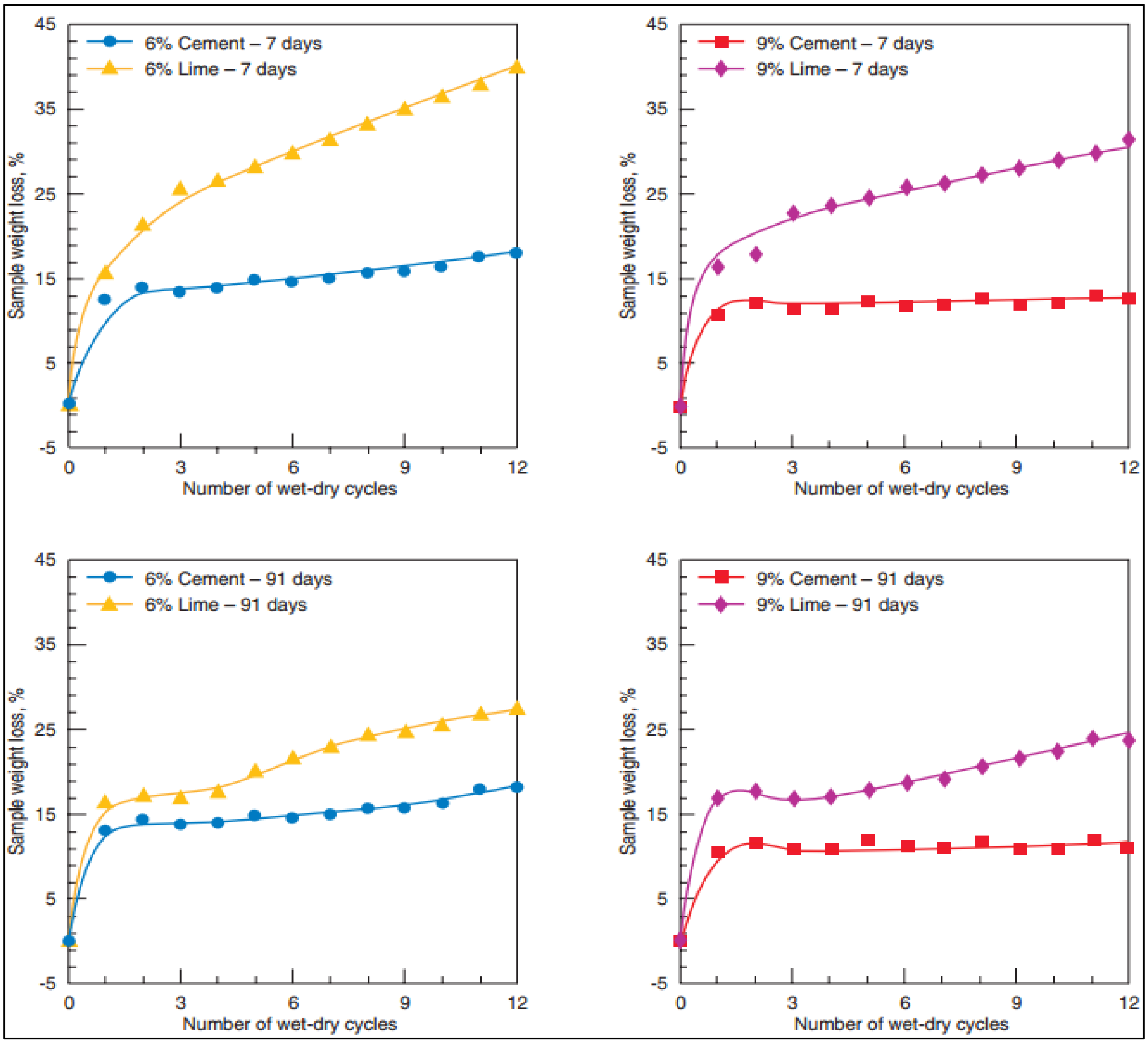


Figure 11
Weight loss in wet-dry durability testing of Cal soil stabilized with 6 and 9% portland cement and lime by dry weight *[49]*

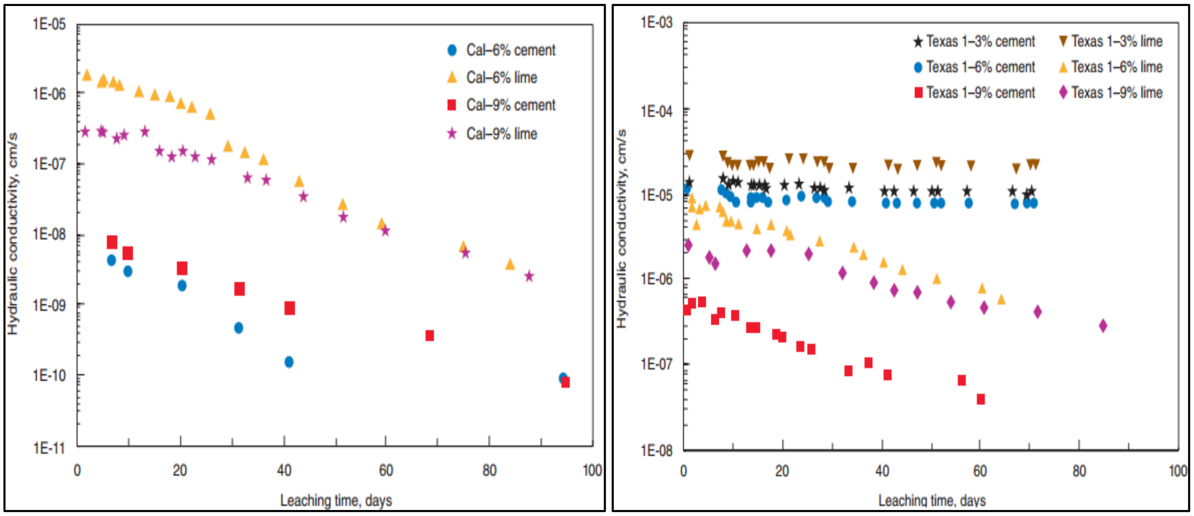


Figure 12
Change in hydraulic conductivity with time for Cal and Texas 1 soils *[49]*

A leaching test was performed on soil samples compacted at optimum moisture content and cured for seven days *[50]*. The leaching apparatus consisted of a clear tank with flexible membrane confinement for the samples and the test involved leaching distilled water through a soil sample under a constant head of 5.4 ft. for 28 days. The pH and flow-rates of the leachate that flowed through the compacted soil sample was monitored over the 28-day leaching period.

Figure 13 presents the strength of the soil samples before and after leaching. The lime-stabilized soil samples were observed to retain much of the stabilized strength after leaching; the CL soils retained 280 to 380% of the initial strength and the Beto “Brown” soils retained 300% strength with initial values representing the peak strengths of the soil without leaching. One soil sample (Beto “Tan”) experienced a large flow of water suggesting a higher loss in strength after leaching. The leaching permeability and Atterberg limit values for lime treated soil samples are presented in Table 11.

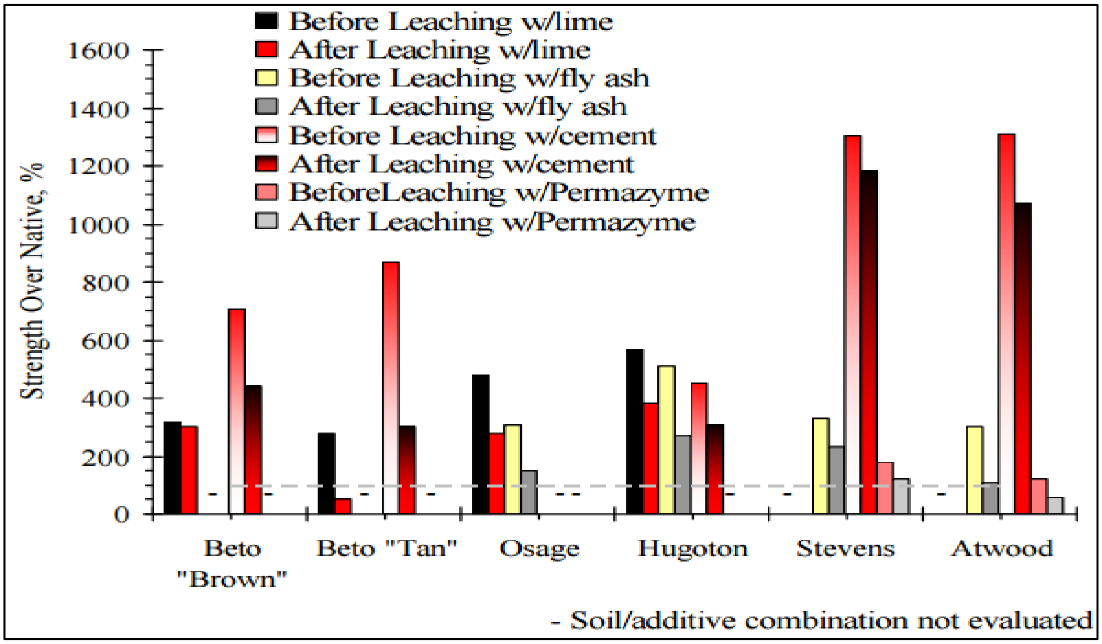


Figure 13
Strengths before and after leaching *[50]*

Table 11
Leaching permeability and Atterberg limit values *[50]*

Soil Type	Permeability, cm/s				Atterberg Limits					
					Native		Before		After	
	0-7 days	7-14 days	14-21 days	21-28 days	LL	PI	LL	PI	LL	PI
Beto "Brown" #1	4.60E-06	7.84E-07	6.87E-07	9.84E-07	65	36	NP	NP	NP	NP
Beto "Brown" #2	3.45E-06	3.61E-07	2.82E-07	2.07E-07	65	36	NP	NP	NP	NP
Beto "Tan" #1	2.27E-05	2.14E-05	1.36E-05	9.62E-06	53	31	NP	NP	NP	NP
Osage #1	No Flow	No Flow	No Flow	No Flow	36	16	NP	NP	NP	NP
Osage #2	No Flow	No Flow	No Flow	No Flow	36	16	NP	NP	NP	NP
Hugoton #1	No Flow	No Flow	No Flow	No Flow	35	16	NP	NP	NP	NP
Hugoton #2	No Flow	No Flow	No Flow	No Flow	35	16	NP	NP	NP	NP

White et al. studied the long-term performance of lime and fly ash stabilized subgrade in nine different sections in Texas, Oklahoma, and Kansas of which eight test sites were more than 10 years old and one site was about 5 years old *[10]*. DCP, FWD, LWD, and PLT tests were conducted in each test section. Scanning Electron Microscopy (SEM) and Energy Dispersive Spectrometry (EDS) tests were performed to analyze the mineralogical/micro-structural composition of lime-treated subgrade. It was observed from the SEM analysis that the cementitious reaction products were formed and remained in the lime-treated subgrade even after several years after construction. The results of SEM analysis at various test sites are bulleted hereunder *[10]*:

1. SH 121, TX: The major elements in the stabilized subgrade soil were silica (Si), alumina (Al), and oxygen (O). Additional elements identified included iron (Fe) and magnesium (Mg). The samples at 30 x magnifications showed higher concentrations of calcium (Ca) than the samples at 150 x magnification, while the sample at 500 x magnification showed higher concentrations of Al, O, and Si than the sample at 150 x magnification.

2. FM 1709, TX: The major elements in the stabilized subgrade soil were Ca, Si, Al, and O. Additional elements identified included Fe, K, and Mg. The stabilized subgrade showed higher concentrations of Al, Si, O, and Ca and less concentration of C, Fe, and Mg.

3. US 287, TX: The major elements in the stabilized subgrade soil were Ca, Si, Al, and O. Additional elements identified included Fe, K, and sodium (Na). The stabilized subgrade showed higher concentrations of Al, Si, O, and Ca and less concentration of S, Fe, and Mg.

4. US 183, OK: The major elements in the stabilized subgrade soil were Ca, Si, Al, and O. Additional elements identified included Fe, K, and Na. The natural subgrade showed higher concentrations of Al, Si, O, and Mg and lower concentration of Ca. The natural subgrade samples showed thin clay particles and some pore space while thin needle-like reaction products were observed in stabilized subgrade samples.

5. US 75 SB, KS: The major elements in the natural subgrade soil were Si, Al, and O. The major elements in stabilized subgrade were Ca, Si, Al, phosphorus (P), and O. Additional elements identified included Fe, K, and Na. The natural subgrade showed higher concentrations of Al, Si, and O and lower concentration of Ca and P.

6. US 75 NB, KS: The major elements in the natural subgrade soil were Si, Al, and O. Additional elements identified included K and Mg. The major elements in the stabilized subgrade were Si, Al, K, and O. Additional elements identified included Fe, and Mg. The stabilized subgrade sample showed higher concentrations of Ca and Fe than the natural subgrade.

The impact of hydraulic conditions on the long-term performance of lime-stabilized silty soil was evaluated by Runigo et al. in France *[51]*. The mechanical properties of lime-stabilized soil exposed to water was observed to be highly dependent upon the quantity of water passing through the soil and permeability of the stabilized subgrade. Additionally, lime content higher than the lime modification optimum (LMO) enabled a better homogeneity and less loss of materials due to water circulation. Two distinct evolutions quoted as C1 and C2 were observed for the specimens compacted at optimum level during leaching of specimens treated at 1% lime by weight; 0.12% of calcium was leached for the specimens 1%-OMC-NE-C1 after 90 days and 0.09% of calcium was leached for the specimens 1% OMC-NE-C2 after 200 days (see Table 12). The behavior of specimens compacted wet of optimum was observed to be similar to that of specimens 1%-OMC-NE-C2. The total quantity of calcium was higher for under-compacted specimen compared to the specimens compacted at their optimum level suggesting a lower quantity of cementitious compounds in under-compacted specimens.

Table 13 presents the speciation of calcium during curing and leaching for specimens treated with 3% lime by weight; an 86% decrease for available lime and 22% decrease for carbonates was observed after 320 days of leaching for the specimens compacted at optimum *[51]*. The total calcium content was observed to decrease at 3% lime content compared to 1% lime content suggesting the formation of higher cementitious compounds at 3% lime content. The under-compaction of soil samples lead to rapid leaching of calcium; the percentage of leached calcium after 150 days percolation for under-compacted specimen was similar to that of 320 days percolation for the specimens compacted at the optimum level. The total quantity of lime calcium contents of the specimens compacted wet of optimum after 150 days of leaching was observed to be higher than that of the specimens compacted at the optimum indicating a larger quantity of cementitious compounds. The shear strength and UCS was observed to decrease significantly due to leaching for 1% lime addition by weight while the decrease was negligible for 3% lime. Figure 14 presents the effect of leaching on the UCS of specimens treated with different lime contents.

Table 12
Speciation of calcium after 0 and 25-day curing and after different leaching time for specimens treated at 1% lime and compacted at different initial states *[51]*

Specimen Type	Curing days	leaching days	Carbonates (% Ca)	Available lime (% Ca)	Leached Calcium (% Ca)	Total Calcium (% Ca)
1%-OMC-NE	0	-	0.51	0.64	-	1.15
1%-OMC-NE	25	-	0.77	0.15	-	0.95
1%-OMC-NE-C1	25	90	-	0.04	0.12	-
1%-OMC-NE-C1	25	320	0.78	0.04	0.14	0.96
1%-OMC-NE-C2	25	150	0.77	0.1	0.07	0.94
1%-OMC-NE-C2	25	200	0.78	0.09	0.09	0.96
1%-OMC-LE	25	150	0.87	0.04	0.17	1.08
1%-WMC-NE	25	150	0.77	0.11	0.07	0.95

*Total Calcium corresponds to the addition of carbonates, available lime, porewater calcium and leached calcium.

Table 13
Speciation of calcium after 0 and 25-day curing and after different leaching time for specimens treated at 3% lime and compacted at different initial states *[51]*

Specimen Type	Curing days	leaching days	Carbonates (% Ca)	Available lime (% Ca)	Leached Calcium (% Ca)	Total Calcium (% Ca)
3%-OMC-NE	0		0.51	1.92	-	2.43
3%-OMC-NE	25		1.13	0.88	-	2.15
3%-OMC-NE	25	120	-	0.59	0.31	-
3%-OMC-NE	25	150	1.10	0.47	0.36	1.93
3%-OMC-NE	25	200	1.00	0.41	0.47	1.88
3%-OMC-NE	25	320	0.88	0.12	0.77	1.77
3%-OMC-LE	25	150	1.15	0.23	0.77	2.15
3%-WMC-NE	25	150	1.05	0.66	0.16	1.87

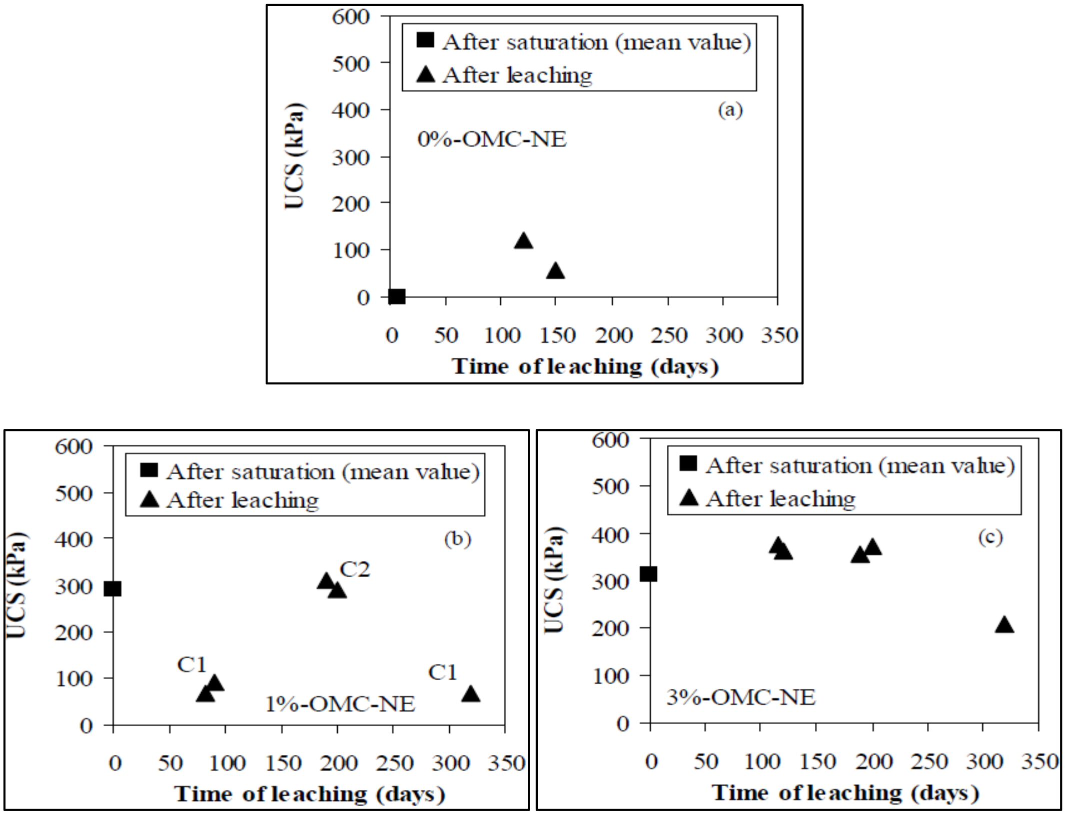


Figure 14
Effect of leaching on the UCS of lime-treated specimens compacted as their optimum: (a) 0% of lime, (b) 1% of lime, (c) 3% of lime *[51]*

Management of Traffic during Lime Construction

In the construction of lime-stabilized roads, various factors should be taken into account. Traffic management is one of the fundamental factors that must be considered by both contractors and engineers *[31]*. It is necessary to maintain traffic during lime-stabilization construction, which could be achieved through re-routing traffic around the construction area until the application of part of the wearing surface is finished. In the case that the traffic must be accommodated during the curing process before the wearing surface is applied, less damage is expected to occur to the stabilized layer if the weight and number of vehicles can be minimized. Heavy trucks carrying 25-ton loads must be sufficiently supported by one-day-old, well-compacted lime-clay subbases. However, heavy wheel loads may cause spot rutting in freshly compacted bases. Such rutting occurs due to insufficient compaction and thus these soft spots can be re-compacted *[31]*. In 2012, the Department of Transport and Main Roads (TMR) provided guidelines on the design requirements for pavements built on lime-stabilized subgrades *[7]*. Maintaining traffic during the stabilization process is one of the priorities considered by the TMR. The TMR restricted the treatment of subgrades under existing pavement using lime, when the removal and replacement of the existing pavement cannot be tolerated by the existing traffic *[7]*. The Federal Highway Administration (FHWA) indicated that the roadway lane should be closed during construction of lime-stabilized subgrade. If possible, it is recommended that the lane remain closed until the application of a wearing surface; otherwise, the treated material can be opened to traffic after one day for temporary use *[52]*.

DISCUSSION OF RESULTS

Survey of State Practices

A nationwide survey was conducted to collect information from state agencies in the US and Canada on the current practices of using lime in various road applications. Figure 15 shows the states that responded to the survey. In total, 29 highway agencies responded to the survey including 28 states and the Saskatchewan Ministry of Highway and Infrastructure (Canada). A list of the respondents is provided in Appendix A and a copy of the survey is provided in Appendix B.

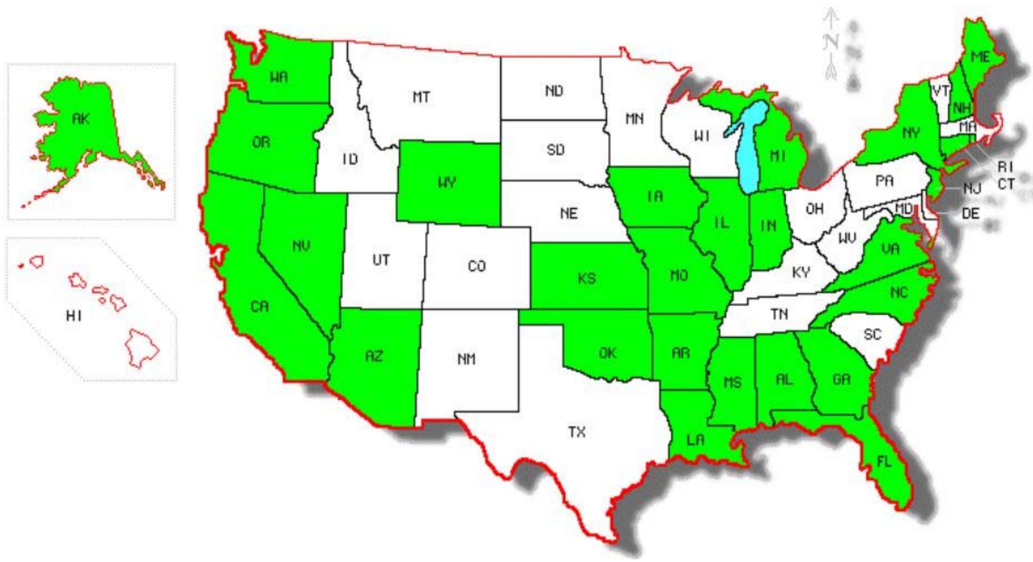


Figure 15
States' response to the survey

The survey was posted online and was advertised through various list serves. A copy of the survey is presented in Appendix B. To expedite the response to the survey, the survey questionnaire focused on 10 main questions:

- What road applications do you currently use lime for (mark all applicable choices)?
- For what type of soil do you use lime (please indicate PL, LL, PI, and percentage Passing # 200)?
- What type of lime does your state allow?
- How is lime content specified (by weight or by volume)?
- For each lime application, how do you determine the lime content?

