Quest Journals
Journal of Architecture and Civil Engineering
Volume 11 ~ Issue 2 (February 2026) pp: 87-97
ISSN(Online): 2321-8193
www.questjournals.org

Research Paper

A Case Study on the Evaluation of Soil–Cement Stabilization for Gravel Road Subgrades in the State of Tennessee: Laboratory Testing and Field Recommendations

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Abstract
Cement stabilization is a widely applied method for improving the mechanical performance of unpaved road subgrades, aiming to increase soil strength, stiffness, and durability under traffic and environmental stresses. This study presents a detailed case investigation of subgrade stabilization for gravel access roads at a 1,200-acre site along Lynchburg Highway in Tullahoma, Tennessee. The project encountered subgrade instability during grading, prompting a comprehensive laboratory testing and geotechnical evaluation program. Representative soil samples were collected from eight locations at depths of 0.5–1.5 ft below the surface and tested with cement contents of 6%, 8%, and 10% by dry weight. Laboratory procedures included Atterberg limits, moisture content, standard Proctor compaction, and unconfined compressive strength (UCS) testing after seven days of molding and curing the samples.The results indicated that none of the soil–cement mixtures achieved the target minimum 7-day UCS of 100 psi, a criterion established by the Tennessee Department of Transportation for acceptable chemical subgrade stabilization. Reduced strength values were attributed to challenges in achieving homogeneous mixing and controlling moisture content for clayey soils in field conditions. Based on these findings, cement stabilization was deemed unsuitable for the site soils, and other stabilization methods such as lime stabilization and geogrid reinforcement of road subgrade were recommended as a more effective alternative. Practical recommendations for subgrade treatment, including proper scarification, chemical application, mixing, compaction, and curing procedures, are provided to ensure long-term stability of aggregate-surfaced roadways. This study highlights the critical influence of soil properties, cement dosage, and field construction practices on stabilization performance and provides site-specific guidelines for improving subgrade reliability in low-volume gravel road applications.
Keywords:Soil–Cement Stabilization,Gravel Roads, Case Study, Molding and Curing, Subgrade Improvement

I. Introduction and Literature Review

Cement stabilization has long been recognized as an effective soil improvement technique for enhancing the mechanical performance of unpaved road subgrades. The overall objective of cement stabilization is to increase soil strength and stiffness, reduce plasticity, and enhance durability under repeated traffic loads and environmental changes [1-11]. The performance of stabilized subgrades is highly dependent on several interrelated factors, including the percentage of cement, mixing quality, soil properties, and depth of treatment [12-19].

The proportion of cement used in stabilization critically influences the mechanical behavior of treated soils. Several studies have documented that increasing cement content generally enhances unconfined compressive strength (UCS) and resilient modulus; however, this relationship exhibits diminishing returns beyond an optimum content [20, 21]. For marginal soils with high fines content, cement contents in the range of 5–12% by weight have been shown to significantly improve strength characteristics [22]. Yang and Benson (2011) [23] found that lower cement contents (4–8%) are effective for granular base materials but may be insufficient for clayey subgrades without fines stabilization.The hydration reactions between cement and soil minerals form cementitious products such as calcium silicate hydrate (C–S–H), which contribute to strength gains [1]. The rate and extent of these reactions are influenced not only by cement content but also by curing conditions and soil mineralogy [21, 24].

Homogeneous mixing of cement with the in-situ soil is essential to ensure uniform stabilization. Field and laboratory studies have demonstrated that deficient mixing results in pockets of untreated soil, leading to variability in strength and service life [25]. Mechanical mixing techniques, including rotary mixers and reclaimer–stabilizers, are commonly used in field applications; quality is evaluated through field density and cement content tests [26]. Laboratory work by Dindarloo and Shahrabi (2017) [27] emphasized that optimal mixing not only affects strength but also mitigates shrinkage cracking problems associated with cement stabilization.In addition, the selection of appropriate mixing equipment influences the energy imparted during blending, which directly affects the microstructure of soil–cement matrices. Inadequate mixing energy can fail to break down soil aggregates, especially for gravely soils used in unpaved road bases, reducing effective bonding surfaces [28].

