ENGINEERING PERFORMANCE OF POLYMER AMENDED SOILS

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ABSTRACT

Engineering Performance of Polymer Amended Soils

Gary Edward Welling

A laboratory test program was undertaken to evaluate a series of engineering properties over a range of soil types; amendment types and addition rates; and moisture contents to enhance understanding of the engineering significance of polymer amendment. Four soils were manufactured and tested with varying ranges of fines and plasticity. A proprietary elastic copolymer was tested at addition rates of 0.5% to 2.5% (dry weight basis). Cement was tested at addition rates of 1% to 4%. Lime was tested at an 8% addition rate. Water addition rates ranged from 4% dry of optimum to 4% wet of optimum. Engineering properties determined throughout the test program included dry unit weight / moisture content relationships through compaction tests; shear strength through unconfined compression strength tests and direct shear tests; durability through freeze-thaw and wet-dry durability tests; and stiffness through resilient modulus tests and through interpretation of the unconfined compression and direct shear test results.

The addition of polymer altered the optimum moisture content of the soils. Change in optimum moisture content ranged from 0.51 to 1.27 times the control water demand. The dry unit weight of polymer amended specimens ranged from 0.97 to 1.01 times their respective control dry unit weight. The peak strength of polymer amended specimens ranged from 1.02 to 18.4 times the control strength. The peak wet-dry and freeze-thaw durability of polymer amended specimens ranged from 6.8 to 10.8 times the control durability. The addition of polymer increased the peak initial stiffness of specimens to approximately 3 times the control stiffness. However, the stiffness was

reduced to 0.68 times the control stiffness with dynamic repeated loading through the resilient modulus test.

The polymer addition rate required to achieve peak engineering performance ranged from 0.5% to 2.5%, based on soil type. Polymer modified the engineering properties of soil through physical bonding. The amount of polymer required to modify the engineering properties was directly related to specific surface and soil particle coating thickness. It was determined that polymer amendment had an optimal addition rate that resulted in the greatest increase in engineering parameters. The addition rate was optimum when polymer was applied at rates high enough to sufficiently coat all soil particle surfaces, but at rates low enough that it did not cause additional particle separation.

Overall, polymer amendment of soil improved or maintained all tested engineering parameters, except the resilient modulus, of all soils. Polymer amended soils displayed a reduced performance compared to cement amended soils, and an improved performance compared to lime amended soils.

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CHAPTER 1: INTRODUCTION

The need for soil improvement is increasing due to pressures to build and rehabilitate infrastructure and other civil works on sites with marginal soils. If the infrastructure cannot be relocated or adapted to the soil conditions, then the soil must be stabilized. Soil stabilization methods are typically mechanically or chemically based. Historically, chemical amendments have been used to stabilize soils. The Appian Way, built during the Roman Empire was often considered the first lime stabilized road (ASCE 1978). Chemical soil stabilization has been extensively used in the United States since the end of World War II (ACI 1990).

Chemical amendments are typically applied in liquid or powder form, and are added to the soil surface at a specified rate as determined by performance tests. Four traditional chemical amendments have been extensively researched and are commonly used: cement, lime, fly ash, and asphalt emulsion. Cement and lime are frequently used to modify roadway subgrades in the United States, and associated approved application specifications are available in most states.

A series of non-traditional amendments have been proposed to be used in lieu of, or in conjunction with, traditional additives. Some of the most common non-traditional additives are: polymers, salts, acids, enzymes, lignosulfonates, petroleum emulsions, and tree resins. Polymer amendment for improvement of soils is a growing industry and has been of particular interest in recent field applications. Polymers improve the soil by providing physical stabilization through the use of binding agents. Polymers are easily modified; therefore, a range of polymer combinations can be prepared to modify soils. Two common polymer products used for soil stabilization are vinyl acetate and acrylic

based copolymers. Both vinyl acetate and acrylic copolymers are hydrophobic and have had moderate success in bonding to a range of soils (Terratech 2012).

Despite the recent interest in polymer amended soils, limited research has been conducted to determine fundamental engineering behavior. Most laboratory and field experimentation to date has focused on performance evaluation rather than evaluation of the mechanism constituting change in the performance of amended soils. Also, due to the proprietary nature of the commercially available stabilization additives, exact chemical compositions are not commonly disclosed. Therefore, relatively little information is available regarding the fundamental stabilization mechanisms between polymer stabilizers and geotechnical materials. In addition, the ease of modification has led to many different available polymers leaving little basis for comparison. Though there is an interest to develop applicable test methods and a standard basis of comparison, currently standardized tests are not available for polymer amended soil.

An extensive laboratory test program was undertaken to evaluate a series of engineering properties over a range of soil, amendment, and water mixture ratios to enhance understanding of the engineering significance of polymer modification. Polymer was tested at amendment rates of 0.5% to 2.5%. Engineering properties determined throughout the test program included dry unit weight – moisture content relationships through the use of compaction tests; shear strength through the use of unconfined compression strength tests and direct shear tests; durability through the use of freeze-thaw and wet-dry durability tests; and stiffness through the use of resilient modulus tests and through interpretation of the unconfined compression test results. Changes in

engineering properties from the addition of amendment were then evaluated to determine the mechanism creating change in the soil performance.

Four test soils were designed and prepared to evaluate the effectiveness of polymer over a range of soil types. Soils included a poorly graded sand with no fines and three clayey sands with gravel. The three clayey sands had varying percentages of fines and varying values of plasticity. The experimental test program was also used to evaluate two traditional additives, cement and lime, to provide a relative basis for the effectiveness of polymer relative to traditional amendments.

A review of the state of knowledge related to chemical stabilization of soil with polymer, cement, and lime, as well as relevant compaction and engineering property test background is presented in Chapter 2. A description of the test materials and experimental testing procedures are presented in Chapter 3. The experimental results for each test, determination of engineering properties, and relevant discussion are presented in Chapter 4. The engineering significance of the test results are presented in Chapter 5. Finally, the summary, conclusions, and recommendations are presented in Chapter 6. References and appendices follow the conclusions.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

A review of current literature related to polymer amended soil is covered in this chapter. General topics including mechanical stabilization of coarse and fine grained soils; and chemical stabilization of polymer, cement, and lime are discussed herein.

2.2 Mechanical Stabilization

2.2.1 Compaction Theory

Mechanical stabilization improves the strength and bearing capacity of soil through the application of energy, load, or compaction. Some common methods include: application of energy with standard compaction equipment, in-situ densification, and grouting (Holtz et al. 2011, Coduto 1999).

It is common practice to compact the soil any time it is used for geomechanical applications. Compaction improves soil strength and bearing capacity of soil through expulsion of air from the soil matrix, thereby increasing the overall density (Holtz et al. 2011, Ingles and Metcalf 1973). Proctor (1933) determined that compaction was a function of: moisture content, soil parameters, compactive effort (the energy that was applied to a given unit volume of soil), and dry density.

Water has an influence on mechanical stabilization. As water is added to a soil matrix, a film develops around the soil particles. The water film has a lubricating effect, allowing the soil particles to re-orient into a denser state (Holtz et al. 2011). Lubrication is obtained through the reduction in capillary tension between the individual soil particles. The capillary tension draws the soil together, causing an increased frictional

resistance between the particles (Berney et al. 2003, Holtz et al. 2011). When this force is reduced, it enables the particles to rearrange into a denser state.

The influence of water is reflected on a typical compaction curve with the increase in dry unit weight as a function of increasing moisture content. In addition to the soil particles arranging themselves in a denser state, at low moisture contents, the water replaces the air voids and further increases the overall density of the mixture. However, once enough water is added to the mixture, water (which has a significantly lower specific gravity than soil solids) begins to replace the soil particles in the structure, resulting in a reduction in the overall dry unit weight of the soil (Figure 1). Considering these two factors, a bell shaped curve is produced when the dry unit weight of soil, at a given compactive energy, is plotted as a function of moisture content. The peak dry unit weight on this curve is considered to occur at the optimum moisture content (Coduto 1999).

Figure 1. Schematic of a typical compaction curve

The concept of the bell shaped curve plays a key role in field compaction. Because the bell shaped curve is for a given compactive effort, the greatest compaction efficiency occurs at optimum moisture content. Therefore, it is common industry practice to modify the in situ moisture content of soil to optimum prior to compaction (Terzaghi et al. 1996).

Soil parameters also effect mechanical stabilization. The coarse grained and fine grained components of soil each have a unique effect on stabilization. The structural arrangement of the coarse grained soil component transitions into new packing arrangements as energy is applied. The change in dry density of a soil during compaction is largely affected by the ability of soil particles to move past one another. Heavy tamping, vibration, and blasting are particularly effective in breaking down the existing particle arrangements (Mitchell 1981). Vibration works well due to the lack of cohesion in the coarse grained soil, and because the gravity of these larger particles is greater than the surface forces (Holtz et al. 2011).

Though water and mechanical compaction can increase the overall dry unit weight, it is impossible to gain 100% efficiency in the particle arrangement, and remove all air voids. A study using marbles and vibration determined that under idealized conditions, the maximum ratio of dry unit weight of uniform spherical particles to the dry unit weight of solids was 60 to 64%. If uniform spherical particles that were at least four different sizes, with at least a sevenfold difference in size between sphere diameters, an idealized maximum dry unit weight of 95% of the dry unit weight of solids could be reached. The relative densities were determined to be independent of size and specific

gravity (McGeary 1961). Therefore, the gradation of soil has an impact on the overall density and packing arrangement of a given soil matrix.

Compaction of fine grained materials is influenced by plasticity and orientation of soil fabric. For fine grained materials, the maximum dry density generally decreases as the plasticity increases (Holtz et al. 2011). Independent of compactive effort, as the moisture content increases, the physical arrangement of the soil fabric becomes increasingly oriented. Dry of optimum moisture content, soil particles are flocculated (i.e., randomly oriented), and wet of optimum the soil fabric is dispersed (i.e., parallel orientation). The transition between flocculated and dispersed soil structure occurs near optimum moisture content (Mitchell 1993).

Two differing theories have been proposed to explain the orientation of fine grained soils during compaction. Lambe (1958) introduced the particle orientation theory that assumes soil is initially oriented in a flocculated pattern. The addition of compactive energy and water (lubricant) transition the particles to become increasingly oriented, reducing the void space and increasing the dry unit weight. When water is added at rates above the optimum moisture content, the clay particles become dispersed, and float in the additional water, causing a reduction in the overall dry unit weight.

The clod theory proposed by Olsen (1962) describes the initial soil condition in clods, or clusters. The addition of water during compaction reduces the inter-particle attraction, and allows the clods to break down into a more dense arrangement with less energy, increasing the overall dry unit weight. When water is added wet of optimum, water prevents the clay particles from packing as tightly, and therefore reduces the overall density.

Compactive effort for dry of optimum moisture contents has a greater effect on increasing the dry density than for wet of optimum moisture contents. The increased dry density dry of optimum is attributed to increased initial voids from the flocculated soil fabric, and because the soil will transition from a flocculated to dispersed structure with additional compactive effort (Holtz et al. 2011).

Soil structure has an effect on the engineering properties of soils. Soils with flocculated structure tend to have a lower density, increased shear strength, increased stiffness, and increased hydraulic conductivity. Soils with a dispersed structure tend to be packed more tightly together, resulting in an increased density and decreased hydraulic conductivity. However, the parallel orientation causes a lower shear strength and stiffness due to preferential shear planes (Coduto 1999, Holtz et al. 2011). Additional soil parameters that influence the effectiveness of compaction within a composite soil matrix include: specific surface, gradation, surface texture, angularity, and sphericity (Mitchell 1993).

An increase in compactive effort applied to a given soil type will result in an increased maximum dry unit weight. As the maximum dry unit weight increases, the optimum moisture content generally decreases (Figure 2). At higher densities, the void space is reduced, and water begins to replace the soil particles at a lower moisture content, reducing the optimum moisture content.

Figure 2. Compaction curves for varying compactive efforts
(from Holtz et al. 2011 after Turnbull and Foster 1956)

The laboratory compaction test (i.e., ASTM D 698-07 and ASTM D 1557-07 (ASTM 2011)) was developed to determine a moisture density curve comparable to what is typically achieved for same material when compacted by means of the equipment and procedures typically used in the field. The energy applied in the standard and modified effort laboratory compaction tests were designed on this basis (Terzaghi et al. 1996).

Per ASTM D 698-07 and ASTM D 1557-07 (ASTM 2011), the standardized unit energy applied in the compaction tests are $600 \text{ kN}\cdot\text{m}/\text{m}^3$ [$12,400 \text{ ft}\cdot\text{lb}/\text{ft}^3$] or $2,700 \text{ kN}\cdot\text{m}/\text{m}^3$ [$56,000 \text{ ft}\cdot\text{lb}/\text{ft}^3$] for the standard and modified compaction tests, respectively. If the compaction energy is held a constant, only water and soil parameters remain as variables to determine the dry density.

2.2.2 Field Compaction

A variety of methods exist to compact soils in the field. Common methods include: in-situ densification (i.e., standard compaction with a roller), vibro-compaction, vibro-displacement compaction, precompression, injection, and grouting (Mitchell 1981, ASCE 1978).

Two standard specification types are used to implement field compaction: method (i.e., procedure) specifications, and end-product (i.e., performance) specifications. The method specification outlines the compaction specified by the engineer (i.e., type and weight of compactor, number of passes, lift thickness). The end product specification requires a minimum final condition, typically in terms of relative compaction or other measureable engineering parameters (Holtz et al. 2011). Relative compaction is the field dry density relative to the laboratory maximum dry density. Typical minimum required relative compaction values are 90% or 95% of the laboratory maximum (Holtz et al. 2011).

Compaction is conducted in the field because it is imperative to maintain mechanical stability under roadways and other infrastructure. To ensure adequate support is met, standard specifications have been developed to provide minimum engineering property parameters. In addition to meeting the minimum engineering property requirements, roadway design takes credit for the actual strength and stiffness of each roadway layer to determine the required thickness (Banks 2002, Caltrans 2006). Therefore, the thickness of the roadway, and subsequent costs of building the roadway, can be reduced if the roadway materials have engineering parameters greater than the minimum thresholds.

2.3 Chemical Stabilization

Chemical stabilization is a viable improvement option when mechanical stabilization does not sufficiently enhance engineering properties, or when the desired engineering properties can be achieved more economically with the use of chemical amendments (Ingles and Metcalf 1973). Four traditional chemical stabilizers have extensively researched and used in modern practice: cement, lime, fly ash, and asphalt emulsion. The associated stabilization mechanisms are understood, and application guidelines and laboratory testing methods are in place (Newman and Tingle 2004, Rauch et al. 2003). Of the four traditional additives, portland cement and lime are the most widely used (Terzaghi et al. 1996).

More recently, several nontraditional additives have been developed including salts, acids, enzymes, lignosulfonates, petroleum emulsions, polymers, and tree resins (Santoni et al. 2002, Rushing and Tingle 2005). Limited research has been reported to identify the fundamental mechanisms for stabilization (Santoni et al. 2002, Newman and Tingle 2004, Rauch et al. 2003).

2.3.1 Cement Stabilization

Cement stabilization has been used extensively in the United States since World War II for slope protection; increasing the bearing capacity under roadways and structures; and decreasing hydraulic conductivity of earthen dams, levees, and landfills (ACI 1990).

Soil cement is a mixture of soil, a specified percentage of portland cement, and water compacted to a high density (ACI 1990). Type 1 or type II cement may be used for stabilization (ACI 1990). Type II is recommended if there is a risk of the presence of

sulfates in the soil. The addition of cement at low percentages (up to 2%) will modify the properties of the soil. Larger addition rates on the order of 5-10% will radically change the properties and often transition the behavior to that of full strength concrete (Ingles and Metcalf 1973). ACI (1990) recommends cement addition rates between 4 and 16% for soil cement. In general, strength increases linearly with cement content (Ingles and Metcalf 1973). The effectiveness of cement varies by soil type (Figure 3). In general, as the clay fraction of soil increases, the required cement increases (ACI 1990).

Figure 3. Unconfined compressive strength relative to cement amendment rate for varying soil types (Ingles and Metcalf 1970)

Generally the limitation of maximum cement addition rate is cost. Within reason, cement is added until the desired engineering properties are reached (Ingles and Metcalf 1973). However, at excessive addition rates, shrinkage cracking becomes an issue (Ingles and Metcalf 1973, Gaspard 2000).

Cement stabilization occurs by hydration. When cement is added to the soil, it draws existing moisture from the soil to form calcium-silicate-hydrate paste that bonds the soil particles together. Cement stabilization is independent of soil mineral composition (Gaspard 2000).

The most common measures of effectiveness in cement stabilization are unconfined compressive strength, resistance to wetting-drying or freezing-thawing conditions, and CBR (California Bearing Ratio) (Ingles and Metcalf 1973). Typically, the addition of cement results in an increase in strength, wet-dry, and freeze-thaw durability (Ingles and Metcalf 1973).

ACI (1990) has established minimum strength and durability guidelines for cement amended soils. Unconfined compressive strength is the most widely referenced property of soil cement ACI (1990). However, in many applications both strength and durability requirements must be satisfied to obtain satisfactory service conditions. Minimum strength requirements vary depending on the application. For roadway applications, minimum requirements are maintained by different organizations including the United States Army Corps of Engineers (USACE) and state departments of transportation. These values generally range between 1400 and 5500 kPa [200 and 800 psi], depending on the state, the thickness of the layer, and the distance between the treated soil and the top of the road surface (ACI 1990, Gaspard 2000).

The Portland Cement Association (PCA) and the USACE have set minimum durability limits as a function of maximum allowable percent weight loss requirements for the wet-dry and freeze-thaw durability tests. Maximum allowable weight loss requirements vary depending on AASHTO soil classification type or percent and type of

fines, and range between 6 and 14% of the original specimen mass (ACI 1990). ASTM D 559-03 and ASTM D 560-03 (ASTM 2011) are test methods used to determine the amount of cement needed to hold the mass of soil together permanently and to maintain stability under the shrinkage and expansive forces that occur in the field (ACI 1990). Due to the extensive time required to run the wet-dry and freeze-thaw durability tests, a correlation to unconfined compressive strength is often used to ensure adequate durability. For example, in the United Kingdom, the durability of a soil is typically considered adequate if the soil has a minimum unconfined compressive strength of 17.6 kgf/cm² [250 lb/in²] (Ingles and Metcalf 1973).

2.3.2 Lime Stabilization

Calcium hydroxide (hydrated lime) or calcium oxide (quicklime) are commercial products available for lime stabilization. Hydrated lime is more stable for storage, and therefore is more commonly used in practice for lime stabilization. Agricultural lime (calcium carbonate) is not the same as hydrated lime and is relatively ineffective in soil improvement (Ingles and Metcalf 1973).

Lime is used extensively to change the engineering properties of fine-grained soil and the fine grained fractions of predominately granular soils. A minimum clay content of 10 to 25% and a plasticity index greater than 10 is required for effective lime stabilization (Berger 2011, Mallela et al. 2004). The soil composition is more important with lime stabilization than cement stabilization because it requires silica and alumina from the soil. Lime is typically more effective than cement in heavy clay soils. The moisture content of the soil at the mixing stage is less important for lime amendment than with cement stabilization (Ingles and Metcalf 1973). It has been reported that lime is

generally effective in reducing the plasticity, compressibility, and swelling potential of clays (Terzaghi et al. 1996). Lime is typically used to reduce the plasticity level of soil to acceptable levels.

Applying lime in slurry or powder form was determined to be equally effective (Ingles and Metcalf 1973). When lime is added to soil, the initial reaction in the mixture is the flocculation/agglomeration of clay particles. This flocculation occurs when the free calcium in the lime exchanges with the adsorbed cations of the clay, resulting in a reduction in the highly diffused water layer surrounding the clay particles (Geiman 2005, Malella 2004). Then, a secondary long-term reaction begins as the lime reacts with the clay minerals of the soil through a pozzolanic reaction, to forming a cementitious gel. The silica and alumina in the clay become available for a pozzolanic reaction in a high pH environment (that is produced by lime). The calcium in the lime and excess water react with the silica and alumina to create cementitious calcium-silicate-hydrates or calcium-aluminate-hydrates. A schematic of the pozzolanic reaction is presented in Figure 4. The reaction continues as long as moisture is available, and silica and alumina remain available by the pH of the soil mixture remaining above 10.5. This reaction results in a slow strength gain that occurs over a long period of time (Berger 2011, Ingles and Metcalf 1973).

Figure 4. Mechanism of lime stabilization of clay soils (Ingles and Metcalf 1973)

The unconfined compressive strength of soil-lime mixtures typically increases with increasing lime content to approximately about 8% addition (Figure 5). Because the pozzolanic reaction is a secondary reaction, the strength gain is relatively slow. Therefore, it is typically not accounted for in the strength design of the soil, especially if the soil is loaded shortly after mixing (Ingles and Metcalf 1973).

Figure 5. Unconfined compressive strength relative to lime amendment rate for varying soil types (Ingles and Metcalf 1973)

A common measure used to determine how much lime is needed to induce long-term stabilization is pH. Eades and Grim (1966) determined that if the soil lime mixture has an initial pH above 12.4, sufficient lime has been added to induce long-term stabilization.

2.3.3 Polymer Stabilization

Polymers consist of long hydrocarbon chains. Polymers are present in many industries including food, cosmetics, paint, and road construction. The polymer industry is larger than the aluminum, copper, and steel industries combined (Chappat 1994).

Polymers are easily modified, resulting in potentially endless combinations of polymers used in different industries. Many different polymers have been proposed as soil stabilizers, including cationic, anionic, and non-ionic (Ingles and Metcalf 1973). Studies have determined that most chemical stabilizers react with soil in one of two ways:

the additive relies on specific chemical reactions with soil particles, or the additive provides physical stabilization through the use of binding agents. Polymers fall into the latter category (Tingle et al. 2007).

In general, a polymer for soil stabilization should have excellent physical properties including high tensile, flexural, and compressive strengths, good adhesion to soil particles, and a high resistance to water, chemical, and ultraviolet effects (Newman and Tingle 2004, Tingle et al. 2007).

The most common polymers used in soil stabilization today are vinyl acetate or acrylic based copolymers. These polymer emulsions typically consist of 40-50% solid particles by weight of emulsion (Newman and Tingle 2004, Rushing and Tingle 2005, Tingle et al. 2007).

Acrylic copolymers are designed to conglomerate soil particles into a solidified matrix with superior engineering properties (Terratech 2012). Acrylic copolymers are dispersed in an aqueous polymer emulsion by surfactants, or wetting agents when mixed with the soil. The polymer then cures by the evaporation of the water, and the remaining polymer particles coalesce to form a continuous film of polymer around the aggregate. This cemented bond creates additional strength between the soil particles as displayed in Figure 6 (Feller 1966, Rushing and Tingle 2005). Because the primary stabilization mechanism of polymer is physical bonding, strength improvement depends on the ability of polymer to adequately coat the soil particles. The strength improvement also depends on the physical properties of the polymer. Therefore, polymers are typically less effective per unit of addition with fine grained soils due to the higher specific surface area, as compared to coarse grained soils (Tingle et al. 2007).

Figure 6. Difference between frictional and physical bonding (Scholen 1995)

Limited testing has been completed on polymer amended soils to date. Most laboratory and field experimentation with nontraditional additives, including polymers, have had a focus on performance evaluation rather than mechanism evaluation. Also, due to the proprietary nature of the commercial stabilization additives, exact chemical compositions are commonly not disclosed. Therefore, relatively little is published regarding the fundamental stabilization mechanisms between non-traditional stabilizers and geotechnical materials, and what was known tends to be subjective (Tingle et al. 2007, Muhunthan and Sariosseiri 2008, Rauch et al. 2003). Some of the products are soil specific or environment sensitive. So some polymers may work well in specific soil types or a given environment, but perform poorly in another soil type or other environment.

Rauch et al. (2003) investigated the mechanisms of an inorganic, sodium silicate based polymer stabilizer. This polymer was tested on illite, montmorillonite, and kaolinite clays, as well as two natural high plasticity clays.

Mixed results have been published regarding the success of polymer based soil stabilizers. Newman and Tingle (2004) determined that acrylic copolymer amendments

improve the strength of soil at addition levels below those of typical cement stabilization. Newman and Tingle also noted that all acrylic copolymers tested had higher strengths than control strengths. Roosevelt (2005) completed a field test with an acrylic polymer (i.e., Soiltac) and concluded that soil stabilizers mixed with crusher run stone do not increase the stiffness or bearing capacity of the material. Rushing and Tingle (2005) determined that polymer emulsions provide excellent initial dust mitigation. The material physically adhered to soil particles and provided bonding. However, heavy wheeled and tracked vehicles were able to break the bonds at the road surface. They also noted that once the soil matrix was disturbed it could not be restored without the addition of additional polymer. Though each of these test programs tested the same type of polymer, each tested different parameters, and used a different proprietary product.

Santoni et al. (2005) conducted a test program with 6 polymers added to silty sand (SM) with an accelerated curing duration. Of the six polymers tested, only one had higher unconfined compressive strength than the control after 7 days. Increased strengths were demonstrated when cement was added as an accelerator.

Santoni et al. (2002) conducted a test program on silty sand (SM) with 28-day curing periods, and unconfined compressive strength as the engineering parameter of comparison. Three polymers were tested at application rates of 0.1% to 5% by dry weight. The polymer additives gained significant strength with time over their 28-day curing duration. Polymer amended specimens had an average of 57% increase in strength in the dry test condition, and 221% in the wet test condition relative to control. An optimum polymer addition rate to obtain maximum unconfined compressive stress was identified. Finally, it was concluded that nontraditional stabilizers gained strength over a

shorter time duration than traditional stabilizers. A summary of the test results is presented in Figure 7 (Santoni et al. 2002).

Figure 7. Increase in unconfined compressive strength as a function of polymer addition rate and time (Santoni et al. 2002)

The addition of acrylic polymer to date has provided mixed results. This may be partially attributed to a lack of standard testing basis. Most case studies used varying soil types, curing periods, and addition rates.

A standard for preliminary evaluation of admixtures for improving engineering properties of fine grained soils is outlined in ASTM D 4609-08 (ASTM 2011). This test is used to evaluate moisture content, particle size, liquid limit, plastic limit, plasticity index, moisture density relations, volume change, and unconfined compressive strength to determine if the admixture possesses enough improvement to warrant further testing. However, Jones (2007) noted that the criteria important for determining enhanced

engineering performance were: resistance to abrasion, resistance to erosion, resistance to leaching, increased shear strength, long term durability, and maintainability.

2.4 Summary

In summary, the proprietary nature of polymer has limited the quantity of testing data published to date. A portion of the data published to date displays potential for improving the engineering properties of soil with the addition of acrylic copolymer, warranting further research. However, the lack of standardization for testing polymer amended soils has led to a variety of test arrangements and basis for comparison. Furthermore, the limited scope within each of these previous test programs does not provide sufficient data to distinguish between products that deliver enhanced performance and those that do not.

Therefore, a test program is needed that evaluates a single polymer product, and conducts a systematic and extensive series of engineering property tests to obtain comparable data on the performance of polymer amended soils across the range of conditions typically encountered in industry. An all-inclusive test program would provide a standard basis to compare the performance of polymer amended soil over typical field conditions. Furthermore, an all-inclusive test program would assist with drawing accurate conclusions, and gaining an understanding of the mechanisms facilitating change in the engineering properties with the addition of polymer. Based on these needs, an all-inclusive test program was developed and executed as described in the following chapters.

CHAPTER 3: EXPERIMENTAL TEST PROGRAM

3.1 Introduction

An extensive laboratory test program was undertaken to evaluate the engineering properties of polymer amended soil. The objectives were to determine the influence of soil types, moisture content, and polymer addition rates on engineering properties. In addition, comparisons were made between polymer modified soil and soil modified with traditional chemical stabilizers, namely lime and cement.

The test program is outlined in this chapter. First, the materials used in the program, including the test soils and the soil amendments are described. Then, procedures for preparation of each of the soils and index tests are described. An overview of the tests conducted to determine the engineering properties of both the control (i.e., non-amended) and amended soils in the test program are then provided. The tests conducted included: compaction tests, shear strength tests (unconfined compressive strength and direct shear), durability tests (wet-dry and freeze-thaw), and resilient modulus tests. Finally, this chapter describes the matrix of specimens prepared and test variables incorporated to achieve the project objectives. The logistics of testing operations, organization and specimen identification schema are also detailed.

3.2 Test Soils

Materials in the test program included four test soils and three amendments. Each of the four test soils were engineered and manufactured by combining multiple soils to obtain desired plasticity and gradation characteristics. Index tests were conducted on each of the component soils to determine proper mixture ratios, and again on the mixed soils,

to assure that target parameters were obtained. Each of the test soils, amendments, index tests, and soil classifications are discussed herein.

Soil parameters were selected to maximize the impact of the test results to represent the greatest breadth of soil types suitable for use as roadway subbase, while using a limited number of test soils. To achieve this, target plasticity and grain size distributions were selected as outlined in Table 1. Preparing specimens in this manner covered soils with no fines, low fines, and moderate fines at varying plasticity rates. The overlap in soil conditions allowed for isolation of soil parameters, to enhance opportunity for investigation of test variables.

Table 1. Target Parameters for Fine Grained Fraction of Test Soils

Soil Parameter	Soil 1	Soil 2	Soil 3	Soil 4
Plasticity	Non Plastic	Low Plasticity	High Plasticity	High Plasticity
Fines Passing 0.075 mm sieve (%)	0	15-17	15-17	30-40

Parameters for the coarse fraction of the soil were also established. Coarse components were incorporated into the soil mixtures to obtain gradations similar to Caltrans Class II type AB aggregate gradation envelope as presented in Figure 8. In addition, the coarse fraction was designed to be as similar as could be practically obtained between samples. A sand size fraction was obtained and used as a filler as necessary to avoid gap grading.

Figure 8. Caltrans Class II aggregate base envelope (Caltrans 2006)

After target grain size distribution and plasticity parameters were established for the test soils, local soils were obtained. To collect the coarse gravel fraction, with particle sizes ranging between 19.1 mm [0.75 in.] and 4.75 mm [No. 4] sieves, two crushed granite soils were obtained from a local quarry. One soil was well graded, entirely passing the 19.1 mm [0.75 in.] sieve, and the other was a 9.5 mm [0.375 in.] soil with no fine fraction. To collect the medium sand fraction, ranging from the 4.75 mm [No. 4] sieve to the 0.075 mm [No. 200] sieve, soils were obtained from a variety of sources including: the finer portion of crushed granite (from the coarse fraction), the coarse fraction of the collected fine grained soils, and a local washed sand from the Santa Maria Valley. To collect the fines fraction, three soils were obtained from local construction sites. These fine-grained soils contained a mixture of sand and fines, and exhibited signs of various levels of plasticity.

3.2.1 Index Tests

Subsequent to obtaining the local soils, a detailed investigation was completed to determine the soil constants prior to final mixing. The D_{60} , D_{30} , D_{10} , C_c , C_u , and percent fines were determined for the coarse and medium fraction following procedures outlined in ASTM D 421-07 and ASTM D 422-07 (ASTM 2011), and as further described below. For the fine fraction, the aforementioned tests were completed. In addition, the hydrometer test following ASTM D 421-07 and ASTM D 422-07 (ASTM 2011), and the Plastic and Liquid Limit test following ASTM D 4318-05 (ASTM 2011) were completed. The soil was then classified according to the USCS classification system as outlined in ASTM D 2487-06 (ASTM 2011) and the AASHTO classification system as outlined in AASHTO (1993). The specific gravity test following ASTM D 854-06 (ASTM 2011) was also conducted for the final mixtures representing the test soils. A more detailed account of each of these tests, and steps followed in the laboratory, are described below.

Grain Size Distribution

The sieve and hydrometer tests were completed as outlined in ASTM D 421-07 and ASTM D 422-07 (ASTM 2011). Each test was performed using a minimum 500 g [1.1 lb] sample. Samples were first sieved on standard geotechnical sieves from the nominal aggregate size through the 2.0 mm [No. 10] sieve. The material passing the 2.0 mm [No. 10] sieve was then soaked in demineralized water with the dispersing agent, sodium hexametaphosphate (calgon). The hydrometer tests were conducted on each sample using a 152 H hydrometer. The tests were performed for a minimum duration of 24 hours and until the percent finer portion was less than 10%. Upon completion of the

hydrometer test, the soil used in the hydrometer test was passed through a 75 μm [No. 200] sieve. Material retained on this sieve was placed in the oven at 105°C [220°F] for a minimum of 24 hours before sieving the samples through all of the standard geotechnical sieves between 2.0 mm and 75 μm [No. 10 and No. 200].

Plastic and Liquid Limits

The standard tests for determining the liquid limit, plastic limit, and plasticity index of soils, also known as the Atterberg limits tests, were completed following the methods and procedures outlined in ASTM D 4318-05 (ASTM 2011). Due to the abundant presence of cations in the local tap water, demineralized water was used for all steps of this test. A sample large enough to provide a minimum of 200 g [0.44 lb] of soil passing the 0.425 mm [No. 40] sieve was obtained and wet sieved over the 0.425 mm [No. 40] sieve. The passing portion was placed in a convection oven at 60°C [140°F] and monitored until all free surface water evaporated, but the soil was still wet of the liquid limit. The soil was then worked by hand on a plastic limit plate with a liquid limit spatula until the moisture content was only very slightly greater than the liquid limit. A paper towel was used to remove excess moisture as necessary. The soil was then covered and allowed to stand for a minimum of 16 hours.

A multipoint liquid limit test was then performed following the steps outlined in Test Method A of ASTM D 4318-05 (ASTM 2011). A liquid limit device, following all specifications and calibrated as outlined in the standard, was used to determine the liquid limit. For each test, a groove was cut into the soil pat, and the cup was dropped at a rate of two blows per second until each of the soil halves made contact over the distance of

12.7 mm [0.5 in.]. The moisture content was adjusted, and the test was repeated until the samples had adequately closed the groove within 12-20 blows, 20-30 blows, and 30-40 blows. The moisture content of the soil at each of these points was determined, and the liquid limit was calculated following the three-point method.

The plastic limit was determined by rolling a 20 g [0.044 lb] soil sample on a plastic limit plate until the soil crumbled and was not re-formable at a 3.2 mm [0.125 in] diameter. A minimum of 6 g [0.013 lb] was collected, and the moisture content was recorded as the plastic limit.

Specific Gravity

The specific gravity test was completed on the final engineered test soils. The test was completed using water pycnometers, following the methods outlined in ASTM D 854-06 (ASTM 2011). A vacuum system was used for all de-airing operations. To calibrate the two 250 mL pycnometers, each was filled with grade 1 de-ionized water and de-aired. After reaching thermal equilibrium in an insulated container, the mass was recorded five times with minimum three hour intervals between readings. These measurements were verified to be within a 0.05 mL tolerance prior to commencement of the specific gravity test.

