MOUNTAIN-PLAINS CONSORTIUM

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EXPANSIVE SOIL MITIGATION FOR TRANSPORTATION EARTHWORKS BY POLYMER AMENDMENT

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Expansive Soil Mitigation for Transportation Earthworks by Polymer Amendment

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ABSTRACT

The objective of this study was to determine the effectiveness of commercially available polymer soil stabilizers in expansive soil swell reduction relative to quicklime and Class C fly ash. A survey of state departments of transportation within the Mountain-Plains region of the United States (Colorado, Montana, North Dakota, South Dakota, Utah, Wyoming) was conducted to define the state-of-practice in expansive soil mitigation, from which lime and fly ash were identified as the most used soil stabilizers. Four commercially available polymers were tested for comparison with lime and fly ash. Untreated and treated soils were classified, and tested for swelling pressure, swelling potential, unconfined compressive strength, and hydraulic conductivity (k). Relative to untreated soil, polymer treatment was less effective at reducing the swelling potential (70% reduction) and increasing unconfined compressive strength (46 kPa increase) of a highly expansive soil relative to lime (100% reduction, 1260 kPa increase) and fly ash (97% swelling potential reduction, 380 kPa increase in UCS). However, lime and fly ash treatments resulted in a 52,000- and 1,100-times increases in k, respectively, while polymer resulted in only a two-times increase in k relative to the untreated soil ($k = 2.9\times10^{-11}$ m/s). Polymer was also shown to be effective at reducing k to below 1.9×10^{-12} m/s when used as a spray-on coating. The results of this study illustrate that commercially available polymers reduce swell in expansive soils by mechanisms that are different than lime and fly ash.

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EXECUTIVE SUMMARY

The objective of this study was to determine the effectiveness of commercially available polymer soil stabilizers in expansive soil swell reduction relative to quicklime and Class C fly ash. A survey of state departments of transportation (DOTs) within the Mountain-Plains region of the United States (Colorado, Montana, North Dakota, South Dakota, Utah, Wyoming) was conducted to define the state-of-practice in expansive soil mitigation, from which lime and fly ash were identified as the most used soil stabilizers. A literature review on expansive soil treatments was also performed to establish the state-of-the-art in expansive soil mitigation. The soil tested was composed of expansive soil from Fort Collins, Colorado, that classified as low swelling, amended with 15% (high swelling) sodium bentonite. Fifteen percent bentonite was selected to meet the Federal Highway Administration (FHWA) classification for highly expansive soil. Treated and untreated soils were classified, and tested for swelling, strength, and hydraulic conductivity. Four commercially available polymers were tested; lime and fly ash, two common techniques used in treatment of expansive soils, were tested for comparison.

Four commercially available polymers were tested for comparison with lime and fly ash. Untreated and treated soils were classified and tested for swelling pressure, swelling potential, unconfined compressive strength, and hydraulic conductivity (k). Relative to untreated soil, polymer treatment was less effective at reducing the swelling potential (70% reduction) and increasing unconfined compressive strength (46 kPa increase) of a highly expansive soil relative to lime (100% reduction, 1260 kPa increase) and fly ash (97% swelling potential reduction, 380 kPa increase in UCS). However, lime and fly ash treatments resulted in a 52,000- and 1,100-times increases in k, respectively, while polymer resulted in only a two-times increase in k relative to the untreated soil ($k = 2.9\times10^{-11}$ m/s). Polymer was also shown to be effective at reducing k to below 1.9×10^{-12} m/s when used as a spray-on coating. Given that ingress of moisture underlies expansive soil swelling, the results of testing did not demonstrate a clear "superior" expansive soil treatment technology. Chemical treatments (lime) and polymer treatments have different advantages. Future comparisons of polymers to conventional chemical stabilizers requires careful consideration of the differing mechanisms by which materials will reduce swelling. Three recommendations for future research were identified: (1) a method is required to test polymer treated expansive soil in a manner that is more representative of field conditions. This method should represent the coupled effects of swelling and hydraulic conductivity (i.e., water ingress and resulting swell). (2) Longevity of commercially available polymers versus lime or fly ash is unknown but may warrant future study. (3) Commercial polymers should be tested for soil conditions under which conventional chemical stabilizers are ineffective and compared with current dominant treatment techniques (excavate and replace or excavate and re-compact).

The outline of this report is as follows. Section 1 introduces the problem. Section 2 provides a literature review of expansive soil classification and treatment methods. Section 3 provides the results of a state-of-practice survey of expansive soil treatment methods by Mountain-Plains region DOTs. Section 4 provides the methods used to evaluate commercially available polymers for expansive soil mitigation. Section 5 describes the materials used in testing. Section 6 presents the experimental results for soils modified by commercially available polymers as well as lime, fly ash, and a control. Section 7 presents a discussion of the results of this study. Section 8 presents the main conclusions. Appendix A provides the full results of the state-of-practice survey of expansive soil treatment methods by the Mountain-Plains region DOTs. Appendix B provides the raw experimental results of tests performed.

The key results of this study were published in Transportation Geotechnics in 2020 (Taher et al. 2020).

1. INTRODUCTION

The shrink-swell behavior of expansive soils reduces infrastructure longevity in many regions of the world (Nelson and Miller 1997). Inyang et al. (2007) estimate that shrink-swell behavior of expansive soils with moisture variation cause more than 50% of soil-related damage to infrastructure globally. The pervasiveness of expansive soils in the northern Mountain-Plains region is illustrated in Figure 1.1. Roadways are particularly susceptible to the effects of expansive soils due the combination of low ground pressures and large surface areas. Economical solutions to mitigate damage from expansive soils are necessary to enhance transportation system longevity. The objective of this study was to compare the effectiveness of commercially available polymer-based soil stabilizers with standard treatments used in practice to assess the relative effectiveness of commercially available polymers to mitigate shrink-swell behavior of expansive soils.

