Investigating the Effectiveness of Enzymatic Stabilizers for Reclaimed Stabilized Base Projects

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About the Transportation Infrastructure Durability Center

The Transportation Infrastructure Durability Center (TIDC) is the 2018 US DOT Region 1 (New England) University Transportation Center (UTC) located at the University of Maine Advanced Structures and Composites Center. TIDC's research focuses on efforts to improve the durability and extend the life of transportation infrastructure in New England and beyond through an integrated collaboration of universities, state DOTs, and industry. The TIDC is comprised of six New England universities, the University of Maine (lead), the University of Connecticut, the University of Massachusetts Lowell, the University of Rhode Island, the University of Vermont, and Western New England University.

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16 Abstract

Reclaimed stabilized base (RSB) with an appropriate stabilizing agent is an appealing option for many rehabilitation projects. Depending on the type of base layer, various traditional stabilizing agents (e.g. cement, lime, calcium chloride, asphalt emulsion) are used in RSB projects to rehabilitate roadways by reclaiming the base material. Despite their advantages, traditional stabilizers entail some disadvantages (e.g. chemical reactions that might lead to disintegration of bonds). An alternative to the traditional stabilizers is using enzymatic stabilizers or a combination of an enzyme with traditional stabilizers in RSB leading to an improved stabilization outcome. This study investigated the effects of Xanthan Gum (XG) biopolymer on the strength and stiffness of roadway subbase materials as a full or partial replacement of cement. The subbase material was created in the lab and designed to represent the general gradation specified by regional departments of transportation. Scanning electron microscope imagery indicated that the XG coats soil particles and creates connections between them. For specimens treated with only XG, the results indicated an optimal treatment level of 1.0% of the dry mass of the subbase material, resulting in an unconfined compressive strength of about 4,000 kPa for specimens cured for 28 days compared to the untreated specimen with a strength of about 200 kPa. For specimens treated with both XG and cement, the results indicated an optimal level of treatment of 1.0% XG and 1.0% cement by dry mass of the subbase material. This combination demonstrated increased compressive strength of about 1,400 kPa. Combinations of XG and cement also resulted in a desirable ductile post-peak behavior in the treated subbase specimens compared to specimens treated with cement alone, which often produces undesirable brittle behavior.

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Abstract

Rehabilitation of existing pavement structures is a primary objective in many roadway constructions projects in New England (NE) region. Reclaimed stabilized base (RSB) with an appropriate stabilizing agent is an appealing option for many rehabilitation projects. Depending on the type of base layer, various traditional stabilizing agents (e.g. cement, lime, calcium chloride, asphalt emulsion) are used in RSB projects to rehabilitate roadways by reclaiming the base material. Despite their advantages, traditional stabilizers entail some disadvantages (e.g. chemical reactions that might lead to disintegration of bonds). An alternative to the traditional stabilizers is using enzymatic stabilizers (e.g. lingosulphonate, terrazyme, bio-grouting) or a combination of an enzyme with traditional stabilizers in RSB leading to an improved stabilization outcome. This study investigated the effects of Xanthan Gum (XG) biopolymer on the strength and stiffness of roadway subbase materials as a full or partial replacement of cement. The subbase material was created in the lab and designed to represent the general gradation specified by regional departments of transportation. Scanning electron microscope imagery indicated that the XG coats soil particles and creates connections between them. For specimens treated with only XG, the results indicated an optimal treatment level of 1.0% of the dry mass of the subbase material, resulting in an unconfined compressive strength of about 4,000 kPa for specimens cured for 28 days compared to the untreated specimen with a strength of about 200 kPa. The compressive strength at different treatment levels was found to be dependent on the moisture content at time of testing, with strength decreasing with increased moisture contents. For specimens treated with both XG and cement, the results indicated an optimal level of treatment of 1.0% XG and 1.0% cement by dry mass of the subbase material. This combination demonstrated increased compressive strength of about 1,400 kPa. Combinations of XG and cement also resulted in a desirable ductile post-peak behavior in the treated subbase specimens compared to specimens treated with cement alone, which often produces undesirable brittle behavior.

Chapter 1: Introduction and Background

1.1 Project Motivation

As awareness of the environmental impact of traditional engineering materials becomes prevalent, demand for innovative and sustainable substitutes increases. These substitutes must be able to provide comparable or improved strength, stiffness, and operational characteristics to the traditional materials, while reducing the associated environmental impacts. Conventional soil improvements can be divided into two broad groups: mechanical and chemical. Mechanical improvements include techniques such as compaction, consolidation, or dewatering of soils to increase their strength. Chemical soil improvement traditionally refers to the use of cement or other pozzolanic materials to increase soil strength, often in conjunction with mechanical improvement [1].

A typical roadway system comprises a pavement layer underlain by a subbase, underlain by the existing soil subgrade. The pavement layer may be either a rigid pavement of Portland cement concrete (PCC) or a flexible pavement of hot mix asphalt (HMA). The existing subgrade is often mechanically improved prior to construction. The subbase plays an invaluable role in managing the interaction between the pavement, and more specifically the wheel loads applied to the pavement, and the existing subgrade. The subbase achieves this by providing uniform support of the pavement layer and distributing wheel loads to the subgrade. It also provides temporary support for equipment during construction [2].

The provision of uniform support for the pavement layer is necessary to prevent both structural and functional failure. For coarse-grained subbase, stiffness is the primary design metric for determining the performance of the roadway system [2]. A subbase with appropriate stiffness will reduce strain of the pavement layer and distribute wheel loads to the subgrade. A subbase that is too stiff will cause excessive stress and strain in the pavement layer, leading to crack development. A subbase that is insufficiently stiff will also result in excessive strain in the pavement layer resulting in rutting and cracking of the pavement layer, and poor distribution of wheel loads to the subgrade, potentially causing failure [2].

In roadway engineering, mixing stabilizers with the subbase is often an appealing and cost-effective solution to increase the stiffness and strength of in-situ or imported soils. Common traditional stabilizers such as cement, calcium chloride, and asphalt emulsion are used for reclaimed stabilized base (RSB) projects [3]. In an RSB project, a portion of the existing roadway and underlying subbase is pulverized and thoroughly mixed with a stabilizing agent, usually with a cutting wheel as depicted in Figure 1, before being reused as a new subbase material. The use of RSB techniques have been shown to improve the service life and reduce maintenance costs of rehabilitated roadways [1].

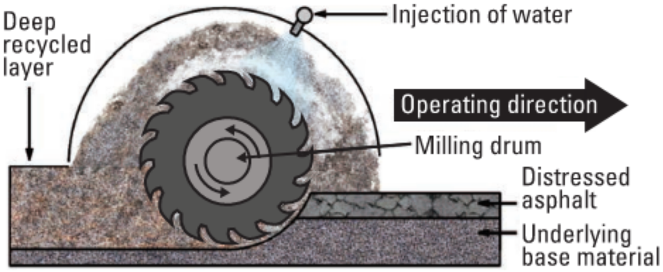


Figure 1: Schematic of roadway reclaimer cutting drum (adapted from [32]).

A typical RSB subbase will contain 20% to 50% recycled asphalt pavement (RAP) by dry mass [5]. Recycled concrete aggregate has also been proposed as a potential component of RSB materials [4]. Cement stabilization of granular soils is another common technique; typically, 2% to 10% cement by dry mass is used [2]. High cement content in the subbase can achieve high strength with the tradeoff of excessive stiffness and brittle post-peak behavior [2]. This can prove especially problematic for HMA pavements that rely on substrate flexibility to reduce stresses in the pavement layer. In general, high modulus and ductile behavior are desired in a roadway subbase. Subbases with ductile behavior can provide a longer time prior to the onset of fatigue cracking compared to subbases with brittle behavior [3]. Fatigue cracking leads to moisture intrusion and, in cold regions, frost heave and eventual potholing and raveling of the asphalt surface.