The test was performed on oven dry soil following Method B of ASTM D 854-06 (ASTM 2011). After the soil was added, water was added until the water level was 1/3 to 1/2 of the depth of the main body of the pycnometer, and the soil-water solution was de-aired for approximately eight hours. The pycnometer was then filled to the calibration line with de-aired water using a small tube. The total mass was obtained prior to oven

drying the water-soil solution to determine the solids content. The recorded values were then used to determine the specific gravity.

3.2.2 Classification

Upon completion of the index tests, soil parameters were used to classify the soil following two methods: USCS classification following ASTM D 2487-06 (ASTM 2011), and AASHTO (1993). The results were compiled as follows: soil parameters for the coarse and sand size fraction of the collected soils are presented in Table 2; soil parameters for the fine fraction of the collected soils are presented in Table 3.

Table 2. Properties of Coarse Grained Components of Test Soils

	Parameter	Sand	Std. Class II	3/8" Drain Rock
Gradation Data	D ₆₀ (mm)	0.8	7.0	6.8
	D ₃₀ (mm)	0.4	1.1	4.3
	D ₁₀ (mm)	0.2	0.2	2.3
	C _c	0.9	0.8	1.2
	C _u	4.0	32.6	3.0
	Fines (%)	2.2	2.9	0.6
Atterberg Limits	Plastic Limit	NP	NP	NP
	Liquid Limit	NP	NP	NP
	Plasticity Index	NP	NP	NP

NP = Non Plastic

Table 3. Properties of Fine Grained Components of Test Soils

	Parameter	Fines #1 (LCL)	Fines #2 (LCH) ^a	Fines #3 (HCH)
Gradation Data	D ₆₀ (mm)	0.2	-----	0.1
	D ₃₀ (mm)	-----	-----	-----
	D ₁₀ (mm)	-----	-----	-----
	C _c	-----	-----	-----
	C _u	-----	-----	-----
	Fines (%)	17.0	40.8	17.6
Atterberg Limits	Plastic Limit	13	11	17
	Liquid Limit	32	58	60
	Plasticity Index	19	47	44

----- = No reported data

a = 11% (by dry mass) non-amended Standard Western National Bentonite clay added to increase plasticity to target value

Soil Mixing Procedure

The tabulated soil parameters for the test soils were analyzed from the perspective of the previously stated objective to establish final mixture ratios. The percentage of each of the components used to prepare the test soils are outlined in Table 4.

Prior to mixing, the moisture content was determined and the ratios were adjusted to account for water in the mixture. Also, several mixing methods were tested to determine which method resulted in the most uniform mixture. These methods included the use of a concrete mixer, a mortar mixer, and hand mixing method using a "walking" technique in which the soil was spread on a concrete surface and piled over itself (Figure 9).

Table 4. Mixture Ratios of Soil Components Contributing to Final Test Soils

Soil Component	SAND	LCL	LCH	HCH
Std. Class II Base	X	87%	X	76%
WP Sand	53%	X	37%	X
3/8" Drain Rock	47%	X	36%	X
Fines #1 (LCL)	X	13%	X	X
Fines #2 (LCH)	X	X	27%	X
Fines #3 (HCH)	X	X	X	24%

X = No soil component added

The hand mixing method yielded the most uniform soil. Soils were mixed in small batches of 45 to 136 kg [100 to 300 lb]; until the minimum target volume of 0.75 m³ [1.0 yd³] was manufactured for each of the four test soils.

Figure 9. a) Pouring measured quantities of soil out to be mixed, b) Hand mixing soil using the "walking technique"

The testing program required several hundred specimens to be prepared following the protocol outlined in ASTM D 698-07 (ASTM 2011). According to this standard, 9.5 mm [0.375 in.] was the nominal allowable aggregate size for test method B of the standard, which uses the 101.6 mm [4 in.] diameter mold. In addition, for soils containing aggregate larger than 9.5mm [0.375 in.], a maximum of 25% of the total sample by mass may be removed by discarding the fraction retained on the 9.5 mm [0.375 in.] sieve.

Each of the four test soils contained aggregate larger than 9.5 mm [3/8 in.]; therefore, grading was required. To ensure uniformity between tests and increase efficiency, each test soil was processed using a 9.5 mm [0.375 in.] sieve prior to storage (Figure 10). During sieving, the coarse fraction was closely monitored to ensure that no clods of fines were retained with the coarse aggregate. The fraction retained from sieving was within the 25% allowance and was discarded.

Figure 10. Sieving test soils prior to storage

Scalping the soil resulted in two gradations: one representative of field conditions, and the other as tested in the laboratory. As a result, an innumerable amount of potential field gradations could have resulted in these modified test soils. Likewise, the modified test soils represent many possible original field gradations as displayed in Figure 11. ASTM D 4718-07 (ASTM 2011) addresses this concern by translating moisture and dry unit weight corrections between the modified condition as tested, and the original field conditions. Because these test conditions do not represent specific field conditions, these corrections are not applicable to this testing program. Therefore, all results from this experimental test program will be presented from the soil in its modified condition.

Figure 11. Grain size distribution of test soil, and corresponding potential field gradations based on scalping allowances in ASTM D 698-07 (ASTM 2011)

The test soils were stored in individual containers. Each 1.0 m^3 [1.25 yd^3] container, presented in Figure 12, was lined with 0.15 mm [6 mil] thick plastic to reduce fluctuation in moisture content, designed to provide mobility with a pallet jack, and shingled for outdoor durability.

Figure 12. Test soil storage containers

Test Soil Characterization

After manufacturing each of the final test soils used in this testing program, all index tests were conducted again. In addition to the index tests, the specific surface of each final test soil was calculated based on idealized soil particles and diameters from the grain size distribution. A summary of the test soil characterization tests are outlined in Table 5. Even though the fines contents of the scalped test soils are slightly finer than the target values, the potential field gradations include fines contents within the target range. The grain size distributions for each test soil are displayed in Figure 13. For clarity, only the bounds of the potential gradations are displayed.

Table 5. Classification Data for Test Soils

	Parameter	Soil			
		SAND	LCL	LCH	HCH
Gradation Data	Nominal Diameter (mm)	9.5	9.5	9.5	9.5
	D ₆₀ (mm)	3.3	1.1	1.1	0.7
	D ₃₀ (mm)	0.6	0.3	0.2	0.03
	D ₁₀ (mm)	0.3	0.06	0.1	0.00
	C _c	0.4	1.6	0.4	0.9
	C _u	12	18	8	522
	Fines (%)	2.5	17.0	17.6	40.8
	Specific Surface ^a (m ² /kg)	4	52	54	141
Atterberg Limits	PL	NP	17	12	13
	LL	NP	27	34	42
	PI	NP	10	22	29
Specific Gravity	G _s	2.68	2.66	2.63	2.68
Soil Classification	USCS	SP: Poorly Graded Sand	SC: Clayey Sand with Gravel	SC: Clayey Sand with Gravel	SC: Clayey Sand with Gravel
	AASHTO	A-1-a (1)	A-2-4 (0)	A-2-6 (0)	A-7-6 (6)

NP = Non plastic

^aSpecific surface based on calculations assuming idealized particles with diameters determined from the grain size distribution curve

Each of the test soils were given a reference name. SAND represents the USCS classified SP test soil with a negligible percentage of low-plasticity fines. LCL represents the USCS classified SC test soil with a low percentage of low-plasticity fines. LCH represents the USCS classified SC test soil with a low percentage of high-plasticity fines. HCH represents the USCS classified SC test soil with a high-percentage of high-plasticity fines. The exact percentages passing the 0.075 mm [No. 200] sieve and the plasticity characteristics of each of these test soils are outlined in Table 5.

Figure 13. Grain size distribution curves for test soils and their corresponding range of potential field gradations

3.2.3 Polymer

An elastic copolymer was one of three soil amendments used to modify the soil in this test program. T Pro-500 (Terratech) polymer was received as an aqueous solution comprised of 65% polymer and 35% water. Prior to mixing with soil, additional water

was mixed with the polymer to ensure a uniform application and to represent conditions consistent with field applications.

Polymer was the primary amendment evaluated in the testing program. Therefore, the change in engineering properties due to polymer modification was evaluated on all four engineering test soils. Per manufacturer recommendation, the polymer was applied in addition rates ranging between 0.5 and 1.5%, with select specimens tested up to 2.5%, on a dry weight basis. In addition, a top-coat of polymer was applied to the outer surface of the wet-dry and freeze-thaw durability specimens.

3.2.4 Cement

Cement was the second soil amendment used in this test program. Cement was chosen because historically it was one of the original chemical soil modifiers used in industry, and because it results in significant strength gain in non-plastic and low-plasticity soils (Ingles and Metcalf 1973).

Type II/V portland cement was used in this testing program to stabilize the test soils. Type II/V portland cement was selected based on its sulfate resistance, availability, and its prevalence in industry. The change in engineering properties caused by cement modification was evaluated on SAND and LCL soils. Two aspects were considered when establishing the appropriate cement addition rate for the test program: industry practice and comparable strength gain to polymer amended soils. Based on these considerations, cement was applied at addition rates of 1 %, 2 %, and 4 % on a dry weight basis.

3.2.5 Lime

Lime was the final soil amendment used to in the test program. The use of lime was based on its extensive use in industry, and because it results in significant strength

gain in high-plasticity soils. While it was acceptable to use hydrated lime or quick lime for soil modification, hydrated lime was used in this test program because it was more commonly used in industry due to greater ease of storage (Ingles and Metcalf 1973). The change in engineering properties caused by lime modification was evaluated on LCH and HCH soils. Following industry protocol, the optimum lime addition rate was determined with the Eades and Grim Test.

The Eades and Grim Test, as outlined in ASTM D 6276-06 (ASTM 2011), was used to determine the lowest percentage of lime that produces a soil-lime mixture with a sustained pH of 12.4. Extensive testing has demonstrated that soil-lime mixtures that sustain this pH produce reliable long term stabilization (National Lime Association 2004).

Because the local tap water was deemed unsuitable according to ASTM specification D 1193-06 (ASTM 2011), grade 1 de-ionized water was used for all aspects of the Eades and Grim test. To begin testing, air-dried soil was sieved over a 0.475 mm [No. 40] sieve, and material passing through the 0.475 mm [No. 40] sieve was used for testing. The in-situ moisture content on this soil was then determined. Five small plastic bottles were prepared with 25 g [0.055 lb] of soil by dry mass. Lime was added to each bottle in increasing increments of 1%, relative to the dry mass of the soil. A control was also prepared with 2.0 g [0.004 lb] of lime. Then, 100 g [0.22 lb] of water was added to each of the bottles, and the samples were shaken for 30 seconds, every 10 minutes, for one hour.

A digital pH meter was calibrated with a pH 10 buffer solution at 25°C [77°F]. The value measured in the pH 10 solution was recorded as the probe pH. At the end of

the shaking period, the calibrated meter was placed in each sample and monitored until the output value reached a plateau of no increase in pH for 10 s. This value was recorded as the measured pH. Samples with increasing lime content were tested until two successive samples were recorded with no increase in pH. Due to laboratory constraints, this test was completed in two series. To ensure uniformity between tests, the lime addition rates were overlapped between the series. Upon completion of the tests, the measured pH values were corrected based on the probe pH calibration values, as displayed in Equation 1. The results are outlined in Table 6.

$$\text{pH}_{\text{corrected}} = \text{pH}_{\text{measured}} + (10 - \text{pH}_{\text{probe}}) \quad (1)$$

Table 6. Eades and Grim Test Data

Lime (%)	Mass of Lime (g)	Corrected pH
4	1.00	12.38
5	1.25	12.40
6	1.50	12.43
7	1.75	12.47
8	2.00	12.49
9	2.25	12.50
10	2.50	12.51
11	2.75	12.51
12	3.00	12.62
Control	2.00	12.64

Two methods can be used to determine the appropriate lime addition rate based on the test results. Either the smallest percentage of lime that results in a pH of 12.4, or the lowest percentage of lime where the subsequently higher pH does not rise for at least

two successive test samples was considered the threshold addition rate. Because the pH was rapidly increasing relative to the increase of lime in the 12.4 pH range, the latter method was used to determine the proper lime addition rate. Based on the results displayed in Table 6, a lime addition of 8% was determined the threshold addition rate.

3.3 Engineering Property Tests

Engineering property tests were conducted to determine a basis of comparison for the test specimens. The engineering property determined with their corresponding tests were as follows: moisture content / dry density relationships using the standard compaction test; shear strength using the unconfined compressive strength test and the direct shear test; durability using the wet-dry and freeze-thaw durability tests; and dynamic and static compressibility using the resilient modulus test and through interpolation of the stress strain curve of the unconfined compressive strength test. A more thorough description of each of these tests as well as steps taken to prepare the specimens are provided in the following sections.

3.3.1 Specimen Preparation

Prior to conducting any of the engineering property tests, it was necessary to prepare the soil specimens. First, in-situ moisture contents were obtained from the test soils. Then, all specimens taken from the test soils were split a minimum of three times to ensure uniformity across test specimens. Samples were split to a final target mass of 3.0 kg [6.6 lb] to provide adequate soil for specimen preparation as well as additional soil to complete a moisture content test. Divided soil was immediately stored in air-tight containers in an effort to minimize fluctuations in moisture content.

After determining the starting mass of soil, proper mixture ratios to obtain desired amendment addition rates and moisture contents were determined. Worksheets (Appendix A) were developed and used for the calculation to increase consistency and reduce error potential.

Once the mixture ratios were determined, soil amendments and water were added as applicable, following the steps outlined in Table 7. Mixing methods were initially set to ensure soil was thoroughly mixed, and to follow mixing methods similar to field application. If the specimen required the addition of polymer, then the polymer was diluted with water to a concentration of approximately one part polymer to two parts water prior to mixing to provide a more uniform application. If the specimen required the addition of cement or lime, then the additive was thoroughly mixed prior to adding any water. After adding amendments, any remaining required water was applied with a pressurized pump sprayer to ensure uniform application. After the mixing was completed, the test specimens were compacted as described in the following section.

Table 7. Soil Mixing Details

Step	Addition	Mixing Duration
1	Amendment	Until uniform by visual inspection
2	Water	Minimum 5 minutes - Mortar mixer, or Minimum 10 minutes - With hand trowel in a flat pan

3.3.2 Compaction

Compacted specimens served as a basis for much of the testing program. Unless otherwise noted, specimens for all engineering property tests were prepared following this method. All compaction specimens were prepared following procedures as outlined

in ASTM D 698-07 (ASTM 2011). Standard compaction was selected for this test program to enhance specimen preparation efficiency, thus maximizing the total number of prepared specimens. Standardized molds with a diameter of 101.6 mm [4 in] and a volume of 944 cm³ [1/30 ft³] were used to prepare specimens. The molds were periodically measured to verify that the diameters remained within the 0.4 mm [0.016 in] tolerance as stated in ASTM D 698-07 (ASTM 2011). Following industry practice, each mold was lightly coated with a silicone lubricant to assist with specimen extrusion. Molds were wiped with a clean rag after applying silicone lubricant to remove all excess lubricant to ensure there was no impact to the specimens. Specimens were then compacted either by hand or with an automatic compactor. A standardized 24.5 N [5.5 lb] manual rammer with a 305 mm [12 in.] drop height following all specifications as outlined in the standard was used to compact the specimens by hand. A mechanically operated hammer was also used to compact a portion of the specimens. The hammer was calibrated prior to use following ASTM D 2168-02a (ASTM 2011).

During compaction, soil was added in three layers, and compacted on a solid surface in the pattern as outlined in the ASTM standard. To ensure optimum adhesion, specimens were scarified to a depth of approximately 3.2 mm [1/8 in] between each layer with 8 grooves in each direction, creating a perpendicular hatch pattern. When the specimen was approximately 50% compacted, a minimum 500 g [1.1 lb] representative sample was taken from the un-compacted soil to obtain the moisture content. After the compaction was completed, the specimen was trimmed level with the top of the mold, and voids on the top surface were filled with soil as needed. The specimen was promptly weighed to determine the compacted mass. If it was apparent that the specimen had

enough cohesive strength to remain intact, it was extruded. If not, the specimen remained in the mold for the duration of the curing period. If the specimen was visibly compressed or deformed from the extrusion, it was discarded and a new specimen was prepared. During the curing period, the dry unit weight and moisture content was calculated and used to prepare compaction curves.

3.3.3 Strength

The shear strengths of the test soils were determined using the unconfined compressive strength test and the direct shear test. The unconfined compressive strength test was used to determine the strength of all soil types that exhibited cohesive properties, including LCL, LCH, and HCH. Because SAND did not exhibit cohesive properties, the direct shear test was used to determine the strength of these specimens.

Unconfined Compressive Strength

The unconfined compressive strength of specimens was determined following the protocol outlined in ASTM D 2166-06 (ASTM 2011). The specimens were prepared following the procedure for compaction tests. The specimens were then cured at room temperature for a duration of 7 days, with an 8 hour tolerance. Prior to commencing the test, the mass and specimen dimensions were recorded. For specimen dimensions, four diameter and three height measurements were recorded. The averages of these values were calculated and used for determining specimen lengths and areas. Caps were not placed on the specimens for the unconfined compression test.

Most tests were conducted at a compression rate of 1.27 mm/min [0.05 in/min], and only adjusted as needed to acquire specimen failure between 5 and 15 minutes.

Failure criterion used for the unconfined compression tests was when either three consecutive readings were recorded below the peak stress, or 15% strain was reached. To obtain accurate strain measurements, either two linear variable differential transformers (LVDTs) or two dial gauges were placed equidistant from the center of the platens, as displayed in Figure 14.

Figure 14. Unconfined compression test setup

The procedures in ASTM D 2166-06 (ASTM 2011) require that specimens conform to a minimum 2:1 height to diameter aspect ratio. The specimens used in this testing program measured a height of 116.3 mm [4.58 in] and a diameter of 101.6 mm [4.0 in]. Though the height to diameter aspect ratio of the specimens was smaller than the 2:1 requirement, they were still used because it greatly increased the overall testing efficiency by allowing the re-use the compaction specimens for this test. Furthermore, this practice has been used extensively in other research. Specimens prepared in a standard compaction mold exhibit approximately a 10% increase in strength compared to standard 2:1 unconfined compression specimens (ACI 1990). Because the test program

was a comparative study where all specimens were compared on a relative basis, this 10% difference was not accounted for in the unconfined compression test results.

Direct Shear

The shear strength of SAND was determined following protocol for the Direct Shear Test as outlined in ASTM D 3080-04 (ASTM 2011). Control specimens were prepared at various moisture contents. Polymer amended specimens were prepared at their optimum moisture content as determined from the compaction tests. All specimens were prepared at the dry density determined in the compaction test that corresponded to the selected moisture content. Three specimens were prepared for each test condition, and were tested at normal stresses of 5.9, 11.8, and 23.5 kPa [122, 246, and 491 psf]. A 100 mm [4.0 in.] box was used to ensure the testing device had a diameter 10 times the maximum nominal aggregate size.

Prior to preparing the specimens, precise measurements were taken to determine volume on the direct shear box to assist with density calculations. Then, sample mixtures were prepared to their required amendment rate and moisture content, and compacted into the direct shear box by consistently dropping a steel tamper from a height of 100 mm [4 in.] until the desired density was obtained. If the specimen did not contain polymer, it was tested immediately. If the specimen contained polymer, it was placed in the oven to cure at 43°C [110°F] for 72 hours. Curing was completed at an elevated temperature due to time constraints. The duration and temperature of the expedited cure was selected per the recommendation of the manufacturer.

For the polymer amended specimens, the direct shear box was lined with aluminum foil prior to compaction of the specimen. The aluminum foil was used to lift the specimen out of the box after 24 hours of curing. The specimen was then cured for the remaining 48 hours outside the direct shear box, allowing the box to be used to prepare additional specimens. At the end of the curing period, each specimen was removed from the foil, and placed back in the direct shear box prior to testing.

Upon the completion of curing, specimens were sheared at a rate of 1.27 mm/min [0.05 in/min]. Shear load and vertical deformation dial readings were taken every 0.127 mm [0.005 in] of horizontal shear until three consecutive readings below the peak shear load were recorded.

3.3.4 Durability

Wet-dry and freeze-thaw durability tests were completed following protocol as outlined in ASTM D 559-03 and ASTM D 560-03, respectively (ASTM 2011). First, specimens were prepared following the same protocol used for unconfined compressive strength specimens. Then the durability specimens were cured, and a polymer top-coat was applied as required. Following an additional cure period, the specimens were conditioned through either wet-dry or freeze-thaw cycles. At the end of each conditioning cycle, specimens were scratched with an abrasive brush following protocol as outlined in ASTM D 559-03 and ASTM D 560-03 (ASTM 2011). The conditioning and scratching applied to each specimen was repeated for 12 cycles or until the specimen was completely deteriorated. Finally, in addition to this main testing program, several specimens were prepared for an additional experiment that evaluated the effectiveness of the polymer coating.

Durability Specimen Preparation

Specimens were initially prepared following the protocol outlined in section 3.3.1, and compacted following methods outlined in section 3.3.2. Specimens were then cured at room temperature for a duration of 7 days, with an 8 hour tolerance.

In the field, a top-coat is applied to the top surface of the amended soil, and it is assumed that the drainage of the road is such that the modified road subgrade is protected from water on the remaining surfaces. To replicate these moisture conditions in the laboratory, it was necessary to coat all sides of the specimen. This provided a similar moisture protection to the field condition, which was the primary function that affects the durability.

Therefore, upon completion of the 7-day cure, a polymer-water solution was applied as a top-coat to all exposed surfaces of all polymer amended specimens. A laboratory process that closely replicates field practice was developed to coat the specimens. A 1:1 polymer-water solution was mixed in small batches, and stirred continuously on a stir plate. The solution was then applied to the durability specimen at a rate of 400 mL polymer/m² exposed surface [1.28 oz polymer/ft² exposed surface], using a siphon feed air sprayer as displayed in Figure 15. The coating was applied evenly until the specimen increased by a pre-determined mass based on the addition rate and specimen area, assuming a unit weight of 1.0 for the polymer solution. If 100% saturation on the exterior of the specimen was achieved before the appropriate mass of polymer-water solution was applied, the specimen was set aside for 10-30 minutes to allow time for absorption before resuming coating. Upon completion of the polymer top-coat

application, all specimens (regardless of top-coat application) were cured for an additional 48 hours at room temperature with constant air circulation.

Figure 15. Coating cured specimens with polymer mixture

Specimen Conditioning

After the durability specimens were prepared and cured, they were subjected to 12 cycles of either wet-dry or freeze-thaw conditioning. Wet-dry conditioning was conducted following procedures as outlined in ASTM D 559-03 (ASTM 2011). For the wetting phase, specimens were placed on perforated metal sheets and submerged in potable tap water for 5 hours. The test setup was presented in Figure 16. For the drying phase, specimens were placed in a convection oven at 60°C [140°F] for 42 hours. Temperature was periodically measured with a digital thermocouple to ensure proper thermal conditions were maintained. Specimens were removed from the oven to cool for

a minimum of 15 minutes prior to specimen scratching to ensure that the integrity of the polymer coatings were not adversely affected by the elevated temperature.

Figure 16. Wet-dry conditioning test setup

Freeze-thaw conditioning was conducted following protocol as outlined in Method B of ASTM D 560-03 (ASTM 2011). Specimens were first subject to a 24-hour freezing period. A freezing chamber to contain specimens was assembled using a modified front-loading freezing chamber as displayed in Figure 17. A supplemental thermostat control was installed to enhance the cooling capabilities of the freezing chamber. In addition, approximately 180 kg [400 lb] of concrete was added to the freezing chamber to enhance the thermal inertia of the system, which reduced thermal fluctuations when specimens were introduced. Temperature was monitored with a digital thermocouple to ensure temperatures remained below the upper limit of -23.3°C [-10°F].

Figure 17. Freezing chamber for freeze-thaw durability tests
Note: soil specimens are located in the center, and concrete is located on the outside edges.

At the commencement of each cycle, specimens were placed on perforated steel trays lined with 6.3 mm [0.25 in.] thick saturated felt pads, and placed in the freezing chamber for 24 hours. Once specimens completed 24 hours in the freezing chamber, they were removed and subject to a thaw period of 23 hours, at 100% humidity and 21°C [70°F].

The thaw chamber, presented in Figure 18, was comprised of a large container filled with approximately 12.7 cm [5 in.] depth of water and covered with a fitted, insulating lid. A water heater and thermostat maintained the required 21°C [70°F] water temperature, while a submerged water pump circulated the water, creating a humid environment. Temperatures of both the water and the ambient air were constantly monitored to ensure they were properly maintained within the variation limits of 1.7°C

[3°F]. Accumulated water on the underside of the lid and sidewalls of the chamber provided evidence that the air in the chamber maintained 100% humidity while it was a closed environment. Blocks held the perforated trays of specimens 6 to 25 mm [0.25 to 1 in.] above the water level. During the thaw process, the specimens were set on a 6.35 mm [0.25 in.] thick layer of felt that was kept saturated to help maintain a high level of saturation.

Figure 18. Thawing chamber

Scratching

At the end of each conditioning cycle, specimens were subject to two brush strokes over the entire exposed surface area of the specimen with an ASTM standardized brush following the requirements of ASTM D 559-03 and ASTM D 560-03 (ASTM

2011). The brushing was conducted using 18 to 20 full-length strokes around the perimeter and 4 strokes on each end. For brush strokes around the perimeter, the long axis of the brush was kept longitudinal with the axis of the specimen. For strokes taken on the end, two strokes were completed, then the specimen was rotated 90 degrees and the remaining two strokes were completed. Stroke pressure was measured by placing the specimen on an electronic balance with the portion of the specimen to be scratched over the edge of the balance so that the stroke could be made vertically. Pressure was applied against the specimen so that the electronic balance registered approximately 13.3 N [3 lb] of force throughout the full length of the stroke. As a supplement to the ASTM requirements, a small platform consisting of grip tape, plywood, and weights was used to add additional friction to the electronic balance surface, and reduce specimen sliding. The configuration used for scratching specimens was presented in Figure 19. The masses of the specimens were measured at the beginning and end of the scratching process to determine the change in mass during each cycle.

Figure 19. Test setup for scratching specimens

3.3.5 Stiffness

Two methods were utilized to determine stiffness in this testing program. The slopes of the stress versus strain plots from the unconfined compression tests were analyzed to determine the stiffness of any specimen tested for strength. Methods used to determine the stiffness from the strength results are discussed in greater detail in Chapter 4. The second method was the resilient modulus test. The resilient modulus test was a dynamic triaxial test and was completed following protocol outlined in AASTHO T 307-99 (AASHTO 2003). The resilient modulus test was the more accurate of the two methods to determine stiffness, but due to the testing complexity and equipment limitations, only a limited number of tests were conducted.

The resilient modulus test was completed on a Geotechnical Consulting and Testing Systems (GCTS) triaxial testing frame machine using the GCTS Computer Aided Testing Software (CATS) program. For this test program, CATS was programmed to automatically control all applied stresses, and collect stress and deformation data at a rate of 50 readings per second. The triaxial cell used compressed air for confining pressure. Axial deformations were measured externally using two 7.62 mm [0.3 in.] Linear Variable Differential Transformers (LVDTs). Loads were measured on a 8.9 kN [2000 lb] load cell. Two 100 mm [4.0 in.] platens were milled to match the specimen size.

Specimens were prepared following procedures outlined in section 3.3.1, deviating only to accommodate a larger sample size. Specimens were compacted into a 101.6 mm by 203.2 mm [4 in. by 8 in.] split vacuum mold. All specimens maintained enough cohesion to maintain integrity without the use of a rubber membrane.

Soil was added to the mold in five lifts. Specimens were compacted with a vibratory hammer and a 100 mm [3.9 in.] diameter steel plate. Compaction effort was applied uniformly to each layer to until the desired pre-determined density was reached. The first four layers were scarified with eight 3.2 mm [0.125 in.] grooves in each direction, creating a perpendicular hatch pattern. Upon completion of compaction, the mold was opened and specimen removed. Specimens were cured for 9 days prior to testing.

At the commencement of the resilient modulus test, specimens were placed in the triaxial cell, and subjected to a conditioning phase of 2000 cycles. The conditioning phase provides realistic exposure for soil intended for transportation (i.e., subbase) applications. The conditioning phase typically involves the application of 500 to 1000 cycles of stress (AASHTO 2003). For this test program, 2000 cycles were used due to an unintentional modification in the test control program. It was expected that the extra cycles did not detrimentally affect the specimens and that this cycling was representative of a higher degree of simulated cycling of the subbase material.

Subsequent to the conditioning phase, the specimen was subjected to 15 individual sequences of testing with 100 cycles in each period. The stresses for each testing period are outlined in Table 8. Stress was applied using a haversine shaped load pulse with a duration of 0.1 s, followed by a 0.9 s rest period.

Table 8. Loading Configuration for Resilient Modulus Tests

Sequence No.	Confining Pressure, S_3		Max. Axial Stress S_{max}		Cyclic Stress S_{cyclic}		Constant Stress $0.1S_{max}$		No. of Load Applications
	kPa	psi	kPa	psi	kPa	psi	kPa	psi	
0	103.4	15	103.4	15	93.1	13.5	10.3	1.5	2000
1	20.7	3	20.7	3	18.6	2.7	2.1	0.3	100
2	20.7	3	41.4	6	37.3	5.4	4.1	0.6	100
3	20.7	3	62.1	9	55.9	8.1	6.2	0.9	100
4	34.5	5	34.5	5	31.0	4.5	3.5	0.5	100
5	34.5	5	68.9	10	62.0	9.0	6.9	1.0	100
6	34.5	5	103.4	15	93.1	13.5	10.3	1.5	100
7	68.9	10	68.9	10	62.0	9.0	6.9	1.0	100
8	68.9	10	137.9	20	124.1	18.0	13.8	2.0	100
9	68.9	10	206.8	30	186.1	27.0	20.7	3.0	100
10	103.4	15	68.9	10	62.0	9.0	6.9	1.0	100
11	103.4	15	103.4	15	93.1	13.5	10.3	1.5	100
12	103.4	15	206.8	30	186.1	27.0	20.7	3.0	100
13	137.9	20	103.4	15	93.1	13.5	10.3	1.5	100
14	137.9	20	137.9	20	124.1	18.0	13.8	2.0	100
15	137.9	20	275.8	40	248.2	36.0	27.6	4.0	100

Upon completion of the test, the data was exported. A MatLAB program was written to reduce the data (Appendix B), and the resilient modulus was determined based on the last five cycles of each sequence.

3.4 Testing Matrix

In this extensive laboratory test program, a series of engineering properties was evaluated over a range of soil, amendment, and moisture configurations to enhance understanding of the engineering significance of polymer modification. Variables in the testing program included soil type; moisture content; and polymer, cement, and lime amendment rates. Engineering properties determined throughout the test program

included dry unit weight – moisture content relationships through the use of compaction tests; shear strength through the use of unconfined compression strength tests and direct shear tests; durability through the use of freeze-thaw and wet-dry durability tests; and stiffness through the use of resilient modulus tests and through interpretation of the unconfined compression test results.

After completion of the classification tests, engineering property tests were divided into 3 testing matrices for each of the four soils. Testing Matrix 1 covered compaction, strength, and stiffness based on the strength results. Testing Matrix 2 covered durability, and testing Matrix 3 covered stiffness through the resilient modulus test. A visual schematic of the engineering property tests are provided in Figure 20.

Table 9 summarizes all initially scheduled tests. In the table, every combination of specimens between each set of horizontal lines was prepared. For example, compaction specimens for Testing Matrix 1 were prepared as follows: SAND and LCL specimens were prepared at control, 0.5%, 1.0%, and 1.5% polymer; and 1%, 2%, and 4% cement amendment rates. Specimens at each amendment rate were prepared at: optimum; 2% and 4% dry of optimum; and 2% and 4% wet of optimum. LCH and HCH specimens were prepared at control, 0.5%, 1.0%, and 1.5% polymer; 8.0% lime, and select specimens were prepared at 2.0% and 2.5% polymer. Specimens at each amendment rate were prepared at: optimum; 2% and 4% dry of optimum; and 2% and 4% wet of optimum. This methodology applies throughout the entire table.

^a1%, 2%, & 4% Cement added to SAND and LCL. ^b8% Lime added to LCH and HCH. ^cDoes Not Apply to Control

Figure 20. Engineering property testing program summary

Table 9. Summary of All Initial Scheduled Tests

	Test	Soil	Amendment and Addition Rate	Water Content ^{b,c}
Classification	Grain Size Distribution	SAND LCL LCH HCH	Control	N/A
	Hydrometer	SAND LCL LCH HCH	Control	N/A
	Liquid Limit	SAND LCL LCH HCH	Control	N/A
	Plastic Limit	SAND LCL LCH HCH	Control	N/A
	Specific Gravity	SAND LCL LCH HCH	Control	N/A
	Eades and Grim	LCH HCH	4% to 12% Lime (1.0% Increments)	N/A
Testing Matrix 1	Compaction	SAND LCL	Control 0.5% Polymer 1.0% Polymer 1.5% Polymer 1% Cement 2% Cement 4% Cement	Optimum 2% Dry of Optimum 4% Dry of Optimum 2% Wet of Optimum 4% Wet of Optimum
		LCH HCH	Control 0.5% Polymer 1.0% Polymer 1.5% Polymer 2.0% Polymer ^a 2.5% Polymer ^a 8% Lime	

^aSelected specimens; ^bRespective to each samples modified moisture content; ^cAdditional tests run as necessary to obtain minimum number of tests wet and dry of optimum; ^dOptimum based on combined properties; ^eSpecimens tested at 3 normal loads

Table 9. Summary of All Initial Scheduled Tests (Continued)

	Test	Soil	Amendment and Addition Rate	Water Content ^{b,c}
Testing Matrix 1	Strength: Unconfined Compression	LCL	Control 0.5% Polymer 1.0% Polymer 1.5% Polymer 1% Cement 2% Cement 4% Cement	Optimum 2% Dry of Optimum 4% Dry of Optimum 2% Wet of Optimum 4% Wet of Optimum
		LCH HCH	Control 0.5% Polymer 1.0% Polymer 1.5% Polymer 2.0% Polymer ^a 2.5% Polymer ^a 8% Lime	
	Strength: Direct Shear	SAND	Control	Optimum (x3) ^e 2% Dry of Optimum (x3) ^e 4% Dry of Optimum (x3) ^e 2% Wet of Optimum (x3) ^e
			0.5% Polymer (x3) ^e 1.0% Polymer (x3) ^e 1.5% Polymer (x3) ^e	Optimum
Testing Matrix 2	Durability: Wet-Dry	SAND LCL LCH HCH	Control 1.0% Polymer	Optimum 2% Dry of Optimum 4% Dry of Optimum 2% Wet of Optimum 4% Wet of Optimum
	Durability: Freeze-Thaw	SAND LCL LCH HCH	Control 1.0% Polymer	Optimum 2% Dry of Optimum 4% Dry of Optimum 2% Wet of Optimum 4% Wet of Optimum
Testing Matrix 3	Stiffness: Resilient Modulus	SAND LCL	Control ^d Polymer ^d Cement ^d	Optimum ^d
		LCH HCH	Control ^d Polymer ^d Lime ^d	Optimum ^d

^a Selected specimens; ^b Respective to each samples modified moisture content; ^c Additional tests run as necessary to obtain minimum number of tests wet and dry of optimum; ^d Optimum based on combined properties; ^e Specimens tested at 3 normal loads

The optimum moisture content of the amended specimens often varied from the control. When this variation occurred, additional specimens were prepared beyond the initial scheduled tests until a minimum of two specimens were prepared each wet and dry of optimum. After specimens were prepared and utilized for their design test, they were re-used for additional tests whenever possible. For example, after determining the unit weight / moisture relationships with the compaction specimens, they were cured for 7 days, and then used to determine the unconfined compressive strength.