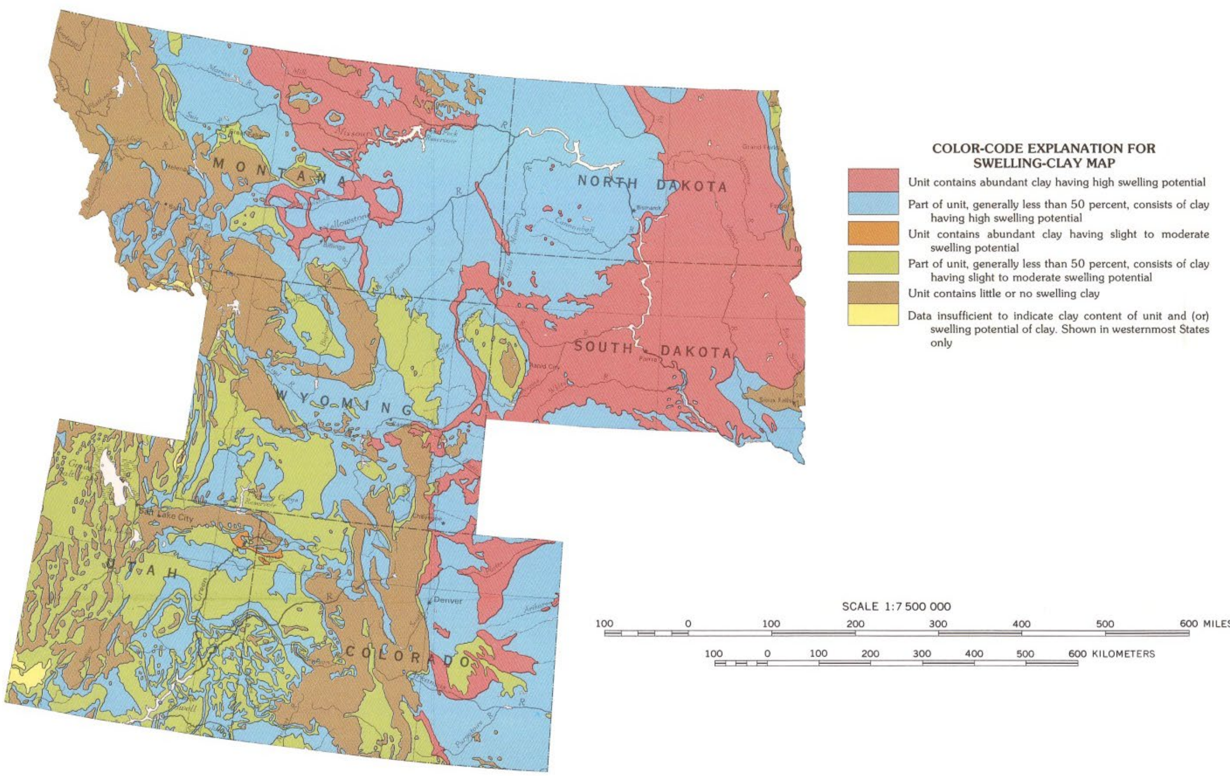

Figure 1.1 Map of expansive soils in the northern Mountain-Plains region of the continental U.S. (adapted from Olive et al. 1989)

Techniques used to mitigate shrink-swell of expansive soils include physical and chemical treatments. Common physical treatments include removal and replacement, over-excavation and re-compaction, pre-wetting, and encapsulation by geomembrane barriers. Removal and replacement reduce shrink-swell behavior by removing the expansive soil within the zone of shrink-swell (active zone) to an appropriate depth and replacing with non-swelling soils (Nelson et al. 2015). Over-excavation and re-compaction mitigate shrink-swell by remolding and compacting an expansive soil at standard Proctor optimum moisture content, or more commonly, at a moisture content greater than optimum (wet-side compaction) (Du Bose 1955, Petry and Little 2002). Pre-wetting reduces the tendency of an expansive soil to undergo substantial additional swell after construction by compacting at a pre-swollen (wetted) condition during construction (Ardani 1992). Physical isolation of expansive soils by geomembrane barriers is also used to mitigate swelling by minimizing moisture migration, thereby eliminating the cause of shrink-swell (McDonald and Potter 1973, Stark et al. 2000). Other physical treatments have included surcharge loading, asphalt treatment, explosive treatment for expansive shales, and electro-osmosis (Haussmann 1990, Nelson and Miller 1997, Brandon et al. 2009); however, these techniques are less common in practice today (Nelson et al. 2015).

Chemical treatments include application of stabilizing additives such as lime, fly ash, cement, polymers, salts, organic compounds, and enzymes. Chemical treatments can be further subdivided into traditional and nontraditional stabilizers. Traditional stabilizers include fly ash, lime, and cement, all with pozzolanic properties that reduce shrink-swell behavior by chemical reactions between the clay minerals and the calcium oxide molecules at the surface level that result in bonding the soil particles together as well as reducing the affinity of the soil to water (Diamond and Kinter 1965, Petry and Lee 1989, Petry and Little 2002, Inyang et al. 2007, Buhler and Cerato 2007, McCarthy et al. 2009). Traditional stabilizers have limited effectiveness in highly active soils, [i.e., soils with a plasticity index (PI) greater than 50; Petry and Little 2002], expansive soils containing carbonates that lead to carbonation and swelling, or expansive soils containing sulfate salts (e.g., gypsum) or sulfur that can lead to ettringite formation and swelling (Majeed et al. 2014). Traditional stabilizers typically require a curing time after placement to allow cementitious bonds to be effective. Finally, there remain environmental concerns with stabilizer production and placement both in terms of impacts on greenhouse gas production and salinization of water resources (Petry and Little 2002).

Nontraditional stabilizers provide an alternative to traditional stabilizers, and include polymers, salts, and enzymes. Salts and enzymes reduce swelling by improving the ionic composition of the soil (e.g., replacing monovalent sodium for divalent calcium) and reducing the concentration gradient between absorbed and free pore water, which reduces swelling (Scholen 1992, Tingle and Santoni 2003). Conversely, natural and synthesized polymers reduce shrink-swell by creating a nano-composite structure that results in bonded soil particles (Tingle et al. 2007, Azzam 2014). Nontraditional stabilizers are attractive alternatives to traditional stabilizers as they have potential to function in soils containing carbonates, sulphate salts or sulphur, require zero or minimal curing time, cost less, and reduce environmental impacts (Kolay et al. 2016). An in-depth review of expansive soil mitigation practice using traditional and nontraditional stabilizers is provided in Taher (2017) and Behnood (2018).

This study provides a comparative assessment in terms of swelling reduction of commercially available (i.e., off the shelf) polymer soil stabilizers relative to traditional stabilizers, i.e., quicklime and Class C fly ash. Polymer-based soil stabilizers have been shown to increase unconfined compressive strength and reduce swell potential, swell pressure, and hydraulic conductivity of expansive soils (Illuri and Nataatmadja 2007, Inyang et al. 2007, Brandon et al. 2009, Mirzababaei et al. 2009, Yazdandoust and Yasrobi 2010, Azzam 2011, Azzam 2014, Mousavi et al. 2014). However, direct comparisions with traditional stabilizers are limited, making effectiveness-driven decisions by practicioners difficult.

A high swell classification expansive soil (classified based on FHWA-RD-77-94; Snethen et al. 1977) was used for all tests. One-dimensional swelling, unconfined compressive strength, and hydraulic conductivity were used to comparatively assess aspects of swell mitigation by different treatments. The effectiveness of polymer treatment relative to traditional stabilizers was evaluated in the context of findings distilled from the tests that reflect mechanisms that govern swelling. The results from this study provide an example of a comparative assessment between technologies, and can be used to guide how treatments are compared. The key results of this study are published in Taher et al. (2020).

2. BACKGROUND

2.1 Identification of Expansive Soils

The two main factors that trigger swelling of soils are unloading and addition of water (Mitchel & Soga 2005). Soil swelling depends on the mineralogical composition and particle size distribution (Yazdandoust & Yasrobi 2010). Clays, particularly those containing significant quantities of smectites, have high swelling potential when hydrated. Swelling and contraction of clayey soils with moisture variation is a phenomenon that causes problems for infrastructures across the globe (Inyang et al. 2007). For example, historically, more than 50% of soil-related damage to structures and infrastructure has been due to soil expansion (John & Holtz 1973). Thus, knowledge of soil swelling potential and methods to reduce swelling are important for preventing such undesirable outcomes. Swelling of expansive soils mostly occurs at the upper soil layers where the soil is affected by moisture variations; therefore, knowledge of the active zone depth is important in expansive soils. The active zone depth is defined as the depth where the expansive soil is affected by moisture variations that trigger swelling (Petry & Little 2002).