- Does your state utilize Quick (pelletized) Lime? What is the typical application? Do you have any special requirements for its application?
- When/how often does your state utilize Lime Slurry? What is the typical application? Do you have any special requirements for its application?
- What acceptance criteria do you use for construction of lime-modified layers and lime-stabilized layers?
- How do you measure and verify application rates (test methods, etc.)?
- How do you account for lime-modified and lime-stabilized soil layers in pavement design? If applicable, what structural layer coefficient do you assign for lime-modified soil/base?

Use of Lime in Road Applications

Figure 16 presents current state practices for lime utilization in road applications, namely, (1) soil drying, (i.e., working tables), (2) soil modification (reduced plasticity), (3) soil modification (pre-treatment for cement stabilization), and (4) soil stabilization (lime alone). It was interesting to learn that 11 states that responded to the survey do not use lime to treat soil in any road applications. This is possibly due to the nature of the soil in these states that do not exhibit high plasticity clayey-type behavior. Survey results indicate that lime is primarily used in soil stabilization (14 states). Lime is also commonly used in soil modification (to reduce plasticity) and in soil drying during construction. Only four states reported that lime is used as pre-treatment for cement stabilization. Some states also use lime in other applications that are not within the scope of this study (e.g., as an anti-strip agent for asphalt mixtures, cold in place recycling, and full-depth reclamation).

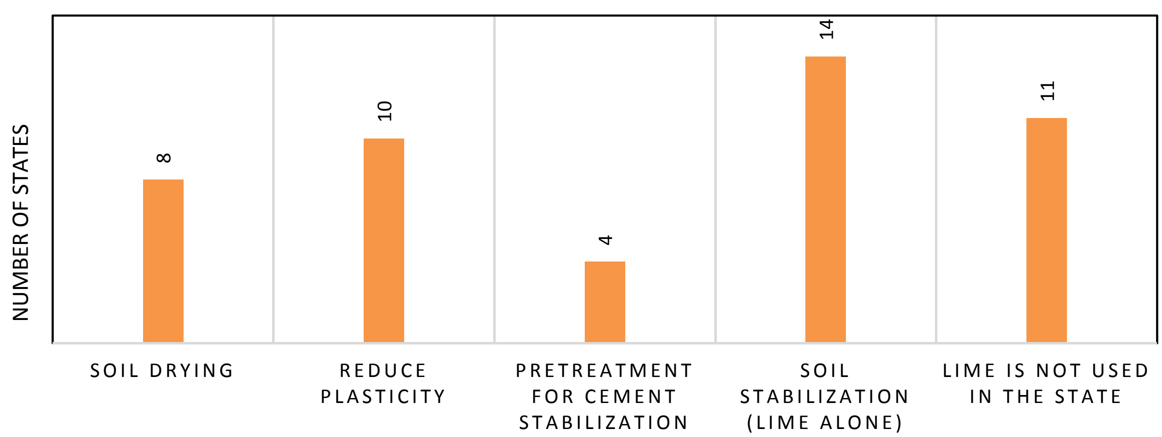


Figure 16
Lime utilization in road applications

Soil Type for Lime Applications

Respondents were queried on the type of soil for lime applications including the range of PL, LL, and PI. Louisiana, Indiana, and Oklahoma use lime for A-6 and A-7 soil types, and Alabama uses lime for A-6 type soil. Lime is mostly applied for CL and CH soils in Missouri, Saskatchewan, Arizona, and California. Kansas uses lime for ML and MH soil types including CL and CH. Lime is used for clays or silty clays in Arkansas, New York, and Michigan. Virginia applies lime for fine soils (usually wet) while Georgia has its own soil classification (GDOT soil classification Class III) for lime applications. The PL, LL, and PI of soils suitable for lime applications for the states that responded to the survey are presented in Table 14.

Table 14
PL, LL, and PI for soils suitable for lime applications

State	PL	LL	PI
Oklahoma	Practically ≥ 10	Practically ≥ 21	≥ 11
Saskatchewan	30 and above	70 and above	40 and above
Virginia	20-30	30-90	30-40
Georgia	N/A	> 25	> 15
Kansas	> 17	> 25 (roughly)	>8
North Carolina	N/A	N/A	> 25
Louisiana	N/A	N/A	> 15
Indiana	N/A	N/A	> 10
Arkansas	N/A	N/A	> 18
Mississippi	N/A	N/A	> 15
Alabama	N/A	N/A	> 12
California	N/A	N/A	> 12

Type of Lime and Method of Specification in the Field

States were queried on the type of lime and the method of specification in the field (by weight or by volume). Figure 17 presents the overall trend on the type of lime and the method of specification in the field. The survey results suggest that the majority of the respondents (approximately 93%) uses quicklime and hydrated lime specified by weight; Louisiana uses both quicklime and hydrated lime specified by volume. Similarly, 75% of the states use lime slurry specified by weight. On the other hand, Louisiana, California, and Kansas use lime slurry specified by volume.

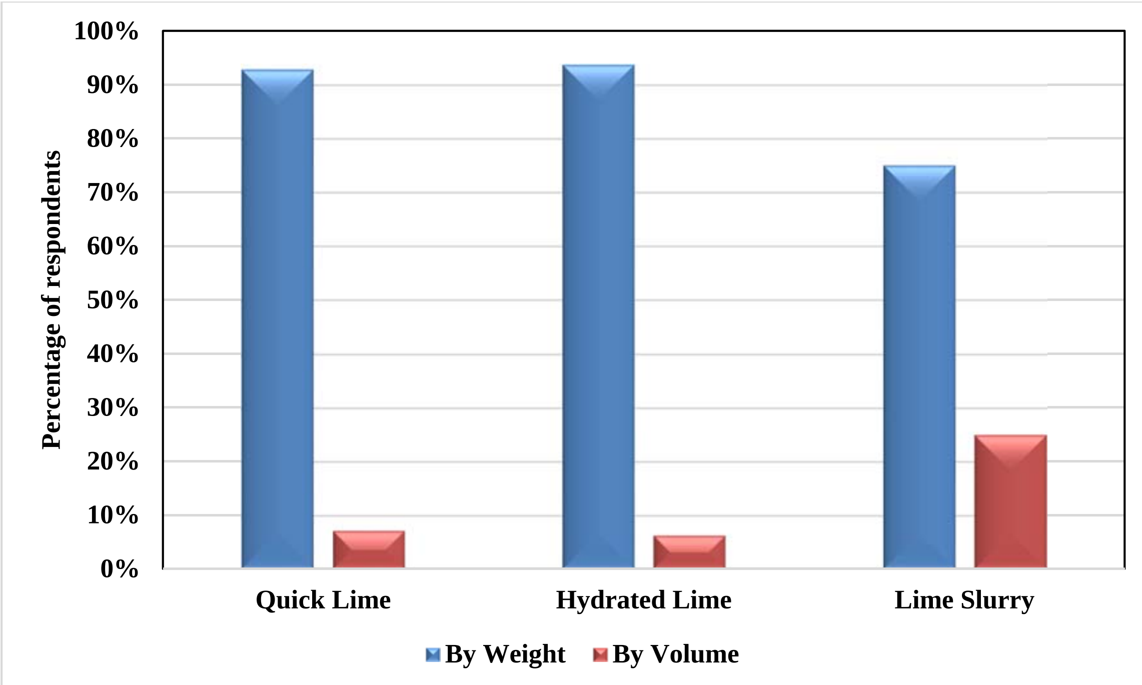


Figure 17
Type of lime and method of specification in the field

Determination of Lime Content in Road Applications

Figure 18 presents a summary of the methods used to determine the lime content for different applications. The majority of the states follow a laboratory design method to determine the optimum lime content for lime-stabilization and lime modification applications. A number of states (Mississippi, Virginia, and Alabama) have their own test methods to determine the lime content. Arizona and Kansas perform the Eades and Grim (E&G), pH test to determine the lime content for soil stabilization. Laboratory tests and contractors discretion are equally followed to determine lime content for soil drying applications. Georgia, New York, and Arkansas use fixed lime content for soil stabilization. Georgia uses 4 to 6% lime by volume depending on the soil-type.

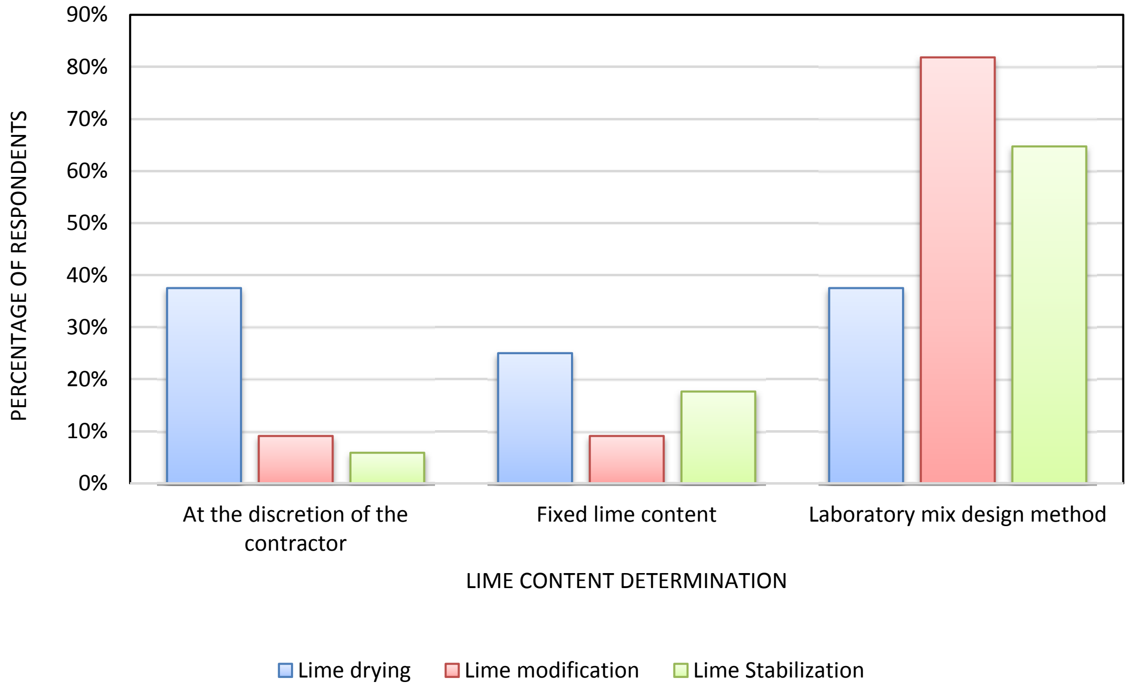


Figure 18
Methods to determine lime content in road applications

Typical Application and Special Requirements for Quicklime

Most of the states do not use, or rarely use, quicklime in road applications, possibly due to issues related to complete hydration of the lime. One of the respondents (Kansas) indicated that they stopped using quicklime due to application problems. Typical application, special requirements, and comments provided by the respondents on quicklime for the states that use it for road applications are presented in Table 15.

Table 15
Typical application, special requirements, and comments on Quicklime

State	Use	Typical Applications	Special Requirements	Comments
Arkansas	As preferred by Contractors	Lime Treated Subgrade (LTS)	Stabilization, Thoroughly mixed	Mix and remix for 3 days ; Moisture ≤ 5% OMC (1st mix); ± 2% OMC (remix)
Alabama	Not tracked but not very often	3-5%	—	—
Georgia	As preferred by Contractors	Special Provision 225	Soil/Lime is remixed after a 24-hour mellowing period	Most projects require stabilized material to be primed with a cutback[1] application
Mississippi	As preferred by Contractors	—	--	Quicklime is 75% of hydrated lime content
Michigan	Rarely	—	Contractor must follow special provision	100% Lime must pass 3/8 in. sieve
North Carolina	10% of time	27 lbs. per square yard	Steam must not cause traffic visibility problems	—
Oklahoma	In projects that do not have high sulfate contents	At the preference of contractor	Sufficient water must be added within 6 hrs. of spreading, allow a curing time of 48 hrs. at temperature above 40°F	Department approved equipment must be used.

[1] A cutback is a combination of asphalt cement and petroleum solvent.

Typical Application and Special Requirements for Lime Slurry

A number of states including Louisiana and Indiana utilize lime slurry in dust sensitive areas. Like quicklime, lime slurry is rarely used by most of the states. Typical application, special requirements, and comments on lime slurry for the states that use it for road applications are presented in Table 16.

Table 16
Typical application, special requirements, and comments on lime slurry

State	Use	Typical Applications	Special Requirements	Comments
Alabama	Not tracked, but not very often	3-5%	—	Quick lime is calculated as 0.833 times hydrated lime[1]
Arkansas	As preferred by Contractors	Lime Treated Subgrade (LTS)	Slurry equal or less than 5% OMC	Quick lime requirements is 1/3 of Hydrated Lime
Kansas	Used with plastic soils	5%	—	—
Mississippi	As preferred by Contractors	Slurry must have 30% dry solid content	—	Quick lime is 75% of hydrated lime content
North Carolina	90% of time	27 lbs. per square yard	—	—

[1] by lime weight

Acceptance Criteria for Lime-Modified and Lime-Stabilized Layers

Survey results indicated that most of the states have systematic acceptance criteria/tests for the acceptance of lime-modified and lime-stabilized layers. The acceptance criteria of lime-treated soils for each state are presented in Table 17.

Table 17
Acceptance criteria for lime-modified and lime-stabilized layers

States	Acceptance Criteria	
	Lime-Modified Layer	**Lime-Stabilized layer**
North Carolina	N/A	Lime purity of at least 84%
Louisiana	Density	N/A
Indiana	DCP or LWD	
Arkansas	Sounding with indicator solution to determine treated depth	Stability for working platform, sounding with indicator solution to determine treated depth
Oklahoma	Application rate, depth and uniformity of application, compacted density and moisture	
Saskatchewan	QA tests are done during construction. These tests can include Atterberg limits, water content and density etc.	
Michigan		Acceptance is based on layer thickness, lime content (%) and density. Testing for acceptance is conducted for each 4000 square yards of stabilized subgrade but at least once per day
Virginia	Spec 306; density, moisture, cure.	
Mississippi	Lime application rate and density	
Alabama	Check of soil pulverization by gradation testing; moisture/density testing by AASHTO T 99 both before and after lime incorporation; In-place density testing by AASHTO T 310; lime application rate checks; and layer thickness checks	
California	Unconfined compressive strength	Relative compaction
Georgia	Compaction testing only	
New York	Follows approved method	
Oregon		Nuclear density testing and proof rolling.
Kansas	Performance and phenolphthalein	
Missouri	Proof rolling	

Measurement and Verification of Application Rates

States' responses on verification of application rates are presented in Table 18. Most of the states perform weight checks and area calculation to measure and verify the application rates.

Table 18
Acceptance criteria for lime-modified and lime-stabilized layers

States	Methods
Kansas	Weight and Volume
Oregon	Yield
New York	As proposed by contractor
Georgia	Spot checks with a square yard cloth, final acceptance by total coverage per tanker
California	Pan test for lime quantity, CT 373 (unconfined compressive strength), Phenolphthalein indicator solution
Alabama	Manual weight checks of square yard canvas, lime quantity checks of shipments delivered and applied over measured area.
Mississippi	Obtain bulk truck weight and calculate area of spread
Virginia	Weight of material from contractor's hopper feed equipment to ground surface
Michigan	Thickness is measured with test holes (must be ± ½ in.), Lime content must not be more than 1% below designed, density testing (must be > 95% of maximum unit weight)
Saskatchewan	Quantity of lime ordered versus used is measured and estimates are made based on the target application rate of lime
Oklahoma	Approval of distributing equipment, visual verification of uniformity, weight/area calculation, Experimenting with XRF.
Arkansas	Weight Tickets and area calculation to verify application rate, Volume and Unit with of Lime to verify application rate.
Indiana	Shipping ticket, by place board under spreader

Incorporation of Lime-Modified and Lime-Stabilized soil in Pavement Design

Eleven states, which use lime and that responded to the survey, do not consider a lime-stabilized layer as a structural layer in pavement design. The states, which account for the lime-treated soils in pavement design along with the assigned value of structural coefficient, are presented in Table 19.

Table 19
Structural coefficients and comments on lime treated soils

States	Structural Layer Coefficient	Comments
North Carolina	0.125	—
Indiana	—	Lime increases MR by 25% over the natural soils.
Arkansas	0.07 (Lime Treated Subgrade)	SN is only used for LTS in roadway typical section. SN value is not assigned for stabilization.
Oklahoma	0.05	Stabilized layers may be considered as a structural layer in areas that do not have a high water table.
Virginia	0.18	Virginia typically do not count modified subgrade in pavement design.
Mississippi	0.2	Only account lime treated subbase/base in pavement design.
Alabama	0.1	ALDOT generally performs soil modification than soil stabilization.
California	Gravel Factor = 0.9 + ucs /1000 (only for flexible pavement)	—
Kansas	0.14	—

CONCLUSIONS

The objective of this study was to review and report the best practices of using lime (i.e., granulated lime, hydrated lime, and slurry lime) to dry soil, in working tables, and in pavement applications. The project also reviewed and documented the incorporation of lime in pavement design in other states as well as test methods, field application, and evaluation techniques to assess the quality of field construction. Based on the results of the literature review and the survey questionnaire, the following statements have been validated in the literature:

- The overwhelming majority of laboratory and field studies involving lime indicates that lime-stabilized subgrades over-perform non-stabilized subgrades, when due regard is given to materials design, structural design, durability, and construction. Enhanced performance is typically reported in terms of number of traffic loads to failure and strength properties of the subgrade soil.

- Test results suggest that lime does not leach over time and remains in the subgrade after 5 to 11 years in service. Yet, other results suggest that lime treatment may leach if the optimum content is not used.

- Lime-stabilization is typically suitable for clayey soils with at least 25% passing No. 200 sieve and a minimum PI of 10.

- Numerous states account for lime-stabilized subgrade and base in pavement design. A structural layer coefficient around 0.11 has been suggested by many studies.

- Survey results suggest that the majority of the respondents uses quicklime and hydrated lime specified by weight. Similarly, 75% of the states use lime slurry specified by weight.

RECOMMENDATIONS

Based on the results of this study, the research team concluded that the existing Louisiana specifications are on the safe side and may be modified to reflect the structural-contribution of stabilized subgrade soil. These changes will allow DOTD to save funds, which may be used for other needs. Therefore, the following course of actions are recommended:

- Lime-stabilized layers should be considered in the pavement design. Yet, lime modification, drying, and working table applications should not be considered in the pavement design. These other applications will improve the strength of the subgrade/subbase, and add value and life, even though not counted in the design.

- Structural layer coefficients should be assigned for cement and lime-stabilized subgrade in the Louisiana specifications. Subgrade may be dealt with in the design as a subbase layer such that a layer coefficient can be assigned. As shown in Table 20 (DOTD Specifications, Section 305.04.a.2), a UCS requirement was recently added by DOTD. The layer coefficients in the next column are recommended based on this research.

Table 20
Recommended layer coefficients for lime treatment

PI	Minimum Lime or Cement (% by volume)	Minimum UCS requirements (psi)	Recommended layer coefficients
0-15	9-6% cement	100	0.05
16-25	6% lime and 9-6% cement	100	0.05
26-35	9% lime and 9-6% cement	100	0.05

- While lime-stabilization is not considered alone in the table above, it should be added in the future as a feasible alternative.

A concurrent study regarding an equivalent modulus for stabilized subgrade layers is also ongoing by LTRC. The research team recommends that a follow-up study be conducted in order to evaluate the values recommended in this study using field testing such as FWD, DCP, and PMS data of treated and untreated soil. The stability of soil properties over time should also be evaluated by testing soil conditions with different ages.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
ADOT	Arizona Department of Transportation
AHTD	Arkansas State Highway and Transportation Department
Al	Aluminum
ALDOT	Alabama Department of Transportation
ASTM	American Society of Testing and Materials
C-	Clay
C	Centigrade
Ca	Calcium
CBR	California Bearing Ratio
CEC	Cation Exchange Capacity
CL	Clay of low plasticity
CH	Clay of high plasticity
cm	centimeter(s)
CP	Colorado Procedure
DCP	Dynamic Cone Penetration
DOT	Department of Transportation
DOTD	Louisiana Department of Transportation and Development
E&G	Eades and Grim
EDS	Energy Dispersive Spectrometry
ESAL	Equivalent Single Axle Load
F	Fahrenheit
Fe	Iron
FFRC	Free-Free Resonant Column
FHWA	Federal Highway Administration
ft.	foot (feet)
FWD	Falling Weight Deflectometer
G-	Gravel
g	gram(s)
gal	gallons
GDOT	Georgia Department of Transportation
HMA	Hot Mix Asphalt
hr.	hour(s)
IBV	Immediate Bearing Value

ICP	Inductively Coupled Plasma
ICS	Initial Consumption of Stabilizer
in.	inch (es)
K	Potassium
kg	kilogram(s)
KM	Kentucky Method
KPa	kilopascal
ksi	Kilo pounds per square in.
km	kilometer(s)
KYTC	Kentucky Transportation Cabinet
lb.	pound(s)
LL	Liquid Limit
LMO	Lime Modification Optimum
LTRC	Louisiana Transportation Research Center
LTS	Lime Treated Subgrade
LWD	Light Weight Deflectometer
M-	Silt
m	meter(s)
MC	Moisture Content
MDD	Maximum Dry Density
MDOT	Michigan Department of Transportation
MEPDG	Mechanistic Empirical Pavement Design Guide
Mg	Magnesium
mg	milligram(s)
MH	Silt of High Plasticity
ML	Silt
ml	milliliter(s)
mm	millimeter(s)
MnDOT	Minnesota Department of Transportation
M_R	Modulus of Resilience
MPa	Mega pascals
msa	million standard axle
MT	Mississippi Test
Na	Sodium
NCHRP	National Cooperative Highway Research Program
NCSU	North Carolina State University
NLA	National Lime Association

O	Oxygen
O-	Organic
OH	Organic Clay
OMC	Optimum Moisture Content
P	Phosphorus
PCC	Portland cement Concrete
pcf	Pounds per cubic foot
PL	Plastic Limit
PLT	Plate Load Test
PI	Plasticity Index
ppm	parts per million
psi	Pounds per square in.
PSPA	Portable Seismic Pavement Analyzer
q_u	Unconfined Compressive Strength
Si	Silica
S-	Sand
S	Sulphur
s	second(s)
SEM	Scanning Electron Microscopy
SN	Structural Number
SSA	Specific Surface Area
SSV	Soil Support Value
SPT	Standard Penetration Test
TGA	Thermogravimetric Analysis
TMR	Transport and Main Roads
ton	tonne(s)
TST	Tube Suction Test
TxDOT	Texas Department of Transportation
UCS	Unconfined Compressive Strength
UKTC	University of Kentucky Transportation Center
VTM	Virginia Test Method
WOMC	Wet of Optimum Moisture Content
XRD	X-ray Diffraction
XRF	X-ray Fluorescence
yd.	yard(s)
3D	Three Dimensional
µm	Micro meter(s)

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APPENDIX A: LIST OF SURVEY RESPONDENTS

List of respondents to the survey questionnaire:

Alabama
Alaska
Arizona
Arkansas
California
Connecticut
Florida
Georgia
Illinois
Indiana
Iowa
Kansas
Louisiana
Maine
Michigan
Mississippi
Missouri
Nevada
New Hampshire
New Jersey
New York
North Carolina
Oklahoma
Oregon
Saskatchewan Ministry of Highway and Transportation
State of Rhode Island
Virginia
Washington
Wyoming

APPENDIX B: QUESTIONNAIRE

LTRC Research Questionnaire
Lime Utilization in the Laboratory, Field, and Design of Pavement Layers

The Louisiana Transportation Research Center (LTRC) is funding a study to review and report the best practices of using lime (i.e., granulated lime, hydrated lime, and slurry lime) to dry soil, in working tables, and in pavement applications. Please complete the questionnaire online or return the completed questionnaire to Mostafa A Elseifi, Associate Professor, Louisiana State University, through email to elseifi@lsu.edu. Should you have any questions regarding this questionnaire, please call Mostafa Elseifi at (225) 578-4821. The results of this survey will be shared with the respondents.