A total of 12 control and 9 polymer amended direct shear tests were conducted in two test series. The first series tested control specimens at 4%, 6.1%, 8.1%, and 10.5% moisture content. Specimens were tested at a normal load of 6, 12, and 24 kPa [122, 246, and 491 psf] at each moisture content. The second series tested polymer amended specimens at 0.5%, 1.0% 1.5% amendment rate relative to the dry mass of the soil. Each specimen was prepared at the moisture content corresponding to the optimum determined in the compaction tests. Each amendment rate was tested at a normal stress of 6, 12, and 24 kPa [122, 246, and 491 psf].

Prior to the commencement of durability testing, optimum moisture contents were determined from the compaction tests. Durability specimens were prepared at optimum, 2% and 4% wet and dry of optimum. A small durability test program was completed in addition to the initially scheduled tests. One polymer amended durability specimen was prepared at optimum moisture content for each soil type for wet-dry and freeze-thaw durability. These specimens were not coated with polymer prior to the commencement of conditioning. Based on preliminary results (section 4.4) a supplemental top-coat test

program was conducted. When the top-coat was penetrated, then the rate of sample failure exponentially increased.

Due to the complexity of the resilient modulus test, only 12 resilient modulus tests were conducted. One specimen was prepared for each control, polymer amended, and alternate amended condition for each soil type.

To maximize the benefit of each resilient modulus test, the results from the compaction, strength, stiffness, and durability tests were analyzed prior to selecting resilient modulus test specimen parameters. The moisture content and amendment rate where each peak engineering parameter occurred was determined. Then, each resilient modulus specimen was selected at the amendment rate and moisture content that displayed the greatest overall improvement between all engineering parameters. Each engineering property was considered equally when engineering judgment was applied to determine the amendment rate and moisture content. Summary figures displaying all engineering properties were prepared to assist with the final selection of these properties. These figures are included in Appendix C.

Once the amendment rate and moisture content was determined for each resilient modulus specimen, the values were overlain on the compaction curve to determine the target dry density. All resilient modulus specimen parameters are summarized in Table 10.

Table 10. Resilient Modulus Specimen Parameters

Soil	Water Content (%)	Amendment Type	Amendment Rate (%)	Target Density (kN/m ³)
SAND	8.1	None	0.0	19.25
	5	Polymer	1.5	19.35
	7	Cement	4.0	19.65
LCL	8.4	None	0.0	20.3
	8.2	Polymer	0.5	20.2
	8.0	Cement	2.0	19.6
LCH	11.4	None	0.0	19.5
	11	Polymer	1.0	18.9
	12.8	Lime	8.0	18.2
HCH	9.25	None	0.0	18.6
	12.4	Polymer	1.5	18.55
	14.4	Lime	8.0	17.5

An identification scheme was developed to systematically track specimens in the testing program. Identification included the testing matrix; soil type and target moisture content; amendment and amendment rate; and final test for which the specimen was prepared. For example, a specimen with the designation of TM1_LCL8.3_P1.0_UCS would correspond to a specimen prepared for the first testing matrix, consisting of LCL soil prepared at 8.3% water content, modified with 1.0% polymer by mass, and the specimen was prepared for the unconfined compression test.

This identification scheme was used to list all engineering property test specimens completed in this testing program (Appendix D). The comprehensive sample list includes specimen identification, soil type, amendment type and rate, and target moisture content.

CHAPTER 4: EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Introduction

The results of the experimental test program and interpretation of results are provided in this chapter. The results from the compaction and strength tests are presented as a function of moisture content. The results from durability tests are first presented per ASTM reporting guidelines. Then, alternative reporting methods are utilized to consolidate data and highlight trends. Stiffness is first assessed through stress-strain curves from the unconfined compression test data. Finally, the results from the resilient modulus test are presented.

The interpretation of results is provided to aid with the understanding of geomechanistic catalysts that precipitate change in engineering properties. Additional discussion related to the engineering significance of the results was presented in Chapter 5. Throughout this chapter, results are reported using consistent limits (i.e., minimum, maximum) on plots to provide a consistent framework for relative comparison between amendment types.

4.2 Compaction Test Results

Compaction plots (dry unit weight versus moisture content) are presented in Figures 21 through 24. All compaction curves were prepared using a combination of statistical analysis of data and engineering judgment. The resulting plots were generally bell-shaped, following the characteristic shape reported for fine grained soils (Terzaghi et al. 1996, Holtz et al. 2011). Exceptions to the conventional bell shaped curves were found in SAND, which produced relatively flat but concave upward trends (Figure 21). Both the control specimens, and 1% cement amended specimens followed this trend, with the peak

dry unit weight determined to be near 10% moisture content. The peak was determined to not be above 10% because specimens prepared at higher moisture contents were not able to retain additional water, indicating that maximum saturation was achieved. Polymer amended specimens and 2% and 4% cement amended specimens produced conventional bell shaped curves. The transition from bulking behavior to traditional bell shaped curves with the addition of amendment may be attributed to amendments reducing the capillary tension of the water film coating the soil particles. The reduction in capillary tension may have caused the soil particles to re-orient to a denser configuration at a lower moisture content.

Figure 21. Dry unit weight as a function of moisture content for SAND

Figure 22. Dry unit weight as a function of moisture content for LCL

Figure 23. Dry unit weight as a function of moisture content for LCH

Figure 24. Dry unit weight as a function of moisture content for HCH

Sensitivity to water was assessed (Table 11) through the analysis of leading (i.e., dry of optimum) and trailing (i.e., wet of optimum) compaction curve slopes (Figure 25). The maximum leading and trailing compaction curve slopes from control specimens ranged from 0.30 to 0.46 $\text{kN/m}^3/\%w$, and -0.18 to -0.44 $\text{kN/m}^3/\%w$, respectively. The maximum leading and trailing compaction curve slopes from polymer amended specimens ranged from 0.40 to 0.80 $\text{kN/m}^3/\%w$, and -0.22 to -0.44 $\text{kN/m}^3/\%w$, respectively. These results indicate that polymer amended specimens had an increased sensitivity to water on the dry side of optimum and maintained similar sensitivity to water on the wet side of optimum relative to control specimens. The sensitivity of the polymer amended specimens generally increased with higher addition rates of polymer on the dry side of optimum, and remained relatively consistent with higher addition rates of polymer on the wet side of optimum.

Table 11. Compaction Curve Slopes

Soil	Amendment	Amendment Addition Rate (%)	Maximum Dry Unit Weight (kN/m^3)	Leading Slope ($(\text{kN/m}^3)/\%w$)	Trailing Slope ($(\text{kN/m}^3)/\%w$)
SAND	Control	0	19.24	0.30	N/A
SAND	Polymer	0.5	19.18	0.50	-0.40
SAND	Polymer	1	19.37	0.80	-0.40
SAND	Polymer	1.5	19.31	0.73	-0.37
SAND	Cement	1	19.05	0.30	N/A
SAND	Cement	2	19.87	0.26	-0.40
SAND	Cement	4	20.01	0.28	-0.10
LCL	Control	0	20.37	0.44	-0.44
LCL	Polymer	0.5	20.19	0.33	-0.43
LCL	Polymer	1	20.2	0.37	-0.43
LCL	Polymer	1.5	20.07	0.43	-0.36
LCL	Cement	1	20.23	0.0	-0.33
LCL	Cement	2	20.12	0.30	-0.33
LCL	Cement	4	20.21	0.25	-0.24
LCH	Control	0	19.51	0.46	-0.40
LCH	Polymer	0.5	19.27	0.27	-0.25
LCH	Polymer	1	19.12	0.37	-0.27
LCH	Polymer	1.5	19.41	0.50	-0.34
LCH	Lime	8	18.19	0.05	-0.15
HCH	Control	0	18.72	0.37	-0.18
HCH	Polymer	0.5	18.49	0.29	-0.15
HCH	Polymer	1	18.44	0.26	-0.22
HCH	Polymer	1.5	18.62	0.24	-0.20
HCH	Polymer	2	18.39	0.31	-0.20
HCH	Polymer	2.5	18.25	0.40	-0.14
HCH	Lime	8	17.64	0.20	N/A

N/A – Slope not determined during compaction test

The maximum leading and trailing compaction curve slopes from cement amended specimens ranged from 0.30 to 0.44 $\text{kN/m}^3/\%w$, and -0.33 to -0.40 $\text{kN/m}^3/\%w$, respectively. Leading and trailing compaction curve slopes from lime amended specimens ranged from 0.05 to 0.20 $\text{kN/m}^3/\%w$, and were consistent at -0.15 $\text{kN/m}^3/\%w$, respectively. The decreased sensitivity to water was attributed to additional water

required to hydrate the amendments. Sensitivity trends of the traditional amendments are consistent with industry trends (Ingles and Metcalf 1973, Berger 2011). Polymer amended specimens had increased sensitivity to water relative to both cement and lime.

Following a common industry end product specification, the range of moisture content that the compaction curve remained above 95% relative compaction was determined for each compaction curve (Table 12). The average range of moisture contents exceeding 95% relative compaction for all polymer addition rates was greater than control for SAND and LCL, and was less than control for LCH and HCH. The average range of moisture contents exceeding 95% relative compaction across all soil types was 4.0% points for control compaction curves, and 4.4% points for polymer amended compaction curves.

Figure 25. Schematic of leading and trailing compaction curve slopes and range of water contents

Table 12. Range of Moisture Content Exceeding 95% Relative Compaction

Soil	Amendment	Amendment Addition Rate (%)	Range Exceeding 95% Compaction	Average Range Exceeding 95% Compaction
SAND	Control	0	2.5	2.5
SAND	Polymer	0.5	4.2	4.2
SAND	Polymer	1	4.0	
SAND	Polymer	1.5	4.4	
LCL	Control	0	3.4	3.4
LCL	Polymer	0.5	4.1	3.9
LCL	Polymer	1	3.7	
LCL	Polymer	1.5	3.9	
LCH	Control	0	4.4	4.4
LCH	Polymer	0.5	4.6	4.3
LCH	Polymer	1	5.1	
LCH	Polymer	1.5	3.3	
HCH	Control	0	5.8	5.8
HCH	Polymer	0.5	5.5	5.3
HCH	Polymer	1	4.7	
HCH	Polymer	1.5	6.5	
HCH	Polymer	2	4.5	
HCH	Polymer	2.5	5.4	

Though polymer amended specimens had increased sensitivity to water on the leading slopes, in general they also had an increased range of moisture contents where they remained above 95% relative compaction. This was attributed to the hydrophobic nature of the polymer reducing the inter-particle capillary tension, which allowed the polymer amended soil particles to re-arrange into a more densely packed state at a lower moisture content. Polymer has no significant effect on the replacement of particles with water on the wet side of optimum (as seen by similar trailing slopes). Therefore, polymer amended soil particles are re-molded to a more dense particle arrangement structure (for

a given compactive energy) at lower moisture content than the control soil particles, and remain at that dense particle arrangement over a wider range of moisture contents.

The optimum moisture content of the polymer amended SAND exhibited the largest reduction in water demand, relative to its respective control, with 3.5 to 5 percentage points or a 51% reduction in demand at 1% polymer addition, as displayed in Figure 26. The optimum moisture content of the polymer amended LCL maintained approximately 1% reduction in water demand across all polymer addition rates, relative to its respective control. LCH exhibited very little change in water demand relative to its respective control. Finally, the optimum moisture content of polymer amended HCH exhibited an increase in water demand relative to its respective control, with a 27% increase in demand at 1% polymer addition. The trend of increasing water demand was aligned with increasing soil parameters of: plasticity index, liquid limit, and fines content.

Figure 26. Normalized optimum moisture content versus % polymer amendment

The primary stabilization mechanism of polymer amendment was physical bonding, through the coating of soil particles. Therefore, it was probable that the addition of polymer did not significantly alter the plasticity or the liquid limit of the soil from the control condition. The remaining trend correlating with increasing water demand was the fines content, and was quantified as a function of specific surface. An increase in water demand with the addition of polymer was observed with increased specific surface. This trend was attributed to the need to further dilute the polymer, allowing it to cover a greater surface area. The trend of water demand (normalized relative to control water demand) versus specific surface is presented in Figure 27.

Figure 27. Specific surface relative to normalized water demand

It was observed that the addition of polymer at any rate above 1.0% adequately coated the soil surface of the HCH soil. However, at 1.0% addition rate, the polymer was utilizing additional water to dilute the polymer, allowing it to adequately coat all surfaces. At addition rates above 1.0%, the polymer continued to coat all surfaces, but the need to dilute decreased, thereby reducing water demand. The reduced dilution resulted

in a thicker polymer coating that displaced some of the volume that would otherwise be taken with soil particles, reducing the overall dry unit weight.

This concept applied to all soils; however, it was most prevalent in the HCH soil. Other soils had a reduced specific surface; therefore, the polymer was able to coat the soil particles at a reduced polymer addition rate. In addition, other soil types had larger average particle size and larger void sizes, reducing sensitivity to the reduction in dry unit weight through the provision of additional space for excess polymer within the soil structure.

The maximum dry unit weight was determined for each polymer amended compaction curve, and normalized relative to the control maximum dry unit weight. The dry unit weight of all soils decreased with further polymer addition, with the exception of a spike at an intermediate addition rate (Figure 28). The reduction in dry unit weight was attributed to polymer (specific gravity 1.0) reducing the overall specimen density. The increase in dry unit weight was attributed to the polymer reducing the intraparticle capillary tension, and allowing the soil particles to re-arrange into a more dense state. This reduction in capillary tension was assumed to only take place after the soil particles had been sufficiently coated. It should be noted that though these trends are presented in Figure 28, the magnitudes of these trends are small, as the normalized values are all between 0.97 and 1.01. Because of such small magnitude, these trends will not likely have an adverse effect on practical field applications.

Figure 28. Normalized maximum dry unit weight versus polymer addition rate

The maximum dry unit weight of cement and lime stabilized soils as a function of addition rate is displayed in Figure 29. The addition of cement resulted in a slight reduction in dry unit weight before increasing, similar to polymer amended soil. The addition of 8% lime by dry mass resulted in a 5 to 7% reduction in dry unit weight.

Figure 29. Normalized maximum dry unit weight versus traditional amendment addition rate

4.3 Strength Results

Shear strength test results are presented in this section. The strength results for LCL, LCH, and HCH were determined using the unconfined compression tests. The shear strength of SAND was determined using the direct shear test.

Unconfined Compressive Strength

Unconfined compression strength tests were completed on LCL, LCH, HCH, and selected SAND specimens at varying moisture contents. Test results are presented in Figures 30 through 32, as a function of moisture content. Each soil type exhibited varying degrees of change in strength behavior with the addition of polymer.

Figure 30. Unconfined compressive strength versus moisture content for LCL

Figure 31. Unconfined compressive strength versus moisture content for LCH

Figure 32. Unconfined compressive strength versus moisture content for HCH

Polymer amended LCL specimens exhibited strength gain as compared to control specimens, as displayed in Figure 30. Peak strength gain of 4.9, 3.6, and 2.0 times that of the control was obtained with 0.5%, 1.0% and 1.5% polymer amendment, respectively. The peak strength occurred at 8.3% moisture content, approximately 1% dry of control optimum moisture content.

Polymer was able to adequately coat the LCL soil particles at a low addition rate, and additional water was not required to dilute the polymer. Therefore, the polymer was most effective at low addition rates, at a similar moisture content to the control value.

LCL soil also displayed an increase in strength with the addition of cement. A peak strength gain of nearly 17 times that of the control was obtained with the addition of 4.0% cement. This peak strength occurred at 9% moisture content, which was near the

optimum moisture content of the cement amended (8.25%) and control (9.25%) specimens.

The polymer amended LCH strength was similar to the control conditions, as presented in Figure 31. Peak strength gain of 0.85, 1.02, and 0.89 times that of control was obtained with 0.5%, 1.0%, 1.5% polymer amendment respectively. The peak strength was obtained at 9.6% moisture content, which was approximately 1% dry of control optimum moisture content (10.4%). This is attributed to montmorillonite in the soil reducing the effectiveness of the polymer amendment.

Lime addition resulted in a reduction in strength for LCH, with a peak strength of 745 kPa, 0.60 times the peak control strength. The reduction of strength resulting from the lime addition may be attributed to the low fines content in the LCH soil (Berger 2011). The lime may have promoted a higher water demand for the soil with insufficient fines to react with the lime. The peak strength occurred wet of optimum, which was fully consistent with reported industry trends (Berger 2011).

HCH exhibited strength gain as compared to control specimens, as displayed in Figure 32. Peak strength gain ranged from 328 to 1245 kPa over the range of polymer addition. Significant strength gain only occurred at polymer addition rates above 1.5%. Peak strength gain of 3.4 times that of control was demonstrated with 2.5% polymer amendment. This peak strength was obtained at 12.9% moisture content, which was approximately 3% wet of the control optimum moisture content (9.7%).

An increased percentage of polymer was required to achieve the greatest improvement in strength, relative to the other soils. This was attributed to the additional surface area per unit volume (i.e., increased specific surface) in the HCH soil. The

additional moisture was necessary to dilute the polymer to allow it to sufficiently coat all of the soil surfaces. This increased water demand indicates that higher addition rates of polymer may produce an additional increase in strength.

Lime produced a peak strength of 948 kPa, 2.7 times the peak control specimen strength. However, the peak lime strength was only 76% of the peak polymer amended strength of 1244 kPa. Similar to LCH, the peak strength was obtained wet of the optimum moisture content.

In summary, all soils increased in strength with the addition of polymer. LCL and HCH demonstrated the greatest increase. The specimens with increased plasticity and fines developed greater strength with higher levels of polymer addition. The polymer amended specimens exhibited greater strength gain than the lime modified specimens. The cement modified specimens exhibited greater strength gain than the polymer amended specimens. A summary of normalized maximum soil strength for control, polymer amended, and traditional amended specimens is presented in Figure 33.

Selected polymer amended SAND specimens were prepared to determine if the polymer provided sufficient cohesion to obtain the shear strength of the specimen using the unconfined compression test. These specimens did not have enough cohesion at the time of preparation to remove from the mold, and were therefore cured for 7 days within the molds. At the end of the curing period, the specimens had cured on both ends, but not in the centers. A schematic of a cured specimen immediately after extrusion is presented in Figure 34. This observation indicates that access to air affects curing efficiency for polymer amended soil. Due to this problem, it was determined that the direct shear test

was the most appropriate method for establishing the strength of control and polymer amended SAND.

Figure 33. Normalized peak traditional amended, polymer amended, and control UCS strength for LCL, LCH, and HCH specimens

Figure 34. Schematic of polymer amended SAND specimen after 7 day cure in mold

Shear Strength of SAND

Two series of direct shear tests were conducted. The first series was used to test control specimens over a range of moisture contents (4 to 10.5%) and normal stresses (6 to 24 kPa) to determine if the peak shear strength of the SAND soil occurred at optimum moisture content. The second test series was used to determine the response of shear strength of polymer amended specimens at their respective optimum moisture contents.

The results of the direct shear tests performed on the control specimens are presented in terms of strength versus displacement in Figure 35. For control specimens, the greatest shear strength was obtained at 8.1% moisture content. For all specimens, the peak strength was higher than the residual strength indicating that the soil demonstrated strain softening consistent with expected behavior for densely packed coarse grained soils (Holtz et al. 2011). The second series of tests was used to determine the response of specimens with 0.5%, 1.0%, and 1.5% polymer addition. Based on the results from the first test series, it was assumed for the second test series that the peak shear strength was obtained at the optimum moisture content. Each polymer addition rate was tested at the same 3 normal stresses as the control specimens. The test results for the polymer amended specimens are presented in Figure 36.

Figure 35. Nominal shear stress versus strain for non-amended SAND at varying moisture content and confining stresses

Figure 36. Nominal shear stress versus strain for SAND at varying rates of polymer addition

Vertical displacement relative to shearing strain for control SAND at 8.1% moisture content is presented in Figure 37. Dilative behavior was observed, indicating that the soil was densely packed (e.g., Coduto 1999). The volumetric strain response during shearing was not largely affected by the level of normal stress application. Similar trends were observed for all polymer amended and control direct shear tests.

Figure 37. Volumetric strain relative to shearing strain for non-amended SAND at 8.1% moisture content

The Mohr-Coulomb failure criterion was applied to direct shear test results. The failure envelopes for control specimens are presented in Table 13 and Figure 38. The internal angle of friction ranged from 40° to 49° . Values of cohesion ranged from 0 to 3 kPa. The peak control internal angle of friction (49°) was obtained at 8.1% moisture content. The cohesion values are consistent with poorly graded sands, with any cohesion attributed to apparent mechanical forces (Mitchell 1993). The internal angle of friction was 5° to 10° higher than average densely packed poorly graded sand, but still within

acceptable range (Mitchell 1993, NAVFAC 1986, Schmertmann 1978). The higher values were attributed to testing at a relatively low normal stress. Following standard practice, the trendline was forced through the origin ($c=0$), for any case where linear curve fit of test data produced a negative value for cohesion.

Table 13. Direct Shear Test Data Summary for Control Specimens

Test Series	Moisture Content (%)	Peak Shear Stress (kPa)			Internal Angle of Friction (deg)	Cohesion (kPa)
		Normal Stress = 6 kPa	Normal Stress = 12 kPa	Normal Stress = 24 kPa		
SAND 4	4.0	7	12	22	40	2.1
SAND 6.1	6.0	5	11	19	39	0.7
SAND 8.1	8.1	6	12	29	50	0.0
SAND 10.5	10.5	9	12	25	43	2.7

Figure 38. Shear stress versus normal stress for control specimens over a range of moisture content

The Mohr-Coulomb failure criterion for polymer-amended specimens is summarized in Table 14 and Figure 39. Test results for the 1.5% polymer amended specimen with the lowest normal stress were omitted for the calculation of the friction angle due to the extremely high shear stress relative to normal stress. The friction angles for polymer amended specimens were 49, 63, 83, and 84 degrees for control, 0.5, 1.0, and 1.5% polymer amendment, respectively. The high friction angles are unreasonable, and may not be representative of the actual conditions. It was hypothesized that the high friction angle values were attributed to the limited range and low magnitude of normal stresses tested. Testing soils in this range yielded points on the very lowest portion of the Mohr-Coulomb failure line. The non-linearity of the Mohr-Coulomb failure line yields results with a higher friction angle and lower cohesion value (Holtz et al. 2011).

The 1.0% and 1.5% polymer amended specimens did not shear across the intended shear plane. An angled plane near the edge of the specimen sheared, while the remainder of the specimen lifted out of the bottom of the shear box, as displayed in Figure 40. This observation added further evidence that more test data is warranted for direct shear tests conducted at higher normal stress levels.

Table 14. Polymer Amended Direct Shear Test Data Summary

Test Series	Polymer Addition Rate (%)	Moisture Content (%)	Peak Shear Stress (kPa)			Internal Angle of Friction (deg)	Cohesion (kPa)
			Normal Stress = 6 kPa	Normal Stress = 12 kPa	Normal Stress = 24 kPa		
Control	0.0	8.0	6	12	29	50	0
0.5% Polymer	0.5	6.0	239	255	274	63	229
1.0% Polymer	1.0	4.0	325	436	477	83	305
1.5% Polymer	1.5	5.0	590 ^a	421	529	84	313

^aPoint omitted for analysis

Figure 39. Shear stress versus normal stress for various polymer amendment rates

Figure 40. 100 mm [4.0 in.] failed polymer amended specimen
Note: specimen is inverted in photo

Due to these uncertainties, the shear strength for the polymer amended SAND specimens was taken as the directly measured peak stress at a given normal stress of 24 kPa. This value was equivalent to the normal stress of soil overburden at 300 mm [12 in.] depth with the load application of a tire associated with a 15.6 kN [3500 lb] four-wheeled vehicle. Stress distribution was calculated using the Boussinesq method. The resulting shear strengths for the control specimens are plotted relative to moisture content in Figure 41 and polymer addition in Figure 43.

The shear strength of the control specimens first reduced then increased with increasing moisture content. The peak shear stress was obtained at 8.1% moisture content. This trend was consistent with trends of dry unit weight results, as presented in Figure 42. The initial reduction in strength was attributed to increased particle spacing. Greater particle spacing reduced the interlocking of soil particles reducing the shear strength.

Figure 41. Normalized peak shear strength versus moisture content for control SAND

Figure 42. Normalized shear stress and dry unit weight, relative to moisture content, for control SAND

An increase in strength with the addition of polymer was observed (Figure 43). The convex shape of the curve indicates that the relative benefit of polymer as a function of addition rate was highest at the 0.5% polymer addition rate. However, the strength gain was notable over all addition rates. The data suggests that the specific surface of SAND was very low, and the polymer was able to coat the specimens at low addition rates. Once the particles were coated, and the polymer had increased the bond strength in the soil matrix, adding polymer provided a limited further benefit.

In summary, the normalized strength is plotted against polymer addition for each of the four soils tested (Figure 44). The addition of polymer improved the strength of all soils relative to their respective control specimens. The magnitude of improvement varied between soil types. The rate of amendment required for improvement increased with specific surface.

Figure 43. Normalized peak shear stress of SAND versus polymer addition

Figure 44. Normalized strength versus polymer addition

4.4 Durability Results

Results from both wet-dry and freeze-thaw durability tests are presented in this section. Due to the cyclic nature of the durability tests; an extensive set of data was generated. In the following sections, all data will first be reported in accordance with ASTM D 559-03 and ASTM D 560-03 (ASTM 2011). Then, in an effort to condense results to an effective summary, two alternate methods of analysis will be utilized: integrated area and differential durability. Each of these analysis methods will be explained in greater detail in their corresponding sections. Durability testing of traditional amendments is beyond the scope of this research. However, a comparative analysis of polymer durability relative to highway specifications used for traditional amendments is discussed in Chapter 5.

4.4.1 Wet-Dry Durability

Wet-dry durability test results are presented in Figures 45 through 48. The results were recorded as the percent original mass retained at the end of each cycle.

Figure 45. Wet-dry durability for control and 1.0% polymer modified SAND at varying moisture content

Figure 46. Wet-dry durability for control and 1.0% polymer modified LCL at varying moisture content

Figure 47. Wet-dry durability for control and 1.0% polymer modified LCH at varying moisture content

Figure 48. Wet-dry durability for control and 1.0% polymer modified HCH at varying moisture content

For SAND soil, all control specimens and the polymer amended specimens prepared at 2, 7, and 9% moisture content all failed prior to the commencement of conditioning. Only the polymer amended SAND specimens prepared at 2.5 and 4.2% moisture content survived curing and commenced testing. The data suggests that if the polymer specimens were extruded without crumbling, the exposure to air promoted curing of the specimens. If specimens were adequately cured, they performed well in the wet dry durability test.

Polymer amended LCL specimens resulted in increased durability over the control specimens. The failure pattern was similar to control specimens, and occurred approximately 2 cycles after the control specimens.

Polymer amended LCH specimens displayed the strongest performance of all soil types, with very little deterioration for the first 4 cycles of the durability test. All polymer amended LCH specimens remained partially intact for a minimum of 8 cycles.

Polymer amended HCH specimens resulted in 2 to 5 cycles of increased durability over the control specimens. HCH specimens displayed an increase in mass (i.e., swelling), immediately prior to failing. This swelling was attributed to expansion of the clay fraction of the specimen after water was able to penetrate the exterior top-coat.

The mechanisms providing increased durability were similar to that providing increased shear strength. The polymer bond between the soil particle surfaces provided increased strength as well as increased durability. The primary difference between the tests is that the strength tests measured the initial resistance to stress, while the durability tests evaluated the longevity of the increased stress with repeated exposure to adverse conditions.

In general, polymer amended specimens showed higher resistance to wet-dry conditioning relative to control specimens. Once polymer amended specimens began to fail, they generally failed more rapidly than the control specimens.

In an effort to consolidate data to produce a more effective summary of results, the results were also expressed as a function of integrated area. The integrated area method was used to apply a single representative durability value to the specimen by integrating the area under the curve of percent original mass versus cycles. A schematic outlining the integrated area method is displayed in Figure 49.

The integrated area results are displayed as a function of moisture content in Figures 50 through 53. Each of the plots contain a vertical dashed line indicating the optimum moisture content of 1% polymer amended soil (ASTM D 698 (ASTM 2011)).

Figure 49. Schematic of integrated area method

Figure 50. Integrated area method wet-dry durability of control and polymer amended SAND over varying moisture content

Figure 51. Integrated area method wet-dry durability of control and polymer amended LCL over varying moisture content

Figure 52. Integrated area method wet-dry durability of control and polymer amended LCH over varying moisture content

Figure 53. Integrated area method wet-dry durability of control and polymer amended HCH over varying moisture content

The peak polymer amended wet-dry durability values ranged from 2% points dry of optimum (SAND), near optimum (LCL and LCH), to 3% points wet of optimum (HCH). The trend of increasing water demand was correlated to increasing specific surface in the soils.

The maximum increase in polymer amended integrated area method durability was 7.4, 7.3, 10.8, and 6.8 cycles for SAND, LCL, LCH, and HCH soils, respectively. The integrated area durability increased for all specimens with the addition of 1.0% polymer, with LCH exhibiting the greatest improvement (Figure 54).

The greatest increase with LCH soil was attributed to the limited number of polymer amendment rates tested. Other engineering property tests determined that 1.0% polymer addition was the optimum addition rate for LCH. Because 1.0% was the only rate tested for durability, the LCH displayed the greatest relative improvement.

Figure 54. Change in wet-dry integrated area as a function of polymer addition

Differential durability, or the difference between the polymer amended specimens and control specimens for each moisture content, is presented in Figures 55 through 58. The area under the curve quantifies the total improvement between polymer amended and the control specimens. The magnitude of the curve at any given cycle displays the improvement that polymer provides at that respective point in the test.

All polymer amended specimens exhibited improved performance over the control specimens for durability. The differential durability indicated that the polymer amendment caused the specimen to remain entirely intact for a longer duration. It also indicated that the polymer amended specimens generally failed rapidly, similar to the control specimens.

Figure 55. Differential wet-dry durability for SAND

Figure 56. Differential wet-dry durability for LCL

Figure 57. Differential wet-dry durability for LCH

Figure 58. Differential wet-dry durability for HCH

4.4.2 Freeze-Thaw Durability

Freeze-thaw durability tests were analyzed following the same methodology as the wet-dry durability tests. Test results are presented in Figures 59 through 62. The results are presented as the percent original mass retained at the end of each cycle, following the same format as the wet-dry durability test results.

Figure 59. Freeze-thaw durability for control and 1.0% polymer amended SAND at varying moisture content

Figure 60. Freeze-thaw durability for control and 1.0% polymer amended LCL at varying moisture content

Figure 61. Freeze-thaw durability for control and 1.0% polymer amended LCH at varying moisture content

Figure 62. Freeze-thaw durability for control and 1.0% polymer amended HCH at varying moisture content

For SAND soil, all control specimens and the polymer amended specimens prepared at 1, and 2.5% moisture content all failed prior to the commencement of conditioning. Generally the specimens that were adequately cured performed well in the freeze-thaw durability test.

Polymer amended LCL specimens resulted in increased durability over the control specimens. All polymer amended specimens remained intact for a minimum of 8 additional cycles beyond the highest performing control specimen.

Similar to the wet-dry durability test, polymer amended LCH specimens displayed the strongest performance of all soil types, with 3 polymer amended specimens completing all 12 cycles.

Polymer amended HCH specimens resulted in 3 to 8 cycles of increased durability over the control specimens. Polymer amended HCH specimens failed slowly relative to the other freeze-thaw durability specimens. In general, polymer amended specimens showed higher resistance to freeze-thaw conditioning than control specimens. Once polymer amended specimens began to fail, they generally failed more rapidly (i.e., steeper slope indicating failure over fewer number of cycles) than the control specimens.

Similar to the results from the wet-dry durability tests, the polymer amended freeze-thaw specimens exhibited improvement over the control specimens. Contrasting the wet-dry durability tests, the polymer amended freeze-thaw specimens slowly deteriorated around the edges for several cycles prior to rapid deterioration at the end of the test.

The freeze-thaw durability results as a function of integrated area are summarized in Figures 63 through 66. The vertical line delineates the optimum moisture content of

1% polymer modified soil, determined through the peak dry unit weight from the compaction tests. The peak polymer amended freeze-thaw durability was generally near optimum moisture content for all soils.

Figure 63. Integrated area method freeze-thaw durability of control and polymer amended SAND over varying moisture content

Figure 64. Integrated area method freeze-thaw durability of control and polymer amended LCL over varying moisture content

Figure 65. Integrated area method freeze-thaw durability of control and polymer amended LCH over varying moisture content

Figure 66. Integrated area method freeze-thaw durability of control and polymer amended HCH over varying moisture content

Freeze-thaw differential durability is highlighted in Figures 67 through 70. All polymer amended specimens exhibited improvement over the control specimens. Except for SAND, the freeze-thaw durability specimens failed under influence of larger number of cycles than the wet-dry durability specimens, as was indicated by the more gently sloping differential durability curves. In addition, the slopes of the curves were similar, providing indication that polymer amended specimens maintained similar failure characteristics to the control specimens.