Cement is a ubiquitous material in civil engineering construction projects and has been shown to be an effective stabilizer of RSB materials. However, cement production is an energy intensive process: approximately 0.95 tons of Carbon Dioxide (CO_2) are released per ton of cement produced, accounting for approximately 8.0% of global CO_2 emissions in 2024. Approximately 2% of the total CO_2 emissions associated with cement production can be attributed to the use of cement in geotechnical applications.

Using more sustainable materials in geotechnical projects would have a meaningful impact on global CO_2 emissions.

Non-traditional soil stabilizers encompass a broad classification of materials ranging from enzymes and salts to resins and polymers [16]. While the stabilization mechanisms of these diverse additives differ, they can be broadly categorized as chemical or physical. Additives such as salts and enzymes work by chemically interacting with the soil particles primarily thought cation exchange. This results in a reduction in the double-diffusive water layer around clay minerals leading to flocculation (e.g. [17, 18, 19]). Additives that chemically interact with the soil are only effective if the soil consists of a substantial amount of clay minerals.

Additives such as lignosulfonate, resins (both petroleum and tree based), and polymers interact physically with the soil by coating individual particles and binding them together. Such additives that physically interact are effective for both fine- and coarse-grained soils. Due to differences in the stabilization mechanism of non-traditional additives, it is crucial to know the target soil's composition before selecting an appropriate additive. This study focused on roadway subbase materials, which typically have very low fines contents, and is the dominant subbase material in the northeastern United States. For this reason, an appropriate additive would be one that physically interacts with the soil.

Biopolymers are produced naturally in the environment and are derived from plants, animals, or microorganisms [10]. Plant-based biopolymers include Guar Gum, extracted from the Guar plant, and Lignin, a polymer derived from plant tissues. Animal-based biopolymers include Chitosan, produced from the waste shells of crustaceans, and Casein, a protein extracted from dairy products [10]. XG is a microorganism-derived polysaccharide and is an extra-polymeric substance (EPS) which, in nature, is the primary constituent of biofilms [9]. The role of an EPS / biofilm is to protect the microorganism that produces it. Microorganisms produce polysaccharides for several reasons, primarily: for adhesive and cohesive properties, retention of water and nutrients, and protection from extreme conditions (temperature, pH, salinity) [9]. Most applied XG research has focused on its hydrophilic qualities and potential applications to the agricultural industry. XG is considered a superabsorbent polymer (SAP), capable of absorbing water over 1,000 times its dry weight. In agricultural applications, soils treated with SAPs exhibit longer moisture retention times than untreated soils, making water available for plant intake over longer time periods and increasing crop yields [20]. Mixing XG with water forms a gel that rapidly gains viscosity, reaching 90% maximum apparent viscosity of about 80 MPa·s in about 13 minutes [9]. The XG gel also demonstrates shear softening behavior, with the apparent viscosity decreasing by three orders of magnitude at high shear rates associated with "spraying" or "pumping" actions [9]. XG has been shown to be stable over wide temperature and pH ranges [21] as well as in high salt concentration environments and resists oxidation [23]. XG is, however, biodegradable via depolymerization from enzyme attack and as many as five XG-degrading enzymes are required to achieve complete depolymerization [9]. Commercial production of XG occurs in two main phases: first, a simple carbohydrate is fermented by *Xanthomonas campestris*, then the target substance is precipitated out, dried, milled and further processed to arrive at the final product [9]. Commercially available XG is a fine, off-white powder and is available in different grades corresponding to the purity level and presence of active enzymes or reagents remaining after the production and processing.

Several studies have demonstrated the suitability of XG in both soil stabilization and soil strengthening. Soil treatment with XG has shown promise in a wide range of geotechnical applications including stabilization of collapsible soils and solidified dredged soil, improving erosion resistance, and strengthening of both coarse-grained soils and clays. XG has been shown to outperform other biopolymers in terms of unconfined compressive strength (UCS) [10]. Dehghan et al. [21] investigated geotechnical properties of collapsible Loess treated with XG and showed that shear strength increased with the addition of XG. In addition, XG has been shown to be effective in the treatment of collapsible soils, reducing the collapse potential and increasing the shear resistance [23]. Addition of XG has also been shown to significantly increase the compressive strength and elastic modulus of fine-grained soils (clay), coarse-grained soil (sand-gravel mixtures), and mixtures of silt, clay, and sand [23]. Missoum Benziane et al. demonstrated significant improvement in the shear strength and cohesion of sandy soils treated with XG, even at low treatment levels (less than 1% XG) [24]. Erosion resistance of soils has also been shown to increase substantially with the addition of XG and other biopolymers, primarily due to filling of void spaces by the XG gel and jellification when hydrated (e.g. [6, 11]). In hydraulic flume testing, soils treated with XG demonstrated an 80% reduction in hydraulic erosion compared to untreated soils due to the formation of a gel layer on the surface of the soil [12]. XG has also shown promise when used in conjunction with fibers. Feng et al. demonstrated significant improvement in the UCS of solidified dredged soil by treatment with XG and jute fibers, not only improving the UCS but also changing the failure mode from brittle to ductile under specific XG and fiber ratios [25]. Baldovino et al. showed a significant improvement in the mechanical properties of clays treated with XG and polypropylene fibers, noting the ability of XG to act as a binding agent between the fibers and the soil matrix, filling microcracks, and reducing porosity [26]. Principal drawbacks of XG at field-scale include its high cost, limited availability, and the absence of standardized procedures for mixing, laboratory sample preparation and testing, sensitivity to water content, and field testing and performance verification, especially over long-term [26, 27].

A number of researchers have hypothesized mechanisms for the increase in soil strength with the addition of XG (e.g., [10, 23]). The XG gel becomes more rigid as it dries, thus adding rigidity to the soil matrix. Chang et al. [22] suggested that for coarse-grained soils, XG both coats individual particles and fills the interstitial spaces of the soil matrix. The XG gel coating on the particles forms connective bridges between particles upon drying. Scanning electron microscope (SEM) images appeared to confirm the bridging hypothesis for coarse-grained soils [23].

The environmental and economic aspects of biopolymers are often interrelated: niche materials tend to have a considerably higher cost than the conventional materials they aim to replace, which often prohibits their application in regular use. In 2014, XG's cost was $2,700 per ton, considerably higher than ordinary Portland cement at just under $100 per ton [6]. When environmental costs are factored into the cost analysis, however, biopolymers have been shown to be cost-effective. Chang et al. [22] reported that when considering treatment rates of 10% cement and 0.5% XG by mass and the costs of CO_2 emissions associated with producing each, the total treatment costs of 1 ton of soil accounting for carbon trade exchange are $12.50 and $12.95 for cement and XG, respectively [6]. The environmental and economic advantages of XG make it potentially competitive with conventional materials. In fact, the production of XG has a net CO_2 intake of approximately 5 kg per 1 kg of XG. However, research has indicated that higher proportions (above 1.0%) of XG would be cost-prohibitive even after accounting for carbon credit offsets [6].