Implementing cement stabilization in the field presents practical challenges. Moisture control is critical; excessive moisture content can lead to dilution of cement paste and reduced strength, while insufficient moisture can impede hydration reactions [22]. Environmental conditions such as temperature and wind speed further complicate moisture management during mixing and curing stages [26].Furthermore, variability in gravel road materials often requires on-the-spot adjustments to cement application rates and mixing strategies. Studies by Omar (2018) [21] reported that heterogeneity in gravel gradation influences the distribution of cementitious binders, leading to inconsistent mechanical performance across the stabilized section.

Determining the appropriate depth of cement stabilization is fundamental to achieving structural adequacy. Many road agencies recommend treating depths that extend to the zone of significant stress influence or anticipated traffic load penetration [29-35]. Laboratory modeling and field performance evaluations have suggested that stabilization depths of 8–15 cm for light traffic and up to 20–30 cm for heavy load conditions are effective in improving bearing capacity while controlling deformation [24].Finite element analyses have been used to investigate the influence of stabilization depth on stress distribution and performance under cyclic loading, indicating that inadequate depth may lead to premature failure at the untreated subgrade interface [23]. Thus, depth design must consider traffic loading, moisture regimes, and soil profile characteristics [36-62].

Existing research underscores the importance of selecting appropriate cement content, ensuring homogeneous mixing, and choosing the correct treatment depth. However, challenges remain in optimizing mixing techniques under field conditions for highly variable gravel subgrades. There is a need for improved in-situ quality assurance methods that can dynamically adjust cement dosage and mixing energy based on real-time soil feedback. Additionally, further investigation into the interactions between cement stabilization and environmental moisture variations will support more resilient unpaved road designs.This study emphasizes the significant influence of soil characteristics, cement content, and field construction practices on stabilization performance, and presents site-specific recommendations to enhance subgrade reliability for low-volume gravel roads.

II. Practical Case Study

This case study project is located along Lynchburg Highway, approximately 3 to 5 miles west of South Jackson Street in Tullahoma, Moore County, Tennessee. The approximate location of the 1,200-acre site is shown in Figure 1. The project involved the construction of gravel access roads throughout the site. During grading operations, several roadway sections were reported to exhibit subgrade instability, prompting the need for a detailed geotechnical evaluation.

This case study documents the laboratory testing program and geotechnical engineering services performed to evaluate and mitigate subgrade stability issues for the proposed gravel roadway system. The study presents the results of laboratory soil–cement testing conducted at varying cement contents and provides engineering recommendations for roadway subgrade stabilization. The primary objectives of this research were to evaluate laboratory testing procedures and results for soil–cement stabilization at varying cement percentages; assess the effectiveness of cement treatment for improving subgrade performance; develop geotechnical recommendations for subgrade stabilization of gravel roads; and recommend appropriate aggregate (gravel) section thicknesses for long-term roadway performance.

A total of eight (8) sampling and testing locations were selected across the site to represent varying subsurface conditions. Laboratory testing was performed on the collected subgrade soils using multiple cement contents to assess strength improvement and suitability for stabilization. The results of these tests were used to develop practical and site-specific recommendations for gravel road construction in areas where subgrade instability was observed during grading.The geotechnical engineering scope of services for this project included laboratory testing of collected soil samples, engineering analysis of test results, and preparation of stabilization recommendations documented in this study.