Figure 67. Differential freeze-thaw durability for SAND

Figure 68. Differential freeze-thaw durability for LCL

Figure 69. Differential freeze-thaw durability for LCH

Figure 70. Differential freeze-thaw durability for HCH

Freeze-thaw integrated durability as a function of polymer addition is presented in Figure 71. Similar to wet-dry durability, all specimens demonstrated improved durability with the addition of polymer, with LCH maintaining the best overall performance. SAND experienced the greatest overall improvement. This improvement can be attributed to the ability of the polymer to adhere to the sand particles.

Figure 71. Change in freeze-thaw integrated area method durability as a function of polymer addition

4.4.3 Polymer Coating of Durability Specimens

Polymer coating of durability specimens was initially completed to simulate the water protection that a top-coat provides in the field. However, coating the specimens may have provided additional strength which held the specimen together. Rapid specimen failure in the wet-dry durability tests indicated uncertainty regarding improvement resulting from the polymer coating versus improvement resulting from polymer mixed in

the soil. To provide further insight, eight additional polymer amended specimens were prepared without a polymer top-coat. One specimen from each soil type for both wet and dry durability were prepared at optimum moisture content.

Test results from the polymer amended specimens without a polymer top-coat (N.C.) are presented in Figures 72 and 73, and summarized in Table 15. For comparison, the optimum moisture content control and polymer amended specimens with polymer top coat are presented as well.

The increase in durability in polymer amended specimens was partially attributed to the coating on the exterior of the specimens. The non-coated polymer amended wet-dry specimens yielded variable results. The non-coated SAND and HCH specimens performed similarly to their respective control specimens; while the non-coated LCL and LCH specimens performed similarly to their respective coated polymer amended specimens. The average integrated area durability across all soil types for wet-dry conditioned specimens was 0.1, 5.3, and 8.0 cycles for control, no coating polymer amended, and coated polymer amended, respectively. The average integrated area durability across all soil types for freeze-thaw conditioned specimens was 2.0, 1.9, and 6.0 cycles for control, no coating polymer amended, and coated polymer amended, respectively. Approximately 35% of the increase in durability of the wet-dry conditioned specimens was attributed to the polymer coating, and the entire increase in durability of the freeze-thaw specimens was attributed to the polymer coating. This indicated that polymer mixed in the soil matrix provided adhesion, and effectively improved durability in submerged conditions. However, at sub-freezing temperatures, the soil-polymer matrix

was not able to withstand the expansion forces of freezing soil. In addition, the importance of coating exposed soil surfaces in field conditions was highlighted.

Except for the LCL and LCH specimens in the wet-dry test, most of the increased durability came from the top coat, not from mixing the polymer in the soil. The increased durability is attributed to the top coat forming a barrier, preventing moisture from entering the soil structure.

Figure 72. Percent original mass versus cycles for control, no coating polymer amended, and polymer amended wet-dry durability specimens at optimum moisture content

Figure 73. Percent original mass versus cycles for control, no coating polymer amended, and polymer amended freeze-thaw durability specimens at optimum moisture content

Table 15. Peak Integrated Area Method Durability of Specimens

Soil	Conditioning	Control	1.0% Polymer Amended	
			No Coating	Top-Coat
SAND	Wet-Dry	0.0	0.0	7.4
LCL	Wet-Dry	0.0	10.7	7.3
LCH	Wet-Dry	0.4	10.1	10.7
HCH	Wet-Dry	0.0	0.3	6.7
Average		0.1	5.3	8.0
SAND	Freeze-Thaw	0.0	0.0	7.3
LCL	Freeze-Thaw	2.2	2.3	4.3
LCH	Freeze-Thaw	5.6	4.9	9.0
HCH	Freeze-Thaw	0.0	0.3	3.5
Average		2.0	1.9	6.0

4.5 Stiffness Results

Two methods were used to determine stiffness of the test specimens. Results from each of these two methods are reported in this section. First, stiffness determined as the slope of the unconfined compression and direct shear stress strain curves is covered. Then, stiffness defined using the resilient modulus test is presented.

4.5.1 Tangent Modulus Stiffness

An inflection point tangent modulus was used to determine the peak stiffness of each specimen from the UCS and direct shear strength results. Several methods to determine the stiffness were attempted including: secant modulus, 50% peak tangent modulus, and inflection point tangent modulus. The inflection point tangent modulus was determined to be the most appropriate because the stiffness was calculated independent of the compression required to make full contact with the specimen, which varied significantly between specimens. This variation was attributed to testing the specimens with no caps on the ends, causing the seating load to vary between specimens.

The inflection point tangent modulus was determined by taking the derivative of the compressive stress with respect to the strain to determine the inflection point, as displayed by the schematic (Figure 74). The inflection point was defined as the first point where the rate of change decreased. Once this inflection point was determined, the tangent slope was drawn at that location.

Figure 74. Schematic of inflection point tangent modulus

Stiffness was determined for LCL, LCH, and HCH soils using results from the unconfined compression test. Stiffness was determined for SAND using results from the direct shear test. The stiffness of control, polymer amended, and cement/lime amended LCL, LCH, and HCH soils are presented in Figures 75 through 77 as a function of moisture content.

Figure 75. Modulus of elasticity as a function of water content for control, polymer modified, and cement modified LCL soil

Figure 76. Modulus of elasticity as a function of water content for control, polymer modified, and lime modified LCH soil

Figure 77. Modulus of elasticity as a function of water content for control, polymer modified, and lime modified HCH soil

Peak stiffness gain of 2.8, 1.9, and 4.4 times that of the control was obtained for LCL, LCH, and HCH specimens, respectively (Figure 78). The trend of stiffness increase in was nearly identical the strength improvement. The increase in stiffness is attributed to the polymer bonding the soil-polymer matrix together.

The peak stiffness of the control SAND specimens was approximately 10 kPa, and the peak stiffness of the polymer amended specimens (at 1.5% addition rate) was approximately 400 kPa. The data indicates that the stiffness was very low for the control specimens and approximately 40 times the control for the polymer amended specimens. In addition, polymer amended specimens failed more abruptly than the control specimens, indicating relatively brittle behavior in polymer amended specimens. The brittle response of the polymer amended specimens was attributed to the polymer bonding the soil particles together. As the specimen sheared, the soil particles were

bound rigidly together until the polymer bonds were broken. Once the polymer bonds were broken, the additional strength gained from the polymer was lost, and the specimen failed rapidly.

Figure 78. Peak stiffness normalized to each soils respective control peak dry unit weight.

4.5.2 Resilient Modulus

Resilient modulus specimens were selected as outlined in Section 3.4 using the plots in Appendix C. Upon completion of each test, the data was reduced and the recoverable strain was calculated for the final 5 cycles of each of the 15 stages (Appendix E). Each resilient modulus value for the final 5 cycles, as well as the average of these 5 cycles are tabulated in Appendix E. The final resilient modulus value was taken as the average of all 15 stages, and is presented in Table 16.

Table 16. Summary of Resilient Modulus Test Results

Amendment	Resilient Modulus (MPa)			
	SAND	LCL	LCH	HCH
Control	142	171	159	76
Polymer	97	48	194	39
Cement/Lime	135	33	150	126

The normalized polymer amended resilient modulus relative to the control resilient modulus for each of the 15 cycles is presented in Figure 79. The normalized polymer amended resilient modulus relative to the traditional amended resilient modulus for each of the 15 cycles is presented in Figure 80.

Figure 79. Normalized resilient modulus resilient modulus versus sequence number for polymer amended specimens

A decreasing slope in Figure 79 indicates a relative increase in control specimen resilient modulus, and an increasing slope indicates a relative increase in polymer

amended specimen resilient modulus. Therefore, generally from the beginning of the test through sequence 6, the polymer amended specimens break down, and the resilient modulus reduces from the peak value. Then from sequence 7 to sequence 10, the control specimens break down and their resilient modulus reduces from their peak value. Finally, from sequence 11 through the end of the test, the relative performance of the specimens leveled out, indicating that the relative performance had stabilized. The only exception to these findings may be SAND, where the polymer amended specimens never saw a relative increase in resilient modulus.

The average normalized resilient modulus for LCL and LCH specimens for the last 5 sequences was 1.30 times the control strength, while the average normalized resilient modulus for SAND and LCL specimens was 0.63 times the control strength. This was attributed to the particle spacing being greater in the SAND and LCL specimens. The distance that the polymer spans was much smaller when the particles are in close proximity as they are with the LCL and LCH specimens. Furthermore, the number of voids that are filled with polymer are much greater. Therefore, the average deflection that each void must undergo was much smaller, resulting in less movement. When this was the case, the polymer was able to recover from these small movements and return to its original configuration.

When the void spaces are much larger and much more frequent, each void filled with polymer must adsorb more deflection. It was assumed that this greater deflection causes non-recoverable, (i.e., permanent) deformations in the polymer-soil matrix, and a reduced overall resilient modulus.

Figure 80. Normalized resilient modulus with respect to traditional amendment versus sequence number for polymer amended specimens

The LCL and LCH specimens had an increased stiffness relative to traditional amendments. The polymer amended resilient modulus was an average of 1.38 times the traditional amendment resilient modulus. The relative performance of polymer decreased over the duration of the test. The SAND and HCH specimens had a decreased stiffness relative to traditional amendments. The polymer amended resilient modulus was an average of 0.53 times the traditional amendments.

These trends may be attributed to the difference in bond type between the traditional and polymer amendments. Traditional amendments reacted with the soil, altering the soil structure. Polymer amendment developed a physical bond between the individual soil particles. The data suggests that the physical bond of the polymer was more susceptible to deterioration over repeated loading than the bond formed by the traditional amendments. However, results for HCH were an exception to this trend.

CHAPTER 5: ENGINEERING SIGNIFICANCE

5.1 Introduction

The engineering significance of major findings from the entire investigation are provided in this chapter. First, the effect of polymer on water demand is discussed. Then, an overview of the significance of polymer across soil types and engineering parameters is covered. Finally, the engineering significance of polymer addition is assessed with relevance to strength, durability, and stiffness.

5.2 Water Demand

The addition of polymer had a significant effect on water demand. The water demand between the moisture content of the maximum control dry unit weight and the moisture content of the peak engineering parameter reduced by 4 to 6% points in SAND soil; generally remained within 2% points (with an average 1% point reduction) in LCL and LCH; and increased by an average of 1.5% in HCH soil. In general, greater variation in change in water demand between peak engineering properties in the LCH and HCH soils was observed.

The difference in water demand between the moisture content of the maximum control dry unit weight, and the moisture content where maximum engineering property value was determined for each condition (Figures 81 through 84). Each polymer addition rate was plotted for each engineering property and soil type. Negative values indicate that peak engineering performance occurred dry of optimum (as determined for control specimens) and positive values indicate that peak engineering performance occurred wet of optimum.

Figure 81. Variation in water demand for SAND soil

Figure 82. Variation in water demand for LCL soil

Figure 83. Variation in water demand for LCH soil

Figure 84. Variation in water demand for HCH soil

The reduction in water demand in SAND was attributed to the addition of polymer reducing the capillary tension between the soil particles (i.e., lower effective stress), allowing the soil particles to re-arrange into a denser configuration at a lower moisture content. Essentially, the presence of polymer increased the lubricating effect that water has on soil, and reduced the water demand.

Polymer was added to the soil as an aqueous solution of 65% polymer and 35% water. When polymer was added to soils with high specific surface, additional water was required to dilute the polymer so that the solution could sufficiently coat all soil particles. For soils with higher specific surface, more dilution was required to effectively coat the particles. Once sufficient polymer was added to coat the particles, any additional polymer added to the soil-polymer matrix reduced the need for dilution, lowering the water demand.

In summary, the two catalysts changing water demand worked in parallel. The reduced capillary tension reduced the water demand. Additional water necessary to dilute the polymer resulted in a spike in water demand prior to reducing, as a function of polymer addition. A greater spike in water demand was observed for soils with higher specific surface.

The thickness of the polymer coating affected engineering property performance. In test configurations where limited test data was acquired (i.e., 1.0% polymer amendment in HCH soil), the amendment rate tested may be lower than the peak performing amendment rate. Therefore, further research is warranted to investigate water demand trends at higher polymer addition rates.

5.3 Performance Summary of Polymer

The addition of polymer caused a significant modification to engineering properties. The normalized change in engineering properties (maximum engineering property value of polymer amended specimen relative to maximum engineering property value of control specimen) for all engineering properties and soil types is summarized in Tables 17 and 18. The average normalized improvement was 1.0, 7.0, 3.0, 0.7, 8.1, and 4.5 for dry unit weight, strength, tangent modulus stiffness, resilient modulus stiffness, wet-dry durability, and freeze thaw durability, respectively. The greatest engineering property improvements were strength and durability. The increase in these engineering properties was attributed to polymer bonding the surface of the soil. Polymer demonstrated increased strength in both sets of engineering property tests. This indicated that the polymer had an initial increased strength (7.0 times control strength in unconfined compression test), and also maintained this increased strength when exposed to conditioning (average 6.0 times control durability).

Polymer amended specimens displayed an increase in stiffness over control specimens (3.0 times control stiffness). However, when subject to repeated dynamic loading, the polymer amended specimens decrease in recoverable strain decrease below the control stiffness (0.68 times control stiffness). This indicated that the polymer bonds broke down when subjected to the repeated loading.

Table 17. Normalized Peak Dry Unit Weight, Strength, and Stiffness Parameters for Polymer, Cement, and Lime

Engineering Property	Soil	Polymer Addition Rate (%)	Normalized Polymer Improvement Relative to Control	Trad. Am.	Trad. Addition Rate (%)	Normalized Traditional Am. Improvement Relative to Control	Normalized Improvement of Polymer Relative to Trad. Am.
Dry Unit Weight	SAND	1.0	1.01	Cement	4	1.04	0.97
	LCL	1.0	0.99	Cement	1	0.99	1
	LCH	1.5	1	Lime	8	0.93	1.07
	HCH	1.5	1	Lime	8	0.94	1.06
Average			1.00			0.98	1.03
Standard Deviation			0.01			0.04	0.04
Strength	SAND	1.5	18.45 ^a	Cement	4	N/A	N/A
	LCL	0.5	4.91	Cement	4	16.96	0.29
	LCH	1.0	1.02	Lime	8	0.6	1.71
	HCH	2.5	3.43	Lime	8	2.62	1.31
Average			6.95			6.73	1.10
Standard Deviation			6.78			7.28	0.60
Stiffness (Tangent Modulus)	SAND	N/A	N/A	Cement	N/A	N/A	N/A
	LCL	0.5	2.84	Cement	2	41.8	0.09
	LCH	1.0	1.86	Lime	8	0.7	2.65
	HCH	2.5	4.43	Lime	8	7.33	0.6
Average			3.04			16.61	1.11
Standard Deviation			1.06			18.02	1.11
Stiffness (Res Mod)	SAND	1.5	0.68	Cement	4	0.95	0.72
	LCL	0.5	0.28	Cement	2	0.2	1.45
	LCH	1.0	1.23	Lime	8	0.95	1.3
	HCH	1.5	0.51	Lime	8	1.66	0.34
Average			0.68			0.94	0.95
Standard Deviation			0.35			0.52	0.45

N/A – Test not completed / no comparison available

^aControl strength determined by direct shear test with 24 kPa normal stress

Table 18. Normalized Peak Durability Parameters for Polymer, Cement, and Lime

Engineering Property	Soil	Polymer Addition Rate (%)	Normalized Polymer Improvement Relative to Control
Wet-Dry Durability	SAND	1.0	7.4
	LCL	1.0	7.3
	LCH	1.0	11.2
	HCH	1.0	6.8
Average			8.18
Standard Deviation			1.76
Freeze-Thaw Durability	SAND	1.0	7.3
	LCL	1.0	2.0
	LCH	1.0	1.8
	HCH	1.0	3.8
Average			3.7
Standard Deviation			2.21

The amendment rate coinciding with the peak engineering parameter improvement may not be the actual peak performing amendment rate. This was because only a finite, and sometimes limited, number of amendment rates were tested. For example, the only polymer amendment addition rate tested for durability was at 1.0%. Based on the results of the other engineering properties, the peak performing amendment rate varied between soil types. Therefore, the polymer amendment may result in increased durability performance if tested at other (i.e., higher) amendment addition rates.

In relation to traditional amendments, in general, the overall engineering benefit of adding polymer to soil was greater than that for adding lime. However, the overall engineering benefit of adding cement was better than polymer.

The summaries provided herein assessing benefit are independent of cost and specialized engineering need. Though material cost and implementation methods pose a

major consideration in the benefit of using any amendments (traditional or non-traditional), a relative comparison is difficult without assessing the large scale polymer production. Therefore, this assessment was considered beyond the scope of this investigation.

5.4 Dry Unit Weight-Moisture Relations

The addition of polymer resulted in very little change of maximum dry unit weight. Maximum dry unit weights for all polymer amendment rates were within 2.5% of the maximum control dry unit weights. However, assessment of water demand required to achieve peak dry unit weight may be used to determine the optimum polymer addition rate for a given soil.

When sufficient polymer had been added to the soil polymer matrix to coat particles, an increase in the peak dry unit weight was observed. At this addition rate, other engineering properties were noticeably affected. In future testing, this increase in peak dry unit weight could be utilized to indicate that sufficient polymer has been added to coat the soil particles, and consequently improve the engineering properties.

In addition, as polymer was added to the soil a reduction in water demand required to achieve optimum moisture content that coincided with increased engineering properties was observed. Using the reduction in water demand as a method to specify polymer addition rate may be a reliable approach because the peak engineering properties were observed at greater polymer addition rates than the amount required to coat the soil particles in soils with high specific surface.

Independent of use for determining optimum polymer addition rate, caution should be taken regarding moisture with polymer amendment. The data highlights the

variation from optimum control moisture content with different types of soil and different polymer addition rates.

5.5 Strength Significance

Results from strength tests (Chapter 4) indicated that the addition of polymer increased the strength of specimens relative to control specimens. Current standards are not in place to determine acceptance criteria for polymer amended soil. However, the United States Army Corps of Engineers (USACE) has developed minimum unconfined compressive strength criteria for cement amended soil. The minimum unconfined compressive strength for subbase course, select material, or subgrade is 1725 kPa [250 psf] under flexible pavement, or 1380 kPa [200 psf] under rigid pavement (ACI 1990).

Therefore, the minimum unconfined compressive strength criterion for cement amended soil was used to compare amended specimen test results against a reasonable acceptance threshold (Figure 85). The only cement amended specimens to exceed this threshold were SAND and LCL at a 4% addition rate. Polymer amended specimens displayed significant strength gain (i.e., polymer amended HCH gained 65% of the strength necessary to exceed the threshold), but no tested values for polymer amended specimens exceeded this threshold.

Figure 85. Strength of amended specimens relative to USACE threshold strength for soil cement

5.6 Durability Significance

Due to extensive time required to run the wet-dry and freeze-thaw durability tests, many state departments rely solely on unconfined compressive strength for acceptance criteria of cement amended specimens. However, wet-dry and freeze-thaw durability tests are used on critical projects because they provide representative durability data. The Portland Cement Association (PCA) criterion for soil cement determined by wet-dry and freeze-thaw durability tests has a maximum allowable weight loss of 10 to 14%, for the

range of soils tested in this program. Though polymer amended specimens displayed an increase in durability, LCL in the freeze-thaw durability test was the only polymer amended soil to meet this criterion. Polymer amended LCL specimens (1.0% addition rate) prepared at 7.1, 11.1, and 14.8% moisture content all lost less than 10% during the 12 cycle test, meeting the current soil-cement durability requirements. All other tested specimens lost greater than 10% of the specimen during testing. However, it should be noted that a standard 1.0% polymer addition rate was selected for the durability tests. Test data from the compaction and strength tests indicated that the durability performance of polymer amended specimens could vary significantly if tested at optimum polymer addition rates.

5.7 Stiffness Significance

The addition of polymer increased the tangent modulus stiffness of soil specimens (Average 3.0 times the control stiffness). This indicated that a cured soil-polymer matrix provided increased stiffness under initial static loading. Not considering secondary compression, the increased stiffness suggests that the polymer amended soil will reduce settlement of surcharge loads (e.g., buildings, embankments).

Contrary to initial static stiffness, the addition of polymer decreased the resilient modulus stiffness. The resilient modulus of polymer amended soil averaged 68% of the control stiffness. This indicates that polymer amended soil had less strain recovery when the stress on the specimen was removed. The resilient modulus is an integral part of pavement design. Therefore, if polymer amended soil is to be used under highway subgrades, adding a secondary amendment to the soil-polymer mixture may be

considered to increase the resilient modulus. Alternately, polymer formations can be developed to better resist cyclic loading.

Similar to polymer, the addition of traditional amendments increased the tangent modulus stiffness of the soil specimens. Over the range of soils, cement and lime specimens had an average increase in stiffness of 16 times that of control specimens. Traditional amended specimens also had reduced resilient modulus stiffness. This indicates that the stiffness trends determined with polymer amended specimens are not unique to polymer amendment. The reduction in resilient modulus for amended soils (polymer, cement, and lime) was attributed to a microfracturing of the thin film of chemical amendment at the particle contact locations when subjected to cyclic loading.

In summary, polymer amendment of soil improved or maintained all tested engineering parameters (except resilient modulus) of all soils. Polymer amendment displayed a lesser performance relative to cement amendment, and an increased performance relative to lime amendment.

CHAPTER 6: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 Summary

An extensive laboratory test program was undertaken to evaluate a series of engineering properties over a range of soil types, amendment types and addition rates, and moisture contents. Results were then used to enhance understanding of the engineering significance of polymer modification. Engineering properties determined throughout the test program included dry unit weight / moisture content relationships through the use of compaction tests; shear strength through the use of unconfined compression strength tests and direct shear tests; durability through the use of freeze-thaw and wet-dry durability tests; and stiffness through the use of resilient modulus tests and through interpretation of the unconfined compression test results. Test soils included poorly graded sand and three clayey sands with gravel. Fines contents (Passing 0.075 mm [No. 200] sieve) ranged from 2.5% to 41%, and represented both low and high plasticity conditions. Tested amendments included polymer, lime, and cement. Polymer addition rates ranged from 0.5% to 1.5%; cement addition rates ranged from 1% to 4%; and lime was added at 8%. Moisture contents generally ranged from 4% dry of optimum to 4% wet of optimum.

6.2 Conclusions

Compaction tests were used as a baseline for much of the testing program. Specimens were prepared in a 101 mm [4 in.] diameter mold using standard compaction effort. Based on the compaction tests, the following conclusions were drawn:

1. The addition of polymer altered the optimum moisture content. Water demand ranged from a 4.9% point reduction with SAND to a 2.6% point increase with

HCH. The trend of increasing water demand was correlated to increasing specific surface. SAND provided evidence that the addition of polymer potentially reduced the capillary tension between the soil particles, allowing the soil particles to rearrange into a more densely packed state at a lower moisture content.

2. Slopes of compaction curves were determined for leading (i.e., dry of optimum) and trailing (i.e., wet of optimum) portions of curves. Maximum leading and trailing compaction curve slopes for control specimens ranged from 0.30 to 0.46 $\text{kN/m}^3/\%w$, and -0.18 to -0.44 $\text{kN/m}^3/\%w$, respectively. Maximum leading and trailing compaction curve slopes for polymer amended specimens ranged from 0.40 to 0.80 $\text{kN/m}^3/\%w$, and -0.22 to -0.44 $\text{kN/m}^3/\%w$, respectively. Control and polymer amended specimens remained above 95% relative compaction for an average moisture content range of 4.0 and 4.4%, respectively. Polymer amended specimens demonstrated increased sensitivity (i.e., steeper slopes) to water on the dry side of optimum and maintained similar sensitivity to water on the wet side of optimum relative to control specimens. However, polymer amended specimens remained at or near peak dry unit weight over a greater range of moisture. The reduced sensitivity dry of optimum was attributed to polymer reducing capillary tension, increasing specimen dry unit weight above 95% relative compaction at a lower moisture content. Higher dry unit weight at lower moisture content increased the range of moisture that specimens remained above 95% relative compaction. Even though the range of moisture for the polymer amended specimens increased, the peak dry unit weight generally did not increase, resulting in a flatter compaction curve near the maximum dry unit weight.

3. For all soils, dry unit weight decreased with increasing polymer addition rate, with the exception of a spike at an intermediate addition rate. Even, though the magnitude of the change in dry unit weight was relatively small (all polymer amended specimens remained within 2.5% of their respective control dry unit weight), the changes are significant from an engineering standpoint. The reduction in dry unit weight was attributed to the polymer (specific gravity approximately 1.0) replacing volume in the soil-polymer matrix otherwise taken by soil (specific gravity approximately 2.65). The spike at an intermediate addition rate was attributed to particles re-arranging into a more dense state once sufficient polymer was added to coat the particles. The polymer coating on the soil particles reduced the intraparticle capillary tension and caused a lubricating effect.

The unconfined compression test was used to determine the shear strength properties of LCL, LCH, and HCH soils. Testing was conducted on compaction specimens that were cured for 7 days. The direct shear test was used to determine the strength of SAND, due to the lack of cohesion in the soil. Based on the strength tests, the following conclusions were drawn:

1. The peak strength of polymer amended specimens across all tested soil types ranged from 528 to 1276 kPa. The strength increased from 1.0 to 18.4 times the control strength, with an average increase of 7.0 times that of control. The strength increase was attributed to the polymer coating the surface of the soil particles and increasing the inter-particle shear strength.
2. The peak strength for each soil type was achieved at polymer addition rates ranging from 0.5% (LCL) to 2.5% (HCH). It was hypothesized that polymer amendment has

the greatest strength increase when it was applied at rates high enough to sufficiently coat all soil particle surfaces, but at rates low enough that it did not cause additional particle separation. Therefore, a peak amendment rate can be determined as a function of soil properties.

3. Polymer amended LCH demonstrated a peak strength of 1276 kPa, 1.0 times that of control. This low strength increase relative to other soil types was attributed to the increased slip planes of the LCH soil due to the inclusion of 3% montmorillonite clay in the test soil. It was hypothesized that the polymer coated clumps of soil particles, but was not able to sufficiently coat all of the individual clay particles, allowing shear failure through interconnected non-amended particle surfaces.
4. At addition rates tested, polymer amended strengths were greater than lime amended strengths, but less than cement amended strengths. The peak polymer amended strengths of SAND and LCL were 528 and 568 kPa, or 0.22 and 0.29 times the peak cement strength, respectively. The peak polymer amended strengths of LCH and HCH were 1276 and 1244 kPa, or 1.7 and 1.3 times peak amended lime strength, respectively.

Wet-dry and freeze-thaw durability tests were conducted in this testing program. Polymer specimens were amended at a rate of 1.0%, and were top coated with a polymer-water solution to represent field conditions. All specimens were cured for 9 days, with polymer amended specimens coated after 7 days of curing. Specimens were subjected to 12 wet-dry or freeze-thaw conditioning cycles, and were subjected to scratching at the end of each conditioning cycle. Comparative analysis was completed by integrating the area under the cycles versus percent remaining curve. The resulting value was reported in

units of cycles (i.e., a durability value of 6 indicates that the summation of mass recorded the conclusion of each cycle equals 6 times the initial specimen mass). Based on the durability tests, the following conclusions were drawn:

1. The peak wet-dry durability of polymer amended specimens ranged from 7.3 to 11.2 cycles, or 6.8 to 10.8 times the control durability, with an average of 8.1 times the control durability across the range of soils tested. The peak freeze-thaw durability of polymer amended specimens ranged from 4.3 to 10.3 cycles, or 2.1 to 7.3 times the control durability, with an average of 4.1 times the control durability across the range of soils tested. The peak wet-dry durability of the polymer amended specimens was observed dry of optimum moisture content for SAND specimens, near optimum for LCL and LCH specimens, and wet of optimum for HCH specimens.
2. The increase in durability in polymer amended specimens was partially attributed to the coating on the exterior of the specimens. The average integrated area durability values across all soil types for wet-dry conditioned specimens were 0.1, 5.3, and 8.0 cycles for control, no coating polymer amended, and coated polymer amended, respectively. The average integrated area durability values across all soil types for freeze-thaw conditioned specimens were 2.0, 1.9, and 6.0 cycles for control, no coating polymer amended, and coated polymer amended, respectively. Approximately 35% of the increase in durability of the wet-dry conditioned specimens was attributed to the polymer coating, and the entire increase in durability of the freeze-thaw specimens was attributed to the polymer coating. This indicated that polymer mixed in the soil matrix provided adhesion, and effectively

improved durability in submerged conditions. However, at sub-freezing temperatures, the soil-polymer matrix was not able to withstand the expansion forces of freezing soil. In addition, the importance of coating exposed soil surfaces in field conditions was highlighted.

3. After specimens began to deteriorate, polymer amended specimens generally failed more rapidly than control specimens. This was attributed to loss of the exterior polymer coating, which provided rigidity to the specimen while the top-coat was intact.
4. Wet-dry durability specimens generally demonstrated a more rapid progression to failure than freeze-thaw durability specimens.

Stiffness was determined through interpretation of the unconfined compression test using the tangent modulus method and through the resilient modulus test. The tangent modulus stiffness was determined as the peak slope of the stress strain curve to provide the initial stiffness of the specimens. The resilient modulus stiffness test was used to determine the stiffness under repeated dynamic loading. Based on the stiffness tests, the following conclusions were drawn:

1. The peak tangent modulus stiffness of control specimens ranged from 0.01 to 80 MPa. The peak stiffness of polymer amended specimens ranged 0.4 to 148 MPa. The relative peak stiffness improvement with the addition of polymer ranged from 1.9 to 4.4 times the control stiffness across the range of soil types.
2. The peak tangent modulus stiffness was determined at 0.5%, 1.0%, and 2.5% polymer addition rate in the LCL, LCH, and HCH soils, respectively. The peak tangent modulus stiffness from the direct shear test was determined at the highest

addition rate tested (1.5%) in SAND. For specimens with a fines fraction, the amendment rate to achieve peak stiffness increased with increasing specific surface, following similar trends to the unconfined compression test results.

3. The peak resilient modulus stiffness of polymer amended specimens ranged from 39 to 195 MPa, 0.3 to 1.3 times the control stiffness across the range of soil types. The average stiffness was 0.7 times the control stiffness. The reduced stiffness in the resilient modulus tests of polymer amended specimens was attributed to the repeated loading prematurely breaking the polymer-soil bond in the cured specimens.
4. The polymer amended specimens displayed a reduced relative stiffness in the first 6 stages of the resilient modulus test. Then the polymer amended specimens displayed an increased relative stiffness between stages 7 to 10. Finally, the polymer amended specimens maintained a constant relative stiffness over the 5 final stages of the resilient modulus test. Over the final 5 stages, the LCL and LCH specimens maintained an average of 1.3 times the control resilient modulus, while the average normalized stiffness for SAND and LCL specimens was 0.6 times the control resilient modulus. The difference in final relative stiffness was attributed to increased particle contact frequency in the LCH and HCH specimens. The number of particle contacts per unit area was greater in the LCH and HCH specimens than the SAND and LCL specimens. Therefore, for a given amount of sample deformation, the average absolute displacement was much less at each particle contact in LCH and HCH specimens. Assuming polymer provided adhesion at each of these contacts, the polymer was better able to recover from the small movements in the LCH and HCH specimens and return to its original configuration during the resilient

modulus test. However, the polymer bonds in the SAND and LCL specimens were broken and not able to recover, leading to relatively low resilient modulus values.

Overall the following conclusions were drawn from the entire test program:

1. Polymer changed the engineering properties of soil through physical bonding. The amount of polymer required to modify the engineering properties was directly related to the specific surface.
2. Polymer amended specimens that were cured in the mold, cured successfully on both ends but not in the centers. This was evident by the deterioration of the center of the specimens, with a hardened cone of soil on each end. This observation indicated that access to air affects curing efficiency for polymer amended soils.
3. Polymer had an optimum addition rate. If polymer was added below the optimum addition rate, additional moisture was required in the soil-polymer mixture to thin the polymer and allow it to cover a greater surface area. If polymer was added above the optimum addition rate, the overall engineering benefit began to decrease.

6.3 Recommendations

Based on the results of the test program, opportunities exist for further research. Upon assessment of the strength and stiffness results, the data suggests that polymer amendment provided improvement of engineering properties at higher addition rates. This was especially evident in soils with higher plasticity and a higher percentage of fines. Peak engineering performance may not have been achieved in all testing areas for most soils. Therefore, the addition of polymer at higher rates could lead to further understanding of soil-polymer interaction, and aid in the evaluation of performance of polymer in all soil types.

Data from the entire test program suggested that the soil-polymer bond was physical. A microscopic investigation could enhance understanding of the soil-polymer interaction and overall system behavior. A fundamental understanding of this interaction would assist with preparing specifications for industry use of polymer as a soil amendment.

Future direct shear tests should be conducted at higher normal stresses than what was used in this test program to gain perspective on the shear strength response of polymer amended clean sands and gravels over a broader range of stress conditions than that tested herein.

Engineering behavior observed in the test program was attributed to polymer coating the exterior surface of the soil particles. This polymer coating resides directly in the shear plane between individual soil particles. Further testing to determine the shear strength of pure polymer and the soil-polymer bond strength would assist in determining if shear failure in polymer amended soils occurs within the polymer itself, or if it was fracturing at the soil-polymer interface. This information could enhance specification of addition rates, as well as provide valuable information for further development of polymer.

Overall, polymer proved to be a viable amendment option to improve the engineering properties of soil. However, for successful field-scale implementation, further enhancement of standards and methods is needed.