Please return the questionnaire by May 31, 2015. We appreciate your timely response.

Name (Completed by):	Name (follow-up contact):
Title:	Title:
State Agency:	State Agency:
Phone Number:	Phone Number:
Fax Number:	Fax Number:
E-mail:	E-mail:

QUESTION 1: ***What applications do you currently use lime for (mark all applicable choices)?***

- Soil drying, i.e., working tables
- Soil modification (reduced plasticity)
- Soil modification (pre-treatment for cement stabilization)
- Soil stabilization (lime alone)
- Other: ____________________

QUESTION 2: ***On what soil types do you utilize lime (please indicate PL, LL, PI, and percentage Passing # 200 along with Purpose – modify, pretreat, stabilize, etc.)?***

Soil classification	*PL (range)*	*LL (range)*	*PI (range)*	*Purpose*

QUESTION 3: ***What type of lime does your state allow? Check all that apply. - - Note where/application type for each, especially if it varies.***

☐ Quick Lime ☐ Hydrated Lime ☐ Lime Slurry

QUESTION 4: ***How is lime content required in your specifications? Check by weight or by volume. Please reference any lab to field conversion methods.***

☐ By Weight ☐ By Volume

Conversion method/ Test Method reference:____________________

QUESTION 5: ***In soil drying applications, how do you determine the lime content?***

- At the discretion of the contractor
- Fixed lime content. Reference :__________________
- Laboratory mix design method. Test Method:__________________
- Table in specification. Specification:__________________

QUESTION 6: ***In lime modification applications, how do you determine the lime content?***

- At the discretion of the contractor
- Fixed lime content, Reference :__________________
- Laboratory mix design method Test Method:__________________
- Table in the specification: Specification:__________________

QUESTION 7: ***In lime-stabilization applications, how do you determine the lime content? (Check all that apply).***

- At the discretion of the contractor
- Fixed lime content, Reference :__________________
- Laboratory mix design method Test Method:__________________
- Table in the specification: Specification:__________________
- Eades-Grim test

QUESTION 8: Pelletized Lime, Lime Slurry applications. Variations from hydrated lime.

A. When/how often does your state utilize Quick (peletized) Lime? What is the typical application? Do you have any special requirements for its application?

B. When/how often does your state utilize Lime Slurry? What is the typical application? Do you have any special requirements for its application?

C. Is the lime content different with pelletized and/or lime slurry applications than with quicklime or hydrated lime?

QUESTION 9: Field Construction

A. What acceptance criteria do you use for construction of lime-modified layer?

B. How do you measure and verify application rates?

QUESTION 10: ***How do you account for lime-modified soil in pavement design? If applicable, what structural layer coefficient do you assign for lime in case of?***

Application	Structural Coefficient	M_R (psi)
Lime modification		
Lime-stabilization		
other		

Thanks!

APPENDIX C: REVIEW OF STATE SPECIFICIATIONS ON THE USE OF LIME IN ROAD APPLICATIONS

Louisiana

Use of Lime in Road Applications

Lime is used in road application to: *(1)* stabilize base or subbase (Type B treatment), *(2)* condition cement treatment or stabilization (Type C treatment), *(3)* working table treatment under an embankment (Type D treatment), and *(4)* condition and dry subgrades under a base course (Type E treatment).

Soil Type for Lime Application

The soil with sand or silt content less than 79% or 69% respectively, and plasticity index not exceeding 35, is acceptable for lime application.

Type of Lime

The lime for soil stabilization shall be quicklime or hydrated lime that meets the requirements of AASTHTO M 216. The lime is tested in accordance with DOTD TR 525 with some modifications; *(1)* maximum free moisture content shall be 1.5% for hydrated lime, and *(2)* quicklime shall not contain more than 8% of magnesium oxide by weight and 100% moisture free, free flowing and well graded lime shall pass a 3/8 in. sieve. In case of lime slurry, a minimum of 95% shall pass ¾ in. sieve.

Lime Content

The lime content for Types C and D shall be as required by the plans or as directed by the Engineer. For type B and type E treatments, lime content shall be determined in accordance with DOTD TR 416. Table 21 presents the minimum quantities of Portland cement and lime that shall be applied for subgrade stabilization according to the soil plasticity index.

Table 21
Minimum quantities of cement and lime

PI	Lime or Cement (Percent by volume)
0-15	9% cement
16-25	6% lime and 9% cement
26-35	9% lime and 9% cement

Construction

For Type B and Type C treatments, the lime is spread, mixed with soil, sprinkled with water, sealed, and mellowed for at least 48 hours, remixed until pulverization requirements are met, compacted, finished, and maintained as per specifications. For Type D and Type E treatments, one increment of lime is spread and mixed with the materials, sprinkled frequently with water, compacted, and finished as per requirements. The application process for subgrade stabilization is suspended when air temperature is below 35°F. The construction is suspended when the ground is frozen and under adverse wind condition that would blow away the material. Table 22 presents a summary of the lime treatment types.

Table 22
Types of lime treatment

Type	Use	Characteristics
B	Base or Subbase	1. One application of lime 2. Initial mixing 3. 48-hour mellowing or aging period 4. Pulverization 5. Density control 6. Minimum thickness and width 7. 72-hour cure with asphalt curing membrane
C	Conditioning for Cement Treatment or Stabilization	1. One application of lime 2. Initial mixing 3. 48-hour mellowing or aging period 4. Pulverization 5. Compact to engineer's satisfaction 6. No cure required
D	Working Table (Under Embankment)	1. One application of lime 2. Initial mixing 3. Compact to engineer's satisfaction 4. No cure required
E	Conditioning and Drying (Subgrades Under a Base Course)	1. One application of lime per embankment lift 2. Mixing 3. Embankment construction requirements including density 4. No cure required

Lime Application and Mixing. The application rate of lime is first determined in accordance with DOTD TR 436. A unit weight of 35 lb./ft^3 is used to determine the application rate regardless of the actual unit weight of the lime used. The lime content as determined from the mix design is uniformly applied over the entire area at the rate as determined. The distribution is limited to an area that can be integrated and mixed on a working day. For Type B and Type C treatments, the spread lime is allowed to mellow for a minimum of 48 hours before mixing in-place to meet the pulverization requirements. Type D and E does not require pulverization and are mixed in-place with approved mixers.

Pulverization. The mix treated as Type B and Type C treatment when pulverized shall meet the gradation requirements presented in Table 23.

Table 23
Gradation requirements for Types B and C lime treatment

U. S. Sieve, In. (mm)	Percent Passing By Weight (Mass)
3/4 (19.0)	95
No. 4 (4.75)	50

Compaction and Finishing. The material is compacted uniformly throughout the treated area until the entire depth is compacted to at least a 95% maximum dry density as determined in accordance with DOTD TR 401. The density test is conducted at every 1,000 linear ft. per roadway or at every 2,000 linear ft. per shoulder. The compaction operation shall be completed within 6 hours of pulverization. Appropriate equipment is used to compact the areas inaccessible to rollers to the specified density. The soft spots, depressions, and defective areas if observed are either removed, treated with lime, or reshaped and compacted in accordance with the specifications. The areas that do not meet the density requirements are re-treated with specified quantity of lime. After the compaction is completed, the compacted layer (For Type c and Type D treatment) is brought to line, grade and typical cross section as specified in the plan. The compacted surface shall have a smooth, uniform, closely knit surface, free from ridges, waves, loose material and laitance. An optimum rolling pattern is established if certain conditions such as a yielding restrain a proper compaction. For Type E treatment, the lime treated material is compacted and finished in accordance with the normal embankment construction procedure. For all the treatment types, the lime spread, mixing and density are controlled such that the completed layer is uniform and meet the acceptance requirements.

Immediately after compaction and finishing (Type B treatment), the surface is protected against rapid drying and cured for 72 hours by sprinkling water frequently. The section is removed or reconstructed if the thickness is observed to deviate from the thickness shown on the plans. The thickness of the finished layer shall not be deficient by more than ¾ in. and shall not exceed 1 in. with the plan specified thickness. The width of the roadway base course and shoulder base course, when constructed separately shall not vary by in excess of 6 in. and 3 in. respectively. If both courses are constructed at the same time, a tolerance of 6 in. is applied.

Quality Assurance. To establish a quality subgrade stabilization (Type B and Type C), the contractor shall be responsible for various tasks as bulleted below.

- The rate of spread and length of spread for each individual truck shall be pre-determined and pre-approved by the engineer.
- DOTD TR 436 test shall be performed to ensure the application of correct percentage of lime.
- When lime is delivered and applied by bags, the bags shall be spaced such that a minimum spread rate requirements are met. The lime application and water spray shall be examined frequently to ensure a uniform application and complete coverage.
- The moisture content of the mixture as determined in accordance to DOTD TR 403 and the percent pulverization as determined in accordance to DOTD TR 431 shall be within the acceptable limit.
- The material for density test shall be obtained from beneath the nuclear device or form the area adjacent to the sand cone density hole.
- The finishing and pulverization shall be completed within six hours.
- Any soft spots, irregularities, segregation, undulations, or other variations shall be corrected as required.
- Thickness, width, and grade shall comply with the specifications in plan.

Note:

1. Quality control requirement for Type D treatment shall be similar as for Type B and Type C treatment, except pulverization test is not required.
2. Quality control for Type E treatment shall be in accordance with the Quality Control Plan, as required by the project engineer, and the material sampling manual.

Alabama

Use of Lime in Road Applications

Lime is employed to stabilize and to prepare subgrade for overlying base and pavement structure.

Soil Type for Lime Application

Lime is used to treat subgrade soil excluding roots, stumps, or other deleterious materials and aggregate particles larger than those passing 3 in. sieve.

Type of Lime

Hydrated or quicklime obtained from approved source, sampled, and tested in accordance to AASHTO T-218 and AASHTO T-27, may be utilized for soil stabilization.

Lime Content

The ALDOT-292(96) test is conducted to determine the percent lime required for soil stabilization. For raw soil, a sufficient amount of water is added to oven-dried sample of soil passing No. 16 sieve to obtain moisture content of one percentage point above the optimum. AASHTO T 307 procedure is followed to compact five specimens of the raw soils to 99.5% - 102.0% density at ±1.0% of the optimum moisture content. The compaction will result in specimen with 2.8 in. diameter and 5.6 in. length at optimum moisture and maximum density. For soil-lime mixture, 3% lime by dry weight of soil is added and mixed uniformly to oven-dried sample of soil passing No. 16 sieve. Sufficient amount of water is added to obtain moisture content of one percentage point above the optimum. The soil, lime, and water are mixed for 2.5 minutes and stored in a closed container to allow to mellow for one hour. A similar procedure is followed with 5 and 7% lime. The samples for raw soil and soil-lime mixtures are stored in zip lock bags for 72 hours at 105°F. The samples are then tested for unconfined compression at room temperature according to AASHTO T 208. An average of five tests are calculated for raw soil and soil-lime mixtures for each lime content. The lowest percentage lime, which yields an average compressive strength gain of 50 psi above the average compressive strength of raw soil, will be the design lime content. If none of the lime content produces the required strength gain, the lowest percent lime that produces a significant reduction in PI of soil shall be used.

Construction

Subgrade Preparation. The roadbed is scarified and partially pulverized to the required depth of stabilization such that the surface of roadbed below scarified material is undisturbed and comply with the cross-section of the plan. All undesirable materials and materials retained on a 3-in. sieve are removed before lime application.

Lime Application. When the design lime content is 5% and the lime has to be applied in two applications designated as Class I lime treatment, 3% lime shall be applied in the first application. Whereas, if the design lime content is 7%, the first application of lime shall contain at least 3% not exceeding 3.5% lime. When lime is applied in dry form, an approved spreader shall be used to spread the lime uniformly over the scarified surface. Application shall be postponed under adverse wind conditions that would blow away the material. When lime is applied as a slurry, the slurry must be kept in suspension throughout the application and uniformly applied by making successive passes over the area to be stabilized. Lime-stabilization is not performed in the months between October and April.

Mixing. For class I or class II lime treatment, the mixing and watering operation is considered complete when a homogenous mixture of the lime treated material passes through a 3 in. sieve. The treated course is reshaped to the approximate line, grade and typical section, sealed with light roller and allowed to mellow for 3 to 21 days by frequent sprinkling of water. The layer is then scarified and another application of lime is added (for Class I only). Mixing is continued until 100% of the material by dry weight, excluding rock and stone particles pass a 2 in. sieve and 60% pass a No. 4 sieve, such that the moisture content is within 2% of the laboratory specified optimum moisture. The top surface of the layer is sealed with a rubber-tired roller if mixing cannot be completed in one day. For class 3 treatment, lime and water are mixed uniformly in a rotary mixture until a homogeneous mixture of soil, lime and water is obtained and the moisture content is within 2% of the laboratory specified optimum moisture.

Compaction. The compaction operation shall be started as early as possible after final mixing and the whole process shall be completed within 72 hours of the start. The material is compacted uniformly throughout the treated area until the entire depth is compacted to a specified density. The soft spots, depressions, and defective areas if observed are either removed, treated with lime or reshaped and compacted in accordance with the specifications. The moisture content shall be maintained within two percentage of optimum moisture content by frequent sprinkling of water or with aeration. If the compaction is not completed within 72 hours, the incomplete section shall be further treated with lime as directed by the engineer and the compaction process shall be restarted.

Finishing and Curing. After compaction, the compacted layer is brought to line, grade, and cross-section as specified in the plan. The thickness of the lime-stabilized layer is determined, at intervals not to exceed 500 ft. The section is reconstructed if the thickness is observed to vary by 1 in., plus or minus, from the thickness shown on the plans. Additional lime is added and the material is remixed to the specified depth and width to correct the deficiency of any section exceeding the tolerance. Any deficient section shall be reconstructed immediately according to the specifications. Immediately after compaction and finishing, the surface is protected against rapid drying and cured for 7 days, unless covered by subsequent layers of pavement. The treated section may be opened to traffic after 7 days of curing period. The treated surface shall be re-stabilized if failure, tenderness or damage is observed after curing has been completed.

Arizona

Use of Lime in Road Applications

Lime is utilized to lower the volume change characteristics and plasticity of the soil so that the load carrying capacity of the pavement is enhanced.

Type of Lime

Both hydrated and quicklime may be used for soil treatment; hydrated lime shall be chemically combined with water while quicklime shall be used in a dry form. The total quantity of lime required for subgrade treatment shall be obtained from the same source.

Construction

Subgrade Preparation. The roadbed is scarified, pulverized, mixed, and re-laid; the unstable, soft, or oversized materials are either removed or replaced before lime application.

Lime Application. Dry lime or lime slurry is uniformly applied over the entire area by a mechanical device adjusted to provide the spread within 10% of the amount specified. Lime is not applied or mixed when the ground is frozen and under adverse wind condition that would blow away the material.

Mixing. The moisture content of the mix is controlled by frequent spreading of water through the mixing machine. Quicklime requires more water than hydrated lime for effective slaking of the larger particles. The subgrade is allowed to cure until a bituminous curing seal is applied.

Compaction and Finishing. The mixture is compacted using density control to at least 100% of the maximum density unless specified otherwise by special provisions.

Arkansas

Soil Type for Lime Application

A soil with all particles passing No. 4 sieve (50lbs) or with 15% or more retained on No. 4 sieve (150lbs) is suitable for lime-stabilization. Adequate quantities of soil (50lbs for each different soil) shall be supplied to Materials Division to test the lime requirements.

Type of Lime

Quicklime or Hydrated lime in both slurry and dry form may be applied as per the requirement. The lime shall comply with AASHTO M 216.

Construction

Subgrade Preparation. The subgrade is graded and shaped to the specified lines, grades and cross section. The foundation is dried, compacted (top 8 in. of the surface) to a uniform density to prevent rutting during construction, and soft materials, if present are stabilized to provide uniform stability. All detrimental materials nearby the construction area are removed and disposed of from the soil. The roadbed is then scarified and partially pulverized to the required depth of stabilization such that the surface of roadbed below scarified material is undisturbed and comply with the cross-section of the plan.

Lime Application. The lime may be applied in a dry form as well as a slurry form at a rate as determined by laboratory design or as per the condition and requirement. The partially pulverized material may be treated with quicklime (slurry) or with hydrated lime either in a slurry or in the dry condition. Dry quicklime may be applied to partially pulverized material in the dry condition. Lime in both slurry and dry form is dispersed uniformly with distributors or equipment approved by the Engineer. The material is sprinkled with water immediately after placing, however, the added amount of water shall not exceed the OMC of the prepared roadway by more than 5%. The application process shall be suspended when the surface temperature is below 50°F. The construction shall be started and completed between the months of April and October.

Mixing. Immediately after the application of lime, the lime is mixed uniformly and thoroughly using a rotary mixer, pulvimixers, or other mechanical equipment. The moisture content of the mix is brought to 3% to 5% above the optimum content by spreading enough water. After the initial mixing is completed, the surface is rolled with pneumatic tire and allowed to set for a minimum of three days. The soil is then scarified and uniformly remixed with rotary tillers or pulvimixers until the quicklime is homogeneously and uniformly distributed to the required depth. It must be noted that the moisture content of the mixed material shall be within two percentages of the optimum.

Compaction. The compaction process is commenced immediately after final mixing when the moisture content is raised to optimum plus minus 2%. The density of the compacted material shall not be less than 95% of maximum density as determined in laboratory. AASHTO T 99 and AASHTO T 180 shall be used to determine the maximum density as shown in Table 24.

Table 24
Test method to determine maximum laboratory density

% Retained #4 (4.75 mm) Sieve	Test Method
10 Maximum	AASHTO T 99, Method A
11 - 30	AASHTO T 99, Method C
31 Minimum	AASHTO T 180, Method D

The in-place compacted density and moisture content are determined in accordance to AASHTO T 310; AHTD Test Method 347 or 348 may be employed to determine the moisture content. The moisture content shall be maintained at appropriate level with frequent sprinkling of water and irregularities shall be removed by sufficient blading. After the compaction is completed, the compacted layer is brought to line, grade, and cross-section as specified in the plan. A pneumatic tire roller is used for final rolling of the completed surface.

Quality Assurance. The density and moisture test of the finished material must be performed per each 12,000 square yards of subgrade area on random locations selected as per AHTD 465, with 8 in. as the minimum depth of test. The field result of stabilization shall comply with certain specifications of construction. In case deficiencies in density and moisture content are observed, all in-place unacceptable materials shall be re-compacted, replaced or repaired. When the material is rocky such that it cannot be tested for density by the specified methods, the respective Engineer will determine the acceptance.

California

Use of Lime in Road Applications

Caltrans utilize lime to modify and stabilize subgrade soils, primarily with high clay content. The availability of sufficient stabilizer, clay fraction, moisture, and a pH in excess of about 12, promotes ion exchange and flocculation of clay mineral structure. This results in development of colloidal gels of hydrated calcium and alumina silicate, which have cementing properties similar to that of Portland cement.

Soil Type for Lime Application

Lime-stabilization may be considered for the following soil types:

- Soil with high moisture content to dry out the soil;
- Soils with plasticity and R-value less than designed for a project;
- Coarse-grained soils with low-strength; typically G- and S- soils;
- Soils with high plasticity; typically CL, MH, CH, and OH soils;
- Fine-grained soils with low-strength; typically M-, C-, and O- soils;
- Soils with high organic content (PT soils).

Soils with a plasticity index less than 12, R-value greater than 20, and DCP less than 20 typically do not require stabilization. If the soil samples do not meet these requirements or if the soil is to be used as a subbase material, chemical stabilization shall be performed. Mechanical stabilization such as compaction or blending and asphalt stabilization are alternatives of cement stabilization (lime and cement) and may be employed if the results from lime-stabilization are not satisfactory. Decision trees for cementitious stabilizer type required for subgrade stabilization are presented in Figure 19, Figure 20, and Figure 21.