Figure 1. The approximate location of the 1,200-acre site

III. Methodology, Field Sampling and Laboratory Testing Scope

The scope of work included performing a soil–cement study on near-surface subgrade materials obtained from the project site. Representative soil samples were collected from depths ranging between approximately 0.5 and 1.5 ft below the existing ground surface. All samples were obtained beneath the topsoil layer and included five 5-gallon bucket samples from each representative testing location. The collected soil samples, along with the cement materials, were transported to the Terracon Cincinnati laboratory for testing.For this soil–cement case study, laboratory testing was performed on remolded soil specimens prepared with cement contents of 6, 8, and 10 percent by dry weight of soil. The laboratory testing program included Atterberg limits testing in accordance with ASTM D4318 [63] and moisture content determination per ASTM D2216 [64] for all collected soil samples. Moisture–density relationship (Proctor) testing of soil–cement mixtures was conducted in accordance with ASTM D558 [65] for samples containing 6, 8, and 10 percent cement. In addition, soil–cement compression specimens were molded and cured following ASTM D1632 [66] and subsequently tested for unconfined compressive strength in accordance with ASTM D1633 [67] after seven days of curing.

For comparison purposes, standard Proctor compaction testing was also performed on untreated soil samples (0 percent cement) in accordance with ASTM D698 [68] to establish baseline compaction characteristics for materials from all sampling locations. The types, applicable standards, and quantities of laboratory tests performed for this study are summarized in Table 1.

Table 1- Performed laboratory tests on selected soil samples of the Project (8 Total Locations)

Test	**Standard**	**Quantity**
Standard Proctor (Samples with 0% Cement)	ASTM D698 [68]	8
Moisture-Density Relations of Soil-Cement Mixtures (samples with 6, 8 and 10% cement content)	ASTM D558 [65]	24
Molding and Curing Soil-Cement Compression Specimens at 6, 8 and 10% cement content	ASTM D1632 [66]	24
Compressive Strength of Remolded Soil-Cement Cylinders at 6, 8 and 10% cement content	ASTM D1633 [67]	24
Natural Moisture Content	ASTM D2216 [64]	8
Atterberg Limits (3 pt.)	ASTM D4318[63]	8

Our laboratory testing program often includes examination of soil samples by an engineer. Based on the results of our field and laboratory programs, we will describe and classify soil samples in accordance with the Unified Soil Classification System (USCS)[69].

IV. Summary and the Results of Performed Laboratory Testing

Tennessee Department of Transportation (TDOT) practice and research materials recent research report on chemical subgrade stabilization (Chemical Subgrade Stabilization of Tennessee Soils – Recommended Practices report No RES2023-13 dated July 2024) [70] explicitly uses a minimum 7-day UCS target of 100 psi as the design acceptance criterion. This criterion was applied across tested cement treated soils and considered appropriate based on performance trends in the study. This criterion is now referenced in TDOT's testing manuals and typical practice for chemical subgrade stabilization (including cement and lime stabilization) especially for subgrade soil treatment under flexible pavements. The 100-psi value is widely used in TDOT test manuals and research to indicate a minimum stabilization threshold for subgrade soil treatment.

The site grading is typically completed relatively early in the construction phase, with fill materials placed and compacted in a uniform manner. However, as construction progresses, the prepared subgrade may become disturbed due to utility excavations, construction traffic, desiccation, or rainfall and snowmelt. As a result, the aggregate-surfaced roadway subgrade may become unsuitable for construction, and corrective measures may be required. The subgrade should be carefully evaluated at the time of construction for signs of disturbance or instability. Accordingly, the objective of the laboratory testing program was to determine the optimum cement content required to achieve a minimum laboratory unconfined compressive strength of at least 100 psi after a 7-day curing and this criteria can be used as a minimum requirement for subgrade stabilization. Additional factors influencing the recommended cement content are discussed below. A summary of the moisture content and Atterberg limits test results for samples with 0 percent cement is presented in Table 2.