Direct and indirect laboratory tests can be conducted to identify expansive soils. Direct tests involve measurement of soil swell, whereas indirect tests, such as Atterberg limits, involve measuring a corollary property and are the most commonly used identifiers of expansive soils. The following methods are commonly used to identify expansive soils:

- Swell potential (%) and swell pressure (kPa) are direct methods to measure expansivity of soils. One-dimensional swell tests (ASTM D4546 - Standard Test Methods for One-Dimensional Swell or Collapse of Soils) are used to measure swell potential and swell pressure, which is more time consuming than measuring Atterberg limits. A soil having a swell potential of less than 0.5% is considered as low expansive (Federal Highway Administration report number FHWA-RD-77-94).

- Liquid limit (*LL*) defines the water content where a soil transitions from a plastic to a liquid and is a measure of the ability of a soil to hold water (ASTM D4318 - Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils). The greater the *LL*, the higher the affinity to water, and the greater the correlated potential degree of expansivity. A soil having an *LL* of less than 50% is considered to be low swelling (FHWA-RD-77-94).

- Plastic limit (*PL*) defines the water content where a soil transitions from a semi-solid to a plastic (ASTM D4318 – Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils). Plastic limit values reduce the plasticity index (*PI*), which is also used as an indicator of stability against swelling. A soil with a *PI* of less than 25% is considered to be low swelling (FHWA-RD-77-94). Moreover, a PI of 10% or less is considered as an indicator of a stable (i.e., non-expansive) soil (American Coal Ash Association 2003).

2.2 Classification of Expansive Soils

A summary of expansive soils identification and classification metrics from FHWA-RD-77-94, which classifies potential swell based on *LL* and *PI*, is provided in Table 2.1. Soil swell potential is categorized as low, marginal, or high.

Table 2.1 Classification of expansive soils from FHWA-RD-77-94

LL, %	PI, %	Potential Swell, %	Potential Swell Classification
> 60	> 35	> 1.5	High
50-60	25-35	0.5-1.5	Marginal
< 50	< 25	< 0.5	Low

Rao (2006) notes that the United States Bureau of Reclamation uses the classification system presented in Table 2.2, based on the work of Holtz and Gibbs (1956). This classification system relies on colloid percent to define the active portions of the soil, coupled with *PI*, and shrinkage limit (*SL*: the water content where a soil transitions from a solid to a semi solid).

Table 2.2 Classification of expansive soils from United States Bureau of Reclamation

Colloid Content, %	PI, %	SL, %	Total Volume Change, %	Degree of Expansion
< 15	< 18	< 10	< 10	Low
13-23	15-28	10-20	10-20	Medium
20-31	25-41	20-30	20-30	High
> 28	> 35	> 30	> 30	Very High

2.3 Expansive Soils Treatment Methods

This section includes a summary of the mitigation techniques and treatments commonly used in the United States to mitigate expansive soils. Mitigation methods have been categorized into physical and chemical treatments. The pros and cons of each method also are listed. This summary is based on the work of Petry and Little (2002) and Nelson and Miller (1997). Supplemental references are included as relevant.

2.3.1 Physical Treatments

Permanent mitigation of expansive soils can be achieved by removing the upper layer of the expansive soils within the active zone depth (where the expansive soil is affected by moisture variations). This ideal solution, in many cases, is costly and may not be practical. Physical treatments, in general, involve application of external factors to treat expansive soils rather than internally changing expansive soils to non-expansive. In this section, the most practiced physical treatments are presented.

2.3.1.1 Removal and Replacement

This method involves removing a specified depth of expansive soil and replacing it with a non-expansive (stable) soil. The excavation depth is decided based on the active zone depth, which removes the depth where the expansive soil is most detrimental. Ardani (1992) states that the backfill soil should be silts or low-permeable, non-expansive clays. However, the soil to be replaced should not be granular because this simply shifts the problem due to high rates of permeability. Ardani (1992) states that the Colorado Department of Transportation (CDOT) relies upon *PI* to determine depth of excavation.

<u>Advantages:</u>

1. Non-expansive fill material can be compacted to a higher density, which leads to higher strength.
2. It does not require specialized equipment.
3. It requires no soil additives.

Disadvantages:
1. It requires available fill material.
2. The high volume of excavation can be costly.
3. Even after excavation, the underlying and adjacent expansive soils often must be protected by horizontal or vertical membranes.

2.3.1.2 Remolding and Compaction

Remolding and compaction is defined as excavating the expansive soils to a prescribed depth, determined based on the active zone depth, and re-compacting the same soil to a desired density. Remolding and compacting a soil at a moisture content higher than optimum and with a lower density than the maximum dry density results in less swelling (Dubose 1955, Petry & Little 2002).

Advantages:
1. This method is economical for soils with low swelling tendency, high dry density, and low initial water content.

Disadvantages:
1. If the active zone depth of the expansive soil is too deep, a drainage system to minimize access of water to the underlying unmolded expansive soil is often necessary.
2. Careful control of density and water content are required.
3. This method minimizes, but does not prevent, swelling/collapse.

2.3.1.3 Surcharge Loading

Swelling can be prevented by applying a pressure to the soil that is greater than the swelling pressure (Ardani 1992).

Advantages:
1. This method is good when the expansive soil has low tendency to swell or the overlying structure is heavy.

Disadvantages:
1. Determining the active zone is needed to evaluate the maximum potential swell pressure.
2. This method is only applicable for low to moderate expansive clays (Petry & Little 2002).
3. This method is not effective for lightly loaded structures, such as highways, because the loads from these structures are not sufficient to exceed the swell pressure of most expansive soils.

2.3.1.4 Pre-wetting

Pre-wetting involves ponding of water on the expansive soil to induce initial swelling. This reduces the soil's tendency to swell in the future. This method is more effective for desiccated clays in dry and hot seasons. To facilitate water percolation, sand drains can be drilled in the soil vertically to lessen the time required to provide sufficient water.

Advantages:
1. Pre-wetting can be highly effective for desiccated soils.
2. Pre-wetting can be the most economical expansive soil treatment method if done well (Ardani 1992).

Disadvantages:

1. A long period of time, up to two years, is required to increase the water content of the expansive soil effectively.
2. If not combined with an additive, such as lime, the soil may not be workable and meet strength requirements.
3. Protection of the surface from evaporation is required to prevent shrinkage. Polyethylene sheets can be used after water is injected to the desired depth of the expansive soil to retain moisture (Petry & Little 2002).
4. Uncertainty in specifying a reasonable time of ponding and determining the active zone diminishes the usefulness of this method (Ardani 1992).

2.3.1.5 Horizontal Barriers

Moisture barriers are horizontally placed to prevent moisture migration to the expansive soils (McDonald 1973). These barriers are typically polymeric geomembranes. Horizontal barriers are typically constructed around buildings or used in highway shoulders. These barriers remove the source of soil swelling (i.e., addition of moisture).

Advantages:

1. Horizontal moisture barriers are effective in preventing moisture intrusion into a specific area.
2. Horizontal barriers do not require extensive excavation or reworking of existing soils.

Disadvantages:

1. The length of horizontal barriers must be sufficient to prevent moisture intrusion.
2. Proper techniques are required to attach the barriers to the building foundations.
3. Barriers can be easily damaged during placement and may be damaged by vegetation.
4. Slopes are required for the barriers to provide proper drainage.
5. The swelling potential of the soil will remain the same after installing horizontal barriers.

2.3.1.6 Vertical Barriers

Vertical barriers are placed vertically to prevent moisture migration to expansive soils and are typically used in conjunction with horizontal barriers. Vertical barriers can be constructed from asphalt, lean concrete, polyethylene, or by creating capillary barriers using adjacent dissimilar soils. Vertical barriers should be installed to at least half of the active zone of expansive soils. These barriers remove the source of soil swelling (i.e., addition of moisture).