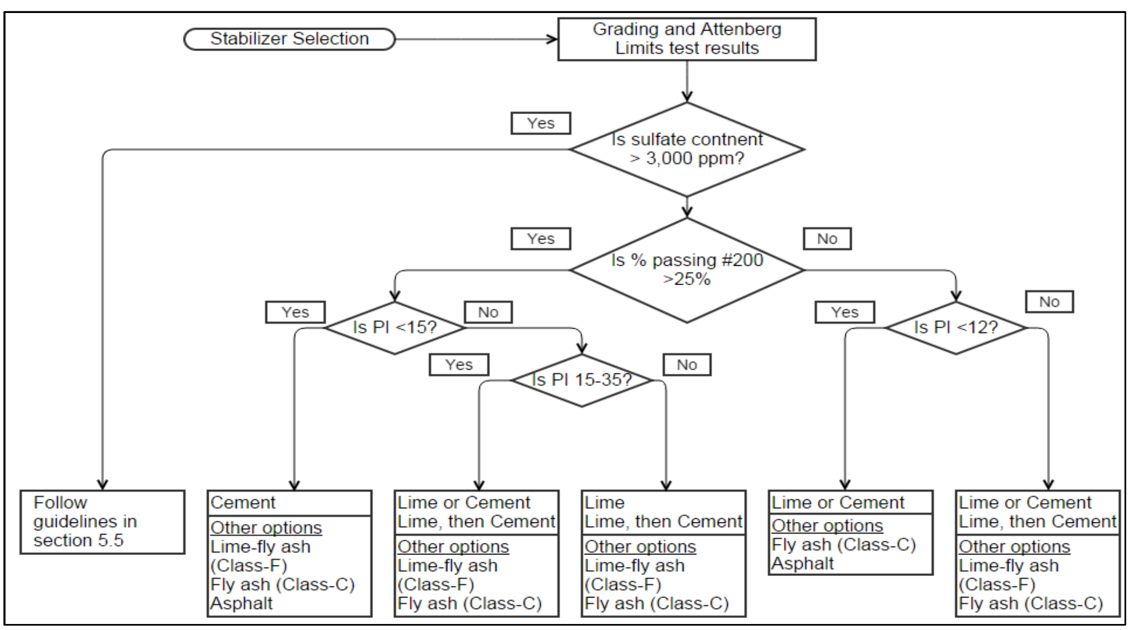


Figure 19
Decision tree for selecting cementitious stabilizer type

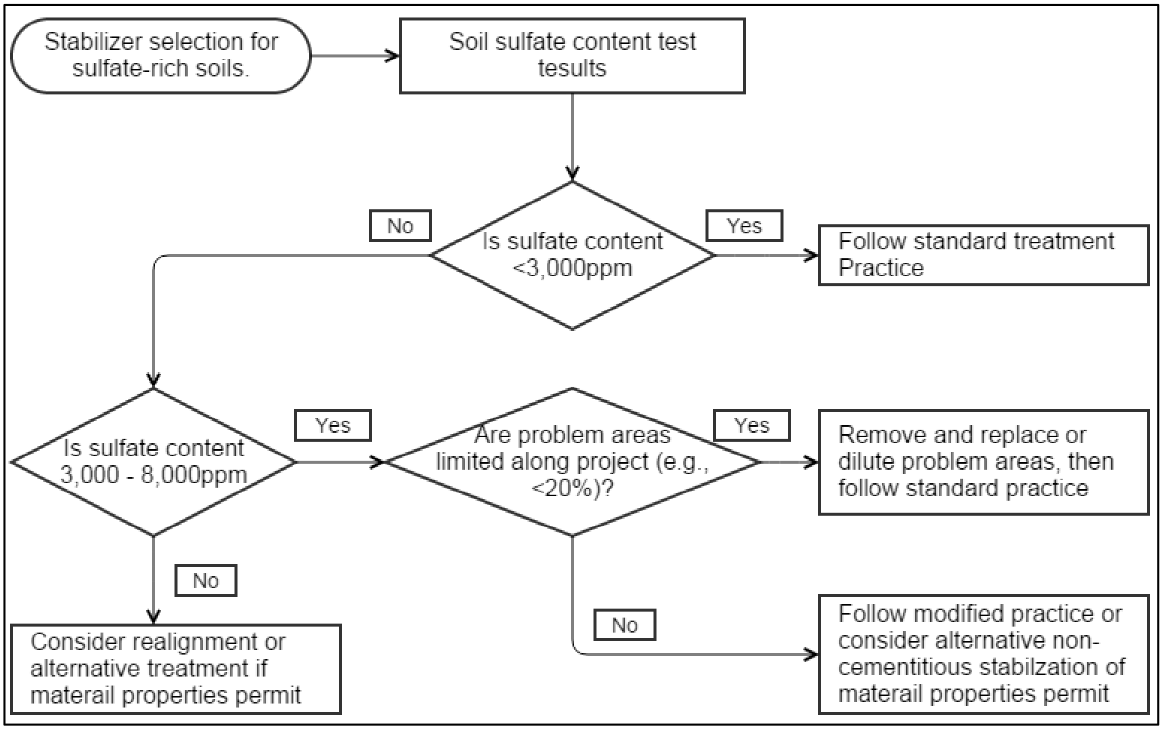


Figure 20
Guide for selecting a stabilization strategy for sulfate-rich soils

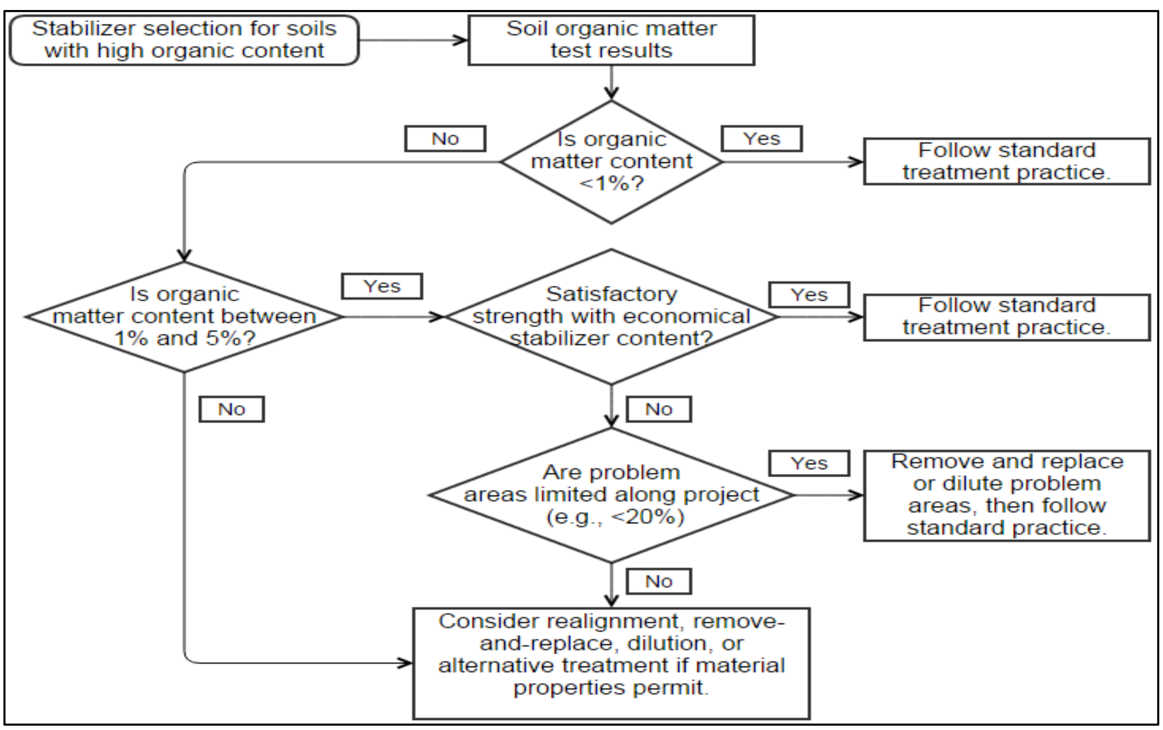


Figure 21
Guide for selecting a stabilization strategy for soils with high organic matter

Type of Lime

Lime-stabilization specification only permits the use of high calcium quicklime (CaO >90) or dolomite quicklime (CaO >55 and CaO + MgO >90) for subgrade stabilization. The lime must comply with ASTM C977 and meet the requirements shown in Table 25.

Table 25
Lime quality

Quality Characteristic	Test Method	Requirement
Available calcium and magnesium oxide (min, %)	ASTM C25 or ASTM C1301 and C1271	High calcium quicklime: CaO >90 Dolomite quicklime: CaO >55 and caO+ MgO >90
Loss on ignition (max, %)	ASTM C25	7 (total loss), 5(carbon dioxide), 2(free moisture
Slaking rate	ASTM C110	30°C rise in 8 minutes

Lime Content

Caltrans has specific provision of lime content for each lime application. These provisions are briefly described hereunder.

Soils with High Moisture Content. Lime is added at the rates of 0.5, 1.0, 1.5, 2.0, and 2.5% by weight to the five samples prepared with actual moisture content of subgrade samples. The lime content that reduces the moisture content to near to optimum moisture content is the required stabilizer content to dry the soil. Mechanical stabilization may be required along with lime treatment if the required lime content is greater than 2.5%. The final lime content is selected after the sample is inspected for relative compaction at actual moisture content and selected lime content; the wet density is required to be equal to or higher than the relative compaction.

Soils with High Plasticity. Five samples of soil are tested with lime content of 0, 1.0, 2.0, 3.0, and 4.0% of the dry soil weight. It should be noted that the soils with high salt content or low pH may require high lime content. After the Atterberg limits of the soil samples are determined according to CT 204, the lime content that reduces the plasticity index in the defined depth range to below the design requirements is selected. Alternative stabilization (mechanical or asphalt) or higher lime content may be employed if the plasticity is not reduced to satisfactory level. Lime content above 4.0% may be uneconomical and lead to shrinkage problems.

Soils with Low Strength. The soil is first tested for sulfate content and organic content. The procedure to determine lime content for sulfate-rich soils is followed if the sulfate content is higher than 3,000 ppm and organic content is less than 1%. For high plastic soils, a combination of lime and cement may be considered; lime reduces plasticity and cement develops strength. Minimum lime content required to maintain the pH of soil at 12.4 or higher is first determined from initial consumption of stabilizer (ICS) test using ASTM D 6276; stabilizer contents lower than ICS value may result in strength and plasticity reduction and even carbonation. Alternative stabilization strategies are considered if the lime content determined is inadequate to raise the pH of soil to 12.4 or higher. Three soil samples are prepared with lime content equal to ICS, ICS+1.0%, and ICS+2.0%, compacted using ASTM D 1577 and then tested for UCS using ASTM D 5102. A soaked UCS of between 30 psi and 60 psi is considered suitable for subgrade stabilization. If the results are not satisfactory; further tests are performed with higher lime content. However, it should be noted that lime content greater than 4.0% may be considered uneconomical and lead to shrinkage problems.

Soils with High Sulfate Content. To obtain the lime content that can stabilize high sulfate rich soils, the ICS and optimum moisture content of the soil are first determined using ASTM D 6276 and CT 216. Three soil samples at designed moisture content and four soil samples at designed moisture content plus 1, 2, 3, and 4% are prepared to test for sulfate content using CT 417 or AASTHO T 290. The best combination of lime content and moisture content that reduce the sulfate content to 3,000 ppm is selected and tested for strength requirements. The test is repeated with higher lime content or alternative stabilizers if the strength requirements are not met.

Soils with High Organic Matter Content. If the organic content of soil is less than 1%, either of the procedures to determine the lime content for soil with high plasticity or soil with low strength is followed depending upon the requirement. The same procedure is followed for the soil with organic content less than 5% to evaluate the results from ICS. The soil is either replaced with alternative soils or an alternative stabilization is considered if the results are not satisfactory.

Soils with Low pH or High Chloride Content. The problems related with higher plasticity and low strength can be effectively corrected with lime for the soils with low pH or high chloride content. However, due to requirement of higher amount of stabilizer than that required for soils with normal pH and chloride contents, the project may demand an uneconomical amount of stabilizer. Before undertaking any mix design procedures, the soil is first neutralized with lime or other stabilizer. An alternative stabilization strategy is considered if the results are not satisfactory.

Construction

Lime Application. The lime is generally applied in dry form and uniformly all over the surface using a vane spreader. The application rate of dry lime is verified with a calibrated tray once per 40,000 sq. ft. of stabilized soil, or twice per day, whichever is greater. If the lime is applied as a slurry, the slurry must be in suspension throughout the application and uniformly applied making successive passes over the area to be stabilized until the specified lime content is obtained. The quantity of slurry lime that has been placed is reported by measuring the volume of slurry in the holding tank once per 40,000 sq. ft. of stabilized soil, or twice per day, whichever is greater.

Mixing. Lime is mixed on the same day of application. The mix is allowed to mellow for a period of 36 hours between initial and final mixing and the process is completed within 7 days of the initial application. The in-place moisture of the material to be stabilized should be maintained at a minimum of 3% above the optimum. The mixed material gradation must be within the percentage passing limits for the sieve sizes as shown in Table 26. The material must be mixed with the stabilizer to a specified depth but the moisture content may be varied above or below the optimum depending on the soil type. Mixing to a greater depth will not provide a sufficient plasticity reduction and strength as the stabilizer application rate gets lower.

Table 26
Mixed material gradation

Sieve sizes	Percentage Passing
1 in.	98-100
No. 4	60-100

Compaction. The lime-stabilized soil is compacted to at least 95% relative compaction. It is recommended to start the compaction process as early as possible after final mixing. The maximum time before starting compaction for lime modification and lime-stabilization are respectively 24-48 hours and 6-8 hours. The modified/stabilized soil is compacted to pre-determined density at the roller speed and rolling pattern as determined during construction of test strip. When using a rotary mixer/recycler for the compaction process, the material between the wheel paths must be compacted to at least the same density as the rotary mixer will provide for the material under wheel path to ensure a uniform density throughout and avoid permanent failure in the wheel paths. To avoid density differential, it must be ensured that the drum of the roller bridges the wheel paths and at the end of the run of the first pass, the blade should be lowered and the roller reversed back down the same path while dragging material into the pad foot impressions and wheel paths of the rotary mixer/recycling train. A conventional rolling pattern may be followed on the next passes of the recycler. The compaction processes are suspended if the ground surface temperature is below 35°F.

Mellowing. Some lime applications such as stabilizing a sulfate rich soils require mellowing. Prior to mellowing, the material should be compacted lightly to seal the surface and prevent oxidation and carbonation. The moisture content should be maintained at an appropriate level throughout the mellowing period. A 24 to 48 hours of mellowing period between initial and subsequent mixing is recommended for high plasticity clays to improve the workability and uniform moisture distribution. The material is remixed after mellowing.

Finishing and Curing. The moisture content of lime-stabilized soil is maintained at a minimum of 3% above the optimum moisture content and the finished surface of the stabilized soil should not vary more than 0.08 ft. above or below the pre-established grade. However, if the stabilized soil is covered by material paid for by the cubic yard, the finished surface must not vary above the pre-established grade. The material is cured within 48 hours of compaction using a suitable curing method.

Quality Assurance. Unique and sequentially numbered lock seals are placed on each load and affixed to trailer blow down valves that are locked open. The bill of loading for each lime delivery must have that specific lock seal number legibly and visibly imprinted.

Colorado

Use of Lime in Road Applications

Lime is used to stabilize the subgrade layer by reducing the moisture content and increasing the soil support value. The subgrade layer is stabilized to at least 12 in. or to a depth as determined by the engineer and shall extend to the back of curb as a minimum. The major purpose of lime treatment is to provide a structural section to meet the design specifications and to protect the underlying subgrade soils.

Type of Lime

The lime employed for subgrade stabilization shall be hydrated or quick lime that conforms to the requirements of ASTM C 977 specifications and shall be a product of high-calcium limestone as defined by ASTM C 51. The lime is generally applied in slurry form; dry application of lime is permitted only under engineer’s approval. The rate of slaking test for moderate reactivity shall conform to ASTM C 110.

Construction

Subgrade Preparation. The existing roadway is finished to smooth and uniform surface and graded and shaped to the specified lines, grades and cross section; the subgrade elevations shall not vary by ±0.1 ft. The roadbed is then proof-rolled and the unstable or soft materials below the required depth is either removed or replaced with a suitable material so that uniform stability is established throughout. The in-place density of the prepared subgrade shall not be less than 95% of AASHTO T 99 density and moisture content shall not be greater than 3% of the optimum moisture content.

Test Section. Lime-stabilization procedure is tested on a 100 linear ft. of test section comprising of two spreading and mixing lanes wide. The contractor shall determine the lime application rate, design lime percent, maximum dry density, and optimum moisture content prior to the test. The stabilization procedure is implemented if the test section meets the required specifications.

Lime Application. Before lime application, the roadbed is scarified and partially pulverized to the required depth of stabilization such that the surface of roadbed below scarified material is undisturbed and complies with the depth and width of the plan. The loose materials shall be uniformly cut and pulverized to a depth of less than 10% over the thickness of the stabilized layer. The lime is then applied in slurry form over the area that can be integrated and mixed on a working day. The slurry is kept in suspension throughout the application and uniformly applied using the spray bars over the area to be stabilized until the specified lime content is obtained. The application and mixing processes are suspended when the ground is frozen and/or when the air temperature is below 35°F.

Mixing. The lime is uniformly and thoroughly mixed in soil immediately after lime application using a self-propelled rotary type mixture to obtain a homogenous layer of desired thickness and width. The colds and lumps in the mixture shall not be larger than 2 in. after mixing and the moisture content of the mix shall be above the optimum moisture content as determined by AASHTO T 99, with additional moisture for hydration. A minimum overlap of 6-in. shall be maintained to ensure proper mixing and disintegration of the material. The lime is mixed by making successive passes, at least two over the entire area and depth using an approved rotatory mixture. The uniformity of the mixture is tested using standard phenolphthalein indicator; the colors of the indicator are inspected to ensure the proper mixing of lime to required depth. After the initial mixing is completed, the surface is lightly rolled and sealed and allowed to mellow for 2 days. The soil is then remixed using a self-propelled rotary type mixer until the lime is homogeneously and uniformly distributed to the required depth. It must be ensured that the moisture in the mixture does not vary from the specified moisture content. 100% of the soil colds broken down, excluding the rock particles shall pass a 1-in. screen and at least 60% shall pass No. 4 sieve.

Compaction. The mixture is sprinkled and rolled simultaneously. The mixture is compacted using density control to at least 95% of the maximum density determined in accordance to AASHTO T 99; the in-place density of the mixture is determined in accordance to Colorado Procedure, CP-80. The moisture content shall be maintained at a 2 ± 1% of the optimum moisture content with frequent sprinkling of water and irregularities shall be removed by sufficient blading. All irregularities, depressions, and soft materials are either removed or replaced by appropriate material so that uniform compaction and stability is established throughout. The subgrade shall be reworked if the density and strength requirements are not met. The shape, grade and cross-sections of the finished subgrade shall be maintained according to the specification by frequent sprinkling and blading. The elevation of the finished layer shall not exceed the specified elevation by more than 0.04 ft.

Finishing and Curing. After compaction, the compacted layer is brought to line, grade, and cross-section as specified in the plans. The moisture content of the finished surface is maintained either by *(a)* curing for 7 days by sprinkling water frequently, or *(b)* by sprinkling for a period of less than 7 days until an emulsified asphalt prime coat diluted 1 to 1 with water is applied, or *(c)* by applying the emulsified prime coat at a rate 0.20 gallon per square yard immediately after compaction. The treated section may be opened to traffic after 7 days of curing period. The compressive strength of the material shall be within 160-500 psi.

The thickness of the finished surface shall be measured for each lot of 1500 square yards, with one core per lot. The stabilization is considered proper if the measured thickness of the lime-stabilized soil is within ½ in. of plan thickness. If the observed thickness is not within the tolerance, two additional cores shall be taken and the average thickness shall be determined. If the average thickness is observed to be deficient by more than 2 in., the areas shall be scarified, treated with additional lime, remixed, and re-compacted as required.

Georgia

Use of Lime in Road Applications

Georgia DOT employs lime to: *(1)* stabilize very poor subgrade soils, *(2)* increase the soil support value (SSV), and *(3)* eliminate wasting bad soils. Lime-stabilization is primarily implemented on high clay content soils, mainly to reduce initial construction costs through increased subgrade stability, to reduce pavement layer thicknesses, to increase long-term stability of pavement structure, and to lower life-cycle costs through reduced pavement maintenance.

Soil Type for Lime Application

Lime-stabilization is primarily performed on IIIC soils (soils that have severe limitations because of climate) and/or poor quality soils (IIB4) in both cuts and fills. However, cement stabilization is considered if the soil is observed to be micaceous, as lime is inert to micaceous soils. In Georgia, SSV is used to quantify the strength of the soil. If the SSV of the soil is less than 2.0, then either a cement or lime-stabilization is considered. The SSV of the soil may be raised to 3.5 or 4.0 if the soil is recommended for stabilization. Typically, the SSV is increased to 3.2 when lime is used for stabilization. Lime-stabilization is considered for soils having:

- Plasticity Index > 15-18;
- Volume Change > 20-30%; and
- Clay Content > 25-30%.

Type of Lime

Hydrated lime or quick lime may be applied in dry or slurry form for soil stabilization. Hydrated lime that meets the requirements of ASTM C 977 and has at least 85% by weight passing the No. 200 sieve is used. Hydrated lime can be used in slurry form for the construction projects except for rural areas and airports reconstruction, as the calcium in lime may damage aluminum on aircraft. Quicklime must meet the requirements of ASTM C 977, and should have 100% by weight passing 3/8 in. sieve. The slurry form of quicklime should contain at least 94% total calcium oxide and magnesium oxide, and at least 90% total available calcium oxide. Quicklime is normally applied in a slurry form through special slurry tanks with agitators to keep the lime in suspension during transport and placement. The quicklime is required to be slaked properly in a slaking tank, as the pebbles may swell in the soil and cause pavement failure.

Lime Content

Lime content is based on the soil types on the project; higher percentage of lime content is recommended for the poorest soils. The range of lime content is normally 4 to 6% by weight with a stabilization depth of 6 in. minimum for marginal soils, 8 to 9 in. for poorer soils, and 10 to 12 in. for the poorest soils. CBR testing with 4%, 5%, and 6% lime may be performed to determine the optimum lime content. The lime content for hydrated lime is based on the dry weight of the soil. For quicklime, the following formula is used to obtain the correct amount:

$$AR_Q = \frac{AR_H}{(1.32)\,(P)} \qquad (2)$$

where,

ARQ = Application rate for quicklime;

ARH = Application rate based on hydrated lime;

1.32 = Ratio of molecular weights for hydrated lime (74) and quicklime (56); and

P = Certified purity of the quicklime.

Construction

The following procedures are followed for Class A, Class B, and Class C treatments.

Class A

1. Spread first increment of lime;
2. Mix the material;
3. Allow the material to mellow to a loamy consistency;
4. Spread the second increment of lime;
5. Mix the material; and
6. Compact and finish the material.

Class B

1. Spread the Lime;
2. Mix the material;
3. Allow the material to mellow to a loamy consistency;
4. Mix the material; and
5. Compact and finish the material.

Class C

1. Spread the lime;
2. Mix the lime; and
3. Compact and finish the lime.

The construction procedure is described for all applications in the following subsections.

Subgrade Preparation. The underlying foundation is graded and shaped to the specified lines, grades and cross section. The foundation is dried, compacted to a uniform density and soft materials, if present, are stabilized. Each layer of materials to be treated are scarified and pulverized to the necessary depth and all detrimental materials are removed from the soil. The first section of each mixing operation is a test section with a length required to use all of the lime on one truck. Additional test sections shall be constructed if changes in equipment, methods, or grade elevations are made based on the results.

Lime Application. Lime is applied uniformly so that the quantity applied remains within 10% of the quantity specified for each section and is distributed by making a repeated pass until the specified percentage has been spread. The lime is incorporated into the soil after each pass and, if needed, water is added to accelerate the mellowing operation. If the depth of lime application is more than 6 in., the soil is treated in approximately equal layers with depth not exceeding 6 in. and the upper layers of the compacted soil is bladed in windrows outside the areas to be treated until the lower layer is mixed, compacted, and approved by the engineer. Construction is allowed only if the ambient air temperature is above 45ºF and only between April 1 and October 15, unless otherwise specified by the engineer. One of the three methods of application, namely *(a)* dry application with quicklime, *(b)* slurry made with hydrated lime, and *(c)* slurry made by slaking quicklime, may be selected for lime-stabilization. For method *(a)*, the application rate is determined from equation (2) and the applied lime is slaked on the ground by water until the pebbles turn into liquid. For method *(b)*, lime slurry is prepared by mixing 30% dry lime soils, by weight, with 70% water in agitating equipment until arriving at the roadbed. For method *(c)*, the quicklime is slaked using special equipment and applied after the engineer's approval.

Mixing. For class A or class B lime treatment, the moisture content of the material is maintained as specified or not more than 5% over optimum during mixing; if necessary, water is added to sustain the chemical reaction between lime and water. After ensuring that the lime and water mixed in rotary mixture passes through 2-in. sieve, the treated course is reshaped to the approximate line, grade and typical section, sealed with light, pneumatic-tired roller and allowed to mellow for 3 to 14 days. The layer is then scarified and mixing is continued until 100% of the material by dry weight passes a 2-in .sieve and 60% passes a No. 4 sieve, such that the moisture content is at or above the laboratory specified optimum moisture. The surface of the layer is sealed with a rubber-tired roller if mixing cannot be completed in one day. For class C treatment, the lime and water is mixed uniformly in a rotary mixture until a homogeneous mixture of soil, lime and water is obtained. It is ensured that 100% of the material by dry weight passes a 1.5-in. sieve and 80% by weight passes a No. 4 sieve.

Compaction, Finishing, and Curing. The material is compacted such that the moisture content is maintained at the specified optimum level or up to 2% over the optimum. Sheepfoot-type rollers are used to compact the material uniformly throughout until the entire depth is compacted to a specified density. The soft spots and depressions, if observed, are either removed or treated with lime.

After the compaction operation, the treated soil is kept moist for 7 days and cured by applying water. A bituminous prime material is applied not later than 24 hours of compaction to protect the lime-stabilized material; any loose and extraneous material that may contain sufficient moisture to prevent penetration of bituminous prime is swept and cleaned off before application. The prime is applied uniformly to the surface at the rate of 0.15 to 0.30 gal/yd^2 and curing is completed prior to placing of the subsequent layers.

Quality Acceptance. The mixture is rolled until uniformly compacted to a specified density. The percentage of the maximum dry density presented in Table 27 is used. The surface of the compacted layer should be smooth, dense, well-bounded, free of loose materials, unyielding, with uniformly distributed lime.