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Appendix A: Sample Worksheets

Sieve Analysis:

Sample ID: _____	Pre-mix / Post - mix _____
Test Performed By: _____	
Date: _____	Max Agg. Size _____
Time: _____	
Original _____	Wet Sieve Completed? Yes / No _____
Sample Mass: _____ g	Oven Dried? Yes / No _____

Sieve Diameter (mm)	Sieve Size or Number	Mass Retained (g)
25.4	1"	
19.00	3/4"	
14.25	1/2"	
9.50	3/8"	
4.75	4	
2.00	10	
0.875	20	
0.425	40	
0.250	60	
0.150	100	
0.075	200	
-	Fines	
Total:		
% Error:		

Observations: _____

_____

_____

Appendix A: Sample Worksheets

Standard Proctor Sample Preparation

Created By: _____	Sample ID: _____
Date: _____	Mold #: _____
Time: _____	
Amendment Type: _____	
Amendment Rate: _____ %	Soil Type: _____
Initial Sample Mass: _____ g	
Initial Mc: _____ %	
Target Mc: _____ %	
Wt. of Solids (dry): _____ g	→ Mass of Amnt.: _____ g
Wt. at Target Mc: _____ g	Mass of Amnt. Solution: _____ g
	Mass of Water in Amnt. Solution: _____ g
Water Needed: _____ g	
↓	
- Mass of water in Amndt Solution: _____ g	←
Total Water: _____ g	
	↓
	Total Water: _____ g
	Total Ammendment: _____ g
Observations: _____	
_____	
_____	

Appendix A: Sample Worksheets

Standard Proctor Compaction Test

Initials: ____ Date: ____ Time: ____ Amnt. Type: ____ None / Poly / Cem / Lime Amnt. Rate: ____ % Assumed Wc: ____ % Machine Used: ____ Brown / Green / Hand Mold #: ____ Moisture Tin #: ____ Mass of Tin: ____ g Tin + Moist Soil: ____ g Tin + Dry Soil: ____ g Mass of Water: ____ g Water Content: ____ %	Sample ID: ____ <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 30%; text-align: center;">Soil Type:</td> <td> ____ SAND ____ LCL ____ LCH ____ HCH ____ Other: </td> </tr> </table> # of Layers: ____ Blows/Layer: ____ Vol of Mold: ____ cm³ Mass of Mold: ____ kg Soil + Mold: ____ kg Mass of Soil: ____ kg Wet Unit Weight: ____ kN/m³ Dry Unit Weight: ____ kN/m³ Observations: ____ ____ ____	Soil Type:	____ SAND ____ LCL ____ LCH ____ HCH ____ Other:
Soil Type:	____ SAND ____ LCL ____ LCH ____ HCH ____ Other:		

Appendix A: Sample Worksheets

Unconfined Compression Test

Test Performed By: _____ Date: _____ Time: _____	Sample ID: _____
Amendment Type: _____ Amendment Rate: _____ % Assumed Wc: _____ %	Soil Type: _____
Moisture Tin #: _____ Mass of Tin: _____ g Tin + Moist Soil: _____ g Tin + Dry Soil: _____ g Mass of Water: _____ g Water Content: _____ %	Diameter (X4): _____ Height (X3): _____ LRC: _____ lb/div Speed: _____ dial Speed: _____ (in/min)

Time (min)	Def. -LVDT 1 (in)	Def. -LVDT 2 (in)	Load (lbs)

Max Load Reading _____ lbs   At Time _____ min
 Observations: _____
 _____
 _____

Appendix A: Sample Worksheets

Wet Dry Test Sample Data						
Sampl ID _____		Soil Type _____		Amdt. Rate _____ %		
		Top Dia (cm)	Bot. Dia (cm)	Height (cm)	Mass (g)	
Pre-Test	Int: _____					Vol: _____ cm ³
	Date: _____					
	Time: _____					Den: _____ kN/m ³
:Average						
Cycle 1	Pre Scratch Mass _____		Notes: _____			
	Post Scratch Mass _____		Notes: _____			
Cycle 2	Pre Scratch Mass _____		Notes: _____			
	Post Scratch Mass _____		Notes: _____			
Cycle 3	Pre Scratch Mass _____		Notes: _____			
	Post Scratch Mass _____		Notes: _____			
Cycle 4	Pre Scratch Mass _____		Notes: _____			
	Post Scratch Mass _____		Notes: _____			
Cycle 5	Pre Scratch Mass _____		Notes: _____			
	Post Scratch Mass _____		Notes: _____			
Cycle 6	Pre Scratch Mass _____		Notes: _____			
	Post Scratch Mass _____		Notes: _____			
Cycle 7	Pre Scratch Mass _____		Notes: _____			
	Post Scratch Mass _____		Notes: _____			
Cycle 8	Pre Scratch Mass _____		Notes: _____			
	Post Scratch Mass _____		Notes: _____			
Cycle 9	Pre Scratch Mass _____		Notes: _____			
	Post Scratch Mass _____		Notes: _____			
Cycle 10	Pre Scratch Mass _____		Notes: _____			
	Post Scratch Mass _____		Notes: _____			
Cycle 11	Pre Scratch Mass _____		Notes: _____			
	Post Scratch Mass _____		Notes: _____			
Cycle 12	Pre Scratch Mass _____		Notes: _____			
	Post Scratch Mass _____		Notes: _____			

Appendix A: Sample Worksheets

Resilient Modulus Checklist

For Each Sample	
Sample Number	
Material Type	
Sample Preparation Date and Time	
Test Date and Time	
Test Completed By	
Preconditioning - Greater than 5% perm. Strain?	
Testing - Greater than 5% Perm. Strain?	
Testing - Number of Sequences Completed	
Spec. Diameter: Top, Middle, Bottom, Average	
Height of Specimen, Cap, and Base	
Height of Cap and Base	
Initial Length	
Initial Area	
Initial Volume	
Initial weight of container and Wet Soil	
Final Weight of Container and Wet Soil	
Weight of Wet Soil Used	
Optimum Moisture Content (as specified for soil sample)	
Max Dry Density (as specified for soil sample)	
Compaction Moisture Content, (%)	
Moisture content after resilient modulus test	
Compaction Dry Density	
Average Resilient Modulus	
Standard Deviation	
For Each Testing Sequence	
Actual Chamber Confining Pressure	
Nominal Maximum Axial Stress	
Average Resilient Modulus	
Standard Deviation	
For Each Cycle	
Actual Applied Max Axial Load	
Actual Applied Cycle Load	
Actual Applied Contact Load	
Actual Applied Cyclic Stress	
Actual Applied Contact Stress	
Recovered Deformation (LVDT #1)	
Recovered Deformation (LVDT #2)	
Average Recovered Deformation (LVDT #1 & 2)	
Resilient Strain	
Resilient Modulus	

Appendix B: Resilient Modulus MatLAB Code

```
% RMTA: Resilient Modulus Test Analysis
%
% input:
%
% output:
%   Mr: the resilient modulus
%
% Note: DATA.txt must be placed in MATLAB folder and in specific
format

clear all
close all
clc
format long g

% Load the data file

name = input('What is the name (w/out extension) of the data
file? ', 's');
ext = '.txt';
filename = strcat(name,ext);
disp(' ')
M = load(filename);

% Set columns

time   = 1;
stagenum = 11;
devstr = 3;
displace = 12;

% Set defaults

pri = questdlg('Would you like to save pdf files of the stress
and strain plots? (Default = N)', 'Save PDFs', 'Y', 'N', 'N');
gage = input('Specify the gage length for this test in
millimeters? ');
disp(' ')

% Correct data to ensure no plateaus

for t = 2:size(M,1)
    if M(t, devstr) == M(t - 1, devstr)
        M(t, devstr) = M(t, devstr)- 1e-5;
    end
    if M(t, displace) == M(t - 1, displace)
        M(t, displace) = M(t, displace)- 1e-5;
    end
end
```

Appendix B: Resilient Modulus MatLAB Code

```
% Identify conditioning period

cond = M(:,stagenum);
[~, low] = min(abs(cond-1));
cond = M(1:(low-1),:);
M = M(low:end,:);

% Check conditioning for 5% strain

STRAIN = cond(:,displace)/ gage;
STRAINZ = le(0.05,STRAIN);
[limit]=find(STRAINZ,1);
if isempty(limit)
    disp('Strain limit is not reached during conditioning')
    disp(' ')
else
    disp('Strain limit is reached during conditioning')
end

% Find where, if anywhere, the sample reaches 5% strain

STRAIN = M(:,displace)/ gage;
STRAINZ = le(0.05,STRAIN);
[limit]=find(STRAINZ,1);
if isempty(limit)
    disp('Strain limit is not reached during testing.')
    disp(' ')
else
    disp('Strain limit is reached during testing')
end

% Set arrays S for peak detection

S = [10 25 30 20 40 40 30 50 50 40 40 60 60 60 60];

% Loop the 15 stages

Mr_tot = zeros(15,1);
for stage = 1:15

    [~, stagestart] = min(abs(M(:, 11) - stage));
    [~, stagestop] = min(abs(M(:, 11) - stage - 1));
    stagestop = stagestop -1;
    MPEAK = M(stagestart:stagestop, :);

    % Find stress and deformation peaks of the stage

    [PKS_STR, LOCS_STR] = findpeaks(MPEAK(:, 3), 'MinPeakHeight',
S(1, stage),'MinPeakDistance', 1);
    LOCS_DIS = LOCS_STR;
    PKS_DIS = transpose(MPEAK(LOCS_DIS, displace));
```


Appendix B: Resilient Modulus MatLAB Code

```
[PKNUM,~] = size(PKS_STR);
if PKNUM > 5
    for p = 6:PKNUM;
        PKS_STR(6,:) = [];
        LOCS_STR(6,:) = [];
        PKS_DIS(:,6) = [];
        LOCS_DIS(6,:) = [];
    end
end

% Compute mean rest stress

low = 1;
hi = size(MPEAK);
high = hi(1,1);
d = MPEAK(1, 1);
for b = d:MPEAK(high, 1)
    [~, locastrhi(floor(b -(d - 1)), 1)] = min(abs(MPEAK(:,
1)- b -1)));
    [~, locastrlo(floor(b -(d - 1)), 1)] = min(abs(MPEAK(:,
1)- b -.25)));
end
str_avg = zeros(1, 5);
k = zeros(1, locastrhi(1, 1)- locastrlo(1, 1));
for b = 1:5
    for d = 1:locastrhi(b, 1)- locastrlo(b, 1)
        k(1, d) = M(locastrlo(b, 1)- 1 + d, devstr);
    end
    str_avg(1, b) = mean(k);
end

% Compute mean rest deformation

d = MPEAK(1, 1);
for b = d:MPEAK(high, 1)
    [~, locadishi(floor(b -(d - 1)), 1)] = min(abs(MPEAK(:,
,1)- b - 1)));
    [~, locadislo(floor(b -(d - 1)), 1)] = min(abs(MPEAK(:,
,1)- b - .25)));
end
dis_avg = zeros(1, 5);
k = zeros(1, locadishi(1, 1)- locadislo(1, 1));
for b=1:5
    for d = 1:locadishi(b, 1)- locadislo(b, 1)
        k(1, d) = M(locadislo(b, 1)- 1 + d, displace);
    end
    dis_avg(1, b) = mean(k);
end

% Plot range

if pri == 'Y'
```

Appendix B: Resilient Modulus MatLAB Code

```

        subplot(2,1,1)
        plot(MPEAK(:, time), MPEAK(:, devstr), '-b',
MPEAK(LOCS_STR, time), PKS_STR, 'om')
        title('Stress', 'fontweight', 'b', 'fontsize', 12); grid
on
        xlabel('Time [sec]'); ylabel('Stress [kPa]');
        subplot(2,1,2)
        plot(MPEAK(:, time), MPEAK(:, displace)/ gage * 100, '-
b', MPEAK(LOCS_DIS, time), PKS_DIS/ gage * 100, 'om')
        title('Strain', 'fontweight', 'bold', 'fontsize', 12);
grid on
        xlabel('Time [sec]'); ylabel('Strain [%]')
        printdlg
        close all
    end

    % Calculate cyclic stress 'CS' and recoverable strain 'RS'

    PKS_STR = transpose(PKS_STR);
    CS = (PKS_STR - str_avg);
    RS = ((PKS_DIS - dis_avg)) / gage;

    % Calculate Resilience Modulus 'Mr'

    res_mod = CS./ RS;
    Mr = mean(res_mod);
    Mr_tot(stage,1) = Mr;

    % Display results

    disp(' ')
    disp('Stage Number')
    disp(stage)
    disp(' ')
    disp('Actual Applied Max Axial Stress [kPa]')
    disp(transpose(PKS_STR))
    disp(' ')
    disp('Actual Applied Contact Stress [kPa]')
    disp(transpose(str_avg))
    disp(' ')
    disp('Actual Applied Cyclic Stress [kPa]')
    disp(transpose(CS))
    disp('Average Recoverable Deformation from LVDT Average
[mm]')
    disp(transpose((PKS_DIS - dis_avg)))
    disp('Resilient Strain [%]')
    disp(transpose(RS))
    disp('Resilient Moduli [kPa]')
    disp(transpose(res_mod))
    disp(' ')
    disp(' Average Resilient Modulus [kPa]')
    disp(Mr)

```

Appendix B: Resilient Modulus MatLAB Code

```
disp(' ')

% Write to file

N(1,10) = stage;
N(1,13) = gage;
N(1,14) = Mr;
Data = MPEAK;
[Success] = xlswrite('Data Analyzed.xls', Data, stage, 'A3');
[Success] = xlswrite('Final Output.xls', transpose(PKS_STR),
stage, 'E5');
[Success] = xlswrite('Final Output.xls', transpose(CS),
stage, 'F5');
[Success] = xlswrite('Final Output.xls', transpose(dis_avg),
stage, 'G5');
[Success] = xlswrite('Final Output.xls', transpose((PKS_DIS -
dis_avg)), stage, 'H5');
[Success] = xlswrite('Final Output.xls', transpose(RS),
stage, 'I5');
[Success] = xlswrite('Final Output.xls',
transpose(res_mod)/1000, stage, 'J5');

end

Mr_avg = mean(Mr_tot)
[Success] = xlswrite('Data Analyzed.xls', Mr_avg, 16, 'B3');
beep
disp(' ')
disp('FINISHED!')
```

Appendix C: Selection Figures for Resilient Modulus Specimens

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Appendix C: Selection Figures for Resilient Modulus Specimens

Appendix D: Summary of All Tested Specimens

Sample ID	Soil Type	Am. Type	Am. Rate (%)	Target Water Content (%)	Actual Water Content (%)	Dry Unit Weight (kN/m ³)
TM1_SAND2_N_UCS	SAND	Control	0.0	2.0	1.9	18.51
TM1_SAND4_N_UCS	SAND	Control	0.0	4.0	4.0	18.31
TM1_SAND6_N_UCS	SAND	Control	0.0	6.0	6.1	18.52
TM1_SAND8_N_UCS	SAND	Control	0.0	8.0	8.1	19.24
TM1_SAND10_N_UCS	SAND	Control	0.0	10.0	10.2	18.74
TM1_SAND12_N_UCS	SAND	Control	0.0	12.0	10.5	19.47
TM1_SAND2_N_UCS_R	SAND	Control	0.0	2.0	2.4	18.26
TM1_SAND4_N_UCS_R	SAND	Control	0.0	4.0	4.2	18.07
TM1_SAND6_N_UCS_R	SAND	Control	0.0	6.0	6.2	18.35
TM1_SAND8_N_UCS_R	SAND	Control	0.0	8.0	8.1	18.37
TM1_SAND10_N_UCS_R	SAND	Control	0.0	10.0	10.2	18.89
TM1_SAND12_N_UCS_R	SAND	Control	0.0	12.0	10.3	18.94
TM1_SAND2_P0.5_UCS	SAND	Polymer	0.5	2.0	2.1	17.81
TM1_SAND4_P0.5_UCS	SAND	Polymer	0.5	4.0	3.9	18.66
TM1_SAND6_P0.5_UCS	SAND	Polymer	0.5	6.0	5.9	19.14
TM1_SAND8_P0.5_UCS	SAND	Polymer	0.5	8.0	8.4	18.19
TM1_SAND10_P0.5_UCS	SAND	Polymer	0.5	10.0	10.8	17.98
TM1_SAND2_P1_UCS	SAND	Polymer	1.0	2.0	2.0	17.97
TM1_SAND4_P1_UCS	SAND	Polymer	1.0	4.0	4.1	19.30
TM1_SAND6_P1_UCS	SAND	Polymer	1.0	6.0	6.2	18.92
TM1_SAND8_P1_UCS	SAND	Polymer	1.0	8.0	9.4	18.55
TM1_SAND10_P1_UCS	SAND	Polymer	1.0	10.0	11.0	17.22
TM1_SAND2_P1.5_UCS	SAND	Polymer	1.5	2.0	2.1	17.89
TM1_SAND4_P1.5_UCS	SAND	Polymer	1.5	4.0	4.1	19.20
TM1_SAND6_P1.5_UCS	SAND	Polymer	1.5	6.0	6.1	19.18
TM1_SAND8_P1.5_UCS	SAND	Polymer	1.5	8.0	7.8	18.04
TM1_SAND10_P1.5_UCS	SAND	Polymer	1.5	10.0	9.9	17.91
TM1_SAND12_P1.5_UCS	SAND	Polymer	1.5	12.0	12.0	17.80
TM1_SAND4_C1_UCS	SAND	Cement	1.0	4.0	3.4	18.39
TM1_SAND6_C1_UCS	SAND	Cement	1.0	6.0	5.4	18.39
TM1_SAND8_C1_UCS	SAND	Cement	1.0	8.0	7.2	18.35
TM1_SAND10_C1_UCS	SAND	Cement	1.0	10.0	9.1	19.05
TM1_SAND12_C1_UCS	SAND	Cement	1.0	12.0	10.9	19.03
TM1_SAND4_C2_UCS	SAND	Cement	2.0	4.0	3.5	18.86
TM1_SAND6_C2_UCS	SAND	Cement	2.0	6.0	5.2	18.81
TM1_SAND8_C2_UCS	SAND	Cement	2.0	8.0	7.4	18.95
TM1_SAND8_C2_UCS_R	SAND	Cement	2.0	0.0	6.4	19.47
TM1_SAND10_C2_UCS	SAND	Cement	2.0	10.0	8.8	19.87
TM1_SAND12_C2_UCS	SAND	Cement	2.0	12.0	10.6	19.38
TM1_SAND4_C4_UCS	SAND	Cement	4.0	4.0	4.7	19.32
TM1_SAND6_C4_UCS	SAND	Cement	4.0	6.0	5.4	18.95
TM1_SAND8_C4_UCS	SAND	Cement	4.0	8.0	7.0	19.65
TM1_SAND10_C4_UCS	SAND	Cement	4.0	10.0	8.7	19.98
TM1_SAND12_C4_UCS	SAND	Cement	4.0	12.0	10.4	19.90
TM1_LCL4_N_UCS	LCL	Control	0.0	4.0	4.2	18.90
TM1_LCL6_N_UCS	LCL	Control	0.0	6.0	6.5	19.48
TM1_LCL8_N_UCS	LCL	Control	0.0	8.0	8.3	20.30
TM1_LCL10_N_UCS	LCL	Control	0.0	10.0	10.1	20.32
TM1_LCL12_N_UCS	LCL	Control	0.0	12.0	12.1	19.57
TM1_LCL14_N_UCS	LCL	Control	0.0	14.0	13.5	18.86

Appendix D: Summary of All Tested Specimens

Sample ID	Soil Type	Am. Type	Am. Rate (%)	Target Water Content (%)	Actual Water Content (%)	Dry Unit Weight (kN/m ³)
TM1_LCL4_P0.5_UCS	LCL	Polymer	0.5	4.0	4.2	19.17
TM1_LCL6_P0.5_UCS	LCL	Polymer	0.5	6.0	6.7	19.61
TM1_LCL8_P0.5_UCS	LCL	Polymer	0.5	8.0	8.2	20.16
TM1_LCL10_P0.5_UCS	LCL	Polymer	0.5	10.0	10.7	19.47
TM1_LCL12_P0.5_UCS	LCL	Polymer	0.5	12.0	12.0	18.94
TM1_LCL4_P1_UCS	LCL	Polymer	1.0	4.0	4.4	18.88
TM1_LCL6_P1_UCS	LCL	Polymer	1.0	6.0	6.3	19.76
TM1_LCL8_P1_UCS	LCL	Polymer	1.0	8.0	8.5	20.19
TM1_LCL10_P1_UCS	LCL	Polymer	1.0	10.0	10.1	19.72
TM1_LCL12_P1_UCS	LCL	Polymer	1.0	12.0	12.4	18.76
TM1_LCL4_P1.5_UCS	LCL	Polymer	1.5	4.0	4.5	18.96
TM1_LCL4_P1.5_UCS_R	LCL	Polymer	1.5	4.0	3.8	18.57
TM1_LCL6_P1.5_UCS	LCL	Polymer	1.5	6.0	6.4	19.37
TM1_LCL8_P1.5_UCS	LCL	Polymer	1.5	8.0	7.9	20.04
TM1_LCL10_P1.5_UCS	LCL	Polymer	1.5	10.0	10.9	19.35
TM1_LCL12_P1.5_UCS	LCL	Polymer	1.5	12.0	12.3	18.85
TM1_LCL8_C1_UCS	LCL	Cement	1.0	8.0	7.3	20.21
TM1_LCL10_C1_UCS	LCL	Cement	1.0	10.0	8.9	20.05
TM1_LCL12_C1_UCS	LCL	Cement	1.0	12.0	10.7	19.64
TM1_LCL14_C1_UCS	LCL	Cement	1.0	14.0	13.0	18.85
TM1_LCL6_C2_UCS	LCL	Cement	2.0	6.0	5.8	19.51
TM1_LCL8_C2_UCS	LCL	Cement	2.0	8.0	7.5	19.58
TM1_LCL10_C2_UCS	LCL	Cement	2.0	10.0	9.8	20.03
TM1_LCL10_C2_UCS_R	LCL	Cement	2.0	10.0	10.4	20.09
TM1_LCL12_C2_UCS	LCL	Cement	2.0	12.0	9.6	19.83
TM1_LCL14_C2_UCS	LCL	Cement	2.0	14.0	12.8	19.07
TM1_LCL6_C4_UCS	LCL	Cement	4.0	6.0	5.3	19.62
TM1_LCL8_C4_UCS	LCL	Cement	4.0	8.0	6.8	20.23
TM1_LCL8_C4_UCS_R	LCL	Cement	4.0	8.0	7.4	19.92
TM1_LCL10_C4_UCS	LCL	Cement	4.0	10.0	9.3	20.50
TM1_LCL12_C4_UCS	LCL	Cement	4.0	12.0	11.2	19.47
TM1_LCL14_C4_UCS	LCL	Cement	4.0	14.0	13.3	18.94
TM1_LCH7_N_UCS	LCH	Control	0.0	7.0	7.8	18.15
TM1_LCH8_N_UCS	LCH	Control	0.0	8.0	7.4	19.16
TM1_LCH12_N_UCS	LCH	Control	0.0	12.0	11.4	19.51
TM1_LCH14_N_UCS	LCH	Control	0.0	14.0	13.4	19.25
TM1_LCH7_P0.5_UCS	LCH	Polymer	0.5	7.0	6.8	18.74
TM1_LCH9_P0.5_UCS	LCH	Polymer	0.5	9.0	9.2	18.84
TM1_LCH11_P0.5_UCS	LCH	Polymer	0.5	11.0	10.7	19.25
TM1_LCH13_P0.5_UCS	LCH	Polymer	0.5	13.0	11.3	19.07
TM1_LCH15_P0.5_UCS	LCH	Polymer	0.5	15.0	14.3	18.40
TM1_LCH7_P1_UCS	LCH	Polymer	1.0	7.0	7.1	18.40
TM1_LCH10_P1_UCS	LCH	Polymer	1.0	10.0	9.7	19.06
TM1_LCH12_P1_UCS	LCH	Polymer	1.0	12.0	11.0	19.02
TM1_LCH13_P1_UCS	LCH	Polymer	1.0	13.0	12.8	18.64
TM1_LCH14_P1_UCS	LCH	Polymer	1.0	14.0	12.1	18.94
TM1_LCH7_P1.5_UCS	LCH	Polymer	1.5	7.0	7.2	18.21
TM1_LCH9_P1.5_UCS	LCH	Polymer	1.5	9.0	9.7	19.40
TM1_LCH11_P1.5_UCS	LCH	Polymer	1.5	11.0	11.0	18.89
TM1_LCH13_P1.5_UCS	LCH	Polymer	1.5	13.0	12.9	18.28

Appendix D: Summary of All Tested Specimens

Sample ID	Soil Type	Am. Type	Am. Rate (%)	Target Water Content (%)	Actual Water Content (%)	Dry Unit Weight (kN/m ³)
TM1_LCH15_P1.5_UCS	LCH	Polymer	1.5	15.0	14.7	17.89
TM1_LCH7_L8_UCS	LCH	Lime	8.0	7.0	9.1	18.04
TM1_LCH9_L8_UCS	LCH	Lime	8.0	9.0	N/A	N/A
TM1_LCH11_L8_UCS	LCH	Lime	8.0	11.0	12.8	18.19
TM1_LCH13_L8_UCS	LCH	Lime	8.0	13.0	14.5	18.02
TM1_LCH15_L8_UCS	LCH	Lime	8.0	15.0	16.3	17.75
TM2_LCH7_N_UCS	LCH	Control	0.0	7.0	6.4	18.86
TM2_LCH9_N_UCS	LCH	Control	0.0	9.0	8.8	18.93
TM2_LCH11_N_UCS	LCH	Control	0.0	11.0	9.4	19.49
TM2_LCH13_N_UCS	LCH	Control	0.0	13.0	12.3	18.77
TM2_LCH15_N_UCS	LCH	Control	0.0	15.0	13.7	18.39
TM2_LCH7_P1_UCS	LCH	Polymer	1.0	7.0	6.1	17.71
TM2_LCH9_P1_UCS	LCH	Polymer	1.0	9.0	8.6	18.80
TM2_LCH11_P1_UCS	LCH	Polymer	1.0	11.0	10.9	19.08
TM2_LCH13_P1_UCS	LCH	Polymer	1.0	13.0	10.9	18.95
TM2_LCH15_P1_UCS	LCH	Polymer	1.0	15.0	15.1	17.90
TM2_LCH8_P1_UCS	LCH	Polymer	1.0	8.0	7.4	18.58
TM2_LCH10_N_UCS	LCH	Polymer	0.0	10.0	9.0	19.25
TM1_HCH6_N_UCS	HCH	Control	0.0	6.0	5.8	17.80
TM1_HCH8_N_UCS	HCH	Control	0.0	8.0	7.7	17.75
TM1_HCH8_N_UCS_R	HCH	Control	0.0	8.0	8.1	17.98
TM1_HCH10_N_UCS	HCH	Control	0.0	10.0	9.7	18.70
TM1_HCH12_N_UCS	HCH	Control	0.0	12.0	11.5	18.42
TM1_HCH14_N_UCS	HCH	Control	0.0	14.0	13.5	18.38
TM1_HCH16_N_UCS	HCH	Control	0.0	16.0	16.0	17.83
TM1_HCH6_P0.5_UCS	HCH	Polymer	0.5	6.0	5.7	17.36
TM1_HCH8_P0.5_UCS	HCH	Polymer	0.5	8.0	7.8	17.62
TM1_HCH10_P0.5_UCS	HCH	Polymer	0.5	10.0	9.5	18.12
TM1_HCH12_P0.5_UCS	HCH	Polymer	0.5	12.0	11.9	18.45
TM1_HCH14_P0.5_UCS	HCH	Polymer	0.5	14.0	13.8	18.14
TM1_HCH16_P0.5_UCS	HCH	Polymer	0.5	16.0	13.2	18.22
TM1_HCH6_P1_UCS	HCH	Polymer	1.0	6.0	6.0	17.03
TM1_HCH8_P1_UCS	HCH	Polymer	1.0	8.0	7.5	17.58
TM1_HCH10_P1_UCS	HCH	Polymer	1.0	10.0	9.4	17.82
TM1_HCH12_P1_UCS	HCH	Polymer	1.0	12.0	11.6	18.40
TM1_HCH14_P1_UCS	HCH	Polymer	1.0	14.0	12.8	18.37
TM1_HCH16_P1_UCS	HCH	Polymer	1.0	16.0	15.4	17.81
TM1_HCH6_P1.5_UCS	HCH	Polymer	1.5	6.0	4.7	17.44
TM1_HCH8_P1.5_UCS	HCH	Polymer	1.5	8.0	6.6	18.11
TM1_HCH10_P1.5_UCS	HCH	Polymer	1.5	10.0	8.1	18.14
TM1_HCH12_P1.5_UCS	HCH	Polymer	1.5	12.0	11.1	18.63
TM1_HCH14_P1.5_UCS	HCH	Polymer	1.5	14.0	13.2	14.05
TM1_HCH14_P1.5_UCS_R	HCH	Polymer	1.5	0.0	13.5	18.35
TM1_HCH16_P1.5_UCS	HCH	Polymer	1.5	16.0	15.6	17.65
TM1_HCH8_P2_UCS	HCH	Polymer	2.0	8.0	7.3	17.34
TM1_HCH10_P2_UCS	HCH	Polymer	2.0	10.0	8.6	17.45
TM1_HCH10_P2_UCS_R	HCH	Polymer	2.0	10.0	8.8	17.93
TM1_HCH12_P2_UCS	HCH	Polymer	2.0	12.0	12.5	18.40
TM1_HCH12_P2_UCS_R	HCH	Polymer	2.0	12.0	10.7	18.40
TM1_HCH14_P2_UCS_R	HCH	Polymer	2.0	14.0	12.8	18.09

Appendix D: Summary of All Tested Specimens

Sample ID	Soil Type	Am. Type	Am. Rate (%)	Target Water Content (%)	Actual Water Content (%)	Dry Unit Weight (kN/m ³)
TM1_HCH8_P2.5_UCS	HCH	Polymer	2.5	8.0	7.1	17.31
TM1_HCH10_P2.5_UCS	HCH	Polymer	2.5	10.0	8.8	17.63
TM1_HCH10_P2.5_UCS_R	HCH	Polymer	2.5	10.0	8.8	18.05
TM1_HCH12_P2.5_UCS	HCH	Polymer	2.5	12.0	11.0	18.35
TM1_HCH12_P2.5_UCS_R	HCH	Polymer	2.5	12.0	10.8	18.21
TM1_HCH14_P2.5_UCS	HCH	Polymer	2.5	14.0	14.4	17.88
TM1_HCH14_P2.5_UCS_R	HCH	Polymer	2.5	12.0	12.9	17.94
TM1_HCH8_L4_UCS	HCH	Lime	4.0	8.0	7.6	17.49
TM1_HCH12_L4_UCS	HCH	Lime	4.0	12.0	12.0	18.08
TM1_HCH14_L4_UCS	HCH	Lime	4.0	14.0	13.4	18.26
TM1_HCH8_L8_UCS	HCH	Lime	8.0	8.0	6.6	17.12
TM1_HCH10_L8_UCS	HCH	Lime	8.0	10.0	8.8	16.98
TM1_HCH12_L8_UCS	HCH	Lime	8.0	12.0	10.4	16.97
TM1_HCH14_L8_UCS	HCH	Lime	8.0	14.0	12.6	17.54
TM1_HCH16_L8_UCS	HCH	Lime	8.0	16.0	14.4	17.44
TM1_HCH18_L8_UCS	HCH	Lime	8.0	18.0	15.7	17.64
TM1_SAND4.0_N_DS_6kPa	SAND	Control	0.0	4.0	N/A	16.24
TM1_SAND4.0_N_DS_12kPa	SAND	Control	0.0	4.0	N/A	16.75
TM1_SAND4.0_N_DS_24kPa	SAND	Control	0.0	4.0	N/A	16.75
TM1_SAND6.1_N_DS_6kPa	SAND	Control	0.0	6.1	N/A	16.81
TM1_SAND6.1_N_DS_12kPa	SAND	Control	0.0	6.1	N/A	17.06
TM1_SAND6.1_N_DS_24kPa	SAND	Control	0.0	6.1	N/A	17.44
TM1_SAND8.1_N_DS_6kPa	SAND	Control	0.0	8.1	N/A	17.01
TM1_SAND8.1_N_DS_12kPa	SAND	Control	0.0	8.1	N/A	17.11
TM1_SAND8.1_N_DS_24kPa	SAND	Control	0.0	8.1	N/A	17.31
TM1_SAND10.5_N_DS_6kPa	SAND	Control	0.0	10.5	N/A	17.94
TM1_SAND10.5_N_DS_12kPa	SAND	Control	0.0	10.5	N/A	17.36
TM1_SAND10.5_N_DS_24kPa	SAND	Control	0.0	10.5	N/A	17.97
TM1_SAND6.0_P0.5_DS_6kPa	SAND	Polymer	0.5	6.0	6.2	15.58
TM1_SAND6.0_P0.5_DS_12kPa	SAND	Polymer	0.5	6.0	5.9	15.48
TM1_SAND6.0_P0.5_DS_24kPa	SAND	Polymer	0.5	6.0	6.0	16.33
TM1_SAND4.0_P1.0_DS_6kPa	SAND	Polymer	1.0	4.0	4.1	16.22
TM1_SAND4.0_P1.0_DS_12kPa	SAND	Polymer	1.0	4.0	4.0	15.43
TM1_SAND4.0_P1.0_DS_24kPa	SAND	Polymer	1.0	4.0	4.5	14.59
TM1_SAND5.0_P1.5_DS_6kPa	SAND	Polymer	1.5	5.0	5.3	15.63
TM1_SAND5.0_P1.5_DS_12kPa	SAND	Polymer	1.5	5.0	5.1	16.50
TM1_SAND5.0_P1.5_DS_24kPa	SAND	Polymer	1.5	5.0	5.0	14.64
TM2_SAND2_N_WD	Specimen not prepared due to lack of cohesion observed in TM1					
TM2_SAND3_N_WD	Specimen not prepared due to lack of cohesion observed in TM1					
TM2_SAND5_N_WD	Specimen not prepared due to lack of cohesion observed in TM1					
TM2_SAND7_N_WD	Specimen not prepared due to lack of cohesion observed in TM1					
TM2_SAND9_N_WD	Specimen not prepared due to lack of cohesion observed in TM1					
TM2_SAND2_P1_WD	SAND	Polymer	1.0	2.0	1.2	
TM2_SAND3_P1_WD	SAND	Polymer	1.0	3.0	2.5	
TM2_SAND5_P1_WD	SAND	Polymer	1.0	5.0	4.2	
TM2_SAND7_P1_WD	SAND	Polymer	1.0	7.0	6.4	
TM2_SAND9_P1_WD	SAND	Polymer	1.0	9.0	7.6	
TM2_LCL_5.25_N_WD	LCL	Control	0.0	5.3	4.8	
TM2_LCL_7.25_N_WD	LCL	Control	0.0	7.3	6.6	
TM2_LCL_9.25_N_WD	LCL	Control	0.0	9.3	9.1	
TM2_LCL_11.25_N_WD	LCL	Control	0.0	11.3	10.6	