Advantages:

1. Vertical moisture barriers prevent lateral moisture intrusion into a specific soil volume.

Disadvantages:

1. The backfill materials must be impervious to prevent water accumulation, which can be uneconomical.
2. The swelling potential of the soil will remain the same after installing vertical barriers.

2.3.1.7 Membrane Encapsulated Soil Layers (MESL)

Membrane encapsulated soil layers (MESL) are moisture barrier soil-membranes. MESL are sometimes used with lime and fly ash additives to prevent expansive soils from absorbing moisture (Stark et al.

2000). For highway construction, MESL is applied over the subgrade and then bent at the ends vertically to a depth of 3 to 4 feet (Falk & Hager 1994) to form both a horizontal and vertical barrier.

Advantages:

1. This method deactivates any moisture migration into the soil.
2. It can be economical for low expansion soils. For high expansion soils, even one puncture in the MESL may allow enough water to reach the soil and cause failure of the MESL with high swelling clays.
3. It can be more effective than soils stabilized with lime in preventing swelling.

Disadvantages:

1. The swelling potential of the soil will remain after installing MESL.
2. This method is not economical for deep highly expansive soils.
3. The MESL material must be strong enough to withstand potential damages during placement from folds and wrinkles (Falk & Hager 1994).

2.3.1.8 Asphalt Treatment

Asphalt treatment involves adding asphalt layers on expansive soils to prevent moisture migration.

Advantages:

1. It is easier to fix asphalt failures than failures associated with cement.

Disadvantages:

1. Asphalt must be applied in a continuous manner on subgrades and ditches (in highways) to prevent localized wetting.

2.3.1.9 Electrochemical Soil Treatment

Haussmann (1990) defined electro-osmosis as the pulling out of moisture from soils using an electrical potential. Brandon et al. (2009) mention that using electro-osmosis can accelerate flow from the soil when drainage is required or into the soil when applying another stabilizer, such as aluminum. The latter is called electro-kinetic treatment.

Advantages:

1. This method dewaters and hardens expansive soil by providing a high concentration of desired exchangeable cations.
2. By placing electrodes into the expansive soil, desired stabilizing solutions can be transferred into the soil.

Disadvantages:

1. Skilled labor is required to apply treatment.
2. This method is typically not economical.

2.3.1.10 Explosive Treatment for Expansive Shales

This method is similar to excavation and re-compaction of the same soil except that, instead of using heavy equipment, the soil is exploded to restructure the expansive soil layers. Explosives used are typically dynamite or ammonium nitrate and fuel oil mixtures (ANFO).

Advantages:
1. This method can be less costly than removal and replacement.

Disadvantages:
1. Skilled labor, careful drill procedures, and precise calculation of explosive charges are required (Ardani 1992).

2.3.2 Chemical Treatments

Swelling of expansive soils can be reduced (i.e., soil stabilization can be achieved) by adding materials that 1) reduce the affinity of the clay to water, 2) bond the clay particles together (Inyang et al. 2007), and 3) reduce the access of water to the soil. The following are commonly used chemical treatments in the United States.

2.3.2.1 Lime Treatment

Quicklime (CaO) treatment relies on the cementitious properties of CaO. Lime inclusion improves the soil strength, compressibility, and swelling. In the late 1960s, lime treatment became, and remains, the most widely used method by U.S. DOTs (National Lime Association 1991). Lime for soil stabilization is categorized as quicklime and hydrated lime. Lee (1989) suggested that quicklime slurries can be more beneficial than hydrated lime slurries. Calcareous soils with more than 15% calcium carbonate ($CaCO_3$) and alkaline soils react well with lime. A lime proportion of 2% to 10% and a mixing depth of 1 to 2 feet can be effective in stabilizing soils.

Advantages:
1. Lime can increase unconfined compressive strength and produce stable soils that can resist swelling and collapse.
2. Lime can be used dry when enough water is available in the soil or can be used as a slurry. Before applying lime, leaving the mixed lime for a few days after the final mixing is effective in increasing workability and compaction.
3. Lime can improve pozzolanic reactions and reduce leaching of calcium from expansive soils (McCallister and Petry 1990).

Disadvantages:
1. A curing temperature of over 21°C is required for up to two weeks to produce proper soil strength.
2. Some components in the lime-treated soils, such as organics, carbon dioxide, iron compounds, and sulfate, can slow the pozzolanic reactions of lime leading to strength loss (Mitchell 1986). The source of sulfate in soils could be soil minerals and water. Calcium and aluminum in the treated soil react with soluble sulfates and produce ettringite, which causes expansion (Majeed et al. 2014).
3. Soil-pH tests are required to determine the percentage of lime needed.
4. The degree of pulverization of quicklime can often be difficult to control. Quicklime needs good pulverization to facilitate the pozzolanic process (Petry & Little 2002).

1. Water, either surface or groundwater, should be prevented from saturating the soil; saturation of lime-treated soils causes the lime to leach, thereby reducing treatment effectiveness.
2. Lime has been shown to substantially increase hydraulic conductivity of treated soils (Majeed et al. 2014).

2.3.2.1 Fly Ash Treatment

Fly ash is primarily composed of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and calcium oxide (CaO), although the property and composition of fly ash is dependent upon the coal fired. Inclusion of fly ash into an expansive soil decreases plasticity index, hydraulic conductivity, swell potential ($S\%$), and swell pressure (P_s) depending on the amount of the fly ash added. Fly ash also increases dry unit weight, shear strength, and resistance to penetration of the treated soils. Kumar and Sharma (2004) found a 20% fly ash content, which may not be practical for enhancing the mentioned properties.

<u>Advantages:</u>

1. For silty soils, fly ash can be effective in increasing pozzolanic reactions.
2. Fly ash can also solve problems associated sulfate bearing lime-treated soils (McCarthy et al. 2009).

<u>Disadvantages:</u>

1. Fly ash often requires combination with lime or other pozzolans.
2. The cost of self-cementitious Class C fly ash is relatively higher than the other types of fly ash that require supplemental additives (such as lime or cement).

2.3.2.2 Cement Treatment

Similar to lime treatment, cement treatment involves inclusion of an amount of cement (dry or slurry) into the top layer of expansive soils. In the early 1970s, the Portland Cement Association showed that Portland cement could be effective in reducing swelling of soils having low to moderate plasticity. A cement proportion range of 4% to 6% could be effective in stabilizing soils.

<u>Advantages:</u>

1. Generally, cement treatment gives more strength to soils than the other methods.
2. This method can be more effective than lime in minimizing shrinkage.
3. Less time is required between applying cement treatment and final mixing for reactions to occur.
4. For soils that are not lime reactive, Portland cement is a good alternative.

<u>Disadvantages:</u>

1. Portland cement treatment is less effective than lime for clays with high plasticity.
2. Cement may cause the stabilized soils to crack more easily.
3. More energy is required to produce cement from limestone than lime.

2.3.2.3 Salt Treatment

Salt treatment includes adding salt solutions, such as $CaCl_2$ or NaCl, into expansive soils to decrease the clay activity. Brandon et al. (2009) state that adding salt changes the ionic composition of the clay and densifies the soil particles, thus leading to greater strength and reduced swelling.