XG is hydrophilic. From a roadway construction perspective, requiring that a subbase be thoroughly dry to achieve acceptable strength could raise concern in some application areas. Reintroduction of moisture into the subbase during curing, construction, and service is likely. Several studies have examined the influence of repeated wetting-drying and freeze-thaw cycles on the strength and stiffness of soil treated with XG. Lee et al. (2022) found that sand treated with 1.0% and 2.0% XG demonstrated gradual reduction in both strength and stiffness with repeated wetting-drying cycles, likely due to the swelling of the hydrophilic XG in the soil matrix when exposed to moisture. Freeze-thaw cycles had minimal effect on degradation of both strength and stiffness [7]. Fateh et al. (2025) found that treatment of clay with1.0% XG enhanced the durability under repeated freeze-thaw cycles, likely due to increased adhesion from the XG gum and reduced permeability limiting water intrusion into the soil matrix [8]. This study therefore aims to provide a more complete understanding of the effects of XG as a standalone stabilizer and as a partial replacement of cement on the engineering properties of roadway subbases under both dry and wet curing environments to bring the application of biopolymers in the field a step closer to fruition.

This study explored the potential use of a Xanthan Gum (XG) biopolymer as a non-traditional binder for road subbase materials. XG is a polysaccharide synthesized by fermenting sugars with *Xanthomonas Campestris* bacteria and processed to produce a fine powder that creates a viscous gel when mixed with water, even at low proportions. The gel hardens as it dries, but is hydrophilic and readily absorbs water when exposed, returning to a viscous gel state. XG is produced commercially and is commonly used in food products and cosmetics as a thickening agent and binder [9].

1.2 Research Objectives

In this study, we investigate the efficacy of using XG powder as a full or partial replacement of cement to stabilize roadway subbase by exploring the effects of XG and cement treatment level, curing time, and curing environment on the strength and stiffness of treated subbase material. The unique contributions of this study lie in the following objectives. The primary objective of the study is to compare the strength and stiffness of specimens cured in both a dry and humid environment to examine the effect of moisture retention on UCS and elastic modulus, and the development of linear relationships between the moisture content and the UCS at five different treatment levels. A secondary objective is to expand the general understanding of the effect of XG on the strengthening of roadway subbase materials, potentially as a full or partial replacement of cement, and to provide contributions to the field application of XG as a non-traditional stabilizer. A tertiary objective of this study is to provide recommendations for field-scale implementation of XG soil treatment. Although the focus of this study centered on subbase stabilization, the information learned about the behavior of XG in porous media can be used to explore other geotechnical uses for XG. Research has already shown that XG treated soils may be effective for erosion control [6, 10, 11, 12], stabilization of embankments constructed with coal combustion residual materials [13], and as a replacement for bentonite in slurry wall construction [30]. This study adds to the growing literature on XG soil treatment by specifically framing it around roadway subbase stabilization and evaluating the potential of supplementing traditional cement stabilization with combinations of XG and cement.

1.3 Report Overview

Chapter 2 provides research methodology and testing procedure. Chapter 3 provides results and discussion followed by recommendations for field implementation. Conclusions are provided in chapter 4.

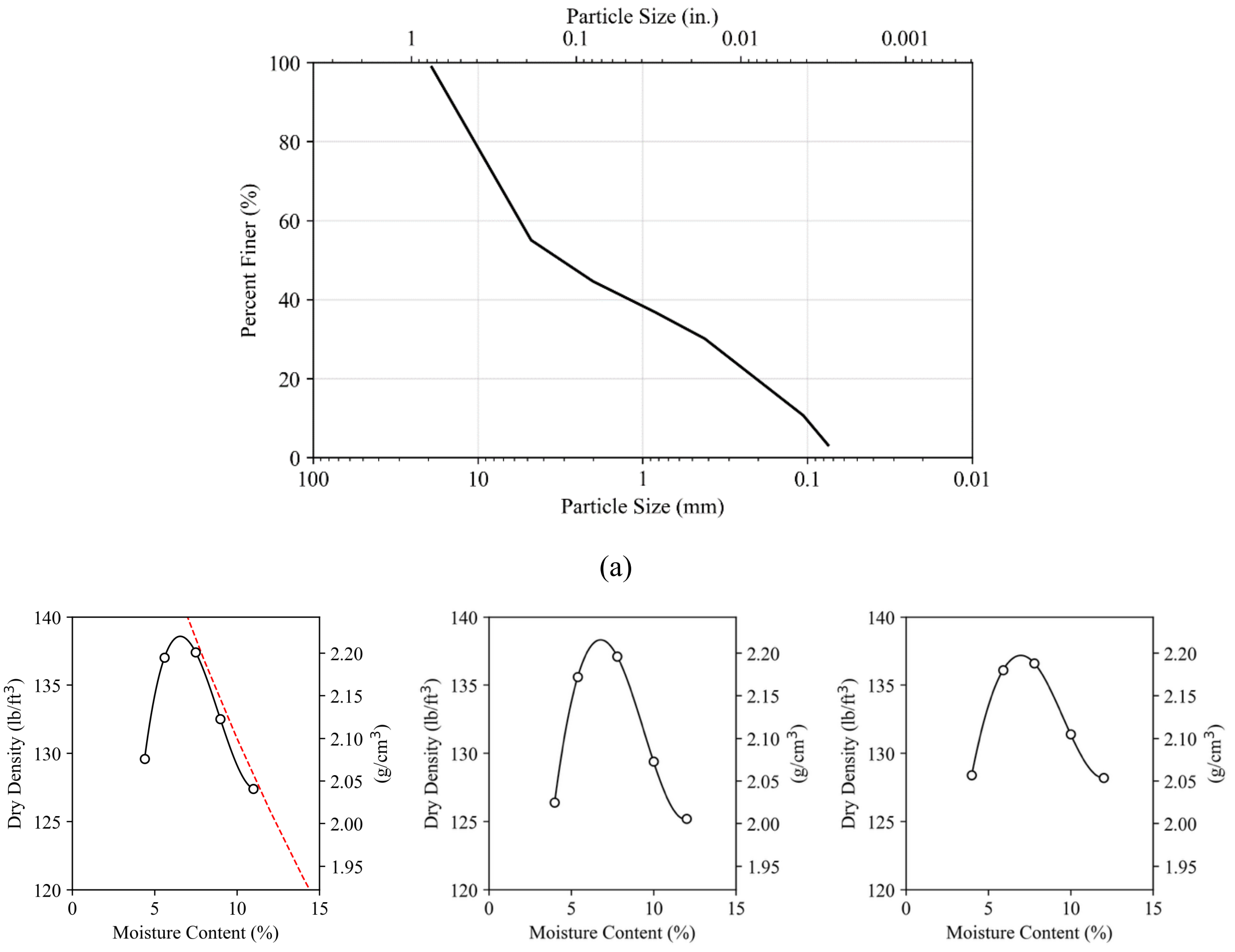
Chapter 2: Research Methodology

For the purposes of this study and the availability of materials, the subbase strength requirements and gradation were selected based on regional recommendations, which may vary by location and by the specifics of a given project; thus, results of this study may not extend to materials that are considerably different from those tested. This study assessed whether XG may completely or partially replace cement for roadway subbase stabilization and investigated the optimal percentages of XG for complete replacement and percentages when combining XG and cement for partial replacement. Specimen preparation procedure for subbase treated with XG and combinations of XG and cement are the same; but the curing requirements, notably the moisture level of the curing environment, are different for specimens treated with only XG and those with both XG and cement. Details regarding specimen preparation and curing procedures are provided in the subsequent subsections.

2.1 Materials

2.1.1 Subbase Material

This study used a lab-created subbase as a surrogate for a reclaimed asphalt subbase and designed based on review of regional roadway subbase recommendations [12, 28, 29] using particle size distributions of the historical subbases. A mixture of gravel, crushed stone, and sand was used to develop the lab-created gradation with the goal of representing this set of typical subbases and is shown in Figure 2(a). The Proctor compaction curve is shown in Figure 2(b): the optimal moisture content was determined to be 7.0% with a maximum dry density of 137.2 lb/ft^3.