Appendix D: Summary of All Tested Specimens

Sample ID	Soil Type	Am. Type	Am. Rate (%)	Target Water Content (%)	Actual Water Content (%)	Dry Unit Weight (kN/m ³)
TM2_LCL_13.25_N_WD	LCL	Control	0.0	13.3	12.2	
TM2_LCL5_P1_WD	LCL	Polymer	1.0	5.0	4.5	
TM2_LCL7_P1_WD	LCL	Polymer	1.0	7.0	6.3	
TM2_LCL9.25_P1_WD	LCL	Polymer	1.0	9.3	8.5	
TM2_LCL11_P1_WD	LCL	Polymer	1.0	11.0	11.5	
TM2_LCL13_P1_WD	LCL	Polymer	1.0	13.0	11.1	
TM2_LCH7_N_WD	LCH	Control	0.0	7.0	6.5	
TM2_LCH9_N_WD	LCH	Control	0.0	9.0	9.5	
TM2_LCH11_N_WD	LCH	Control	0.0	11.0	9.3	
TM2_LCH13_N_WD	LCH	Control	0.0	13.0	11.7	
TM2_LCH15_N_WD	LCH	Control	0.0	15.0	13.9	
TM2_LCH7_P1_WD	LCH	Polymer	1.0	7.0	7.1	
TM2_LCH9_P1_WD	LCH	Polymer	1.0	9.0	7.6	
TM2_LCH11_P1_WD	LCH	Polymer	1.0	11.0	11.1	
TM2_LCH13_P1_WD	LCH	Polymer	1.0	13.0	12.7	
TM2_LCH15_P1_WD	LCH	Polymer	1.0	15.0	14.8	
TM2_HCH_6.25N_WD	HCH	Control	0.0	6.3	6.1	
TM2_HCH_8.28N_WD	HCH	Control	0.0	8.3	7.9	
TM2_HCH_10.25N_WD	HCH	Control	0.0	10.3	10.9	
TM2_HCH_12.25N_WD	HCH	Control	0.0	12.3	11.5	
TM2_HCH_14.25N_WD	HCH	Control	0.0	14.3	13.8	
TM2_HCH8_P1_WD	HCH	Polymer	1.0	8.0	7.9	
TM2_HCH10_P1_WD	HCH	Polymer	1.0	10.0	10.1	
TM2_HCH12_P1_WD	HCH	Polymer	1.0	12.0	11.3	
TM2_HCH14_P1_WD	HCH	Polymer	1.0	14.0	13.3	
TM2_HCH16_P1_WD	HCH	Polymer	1.0	16.0	15.4	
TM2_SAND2_N_FT	Specimen not prepared due to lack of cohesion observed in TM1					
TM2_SAND3_N_FT	Specimen not prepared due to lack of cohesion observed in TM1					
TM2_SAND5_N_FT	Specimen not prepared due to lack of cohesion observed in TM1					
TM2_SAND7_N_FT	Specimen not prepared due to lack of cohesion observed in TM1					
TM2_SAND9_N_FT	Specimen not prepared due to lack of cohesion observed in TM1					
TM2_SAND2_P1_FT	SAND	Polymer	1.0	2.0	1.2	
TM2_SAND3_P1_FT	SAND	Polymer	1.0	3.0	2.5	
TM2_SAND5_P1_FT	SAND	Polymer	1.0	5.0	4.2	
TM2_SAND7_P1_FT	SAND	Polymer	1.0	7.0	6.4	
TM2_SAND9_P1_FT	SAND	Polymer	1.0	9.0	7.6	
TM2_LCL5.25_N_FT	LCL	Control	0.0	5.3	4.8	
TM2_LCL7.25_N_FT	LCL	Control	0.0	7.3	6.6	
TM2_LCL9.25_N_FT	LCL	Control	0.0	9.3	9.1	
TM2_LCL11.25_N_FT	LCL	Control	0.0	11.3	10.6	
TM2_LCL13.25_N_FT	LCL	Control	0.0	13.3	12.2	
TM2_LCL5_P1_FT	LCL	Polymer	1.0	5.0	4.5	
TM2_LCL7_P1_FT	LCL	Polymer	1.0	7.0	6.3	
TM2_LCL9.25_P1_FT	LCL	Polymer	1.0	9.3	8.2	
TM2_LCL11_P1_FT	LCL	Polymer	1.0	11.0	11.5	
TM2_LCL13_P1_FT	LCL	Polymer	1.0	13.0	11.1	
TM2_LCH7_N_FT	LCH	Control	0.0	7.0	5.9	
TM2_LCH9_N_FT	LCH	Control	0.0	9.0	8.1	
TM2_LCH11_N_FT	LCH	Control	0.0	11.0	10	
TM2_LCH13_N_FT	LCH	Control	0.0	13.0	11.5	
TM2_LCH15_N_FT	LCH	Control	0.0	15.0	14.1	

Appendix D: Summary of All Tested Specimens

Sample ID	Soil Type	Am. Type	Am. Rate (%)	Target Water Content (%)	Actual Water Content (%)	Dry Unit Weight (kN/m ³)
TM2_LCH7_P1_FT	LCH	Polymer	1.0	7.0	6.4	
TM2_LCH9_P1_FT	LCH	Polymer	1.0	9.0	7.7	
TM2_LCH11_P1_FT	LCH	Polymer	1.0	11.0	8.7	
TM2_LCH13_P1_FT	LCH	Polymer	1.0	13.0	12.8	
TM2_LCH15_P1_FT	LCH	Polymer	1.0	15.0	11.4	
TM2_HCH6.25_N_FT	HCH	Control	0.0	6.3	6.1	
TM2_HCH_8.25N_FT	HCH	Control	0.0	8.3	7.9	
TM2_HCH_10.25_FT	HCH	Control	0.0	10.3	10.9	
TM2_HCH_12.25N_FT	HCH	Control	0.0	12.3	11.5	
TM2_HCH_14.25N_FT	HCH	Control	0.0	14.3	13.8	
TM2_HCH8_P1_FT	HCH	Polymer	1.0	8.0	7.9	
TM2_HCH10_P1_FT	HCH	Polymer	1.0	10.0	10.1	
TM2_HCH12_P1_FT	HCH	Polymer	1.0	12.0	10.54	
TM2_HCH14_P1_FT	HCH	Polymer	1.0	14.0	13.3	
TM2_HCH16_P1_FT	HCH	Polymer	1.0	16.0	15.4	
TM2_SAND5_P1NC_WD	SAND	Polymer	1.0	5.0	4.2	
TM2_SAND5_P1NC_FT	SAND	Polymer	1.0	5.0	4.2	
TM2_LCL9.25_P1NC_WD	LCL	Polymer	1.0	9.3	9	
TM2_LCL9.25_P1NC_FT	LCL	Polymer	1.0	9.3	9	
TM2_LCH11_P1NC_WD	LCH	Polymer	1.0	11.0	10.2	
TM2_LCH11_P1NC_FT	LCH	Polymer	1.0	11.0	11.2	
TM2_HCH12_P1NC_WD	HCH	Polymer	1.0	12.0	11.8	
TM2_HCH12_P1NC_FT	HCH	Polymer	1.0	12.0	11.8	
TM3_SAND_N_WD	Specimen not prepared due to lack of cohesion observed in TM1					
TM3_SAND_N_FT	Specimen not prepared due to lack of cohesion observed in TM1					
TM3_SAND_P_WD	SAND	Polymer				
TM3_SAND_P_FT	SAND	Polymer				
TM3_SAND_C_WD	SAND	Cement				
TM3_SAND_C_FT	SAND	Cement				
TM3_LCL8.3_N_WD	LCL	Control	0.0	8.3		
TM3_LCL8.3_N_FT	LCL	Control	0.0	8.3	7.67	20.07
TM3_LCL_P_WD	LCL	Polymer				
TM3_LCL8.2_P0.5_FT	LCL	Polymer	0.5	8.2		
TM3_LCL_C2_WD	LCL	Cement	2.0			
TM3_LCL_C2_FT	LCL	Cement	2.0			
TM3_LCH_N_WD	LCH	Control	0.0			
TM3_LCH_N_FT	LCH	Control	0.0			
TM3_LCH_P_WD	LCH	Polymer				
TM3_LCH_P_FT	LCH	Polymer				
TM3_LCH_L8_WD	LCH	Lime	8.0			
TM3_LCH_L8_FT	LCH	Lime	8.0			
TM3_HCH8.8_N_WD	HCH	Control	0.0	8.8		
TM3_HCH8.8_N_FT	HCH	Control	0.0	8.8		
TM3_HCH_P_WD	HCH	Polymer				
TM3_HCH12_P1.5_FT	HCH	Polymer	1.5	12.0		
TM3_HCH_L8_WD	HCH	Lime	8.0			
TM3_HCH_L8_FT	HCH	Lime	8.0			
TM3_SAND8.1_N_RM	SAND	Control	0.0	8.1	7.75	
TM3_SAND5_1.5P_RM	SAND	Polymer	1.5	5.0	5.47	
TM3_SAND7_4C_RM	SAND	Cement	4.0	7.0	5.77	

Appendix D: Summary of All Tested Specimens

Sample ID	Soil Type	Am. Type	Am. Rate (%)	Target Water Content (%)	Actual Water Content (%)	Dry Unit Weight (kN/m ³)
TM3_LCL8.4_N_RM	LCL	Control	0.0	8.4	7.88	
TM3_LCL8.2_.5P_RM	LCL	Polymer	0.5	8.2	7.95	
TM3_LCL8.0_2C_RM	LCL	Cement	2.0	8.0	7.12	
TM3_LCH11.4_N_RM	LCH	Control	0.0	11.4	13.95	
TM3_LCH11.0_1P_RM	LCH	Polymer	1.0	11.0	10.69	
TM3_LCH12.8_8L_RM	LCH	Lime	8.0	12.8	11.52	
TM3_HCH9.25_N_RM	HCH	Control	0.0	9.3	9.18	
TM3_HCH12.4_1.5P_RM	HCH	Polymer	1.5	12.4	13.01	
TM3_HCH14.4_8L_RM	HCH	Lime	8.0	14.4	12.52	

Appendix E: Resilient Modulus Test Data

Table E-1 Resilient Modulus Test Data

Sample No. SAND8.1 N_RM

Material Type: SAND/Control

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	kPa	kPa	kPa	mm	mm/mm	MPa
Sequence 1	20.7	20.7	1	14.4	12.2	0.3	0.01668	0.00008	149
			2	16.6	14.4	0.3	0.01723	0.00008	170
			3	17.9	15.7	0.3	0.01966	0.00010	163
			4	17.3	15.1	0.3	0.01916	0.00009	160
			5	14.4	12.2	0.3	0.01752	0.00009	142
	Average			16.1	13.9	0.3	0.01805	0.00009	157
	Standard Deviation			1.6	1.6	0.0	0.00129	0.00001	11
Sequence 2	20.7	41.4	1	40.4	38.2	0.3	0.03980	0.00020	195
			2	38.4	36.2	0.3	0.04052	0.00020	182
			3	35.8	33.6	0.3	0.03721	0.00018	183
			4	37.7	35.5	0.3	0.03806	0.00019	190
			5	40.0	37.8	0.3	0.04058	0.00020	189
	Average			38.4	36.2	0.3	0.03923	0.00019	188
	Standard Deviation			1.9	1.9	0.0	0.00152	0.00001	5
Sequence 3	20.7	62.1	1	59.7	57.5	0.3	0.05725	0.00028	204
			2	59.0	56.8	0.3	0.05832	0.00029	198
			3	56.0	53.7	0.3	0.05771	0.00028	189
			4	56.2	54.0	0.3	0.05526	0.00027	199
			5	60.1	57.9	0.3	0.05778	0.00028	204
	Average			58.2	56.0	0.3	0.05726	0.00028	199
	Standard Deviation			2.0	2.0	0.0	0.00118	0.00001	6
Sequence 4	34.5	34.5	1	32.3	30.1	0.3	0.03480	0.00017	176
			2	31.1	28.9	0.3	0.03567	0.00018	165
			3	29.6	27.4	0.3	0.03216	0.00016	173
			4	32.0	29.8	0.3	0.03461	0.00017	175
			5	32.3	30.1	0.3	0.03608	0.00018	170
	Average			31.5	29.3	0.3	0.03466	0.00017	172
	Standard Deviation			1.2	1.2	0.0	0.00153	0.00001	5
Sequence 5	34.5	68.9	1	64.9	62.8	0.3	0.06175	0.00030	207
			2	65.7	63.5	0.3	0.06367	0.00031	203
			3	61.4	59.2	0.3	0.06236	0.00031	193
			4	61.2	59.0	0.3	0.06066	0.00030	198
			5	65.2	63.0	0.3	0.06298	0.00031	204
	Average			63.7	61.5	0.3	0.06228	0.00031	201
	Standard Deviation			2.2	2.2	0.0	0.00116	0.00001	5

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 6	34.5	1.3	1	99.3	97.2	0.3	0.08455	0.00042	234
			2	100.4	98.2	0.3	0.08502	0.00042	235
			3	95.0	92.7	0.3	0.08691	0.00043	217
			4	94.5	92.3	0.3	0.08436	0.00041	223
			5	98.7	96.5	0.3	0.08778	0.00043	224
	Average			97.6	95.4	0.3	0.08572	0.00042	226
	Standard Deviation			2.7	2.7	0.0	0.00153	0.00001	8
Sequence 7	68.9	68.9	1	53.4	51.3	0.3	0.06315	0.00031	165
			2	57.4	55.2	0.3	0.06007	0.00030	187
			3	69.5	67.2	0.3	0.07186	0.00035	190
			4	60.1	57.8	0.3	0.07016	0.00034	168
			5	52.3	50.1	0.3	0.06318	0.00031	161
	Average			58.5	56.3	0.3	0.06568	0.00032	174
	Standard Deviation			6.8	6.8	0.0	0.00506	0.00002	13
Sequence 8	68.9	137.9	1	132.3	130.1	0.3	0.14140	0.00069	187
			2	132.8	130.6	0.3	0.14617	0.00072	182
			3	120.7	118.5	0.3	0.14166	0.00070	170
			4	123.4	121.2	0.3	0.13906	0.00068	177
			5	132.5	130.3	0.3	0.14303	0.00070	185
	Average			128.4	126.2	0.3	0.14226	0.00070	180
	Standard Deviation			5.8	5.8	0.0	0.00261	0.00001	7
Sequence 9	68.9	206.8	1	191.1	188.9	0.3	0.30485	0.00150	126
			2	200.6	198.4	0.3	0.30987	0.00152	130
			3	190.2	187.9	0.3	0.31351	0.00154	122
			4	171.3	169.1	0.3	0.29961	0.00147	115
			5	191.8	189.6	0.3	0.30143	0.00148	128
	Average			189.0	186.8	0.3	0.30585	0.00150	124
	Standard Deviation			10.7	10.7	0.0	0.00579	0.00003	6
Sequence 10	103.4	68.9	1	66.4	64.2	0.3	0.23145	0.00114	56
			2	65.0	62.8	0.3	0.23302	0.00115	55
			3	58.9	56.7	0.3	0.22366	0.00110	52
			4	63.6	61.3	0.3	0.23041	0.00113	54
			5	66.3	64.1	0.3	0.23238	0.00114	56
	Average			64.0	61.8	0.3	0.23018	0.00113	55
	Standard Deviation			3.1	3.1	0.0	0.00378	0.00002	2

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 11	103.4	103.4	1	97.0	94.8	0.3	0.25500	0.00125	76
			2	98.5	96.3	0.3	0.25262	0.00124	78
			3	94.2	92.0	0.3	0.25649	0.00126	73
			4	91.0	88.8	0.3	0.25156	0.00124	72
			5	97.2	95.0	0.3	0.25547	0.00126	76
	Average			95.6	93.4	0.3	0.25423	0.00125	75
	Standard Deviation			3.0	3.0	0.0	0.00206	0.00001	2
Sequence 12	103.4	206.8	1	196.3	194.2	0.3	0.32545	0.00160	121
			2	205.1	202.9	0.3	0.33052	0.00162	125
			3	195.8	193.6	0.3	0.33074	0.00163	119
			4	178.3	176.1	0.3	0.32011	0.00157	112
			5	197.1	194.8	0.3	0.32560	0.00160	122
	Average			194.5	192.3	0.3	0.32648	0.00160	120
	Standard Deviation			9.8	9.8	0.0	0.00438	0.00002	5
Sequence 13	137.9	103.4	1	98.2	96.0	0.3	0.27420	0.00135	71
			2	99.0	96.8	0.3	0.27542	0.00135	71
			3	93.4	91.1	0.3	0.27479	0.00135	67
			4	93.6	91.4	0.3	0.27236	0.00134	68
			5	97.5	95.3	0.3	0.27500	0.00135	71
	Average			96.3	94.1	0.3	0.27435	0.00135	70
	Standard Deviation			2.6	2.7	0.0	0.00120	0.00001	2
Sequence 14	137.9	137.9	1	130.9	128.7	0.3	0.29390	0.00144	89
			2	131.9	129.7	0.3	0.29762	0.00146	89
			3	122.3	120.1	0.3	0.29249	0.00144	84
			4	121.6	119.4	0.3	0.28906	0.00142	84
			5	131.6	129.4	0.3	0.29545	0.00145	89
	Average			127.7	125.4	0.3	0.29370	0.00144	87
	Standard Deviation			5.2	5.2	0.0	0.00322	0.00002	3
Sequence 15	137.9	275.8	1	244.0	241.8	0.3	0.42955	0.00211	115
			2	263.2	261.0	0.3	0.43727	0.00215	121
			3	263.1	260.9	0.3	0.44019	0.00216	121
			4	239.2	237.0	0.3	0.43761	0.00215	110
			5	244.1	241.9	0.3	0.43093	0.00212	114
	Average			250.7	248.5	0.3	0.43511	0.00214	116
	Standard Deviation			11.5	11.5	0.0	0.00461	0.00002	5
Resilient Modulus:									143

Appendix E: Resilient Modulus Test Data

Table E-2 Resilient Modulus Test Data

Sample No. SAND5_1.5P_RM

Material Type: SAND/Polymer

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	kPa	kPa	kPa	mm	mm/mm	MPa
Sequence 1	20.7	20.7	1	14.4	12.2	0.6	0.01909	0.00009	136
			2	16.9	14.8	0.6	0.02339	0.00011	136
			3	16.8	14.7	0.6	0.02413	0.00011	130
			4	15.2	13.1	0.6	0.01903	0.00009	148
			5	15.3	13.2	0.6	0.02101	0.00010	135
	Average			15.7	13.6	0.6	0.02133	0.00010	137
	Standard Deviation			1.1	1.1	0.0	0.00237	0.00001	6
Sequence 2	20.7	41.4	1	36.0	33.8	0.6	0.06336	0.00030	114
			2	35.4	33.3	0.6	0.06131	0.00029	116
			3	38.5	36.3	0.6	0.06298	0.00029	123
			4	39.1	36.9	0.6	0.06559	0.00031	121
			5	36.7	34.7	0.6	0.06444	0.00030	115
	Average			37.1	35.0	0.6	0.06354	0.00030	118
	Standard Deviation			1.6	1.6	0.0	0.00161	0.00001	4
Sequence 3	20.7	62.1	1	58.2	56.1	0.6	0.09491	0.00044	127
			2	53.0	50.9	0.6	0.08896	0.00042	122
			3	57.5	55.4	0.6	0.09203	0.00043	129
			4	59.4	57.3	0.6	0.09629	0.00045	127
			5	58.5	56.5	0.6	0.09549	0.00045	127
	Average			57.3	55.2	0.6	0.09354	0.00044	126
	Standard Deviation			2.5	2.5	0.0	0.00302	0.00001	2
Sequence 4	34.5	34.5	1	27.7	25.6	0.6	0.05166	0.00024	106
			2	29.2	27.1	0.6	0.05066	0.00024	114
			3	30.9	28.8	0.6	0.05218	0.00024	118
			4	31.0	28.9	0.6	0.05409	0.00025	114
			5	28.0	26.0	0.6	0.05274	0.00025	105
	Average			29.4	27.2	0.6	0.05227	0.00024	112
	Standard Deviation			1.6	1.5	0.0	0.00128	0.00001	6
Sequence 5	34.5	68.9	1	64.9	62.8	0.6	0.10376	0.00048	130
			2	59.9	57.7	0.6	0.10061	0.00047	123
			3	63.4	61.3	0.6	0.09923	0.00046	132
			4	65.3	63.2	0.6	0.10259	0.00048	132
			5	64.6	62.6	0.6	0.10139	0.00047	132
	Average			63.6	61.5	0.6	0.10152	0.00047	130
	Standard Deviation			2.2	2.2	0.0	0.00175	0.00001	4

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 6	34.5	1.3	1	99.8	97.6	0.6	0.14091	0.00066	148
			2	90.5	88.4	0.6	0.13686	0.00064	138
			3	89.2	87.1	0.6	0.13008	0.00061	143
			4	99.3	97.2	0.6	0.13739	0.00064	151
			5	99.6	97.5	0.6	0.14069	0.00066	148
	Average			95.7	93.6	0.6	0.13719	0.00064	146
	Standard Deviation			5.3	5.4	0.0	0.00438	0.00002	5
Sequence 7	68.9	68.9	1	64.7	62.6	0.6	0.10646	0.00050	126
			2	61.8	59.7	0.6	0.10546	0.00049	121
			3	61.3	59.2	0.6	0.10123	0.00047	125
			4	64.7	62.6	0.6	0.10094	0.00047	133
			5	64.8	62.8	0.6	0.10824	0.00051	124
	Average			63.5	61.4	0.6	0.10447	0.00049	126
	Standard Deviation			1.8	1.8	0.0	0.00325	0.00002	4
Sequence 8	68.9	137.9	1	133.7	131.6	0.6	0.23171	0.00108	122
			2	127.8	125.6	0.6	0.23321	0.00109	115
			3	111.6	109.5	0.6	0.21748	0.00102	108
			4	127.0	124.9	0.6	0.22674	0.00106	118
			5	132.9	130.8	0.6	0.23294	0.00109	120
	Average			126.6	124.5	0.6	0.22842	0.00107	117
	Standard Deviation			8.9	8.9	0.0	0.00665	0.00003	5
Sequence 9	68.9	206.8	1	195.6	193.4	0.6	0.46136	0.00216	90
			2	196.7	194.6	0.6	0.46596	0.00218	89
			3	179.6	177.4	0.6	0.46183	0.00216	82
			4	175.8	173.7	0.6	0.45194	0.00211	82
			5	195.9	193.9	0.6	0.46444	0.00217	89
	Average			188.7	186.6	0.6	0.46111	0.00215	87
	Standard Deviation			10.2	10.2	0.0	0.00546	0.00003	4
Sequence 10	103.4	68.9	1	64.4	62.3	0.6	0.34616	0.00162	38
			2	60.9	58.8	0.6	0.33766	0.00158	37
			3	61.2	59.0	0.6	0.33558	0.00157	38
			4	64.5	62.4	0.6	0.33874	0.00158	39
			5	64.5	62.4	0.6	0.33899	0.00158	39
	Average			63.1	61.0	0.6	0.33943	0.00159	38
	Standard Deviation			1.9	1.9	0.0	0.00400	0.00002	1

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 11	103.4	103.4	1	96.3	94.1	0.6	0.37756	0.00176	53
			2	87.8	85.7	0.6	0.37431	0.00175	49
			3	89.4	87.3	0.6	0.36944	0.00173	51
			4	97.1	94.9	0.6	0.37589	0.00176	54
			5	97.4	95.3	0.6	0.37956	0.00177	54
	Average			93.6	91.5	0.6	0.37535	0.00175	52
	Standard Deviation			4.6	4.6	0.0	0.00384	0.00002	2
Sequence 12	103.4	206.8	1	201.3	199.2	0.6	0.48761	0.00228	87
			2	200.6	198.5	0.6	0.48881	0.00228	87
			3	181.6	179.5	0.6	0.48589	0.00227	79
			4	181.6	179.5	0.6	0.47659	0.00223	81
			5	201.2	199.1	0.6	0.48779	0.00228	87
	Average			193.3	191.1	0.6	0.48534	0.00227	84
	Standard Deviation			10.7	10.7	0.0	0.00500	0.00002	4
Sequence 13	137.9	103.4	1	97.7	95.6	0.6	0.40666	0.00190	50
			2	90.0	87.9	0.6	0.40351	0.00189	47
			3	89.3	87.1	0.6	0.39634	0.00185	47
			4	97.9	95.8	0.6	0.40404	0.00189	51
			5	98.4	96.3	0.6	0.40684	0.00190	51
	Average			94.7	92.5	0.6	0.40348	0.00188	49
	Standard Deviation			4.6	4.6	0.0	0.00426	0.00002	2
Sequence 14	137.9	137.9	1	133.1	131.0	0.6	0.43506	0.00203	64
			2	126.6	124.4	0.6	0.43511	0.00203	61
			3	111.6	109.5	0.6	0.42629	0.00199	55
			4	125.4	123.3	0.6	0.42794	0.00200	62
			5	133.1	130.9	0.6	0.43489	0.00203	64
	Average			126.0	123.8	0.6	0.43186	0.00202	61
	Standard Deviation			8.8	8.8	0.0	0.00437	0.00002	4
Sequence 15	137.9	275.8	1	253.8	251.6	0.6	0.63101	0.00295	85
			2	265.7	263.6	0.6	0.64186	0.00300	88
			3	249.9	247.7	0.6	0.64039	0.00299	83
			4	223.5	221.4	0.6	0.62029	0.00290	76
			5	253.6	251.5	0.6	0.63314	0.00296	85
	Average			249.3	247.2	0.6	0.63334	0.00296	83
	Standard Deviation			15.6	15.6	0.0	0.00863	0.00004	4
Resilient Modulus:									98

Appendix E: Resilient Modulus Test Data

Table E-3 Resilient Modulus Test Data

Sample No. SAND7_4C_RM

Material Type: SAND/Cement

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	kPa	kPa	kPa	mm	mm/mm	MPa
Sequence 1	20.7	20.7	1	14.6	12.3	0.9	0.02240	0.00010	117
			2	16.2	14.0	0.9	0.02479	0.00012	121
			3	16.2	14.0	0.9	0.02524	0.00012	118
			4	15.1	12.9	0.9	0.02509	0.00012	110
			5	14.0	11.7	0.9	0.02178	0.00010	115
	Average			15.2	13.0	0.9	0.02386	0.00011	116
	Standard Deviation			1.0	1.0	0.0	0.00164	0.00001	4
Sequence 2	20.7	41.4	1	37.9	35.7	0.9	0.05540	0.00026	137
			2	34.9	32.7	0.9	0.05131	0.00024	136
			3	37.6	35.5	0.9	0.04623	0.00022	164
			4	40.7	38.4	0.9	0.05506	0.00026	149
			5	37.5	35.3	0.9	0.05471	0.00026	138
	Average			37.7	35.5	0.9	0.05254	0.00025	145
	Standard Deviation			2.1	2.0	0.0	0.00389	0.00002	12
Sequence 3	20.7	62.1	1	50.7	48.4	0.9	0.05915	0.00028	175
			2	61.7	59.5	0.9	0.07071	0.00033	179
			3	52.4	50.2	0.9	0.06828	0.00032	157
			4	38.6	36.3	0.9	0.06316	0.00030	123
			5	49.8	47.5	0.9	0.05796	0.00027	175
	Average			50.6	48.4	0.9	0.06385	0.00030	162
	Standard Deviation			8.2	8.3	0.0	0.00557	0.00003	24
Sequence 4	34.5	34.5	1	29.3	27.0	0.9	0.05110	0.00024	113
			2	27.5	25.3	0.9	0.04791	0.00022	113
			3	31.0	28.8	0.9	0.05073	0.00024	121
			4	31.7	29.4	0.9	0.05201	0.00024	121
			5	29.6	27.4	0.9	0.05091	0.00024	115
	Average			29.8	27.6	0.9	0.05053	0.00024	116
	Standard Deviation			1.6	1.6	0.0	0.00154	0.00001	4
Sequence 5	34.5	68.9	1	62.4	60.2	0.9	0.06365	0.00030	202
			2	69.0	66.8	0.9	0.07216	0.00034	198
			3	64.4	62.2	0.9	0.07263	0.00034	183
			4	54.3	52.0	0.9	0.07696	0.00036	144
			5	55.1	52.9	0.9	0.05526	0.00026	204
	Average			61.0	58.8	0.9	0.06813	0.00032	186
	Standard Deviation			6.3	6.3	0.0	0.00866	0.00004	25

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 6	34.5	1.3	1	98.6	96.3	0.9	0.09295	0.00044	221
			2	99.8	97.6	0.9	0.09476	0.00044	220
			3	93.2	91.0	0.9	0.09453	0.00044	205
			4	93.0	90.7	0.9	0.09076	0.00043	213
			5	98.3	96.1	0.9	0.09316	0.00044	220
	Average			96.6	94.4	0.9	0.09323	0.00044	216
	Standard Deviation			3.2	3.2	0.0	0.00160	0.00001	7
Sequence 7	68.9	68.9	1	65.0	62.8	0.9	0.08555	0.00040	157
			2	68.3	66.1	0.9	0.08021	0.00038	176
			3	62.9	60.7	0.9	0.07893	0.00037	164
			4	54.7	52.4	0.9	0.07681	0.00036	146
			5	54.3	52.0	0.9	0.06191	0.00029	179
	Average			61.0	58.8	0.9	0.07668	0.00036	164
	Standard Deviation			6.3	6.3	0.0	0.00887	0.00004	14
Sequence 8	68.9	137.9	1	131.5	129.3	0.9	0.13780	0.00065	200
			2	130.5	128.3	0.9	0.14086	0.00066	194
			3	119.7	117.5	0.9	0.14043	0.00066	179
			4	124.1	121.9	0.9	0.13511	0.00063	192
			5	132.3	130.1	0.9	0.14001	0.00066	198
	Average			127.6	125.4	0.9	0.13884	0.00065	193
	Standard Deviation			5.5	5.5	0.0	0.00240	0.00001	9
Sequence 9	68.9	206.8	1	195.8	193.5	0.9	0.27650	0.00130	149
			2	199.2	197.0	0.9	0.28066	0.00132	150
			3	183.3	181.1	0.9	0.28023	0.00131	138
			4	174.9	172.6	0.9	0.27081	0.00127	136
			5	196.4	194.2	0.9	0.27746	0.00130	149
	Average			189.9	187.7	0.9	0.27713	0.00130	145
	Standard Deviation			10.4	10.4	0.0	0.00396	0.00002	7
Sequence 10	103.4	68.9	1	66.9	64.6	0.9	0.22285	0.00104	62
			2	66.7	64.5	0.9	0.22291	0.00104	62
			3	61.7	59.5	0.9	0.22263	0.00104	57
			4	63.2	61.0	0.9	0.22071	0.00103	59
			5	67.4	65.2	0.9	0.22216	0.00104	63
	Average			65.2	62.9	0.9	0.22225	0.00104	60
	Standard Deviation			2.6	2.5	0.0	0.00091	0.00000	2

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 11	103.4	103.4	1	97.3	95.0	0.9	0.23955	0.00112	85
			2	99.4	97.2	0.9	0.24176	0.00113	86
			3	90.4	88.2	0.9	0.24128	0.00113	78
			4	94.6	92.3	0.9	0.23866	0.00112	83
			5	98.7	96.4	0.9	0.23928	0.00112	86
	Average			96.1	93.8	0.9	0.24011	0.00113	83
	Standard Deviation			3.7	3.7	0.0	0.00134	0.00001	3
Sequence 12	103.4	206.8	1	203.6	201.4	0.9	0.30470	0.00143	141
			2	202.7	200.6	0.9	0.30636	0.00144	140
			3	185.3	183.1	0.9	0.30443	0.00143	128
			4	184.2	181.9	0.9	0.29666	0.00139	131
			5	202.9	200.7	0.9	0.30352	0.00142	141
	Average			195.7	193.5	0.9	0.30314	0.00142	136
	Standard Deviation			10.1	10.1	0.0	0.00376	0.00002	6
Sequence 13	137.9	103.4	1	99.9	97.7	0.9	0.26555	0.00124	78
			2	100.4	98.2	0.9	0.26541	0.00124	79
			3	91.8	89.6	0.9	0.26623	0.00125	72
			4	92.0	89.8	0.9	0.26236	0.00123	73
			5	100.3	98.0	0.9	0.26562	0.00124	79
	Average			96.9	94.7	0.9	0.26504	0.00124	76
	Standard Deviation			4.5	4.5	0.0	0.00153	0.00001	3
Sequence 14	137.9	137.9	1	133.1	130.9	0.9	0.28120	0.00132	99
			2	130.9	128.7	0.9	0.28191	0.00132	97
			3	119.9	117.7	0.9	0.28253	0.00132	89
			4	125.1	122.9	0.9	0.27576	0.00129	95
			5	131.9	129.6	0.9	0.28032	0.00131	99
	Average			128.2	126.0	0.9	0.28035	0.00131	96
	Standard Deviation			5.6	5.5	0.0	0.00269	0.00001	4
Sequence 15	137.9	275.8	1	252.6	250.4	0.9	0.38990	0.00183	137
			2	266.1	263.9	0.9	0.39661	0.00186	142
			3	251.0	248.9	0.9	0.39683	0.00186	134
			4	222.2	219.9	0.9	0.38201	0.00179	123
			5	253.6	251.3	0.9	0.39129	0.00183	137
	Average			249.1	246.9	0.9	0.39133	0.00183	135
	Standard Deviation			16.2	16.2	0.0	0.00606	0.00003	7
Resilient Modulus:									135

Appendix E: Resilient Modulus Test Data

Table E-4 Resilient Modulus Test Data

Sample No. LCL8.4_N_RM

Material Type: LCL/Control

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	kPa	kPa	kPa	mm	mm/mm	MPa
Sequence 1	20.7	20.7	1	18.0	16.0	1.1	0.01374	0.00007	235
			2	17.2	15.2	1.1	0.01798	0.00009	171
			3	17.5	15.6	1.1	0.01420	0.00007	221
			4	18.1	16.2	1.1	0.01442	0.00007	226
			5	17.9	15.9	1.1	0.01430	0.00007	224
	Average			17.8	15.8	1.1	0.01493	0.00007	216
	Standard Deviation			0.4	0.4	0.0	0.00172	0.00001	26
Sequence 2	20.7	41.4	1	38.8	36.8	1.1	0.02915	0.00014	254
			2	37.6	35.6	1.1	0.02911	0.00014	246
			3	34.7	32.8	1.1	0.02347	0.00012	281
			4	37.6	35.6	1.1	0.02716	0.00013	264
			5	38.8	36.8	1.1	0.03043	0.00015	244
	Average			37.5	35.5	1.1	0.02787	0.00014	258
	Standard Deviation			1.7	1.6	0.0	0.00272	0.00001	15
Sequence 3	20.7	62.1	1	57.0	55.0	1.1	0.03890	0.00019	285
			2	53.9	52.0	1.1	0.03936	0.00020	266
			3	52.9	50.9	1.1	0.03762	0.00019	273
			4	56.3	54.3	1.1	0.03796	0.00019	288
			5	57.7	55.8	1.1	0.04013	0.00020	280
	Average			55.6	53.6	1.1	0.03880	0.00019	278
	Standard Deviation			2.1	2.1	0.0	0.00102	0.00001	9
Sequence 4	34.5	34.5	1	31.3	29.3	1.1	0.02540	0.00013	232
			2	30.0	28.0	1.1	0.02466	0.00012	229
			3	28.9	27.0	1.1	0.02382	0.00012	228
			4	31.0	29.0	1.1	0.02481	0.00012	236
			5	31.2	29.2	1.1	0.02538	0.00013	232
	Average			30.5	28.5	1.1	0.02482	0.00012	231
	Standard Deviation			1.0	1.0	0.0	0.00065	0.00000	3
Sequence 5	34.5	68.9	1	63.6	61.6	1.1	0.04320	0.00021	287
			2	59.3	57.3	1.1	0.04351	0.00022	266
			3	60.2	58.3	1.1	0.04092	0.00020	287
			4	65.1	63.1	1.1	0.04226	0.00021	301
			5	63.7	61.8	1.1	0.04153	0.00021	300
	Average			62.4	60.4	1.1	0.04229	0.00021	288
	Standard Deviation			2.5	2.5	0.0	0.00109	0.00001	14