<u>Advantages:</u>

1. For soils having high sulfur content, salts ($CaCl_2$) are good alternatives to lime stabilizers.
2. Salts reduce the freezing and thawing effect on expansive soils, as salts make the soil freeze at a lower temperature (Brandon et al. 2009).
3. Singh and Das (1998) showed that NaCl increases unconfined compressive strength and CBR of treated soils.

Disadvantages:

1. The only two salt types that can be used economically for soil stabilization are NaCl and $CaCl_2$.
2. Salts can leach easily from the stabilized soils, adversely affecting the stability of the soils.
3. Relative humidity as high as 30% should be maintained before salt is applied.

2.3.2.4 Organic Compounds Treatment

Organic compounds have been tested to stabilize expansive soils but have not been effective or practical for field application (Petry & Little 2002). For example, Trembly et al. (2002) tested organic compounds with cement to test if mixtures increase the strength of a fine-grained soil. Tremblay et al. (2002) found that no considerable change of strength was seen; however, the mixture increased soil pH and SO_4 concentration in the soil, which is indicative of cementing effectiveness. Enzymes are also among the organic treatment methods that have been tested to stabilize expansive soils (Scholen 1992). Tingle and Santoni (2003) found no strength improvement in soils treated with enzymes.

Advantages:

1. Enzymes have large positive charges that causes the negatively charged clay surfaces to neutralize, and have less tendency to react with water, thus, theoretically, making the soil more stable (Scholen 1992).

Disadvantages:

1. Organic compounds have low diffusion rates into expansive soils limiting the effectiveness of the treatments.
2. Many organic compounds are not soluble in water. This insolubility in water may result in decreased reactivity and lower effectiveness.
3. Compared to lime and other treatment technologies, organic compounds have shown inferior stabilizing effectiveness (Petry & Little 2002).

2.3.2.5 Polymer Treatment

The exact composition of polymers used in stabilization is generally undisclosed, and only the brand name is provided. Researchers tested various types of polymers for soil stabilization, some of which are commercially available (and some of which are not). Two types of polymers are generally available to stabilize soils: natural polymer and synthesized polymer (Brandon et al. 2009). Most commercially available polymers are synthesized polymers. Brandon et al. (2009) state that polymer glues the soil particles together and creates a more stabilized system. Azzam (2014) shows the effect of polymer in creating a nano-composite structure giving the soil more strength and resistance to volume change.

Advantages:

1. Polymers increase unconfined compressive strength and reduce Atterberg limit, swell potential, swell pressure, and hydraulic conductivity (Azzam 2012).
2. Unlike lime and fly ash, polymers do not require curing, thus requiring shorter construction times.

Disadvantages:

1. The effectiveness of commercially available polymer treatments is largely unknown.
2. Natural polymers may have leaching and degradation problems.
3. The cost of polymer is generally higher than lime (Brandon et al. 2009).

3. STATE OF PRACTICE IN MOUNTAIN-PLAINS REGION

Prior to testing, a survey of expansive soil treatment methods used by state departments of transportation (DOTs) in the Mountain-Plains region (Colorado, Montana, North Dakota, South Dakota, Utah, Wyoming) was conducted to identify the state of practice in expansive soil mitigation for roadway applications. DOTs in the Mountain-Plains region were selected based on the prevalence of moderate and high swelling potential soils across much of the region (Olive et al. 1989). Six state DOTs were solicited for the survey and five states responded. Each state DOT was asked to respond to the following seven statements and questions; state-by-state survey results are provided in Appendix A.

1. List methods your DOT uses to identify expansive soils. How does your DOT decide on the severity of expansive soils based on your identification methods?

2. List any remedial measures that your DOT has ever taken to eliminate or mitigate swelling problems.

3. Identify and describe the mitigation techniques that have worked best.

4. Identify and describe techniques that have not worked, or that your DOT no longer uses.

5. Provide the names or links of the document guidelines that your DOT uses in dealing with expansive soils.

6. Does your DOT use polymer as a stabilization technique? If yes, please explain why? What is the manufacturer/company that provides the polymer for your DOT?

7. Please provide any additional comments/suggestions.

Based on the state-of-practice survey, the two primary physical techniques used to mitigate expansive soils are removal and replacement (5 of 5 DOTs surveyed) and remolding and compaction (3 of 5 DOTs surveyed). Lime (5 of 5 DOTs surveyed) and fly ash (2 of 5 DOTs surveyed) are the most commonly used chemical treatments but were less commonly used than physical techniques. Based on these findings, lime and fly ash were selected for comparative testing with commercially available polymers. When the survey was taken in 2016, commercial polymers were not used for mitigation of expansive soils by any of the DOTs surveyed.

4. METHODS

Atterberg limit, standard Proctor compaction, one-dimensional swelling, unconfined compressive strength, and saturated hydraulic conductivity tests were used to evaluate untreated (baseline) and treated expansive soil. All soil was air-dried and passed through a number 40 sieve prior to specimen preparation. Lime and fly ash treated specimens were prepared according to the ASTM standard procedures for each test and were manually mixed at specific mixing ratios (described in Materials) in an air-dry condition until no heterogeneity and particle segregation was visually observed in the mixture. For the Atterberg limit tests, water was added to determine the liquid limit and plasticity index; for the one-dimensional swell, unconfined compressive strength, and hydraulic conductivity tests, water was added and soils were compacted to reach (standard Proctor) optimum moisture content and maximum dry density.

Polymer solutions were also tested as bulk treatments and all sieving, compaction, and curing procedures applied to lime and fly ash treated soils were repeated; however, moisture addition and mixing was performed differently because, unlike lime and fly ash, commercial polymers were supplied dissolved in water. Therefore, polymer solutions were mixed (diluted) with a designated amount of water needed to achieve the test target moisture content (i.e., optimum moisture content). The diluted polymer solution was then added to the sieved air-dry expansive soil by spraying while simultaneously manually mixing with a spatula until a visually homogeneous paste was formed.

4.1 Atterberg Limits

Atterberg limits were performed in accordance with ASTM D4318-00 (ASTM 2000) and were run immediately after mixing with no curing period. Atterberg limits were used for preliminary swell prediction based on FHWA-RD-77-94 (Snethen et al. 1977) to select polymer stabilizers that had a maximum impact on predicted specimen swelling.

4.2 Standard Proctor Compaction Test

Standard Proctor compaction tests were performed in accordance with ASTM D698-12 (ASTM 2012) to prepare specimens for swelling, unconfined compressive strength, and hydraulic conductivity testing at maximum dry density and optimum water content for each soil. Compaction at maximum dry density and optimum water content is similar to, but slightly denser than, typical compaction criteria for over-excavation and re-compaction in practice (e.g., CDOT 2011).

4.3 One-Dimensional Swell Tests

To assess the effects of treatments on swelling, one-dimensional swelling tests were performed in accordance with ASTM D4546-14 (ASTM 2014) following Method A (for reconstituted specimens). After preparation at optimum water content and maximum dry density, soil specimens within odometer rings were wrapped in plastic and cured for seven days at 40°C; curing at 40°C was performed to achieve accelerated curing as described in ASTM D5102-09 (ASTM 2009). Excess pore water pressure was not measured during testing; however, excess pore water pressure was inferred to have dissipated by the end of the swell test based on continuation of tests until no continued deformation (swell/collapse) was measurable over a four-day period.