Table 2. Atterberg Limits testing and moisture content testing on the samples

Sample	**cement %**	**Liquid Limit**	**Plastic Limit**	**Plasticity Index**	**Moisture content**
B-1	0	32	21	11	20.9
B-2	0	23	19	4	15.9
B-3	0	24	20	4	20.1
B-4	0	28	20	8	14.8
B-5	0	28	19	9	20
B-6	0	70	22	48	23.2
B-7	0	39	23	16	14
B-8	0	29	21	8	20.7

A standard Proctor test was performed on each sample with no cement and at three separate cement contents of 6, 8 and 10 percent. The compressive strength samples were targeted to be about 98 percent compaction of the dry density at or near optimum moisture. Variations from targeted dry density and optimum moisture do occur due to normal variances in soils testing. Three unconfined compressive strength specimens were cast for each cement content percentage. Note that type 1L cement was used for the cement content. Figure 2 illustrates three molded and cured soil–cement compression specimens from Location B-5 with 10% cement prior to compressive strength testing, shown as a representative example. The same procedures were performed for all other samples, including untreated specimens (0% cement) and specimens prepared with cement contents of 6%, 8%, and 10%.Figures 3A through 3C illustrate three fractured soil–cement compression specimens from Location B-5 with 10% cement after completion of the compressive strength testing.

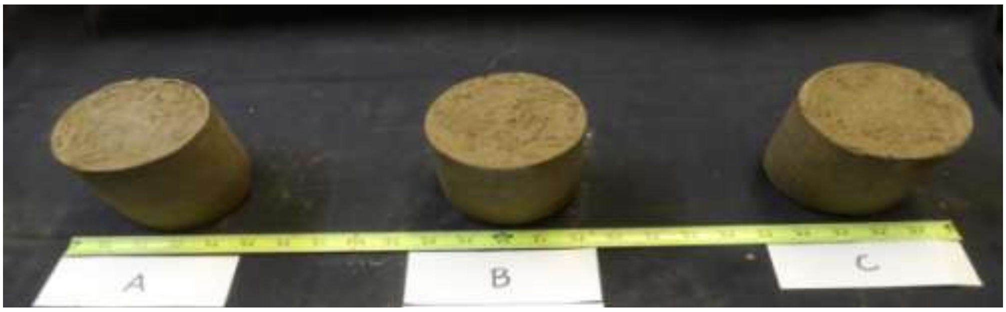
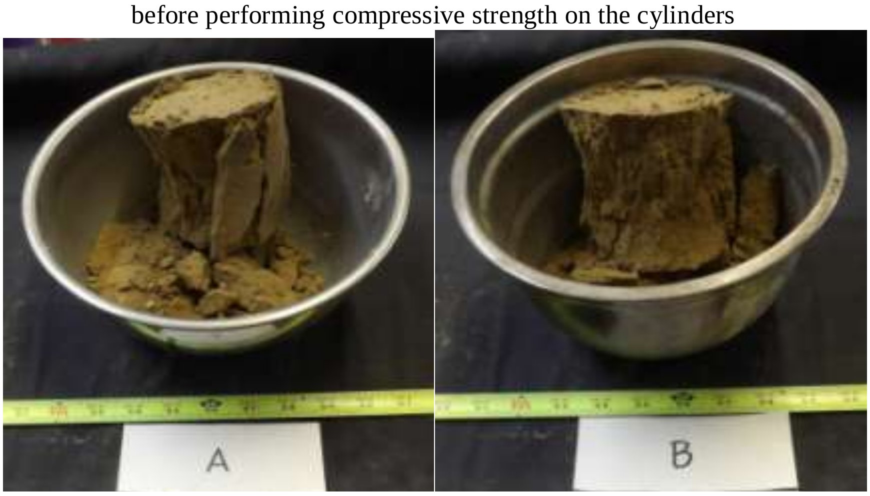
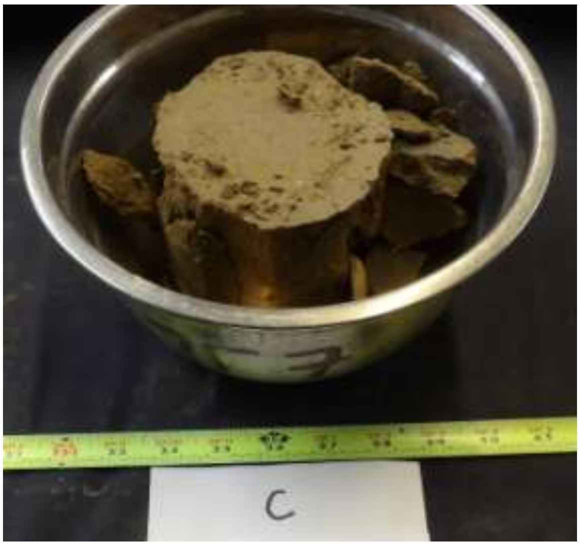