(a)

(b)

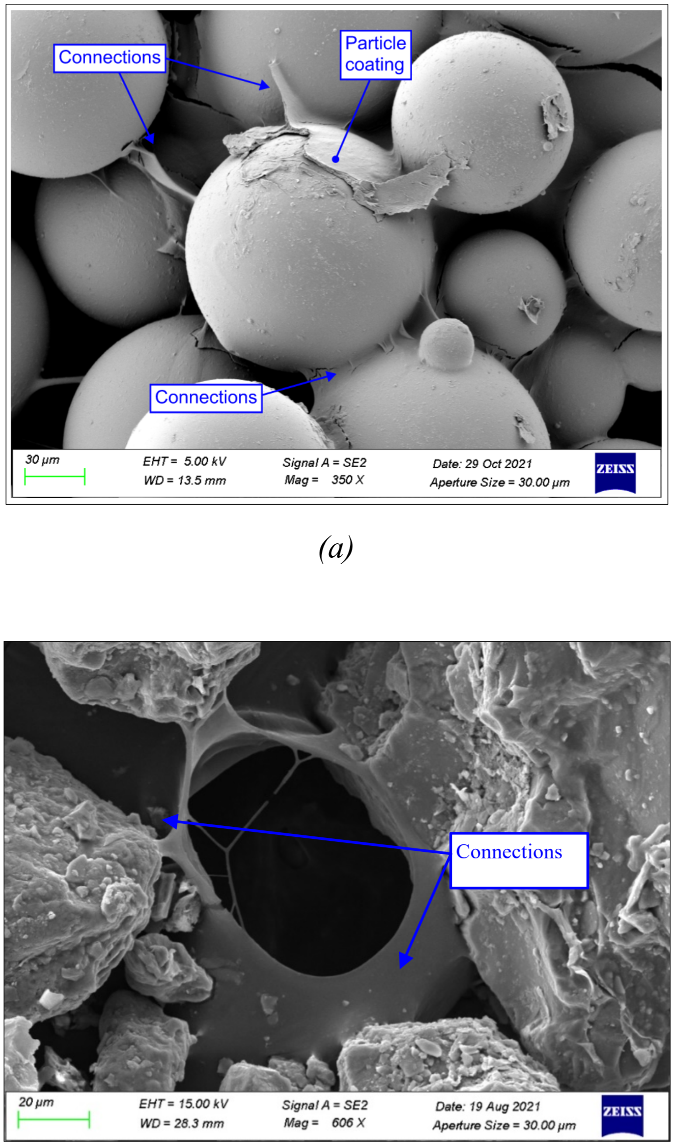
(c)

(d)

Figure 2: (a) Particle size distribution and (b) Proctor compaction curve of the untreated study material (zero air voids shown as red dashed line) (optimum moisture content 7.0%, maximum dry density 138.6 pcf), (c) for the study material treated with 1.0% XG (optimum moisture content 6.9%, maximum dry density 138.3 pcf),, and (d) treated with 1.0% XG and 1.0% cement (optimum moisture content 7.2%, maximum dry density 137.4 pcf),.

2.1.2 Xanthan Gum

This study used pure, food-grade, commercially available XG powder manufactured by 138 Foods, Inc. The XG powder has an off-white color and is very fine, passing a #200 sieve. The density when placed in a loose state is approximately 1.45 g/cm^3. Prior to creation of the test specimens, a Zeiss Sigma 300 VP Field-Emission SEM was used to observe the particle-scale interaction between the XG and spherical glass beads. SEM images revealed a coating around the glass beads and the “connectional bridges” acting to bind the particles to one another, as shown in Figure 3. These observations agree with the findings of other studies (e.g. [6, 10]).



(a)

(b)

Figure 3: SEM images of glass beads (a) and sand (b) treated with XG.

2.2 Specimen Preparation

Specimens were prepared using a dry mixing technique in which the dry treatment materials (XG powder, cement, or a combination of both) were added to dry subbase material and mixed thoroughly prior to the addition of water. The dry mixing technique has been shown to result in higher compressive strength than wet mixing, when XG and water are combined before mixing with the soil [23]. It is easier to achieve a homogeneous mixture of treatment powder and subbase material with dry mixing than wet mixing given the high viscosity of the XG and water mixture. For specimens treated with only XG, proportions of 0.3, 0.5, 1.0, 2.0, and 4.0% of the dry subbase mass were used, and these specimens cured at room temperature and humidity for 7, 14, and 28-day periods. For specimens treated with only cement or a combination of XG and cement, the total mass of stabilizers was kept at 2.0% of the dry mass of the subbase , which was found to be an optimal cement treatment level in similar material [1], with the relative ratio of XG to cement ranging from 0:1 to 1:0, in increments of 0.25. The total stabilizer proportion was set to 2.0% based on previous work, which was found to be the optimal cement treatment level in a similar subbase material, above which the treated subbase became too brittle and failed to meet serviceability requirements [1]. Additional specimens were prepared with 0.0% XG (control), 1.0% cement, and 1.0% XG, 0.0% cement. These specimens were cured either at room temperature and humidity or in a fog room for 7 days. Specimens that were cured in the fog room (a Darwin Curing Chamber) remained in the fog room for the entirety of the curing duration at a controlled temperature of 22°C and humidity of 98%. A complete list of treatment types, proportions, and curing conditions is provided in Table 1. All specimens were prepared using standard Proctor compaction in general accordance with ASTM D698 Method B [30] at the optimal moisture content of 7.0%. Specimens remained in the Proctor mold for 24 hours before being extruded.

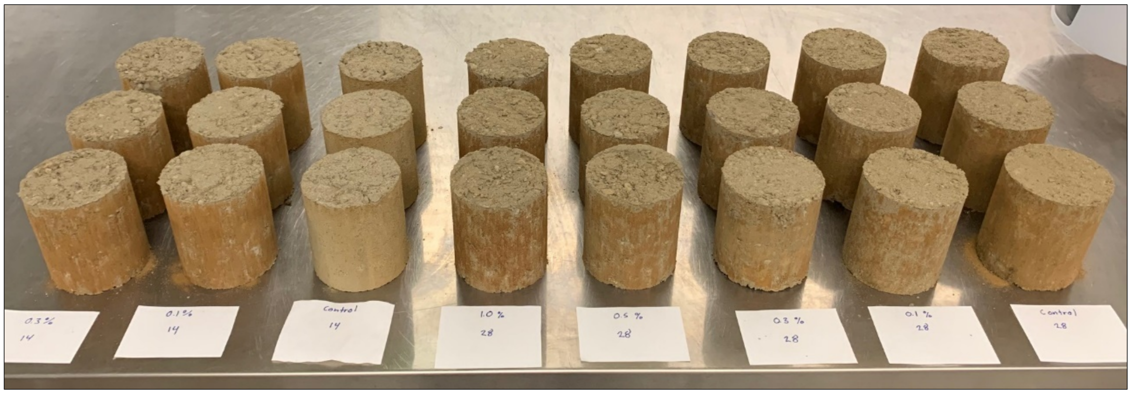


Figure 4: Typical prepared specimens.

Table 1: Treatment type, proportion, and curing condition of prepared specimens. Abbreviations: Xanthan Gum (XG) and cement (C).