4.4 Unconfined Compressive Strength Tests

Unconfined compressive strength was measured in accordance with ASTM D5102-09 (ASTM 2009) to assess the effect of treatments on soil strength. The strain-controlled method for brittle specimens was used with an axial strain rate of 2.0% per minute. Test specimens were prepared in a cylindrical plastic split-mold with a diameter equal to a standard compaction mold (101.6 mm) and a height equal to double a standard compaction mold (232.9 mm) and used in accordance with ASTM D5102-09, Procedure A (ASTM 2009). Soils were compacted in six layers with 25 blows per layer to meet the standard compaction effort. The cylindrical split-mold was lined with plastic wrap to facilitate removing specimens and wrapping them along the long axis for subsequent hydration and cure. After compaction and removal from the mold, soil specimens were wrapped in plastic and cured for seven days at 40°C. Specimens were then placed on porous stones in a pan of tap water and soaked for 24 hours, during which the water level in the pan was maintained at the top of the porous stone. Three specimens were performed for each treatment and the mean of each is reported herein.

4.5 Hydraulic Conductivity Tests

Saturated hydraulic conductivity tests were performed in flexible-wall permeameters in accordance with ASTM D5084-16a (ASTM 2016), Method C (falling headwater, rising tailwater elevation) to assess the effect of treatment on moisture movement. The specimen preparation and compaction method described in Tong and Shackelford (2016) was used in this study, and included a specimen height of 29.3 mm and diameter of 101.6 mm. Compaction was accomplished in a single layer with 19 blows of a standard Proctor compaction hammer to achieve the standard Proctor compaction energy. Hydraulic conductivity tests were performed such that the applied effective stress was equal to the soil swelling pressure, as per ASTM D5084-16a, to minimize any volume change during testing. Tap water from Fort Collins, Colorado, was used as the permeant solution.

5. MATERIALS

5.1 Expansive Soil

A highly expansive soil was created for this study from a local clay blended with 15% (dry mass basis) natural sodium bentonite. Characteristics of the local "base" clay and the expansive soil are in Table 5.1. The base clay was a low plasticity clay (*LL* = 31.0; *PL* = 18.1) from Fort Collins, Colorado, and the natural sodium bentonite was a high plasticity clay (*LL* = 420; *PL* = 381) from Wyoming (the natural sodium bentonite used is characterized in detail in Bohnhoff and Shackelford 2014). The highly expansive soil was used for all tests; for brevity, this soil is described as "expansive soil" henceforth. Base clay was only used for polymer-as-physical-treatment tests described in Section 5.6. Characteristics of base clay are also included in Table 5.1.

Table 5.1 Results of characterization and treatment of untreated and treated expansive soil after 7-day cure at 40ºC cure

Test	Units	Base clay	Expansive soil	Lime (3%) treated	Fly ash (15%) treated	P4 polymer (5%) treated
Liquid limit, *LL*	[%]	31.0	75.8	50.5	56.4	70.3
Plastic limit, *PL*	[%]	18.1	17.7	32.6	17.6	19.5
Plasticity index, *PI*	[%]	12.9	58.1	17.9	38.8	50.8
Optimum water content, $w_{\%opt}$	[%]	16.1	18.4	20	17.5	19.4
Maximum dry density, $\rho_{d\,\max}$	[kg/m^3]	1797	1680	1618	1650	1658
Swell potential, $S_{\%}$	[%]	0.3	14.9	0	0.5	4.5
Swell pressure, p_s	[kPa]	8.0	139	2	33	120
Unconfined compressive strength (UCS), q_u	[kPa]	142	~0	1260	382	46
Hydraulic conductivity, *k*	[m/s]	1.8×10^{-9}	2.9×10^{-11}	1.5×10^{-6}	3.1×10^{-8}	7.2×10^{-11}
Effective stress for k, σ'	[kPa]	8.0	139	7	33	120

5.2 Lime Treated Soil

Three treatment percentages of quicklime (CaO) were mixed with expansive soil to create lime-treated soil mixtures. A 3% (by solid mass) quicklime addition was chosen based on the range provided by Akawwi and Al-Kharabsheh (2002) for testing with a 7-day cure. Characteristics of 3% quicklime treated expansive soil are presented in Table 5.1.

5.3 Fly Ash Treated Soil

Fifteen percent (by solid mass) Class C fly ash (ASTM C618-15; ASTM 2015) was added to create fly-ash-treated soil mixtures. A 15% fly ash addition was selected based on American Coal Ash Association (2003) guidance. Characteristics of 15% fly ash treated expansive soil are presented in Table 5.1.

5.4 Commercial Polymers

Four commercially available polymers were considered for testing. Polymers are denoted henceforth as P1, P2, P3, and P4. P1 is a vinyl copolymer, which is claimed by the manufacturer to be both a soil stabilizer and dust controller. P2, P3, and P4 are also vinyl copolymers, and are claimed to be soil stabilizers. The exact composition of these polymers is proprietary. Polymers were received as milky white liquids containing polymer hydrated in water. Drying of these polymers at 40°C revealed P1, P2, P3, and P4 contained 55.0%, 57.5%, 57.5%, and 37.0% (by mass) polymer solids, respectively. The viscosity of P1, P2, P3, and P4 are ~1000 centipoises (comparable with castor oil). All polymers were transparent once cured. Based on manufacturer safety data sheets: P1 was composed of 55% (by weight) synthetic vinyl copolymer dispersed in 45% water, P2 was composed of (by weight) 1% to 5% polyethylene glycol octyl phenoxy ether and 1% to 5% polyethylene glycol octyl phenyl ether dispersed in water, P3 was composed of 20% to 60% vinyl copolymer and 40% to 80% water, and P4 was composed of (by weight) 39% to 43% acrylic copolymer and 57% to 61% water with less than 0.1% residual monomer. P4 was selected for this study because of the high effectiveness of P4 from preliminary swell tests (discussed in Results). A photograph of as-received P4 is shown in Figure 5.1. A 5% (by soil solid mass) P4 treatment was used based on manufacturer recommendations for "heavy use" to create P4-treated soil mixtures.

Figure 5.1 Photograph of as-received P4 (liquid) in a porcelain evaporating dish

6. RESULTS

6.1 Preliminary Swell Tests for Selecting Treatment Addition/Type

Preliminary swell tests were performed to identify sensitivity to selected treatment levels of lime and fly ash and to select a polymer type among P1, P2, P3, and P4. An advertised advantage of commercial polymer stabilizers is the lack of required curing time; therefore, all of these preliminary swell tests were performed after a 24-hour air-drying/curing (at 20°C) period.

Quicklime additions of 2%, 3%, 4%, 5%, and 6% (by solid mass) were tested. The effect of quicklime addition percentage after a 24-hour air drying period prior to swell testing at each treatment level is shown in Figure 6.1. Swelling potential was generally insensitive to lime treatment level across the range tested. Similarly, Class C fly ash addition ratios of 9%, 11%, 13%, 15%, and 17% (by solid mass) were tested. Additional replicate tests were performed at fly ash addition ratios of 11 (number of tests, $n = 2$), 15 ($n = 3$), and 17% ($n = 2$) to test repeatability of the swell test. The effect of fly ash addition percentage after a 24-hour air drying period prior to swell testing is shown in Figure 6.1. Swelling potential was generally insensitive to fly ash treatment level across the range tested and was within the repeatability of a maximum of 0.6% measured at a 15% treatment level. Thus, this study focused on constant amendment percentages of fly ash (15%) and lime (3%) to assess swell potential, swell pressure, unconfined compressive strength, and hydraulic conductivity.