Figure 2. Three molded and cured soil-cement compression specimens from location b-5 with 10% cement before performing compressive strength on the cylinders



A) B)



C)

Figure 3. A through C) Three fractured soil–cement compression specimens from Location B-5 with 10% cement after completion of the compressive strength testing.

Table 3 illustrates Standard test method for compressive strength of molded soil cement cylinders for sample B-5 with 10% cement. As mentioned before, the same procedures were performed for all other samples, including untreated specimens (0% cement) and specimens prepared with cement contents of 6%, 8%, and 10%. Also figure 4 and table 4 illustrateperformed results of Moisture-Density Relations of Soil-Cement Mixtures for sample B-5 with 0% cement content for all three samples. Figure 5 and table 5 illustrate performed results of Moisture-Density Relations of Soil-Cement Mixtures for sample B-5 with 10% cement content for all three samples as well.

Table 3. Standard test method for compressive strength of molded soil cement cylinders for sample B-5 with 10% cement

Initial sample conditions				
Sample Number	**1**	**2**	**3**	**Average**
Average Diameter (in.)	3.974	3.973	3.978	3.975
Average Height (in.)	3.92	3.94	3.921	3.927
Cross-Sectional Area (in²)	12.404	12.394	12.429	12.409
Mass (grams)	1660.3	1660.8	1659.5	1660.2
Dry Unit Weight (pcf)	112.83	112.511	112.858	112.733
Moisture (%)	15.29	15.17	14.96	15.14
Post immersion sample conditions				
Sample Number	**1**	**2**	**3**	**Average**
Average Diameter (in.)	3.989	3.963	3.965	3.972
Average Height (in.)	3.935	3.962	3.937	3.945
Cross-Sectional Area (in²)	12.497	12.332	12.347	12.392
Mass (grams)	1663.2	1668.4	1668.4	1666.7
Unit Weight (pcf)	111.213	112.321	113.064	112.2
Moisture (%)	15.86	15.81	15.63	15.77
Test data				
Sample Number	**1**	**2**	**3**	**Average**
Maximum Load (lbs)	925	1075	1110	1036.7
Conversion Factor	1	1	1	1
Compressive Strength (psi)	74.02	87.17	89.9	83.7