XG Only			
Stabilizer %		**Curing**	
XG	**C**	**Time (d)**	**Condition**
0.0	*0.0*	*7, 14, 28*	*Lab bench*
0.3	*0.0*		
0.5	*0.0*		
1.0	*0.0*		
2.0	*0.0*		
4.0	*0.0*		

XG and Cement				
Stabilizer %		**Curing**		
XG	**C**	**Time (d)**	**Fog Room**	**Lab Bench**
0.0	*2.0*	*7*	*x*	
0.5	*1.5*		*x*	
1.0	*1.0*		*x*	*x*
1.5	*0.5*		*x*	*x*
2.0	*0.0*		*x*	
0.0	*1.0*		*x*	*x*
1.0	*0.0*		*x*	*x*

Untreated control specimens were created alongside the treated specimens for each curing time, curing condition, and stabilizer combination and quantity. All specimens were created in triplicate to assess variability.

2.3 Test Procedures

A representative element of a roadway subbase could be considered unconfined given the relatively shallow depth of the subbase compared to the roadway length and width. As a result, the unconfined compressive strength (UCS) test procedure was chosen to evaluate the specimen strength and elastic modulus. Specimens were tested for UCS using a LoadTrac II developed by Geocomp Corporation of Acton, Massachusetts in general accordance with the relevant ASTM D1633 Method A standard, intended for UCS testing on soil specimens prepared in a standard Proctor mold [30]. Specimens were subjected to a constant displacement rate of 0.25 mm/min. Loading proceeded until fracturing/collapsing of the specimen was observed. A typical specimen set up in the LoadTrac II is shown in Figure 5.

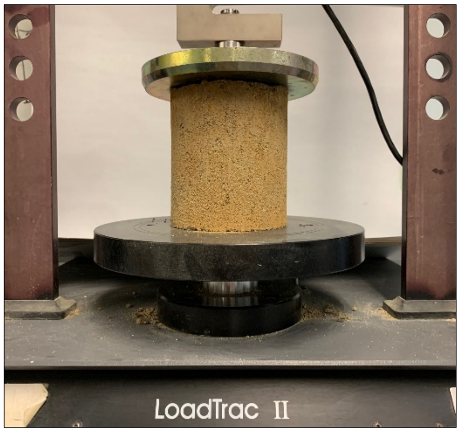


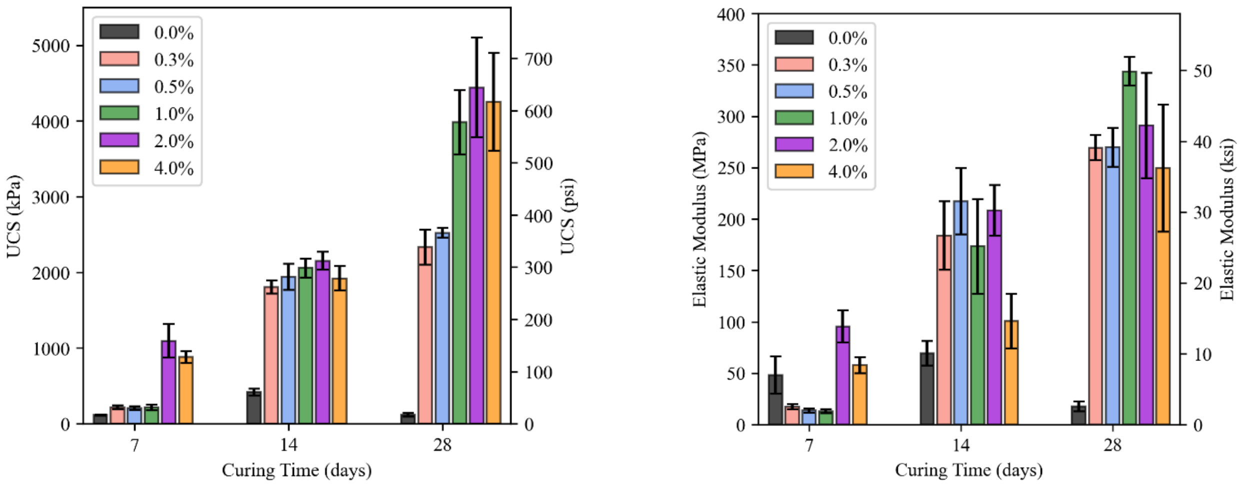
Figure 5: A specimen set up in the LoadTrac II prior to testing.

Chapter 3: Results and Discussion

This section is divided into three subsections. Section 3.1 discusses test results for specimens that were treated with only XG. This includes analysis of the effects of different XG treatment levels and curing times on the UCS and elastic modulus, as well as an evaluation of the relationships between moisture content, XG content, and UCS. Section 3.2 discusses test results for specimens that were treated with combinations of XG and cement. This includes analysis of the effect of XG and cement treatment level on UCS and elastic modulus, as well as a comparison between specimens that were cured at room temperature and humidity with those cured in the fog room. Section 3.3 evaluates the effects of XG and cement treatment on the post-failure behavior of treated specimens. Section 3.4 evaluates changes in post-failure stress-strain behavior of specimens treated with XG and combinations of XG and cement. Statistics were computed on the test results (including mean, median, standard deviation, minimum, and maximum values) and are available in the supplemental material.

3.1 Specimens Treated with Xanthan Gum Only

The testing of specimens treated only with XG indicate that UCS generally increases with increasing XG content and increasing curing time, with some exceptions as seen in the bar chart of UCS and elastic modulus for the study subbase in Figure 6. The elastic modulus was measured as the slope of the linear portion of a stress-strain curve. Treated subbase specimens were stronger than the 0.0% control specimens for all curing times and all XG proportions. At 7 days of curing, XG contents below 2.0% have a minimal effect on the UCS compared to the control; XG contents of 2.0 and 4.0%, however, show considerable increase in strength. At 14 days of curing, the UCS of all treated specimens were very similar and showed considerable increase in strength compared to the 7 day cured specimens and the control. At 28 days of curing, XG contents below 1.0% showed little increase in UCS, while XG contents of 1.0% and greater continued to show strengthening.

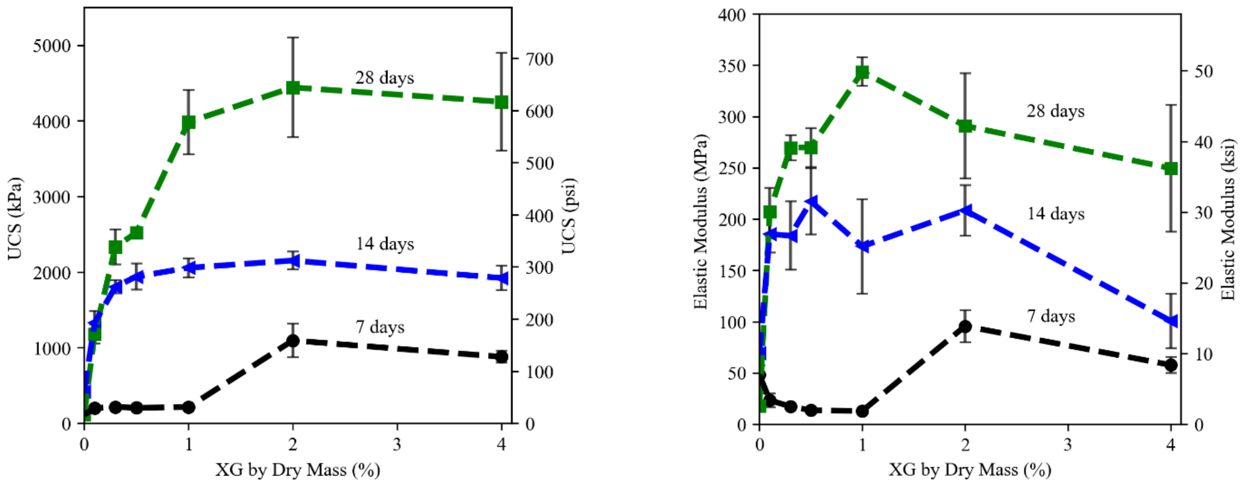


(a) **(b)**

Figure 6: (a) UCS and (b) elastic modulus for the study subbase treated with only XG. Error bars indicate the range of test results about the median.