Table 27
Maximum dry density requirements

All base, subbase, or shoulder courses	100%
Top 1 ft. (300 mm) of embankment (subgrade)	100%
To within 1 ft. (300 mm) of the top of the embankment	95%

The thickness of the lime-stabilized layer is determined, at intervals not to exceed 500 ft. The section is reconstructed if the thickness is observed to vary by +/- 1 in. from the thickness shown on the plans. Additional lime is added and the material is remixed to the specified depth and width to correct the deficiency of any section exceeding the 1-in. tolerance.

Illinois

Use of Lime in Road Applications

Illinois employs lime for soil modification and soil stabilization.

Soil Type for Lime Application

A soil having a minimum clay content of 15% and a maximum organic content of 10% as determined respectively in accordance to AASHTO T 88 and AASHTO T 194 shall be used for soil modification and lime-stabilization. When treated with 3% lime, the soil shall exhibit a compressive strength gain of at least 50 psi greater than that for the untreated soil when tested after 48 hours of curing at 120°C.

Type of Lime

Hydrated lime, which meets the requirements of ASTM C 207, Type N shall be used for soil modification and soil stabilization. When lime is used as a slurry, both hydrated and quicklime shall conform to ASTM C 207, Type N and the quantity of lime in slurry shall be 35-45% by total weight of the slurry.

Construction for Soil Modification

Subgrade Preparation. The surface of the existing subgrade is graded and shaped to the specified lines, grades, and cross section. All undesirable materials such as topsoil, roots, organic material, and stone fragments are cleared away. The subgrade is prepared according to the specifications in cut or at grade sections. The Department's "Subgrade Stability Manual" shall be followed for minimum immediate bearing value (IBV) of the soil below the soil to be modified.

Lime Application. Lime is spread and dispersed uniformly on the lightly excoriated subgrade, limiting the distribution to an area that can be integrated and mixed on a working day. The application process is suspended when soil temperature is below 50°F measured 6 in. below the surface, ambient air temperature is below 45°C, and under adverse wind conditions that would blow away the material. The application of lime slurry shall be completed within 30 days of slurry preparation and mixing. The slurry shall be kept in a continuous agitation during application.

Mixing. The lime is uniformly and thoroughly mixed in soil immediately after lime application to obtain a homogenous layer of desired thickness. A minimum of 75% of the mixture shall be smaller than 1 in. after mixing and the moisture content of the mix shall be above the optimum moisture content, not exceeding 3%.

Compaction and Finishing. The compaction process shall be begin within 24 hours of mixing. The mixture is compacted using density control to at least 95% of the maximum density determined in accordance to AASHTO T 310, or Illinois-modified AASHTO T 310. The moisture content shall be maintained at appropriate level with not exceeding 3% above optimum by frequent sprinkling of water or with aeration or drying by further mixing. The thickness of the top lift of soil shall not be less than 6 in. if multiple lifts are used to construct and compact the subgrade layer. After the compaction is completed, the compacted layer is brought to line, grade, and typical cross section as specified in the plans. Any equipment that may cause subgrade rutting is removed and the completed section is sufficiently cured for a minimum of 24 hours. The immediate bearing value (IBV) of the cured subgrade as determined using Illinois Test Procedure 501 shall not be less than 10.

Construction for Soil Stabilization

Subgrade Preparation. The surface of the existing subgrade is graded and shaped to the specified lines, grades, and cross section. All the undesirable materials such as topsoil, roots, organic material, and stone fragments are cleared away. The subgrade is prepared according to the specifications in cut or at grade sections; the Department's "Subgrade Stability Manual" shall be followed for minimum immediate bearing value (IBV) of the soil below the soil to be stabilized.

Lime Application. Lime is spread and dispersed uniformly on the lightly excoriated subgrade, limiting the distribution to an area that can be integrated and mixed on a working day. The application process is suspended when soil temperature is below 50°F measured 6 in. below the surface, ambient air temperature is below 45°C, and under adverse wind conditions that would blow away the material. The application of lime slurry shall be completed within 30 days of slurry preparation and mixing. The slurry shall be kept in a continuous agitation during application. Both dry lime and lime slurry that has been exposed to air for more than six days and damaged by rain shall be replaced.

Mixing. The lime is uniformly and thoroughly mixed in soil immediately after lime application to obtain a homogenous layer of desired thickness and width. The colds and lumps in the mixture shall not be larger than 2 in. after mixing and the moisture content of the mix shall be above the optimum moisture content, not exceeding 3%. After the initial mixing is completed, the surface is lightly rolled and sealed and allowed to mellow for 2 days. The soil is then remixed until the lime is homogeneously and uniformly distributed to the required depth. It must be ensured that the moisture in the mixture does not vary from the specified moisture.

Compaction and Finishing. The compaction process shall be begin within 24 hours of mixing. The mixture is compacted using density control to at least 95% of the maximum density determined in accordance to AASHTO T 310, or Illinois modified AASHTO T 310. The moisture content shall be maintained at an appropriate level while not exceeding 3%

above optimum by frequent sprinkling of water. After the compaction is completed, the compacted layer is brought to line, grade and typical cross section as specified in the plans. Any equipment that may cause subgrade rutting is removed and the completed section is sufficiently cured for a minimum of 24 hours. The immediate bearing value (IBV) of the cured subgrade as determined using Illinois Test Procedure 501 shall not be less than 23. The IBV is measured 10 days prior to the pavement construction.

Indiana

Use of Lime in Road Applications

Lime is utilized to modify and to stabilize the subgrade soil with specified UCS. The soil modification provides platform for the construction equipment and may be considered for all reconstruction and new alignment projects. The soil stabilization strengthens the subgrade soil, which contributes to the pavement structural capacity and may be considered for prepared subgrade soils with a resilient modulus less than 5,000 psi. The soil modification and soil stabilization include the improvement and refinement of soil properties such as strength, compressibility, hydraulic conductivity, workability, swelling potential, and volume change tendencies through chemical processes. The chemical alteration of subgrade soil include, *(1)* increment of particle size by cementation, reduction of plasticity index, increment of internal friction among the agglomerates, and lessening of shrink/swell potential, *(2)* absorption and chemical binding of moisture to facilitate compaction.

Soil Type for Lime Application

The soil with clay content greater than 20% and plasticity index greater than 10 is acceptable for lime modification and stabilization. Mix design is performed based on an increase in the unconfined compressive strength of soil-lime mixture. A pair of specimens and complementary sets of two specimens with height to diameter ratio of 2:1 are prepared at 95% of standard proctor density and optimum moisture content. Add 5% lime and allow the mix to cure for 48 hours at 70°F; test in accordance to AASHTO T-208. The soil is considered suitable for modification and stabilization if the minimum strength gain of the soil samples, when tested for unconfined compressive strength, is greater than that of the natural soil by 50 psi.

Type of Lime

Both hydrated and quicklime meeting the requirements of AASHTO M 216, with a soluble sulfate content of less than 5%, may be employed for subgrade modification and stabilization. The lime by-products meeting the requirements of ASTM C 25 may be employed to stabilize and to modify subgrade soil. The lime by-products shall contain a minimum of 60% total calcium and magnesium oxides on non-volatile basis, and available calcium hydroxide and magnesium oxide (calculated as calcium hydroxide) shall not be less than 30%. The by-products shall meet the gradation requirements (in accordance with ASTM C 110) as presented in Table 28.

Table 28
Gradation requirements for lime by-products (Indiana)

Sieve	**% Retained (Max)**
No. 4 (4.75 mm)	5
No. 30 (600 μm)	10
No. 100 (150 μm)	25

Lime Content

Generally 4 to 6% lime, by weight, is applied. If lime is combined with other chemical stabilizers, a minimum of 2% of quick lime shall be considered in all combinations. The quantities of the hydrated and quick lime shall be generally 4.0 ± 0.5% and of the lime by-products shall be 5.0 ± 0.5% by dry unit weight of the soil. To determine the lime content, the pH of various samples is recorded and plotted against percent lime using the Eades and Grim pH test.

A sufficient amount of lime to produce a pH of 12.4 or equal to the pH of lime before mixing is added to a 150-ml or larger bottles containing a 20 gram of oven-dried minus No. 40 soil, weighed to a nearest 0.1 gram. Optimum moisture content and pH of lime-soil mixtures are determined for five samples with lime contents of 3, 4, 5, 6, and 7%. The lime content providing the optimum moisture content corresponding to the maximum pH of soil is weighed to the nearest 0.01 gram, added and mixed to the soil. 100 ml of carbon dioxide free distilled water is added and the mixture is shaken for a minimum of 30 seconds every 10 minutes for one hour. The pH of the slurry is then measured by a pH meter equipped with a Hyalk electrode and standardized with a buffer solution having a pH of 12.0. The pH of each sample is obtained and plotted against the percent lime as presented in Figure 22. Three conditions apply for the percent lime required to stabilize the soil, (1) for the soil samples with pH 12.4 or higher, the lowest percent lime that gives a pH of 12.4 is the required percent lime to stabilize the soil, (2) if the pH readings does not go beyond 12.3 and 2% lime produces the same reading , a lowest percent lime that gives the reading is the percent lime required for stabilization and, (3) if the highest percentage of lime corresponds to pH reading of 12.30 being the highest pH reading in all samples and only one percent lime gives a pH of 12.30, addition testing is recommended using higher percent lime. The soil lime mixture is tested for Atterberg limits and compaction. A pair of lime-treated specimens, compacted at 95% of standard proctor and cured for 48 hours at 70°F, shall generate a strength gain of 50 psi over the natural soil. The specimens with optimum lime and soil mixture are further tested for Resilient Modulus in accordance with AASHTO T-99 at 95% compaction.

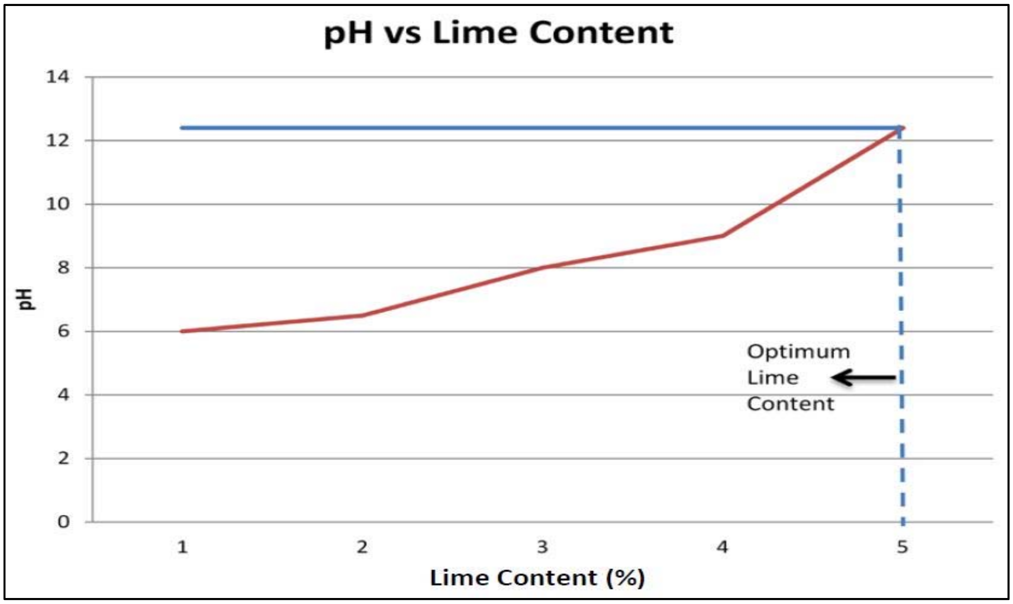


Figure 22
pH vs. lime content

The addition of lime cause reduction in moisture content of the soil due to: *(1)* rapid hydration of calcium oxide to calcium hydroxide, *(2)* exothermic reaction of lime hydration, and *(3)* pozzolanic reaction causing moisture to combine into alumina silica compounds. The increase in moisture content may be observed due to flocculation because of change in texture from parallel alignment to edge to face attraction. Tests to determine a relationship between moisture range and time range are performed at room temperature or at a temperature recommended by the engineer. In-place moisture content, loss on ignition, and sulfate tests are performed on jar of soil sample. pH of soil and lime are determined separately and a typical moisture-density test is performed at each soil and lime mixture. The relationship between percent lime content and moisture content is presented in a tabular or graphical form as presented in

Table 29. The drop in maximum dry density and rise in optimum moisture content with respect to time is determined from the compaction test.

Table 29
Moisture reduction vs. lime

Soil ID	% Above OMC (Untreated)	Untreated MC	Treated MC (By Dry Weight) After one Hour			
			3%	4%	5%	6%
Sta. 16+00	2	17.3	15.8	-	-	-
Sta. 16+00	4	19.5	18	19	-	-
Sta. 16+00	6	21.2	20	18	16	-
Sta. 16+00	8	23.8	22	21	19	18

Construction

Subgrade Preparation. The soil that contains more than 6% by dry weight calcium, magnesium carbonate or organic material, or with a maximum dry density of 95 pcf, or with a soluble sulfate content greater than 1,000 ppm is not allowed in the cut sections and is not allowed within 24 in. of the finished subgrade elevation in fill sections. All the undesirable materials such as frozen soil, roots, organic material, trees, moss, and other unsuitable materials are cleared away and the surface of the existing subgrade is approximately graded and shaped to the specified dimensions and elevations within a tolerance of ½ in. as on plan. Rock fragments with diameter 6 centimeter or more measured in any direction shall be broken off at least 6 in. below the subgrade surface. The subgrade shall be provided with adequate drainage to prevent water stagnation. The subgrade shall be worked accordingly if the density requirement is specified; the top lifts in cut section shall be removed and the bottom 6 in. shall be compacted in-place to comply with the density and moisture requirement. Any shale or shale and rocks mixtures shall be broken off 12 in. below the subgrade elevation and replaced with coarse aggregate No. 53 or No. 73 and compacted accordingly.

Lime Application and Mixing. Lime is spread on the excoriated subgrade on a dry weight basis and is dispersed uniformly with cyclone, screw-type, or pressure manifold type distributor. The distribution is limited to an area that can be integrated and mixed on a working day. The application process is suspended when air temperature is below 45°F measured 4 in. below the surface and under adverse wind conditions that would blow away the material. Immediately after the application, a rotary mixer is used to mix the lime uniformly and thoroughly in soil to a depth of 14 in. Mixing is continued until 100% of the material by dry weight passes a one in. sieve and 60% passes a No. 4 sieve.

Compaction and Finishing. The compaction process shall be completed within 24 hours after final mixing. The material is compacted such that the moisture content is maintained at the specified optimum level or above the optimum as determined from the mix design (ITM 506). The moisture content shall be maintained at appropriate level with frequent sprinkling of water or with aeration or drying by further mixing. A Dynamic Cone Penetration Test (DCPT) is performed on the compacted soil in accordance with ASTM D 6951. The modified soil shall meet the following requirements:

- A minimum DCP blow count of 17 for the top 6 in. of a 14-in. lift.
- A minimum DCP blow count of 16 for the bottom 8 in. of a 14-in. lift.
- A minimum DCP blow count of 20 for an 80-in. lift.
- A minimum of 1 passing test for each 1,500 ft. of chemically modified soil for each 2-lane pavement.

After the compaction is completed, the compacted layer is brought to line, grade and typical cross section as specified in the plan. The completed section is finally proof-rolled with light roller, the treated subgrade is sufficiently cured, and sealed before placing subsequent layer. The finished layer is open to traffic not before 72 hours after compaction.

Kansas

Type of Lime

Hydrated lime confirming the requirements as presented in Table 30 shall be used for soil treatment.

Table 30
Requirements for hydrated lime

Available Lime Index as Calcium Hydroxide	90%, min
Residue retained on a No. 30 sieve	1%, max
Residue retained on a No. 30 sieve	20%, max

Construction

Subgrade Preparation. The existing roadway is graded and shaped to the specified lines, grades and cross section using automatic grade controlled equipment. The subgrade is wetted, bladed and rolled in irregular areas. Necessary precautions is implemented to drain the roadbed and keep it dry. Required stability is obtained by thoroughly mixing and compacting the trimmed subgrade or borrow area.

Lime Application. When a mixing chamber is not used for lime application, the prepared subgrade is scarified to a minimum depth of 4 in. and to a maximum depth of approximately 1 in. less than the specified depth using a positive depth control equipment. If not specified, lime is applied at a rate of 5% of the weight of soil. The lime slurry is uniformly applied over the entire area through spray bars and nozzles. The concentration of lime suspension tested at a minimum rate of 1 per day or 1 per mixed batch, whichever is greater, shall be uniform over the entire area of treatment. Necessary precautions shall be undertaken not to allow the excess increase in moisture of the mixture. The slurry is kept in suspension throughout the application either in central plant or in transit mix. Water is spread frequently to bring the moisture content of the mixture to 8% above the optimum. The application and mixing processes are suspended when the ground is frozen and/or when the air temperature is below 40°F.

The rate of application of lime slurry is checked by placing a planar surface with a minimum surface area of 1 sq. ft. in a flat area and allowing the lime spreader to pass the area. The application rate is determined by calculating the ratio of planar surface before and after the application of lime. The rate so determined shall be ±0.5% of the required application rate.

Mixing. The material is scarified and partially pulverized to required depth using an equipment with positive depth control before application. The depth of mixing shall be maintained within ±0.5 in. of the specified depth for areas more than 20,000 square yards. The lime is mixed uniformly and thoroughly by making successive passes over the entire area using an approved rotatory mixture. The lime is mixed by making successive passes, at least two over the entire area until 95% of the colds broken down passes the 2 in. sieve. After the initial mixing is completed, the surface is rolled with pneumatic tire and the surface is bladed to protect against rain and excessive drying. The mixture is allowed to mellow for a period of at least 2 days. The final mixing shall be performed within 14 days of initial mixing. Additional 1% lime by weight of raw soil shall be added if the final mixing is delayed beyond 14 days. The soil is then remixed until the lime is homogeneously and uniformly distributed to the required depth, with a tolerance of ±0.5 in. 95% of the soil colds that are broken down, excluding the rock particles shall pass a 1 ½ -in. screen and at least 40% by dry weight shall pass the No. 4 sieve. It must be ensured that the moisture in the mixture does not vary from the specified.

Compaction and Finishing. The compaction operations shall be commenced immediately after final mixing for in-place application of lime. When the material is mixed off-site, the material is compacted after it is transported and placed over the trimmed surface. The compacted subgrade is graded and shaped to the specified lines, grades and cross section using automatic grade controlled equipment. The subgrade is wetted, bladed, and rolled in irregular areas and re-compacted with a smooth-wheel or pneumatic-tire roller. After the compaction operations, the treated soil is cured with water for a minimum of seven days, prevented from freezing, and sealed before placing subsequent layer. If the finished subgrade is to be covered with asphalt prime coat, SS-1, CSS-1 or MC-250 shall be applied at a rate of 0.22 gallons per square yard so that a minimum residue of 0.13 gallons per square yard is obtained.

Kentucky

Use of Lime in Road Applications

Lime is utilized to stabilize the existing subgrade to provide a stable platform for the base and pavement structure as a whole. The stabilized layer is used as a structural layer in pavement design. With an assumption that the lime modification increases the CBR of the soil to a value greater than 6, a typical structural layer coefficient of 0.11 is assigned to lime-stabilized layer.

Soil Type for Lime Application

Clayey soil with plasticity index greater than 20, CBR less than 6, and more than 35% passing a No. 200 sieve is acceptable for lime modification and stabilization.

Construction

Subgrade Preparation. The existing roadway is graded and shaped to the specified lines, grades and cross section. All detrimental materials, such as roots and rocks larger than 4 in., are removed and disposed of from the soil. The roadbed is then scarified and partially pulverized to the required depth of stabilization such that the surface of roadbed below scarified material is undisturbed and comply with the cross-section of the plan.

Lime Application. One of the three methods of application namely *(a)* dry application with hydrated or quicklime, *(b)* slurry made with hydrated lime, and *(c)* slurry made by slaking quicklime, may be selected for lime-stabilization. The distribution is limited to an area that can be integrated and mixed on a working day. When lime is applied in dry form, an approved spreader shall be used to spread the lime uniformly over the scarified surface. The dusting is controlled by sprinkling water while spreading the lime. Lime is not applied in dry form under unfavorable wind conditions that would blow away the material. When lime is applied as a slurry, the slurry must be in suspension throughout the application and uniformly applied over the area to be stabilized with approved equipment. The lime application and mixing operations are suspended when the ground is frozen and the ambient air temperature measured on the shade is below 40ºF.

Mixing. The lime is uniformly and thoroughly mixed in soil immediately and within 4 hours lime application and to obtain a homogenous layer of desired thickness and width.

The colds and lumps in the mixture shall not be larger than 2 in. after mixing. After the initial mixing is completed, the surface is shaped to appropriate cross section, lightly rolled, sealed and allowed to mellow for 2 days. The soil is then remixed until the lime is homogeneously and uniformly distributed to the required depth. It must be ensured that the moisture in the mixture does not vary from the specified. Of the soil colds broken down, 100% excluding the rock particles, shall pass a 1-in. screen and at least 50% shall pass No. 4 sieve. The mixing and pulverization shall be completed within 72 hours after initial mixing.

Compaction and Finishing. The material is compacted uniformly throughout the treated area until the entire depth is compacted to at least a 95% of the maximum dry density determined in accordance with KM 64-511. Any soft spots and the areas that does not conform to surface tolerances are corrected and levelled.

Curing and Protection. The compacted surface is sealed uniformly within 24 hours of finishing with a curing seal applied at the rate of approximately 2 pounds per square yard. The curing seal is applied only to dense surface that has sufficient moisture content to prevent the penetration of the sealant. The seal is applied such that a continuous membrane is established throughout and may be applied in two successive applications to avoid excessive runoff. The finished layer is open to traffic not before 7 days after compaction and when the subgrade achieves the minimum strength requirement of 80 psi. If the curing time is short, cores are taken at an interval of every 500 ft. for each lane and tested for unconfined compressive strength. A sand bottler material may be applied at an approximate rate of 5 pounds per square yard, if the curing seal is observed to be sticky or tacky.

Michigan

Use of Lime in Road Application

The Michigan Department of Transportation employs lime to stabilize the subgrade soil. The special provision for lime-stabilized subgrade consists of all materials including water, equipment, labor and tests for constructing a 12 in. of uniformly compacted layer of lime-stabilized subgrade.

Soil Type for Lime Application

The in-place soil subgrade material that is uniform in quality and gradation, free of roots, sod, weeds, and stones larger than 2- ½ in., shall be used for lime-stabilization.

Type of Lime

The lime employed for subgrade stabilization shall be quick lime that confirms to the requirements of ASTM C 977 specifications with modification that the lime shall pass the 3/8 in. sieve. In addition, the lime shall be certified by "Test Data Certification" method as per the MDOT Material Source Guide.

Lime Content

The contractor shall determine the recommended percentage of lime for subgrade stabilization. One soil sample for every 20,000 square yard area of soil to be treated, one sample per major type of soil, or a minimum of five samples are tested to determine the lime content. The soil classification is tested as per AASTHO M145 for untreated soil and ASTM D2487 for lime-treated soil. AASHTO T99 is used to test the moisture and density, the California Bearing Testing (CBR) is tested as per ASTM D 1883, and ASTM D 4318 is used to test liquid, plastic and plasticity index of the soil samples. The unconfined compressive strength (UCS) of the samples cured at 40°C for 7 days is determined according to ASTM D 5102. Eventually, the minimum amount of lime that results in a soil-lime pH of 12.4, CBR of 10 for uncured soil-lime mixture, and a minimum UCS of 125 psi is determined as per ASTM D 6276.