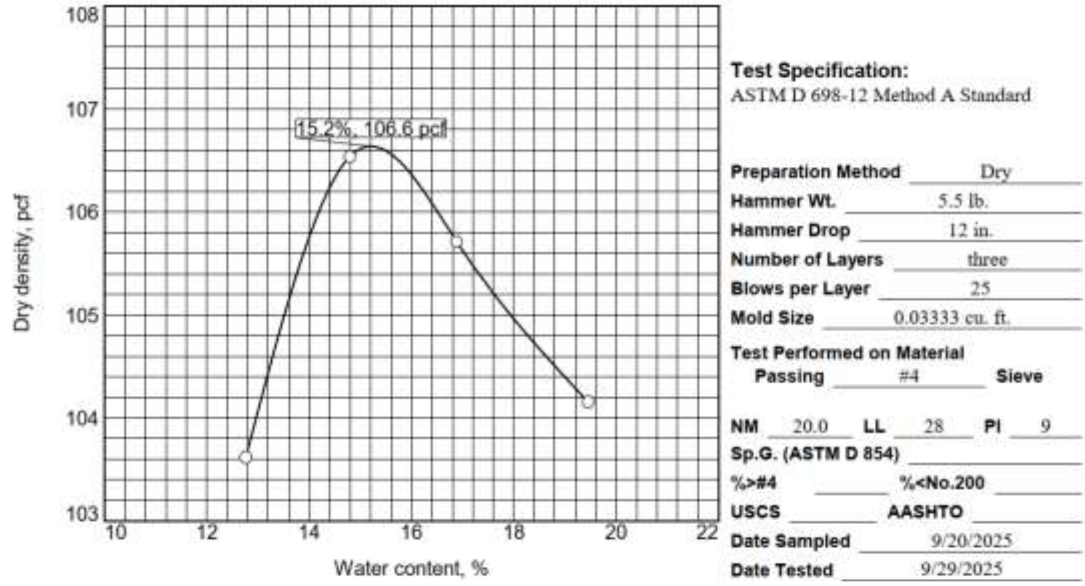


Figure 4. Moisture-Density Relations of Soil-Cement Mixtures for sample B-5 with 0% cement content for all three samples

Table 4. Moisture-Density Relations of Soil-Cement Mixtures for sample B-5 with 0% cement content for all three samples

Parameter	**1**	**2**	**3**	**4**
WM + WS	3801.1	3883.6	3902.6	3915.5
WM	2034.6	2034.6	2034.6	2034.6
WW + T #1	222.3	221.1	207.7	173.9
WD + T #1	204.2	200.7	186.5	155.7
TARE #1	62.4	63.3	60.8	62.5
WW + T #2				
WD + T #2				
TARE #2				
MOISTURE (%)	12.8	14.8	16.9	19.5
DRY DENSITY (pcf)	103.6	106.5	105.7	104.2

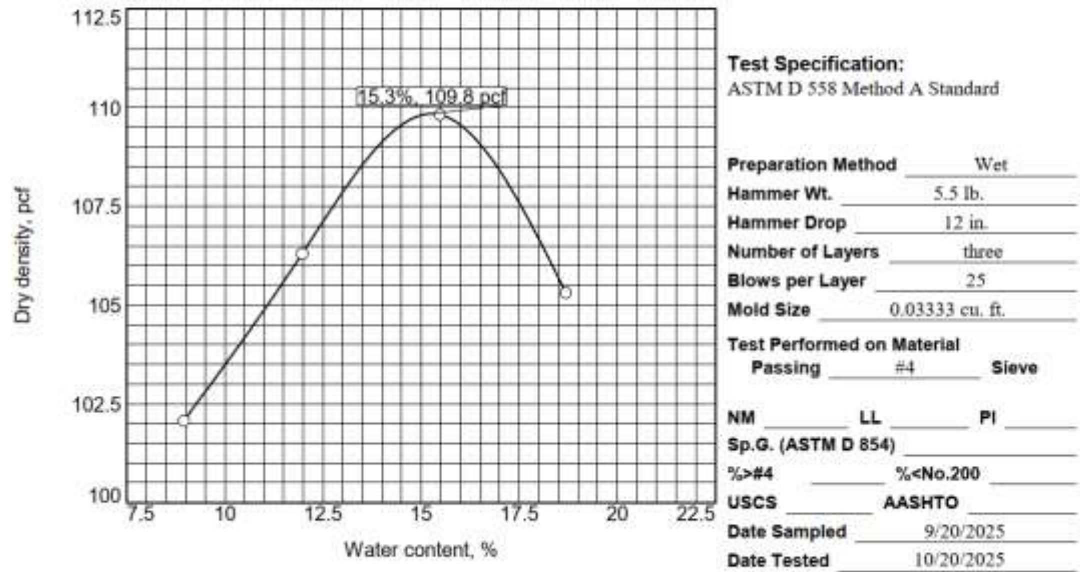


Figure 5. Moisture-Density Relations of Soil-Cement Mixtures for sample B-5 with 10% cement content for all three samples

Table 5. Moisture-Density Relations of Soil-Cement Mixtures for sample B-5 with 10% cement content for all three samples