At 7 days of curing, the moduli of specimens treated with less than 2.0% XG were lower than the control, and those treated with 2.0 and 4.0% XG were higher. All specimens became stiffer with longer curing times. There is considerable variation in the moduli associated with 2.0 and 4.0% XG at 28 days; but all treatment amounts were centered around a similar range of about 250 to 275 MPa (36 to 42 ksi), except for 1.0% which was considerably higher. At 7 days of curing, all treated specimens except for 0.3% XG were stiffer than the control, with stiffness decreasing with higher XG content. At 14 days of curing, all treated specimens were stiffer than the control. For all curing durations, 0.3 and 4.0% treatments resulted in the lowest stiffness. The low end of 0.3% XG treatment may be an insufficient quantity for this coarse material to have a substantive influence on the elastic modulus. The low stiffness from the high end of 4.0% may suggest that too much XG had been added, reducing the strength of interparticle contacts. Similar to UCS, the specimens generally exhibited the greatest increase in stiffness between 7 and 14 days. Increases in strength and stiffness with longer curing times is consistent with literature, which also found significant strengthening at longer curing times of at least 28 days [25, 26, 27]. Baldovino et al. found continued strength gain even after 90 days of curing if the specimens were prepared at optimum moisture content, noting that excessive water contents during sample preparation reduced the strength and stiffness even at long curing times [26].

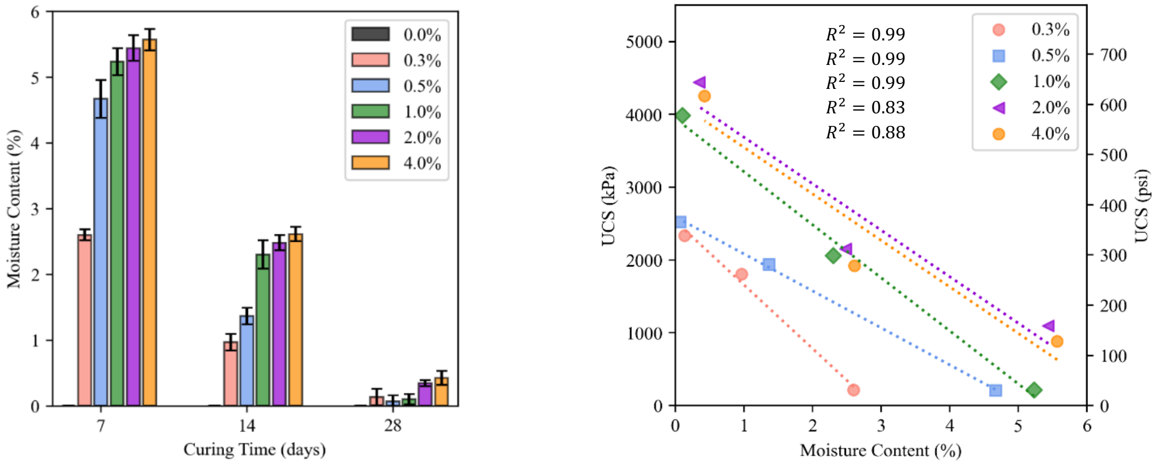
Figure 7 shows the variation of UCS and elastic modulus as a function of XG content for each curing time. There appears to be diminishing returns in both strength and modulus with XG contents greater than about 1.0%. This behavior suggests that, depending on the target strength and curing duration, XG contents greater than about 1.0% will either not contribute further to the increase in strength and stiffness or may result in a decrease in the strength and stiffness, but this may be dependent on the gradation of the material being treated. A recommended treatment level of 1% aligns with findings from other researchers using XG, and similar sensitivities were observed by Feng et al. [25] and Fateh et al. [8] , who found that increases in the UCS of treated soils slows down significantly when XG contents greater than 1.5% were used. However, it is difficult to compare these studies one-to-one since they use different soils (Feng et al. and Fateh et al. use a fine-grained soil, while we use a coarse-grained soil). Nonetheless, we found in this study that treatment level of 1.0% achieves appropriate strength and elastic modulus while remaining more affordable than higher treatment levels. Khorasani et al. [1] explored the use of cement for subbase stabilization on a material with similar gradation to the lab-created material used in this research and therefore provides a suitable comparison to the XG-treated subbase. UCS testing was conducted using the same test equipment and procedures on specimens treated with 1.0, 2.0, and 3.0% cement by dry mass, resulting in UCS of 675, 1,270, and 2,970 kPa, respectively, after curing for 7 days. Figure 7(a) demonstrates that UCS of the XG-treated subbase exceeds that of the cement-treated subbase when dried for longer than 7 days, in some cases by a considerable margin. Both subbases failed within the same general range of strain, from about 1.0 to 1.5% strain.



(a) **(b)**

Figure 7: Variation of (a) UCS and (b) elastic modulus with XG content for each curing time for specimens treated with only XG. Bars indicate the range of test results about the median.

Specimen’s moisture content appeared to be a critical factor in determining its strength for a given XG content. Figure 8(a) shows the moisture content of specimens after UCS testing. The control specimens had 0.0% moisture content at all curing times. The ability of XG to extend moisture retention time is clearly demonstrated. At 7 and 14 days of curing, higher XG content correspond to higher moisture content; after 28 days, moisture content appeared to be independent of XG content.



(a) **(b)**

Figure 8: (a) moisture content with curing time and XG proportions (error bars indicate the range of test results about the median), and (b) linear trends for the relationship between moisture content and UCS at different XG treatment levels.

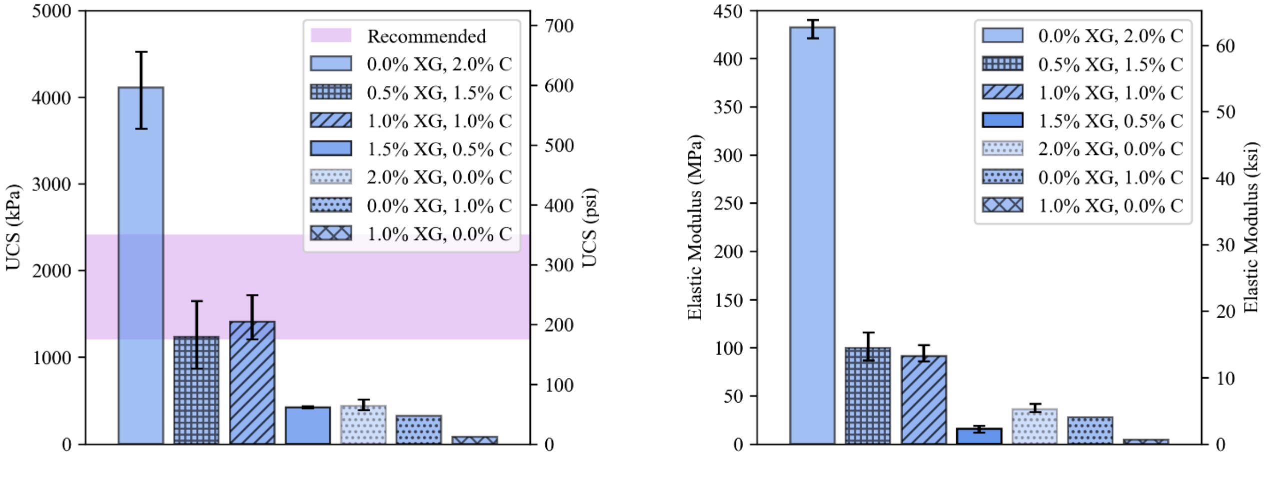
Comparing the trends in moisture content and in UCS, there appeared to be a connection between drying and strengthening, whereby lower moisture content corresponded to higher UCS for a given XG content. Figure 8(b) shows UCS plotted as a function of moisture content for all XG contents. The control specimens are not shown because all specimens had a moisture content of 0.0% at time of testing. The UCS as a function of moisture content, when separated by XG content, produced linear trends with high coefficients of correlation (>0.80). UCS was shown to be higher at any given moisture content for increasing XG contents up to 2.0%, after which the UCS-moisture relationship decreases.