Construction

Test Section. The details of lime-stabilization procedure is tested on a 600 linear ft. of test section comprising of either one of more lane widths. The stabilization procedure is implemented if the test section meets the required specifications. The contractor shall provide the results of the test section at a minimum of 5 working days in advance of the construction of test strip. The test section may be accepted as a part or whole of the total required lime-stabilized area as per the results.

Subgrade Preparation. All the undesirable materials such as topsoil, roots, organic material, and stone fragments larger than 2-1/2 in. are cleared away and the underlying foundation is graded and shaped to the specified lines, grades and cross section prior to addition of lime. The granular and cohesive soils with excessive moisture content may require a modification in lime-stabilization procedure and hence are omitted from a regular lime-stabilization procedure.

Lime Application and Mixing. Lime is spread on the excoriated subgrade on a dry weight basis and is dispersed uniformly with distributors or equipment approved by the Engineer. The distribution is limited to an area that can be integrated and mixed on a working day. The application process is suspended when air temperature is below 40°F and adverse wind conditions that would blow away the material. The dusting is controlled by sprinkling water while spreading the lime. A rotary mixer is used to mix the lime uniformly and thoroughly in soil to a depth of 12 in. immediately after the application. The moisture content of the mix is brought to 3% to 5% above the optimum by spreading enough water. The initial mixing is required to be completed within 4 hours of lime application and all the lime particles are allowed to hydrate for a period of 1 to 24 hours or longer as required after the initial mixing. The soil is then remixed until the quicklime is homogeneously and uniformly distributed to the required depth. All the lime particles shall be hydrated completely after final mixing. The moisture content is raised to 2% to 3% higher than the optimum by adding pre-determined quantity of water. The soil colds broken down, excluding the rock particles shall pass a 2-in. screen and at least 60% shall pass No. 4 sieve. The final mixing is completed within 5 days of initial mixing.

Compaction. The compaction process is commenced immediately after final mixing when the moisture content is raised to optimum plus minus 2% and density not less than 95% of maximum density determined as per AASHTO T99. The rolling is proceeded from the outer edge of the surface to the center; at least one-half width of the roller is overlapped on successive trips. The speed is controlled such that the materials are not displaced. Mechanical compaction shall be employed in the areas inaccessible to rollers. The material is finally compacted with steel wheel smooth drum rollers.

Curing and Re-stabilization. Immediately after compaction and finishing, the surface is protected against rapid drying for 7 days by sprinkling water frequently and cured for 7 days, unless covered by subsequent layers of pavement. The treated section may be opened to traffic after 7 days of curing period. The treated surface shall be re-stabilized if failure, tenderness or damage is observed after curing has been completed.

Quality Control and Assurance. The field result of stabilization shall comply with certain specifications for construction. In case the material source is changed and deficiencies is observed, the extent of unacceptable material shall be determined and all in-place unacceptable materials shall be replaced or repaired. The thickness of the finished surface shall be measured for each 4000 square yards, at least one per day. If the measured thickness of the lime-stabilized soil is not within ½ in. of 12 in., the areas shall be scarified, treated with additional lime, remixed and re-compacted as required. The samples to test the lime content of uncured lime and finished soil mixture shall be obtained from mid-depth of the stabilized layer. At least one test per 4000 square yards, or at least one test per day shall be performed. The lime content of uncured lime or soil mixture as determined using ASTM D 3155 shall not be less than 1% below the pre-designed lime-soil mix design. The field density is tested for soil samples for each 4,000 square yards of lime-stabilized subgrade, but at least one per day.

Minnesota

Use of Lime in Road Applications

Lime can be employed to modify fine-grained soils and fine-grained portion of granular soils for base layer. Lime modification lowers the PI and volume change characteristics of the soil, improves the overall workability, and increase the strength of subgrade soil. The pozzolanic reaction between soil and lime also enhance the subgrade stability and durability. Presently, MnDOT does not use lime for stabilization of layers and has no established specifications.

Soil Type for Lime Application

Fine grained soils and fine-grained portion of granular soils are modified by lime. Lime-stabilization is effective for soils having a plasticity index of 10 or higher and clay content of 10 percent or higher. However, the MnDOT has no established specifications for lime treated bases and upon communication it was known that MnDOT does not use lime to stabilize layers.

Type of Lime

Hydrated lime that confirms to the requirements of AASHTO M 216 shall be used for soil drying and soil stabilization. However, upon communication we came to know that they do not use lime for stabilization.

Mississippi

Use of Lime in Road Applications

Lime is used for soil stabilization in Mississippi through chemical and physical effects. The chemical effect include three specific reactions that take place simultaneously when lime is added to a clay soil; base-exchange, cementation, and carbonation. The physical effect of lime on soil include the influence in plasticity, volume change, grain size, strength, and durability of a soil.

Soil Type for Lime Application

The soil in the existing subgrade which substantially all pass 3 in. sieve is suitable for lime-stabilization. Lime treatment is performed for heavy clay soils and plastic soils (AASHTO A-4 soils with a high group index and AASHTO A-6 soils with a low group index.)

Type of Lime

MDOT primarily employs hydrated lime; quicklime that meet the department specifications may be applied. The hydrated lime shall comply with the requirements of ASTM C 207, Type N. It shall contain at least 90% of calcium and magnesium oxides, at most 7% of carbon oxide, and the moisture loss after 2 hours tested at 120°F shall not exceed 3%. In addition to this, the lime residue on No. 30 and No. 200 sieve after gradation shall not exceed 2.5% and 15%.

The granular or pelletized quicklime used for soil stabilization shall contain at least 90% of calcium and magnesium oxides, at most 7% of carbon oxide. In addition, 100% by weight shall pass ¾ in. sieve and not more than 30% shall pass No. 4 sieve. The dry quicklime shall conform to the requirements of ASTM C 110 and meet the gradation requirements as presented in Table 31.

Table 31
Gradation requirements for dry quicklime

Sieve	Percent Passing by Weight
No. 10	100
No. 20	90-100
No. 100	0-20
No. 200	0-5

Lime Content

The Mississippi test method, MT-27 is used to determine lime content for soil stabilization. The design lime content is based on CBR and swell tests performed on samples with variable lime content. The procedures of test for various treatments (Class A, Class B, and Class C) are briefly described hereunder. For all the treatment types, the lime content that yields a minimum CBR of 20 and a satisfactory minimum swell is the required hydrated lime content for soil stabilization. The required percent lime for quick lime is 83% of the design hydrated lime content.

Class A

The first increment of lime, usually 4 ½ % by dry weight of dry soil is added to two soil samples weighing approximately 15 pounds and 8 pounds with both the samples corrected for hygroscopic moisture; the first sample is prepared for CBR test (AASHTO T 193), and the second sample is prepared for moisture-density relationship test (MT-9). The soil samples are tested for pulverization after curing for 5 to 20 days by adding water as required to keep the moisture content to a saturated level. The samples are dried until the moisture content is below optimum and pulverized until 100% passes ½ in. sieve and at least 60% passes No. 4 sieve. The second increment of lime, usually 2 ½ % by dry weight is added to the pulverized samples. The samples are tested for CBR and moisture-density relationship.

Class B

For class B treatment, three soils samples weighing 15 pounds are selected and corrected for hygroscopic moisture to test for CBR and one soil sample weighing 8 pounds is corrected for hygroscopic moisture to test for moisture-density relationship (MT-9). An estimated percentage lime by dry weight of sample is added to the sample weighing 8 pounds and one sample weighing 15 pounds; 1% above the estimated lime content and 1% below the estimated lime content are added for the other two samples weighing 15 pounds. The soil samples are tested for pulverization after curing for 5 to 20 days by adding water as required to keep the moisture content to a saturated level. The samples are dried until the moisture content is below optimum and pulverized until 100% passes ½-in. sieve and at least 60% passes No. 4 sieve. The samples are tested for CBR and moisture-density relationship.

Class C

An approximately 60 pounds of the sample is air dried and pulverized until 100% passes ½ in. sieve and at least 60% passes No. 4 sieve. Three soils samples weighing 15 pounds are selected and corrected for hygroscopic moisture to test for CBR and one soil sample weighing 8 pounds is corrected for hygroscopic moisture to test for moisture-density relationship (MT-9). An estimated percentage lime by dry weight of sample is added to the sample weighing 8 pounds and one sample weighing 15 pounds; one percent above the estimated lime content and one percent below the estimated lime content are added for the other two samples weighing 15 pounds. The samples are then tested for CBR and moisture-density relationship.

Construction

Subgrade Preparation. The underlying foundation is graded and shaped to the specified lines, grades, and cross section. The foundation is dried to optimum moisture content as per Mississippi Test MT-8 (modified AASHTO T-99). The subgrade material is compacted to a uniform density; the specified value (SV) tested as per Mississippi Test MT-10 or MT-16 (modified AASHTO T-91) shall be 98% and soft materials, if present are either stabilized or disposed of. Each layer of materials to be treated are scarified and pulverized to the necessary depth and all detrimental materials are removed from the soil. The rocks and boulders are either removed or broken off to a depth not less than 8 in. below the subgrade elevation. Each section of the prepared subgrade shall not be less than 500 ft. and the material shall be maintained in a smooth and compacted condition.

Lime Application. The lime may be applied in dry as well as slurry form, as per requirement and approval from Engineer. The quicklime is applied at a same rate as hydrated lime if it is used in a dry form. When lime is applied in dry form, as approved spreader shall be used to spread the lime uniformly over the scarified surface. The dusting is controlled by sprinkling water while spreading the lime. Lime is not applied in dry form under unfavorable wind conditions that would blow away the material. The dispersion of lime dust measured at a distance of 100 ft. shall not exceed a rate of 30,000 $\mu g/^{m3}$. When lime is applied as a slurry, the slurry must be in suspension throughout the application and uniformly applied as a thin water suspension or slurry making successive passes over the area to be stabilized until the specified lime content is obtained; the dry solid content of lime slurry shall be at least 30% by weight. The moisture content is raised to optimum or more than optimum plus 20% of the optimum by adding sufficient quantity of water. The lime is incorporated into soil after each pass and if needed water is added to accelerate the mellowing operation. Additional lime has to be applied before mixing, if the initial quantity of lime applied is observed to be deficient by more than the allowable minus tolerance. The application process for subgrade stabilization is suspended when air temperature is below 40°F. Lime should not be applied when the ground is frozen and under adverse wind condition that would blow away the material. The construction shall be started and completed between the months of March and October.

Mixing. For class A or class B lime treatment, the moisture content of the material is maintained as specified during mixing; if necessary, water is added to sustain the chemical reaction between lime and water. The mixing operation is considered complete when a homogenous mixture of the lime treated material passes through a 3 in. sieve. The treated course is reshaped to the approximate line, grade and typical section, sealed with light, pneumatic-tired roller and allowed to mellow for 5 to 20 days as furnished by the MDOT Central Laboratory or other approved laboratory. The mellowing period is measured in degree days; the average of the high and low temperatures of each day of mellowing period is used to determine the degree days of the mellowing period. However, if the average temperature is 40°F or less, the day will not be used to compute the degree days mellowing period. The layer is then scarified and another application of lime is added (for Class A only). Mixing is continued until 100% of the material by dry weight passes a one in. sieve and 60% passes a No. 4 sieve, such that the moisture content is at or above the laboratory specified optimum moisture. The surface of the layer is sealed with a rubber-tired roller if mixing cannot be completed in one day. For class C treatment, the lime and water is mixed uniformly in a rotary mixture until a homogeneous mixture of soil, lime and water is obtained. It is ensured that 100% of the material by dry weight, exclusive of aggregates passes a 1 in. sieve and 60% by weight passes a No. 4 sieve. The moisture content of the material is brought to the department specified moisture content after the mixing operations to obtain an acceptable density for compaction. The compaction is commenced immediately after completion of the moist mixing without allowing material to mellow.

Compaction. The material is compacted such that the moisture content is maintained at the specified level to obtain the required density. It is recommended to start the compaction process early as possible after final mixing and the whole process shall be completed within one working day. The material is compacted uniformly throughout the treated area until the entire depth is compacted to a specified density. The soft spots, depressions, and defective areas, if observed, are either removed, treated with lime or reshaped and compacted in accordance with the specifications. The acceptance criteria of compaction is tested at each lot of 2,500 ft. per layer measured longitudinally. Each lot of 2,500 ft. shall contain 5 equal sub-lots. The average density measured at these points shall not be less than 95% of maximum density with no single density test below 91%; the sub-lots with density below 91% is corrected as specified.

Finishing, Curing, and Protection. After compaction, the compacted layer is brought to line, grade, and cross-section as specified in the plan. The surface requirement shall be as specified in sub article S-304.08.1 (*Table 8, Table 9, and Table 10*). The surface is protected against rapid drying and cured for 7 days by sprinkling water frequently, unless covered by subsequent layers of pavement. The treated section may be opened to traffic after 7 days of curing period. The first layer shall be compacted to a minimum thickness of 4 in. of a layer of granular material is being placed over it. In case a bituminous curing seal is placed over the lime treated layer, the placement of subsequent layer may be deferred to 21 days after the curing seal is placed. The curing seal is generally placed after 2 days of finishing. The seal shall be applied at a rate of 0.10 to 0.25 gallon per square yard and the emulsified asphalt shall be applied at the specified consistency without further dilution. The treated surface shall be re-stabilized if failure, tenderness or damage is observed after curing has been completed. The finished layer shall be cured and maintained in accordance with the provisions.

The required density from the individual tests and average of five tests shall be as presented in Table 32 and Table Table 33. The vertical tolerance allowed in grade after finishing is presented in Table 34.

Table 32
Density requirements

Granular Material (Class)	Lot Average	Individual Test
7,8,9 or 10	97	93
5 or 6	99	95
3 or 4	100	96
1 or 2	102	98
Crushed Stone Courses	99	95

Table 33
Density requirements for top course (when pavement is not required)

Granular Material (Class)	Lot Average	Individual Test
10	94	90
7,8 or 9	95	91
5 or 6	96	92
3 or 4	97	93
1 or 2	98	94
Crushed Stone Courses	96	92

Table 34
Tolerances from design guide

Where the subbase is not to be treated in place	± 1/2
Where the subbase is to be either mechanically stabilized or treated before stabilization or treatment	± 1
After Treatment In.	± 1/2

Missouri

Use of Lime in Road Applications

Lime is used to modify the subgrade soil to improve stability. The base layer is treated with lime to stabilize subgrade or base materials and provide a working platform and/or pavement structure. The layer is stabilized to a minimum thickness of 6 in.

Type of Lime

Lime used for soil modification and soil stabilization shall be hydrated lime that confirms to the requirements of AASHTO M 216 and shall be free of moisture before use in road applications.

Construction

Lime Application and Mixing. Lime modified subgrades are generally constructed in lifts with one lift not exceeding six centimeters. Dry lime is spread and dispersed uniformly on the prepared subgrade at a rate not less than 15 lbs. /yd^2 and not more than 26 lbs. /yd^2 per 6 in. for the depth modified. The modification is performed in all areas between outside shoulder points plus 18 in. on each side. A longitudinal transition zone at a rate of 30 ft. per 6 in. of the modified depth shall be established when the application is stopped and started. After the application of lime, the lime is mixed uniformly and thoroughly using disc harrow, rotatory mixtures, or other equipment approved by the engineer.

Compaction. The material is compacted uniformly throughout the treated area using a compaction roller. The density and optimum moisture of the compacted specimen shall be according to the specification.

Montana

Use of Lime in Road Applications

Lime is primarily used to strengthen subgrade soil. The formation of cementitious silicates and aluminates due to the pozzolanic reaction between soil and lime enhance the subgrade stability and strength. Lime is also used to increase swelling potential of high sulfate soils.

Soil Type for Lime Application

Soil stabilization with lime is conducted mostly on granular materials, lean clays, and soils with high sulfate content. A-6 and A-7 soils are primarily taken into consideration for stabilization.

Construction

Lime Application. Lime is spread and dispersed uniformly on the scarified subgrade with cyclone, screw-type, or pressure manifold type distributor. The distribution is limited to an area that can be integrated and mixed on a working day. The application process is suspended when air temperature is below 45°F measured 4 in. below the surface and under adverse wind conditions that would blow away the material.

Mixing. Immediately after the application, a rotary mixer is used to mix the lime uniformly and thoroughly in soil to mixture to obtain a homogenous layer of desired thickness, usually 9 in. to 16 in.

Compaction. The compaction process is commenced within 24 hours of mixing. The material is compacted such that the moisture content is maintained at the specified optimum level or up to two percent over the optimum. The finished layer is open to traffic not before 72 hours after compaction.

North Carolina

Use of Lime in Road Applications

Lime and water are added in controlled amounts to the soils that are compatible for stabilization to construct a satisfactory subgrade for pavement structure.

Construction

Subgrade Preparation. The surface of the roadbed is approximately graded and shaped to the specified lines, grades, and cross section. Prior to the lime application, the roadbed is scarified using approved equipment and partially pulverized to the required depth of stabilization by making one pass using a rotary mixer. The unstable or soft materials below the required depth is either removed or replaced with a suitable material so that uniform stability is established throughout. Necessary precautions should be implemented to drain the roadbed and keep it dry.

Lime Application. Lime is spread and dispersed uniformly on the prepared subgrade such that the grade of the roadbed is not raised above the specified grade after application; it is recommended to range the subgrade from ¼ in. to ½ in. below the design elevation. The distribution is limited to an area that can be integrated and mixed on a working day.

Mixing. The lime is mixed uniformly and thoroughly over the entire area such that the moisture content of the mix raises above the optimum moisture content with a tolerance of 3% above the optimum. The size of the soil colds broken down shall not be greater than 2-in. The material is frequently sprinkled with water such that the lime is properly slaked to avoid rutting of the pavement. After the initial mixing is completed, the surface is rolled with and shaped to appropriate grade and compacted lightly to protect against rain and excessive drying. The mixture is allowed to mellow for a 1 to 4 days to allow the breaking down of clay clods. The soil is then remixed using approved equipment until the lime is distributed homogeneously and uniformly over the entire area and the solid colds broken down are no larger than ½ in. At least 80% of the colds by dry weight, excluding rocks shall pass the No. 4 sieve after final mixing and pulverization.

Compaction and Finishing. The material is compacted uniformly throughout the treated area in one lift using a pneumatic roller of sufficient weight. The density and optimum moisture of the compacted specimen shall be according to the specification. The thickness of the lime-stabilized layer is determined, at intervals not to exceed 500 ft. The measured thickness shall not vary by plus 1or by minus 1 in., from the thickness shown on the plans. Standard specifications for corrective measures shall be followed if the measured thickness is not in agreement with the thickness specified in plan. After the compaction operations, the treated soil is covered with bituminous curing coat for a minimum of seven days, prevented from freezing, and sealed before placing subsequent layer.

North Dakota

Use of Lime in Road Applications

Lime is utilized to stabilize the top layer of subgrade.

Type of Lime

Hydrated lime that meets the requirements of AASHTO M 216 shall be used to stabilize the subgrade.

Construction

Subgrade Preparation. The underlying foundation is graded and shaped to the specified grades and cross section as shown on the plans. As per the requirement, the roadbed material shall be scarified to the depths of 6 in., 12 in., 18 in., 24 in., or more. As lime is applied in lifts, bottom 6 in. of the subgrade is scarified and placed on roadway. All the undesirable, soft and weak materials are cleared away, replaced, or stabilized as directed by project engineer.

Lime Application. When lime is applied in dry form, an approved spreader shall be used to spread the lime uniformly over the scarified surface. Application shall be postponed when the wind speed is 15 mph or greater that would blow away the material. When lime is applied as a slurry, the slurry must be kept in suspension throughout the application and uniformly applied making successive passes over the area to be stabilized until the specified lime content is obtained; the dry solid content of lime slurry shall be at least 30% by weight. Pressurized spray bars are used to apply lime as a slurry and the percentage of dry solid colds in the mixture is determined using a metering device attached to each of the distribution unit.

Each load or partial load that is applied is measured and converted to weight, and the dry solid colds are based on the percentage of lime in the slurry to control lime application. Lime should not be applied and/or mixed when the ground is frozen and under adverse wind condition that would blow away the material. The construction shall be started in the spring and shall be completed before the start of October.

Mixing. The lime is mixed uniformly and thoroughly over the entire area using an approved rotary mixture. Lime is mixed until the mixture attains the proper moisture content, not less than optimum and until 100% of the colds broken down pass one in. sieve. The mixture is allowed to mellow for a period of 1 to 2 days.

Compaction and Finishing. The material is compacted such that the moisture content and density of the mixture are maintained at the specified level. It is recommended to start the compaction process early as possible after final mixing. The material is compacted uniformly throughout the treated area until the entire depth of stabilization is compacted to the specified density. The rocks, roots, or other undesirable materials if observed are disposed of in accordance with the specifications. Any soft spots, depressions, and defective areas that do not meet the stability criteria are either removed, or replaced with approved material. Immediately after compaction and finishing, the surface is protected against rapid drying by sprinkling water frequently until the application of bituminous coat.

Ohio

Use of Lime in Road Applications

Lime is primarily used to modify and stabilize the existing subgrade soil by treating the unstable subgrades consisting of A-6b (silty/clay) or A-7-6 (clay) soils having a plasticity index of 20 or higher.

Soil Type for Lime Application

Lime-stabilization is performed on A-6b (silty/clay) or A-7-6 (clay) soils having a plasticity index of 20 or higher and more than 25% passing No. 200 sieve.

Type of Lime

Quicklime (Calcium and Magnesium oxides) or hydrated lime (Calcium and Magnesium hydroxides) that is approved as a qualified product may be applied to stabilize the subgrade soil. Quicklime shall contain about 90% of total oxides (calcium and magnesium).

Lime Content

ASTM D 6276 (the Eades and Grim test) is performed to determine the lime content for soil stabilization. The lowest percent lime that gives a pH of 12.4 is the required percent lime to stabilize the soil as illustrated in Figure 23. Optimum moisture content and unconfined compressive strength are evaluated in accordance to ASTM D 698 and ASTM D 5102 respectively. Compressive strength test is performed to determine the lime content for soil modification and soil stabilization, if specified in the contract documents. Compressive strength test is performed on one soil sample per 5000 cubic yards (one per major type of soil), or a minimum of three soil samples per project, whichever is greater, to determine the lime percentage. Three soil samples for each percentage of lime are prepared at optimum moisture content in accordance to ASTM D 5102 and cured for 5 days. The lime percentage which yields the highest compressive strength is recommended as the required lime content.

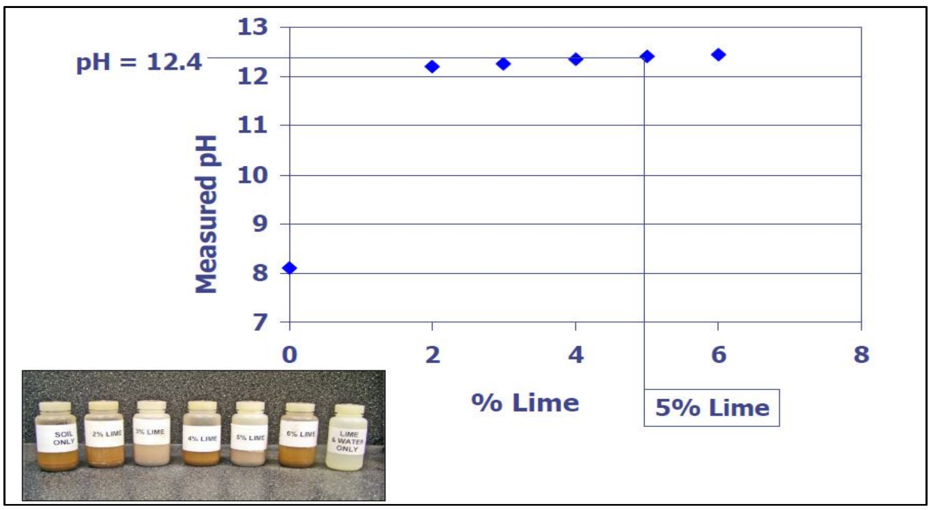


Figure 23
ASTM D 6276 (Eads – Grim Test)

Construction

Subgrade Preparation. The underlying subgrade soil is graded and shaped approximately to the specified lines, grades, and cross-section to meet the thickness requirement.