Parameter	**1**	**2**	**3**	**4**
WM + WS	3716	3834.2	3951.9	3924.3
WM	2034.6	2034.6	2034.6	2034.6
WW + T #1	194.5	188.3	185.9	185.6
WD + T #1	183.7	174.8	169.2	166.2
TARE #1	62.8	62.4	61.4	62.6
WW + T #2				
WD + T #2				
TARE #2				
MOISTURE (%)	9	12	15.5	18.7
DRY DENSITY (pcf)	102.1	106.3	109.8	105.3

Table 6 presents a summary of performed moisture–density relationships of soil–cement mixtures testing on all samples with 0, 6, 8, and 10 percent cement content. Also, Table 7 illustrated a summary of performed compressive strength testing of remolded soil–cement specimens after seven days of curing for all samples with 6, 8, and 10 percent cement content.

Table 6. Moisture–Density Relationships of Soil–Cement Mixtures testing on all samples with 0, 6, 8, and 10 percent cement content

Sample	**Maximum dry density (pcf)**				**Optimum moisture (%)**			
Cement percentage	**0**	**6**	**8**	**10**	**0**	**6**	**8**	**10**
B-1	105	106.9	106.4	107.2	16.8	16.2	16.7	16.9
B-2	109.1	106.2	105.4	105.4	15.7	16.2	17.7	16.4
B-3	103.2	104.5	105.9	105.5	17.4	16.1	16	15.8
B-4	106	103.3	105	104.6	16	17.6	17	17.1
B-5	106.6	108.9	109.2	109.8	15.2	15.9	15.7	15.3
B-6	91	91.9	92.6	91	24.6	22.6	22.4	25.6
B-7	103.8	105.8	105.3	106.3	19.1	16.6	17.2	17
B-8	104.6	108.2	108.9	109	18.5	16.6	16.6	16.3

Table 7. Compressive strength testing of remolded soil–cement specimens after seven days of curing for all samples with 6, 8, and 10 percent cement content

Sample[1]	**Average Compressive Strength (psi)**[2]		
Cement percentage	**6**	**8**	**10**
B-1	59.64	69.58	85.1
B-2	56.17	44.57	82.78
B-3	46.01	42.29	64.04
B-4	40.54	51.14	50.71
B-5	54.15	61.67	83.7
B-6	Note 3	Note 3	54.69
B-7	50.09	45.48	60.8
B-8	34.69	54.24	64.63

1- Curing Conditions: Moist Cured 7-days. Immersed in water for 4 hours prior to compressive strength testing
2- Average compressive strength driven by three samples
3- Sample fell apart during immersion process

Based on the results summarized in Table 7 and the low unconfined compressive strength values (less than 100 psi) obtained during laboratory testing, it is likely that these reduced strength values are associated with improper mixing of soil and cement. Consequently, achieving uniform mixing of cement with low- to high-plasticity clayey soils present across the project sites is expected to be challenging under field conditions and may result in difficulties in attaining adequate subgrade stability. Strict moisture control measures, in addition to thorough soil–cement mixing, will therefore be critical to achieving satisfactory subgrade performance.

V. Conclusions and Recommendations

Proper site preparation is a critical factor governing pavement performance, particularly for low-volume roadways designed in accordance with Chapter 4 of AASHTO (1993) Low-Volume Road Design [29]. Although site grading is typically completed early in construction and fills are placed and compacted in a controlled manner, subgrade conditions may deteriorate as construction progresses due to utility excavations, construction traffic, moisture fluctuations, desiccation, or precipitation events. As a result, aggregate-surfaced roadway subgrades may become unsuitable for construction without corrective measures.

Field evaluation of the subgrade at the time of construction is therefore essential to identify signs of disturbance or instability. Proofrolling with a loaded tandem-axle dump truck prior to final grading and chemical stabilization is recommended to assess subgrade uniformity and identify weak areas. Immediately prior to placement of aggregate surfacing, all subgrade areas should be properly moisture conditioned and compacted in accordance with project specifications. The upper 12 in. of soil at the finished subgrade elevation should be scarified, moisture conditioned, chemically treated, and compacted to at least 98% of the standard Proctor maximum dry density (ASTM D698) [68].