The results show a negative correlation between UCS and moisture content. This relation could potentially be used in field applications to estimate the in-place UCS, which is elaborated on in the discussion section (See section 5). A similar relationship between UCS and moisture content was observed by other researchers in silty sand treated with 1.0% XG [31]. The strong relationship between moisture content and UCS would suggest that rehydration of the specimen would result in a reduction in

UCS. However, it is not known whether this relationship is reversible. The jellification of XG when exposed to water may rule it out as a stabilizer of unpaved gravel roadways, where formation of a slick gel on the roadway surface could have negative safety and maintenance implications.

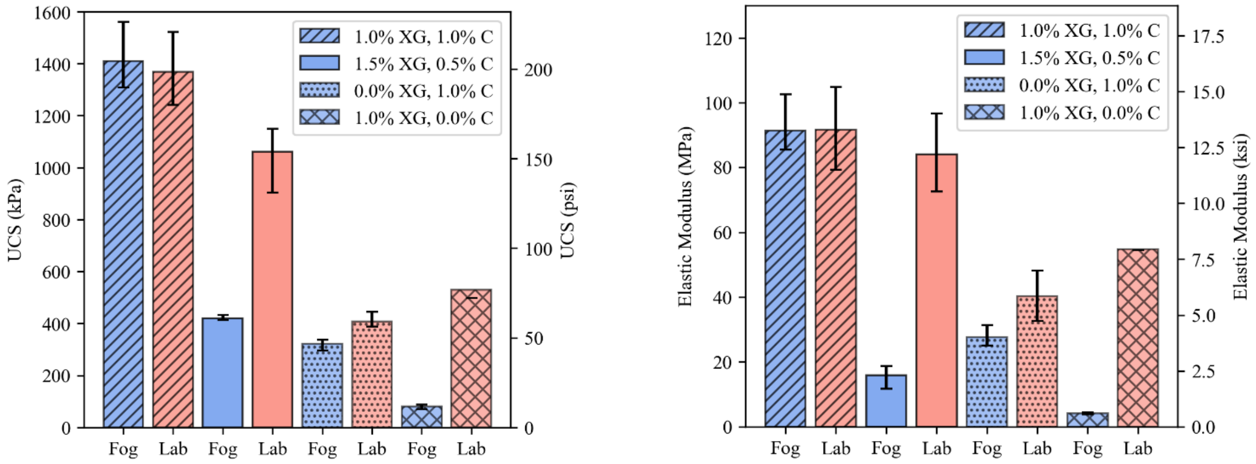
3.2 Specimens Treated with Xanthan Gum and Cement

The results of UCS testing with specimens treated with a combination of XG and cement indicate the importance of balancing the XG and cement proportions to achieve acceptable performance in both dry and humid curing conditions. Figure 9 shows UCS and elastic modulus for specimens treated with different combinations of XG and cement and cured in the fog room. The specimen treated with only cement (0% XG, 2% cement, XG:C ratio of 0:1) is significantly stronger and stiffer than all other combinations, with its strength being outside the recommended range by a considerable margin. Reducing the cement content to 1.5% and increasing the XG content to 0.5% (XG:C ratio of 0.25:0.75) reduces the strength of specimen compared to the cement-only treatment by approximately a factor of 3, staying within the lower limit of the recommended range. Equal proportions of XG and cement (XG:C ratio of 0.5:0.5) do not appear to have a significant effect on strength and stiffness compared to a ratio of 0.25:0.75. Further reductions in cement content and increases in XG content (XG:C ratios of 0.75:0.25 and 1:0) result in significant decreases in both strength and stiffness. Figure 10 shows a comparison between the results shown in Figure 9 and their counterparts cured on the lab bench.



(a) **(b)**

Figure 9: (a) UCS and (b) elastic modulus of specimens treated with different combinations of XG and cement and cured for 7 days in the fog room. Error bars indicate the range of test results about the median.



(a) **(b)**

Figure 10: (a) UCS and (b) elastic modulus comparison between specimens treated with different combinations of XG and cement and cured in either the fog room (blue) or on the lab bench (red). Error bars indicate the range of test results about the median.

The effect of curing environment on subbase strength and stiffness depends on the ratio of XG and cement used in the treatments. The subbase treated with 1.0% each XG and cement (an XG:C ratio of 0.50:0.50) appears to be insensitive to the curing environment, showing similar strength and stiffness for both the fog room and lab cured specimens. Increasing the XG content to 1.5% and decreasing the cement to 0.5% (XG:C ratio to 0.75:0.25) results in both the strength and stiffness being sensitive to the curing environment: specimens cured in the fog room are weaker and less stiff than those cured in the lab. This is likely due to the inability of the XG in the soil matrix to dry and form interparticle connections in the fog room, and the cement content being too small to have a significant effect on strength. Conversely, the higher strength of the lab-cured specimen is likely due to the ability of the XG to dry [35].

The results suggest that, if used as a cement replacement, treatment with 1.0% XG by dry mass produces acceptable strength if the subbase is dried during curing. When used as a cement supplement, treatment with 1.0% XG and 1.0% cement by dry mass produces acceptable strength and is insensitive to the moisture content of the curing environment.

3.3 Stress-Strain Behavior

Treatment with XG and combinations of XG and cement have a significant impact on the stress-strain behavior of subbase specimens. Several selected representative stress strain curves are shown in Figure 11 to demonstrate the effects of treatment. Specimens treated with 2.0% cement demonstrated brittle post-peak behavior resulting in rapid strength loss. Specimens treated with 1.0% XG and cured in the lab for 28 days demonstrated similar elastic modulus and compressive strength to those treated with 2.0% cement, but with a more ductile post-peak behavior showing gradual strength loss. Specimens treated with 1.0% XG and 1.0% cement demonstrated a reduced elastic modulus compared to the former two, with a ductile post-peak behavior showing very gradual strength loss. Specimens treated with 1.0% XG and 1.0% cement showed a more ductile post-failure response than those treated with only XG and only cement. The study by Feng et al. (2023), which investigated combinations of XG and fibers for soil treatment, arrived at a similar finding: the most ductile response was achieved with a combination of XG and jute fiber [25]. Additionally, specimens treated with the combination of XG and jute fiber also showed reduced elastic modulus compared to those treated with only XG, and the authors noted no significant increase in the strain at failure [25].