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 6	34.5	1.3	1	97.1	95.1	1.1	0.05920	0.00029	324
			2	90.4	88.4	1.1	0.05676	0.00028	314
			3	83.6	81.7	1.1	0.05312	0.00026	310
			4	95.2	93.2	1.1	0.05631	0.00028	334
			5	98.4	96.4	1.1	0.06058	0.00030	321
	Average			92.9	91.0	1.1	0.05720	0.00028	320
	Standard Deviation			6.0	6.0	0.0	0.00287	0.00001	9
Sequence 7	68.9	68.9	1	64.0	62.1	1.1	0.04750	0.00024	263
			2	62.6	60.6	1.1	0.04656	0.00023	262
			3	57.7	55.8	1.1	0.04467	0.00022	252
			4	61.1	59.1	1.1	0.03916	0.00019	304
			5	64.4	62.4	1.1	0.04893	0.00024	257
	Average			62.0	60.0	1.1	0.04537	0.00023	268
	Standard Deviation			2.7	2.7	0.0	0.00380	0.00002	21
Sequence 8	68.9	137.9	1	128.3	126.4	1.1	0.13130	0.00065	194
			2	120.2	118.2	1.1	0.13146	0.00065	181
			3	110.4	108.4	1.1	0.12417	0.00062	176
			4	126.9	125.0	1.1	0.12896	0.00064	195
			5	130.7	128.8	1.1	0.13308	0.00066	195
	Average			123.3	121.3	1.1	0.12980	0.00064	188
	Standard Deviation			8.2	8.2	0.0	0.00347	0.00002	9
Sequence 9	68.9	206.8	1	198.5	196.5	1.1	0.36725	0.00182	108
			2	190.7	188.7	1.1	0.36866	0.00183	103
			3	170.1	168.1	1.1	0.36462	0.00181	93
			4	182.3	180.3	1.1	0.36151	0.00179	101
			5	197.7	195.7	1.1	0.37198	0.00185	106
	Average			187.8	185.9	1.1	0.36681	0.00182	102
	Standard Deviation			11.9	11.9	0.0	0.00397	0.00002	6
Sequence 10	103.4	68.9	1	64.2	62.2	1.1	0.31590	0.00157	40
			2	61.2	59.2	1.1	0.31496	0.00156	38
			3	57.2	55.3	1.1	0.31492	0.00156	35
			4	61.5	59.5	1.1	0.31411	0.00156	38
			5	63.8	61.9	1.1	0.31538	0.00157	40
	Average			61.6	59.6	1.1	0.31506	0.00156	38
	Standard Deviation			2.8	2.8	0.0	0.00066	0.00000	2

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 11	103.4	103.4	1	94.2	92.3	1.1	0.33585	0.00167	55
			2	87.4	85.4	1.1	0.33026	0.00164	52
			3	84.1	82.1	1.1	0.33235	0.00165	50
			4	96.4	94.4	1.1	0.33916	0.00168	56
			5	96.8	94.8	1.1	0.33300	0.00165	57
	Average			91.8	89.8	1.1	0.33413	0.00166	54
	Standard Deviation			5.7	5.7	0.0	0.00345	0.00002	3
Sequence 12	103.4	206.8	1	203.8	201.8	1.1	0.39580	0.00196	103
			2	197.4	195.4	1.1	0.39361	0.00195	100
			3	177.3	175.3	1.1	0.39015	0.00194	91
			4	188.8	186.9	1.1	0.38536	0.00191	98
			5	203.1	201.1	1.1	0.39218	0.00195	103
	Average			194.1	192.1	1.1	0.39142	0.00194	99
	Standard Deviation			11.1	11.1	0.0	0.00396	0.00002	5
Sequence 13	137.9	103.4	1	98.1	96.1	1.1	0.35685	0.00177	54
			2	91.5	89.5	1.1	0.35571	0.00177	51
			3	84.0	82.0	1.1	0.35060	0.00174	47
			4	96.8	94.8	1.1	0.35466	0.00176	54
			5	99.1	97.1	1.1	0.35713	0.00177	55
	Average			93.9	91.9	1.1	0.35499	0.00176	52
	Standard Deviation			6.3	6.3	0.0	0.00264	0.00001	3
Sequence 14	137.9	137.9	1	132.1	130.1	1.1	0.37065	0.00184	71
			2	124.3	122.3	1.1	0.37206	0.00185	66
			3	110.1	108.2	1.1	0.36680	0.00182	59
			4	123.3	121.3	1.1	0.36971	0.00183	66
			5	131.2	129.2	1.1	0.36993	0.00184	70
	Average			124.2	122.2	1.1	0.36983	0.00184	67
	Standard Deviation			8.8	8.8	0.0	0.00193	0.00001	5
Sequence 15	137.9	275.8	1	260.1	258.1	1.1	0.46935	0.00233	111
			2	260.1	258.1	1.1	0.47166	0.00234	110
			3	236.2	234.3	1.1	0.47020	0.00233	100
			4	231.0	229.0	1.1	0.45926	0.00228	100
			5	259.6	257.6	1.1	0.46856	0.00233	111
	Average			249.4	247.4	1.1	0.46781	0.00232	107
	Standard Deviation			14.5	14.5	0.0	0.00491	0.00002	6
Resilient Modulus:									171

Appendix E: Resilient Modulus Test Data

Table E-5 Resilient Modulus Test Data

Sample No. LCL8.2_5P_RM

Material Type: LCL/Polymer

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	kPa	kPa	kPa	mm	mm/mm	MPa
Sequence 1	20.7	20.7	1	17.6	15.4	1.7	0.02863	0.00014	109
			2	17.5	15.4	1.7	0.01466	0.00007	213
			3	17.7	15.6	1.7	0.02991	0.00015	106
			4	18.0	15.9	1.7	0.03077	0.00015	105
			5	17.4	15.3	1.7	0.02479	0.00012	125
	Average			17.7	15.5	1.7	0.02575	0.00013	131
	Standard Deviation			0.2	0.2	0.0	0.00661	0.00003	46
Sequence 2	20.7	41.4	1	32.9	30.7	1.7	0.17741	0.00088	35
			2	32.6	30.5	1.7	0.19331	0.00095	32
			3	38.6	36.5	1.7	0.19693	0.00097	38
			4	37.0	34.9	1.7	0.19517	0.00096	36
			5	31.2	29.1	1.7	0.17063	0.00084	35
	Average			34.5	32.3	1.7	0.18669	0.00092	35
	Standard Deviation			3.2	3.2	0.0	0.01188	0.00006	2
Sequence 3	20.7	62.1	1	48.3	46.1	1.7	0.25311	0.00125	37
			2	47.5	45.4	1.7	0.25826	0.00127	36
			3	57.5	55.4	1.7	0.27143	0.00134	41
			4	55.9	53.8	1.7	0.26982	0.00133	40
			5	47.8	45.7	1.7	0.25243	0.00125	37
	Average			51.4	49.3	1.7	0.26101	0.00129	38
	Standard Deviation			4.9	4.9	0.0	0.00908	0.00004	3
Sequence 4	34.5	34.5	1	27.3	25.1	1.7	0.13271	0.00065	38
			2	26.1	24.0	1.7	0.13896	0.00069	35
			3	30.5	28.3	1.7	0.14583	0.00072	39
			4	29.6	27.4	1.7	0.15267	0.00075	36
			5	27.1	25.0	1.7	0.13098	0.00065	39
	Average			28.1	26.0	1.7	0.14023	0.00069	38
	Standard Deviation			1.8	1.8	0.0	0.00908	0.00004	2
Sequence 5	34.5	68.9	1	53.4	51.2	1.7	0.26876	0.00133	39
			2	51.2	49.1	1.7	0.27066	0.00134	37
			3	63.0	60.9	1.7	0.28378	0.00140	43
			4	62.2	60.1	1.7	0.28022	0.00138	43
			5	53.8	51.7	1.7	0.27113	0.00134	39
	Average			56.7	54.6	1.7	0.27491	0.00136	40
	Standard Deviation			5.5	5.5	0.0	0.00665	0.00003	3

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 6	34.5	1.3	1	87.4	85.2	1.7	0.31506	0.00155	55
			2	68.3	66.2	1.7	0.30316	0.00150	44
			3	89.0	86.9	1.7	0.30983	0.00153	57
			4	99.5	97.4	1.7	0.31617	0.00156	62
			5	86.1	84.0	1.7	0.31688	0.00156	54
	Average			86.1	83.9	1.7	0.31222	0.00154	54
	Standard Deviation			11.3	11.3	0.0	0.00577	0.00003	7
Sequence 7	68.9	68.9	1	54.0	51.8	1.7	0.27966	0.00138	38
			2	50.6	48.5	1.7	0.27691	0.00137	35
			3	62.2	60.1	1.7	0.29008	0.00143	42
			4	62.2	60.0	1.7	0.28957	0.00143	42
			5	53.7	51.6	1.7	0.27473	0.00136	38
	Average			56.5	54.4	1.7	0.28219	0.00139	39
	Standard Deviation			5.3	5.3	0.0	0.00719	0.00004	3
Sequence 8	68.9	137.9	1	132.8	130.7	1.7	0.40116	0.00198	66
			2	110.1	108.0	1.7	0.40186	0.00198	54
			3	98.3	96.2	1.7	0.38968	0.00192	50
			4	127.5	125.4	1.7	0.40282	0.00199	63
			5	132.9	130.8	1.7	0.40953	0.00202	65
	Average			120.3	118.2	1.7	0.40101	0.00198	60
	Standard Deviation			15.5	15.4	0.0	0.00716	0.00004	7
Sequence 9	68.9	206.8	1	182.2	180.1	1.7	0.61041	0.00301	60
			2	203.4	201.3	1.7	0.61896	0.00305	66
			3	181.9	179.8	1.7	0.61958	0.00306	59
			4	142.3	140.1	1.7	0.60232	0.00297	47
			5	181.3	179.2	1.7	0.61663	0.00304	59
	Average			178.2	176.1	1.7	0.61358	0.00303	58
	Standard Deviation			22.2	22.2	0.0	0.00726	0.00004	7
Sequence 10	103.4	68.9	1	53.7	51.5	1.7	0.47061	0.00232	22
			2	51.1	49.0	1.7	0.47541	0.00235	21
			3	62.3	60.2	1.7	0.49053	0.00242	25
			4	62.5	60.3	1.7	0.48102	0.00237	25
			5	53.6	51.5	1.7	0.46993	0.00232	22
	Average			56.6	54.5	1.7	0.47750	0.00236	23
	Standard Deviation			5.4	5.4	0.0	0.00853	0.00004	2

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 11	103.4	103.4	1	83.0	80.8	1.7	0.55636	0.00274	29
			2	70.8	68.7	1.7	0.53821	0.00265	26
			3	91.7	89.6	1.7	0.56316	0.00278	32
			4	95.9	93.7	1.7	0.56462	0.00279	34
			5	82.5	80.3	1.7	0.55629	0.00274	29
	Average			84.8	82.6	1.7	0.55573	0.00274	30
	Standard Deviation			9.7	9.7	0.0	0.01051	0.00005	3
Sequence 12	103.4	206.8	1	176.2	174.0	1.7	0.65041	0.00321	54
			2	204.3	202.2	1.7	0.65866	0.00325	62
			3	202.5	200.3	1.7	0.66116	0.00326	61
			4	167.1	164.9	1.7	0.65622	0.00324	51
			5	176.4	174.3	1.7	0.64974	0.00321	54
	Average			185.3	183.2	1.7	0.65524	0.00323	57
	Standard Deviation			17.0	17.0	0.0	0.00503	0.00002	5
Sequence 13	137.9	103.4	1	84.3	82.1	1.7	0.60611	0.00299	27
			2	69.8	67.7	1.7	0.58021	0.00286	24
			3	91.0	88.9	1.7	0.60331	0.00298	30
			4	99.1	96.9	1.7	0.61042	0.00301	32
			5	84.0	81.9	1.7	0.60419	0.00298	27
	Average			85.6	83.5	1.7	0.60085	0.00296	28
	Standard Deviation			10.8	10.8	0.0	0.01186	0.00006	3
Sequence 14	137.9	137.9	1	127.7	125.5	1.7	0.63371	0.00313	40
			2	100.7	98.6	1.7	0.62506	0.00308	32
			3	105.2	103.1	1.7	0.61611	0.00304	34
			4	131.4	129.3	1.7	0.63072	0.00311	42
			5	127.0	124.9	1.7	0.63284	0.00312	40
	Average			118.4	116.3	1.7	0.62769	0.00310	38
	Standard Deviation			14.3	14.3	0.0	0.00730	0.00004	4
Sequence 15	137.9	275.8	1	203.8	201.6	1.7	0.76616	0.00378	53
			2	243.3	241.2	1.7	0.77081	0.00380	63
			3	270.4	268.3	1.7	0.78171	0.00386	70
			4	244.5	242.3	1.7	0.78287	0.00386	63
			5	203.6	201.5	1.7	0.76503	0.00377	53
	Average			233.1	231.0	1.7	0.77331	0.00381	60
	Standard Deviation			29.0	29.0	0.0	0.00848	0.00004	7
Resilient Modulus:									49

Appendix E: Resilient Modulus Test Data

Table E-6 Resilient Modulus Test Data

Sample No. LCL8.0_2C_RM

Material Type: LCL/Cement

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	kPa	kPa	kPa	mm	mm/mm	MPa
Sequence 1	20.7	20.7	1	14.6	12.0	1.2	0.06740	0.00034	35
			2	15.3	12.8	1.2	0.08779	0.00044	29
			3	16.5	13.9	1.2	0.07782	0.00039	35
			4	16.2	13.7	1.2	0.08976	0.00045	30
			5	14.2	11.6	1.2	0.06694	0.00034	34
	Average			15.4	12.8	1.2	0.07794	0.00039	33
	Standard Deviation			1.0	1.0	0.0	0.01083	0.00005	3
Sequence 2	20.7	41.4	1	29.9	27.3	1.2	0.24832	0.00126	22
			2	31.0	28.5	1.2	0.28354	0.00143	20
			3	36.0	33.4	1.2	0.28850	0.00146	23
			4	33.6	31.1	1.2	0.28890	0.00146	21
			5	29.6	27.0	1.2	0.25420	0.00129	21
	Average			32.0	29.5	1.2	0.27269	0.00138	21
	Standard Deviation			2.7	2.7	0.0	0.01979	0.00010	1
Sequence 3	20.7	62.1	1	40.6	38.0	1.2	0.33772	0.00171	22
			2	47.6	45.1	1.2	0.35709	0.00181	25
			3	55.9	53.4	1.2	0.36775	0.00186	29
			4	49.6	47.0	1.2	0.37375	0.00189	25
			5	40.3	37.7	1.2	0.34565	0.00175	22
	Average			46.8	44.3	1.2	0.35639	0.00180	24
	Standard Deviation			6.6	6.6	0.0	0.01496	0.00008	3
Sequence 4	34.5	34.5	1	24.0	21.4	1.2	0.19522	0.00099	22
			2	25.4	22.9	1.2	0.23399	0.00118	19
			3	28.4	25.8	1.2	0.23225	0.00117	22
			4	27.3	24.8	1.2	0.23790	0.00120	21
			5	24.4	21.8	1.2	0.20855	0.00105	21
	Average			25.9	23.3	1.2	0.22158	0.00112	21
	Standard Deviation			1.9	1.9	0.0	0.01870	0.00009	1
Sequence 5	34.5	68.9	1	42.7	40.2	1.2	0.35332	0.00179	22
			2	53.1	50.7	1.2	0.36859	0.00186	27
			3	63.1	60.5	1.2	0.38010	0.00192	31
			4	55.8	53.3	1.2	0.38775	0.00196	27
			5	42.8	40.2	1.2	0.36125	0.00183	22
	Average			51.5	49.0	1.2	0.37020	0.00187	26
	Standard Deviation			8.8	8.8	0.0	0.01391	0.00007	4

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 6	34.5	1.3	1	75.2	72.7	1.2	0.40517	0.00205	35
			2	66.2	63.7	1.2	0.39099	0.00198	32
			3	92.6	90.0	1.2	0.40490	0.00205	44
			4	96.4	93.9	1.2	0.42380	0.00214	44
			5	75.6	73.0	1.2	0.41405	0.00209	35
	Average			81.2	78.6	1.2	0.40778	0.00206	38
	Standard Deviation			12.8	12.8	0.0	0.01218	0.00006	5
Sequence 7	68.9	68.9	1	43.3	40.7	1.2	0.36422	0.00184	22
			2	52.0	49.5	1.2	0.38204	0.00193	26
			3	62.2	59.7	1.2	0.39410	0.00199	30
			4	54.7	52.1	1.2	0.40170	0.00203	26
			5	43.8	41.2	1.2	0.37340	0.00189	22
	Average			51.2	48.6	1.2	0.38309	0.00194	25
	Standard Deviation			7.9	7.9	0.0	0.01515	0.00008	3
Sequence 8	68.9	137.9	1	125.9	123.4	1.2	0.48067	0.00243	51
			2	95.6	93.2	1.2	0.48129	0.00243	38
			3	101.4	98.9	1.2	0.45975	0.00233	43
			4	129.5	126.9	1.2	0.48590	0.00246	52
			5	126.7	124.1	1.2	0.49005	0.00248	50
	Average			115.8	113.3	1.2	0.47953	0.00243	47
	Standard Deviation			16.0	16.0	0.0	0.01169	0.00006	6
Sequence 9	68.9	206.8	1	183.1	180.6	1.2	0.59857	0.00303	60
			2	203.5	201.0	1.2	0.62534	0.00316	64
			3	180.3	177.7	1.2	0.62305	0.00315	56
			4	63.2	60.6	1.2	0.55815	0.00282	21
			5	143.2	140.6	1.2	0.59375	0.00300	47
	Average			154.7	152.1	1.2	0.59977	0.00303	50
	Standard Deviation			55.6	55.6	0.0	0.02723	0.00014	17
Sequence 10	103.4	68.9	1	46.6	44.0	1.2	0.47937	0.00242	18
			2	48.9	46.4	1.2	0.50649	0.00256	18
			3	60.6	58.0	1.2	0.52055	0.00263	22
			4	56.7	54.1	1.2	0.52545	0.00266	20
			5	46.1	43.5	1.2	0.48305	0.00244	18
	Average			51.8	49.2	1.2	0.50298	0.00254	19
	Standard Deviation			6.5	6.5	0.0	0.02110	0.00011	2

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 11	103.4	103.4	1	69.1	66.6	1.2	0.55152	0.00279	24
			2	68.6	66.1	1.2	0.54849	0.00277	24
			3	94.8	92.2	1.2	0.56481	0.00286	32
			4	91.6	89.1	1.2	0.57910	0.00293	30
			5	70.3	67.6	1.2	0.56114	0.00284	24
	Average			78.9	76.3	1.2	0.56101	0.00284	27
	Standard Deviation			13.1	13.1	0.0	0.01213	0.00006	4
Sequence 12	103.4	206.8	1	180.3	177.8	1.2	0.63637	0.00322	55
			2	206.0	203.5	1.2	0.65799	0.00333	61
			3	204.8	202.2	1.2	0.65906	0.00333	61
			4	67.3	64.7	1.2	0.60060	0.00304	21
			5	171.6	169.0	1.2	0.65709	0.00332	51
	Average			166.0	163.4	1.2	0.64222	0.00325	50
	Standard Deviation			57.2	57.2	0.0	0.02510	0.00013	17
Sequence 13	137.9	103.4	1	70.5	67.9	1.2	0.58952	0.00298	23
			2	68.2	65.7	1.2	0.58664	0.00297	22
			3	94.1	91.5	1.2	0.60481	0.00306	30
			4	90.7	88.1	1.2	0.61695	0.00312	28
			5	69.9	67.3	1.2	0.59514	0.00301	22
	Average			78.7	76.1	1.2	0.59861	0.00303	25
	Standard Deviation			12.6	12.6	0.0	0.01238	0.00006	4
Sequence 14	137.9	137.9	1	113.3	110.8	1.2	0.62687	0.00317	35
			2	80.4	77.9	1.2	0.61754	0.00312	25
			3	112.2	109.6	1.2	0.61791	0.00313	35
			4	131.5	129.0	1.2	0.64045	0.00324	40
			5	113.5	110.9	1.2	0.63534	0.00321	35
	Average			110.2	107.6	1.2	0.62762	0.00317	34
	Standard Deviation			18.5	18.5	0.0	0.01025	0.00005	5
Sequence 15	137.9	275.8	1	209.5	206.9	1.2	0.71677	0.00363	57
			2	242.7	240.2	1.2	0.73134	0.00370	65
			3	271.8	269.2	1.2	0.73691	0.00373	72
			4	254.7	252.2	1.2	0.76180	0.00385	65
			5	209.9	207.3	1.2	0.72588	0.00367	56
	Average			237.7	235.2	1.2	0.73454	0.00371	63
	Standard Deviation			27.6	27.6	0.0	0.01695	0.00009	7
Resilient Modulus:									34

Appendix E: Resilient Modulus Test Data

Table E-7 Resilient Modulus Test Data

Sample No. LCH11.4 N_RM

Material Type: LCH/Control

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	kPa	kPa	kPa	mm	mm/mm	MPa
Sequence 1	20.7	20.7	1	17.8	15.8	0.2	0.01837	0.00009	173
			2	17.2	15.1	0.2	0.01317	0.00007	231
			3	17.3	15.4	0.2	0.01582	0.00008	195
			4	18.1	16.2	0.2	0.01634	0.00008	199
			5	18.3	16.3	0.2	0.01632	0.00008	201
	Average			17.8	15.7	0.2	0.01600	0.00008	200
	Standard Deviation			0.5	0.5	0.0	0.00186	0.00001	21
Sequence 2	20.7	41.4	1	38.0	36.0	0.2	0.03194	0.00016	227
			2	35.9	33.8	0.2	0.03177	0.00016	214
			3	34.9	32.9	0.2	0.03085	0.00015	215
			4	37.9	36.0	0.2	0.03234	0.00016	224
			5	38.5	36.5	0.2	0.03407	0.00017	215
	Average			37.0	35.0	0.2	0.03219	0.00016	219
	Standard Deviation			1.6	1.6	0.0	0.00118	0.00001	6
Sequence 3	20.7	62.1	1	59.8	57.8	0.2	0.04454	0.00022	261
			2	58.5	56.5	0.2	0.04367	0.00022	261
			3	52.8	50.8	0.2	0.04375	0.00022	234
			4	57.5	55.5	0.2	0.04384	0.00022	255
			5	60.2	58.2	0.2	0.04337	0.00022	270
	Average			57.8	55.8	0.2	0.04383	0.00022	256
	Standard Deviation			3.0	3.0	0.0	0.00043	0.00000	14
Sequence 4	34.5	34.5	1	29.6	27.6	0.2	0.02694	0.00013	206
			2	29.5	27.5	0.2	0.02827	0.00014	196
			3	28.4	26.4	0.2	0.02725	0.00014	195
			4	29.8	27.9	0.2	0.02734	0.00014	205
			5	29.9	27.9	0.2	0.02687	0.00013	209
	Average			29.5	27.4	0.2	0.02733	0.00014	202
	Standard Deviation			0.6	0.6	0.0	0.00056	0.00000	6
Sequence 5	34.5	68.9	1	66.9	64.9	0.2	0.04734	0.00024	276
			2	65.3	63.2	0.2	0.04437	0.00022	287
			3	58.0	56.0	0.2	0.03875	0.00019	291
			4	63.7	61.7	0.2	0.04674	0.00023	266
			5	66.5	64.5	0.2	0.04727	0.00023	275
	Average			64.1	62.1	0.2	0.04489	0.00022	279
	Standard Deviation			3.6	3.6	0.0	0.00364	0.00002	10

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 6	34.5	1.3	1	96.6	94.6	0.2	0.06134	0.00030	310
			2	97.6	95.5	0.2	0.06397	0.00032	301
			3	87.2	85.3	0.2	0.06305	0.00031	272
			4	93.0	91.0	0.2	0.05954	0.00030	308
			5	99.3	97.3	0.2	0.06237	0.00031	314
	Average			94.7	92.7	0.2	0.06205	0.00031	301
	Standard Deviation			4.8	4.8	0.0	0.00170	0.00001	17
Sequence 7	68.9	68.9	1	65.6	63.6	0.2	0.05064	0.00025	253
			2	66.1	64.1	0.2	0.05077	0.00025	254
			3	62.4	60.4	0.2	0.06095	0.00030	200
			4	60.8	58.8	0.2	0.04883	0.00024	242
			5	65.5	63.5	0.2	0.05057	0.00025	253
	Average			64.1	62.1	0.2	0.05235	0.00026	240
	Standard Deviation			2.4	2.3	0.0	0.00487	0.00002	23
Sequence 8	68.9	137.9	1	131.9	129.9	0.2	0.13754	0.00068	190
			2	131.4	129.4	0.2	0.14207	0.00071	183
			3	118.9	116.9	0.2	0.13965	0.00069	169
			4	119.5	117.6	0.2	0.13404	0.00067	177
			5	131.4	129.4	0.2	0.13637	0.00068	191
	Average			126.6	124.6	0.2	0.13793	0.00068	182
	Standard Deviation			6.8	6.8	0.0	0.00307	0.00002	9
Sequence 9	68.9	206.8	1	189.5	187.5	0.2	0.37194	0.00185	102
			2	201.3	199.3	0.2	0.38177	0.00190	105
			3	189.6	187.6	0.2	0.38255	0.00190	99
			4	163.6	161.6	0.2	0.37584	0.00187	87
			5	188.5	186.5	0.2	0.37537	0.00186	100
	Average			186.5	184.5	0.2	0.37749	0.00187	98
	Standard Deviation			13.9	13.8	0.0	0.00453	0.00002	7
Sequence 10	103.4	68.9	1	65.3	63.3	0.2	0.31184	0.00155	41
			2	57.1	55.0	0.2	0.31197	0.00155	36
			3	60.0	58.0	0.2	0.30495	0.00151	38
			4	67.2	65.2	0.2	0.31074	0.00154	42
			5	65.1	63.1	0.2	0.31067	0.00154	41
	Average			62.9	60.9	0.2	0.31003	0.00154	40
	Standard Deviation			4.2	4.2	0.0	0.00290	0.00001	3

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 11	103.4	103.4	1	96.7	94.7	0.2	0.33114	0.00164	58
			2	89.3	87.3	0.2	0.33167	0.00165	53
			3	84.3	82.3	0.2	0.32386	0.00161	51
			4	93.1	91.1	0.2	0.32904	0.00163	56
			5	98.0	95.9	0.2	0.33402	0.00166	58
	Average			92.3	90.3	0.2	0.32995	0.00164	55
	Standard Deviation			5.6	5.6	0.0	0.00384	0.00002	3
Sequence 12	103.4	206.8	1	198.4	196.4	0.2	0.39834	0.00198	99
			2	207.3	205.3	0.2	0.40397	0.00201	102
			3	194.9	193.0	0.2	0.40516	0.00201	96
			4	173.6	171.6	0.2	0.39344	0.00195	88
			5	198.3	196.3	0.2	0.40044	0.00199	99
	Average			194.5	192.5	0.2	0.40027	0.00199	97
	Standard Deviation			12.6	12.5	0.0	0.00469	0.00002	6
Sequence 13	137.9	103.4	1	97.0	95.0	0.2	0.35764	0.00178	53
			2	91.2	89.2	0.2	0.35637	0.00177	50
			3	84.4	82.4	0.2	0.34856	0.00173	48
			4	95.6	93.6	0.2	0.35294	0.00175	53
			5	98.7	96.7	0.2	0.35534	0.00176	55
	Average			93.4	91.4	0.2	0.35417	0.00176	52
	Standard Deviation			5.7	5.7	0.0	0.00358	0.00002	3
Sequence 14	137.9	137.9	1	133.3	131.3	0.2	0.37334	0.00185	71
			2	130.4	128.4	0.2	0.37637	0.00187	69
			3	115.6	113.7	0.2	0.37436	0.00186	61
			4	120.3	118.3	0.2	0.36874	0.00183	65
			5	132.4	130.4	0.2	0.37324	0.00185	70
	Average			126.4	124.4	0.2	0.37321	0.00185	67
	Standard Deviation			8.0	7.9	0.0	0.00280	0.00001	4
Sequence 15	137.9	275.8	1	244.1	242.0	0.2	0.50864	0.00253	96
			2	266.7	264.6	0.2	0.52237	0.00259	102
			3	261.0	259.0	0.2	0.52676	0.00262	99
			4	231.4	229.4	0.2	0.51724	0.00257	89
			5	243.6	241.6	0.2	0.51106	0.00254	95
	Average			249.3	247.3	0.2	0.51721	0.00257	96
	Standard Deviation			14.3	14.3	0.0	0.00757	0.00004	5
Resilient Modulus:									159

Appendix E: Resilient Modulus Test Data

Table E-8 Resilient Modulus Test Data

Sample No. LCH11_1P_RM

Material Type: LCH/Polymer

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	kPa	kPa	kPa	mm	mm/mm	MPa
Sequence 1	20.7	20.7	1	18.2	16.2	1.1	0.00822	0.00004	386
			2	17.8	15.9	1.1	0.00900	0.00005	344
			3	17.8	15.8	1.1	0.00929	0.00005	331
			4	18.1	16.1	1.1	0.01136	0.00006	277
			5	18.3	16.2	1.1	0.00984	0.00005	322
	Average			18.0	16.0	1.1	0.00954	0.00005	332
	Standard Deviation			0.2	0.2	0.0	0.00117	0.00001	39
Sequence 2	20.7	41.4	1	38.0	36.1	1.1	0.02155	0.00011	327
			2	36.7	34.8	1.1	0.02120	0.00011	320
			3	33.0	31.0	1.1	0.01759	0.00009	344
			4	36.5	34.5	1.1	0.02052	0.00011	328
			5	37.9	35.8	1.1	0.02219	0.00011	315
	Average			36.4	34.4	1.1	0.02061	0.00011	327
	Standard Deviation			2.0	2.0	0.0	0.00179	0.00001	11
Sequence 3	20.7	62.1	1	57.0	55.0	1.1	0.02695	0.00014	398
			2	59.0	57.0	1.1	0.03525	0.00018	316
			3	56.5	54.5	1.1	0.03394	0.00017	313
			4	52.8	50.8	1.1	0.03237	0.00017	307
			5	57.1	55.1	1.1	0.03419	0.00018	315
	Average			56.5	54.5	1.1	0.03254	0.00017	330
	Standard Deviation			2.2	2.3	0.0	0.00329	0.00002	39
Sequence 4	34.5	34.5	1	30.3	28.4	1.1	0.01885	0.00010	294
			2	29.4	27.4	1.1	0.02465	0.00013	217
			3	28.2	26.2	1.1	0.01809	0.00009	283
			4	29.8	27.8	1.1	0.02142	0.00011	253
			5	30.0	28.0	1.1	0.01984	0.00010	275
	Average			29.5	27.5	1.1	0.02057	0.00011	264
	Standard Deviation			0.8	0.8	0.0	0.00260	0.00001	30
Sequence 5	34.5	68.9	1	63.0	61.0	1.1	0.03735	0.00019	319
			2	65.6	63.6	1.1	0.03880	0.00020	320
			3	63.8	61.8	1.1	0.03909	0.00020	309
			4	58.4	56.4	1.1	0.03722	0.00019	296
			5	63.1	61.0	1.1	0.03834	0.00020	311
	Average			62.8	60.8	1.1	0.03816	0.00020	311
	Standard Deviation			2.6	2.7	0.0	0.00084	0.00000	10

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 6	34.5	1.3	1	97.4	95.4	1.1	0.06645	0.00034	280
			2	100.5	98.6	1.1	0.06395	0.00033	301
			3	97.5	95.5	1.1	0.06424	0.00033	290
			4	90.0	87.9	1.1	0.06467	0.00033	266
			5	97.5	95.5	1.1	0.06344	0.00032	294
	Average			96.6	94.6	1.1	0.06455	0.00033	286
	Standard Deviation			3.9	3.9	0.0	0.00115	0.00001	14
Sequence 7	68.9	68.9	1	62.7	60.8	1.1	0.04795	0.00025	247
			2	65.3	63.3	1.1	0.04905	0.00025	252
			3	64.2	62.2	1.1	0.04954	0.00025	245
			4	58.7	56.7	1.1	0.04957	0.00025	223
			5	63.0	60.9	1.1	0.04964	0.00025	240
	Average			62.8	60.8	1.1	0.04915	0.00025	242
	Standard Deviation			2.5	2.5	0.0	0.00071	0.00000	11
Sequence 8	68.9	137.9	1	125.8	123.8	1.1	0.12795	0.00066	189
			2	132.1	130.2	1.1	0.13305	0.00068	191
			3	131.8	129.7	1.1	0.13564	0.00069	187
			4	121.9	119.9	1.1	0.13357	0.00068	175
			5	126.7	124.6	1.1	0.13309	0.00068	183
	Average			127.6	125.6	1.1	0.13266	0.00068	185
	Standard Deviation			4.3	4.3	0.0	0.00284	0.00001	6
Sequence 9	68.9	206.8	1	190.4	188.5	1.1	0.27955	0.00143	132
			2	199.1	197.1	1.1	0.28480	0.00146	135
			3	193.3	191.3	1.1	0.28514	0.00146	131
			4	173.9	171.9	1.1	0.28537	0.00146	118
			5	188.6	186.6	1.1	0.28274	0.00145	129
	Average			189.1	187.1	1.1	0.28352	0.00145	129
	Standard Deviation			9.4	9.4	0.0	0.00245	0.00001	7
Sequence 10	103.4	68.9	1	63.7	61.7	1.1	0.22810	0.00117	53
			2	66.2	64.2	1.1	0.23370	0.00120	54
			3	63.9	61.9	1.1	0.23054	0.00118	52
			4	58.3	56.3	1.1	0.22777	0.00117	48
			5	63.4	61.3	1.1	0.22839	0.00117	52
	Average			63.1	61.1	1.1	0.22970	0.00118	52
	Standard Deviation			2.9	2.9	0.0	0.00249	0.00001	2