Where chemical stabilization is not required and the natural subgrade is stable, scarified, and recompacted to the specified density, the use of geogrid reinforcement may be considered to enhance load distribution. For unpaved roadways, an ongoing maintenance program is necessary. Rutting or potholes should be repaired by adding aggregate base material rather than regrading, and adequate drainage must be provided to prevent water ponding and minimize long-term maintenance requirements.

Based on the laboratory testing results summarized in Tables 6 and 7, none of the soil–cement mixtures achieved the target minimum 7-day unconfined compressive strength of 100 psi established as the design acceptance criterion. These findings indicate that cement stabilization may not be suitable for the tested on-site soils under the evaluated conditions. Accordingly, lime stabilization is recommended as a more viable alternative for improving subgrade performance. It is recommended that a minimum 12-in. thickness of subgrade soil be chemically treated with lime and compacted to the required density, followed by placement of at least 8 in. of aggregate base over the stabilized subgrade.

Successful implementation of chemical stabilization is highly dependent on construction practices, including proper material application, thorough mixing, moisture control, and curing. Engagement of an experienced soil–cement/lime stabilization contractor is critical to achieving the desired performance and long-term durability. Contractors familiar with established industry practices, such as those outlined in the Portland Cement Association (PCA) publication Properties and Uses of Cement-Modified Soil, are better equipped to ensure consistent mixing, adequate curing, and compliance with project specifications. Adoption of these best practices can help avoid full undercutting, reduce material import/export, and provide both schedule and cost efficiencies while achieving a stable pavement structure.

- These recommendations are designed to stabilize the subgrade and do not take the place of the pavement design or aggregate base. Subgrade shape and crown (if any) dimensions and specifications still apply.
- Pre-wet dry soils or dry wet soils as needed prior to application of cement. Typical methods include aeration with a disc harrow or rotary mixer disturbance of soils for wetting and drying.
- If necessary to aid subsequent pulverization, scarify full depth with disc harrow, grader, scarifier teeth or other equipment.
- Distribute cement in dry form with mechanical spreader or in slurry form from distributor truck equipment with agitation system.
- Mix with travelling rotary mixer, adding water as necessary, until a homogeneous, friable mixture is obtained that will meet the specified pulverization requirements. In very wet cohesive soils as expected at this site, initial mixing may be performed with several passes of a disc harrow until the material becomes friable enough to use a rotary mixer.
- Prior to compaction, the cement modified soils should be pulverized such that 100 percent of the material passes the 1 ½ inch sieve and a minimum of 60 percent passes the No. 4 sieve.
- Compact with adequate sized equipment such as sheep's foot roller. Note caution at curbs listed above.
- Compact the treated material to a minimum of 98 percent of the material's standard Proctor maximum dry density.
- Complete surface compaction with appropriate smooth drum or similar roller.
- Shape area to final grade or crown (per plans, if needed)
- Seal surface with equipment sufficiently light in weight to prevent hair-line cracking.
- All processing of the soil should be completed in one day (i.e. any one section treated with cement should be completed that day.)
- Begin curing of the treated soil within 24 hours of processing (compaction, fine grading).
- Cure the treated soil by preventing moisture from escaping. Typical curing methods include periodic spraying with water, plastic sheeting, application of a curing seal or application of emulsified asphalt.
- Keep equipment off of the treated soil after fine grading and curing.
- In case this work is delayed, keep the treated soil from freezing for the first 7 days.
- The work plan details by the contractor should be discussed and reviewed by the geotechnical engineer as well as the designer of record.

Acknowledgments

The authors would like to acknowledge the engineers in the soil mechanic laboratory facility, the field group membersin the Terracon company in Nashville, TN, and Cincinnati, OH thank them for their help in providing the data for this research. The opinions, findings, and conclusions presented herein are those of the authors and do not necessarily reflect any sponsors.

Conflict of interest

The authors declare that they have no conflict of interest.

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