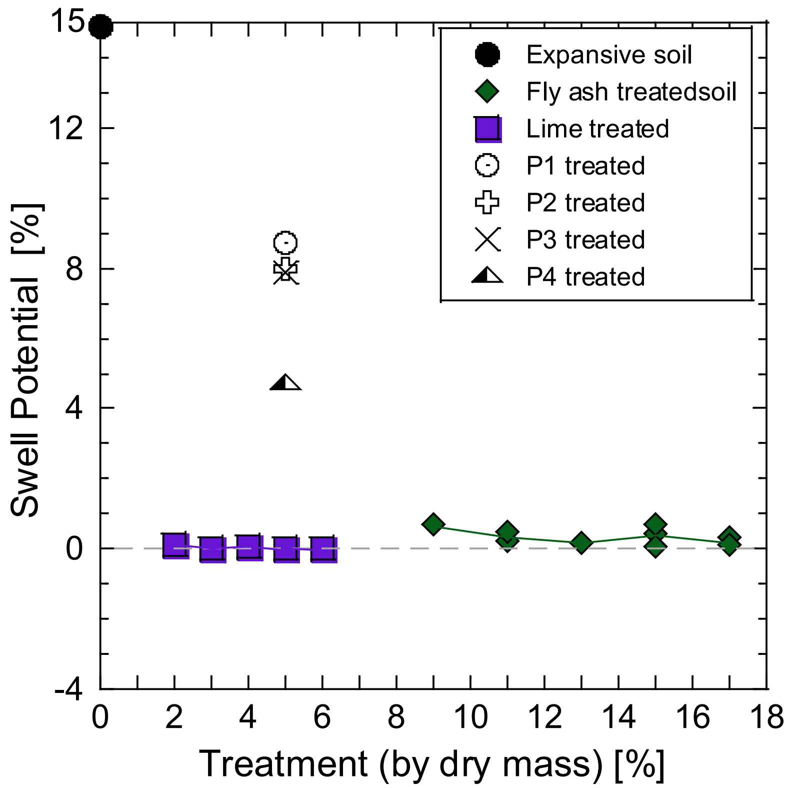

Figure 6.1 The swell potential of untreated expansive soil (control), fly ash, lime, and polymer treated expansive soil at varying treatment percent (by solid mass) for 24-hr air drying

The results of one-dimensional swell tests performed on P1, P2, P3, and P4 treated expansive soil are also presented in Figure 6.2. Specimens were allowed to air-dry for 24 hours prior to testing. Expansive soil treated with polymers P1, P2, P3, and P4 swelled 8.7%, 8.0%, 7.9%, and 4.7%, respectively. Based on these findings and the lower polymer content in P4, P4 was selected for further comparative testing; additional tests on P1, P2, and P3 were not performed.

6.2 Swell Potential and Swell Pressure

Results from one-dimensional swell tests (swell potential and swell pressure) are shown in Figure 6.3 and summarized in Table 5.1. Swell potential is defined in ASTM D4546-14 (ASTM 2014) as a positive strain that specimens experience under 1 kPa. Swell pressure is defined as the pressure under which specimens exhibit zero strain upon inundation. Lime and fly ash were effective at reducing swell potential (to < 1 %) and swell pressure (to < 35 kPa) of the expansive soil tested [similar effectiveness was also concluded by Basma and Tuncer (1991) and Cokca (2001)]. Relative to lime and fly ash, P4 did not considerably reduce swell potential and swell pressure, exhibiting a swell potential reduction from 14.9% (untreated) to 4.5% (P4 treated) and a swell pressure reduction from 139 kPa (untreated) to 120 kPa (P4 treated); P4 was less effective than lime or fly ash at reducing swelling of the expansive soil (Figure 6.2).

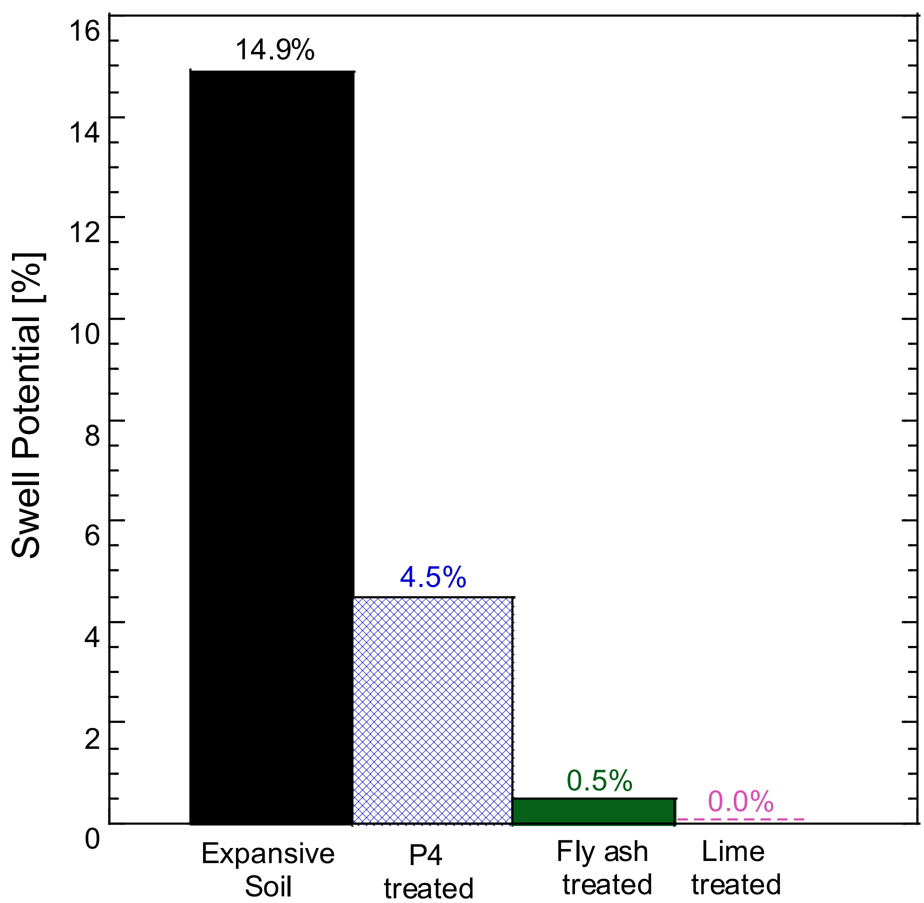

Figure 6.2 The swell test results for treatment methods

Swell reduction effectiveness for both swell potential and swell pressure is defined as the percentage of the swell value for untreated expansive soil minus the swell value for the stabilized expansive soil divided by the swell value for untreated expansive soil. For example, the swell potential of the expansive soil tested with 3% lime decreased from 14.9% to 0.0%, and the swell pressure decreased from 139 kPa to 2 kPa; thus, reduction effectiveness of lime was 100% for swell potential and 99% for swell pressure.

Similarly, the swell reduction effectiveness of fly ash was 97% for swell potential and 76% for swell pressure. In contrast, the swell reduction effectiveness of P4 was 70% for swell potential and only 14% for swell pressure.