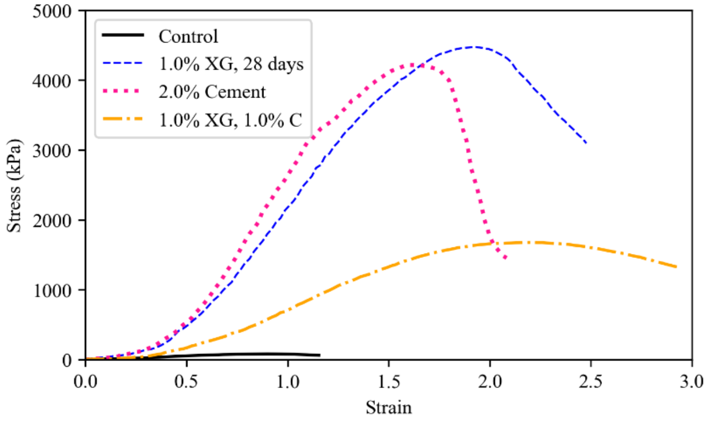


Figure 11: Selected representative stress-strain curves.

While cement is excellent in providing high modulus when added to poor subbase soils, its use can be a risky practice as too much cement results in a brittle subbase. The findings of this study suggest that partially replacing cement with XG creates a desirable ductile post-peak behavior in the treated subbase. This ductility may contribute to longevity of the subbase, increasing the service life by reducing the likelihood of cracking of the surface layer (commonly HMA) and other associated deteriorations.

Additionally, cement alongside XG could present a potential remedy for assisting in the curing and drying XG treated subbase. Cement and other pozzolanic substances use water during the hydration process, thus, drawing moisture away from the XG in the subbase, expediting the drying and strengthening process.

3.4 Field Application, Curing, and Long-Term Stability

As with any new material, there could be challenges associated with the implementation of XG in roadway subbase stabilization as compared to the “tried and true” traditional stabilizers. Perhaps the most notable limitation of using XG as a non-traditional stabilizer replacement of cement for roadway subbase is the sensitivity of compressive strength and elastic modulus to the moisture content. Moisture sensitivity can affect many aspects of the implementation: from mixing XG into the subbase, to curing requirements, and long-term stability in humid climates or regions prone to heavy rains. The results of this study suggest that using XG as a supplement to cement may be an appropriate way to reduce cement use while achieving acceptable strength and being insensitive to different moisture levels of the curing environment.

Mixing dry XG powder with the proposed subbase material could present some challenges if that material is wet. From a practical standpoint, mixing very small quantities of XG, for example less than 1.0%, by dry mass, may be unfeasible at a large scale as the quantity may be too small to evenly incorporate into the material. The subbase being treated would likely have some moisture, and drying the subbase completely before mixing with XG is impractical. Mixing XG with the moist subbase could result in clumping, making it difficult to achieve a homogenous mixture, although clumping would only be anticipated at treatment amounts of 2.0% XG or greater.

Assuming thorough mixing is achieved, placement of the XG-treated subbase could proceed as usual, with placement and compaction in lifts according to project specifications with regular in-place density testing to assure general conformance. Currently, both dry mixing of powdered polymer and wet mixing with injection techniques are used for incorporating other SAPs (such as polyacrylates) into soil for agricultural applications [4]. An alternative mixing method in the field could be the “wet mix” method: XG is first mixed with an appropriate quantity of water to form a slurry. This slurry could potentially be applied to the subbase in-place using the same equipment and techniques used for stabilization with calcium chloride or asphalt emulsion. The shear-softening behavior of XG would make a slurry conducive to pumping or spraying applications [9], and integration with existing equipment and techniques reduces potential complications with experimental application and treatment procedures.

As discussed in this paper and shown in Figure 8, the moisture content decreases with longer curing times. Curing time is analogous to dehydration time and curing in high humidity environments may result in a longer wait time until an appropriate strength has been achieved compared to curing in arid environments. Depending on project specifications and required strength of the subbase, long drying times could result in project delays that could be avoided with traditional treatments. Treatment with XG may not be appropriate in regions with humid climate or frequent heavy rains, or in areas with high groundwater tables. Treatment with XG may be more appropriate in dry / arid regions where rain events are less frequent, and groundwater is generally deep. Given that research has shown a gradual, but nonetheless present, reduction in strength and stiffness of sandy soil treated with XG subjected to wetting-drying cycles, durability of treated roadway subbase under cyclic wetting-drying and freeze-thaw conditions should be evaluated prior to any field-scale implementation.

Using XG as a supplement to cement may be effective in reducing or eliminating the need for dry curing conditions. It is interesting to consider that XG and cement have opposing optimal curing environments: XG requires a dry environment to achieve strength, and cement requires a wet environment. The hypothesis as to why a combination of XG and cement produces acceptable strength and is robust to the curing moisture level has several parts and is informed by the current understanding of how XG interacts in the soil matrix. When first mixed into the soil, the XG gel is viscous and contributes little to the strength of the specimen. The gel, which is hydrophilic, will retain moisture unless exposed to a dry environment. If allowed to dry, the gel hardens and forms interparticle connections, increasing the strength of the treated specimen. However, if the gel cannot dry, then it remains viscous and does not form interparticle connections. Therefore, if curing in a humid environment, such as the fog room, the addition of a material that can draw moisture out of the XG gel is needed so it can dry and form interparticle connections. This is where the addition of cement plays an important role. Cement requires a humid environment to achieve strengthening of the treated subbase. In the fog room, cement draws moisture out of the XG gel allowing it to harden and form interparticle connections, while the cement can undergo hydration reactions with sufficient moisture supply. When cured in the dry lab environment, moisture is readily lost to the environment and there is insufficient moisture to allow for completion of the hydration reactions necessary for strengthening of cement in the soil matrix. However, if combined with the hydrophilic XG gel, cement can draw moisture from the gel resulting in both hardening of the XG gel to form interparticle connections and more complete hydration of the cement. This synergistic relationship may explain why a 50%:50% combination of XG and cement appears to be insensitive to the moisture level of the curing environment, as shown in Figure 9. This suggests that a combination of XG and cement may be appropriate for use in humid environments, or environments that experience both dry and humid conditions. Further investigation would be beneficial to better quantify the effects of moisture intrusion on in-place subbase treated with a combination of XG and cement.

Chapter 4: Conclusions

In this study, we evaluated the relationships between XG content, moisture content, and UCS and elastic modulus of a simulated roadway subbase material. We also analyzed combinations of XG and cement and the effect of different curing environments on strength and stiffness of treated subbase material. UCS testing revealed that higher XG content resulted in stronger and stiffer specimens. UCS was found to be inversely related to moisture content for all XG contents investigated. Previous studies used higher XG contents (e.g., 2.0, 3.0, and 4.0%), which would make treatment on a large scale expensive and economically unfeasible compared to traditional stabilizers. The results of this study indicate that even low XG contents (e.g., below 1.0%) can provide strength and stiffness sufficient for use in roadway applications, and that higher XG contents may result in diminishing returns or even a reduction in strength and stiffness depending on the material gradation.

The requirement for a completely dry curing environment is not realistic in field applications. Therefore, the use of only XG in roadway subbase stabilization may be impractical and the most likely use case is for XG to be used as a supplement to cement. The results indicate that using 1.0% XG and 1.0% cement may result in appropriate strength and stiffness of the subbase, while also contributing to ductile post-peak behavior.

This study shows that XG has promise as a sustainable and innovative engineering material for soil stabilization. As with all new materials, an understanding of the risk of using XG is needed prior to implementation in a project. This risk assessment may include an investigation into the effects of environmental conditions (moisture intrusion, freeze-thaw cycling, chemical exposure) on treated subbase behavior, life cycle and cost analysis, long-term stability and durability testing, and transportation agency and public perception.

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Appendices

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