Lime Application. If not specified, lime is generally spread at a rate of 5% using a mechanical spreader. The rate of lime spreading is based on the dry density for soil of 110 pounds per cubic ft. When lime is applied in dry form, approved spreader shall be used to spread the lime uniformly over the scarified surface. The dusting is controlled by sprinkling water while spreading the lime. Lime is not applied in dry form under unfavorable wind conditions that would blow away the material. When lime is applied as a slurry, the slurry must be in suspension throughout the application and uniformly applied over the area to be stabilized until the specified lime content is obtained. The slurry application of lime shall be completed within 24 hours of spreading with re-agitation of the slurry every 8 hours of undisturbed storage. The application process for subgrade stabilization is suspended when air temperature is below 40°F. Lime should not be applied when the ground is frozen and under adverse wind condition that would blow away the material.

Mixing. When the lime is to be applied as a slurry, the material is scarified and partially pulverized to the required depth using a spring tooth or disc harrow before application. The lime is mixed uniformly and thoroughly by making successive passes over the entire area using an approved rotatory mixture. The moisture content of the mix is brought to optimum moisture content for hydrated lime and 3% above the optimum moisture content for quick lime, by spreading enough water. The size of the soil colds broken down shall not be greater than 2-in. After the initial mixing is completed, the surface is rolled with pneumatic tire to protect against rain and excessive drying. The mixture is allowed to mellow for a 2 to 7 days. The soil is then remixed using approved power-driven rotary-type equipment until the lime is homogeneously and uniformly distributed to the required depth. At least 60% of the colds by dry weight shall pass the No. 4 sieve after final mixing and pulverization. It must be ensured that the moisture in the mixture does not vary from the specified. The uniformity of the mixture is tested using diluted hydrochloric acid or phenolphthalein. The colors of the chemicals are inspected to ensure the proper mixing of lime to required depth.

Compaction. The mixture is sprinkled and rolled simultaneously using a vibratory footed roller weighing at least 10 tons to establish a uniform compaction and stability throughout. It is recommended to start the compaction process no more than 30 minutes after final mixing. The mixture is compacted using density control to 98% of the maximum dry density. The maximum dry density is determined using Ohio typical moisture density curves, the moisture density curves, or maximum dry density obtained from the test section method.

The completed section is finally rolled with smooth drum roller. Fine grading of the completed section is performed either before curing or after curing; in case the fine grading is performed before curing, the mixing, compaction and shaping shall be performed in the same day, and if the fine grading is performed after curing, the subgrade is shaped approximately 1 in. above the grade.

Curing. After the compaction operations, the treated soil is covered with curing coat. The emulsion coat is applied uniformly to the surface at the rate of 1 gallon per 30 ft. and curing is completed prior to drying of the surface; if the curing is delayed and the surface starts to dry, water shall be spread for temporary curing until the curing coat can be applied. The completed section is finally proof-rolled with light roller, the treated subgrade is sufficiently cured, prevented from freezing, and sealed before placing subsequent layer.

Oklahoma

Use of Lime in Road Applications

The Oklahoma Department of Transportation employs lime to modify and stabilize the subgrade soil. Lime is utilized to change the PI of the soil, improve the overall workability as a platform to support construction equipment, increase the strength of subgrade soil, and provide structural value that reduces the overall thickness of the pavement.

Soil Type for Lime Application

The lime application is performed if the sulfate content is within the threshold value specified in Department's Materials Division test methods OHD L-49, OHD L-50, and OHD L-51. The sulfate content is determined in accordance to OHD L-49 and the applicability of lime is determined in accordance to OHD L-50 and OHD L-51.

Type of Lime

The lime for soil stabilization shall be quicklime or hydrated lime that meets the requirements of AASHTHO M 216. The available lime index, expressed as $Ca(OH)_2$ for hydrated lime and as CaO for quicklime is required to be at least 90% as per ASTM C 25. By-product lime is not allowed for any kind of lime application.

Construction

Subgrade Preparation. The surface of the roadbed is approximately graded and shaped to the specified dimensions and elevations as shown on plans or as directed by Engineer. Prior to pulverization, the roadbed is proof rolled and soft spots are corrected as specified. The roadbed is then scarified and partially pulverized to the required depth of stabilization such that the surface of roadbed below scarified material is undisturbed. If at least 25% of materials with a dimension greater than 2-1/2 are encountered during exploratory scarification, the Engineer may waive some portions of the work.

Lime Application. The lime content as determined from the mix design is uniformly applied over the entire area. Construction is not allowed if the ambient air temperature taken in the shade is below 35ºF and under unfavorable weather conditions that would blow away the materials. If lime is applied as a dry placement, the lime is spread with an equipment approved by the department with frequent sprinkling of water; under unusual circumstances and when normal application is impractical, bagged hydrated lime is used for dry application of hydrated lime. When lime is applied as a slurry, the slurry is kept in suspension throughout the application either in central plant or in transit mix. The slurry distributor truck in central plant and the tank transit mix truck mix are equipped with a recirculating pump or agitator that keeps the mixture in continuous agitation during transport. The lime slurry is applied through spray bars in a distributor truck with pump. The pressure in the truck is maintained such that the flow and distribution is uniform throughout the process. The slurry in the mixture shall contain at least 1 ton of lime to 500 gallon of water with a maximum of 40% lime. The application process for subgrade stabilization is suspended when air temperature is below 40°F, while if lime is added to modify the subgrade soil, the process is halted for a temperature below 33°C. Lime should not be applied when the ground is frozen and under adverse wind condition that would blow away the material.

Mixing. A pulver mixer equipped with a spray bar in mixing chamber and capable of maintaining the moisture content at specified range is used to mix the lime uniformly and thoroughly in soil immediately after lime application. The moisture content of the mix is increased from 2% to 5% above the optimum by spreading enough water. The density and optimum moisture content of the compacted soil-additive mixture before field mixing is determined as per AASHTO T 99. Soil, lime and water are mixed uniformly such that the diameter of the mix is not greater than 1- ½ in. The moisture content of the materials during mixing should be adequate enough to ensure proper chemical reaction between lime and subgrade. After the initial mixing is completed the surface is rolled with pneumatic tire and allowed to cure for 72 hours above 40°C if hydrated lime is used and 48 hours above 40°C if quicklime is used. For application of quicklime, a significant portion of quick lime is turned within 2 hour of spreading and before addition of water using department approved equipment. Mixing is commenced within six hours of application and is completed during the same working day. The soil is then remixed until the quicklime is homogeneously and uniformly distributed to at least 8 in. of compacted thickness. All the lime particles shall be hydrated completely after final mixing. The mixed material gradation must be within the percentage passing limits for the sieve sizes as shown in Table 35.

Table 35
Soil-additive mixture gradation

Sieve sizes	Percentage Passing
1 ½ in.	100
No. 4	60 minimum

Compaction and Finishing. The mixture is sprinkled and rolled simultaneously. All irregularities, depressions, and soft materials are either removed or stabilized with lime so that uniform compaction and stability is established throughout. It is recommended to start the compaction process early as possible after final mixing. The mixture is compacted using density control to at least 95% of the maximum density determined in accordance to AASHTO T 310. The moisture content shall be maintained at a moisture content 2 percentage points of optimum with frequent sprinkling of water and irregularities shall be removed by sufficient blading.

After the compaction is completed, the compacted layer is brought to line, grade and typical cross section as specified in the plan. After the completed section is finally rolled with light roller, the treated subgrade is frequently sprinkled with water until placing a prime coat seal or subsequent layer. The subgrade is allowed to cure for sufficient time if deformation is observed under construction loads or for deflection of more than 1 in.

Quality Assurance. After finishing, a color-sensitive indicator (phenolphthalein or thymol blue) is applied along the side of a small hole excavated to the required depth of chemical treatment to measure the thickness and uniformity of the compacted soil and the mixture. The thickness measurement is obtained at intervals not exceeding 1,000ft in each driving lane. The Engineer will use the plan thickness plus ½ in. if the individual measurements exceed the plan thickness by ½ in. If the individual measurements are observed to be less by ½ in. than the plan thickness, then the material has to be reworked to correct the thickness. The elevation of the finished subgrade is required to be within ½ in. of the elevation as shown in plans. The smoothness of the finished layer as measured by placing a 10 ft. straightedge between any two contacts on finished layer shall be within ½ in. in 10 ft.

Oregon

Use of Lime in Road Applications

The top layer of subgrade is treated with lime to improve stability. The layer is treated with water and lime to form a stabilized course of material to the specified locations and to the line, grades, thicknesses, and cross section as directed.

Type of Lime

Quicklime or hydrated lime meeting the requirements as presented in Table 36 may be applied to stabilize the subgrade soil.

Table 36
Requirements for lime

Material	Type	Requirements
Hydrated Lime	AASHTO M 216, Type 1	Grade A
Granular Quicklime (CaO)	AASHTO T 27 and AASHTO T 219 (grading and hydroxide content)	100% passing 3/8 in. sieve 15% max. passing No. 100 sieve min. 85% Calcium Hydroxide

Construction

Subgrade Preparation. The depressions and ruts containing water are drained and all the underground works are completed before the addition of stabilizing material.

Lime Application. The lime content as determined from the mix design is applied with the equipment and methods that will distribute lime uniformly over the entire area. Blade grades are not allowed to distribute lime. Any equipment other than the equipment to apply lime, sprinkle water, and mix the lime to pass over the material until it is mixed with the soil are not allowed during lime application.

Mixing. The lime and soil are mixed until 100% of the material by dry weight, exclusive of aggregates passes a 1 in. sieve. The tolerance of 1 in. is allowed in gradation.

Compaction and Finishing. The material is compacted uniformly throughout the treated area until the entire depth is compacted to a specified density. The mixed material is proof-rolled with a fully loaded 10 to 12 cubic yard dump truck 24 hours prior to placing subsequent layer. The deflection of the subgrade shall not be more than ¼ in. after proof-rolling. The subgrade is excavated to a depth of 12 in. or more to place fabric. It is then backfilled and compacted to the subgrade elevation with a single lift of 1 ½ -0 in. crushed rock. The density of the top 6 in. of compacted material shall meet the required specification. This area is proof-rolled until the subgrade deflects to a depth of no more than ¼ in. The compacted layer is brought to line, grade and typical cross section as specified in the plan. Compaction and finishing is completed within 12 hours maintaining the mixture at proper grade, cross section, density and moisture content. The surface is protected against rapid drying and cured for 7 days by sprinkling water frequently, or until covered by subsequent layers of pavement. If the thickness is observed to be less by ½ in. than the plan thickness, then the material has to be reworked to correct the thickness by adding 50% of stabilizing material. The smoothness of the finished layer as measured by placing a 12 ft. straightedge between any two contacts on finished layer shall be within ½ in. in 12 ft.

Saskatchewan

Construction

Subgrade Preparation. All the undesirable materials, such as frozen soil, roots, organic material, trees, moss, and other unsuitable materials, are cleared away and the surface of the existing subgrade is approximately graded and shaped to the specified dimensions and elevations as shown on plans or as directed by Engineer. Any structures such as temporary ramps, bridges, and culverts adjacent to the existing pavement shall be backfilled to a depth necessary to provide the required thickness of the pavement. Rock fragments with diameter 8 centimeter or more measured in any direction shall be excluded from top 15cm of the subgrade. The subgrade shall be worked accordingly if the density requirement is specified. The subgrade material is pulverized until the soil is reduced to a dimension not exceeding five centimeters measured in any direction.

Lime Application and Mixing. Lime modified subgrades are generally constructed in lifts with one lift not exceeding fifteen centimeters. The lime may be applied in dry as well as slurry form at a rate as determined by laboratory design or as designated by the Engineer, with a tolerance of ±1/2 of 1%. Lime should not be applied when the ground is frozen and under adverse wind condition (with velocity greater than 25 km/hr.) or higher that would blow away the material. Immediately after the application of lime, the lime is mixed uniformly and thoroughly using mechanical mixers with rotary action. The moisture content of the mix is brought to 2% above the optimum (as determined by Test 9200) by spreading enough water. During mixing the surface is rolled with at least 2 passes of the mixing equipment including one dry-mix pass. The mixing can be performed either on one-half width of the road or on full width of the road depending upon the traffic.

Compaction. All irregularities, depressions, and soft materials are either removed or stabilized with lime so that uniform compaction and stability is established throughout. The top 15 centimeters of the mixture is compacted using density control to 100% of the maximum density determined in accordance with Test 9200. The compaction is considered satisfactory when the average density of the finished subgrade is 100% with individual test results not less than 95% of maximum density. The moisture content of the subgrade shall be maintained as specified with frequent sprinkling of water; the top 15 centimeters of the subgrade is dried if excess moisture is observed in the soil. The irregularities of the subgrade not greater than fifteen centimeters above designated grade shall be removed by sufficient blading. After the compaction is completed, the compacted layer is brought to line, grade, and cross-section as specified in the plan. A pneumatic tire roller is used for final rolling of the completed surface.

Tennessee

Use of Lime in Road Applications

Tennessee employs lime for soil stabilization. The soil stabilization consists of uniform mixing of in-place subgrade material and lime. The mixture is moistened, compacted and cured in accordance with the specification and to the line, grades, and cross section as specified.

Soil Type for Lime Application

The in-place soil subgrade material that is uniform in quality and gradation is used for lime treatment. The soil unsuitable for stabilization is removed and replaced. Laboratory testing is performed for in-place soil sample according to AASHTO T 99 to determine the lime content and appropriate moisture content of the lime-soil mixture.

Type of Lime

The lime employed for subgrade stabilization shall be quick lime or hydrated lime that confirms the requirements of ASTM C 977 specifications.

Construction

Subgrade Preparation. The existing roadway is graded and shaped to the specified lines, grades and cross section. The foundation is dried, compacted to a uniform density and soft materials, if present are stabilized to provide uniform stability. All detrimental materials near the construction area are removed and disposed of from the soil. The roadbed, if required, is stabilized to an extra depth by incorporating with lime slurry, or with dry hydrated lime and water at a specified rate to a specified depth. Before lime application the existing overlying material is bladed to the sides. Required stability is obtained by thoroughly mixing and compacting the soil lime mixture. The compacted material is moistened and re-compacted after re-placing the previously bladed overlying material.

Lime Application. The lime may be applied in dry as well as slurry form as per requirement and approval from Engineer. When lime is applied in dry form, the hydrated lime is spread uniformly over the scarified surface using an approved spreader or by bag distribution. When lime is applied as a slurry, lime is mixed with water in an agitating equipment and the slurry is kept in suspension throughout the application and uniformly applied over the area to be stabilized until the specified lime content is obtained; the dry solid content of lime slurry shall be at least 30% by weight.

Mixing. Immediately after the application of dry lime, the material is scarified and mixed to required depth, width, and cross section. When the lime is applied as a slurry, the material is scarified and partially pulverized to required depth and the lime is mixed uniformly and thoroughly by making successive passes over the entire area using appropriate mixing equipment. The moisture content of the mix is brought to 5% above the optimum moisture content, plus or minus 3%, by spreading enough water. After the initial mixing is completed, the surface is rolled with pneumatic tire and allowed to mellow for a 2 to 7 days. The soil is then remixed until the lime is homogeneously and uniformly distributed to the required depth and the material is brought to the required lines, grade, and cross-sections. All the lime particles shall be hydrated completely after final mixing. 100% of the soil colds that are broken down, excluding the rock particles shall pass a 1-in. screen and at least 60% by dry weight shall pass the No. 4 sieve. It must be ensured that the moisture in the mixture and unpulverized soil lumps does not vary more than plus or minus 3% from the specified moisture content.

Compaction, Finishing, and Curing. Before the commencement of the compaction process, the material is bladed to uniform thickness and shape. It is recommended to start the compaction process early as possible after final mixing. The material is compacted uniformly throughout the treated area until the entire depth is compacted to a specified density. The density and optimum moisture of the compacted specimen is tested in accordance to AASHTO T 99. The acceptance criteria of compaction is tested at 5 spots on each lot of 10,000 square yards. The average density measured at these points shall not be less than 95% of maximum density with no single density test below 92%; the spots with density below 92% is corrected as specified. After the compaction is completed, the compacted layer is brought to line, grade and typical cross section as specified in the plan. Final rolling of the completed surface is performed with the roller as specified by the engineer. The compacted surface is sealed uniformly with a bituminous material using a pressure distributor at the rate of 0.10 to 0.25 gallons per square yard. The thickness of the lime-stabilized layer is determined, at intervals not to exceed 500 ft. The section is reconstructed if the thickness is observed to vary by plus 1-1/2 or by minus 1 in, from the thickness shown on the plans. Additional lime is added and the material is remixed to the specified depth and width to correct the deficiency of any section exceeding the tolerance.

Texas

Use of Lime in Road Applications

Lime is used to modify and stabilize subgrade soils and base materials in Texas. For consistent soil modification and stabilization, three steps are followed: *(1)* soil exploration material sampling and classification; *(2)* additive selection; and *(3)* mix design. As a rule of thumb, at least ten 50lbs. of soil is needed to study the effect of soil mineralogy, water table proximity, and soil variation.

Soil Type for Lime Application

The additive for lime treatment is selected based on soil mineralogy, classification, design life, prevalent environmental conditions, desired engineering properties, and mechanisms of stabilization. For both subgrade and base, the additive selection is based on the Plasticity Index (PI) and the percentage passing No. 200 Sieve. The decision tree for additive selection as derived from the studies by Currin et al. (1976), Smith and Epps (1975), and Little et al. (1995) is presented in Figure 24 and Figure 25 *[1 – 3]*.

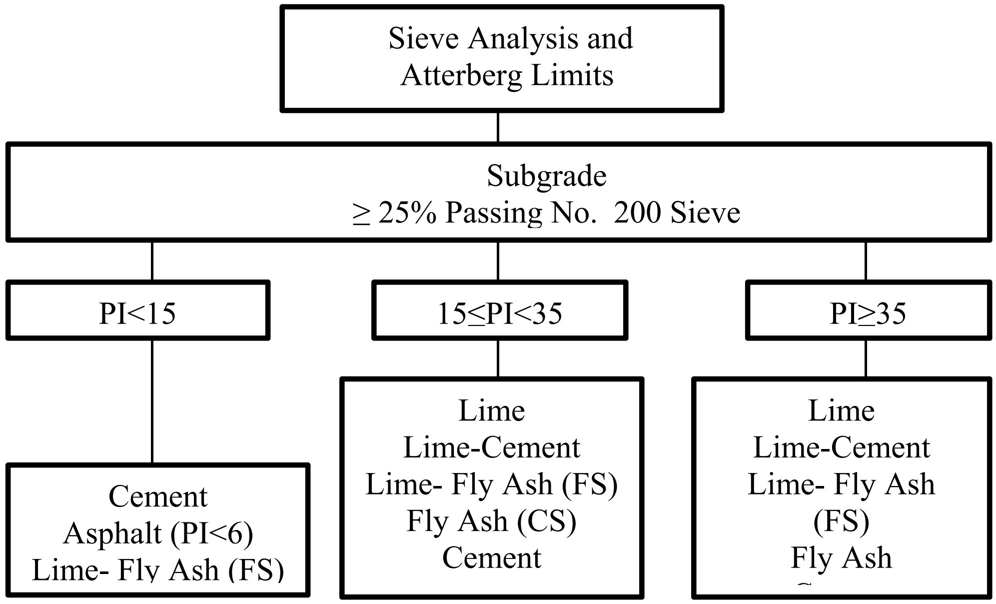


Figure 24
Additive selection for subgrade soils using soil classification

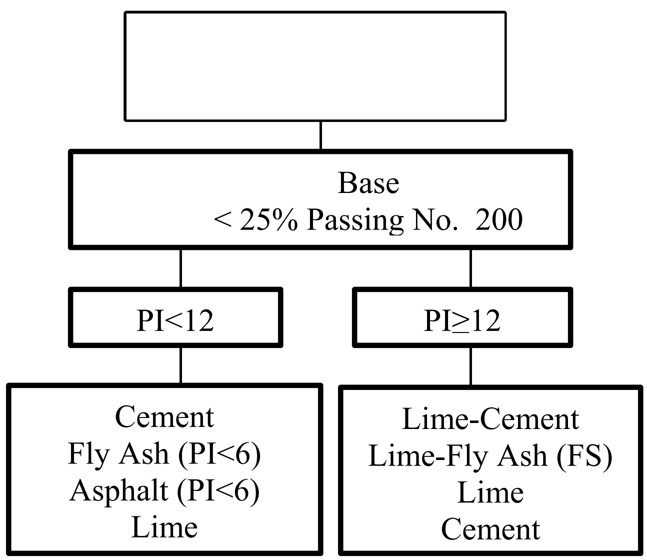


Figure 25
Additive selection for base materials using soil classification

Type of Lime

Hydrated lime, commercial lime slurry, quicklime, and carbide lime slurry may be used in road applications. Quicklime is not recommended to use for soil with sulfate content greater than 3,000 ppm and the construction is suspended if the observed sulfate content is greater than 7,000 ppm or if the organic content is greater than 1%. For soil with sulfate content greater than 3,000 ppm and less than 7,000 ppm, the mixture should be allowed to mellow for a minimum of seven days. The target lime content and optimum moisture content as determined by the department and the contractor are verified before acceptance. Closed and weatherproof containers should be used to store quicklime and dry hydrated lime. Further, slurry tanks equipped with agitation devices should be used for quicklime or slurry hydrated lime. A distribution truck with sampling devices must be provided when using commercial lime slurry or carbide lime slurry and an equipment with rotary vane feeder must be provided for uniform spread of lime throughout the construction area.

Lime Content

Various soil tests such as sulfate and organic testing, moisture/density relationship, pH, plasticity content and strength testing are specified during the mix design. The sulfate concentration in soil is determined from the colorimetric method using the turbidimetric technique in accordance to Tex-145-E and the organic content is determined by the loss-on-ignition (ASTM D 2947) test. For soil with more than 1% organic content, additional additive is recommended to counter the cationic exchange capacity of the organic material. To determine the lime content, pH of various samples is recorded and plotted against percent lime using Tex-121-E part III (Eades and Grim pH test). When required, the compressive strength test is performed in accordance to Tex-121-E part II. Tex-145-E and Tex-121-E parts II and III are briefly described hereunder.