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 11	103.4	103.4	1	96.1	94.1	1.1	0.24530	0.00126	75
			2	98.8	96.8	1.1	0.24680	0.00126	77
			3	96.3	94.3	1.1	0.24799	0.00127	74
			4	89.3	87.3	1.1	0.24517	0.00126	70
			5	95.1	93.1	1.1	0.24549	0.00126	74
	Average			95.1	93.1	1.1	0.24615	0.00126	74
	Standard Deviation			3.5	3.5	0.0	0.00122	0.00001	3
Sequence 12	103.4	206.8	1	197.1	195.1	1.1	0.31045	0.00159	123
			2	206.1	204.2	1.1	0.31245	0.00160	128
			3	198.0	195.9	1.1	0.31419	0.00161	122
			4	180.7	178.7	1.1	0.31107	0.00159	112
			5	197.7	195.7	1.1	0.31180	0.00160	123
	Average			195.9	193.9	1.1	0.31199	0.00160	121
	Standard Deviation			9.3	9.3	0.0	0.00144	0.00001	6
Sequence 13	137.9	103.4	1	95.2	93.2	1.1	0.27385	0.00140	66
			2	98.8	96.8	1.1	0.27370	0.00140	69
			3	97.1	95.1	1.1	0.27419	0.00140	68
			4	91.7	89.7	1.1	0.26847	0.00137	65
			5	95.1	93.1	1.1	0.27375	0.00140	66
	Average			95.6	93.6	1.1	0.27279	0.00140	67
	Standard Deviation			2.6	2.7	0.0	0.00242	0.00001	1
Sequence 14	137.9	137.9	1	125.4	123.4	1.1	0.28785	0.00147	84
			2	132.9	131.0	1.1	0.29020	0.00149	88
			3	131.3	129.3	1.1	0.29144	0.00149	87
			4	122.7	120.7	1.1	0.29002	0.00149	81
			5	125.6	123.5	1.1	0.28925	0.00148	83
	Average			127.6	125.6	1.1	0.28975	0.00148	85
	Standard Deviation			4.3	4.3	0.0	0.00132	0.00001	3
Sequence 15	137.9	275.8	1	243.2	241.2	1.1	0.40575	0.00208	116
			2	264.2	262.3	1.1	0.40900	0.00209	125
			3	261.7	259.7	1.1	0.41219	0.00211	123
			4	242.8	240.8	1.1	0.41187	0.00211	114
			5	241.8	239.8	1.1	0.40502	0.00207	116
	Average			250.8	248.8	1.1	0.40877	0.00209	119
	Standard Deviation			11.2	11.2	0.0	0.00334	0.00002	5
Resilient Modulus:									195

Appendix E: Resilient Modulus Test Data

Table E-9 Resilient Modulus Test Data

Sample No. LCH12.8_8L_RM

Material Type: LCH/Lime

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	kPa	kPa	kPa	mm	mm/mm	MPa
Sequence 1	20.7	20.7	1	18.9	16.8	1.9	0.01543	0.00008	215
			2	18.6	16.5	1.9	0.01489	0.00008	218
			3	18.2	16.2	1.9	0.01569	0.00008	203
			4	19.2	17.1	1.9	0.02498	0.00013	135
			5	18.8	16.7	1.9	0.01569	0.00008	210
	Average			18.7	16.7	1.9	0.01734	0.00009	196
	Standard Deviation			0.3	0.4	0.0	0.00429	0.00002	35
Sequence 2	20.7	41.4	1	40.2	38.1	1.9	0.03609	0.00018	208
			2	39.1	37.1	1.9	0.04285	0.00022	171
			3	35.4	33.3	1.9	0.03507	0.00018	187
			4	39.1	37.1	1.9	0.03532	0.00018	207
			5	40.3	38.2	1.9	0.03607	0.00018	209
	Average			38.8	36.8	1.9	0.03708	0.00019	196
	Standard Deviation			2.0	2.0	0.0	0.00326	0.00002	17
Sequence 3	20.7	62.1	1	58.9	56.9	1.9	0.04954	0.00025	226
			2	59.8	57.8	1.9	0.04950	0.00025	230
			3	56.6	54.6	1.9	0.05892	0.00030	182
			4	55.8	53.7	1.9	0.04847	0.00025	218
			5	59.3	57.2	1.9	0.04967	0.00025	227
	Average			58.1	56.0	1.9	0.05122	0.00026	217
	Standard Deviation			1.8	1.8	0.0	0.00433	0.00002	20
Sequence 4	34.5	34.5	1	32.2	30.2	1.9	0.03104	0.00016	191
			2	30.9	28.9	1.9	0.03085	0.00016	184
			3	28.7	26.6	1.9	0.03002	0.00015	175
			4	31.6	29.6	1.9	0.03087	0.00016	189
			5	32.4	30.4	1.9	0.02672	0.00014	224
	Average			31.2	29.1	1.9	0.02990	0.00015	193
	Standard Deviation			1.5	1.5	0.0	0.00182	0.00001	19
Sequence 5	34.5	68.9	1	65.2	63.1	1.9	0.05384	0.00027	231
			2	65.9	63.9	1.9	0.05400	0.00027	233
			3	63.1	61.1	1.9	0.05897	0.00030	204
			4	60.7	58.7	1.9	0.05222	0.00027	221
			5	65.1	63.1	1.9	0.05382	0.00027	231
	Average			64.0	62.0	1.9	0.05457	0.00028	224
	Standard Deviation			2.1	2.1	0.0	0.00256	0.00001	12

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 6	34.5	1.3	1	97.4	95.3	1.9	0.07394	0.00038	254
			2	99.8	97.8	1.9	0.07445	0.00038	259
			3	96.4	94.4	1.9	0.07637	0.00039	244
			4	92.6	90.5	1.9	0.07322	0.00037	244
			5	97.3	95.3	1.9	0.07432	0.00038	253
	Average			96.7	94.7	1.9	0.07446	0.00038	250
	Standard Deviation			2.6	2.6	0.0	0.00117	0.00001	7
Sequence 7	68.9	68.9	1	64.4	62.4	1.9	0.05834	0.00030	211
			2	65.6	63.5	1.9	0.05845	0.00030	214
			3	62.7	60.7	1.9	0.05967	0.00030	200
			4	61.3	59.2	1.9	0.05797	0.00029	201
			5	64.4	62.4	1.9	0.05902	0.00030	208
	Average			63.7	61.6	1.9	0.05869	0.00030	207
	Standard Deviation			1.7	1.7	0.0	0.00066	0.00000	6
Sequence 8	68.9	137.9	1	131.6	129.6	1.9	0.13049	0.00066	196
			2	132.5	130.5	1.9	0.13190	0.00067	195
			3	124.0	122.0	1.9	0.13287	0.00067	181
			4	121.4	119.3	1.9	0.12637	0.00064	186
			5	131.2	129.2	1.9	0.13157	0.00067	193
	Average			128.1	126.1	1.9	0.13064	0.00066	190
	Standard Deviation			5.1	5.1	0.0	0.00253	0.00001	6
Sequence 9	68.9	206.8	1	189.6	187.5	1.9	0.31674	0.00161	117
			2	195.8	193.8	1.9	0.31905	0.00162	120
			3	189.0	186.9	1.9	0.32207	0.00163	114
			4	170.2	168.2	1.9	0.31302	0.00159	106
			5	190.5	188.5	1.9	0.31872	0.00162	117
	Average			187.0	185.0	1.9	0.31792	0.00161	115
	Standard Deviation			9.8	9.8	0.0	0.00334	0.00002	5
Sequence 10	103.4	68.9	1	64.3	62.3	1.9	0.24514	0.00124	50
			2	65.4	63.4	1.9	0.24585	0.00125	51
			3	62.0	60.0	1.9	0.24642	0.00125	48
			4	61.2	59.2	1.9	0.24512	0.00124	48
			5	64.4	62.4	1.9	0.24677	0.00125	50
	Average			63.5	61.4	1.9	0.24586	0.00125	49
	Standard Deviation			1.8	1.8	0.0	0.00074	0.00000	1

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 11	103.4	103.4	1	96.8	94.7	1.9	0.26974	0.00137	69
			2	98.0	95.9	1.9	0.26845	0.00136	70
			3	94.1	92.1	1.9	0.27248	0.00138	67
			4	92.7	90.7	1.9	0.27027	0.00137	66
			5	96.9	94.8	1.9	0.26944	0.00137	69
	Average			95.7	93.6	1.9	0.27008	0.00137	68
	Standard Deviation			2.2	2.2	0.0	0.00150	0.00001	2
Sequence 12	103.4	206.8	1	196.4	194.4	1.9	0.34404	0.00175	111
			2	204.9	202.8	1.9	0.34755	0.00176	115
			3	197.2	195.1	1.9	0.34933	0.00177	110
			4	176.1	174.1	1.9	0.33937	0.00172	101
			5	195.5	193.5	1.9	0.34453	0.00175	111
	Average			194.0	192.0	1.9	0.34496	0.00175	110
	Standard Deviation			10.7	10.7	0.0	0.00381	0.00002	5
Sequence 13	137.9	103.4	1	98.0	96.0	1.9	0.29049	0.00147	65
			2	98.0	96.0	1.9	0.28945	0.00147	65
			3	92.5	90.4	1.9	0.29673	0.00151	60
			4	93.9	91.9	1.9	0.29607	0.00150	61
			5	97.6	95.6	1.9	0.29678	0.00151	63
	Average			96.0	94.0	1.9	0.29390	0.00149	63
	Standard Deviation			2.6	2.6	0.0	0.00362	0.00002	2
Sequence 14	137.9	137.9	1	130.0	128.0	1.9	0.31639	0.00161	80
			2	133.0	131.0	1.9	0.31815	0.00161	81
			3	124.8	122.8	1.9	0.31523	0.00160	77
			4	120.5	118.5	1.9	0.31442	0.00160	74
			5	130.1	128.1	1.9	0.31618	0.00160	80
	Average			127.7	125.7	1.9	0.31607	0.00160	78
	Standard Deviation			5.0	5.0	0.0	0.00140	0.00001	3
Sequence 15	137.9	275.8	1	241.3	239.3	1.9	0.46709	0.00237	101
			2	261.8	259.7	1.9	0.47285	0.00240	108
			3	264.7	262.6	1.9	0.47778	0.00243	108
			4	244.5	242.4	1.9	0.47517	0.00241	101
			5	241.2	239.2	1.9	0.47318	0.00240	100
	Average			250.7	248.7	1.9	0.47321	0.00240	104
	Standard Deviation			11.6	11.6	0.0	0.00395	0.00002	4
Resilient Modulus:									151

Appendix E: Resilient Modulus Test Data

Table E-10 Resilient Modulus Test Data

Sample No. HCH9.25_N_RM

Material Type: HCH/Control

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	kPa	kPa	kPa	mm	mm/mm	MPa
Sequence 1	20.7	20.7	1	17.4	15.4	0.6	0.02352	0.00011	145
			2	17.1	15.1	0.6	0.02271	0.00010	146
			3	17.0	15.0	0.6	0.02275	0.00010	146
			4	17.9	15.9	0.6	0.02632	0.00012	133
			5	17.4	15.4	0.6	0.02328	0.00011	146
	Average			17.4	15.4	0.6	0.02372	0.00011	143
	Standard Deviation			0.4	0.4	0.0	0.00150	0.00001	5
Sequence 2	20.7	41.4	1	35.4	33.5	0.6	0.05906	0.00027	125
			2	32.3	30.3	0.6	0.05225	0.00024	128
			3	35.5	33.5	0.6	0.04765	0.00022	155
			4	37.1	35.1	0.6	0.05912	0.00027	131
			5	35.4	33.4	0.6	0.05953	0.00027	124
	Average			35.1	33.1	0.6	0.05552	0.00025	133
	Standard Deviation			1.8	1.8	0.0	0.00534	0.00002	13
Sequence 3	20.7	62.1	1	56.0	54.0	0.6	0.10381	0.00047	115
			2	50.0	48.0	0.6	0.09335	0.00042	114
			3	53.7	51.7	0.6	0.09110	0.00041	125
			4	57.3	55.2	0.6	0.09682	0.00044	126
			5	56.0	54.1	0.6	0.09938	0.00045	120
	Average			54.6	52.6	0.6	0.09689	0.00044	120
	Standard Deviation			2.9	2.9	0.0	0.00501	0.00002	6
Sequence 4	34.5	34.5	1	29.8	27.8	0.6	0.04991	0.00023	123
			2	26.5	24.4	0.6	0.04440	0.00020	122
			3	30.3	28.3	0.6	0.04800	0.00022	130
			4	30.6	28.6	0.6	0.05642	0.00026	112
			5	29.2	27.2	0.6	0.05343	0.00024	112
	Average			29.3	27.3	0.6	0.05043	0.00023	120
	Standard Deviation			1.6	1.7	0.0	0.00468	0.00002	8
Sequence 5	34.5	68.9	1	62.3	60.3	0.6	0.10951	0.00050	121
			2	56.8	54.8	0.6	0.10520	0.00048	115
			3	58.0	56.0	0.6	0.10130	0.00046	122
			4	63.1	61.1	0.6	0.10562	0.00048	128
			5	63.1	61.1	0.6	0.11013	0.00050	122
	Average			60.6	58.6	0.6	0.10635	0.00048	122
	Standard Deviation			3.0	3.0	0.0	0.00359	0.00002	5

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 6	34.5	1.3	1	97.1	95.1	0.6	0.15886	0.00072	132
			2	88.2	86.2	0.6	0.15670	0.00071	121
			3	83.0	80.9	0.6	0.13790	0.00062	130
			4	94.7	92.7	0.6	0.15317	0.00069	134
			5	96.0	94.0	0.6	0.15998	0.00072	130
	Average			91.8	89.8	0.6	0.15332	0.00069	129
	Standard Deviation			6.0	6.0	0.0	0.00900	0.00004	5
Sequence 7	68.9	68.9	1	62.4	60.4	0.6	0.11506	0.00052	116
			2	56.6	54.5	0.6	0.11095	0.00050	108
			3	57.7	55.7	0.6	0.10795	0.00049	114
			4	64.0	62.0	0.6	0.11407	0.00052	120
			5	62.7	60.7	0.6	0.11698	0.00053	115
	Average			60.7	58.7	0.6	0.11300	0.00051	115
	Standard Deviation			3.3	3.3	0.0	0.00357	0.00002	4
Sequence 8	68.9	137.9	1	129.5	127.5	0.6	0.35731	0.00162	79
			2	120.8	118.7	0.6	0.35605	0.00161	74
			3	107.8	105.8	0.6	0.33545	0.00152	70
			4	124.7	122.7	0.6	0.34927	0.00158	78
			5	129.5	127.6	0.6	0.35938	0.00163	78
	Average			122.4	120.4	0.6	0.35149	0.00159	76
	Standard Deviation			9.0	9.0	0.0	0.00974	0.00004	4
Sequence 9	68.9	206.8	1	194.7	192.7	0.6	1.01901	0.00462	42
			2	193.1	191.1	0.6	1.02605	0.00465	41
			3	171.8	169.7	0.6	1.01405	0.00459	37
			4	176.9	174.9	0.6	1.00707	0.00456	38
			5	196.4	194.4	0.6	1.03168	0.00467	42
	Average			186.6	184.6	0.6	1.01957	0.00462	40
	Standard Deviation			11.4	11.4	0.0	0.00969	0.00004	2
Sequence 10	103.4	68.9	1	61.8	59.8	0.6	0.84966	0.00385	16
			2	56.1	54.0	0.6	0.84460	0.00383	14
			3	58.8	56.8	0.6	0.84325	0.00382	15
			4	63.9	61.9	0.6	0.84887	0.00385	16
			5	62.4	60.4	0.6	0.85098	0.00386	16
	Average			60.6	58.6	0.6	0.84747	0.00384	15
	Standard Deviation			3.1	3.1	0.0	0.00336	0.00002	1

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 11	103.4	103.4	1	93.8	91.8	0.6	0.90151	0.00408	22
			2	84.3	82.2	0.6	0.89345	0.00405	20
			3	84.2	82.2	0.6	0.88741	0.00402	20
			4	92.2	90.2	0.6	0.89407	0.00405	22
			5	93.9	91.9	0.6	0.89943	0.00408	23
	Average			89.7	87.7	0.6	0.89518	0.00406	22
	Standard Deviation			5.0	5.0	0.0	0.00554	0.00003	1
Sequence 12	103.4	206.8	1	200.9	198.9	0.6	1.10356	0.00500	40
			2	198.2	196.2	0.6	1.10825	0.00502	39
			3	177.5	175.5	0.6	1.09746	0.00497	35
			4	183.9	181.9	0.6	1.09067	0.00494	37
			5	201.6	199.6	0.6	1.10578	0.00501	40
	Average			192.4	190.4	0.6	1.10115	0.00499	38
	Standard Deviation			11.0	11.0	0.0	0.00709	0.00003	2
Sequence 13	137.9	103.4	1	96.5	94.5	0.6	0.98546	0.00447	21
			2	87.0	85.0	0.6	0.97870	0.00443	19
			3	82.8	80.8	0.6	0.96926	0.00439	18
			4	94.0	91.9	0.6	0.96997	0.00440	21
			5	95.3	93.3	0.6	0.98483	0.00446	21
	Average			91.1	89.1	0.6	0.97765	0.00443	20
	Standard Deviation			5.9	5.9	0.0	0.00779	0.00004	1
Sequence 14	137.9	137.9	1	130.4	128.4	0.6	1.02981	0.00467	28
			2	120.6	118.6	0.6	1.02730	0.00465	25
			3	107.7	105.7	0.6	1.00726	0.00456	23
			4	125.1	123.1	0.6	1.02017	0.00462	27
			5	130.4	128.4	0.6	1.02988	0.00467	28
	Average			122.8	120.8	0.6	1.02289	0.00463	26
	Standard Deviation			9.4	9.4	0.0	0.00959	0.00004	2
Sequence 15	137.9	275.8	1	130.4	128.4	0.6	1.02981	0.00467	28
			2	120.6	118.6	0.6	1.02730	0.00465	25
			3	107.7	105.7	0.6	1.00726	0.00456	23
			4	125.1	123.1	0.6	1.02017	0.00462	27
			5	130.4	128.4	0.6	1.02988	0.00467	28
	Average			122.8	120.8	0.6	1.02289	0.00463	26
	Standard Deviation			9.4	9.4	0.0	0.00959	0.00004	2
Resilient Modulus:								76	

Appendix E: Resilient Modulus Test Data

Table E-11 Resilient Modulus Test Data

Sample No. HCH12.4 1.5P_RM

Material Type: HCH/Polymer

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	kPa	kPa	kPa	mm	mm/mm	MPa
Sequence 1	20.7	20.7	1	14.8	12.2	1.7	0.05774	0.00028	43
			2	16.0	13.5	1.7	0.09164	0.00045	30
			3	16.9	14.3	1.7	0.08402	0.00041	35
			4	16.5	14.1	1.7	0.08786	0.00043	33
			5	14.8	12.1	1.7	0.06322	0.00031	39
	Average			15.8	13.3	1.7	0.07690	0.00037	36
	Standard Deviation			1.0	1.0	0.0	0.01535	0.00007	5
Sequence 2	20.7	41.4	1	29.5	26.9	1.7	0.18935	0.00092	29
			2	33.0	30.5	1.7	0.22251	0.00108	28
			3	37.4	34.8	1.7	0.22180	0.00108	32
			4	34.6	32.2	1.7	0.22508	0.00110	29
			5	29.5	26.9	1.7	0.19468	0.00095	28
	Average			32.8	30.3	1.7	0.21068	0.00103	29
	Standard Deviation			3.4	3.4	0.0	0.01719	0.00008	2
Sequence 3	20.7	62.1	1	45.8	43.2	1.7	0.25575	0.00125	35
			2	47.9	45.4	1.7	0.26956	0.00131	35
			3	57.2	54.6	1.7	0.27525	0.00134	41
			4	54.8	52.3	1.7	0.27903	0.00136	38
			5	45.2	42.6	1.7	0.25858	0.00126	34
	Average			50.2	47.6	1.7	0.26763	0.00130	36
	Standard Deviation			5.5	5.5	0.0	0.01018	0.00005	3
Sequence 4	34.5	34.5	1	26.1	23.5	1.7	0.15780	0.00077	31
			2	27.1	24.7	1.7	0.18521	0.00090	27
			3	30.7	28.1	1.7	0.18070	0.00088	32
			4	30.0	27.5	1.7	0.18663	0.00091	30
			5	27.0	24.4	1.7	0.16383	0.00080	31
	Average			28.2	25.6	1.7	0.17483	0.00085	30
	Standard Deviation			2.0	2.0	0.0	0.01315	0.00006	2
Sequence 5	34.5	68.9	1	56.9	54.3	1.7	0.26560	0.00129	42
			2	48.8	46.3	1.7	0.27856	0.00136	34
			3	61.5	58.9	1.7	0.27975	0.00136	43
			4	64.5	62.0	1.7	0.28908	0.00141	44
			5	57.1	54.5	1.7	0.27883	0.00136	40
	Average			57.8	55.2	1.7	0.27836	0.00136	41
	Standard Deviation			5.9	5.9	0.0	0.00836	0.00004	4

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 6	34.5	1.3	1	98.3	95.7	1.7	0.32050	0.00156	61
			2	84.5	82.0	1.7	0.32806	0.00160	51
			3	80.9	78.3	1.7	0.31440	0.00153	51
			4	96.4	93.9	1.7	0.32893	0.00160	59
			5	97.3	94.7	1.7	0.32353	0.00158	60
	Average			91.5	88.9	1.7	0.32308	0.00157	56
	Standard Deviation			8.1	8.1	0.0	0.00594	0.00003	5
Sequence 7	68.9	68.9	1	57.1	54.6	1.7	0.27945	0.00136	40
			2	48.4	46.0	1.7	0.28661	0.00140	33
			3	62.7	60.1	1.7	0.28785	0.00140	43
			4	65.5	63.0	1.7	0.29593	0.00144	44
			5	57.0	54.5	1.7	0.28248	0.00138	40
	Average			58.2	55.6	1.7	0.28646	0.00140	40
	Standard Deviation			6.5	6.5	0.0	0.00626	0.00003	4
Sequence 8	68.9	137.9	1	133.9	131.4	1.7	0.42425	0.00207	64
			2	126.3	123.8	1.7	0.43586	0.00212	58
			3	106.4	103.8	1.7	0.41215	0.00201	52
			4	123.0	120.5	1.7	0.42923	0.00209	58
			5	134.5	132.0	1.7	0.42833	0.00209	63
	Average			124.8	122.3	1.7	0.42596	0.00208	59
	Standard Deviation			11.4	11.4	0.0	0.00877	0.00004	5
Sequence 9	68.9	206.8	1	196.8	194.2	1.7	0.71470	0.00348	56
			2	199.2	196.7	1.7	0.73211	0.00357	55
			3	175.3	172.7	1.7	0.71650	0.00349	49
			4	170.2	167.8	1.7	0.71348	0.00348	48
			5	196.5	194.0	1.7	0.71953	0.00351	55
	Average			187.6	185.1	1.7	0.71926	0.00351	53
	Standard Deviation			13.7	13.7	0.0	0.00753	0.00004	4
Sequence 10	103.4	68.9	1	49.2	46.6	1.7	0.53820	0.00262	18
			2	52.4	49.9	1.7	0.55521	0.00271	18
			3	62.3	59.7	1.7	0.56180	0.00274	22
			4	58.6	56.1	1.7	0.56633	0.00276	20
			5	48.2	45.6	1.7	0.53813	0.00262	17
	Average			54.1	51.6	1.7	0.55193	0.00269	19
	Standard Deviation			6.1	6.1	0.0	0.01317	0.00006	2

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 11	103.4	103.4	1	84.2	81.6	1.7	0.61100	0.00298	27
			2	69.6	67.1	1.7	0.60311	0.00294	23
			3	89.0	86.4	1.7	0.61526	0.00300	29
			4	96.7	94.2	1.7	0.62913	0.00307	31
			5	86.1	83.5	1.7	0.61587	0.00300	28
	Average			85.1	82.6	1.7	0.61487	0.00300	28
	Standard Deviation			9.9	9.9	0.0	0.00946	0.00005	3
Sequence 12	103.4	206.8	1	199.6	197.0	1.7	0.76760	0.00374	53
			2	205.0	202.5	1.7	0.78756	0.00384	53
			3	186.3	183.7	1.7	0.77201	0.00376	49
			4	172.3	169.9	1.7	0.76723	0.00374	45
			5	199.1	196.5	1.7	0.77067	0.00376	52
	Average			192.5	189.9	1.7	0.77301	0.00377	50
	Standard Deviation			13.2	13.2	0.0	0.00838	0.00004	3
Sequence 13	137.9	103.4	1	93.1	90.6	1.7	0.66055	0.00322	28
			2	78.3	75.8	1.7	0.66501	0.00324	23
			3	85.9	83.3	1.7	0.66601	0.00325	26
			4	98.6	96.2	1.7	0.67988	0.00331	29
			5	93.2	90.6	1.7	0.67002	0.00327	28
	Average			89.8	87.3	1.7	0.66829	0.00326	27
	Standard Deviation			7.9	7.9	0.0	0.00730	0.00004	2
Sequence 14	137.9	137.9	1	134.4	131.8	1.7	0.70950	0.00346	38
			2	122.3	119.8	1.7	0.71681	0.00349	34
			3	101.4	98.8	1.7	0.69331	0.00338	29
			4	124.4	122.0	1.7	0.71578	0.00349	35
			5	133.3	130.7	1.7	0.71147	0.00347	38
	Average			123.2	120.6	1.7	0.70937	0.00346	35
	Standard Deviation			13.3	13.3	0.0	0.00947	0.00005	4
Sequence 15	137.9	275.8	1	250.5	247.9	1.7	0.99855	0.00487	51
			2	267.5	265.0	1.7	1.02131	0.00498	53
			3	248.7	246.1	1.7	1.01101	0.00493	50
			4	213.3	210.8	1.7	0.99653	0.00486	43
			5	250.8	248.2	1.7	1.00324	0.00489	51
	Average			246.2	243.6	1.7	1.00613	0.00490	50
	Standard Deviation			19.9	19.9	0.0	0.01015	0.00005	4
Resilient Modulus:									39

Appendix E: Resilient Modulus Test Data

Table E-12 Resilient Modulus Test Data

Sample No. HCH14.4 8L RM

Material Type: HCH/Lime

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	kPa	kPa	kPa	mm	mm/mm	MPa
Sequence 1	20.7	20.7	1	18.0	15.9	1.2	0.00689	0.00003	542
			2	17.2	15.1	1.2	0.00730	0.00003	486
			3	16.6	14.5	1.2	0.00690	0.00003	494
			4	18.3	16.2	1.2	0.00630	0.00003	604
			5	17.6	15.6	1.2	0.00109	0.00000	3358
	Average			17.6	15.5	1.2	0.00570	0.00002	1097
	Standard Deviation			0.7	0.7	0.0	0.00260	0.00001	1265
Sequence 2	20.7	41.4	1	31.9	29.9	1.2	0.13665	0.00058	51
			2	35.1	33.0	1.2	0.15730	0.00067	49
			3	36.5	34.5	1.2	0.15645	0.00067	52
			4	34.1	32.0	1.2	0.14918	0.00064	50
			5	31.0	28.9	1.2	0.13076	0.00056	52
	Average			33.7	31.6	1.2	0.14607	0.00062	51
	Standard Deviation			2.3	2.3	0.0	0.01190	0.00005	1
Sequence 3	20.7	62.1	1	48.6	46.5	1.2	0.20480	0.00087	53
			2	52.1	50.0	1.2	0.21525	0.00092	54
			3	59.4	57.3	1.2	0.22315	0.00095	60
			4	51.7	49.6	1.2	0.21738	0.00093	53
			5	48.1	46.0	1.2	0.20506	0.00087	53
	Average			51.9	49.9	1.2	0.21313	0.00091	55
	Standard Deviation			4.5	4.5	0.0	0.00802	0.00003	3
Sequence 4	34.5	34.5	1	31.0	28.9	1.2	0.09610	0.00041	71
			2	30.7	28.6	1.2	0.09590	0.00041	70
			3	28.7	26.6	1.2	0.09540	0.00041	65
			4	29.6	27.5	1.2	0.09048	0.00039	71
			5	31.4	29.3	1.2	0.09701	0.00041	71
	Average			30.3	28.2	1.2	0.09498	0.00041	70
	Standard Deviation			1.1	1.1	0.0	0.00258	0.00001	2
Sequence 5	34.5	68.9	1	51.9	49.9	1.2	0.21900	0.00093	53
			2	58.5	56.4	1.2	0.23015	0.00098	57
			3	65.5	63.4	1.2	0.23445	0.00100	63
			4	58.0	55.9	1.2	0.22918	0.00098	57
			5	52.2	50.2	1.2	0.22066	0.00094	53
	Average			57.2	55.2	1.2	0.22669	0.00097	57
	Standard Deviation			5.6	5.6	0.0	0.00659	0.00003	4

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 6	34.5	1.3	1	97.2	95.2	1.2	0.28680	0.00122	78
			2	89.0	86.9	1.2	0.28385	0.00121	72
			3	89.2	87.1	1.2	0.28275	0.00121	72
			4	99.3	97.2	1.2	0.28608	0.00122	80
			5	97.0	94.9	1.2	0.28776	0.00123	77
	Average			94.3	92.3	1.2	0.28545	0.00122	76
	Standard Deviation			4.9	4.9	0.0	0.00209	0.00001	4
Sequence 7	68.9	68.9	1	67.0	65.0	1.2	0.22380	0.00095	68
			2	60.5	58.4	1.2	0.22460	0.00096	61
			3	57.6	55.5	1.2	0.22585	0.00096	58
			4	65.6	63.5	1.2	0.22618	0.00096	66
			5	67.9	65.8	1.2	0.22856	0.00097	67
	Average			63.7	61.6	1.2	0.22580	0.00096	64
	Standard Deviation			4.5	4.5	0.0	0.00182	0.00001	5
Sequence 8	68.9	137.9	1	131.9	129.9	1.2	0.36995	0.00158	82
			2	125.6	123.5	1.2	0.35990	0.00153	80
			3	113.5	111.4	1.2	0.35575	0.00152	73
			4	128.6	126.5	1.2	0.36608	0.00156	81
			5	134.5	132.4	1.2	0.36976	0.00158	84
	Average			126.8	124.7	1.2	0.36429	0.00155	80
	Standard Deviation			8.2	8.2	0.0	0.00627	0.00003	4
Sequence 9	68.9	206.8	1	197.6	195.5	1.2	0.65630	0.00280	70
			2	190.2	188.1	1.2	0.65830	0.00281	67
			3	169.7	167.6	1.2	0.64970	0.00277	60
			4	180.0	177.9	1.2	0.65303	0.00278	64
			5	197.2	195.2	1.2	0.65831	0.00281	70
	Average			187.0	184.9	1.2	0.65513	0.00279	66
	Standard Deviation			12.0	12.0	0.0	0.00372	0.00002	4
Sequence 10	103.4	68.9	1	66.9	64.9	1.2	0.51165	0.00218	30
			2	64.2	62.1	1.2	0.51170	0.00218	28
			3	54.1	52.0	1.2	0.50920	0.00217	24
			4	60.8	58.7	1.2	0.50873	0.00217	27
			5	66.9	64.8	1.2	0.51256	0.00219	30
	Average			62.6	60.5	1.2	0.51077	0.00218	28
	Standard Deviation			5.4	5.4	0.0	0.00169	0.00001	2

Appendix E: Resilient Modulus Test Data

Column #	1	2	3	4	5	6	7	8	9
Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Average Recov Def.	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	c _i	S _{max}	S _{cyclic}	S _{contact}	H _{avg}	ε _r	M _r
Unit	kPa	kPa	---	N	kPa	kPa	mm	mm/mm	MPa
Sequence 11	103.4	103.4	1	95.5	93.5	1.2	0.55780	0.00238	39
			2	93.1	91.0	1.2	0.55565	0.00237	38
			3	91.0	88.9	1.2	0.55760	0.00238	37
			4	96.8	94.7	1.2	0.55813	0.00238	40
			5	96.8	94.8	1.2	0.56009	0.00239	40
	Average			94.7	92.6	1.2	0.55785	0.00238	39
	Standard Deviation			2.5	2.5	0.0	0.00158	0.00001	1
Sequence 12	103.4	206.8	1	201.5	199.5	1.2	0.68110	0.00290	69
			2	198.3	196.2	1.2	0.68395	0.00292	67
			3	179.6	177.6	1.2	0.68165	0.00291	61
			4	185.3	183.2	1.2	0.67833	0.00289	63
			5	202.5	200.4	1.2	0.68410	0.00292	69
	Average			193.4	191.4	1.2	0.68183	0.00291	66
	Standard Deviation			10.3	10.3	0.0	0.00237	0.00001	3
Sequence 13	137.9	103.4	1	99.0	97.0	1.2	0.58080	0.00248	39
			2	97.6	95.5	1.2	0.58690	0.00250	38
			3	93.0	90.9	1.2	0.58435	0.00249	36
			4	96.0	93.9	1.2	0.58803	0.00251	37
			5	99.4	97.3	1.2	0.58685	0.00250	39
	Average			97.0	94.9	1.2	0.58539	0.00250	38
	Standard Deviation			2.6	2.6	0.0	0.00289	0.00001	1
Sequence 14	137.9	137.9	1	135.4	133.4	1.2	0.62885	0.00268	50
			2	126.4	124.3	1.2	0.62635	0.00267	47
			3	116.2	114.1	1.2	0.62245	0.00265	43
			4	126.5	124.4	1.2	0.62558	0.00267	47
			5	130.1	128.0	1.2	0.62635	0.00267	48
	Average			126.9	124.8	1.2	0.62592	0.00267	47
	Standard Deviation			7.0	7.1	0.0	0.00230	0.00001	2
Sequence 15	137.9	275.8	1	256.5	254.5	1.2	0.97550	0.00416	61
			2	264.7	262.6	1.2	0.97970	0.00418	63
			3	244.1	242.0	1.2	0.97680	0.00417	58
			4	220.0	217.9	1.2	0.96918	0.00413	53
			5	256.3	254.2	1.2	0.97832	0.00417	61
	Average			248.3	246.2	1.2	0.97590	0.00416	59
	Standard Deviation			17.5	17.5	0.0	0.00408	0.00002	4
Resilient Modulus:									126