Tex-121-E Part III

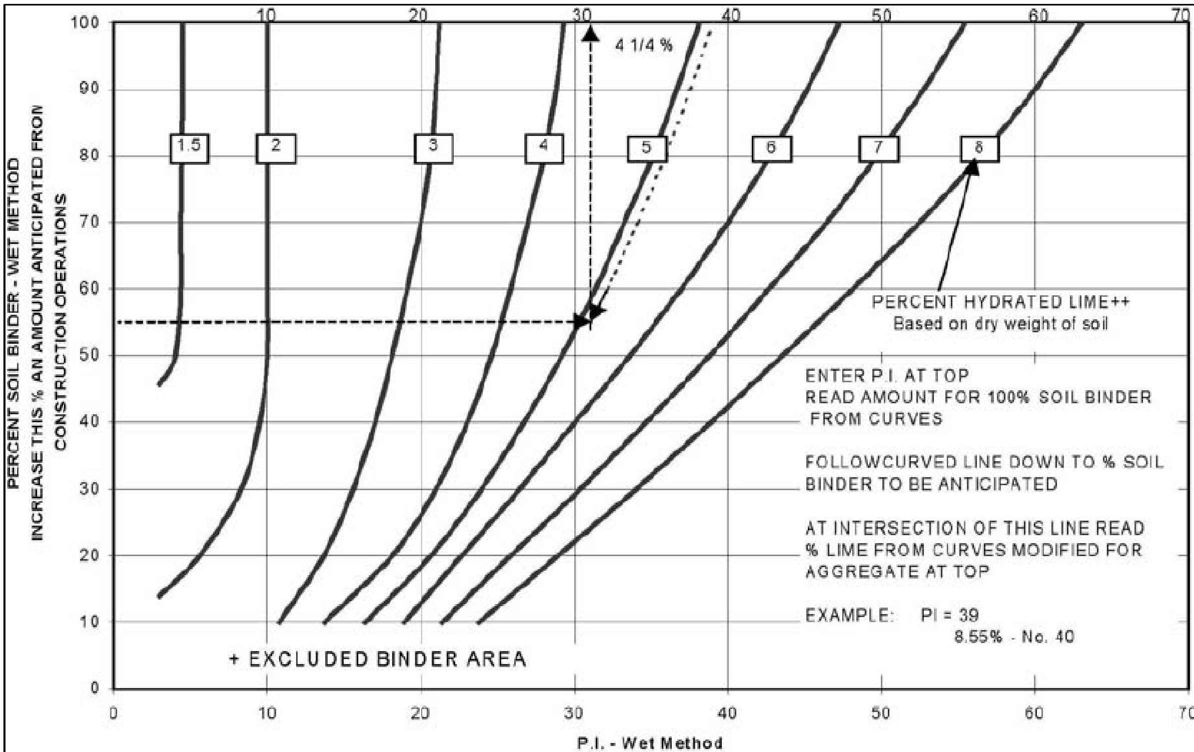
A 200 gram of soil sample (prepared using Tex-128-E) and approximately 1400 mL of distilled water are heated to 45–60°C in separate containers. One of the lime percentages along with 150 mL of distilled water are added and dissolved to 30 grams of separated samples. After one hour of dispersion of mixing, the pH meter is adjusted to the temperature of the mix and the meter is standardized for the test. The pH of each sample is obtained and plotted against the percent lime. Three conditions apply for the percent lime required to stabilize the soil, *(1)* for the soil samples with pH 12.4 or higher, the lowest percent lime that gives a pH of 12.4 is the required percent lime to stabilize the soil, *(2)* for the pH readings of 12.3, a lowest percent lime that gives the reading is the percent lime required for stabilization and, *(3)* if the highest percentage of lime corresponds to pH reading of 12.3 being the highest pH reading in all samples, addition testing is recommended using higher percent lime. The percent lime is reported to the nearest 0.1%. A similar procedure is followed to stabilize the base material except the additive is selected prior to material sampling and testing.

Tex-145-E

For field testing of sulfates, 10 grams of sample soil passing No. 40 (425µm) sieve is diluted with 200 mL (1:20 dilution ration) of distilled water and a filtrate of 10 mL is obtained after 12 hours of mixing for further testing. After the obtained sample is calibrated to zero, one sulfate test tablet is dissolved and dispersed throughout the sample. The sample is then placed in the test chamber to obtain the results; a minimum of three readings per sample is recommended. The average result is multiplied with dilution ratio to obtain the sulfate concentration in parts per million (ppm). Only the sulfate concentration from 100-4000 ppm is read by this test. If the error message as “The result is below the measuring range limit” is displayed, the sulfate concentration is reported to be less than 100 ppm while if the error message reads “The result exceeds the measuring range.”, the dilution ratio should be increased to 1:40, which modifies the sulfate concentration range (100-8000 ppm). If a similar error message is displayed again, the sulfate concentration is reported to be greater than 8,000 ppm. A similar procedure with different sample size (20 g) is followed for the laboratory testing of the sulfate concentration.

Tex-121-E Part II

Three wetted samples prepared with optimum moisture content and maximum dry density are let stand for at least 12 hours before compaction; the standing time may be reduced not less than three hours for samples with PI less than 12. The desired amount of lime is added uniformly and mixed thoroughly. The specimens are then compacted with a compaction effort of 13.26 ft.-lb./in.^{3} in a mold with 6 in. diameter, and 8 in. height. A mold with 4 in. diameter and 6 in. height may be used to determine moisture-density relationship of fine-graded materials with less than 20% retained on the ¼ in. sieve and 100% passing 3/8 in. sieve. The specimens are covered with top and bottom porous stones, placed in triaxial cells and allowed to cure in room temperature for seven days. The cells are removed and the specimens are placed in air dryer oven at a temperature not exceeding 140°F for about six hours or until 1/3 or ½ of the molding moisture has been removed. The specimens are then placed in triaxial cells with a constant lateral and surcharge pressure of 1 psi for ten days and tested for unconfined compression without a cell after ten days. The strength value are reported to a nearest whole psi, density to the nearest 0.1pcf, optimum moisture content to the nearest 0.1%. The test data are calculated, plotted and interpreted to determine the lime content. Recommended lime content are reported to the nearest 0.5%. This test determines the quality of soils treated with lime to be used for subbase or base protected with wearing surface; generally, 3% lime may be used to stabilize flexible base materials and granular soils and a larger amount of lime may be required for very plastic clay subgrade. The unconfined compressive strength of 150 psi is satisfactory for final course of base construction; the material with minimum of 50% passing No. 40 sieve is desirable for such courses. The recommended amount of lime content for subgrade soils and base materials can be determined from Figure 26.



\+ Exclude use of chart for materials with less than 10% minus 425um (No. 40) and cohesionless materials (PI less than 3).
++ Percent of relatively pure lime usually 90% or more of Ca and/or Mg hydroxides and 855 or more of which pass the 75um (No 200) sieve. Percentages shown are for stabilizing subgrades and base courses where lasting effects are desired. Satisfactory temporary results are sometimes obtained by the use of as little as ½ of above percentages. References to cementing strength is implied when such terms as "Lasting Effects" and "Temporary Results" are used.

Figure 26
Recommended amounts of lime for stabilization of subgrades and bases

Construction

Subgrade Preparation. The layer to be treated is constructed and graded maintaining the lines and grades specified in the plan. Prior to pulverization, the roadbed is proof rolled and soft spots are corrected as specified. The engineer is notified when the material is imported from the borrow source so that the borrow source can be tested for organic and sulfate content. Appropriate pulverization equipment is provided in order to uniformly cut and pulverize the material to proper depth, to provide a visible indication of depth, and to uniformly mix the materials such that 100% passes a 2-1/2 in. sieve. The material is excavated to the secondary grade (proposed depth of lime treatment) and is removed to expose the grade. The unstable or soft materials below this grade is either removed or stabilized with lime so that uniform stability is established throughout.

Lime Application and Mixing. The lime content as determined from the mix design is uniformly applied over the entire area. Construction is not allowed if the ambient air temperature taken in the shade is below 35ºF and under the weather conditions that are unfavorable for lime application. If the treatment is applied as a dry placement, the material is sprinkled and the moisture content of the prepared roadway is brought to approximately 2 percentage points above OMC. For slurry application of lime, the lime is mixed with water in a mixer or a truck and is applied through successive passes to secure the designed moisture and lime content. Mixing is commenced within six hours of application and is completed during the same working day. The moisture content of the prepared roadway during mellowing period of 1-4 days should be adequate enough to insure proper chemical reaction between lime and subgrade. Pebble grade quick lime is allowed to mellow for two to four days and a minimum of seven days of mellowing period is allowed for the material with sulfate content between 3,000 ppm to 7,000 ppm. After mixing, the soil is tested in accordance with Tex-101-E and should comply with the gradation requirements presented in Table 37.

Table 37
Gradation requirements

Sieve Size	Minimum % Passing
1-3/4 in. (45 mm)	100
3/4 in. (19 mm)	85
No. 4 (4.75 mm)	60

Compaction, Finishing, and Curing. Before compaction, each layer is sprinkled to adjust the moisture content so that it is no more than 1 percentage point below optimum and 2 percentage points above optimum as determined by Tex-121-E. In place compaction test is performed in accordance to Tex-115-E, after the layer has been rolled as specified. The mixture is compacted using density control to at least 95% of the maximum density determined in accordance to Tex-121-E; the section may be rejected if more than one of the five density tests are below the specified density and failing test is more than 3 pcf below the specified density. An additional lime content of 25% of the predetermined percent lime should be added if a section has to be reworked more than 72 hours after completion of compaction. After the compaction is completed, the compacted layer is brought to line and grade as specified in the plan to a depth of approximately ¼ in. and the finished grade is brought within 0.1 ft. in the cross-section and 0.1 ft. in 16 ft. measured longitudinally. The respective minimum curing days for subgrades with PI less than 35 and PI greater than 35 are two and five days, respectively. The additional course should be applied within 14 days of final compaction.

Virginia

Use of Lime in Road Applications

Lime is primarily used to stabilize the subgrade soil. Lime is expected to:

- reduce plasticity of soil
- provide cementation
- dry soil
- improve strength of soil

Soil Type for Lime Application

Lime-stabilization is primarily performed on fine-grained clays and silts, particularly heavy clays as it modifies the plasticity characteristics of the clay. Lime is not used for non-plastic soils such as sands and gravels; for the same amount of money spent, cement provides better strength in granular soils than lime.

Type of Lime

The lime for soil stabilization shall be quicklime or hydrated lime that meets the requirements of AASTHTO M 216.

Lime Content

Virginia test method 11 is used to determine the lime content to stabilize soils. The soil sample is air-dried at a temperature not over 140°F before performing mechanical analysis. Mechanical analysis (VTM-25), liquid limit test (VTM-7), and compaction test (VTM-1) are conducted on a portion of the sample. As lime affects the optimum moisture and maximum density of the lime-stabilized soil, 6% of hydrated lime by weight is added before the compaction test. The reminder of soil after the compaction test is screened over a No. 4 sieve and stored in air-tight cans to control the moisture. Two samples are prepared from the stored material with addition of two different percent of lime; usually 5% and 7% by weight. The molds are compacted and sealed in 3.8L gallon cans with water on the bottom for humidity.

The samples are cured in oven at 120°F for 3 days and tested for unconfined compressive strength at 2400 pounds per minute. The molds are broken down and re-tested to compare with raw soils, if the effect of lime on Atterberg limits has to be analyzed.

Construction

Subgrade Preparation. The surface of the roadbed is approximately graded and shaped to the specified lines, grades, and cross section. However, the roadbed is not required to be compacted to the depth of the material to be treated prior to lime application. The surface of the roadbed is required to meet certain specifications if the layer above it is to be stabilized. Any structures such as temporary ramps, bridges, culverts adjacent to the existing pavement shall be removed to a depth necessary to provide the required thickness of the pavement. Necessary precautions should be implemented to drain the roadbed and keep it dry. The roadbed is then scarified and partially pulverized to the required depth of stabilization such that the surface of roadbed below scarified material is undisturbed and comply with the cross-section of the plan. All the materials retained on a 3-in. sieve are removed before lime application.

Lime Application. The lime may be applied in dry as well as slurry form as per the condition and requirement. The quicklime is applied at a same rate as hydrated lime of it is used in a dry form. When lime is applied in dry form, approved spreader shall be used to spread the lime uniformly over the scarified surface. Lime is not applied in dry form under unfavorable wind conditions that would blow away the material. When lime is applied as a slurry, the slurry must be in suspension throughout the application and uniformly applied making successive passes over the area to be stabilized until the specified lime content is obtained; the dry solid content of lime slurry shall be at least 30% by weight. The moisture content is raised to optimum or more than optimum plus 20% of the optimum by adding sufficient quantity of water.

Mixing. A self-propelled rotary mixture shall be use to thoroughly mix lime and water by scarifying and blading uniformly over the scarified surface to a compacted depth of at least 12 in. The mixture is spread over the roadbed, sealed with a steel wheel or pneumatic tire roller, and allowed to mellow for 4 to 48 hours. The curing is considered complete if at least 60% of the lime treated material mixed with rotary mixture, excluding the rock particles pass No. 4 sieve. The material may be placed, compacted, and finished immediately after mixing if a stationary mixture is used, while additional mixing with blades, tillers, discs, harrows, or repeated passes of the plants may be required when travelling plants are used.

Compaction and Finishing. The mixture is compacted using density control to at least 95% of the maximum density determined in accordance to Virginia Test Method 1 (VTM-1) or VTM-12. The moisture content shall be maintained at appropriate level with frequent sprinkling of water and irregularities shall be removed by sufficient blading. A pneumatic tire roller is used for final rolling of the completed surface. The final rolling and finishing shall be completed within 12 hours after final mixing. After the compaction is completed, the compacted layer is brought to line and grade as specified in the plan to a depth as determined with requirements of VTM-38A. The section is removed or reconstructed if the thickness is observed to be deficient by more than 1 in, from the thickness shown on the plans. Additional lime equal to 50% of the original amount is added and the material is remixed to the specified depth and width to correct the deficiency of any section exceeding the 1 in tolerance.

Curing. Immediately after compaction and finishing, the surface is protected against rapid drying and cracking for 7 days by sprinkling water frequently and cured for 7 days, unless covered by subsequent layers of pavement. Before any hauling operations for other phase of construction, at least one subsequent layer is required to be placed above the stabilized layer. The material shall be re-stabilized if it loses the required strength, density and moisture before construction of subsequent layer.

Tests

Virginia Test Method – 1

This is a modified AASHTO T 99 test to determine the theoretical maximum density and optimum moisture content of soils, granular subbase, and base materials. AASHTO T 99 test method is only applicable to the soils for which more than 95% particles that pass through No. 4 sieve. The maximum dry density of the particles retained on No. 4 sieve is determined using following formula. It must be noted that, depending upon the variations in the percentage of No. 4 material in the mixture and the position of the material in the site, the density required in the field may vary and can be in a variable percentage of theoretical density obtained from the formula.

$$D = \frac{D_f \times D_c}{P_c D_f + P_f D_c} \quad (3)$$

where,

D_f = Maximum dry laboratory density of minus No. 4 material in lb. /ft^3 (kg/m^3)

D_c = Maximum density of Plus No. 4 material {62.4 lb. /ft^3 (1000 kg/m^3)} x bulk specific gravity by AASHTO Designation: T85 or as estimated by the engineer} in lb. /ft^3 (kg/m^3)
P_c = Percent plus No. 4 material, expressed as a decimal, and
P_f = Percent minus No. 4 material, expressed as a decimal or by nomograph.
The optimum moisture content is determine by following formula:

$$W_t = \left(P_c W_c + P_f W_f\right)100 \qquad (4)$$

where,

W_t = Optimum moisture content for total soil,
W_c = Optimum moisture content, expresses as a decimal, for material retained on No. 4 sieve
W_f = Optimum moisture content, expresses as a decimal, for material passing No. 4 sieve
P_c = Percent, expressed as a decimal, of material retained on a No. 4 sieve, and
P_f = Percent, expressed as a decimal, of material passing a No. 4 sieve.

Virginia Test Method – 38 A

This is a conventional method to test the depth of cement of lime-stabilized subgrade soil. A straightedge is laid across tope of a slit trench excavated to the bottom of the layer, and the depth of the layer to the nearest 0.1 in. is measured in the center of the trench at right angles to straightedge from bottom of layer to bottom of straightedge. Additional depth measurements at 25 ft. on each side of the first test point are required to be conducted if the initial measurement opposes the allowable specification tolerance. Further tests at intervals of 100 ft. measured longitudinally are conducted if the additional measurements still do not comply with the specification tolerance or until the depth is found to be within specification tolerance in both directions.

APPENDIX D: STATES CONSIDERATION OF LIME IN PAVEMENT DESIGN

Kentucky

The lime-stabilized layer is considered a structural layer in pavement design. With an assumption that the lime modification increases the CBR of the soil to a value greater than 6, a subgrade soil stabilized to a minimum thickness of 8 in. is assigned a typical structural layer coefficient of 0.11. The structural number is determined using the following equation;

$$SN = (a_1 d_1) + (a_2 d_2) + (a_3 d_3) + (a_4 d_4) + \dots\dots + (a_n d_n) \tag{5}$$

where,

SN is the required structural number determined from the catalog of structural numbers;

a_1, a_2, a_3, and a_4 are layer coefficients for first, second, third, and fourth (lime-stabilized) layers; and

d_1, d_2, d_3, and d_4 are the layer thickness for the first, second, third, and fourth (lime-stabilized) layers.

California

An untreated soil with a high R-value or the treated soil with UCS in between 100 to 300 psi may be considered as a structural layer and can be used as a subbase in order to reduce the overall thickness of the flexible pavement with a design life less than 20 years. The gravel factor (G_f) is determined from the UCS value, which is used to calculate the layer thickness. Additional testing with higher stabilizer content may be required to achieve the required gravel factor, which is given as;

$$G_f = 0.9 + \frac{UCS_{(psi)}}{1000} \tag{6}$$

The formula of gravel factor calculation is valid for the soil samples tested for UCS using ASTM D 1633 and ASTM D 5102 but with modifications. The modifications include; *(1)* sealing the specimen immediately after compaction to prevent moisture loss, *(2)* curing the specimen in an oven for seven days at 100°F ± 5°F, *(3)* air cooling the specimen after curing, and *(4)* testing for UCS without soaking.

Ohio

Sargand et al. conducted a study to evaluate methods to incorporate lime-stabilized layers as a structural layer in pavement design *[35]*. Portable Seismic Pavement Analyzer (PSPA), FWD, core collection, and dynamic cone penetrometer (DCP) measurements were taken at a number of locations across Ohio to determine the resilient moduli and layer coefficients of aggregate base and stabilized subgrade. Lime-stabilized subgrade was observed to enhance performance in the long-term compared to unstabilized subgrade. Furthermore, the modulus and stiffness of the base course was also observed to increase with subgrade stabilization, which has a significant impact on pavement design. The structural layer coefficients were determined directly using the "AASHTO" version of the procedure employed by B.K. Roy and DCP test data. Figure 27 presents the box plot of the layer coefficients as determined by various sites. In average, respective layer coefficients of 0.27, 0.36 and 0.29 were determined by three different calculation methods; *(1)* FWD backcalculation and AASHTO method, *(2)* DCP data and BK Roy method, and *(3)* DCP data and AASHTO method.

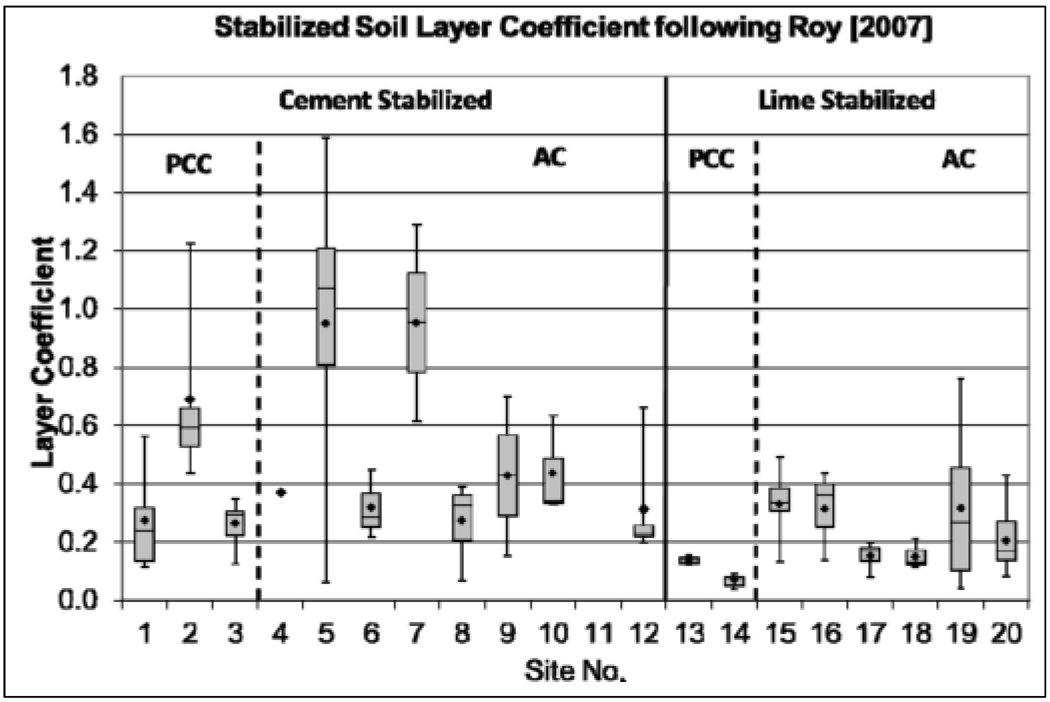


Figure 27
Box plot of layer coefficient of stabilized subgrade layer using BK Roy's method

Illinois

The Immediate Bearing Value (IBV) of the stabilized soil is used in pavement design using the modified AASHTO design methodology. Testing shall be performed on soil samples to be used in construction and the IBV shall represent a minimum value for the soil to be used. The IBV values presented in Table 38 shall be used in the design if testing is not available.

Table 38
Suggested IBV values for various soil classification

Soil Classification	IBV
A-1	20
A-2-4, A-2-5	15
A-2-6, A-2-7	12
A-3	10
A-4, A-5, A-6	3
A-7-5, A-7-6	2

Once the IBV value is obtained for the soil, the required structural number is obtained by projecting a line through the traffic factor and the IBV on the appropriate nomograph. To obtain the existing pavement structural number, the existing layer thicknesses are multiplied by their corresponding layer coefficients; a layer coefficient of 0.08-0.1 is used for lime-stabilized subgrade. The existing structural number is subtracted from the required structural number and divided by the resurfacing layer coefficient to determine the structural overlay thickness. A summary of the states' consideration of the structural contribution of lime-stabilized subgrade is presented in Table 39.

Table 39
Lime consideration in structural layers

States	Structural Layer Coefficient	Comments
Ohio	0.086	Based on the FWD data.
North Carolina	0.125	-
South Carolina	0.15	-
Georgia	Soil Support Value	The soil support values for lime-stabilized subbases and bases are increased to 3.2
Colorado	0.11-0.15	The value ranges depending on the compressive strength of the treated subgrade (125 psi to 425 psi or higher)
Kansas	0.11	-
Kentucky	0.106/0.11	Layer coefficient is 0.106 when hydrated lime is used and for the soils treated with lime/cement it is 0.11
Indiana	N/A	Modulus recommendation is 1.25 x M_R of compacted soils and may go up to 9500 psi.
Montana	0.07-0.14	The values depend on the compressive strength of the layer (200-400 psi)
Missouri	N/A	MoDOT uses the current AASHTO Mechanistic-Empirical Pavement Design Guide for full depth pavement design, which does not utilize the concept of structural layer coefficients.
Illinois	0.07-0.1	The value ranges from 0.07-0.09 for base and 0.08-0.10 for subbase
Arkansas	0.07 (Lime Treated Subgrade)	SN is only used for LTS in roadway typical section. SN value is not assigned for stabilization.
Texas	0.1-0.3	For lime-stabilized base the value ranges from 0.15 - 0.30 and for lime-stabilized subgrade the value ranges from 0.10 - 0.12
Oklahoma	0.05	Stabilized layers may be considered as a structural layer in areas that do not have a high water table.
Oregon	0.42	ODOT uses 0.42 for new asphalt pavement in the 1993 AASHTO Design Procedure
Virginia	0.18	Virginia typically do not count modified subgrade in pavement design.
Mississippi	0.2	Only account lime treated subbase/base in pavement design.
Alabama	0.1	ALDOT generally performs soil modification than soil stabilization.
California	N/A	Gravel Factor = 0.9 + ucs /1000 (only for flexible pavement)

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