6.3 Unconfined Compressive Strength

Unconfined compressive strength tests were conducted to assess the effect of each stabilizer on compressive strength of expansive soil and 7-day-cured treated soils; results are shown in Figure 6.3 and summarized in Table 5.1. The lime treated soil exhibited the greatest unconfined compressive strength (1260 kPa) followed by fly ash treated soil (382 kPa); these results were consistent with past studies [similar to results presented in Anday (1961), Diamond and Kinter (1965), Little (1999), and Bhuvaneshwari et al. (2005)]. The P4 treated specimens exhibited low strength after 24-hour soaking, with a measured unconfined compressive strength of 46 kPa. Untreated expansive soil had insufficient strength for measurement of unconfined compressive strength.

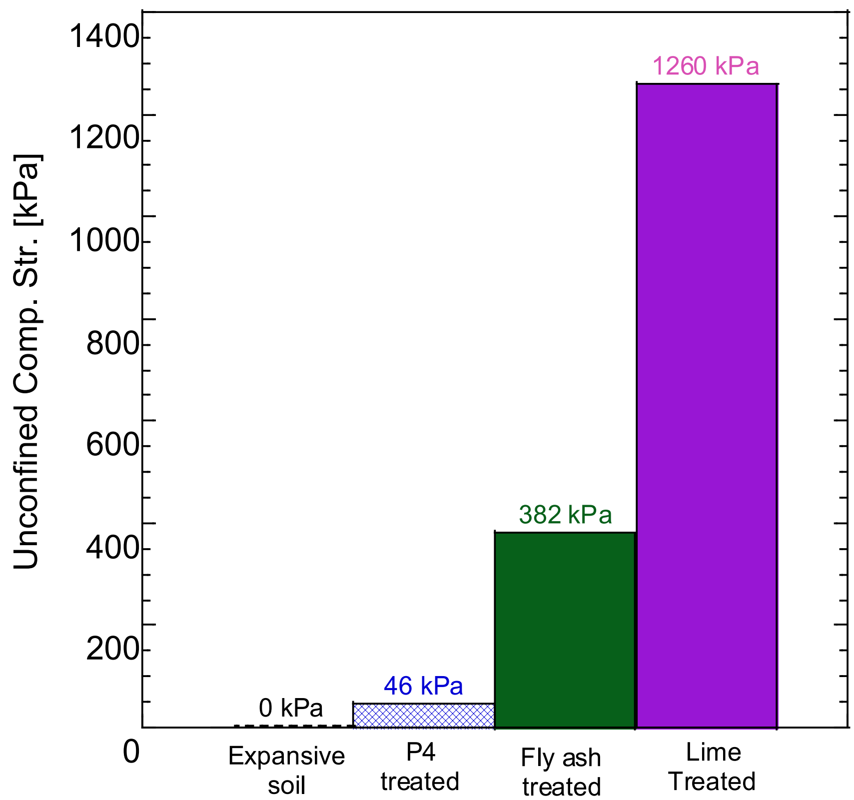

Figure 6.3 Unconfined compressive strength for treated and untreated expansive soil

6.4 Hydraulic Conductivity

The results of hydraulic conductivity tests are shown in Figure 6.4 and summarized in Table 5.1. Specimens were tested under effective stresses equal to swell pressure to minimize volume change from specimen saturation (for lime, a minimum effective stress of 7 kPa was used based on the minimum maintainable pressure of the pressure panel used). Lime and fly ash treated expansive soil exhibit high hydraulic conductivity (1.5×10^{-6} and 3.1×10^{-8} m/s, respectively). This behavior is hypothesized to be due to agglomeration of particles into clods (Benson and Daniel 1990, Alhomair et al. 2017) in combination with the effectiveness of lime and fly ash treatments at preventing swelling (Figure 6.2), thus allowing inter-clod preferential flow paths within the soil to remain unsealed. As shown in the plot between pore volume of flow and hydraulic conductivity in Figure 6.5, fly ash treated soil exhibits a hydraulic conductivity 50 times lower than that of lime treated soil, which correlates with swell potential differences of lime and fly ash. Treatment with P4 resulted in a 20,000-times lower hydraulic conductivity than treatment with lime, and a 400-times lower hydraulic conductivity than that of fly ash. However, the hydraulic conductivity of P4 treated soil was still two times higher than untreated expansive soil (2.9×10^{-11} m/s).

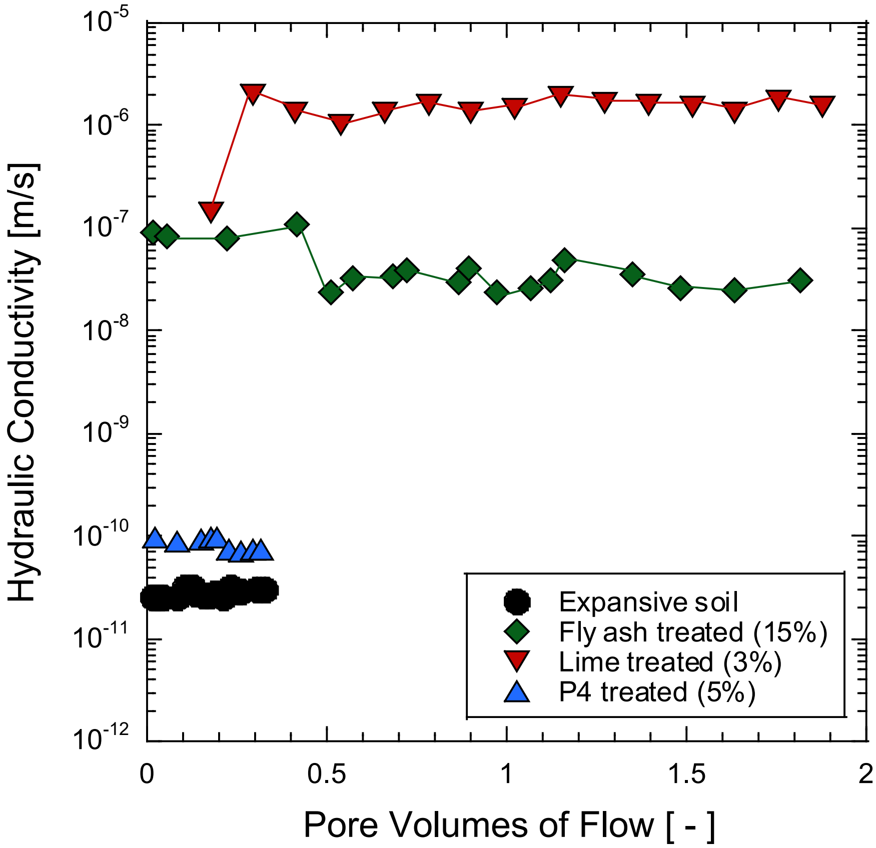

Figure 6.4 Hydraulic conductivity for treated and untreated expansive soil

6.5 Effect of Curing Time

One potential advantage of commercially available polymers is that they do not require a long curing time to be effective, whereas a curing time is required for lime and fly ash treated soils. To evaluate this effect, swelling potential of specimens prepared by 24-hour air drying are compared to 7-day cured specimens in Figure 6.5. Seven-day curing resulted in reductions in swelling potential from 0.8% to 0.0% (100% reduction) for lime and 3.1% to 0.5% (84% reduction) for fly ash treated expansive soil. However, the P4 treated soil showed little improvement between 24-hour air dried and 7-day cured conditions (4.7% to 4.5%; 4% reduction). Thus, although swelling reduction occurs more rapidly with P4 because the magnitude of swelling reduction is lower, curing time does not appear to be a substantial advantage for the polymer and soil tested herein.

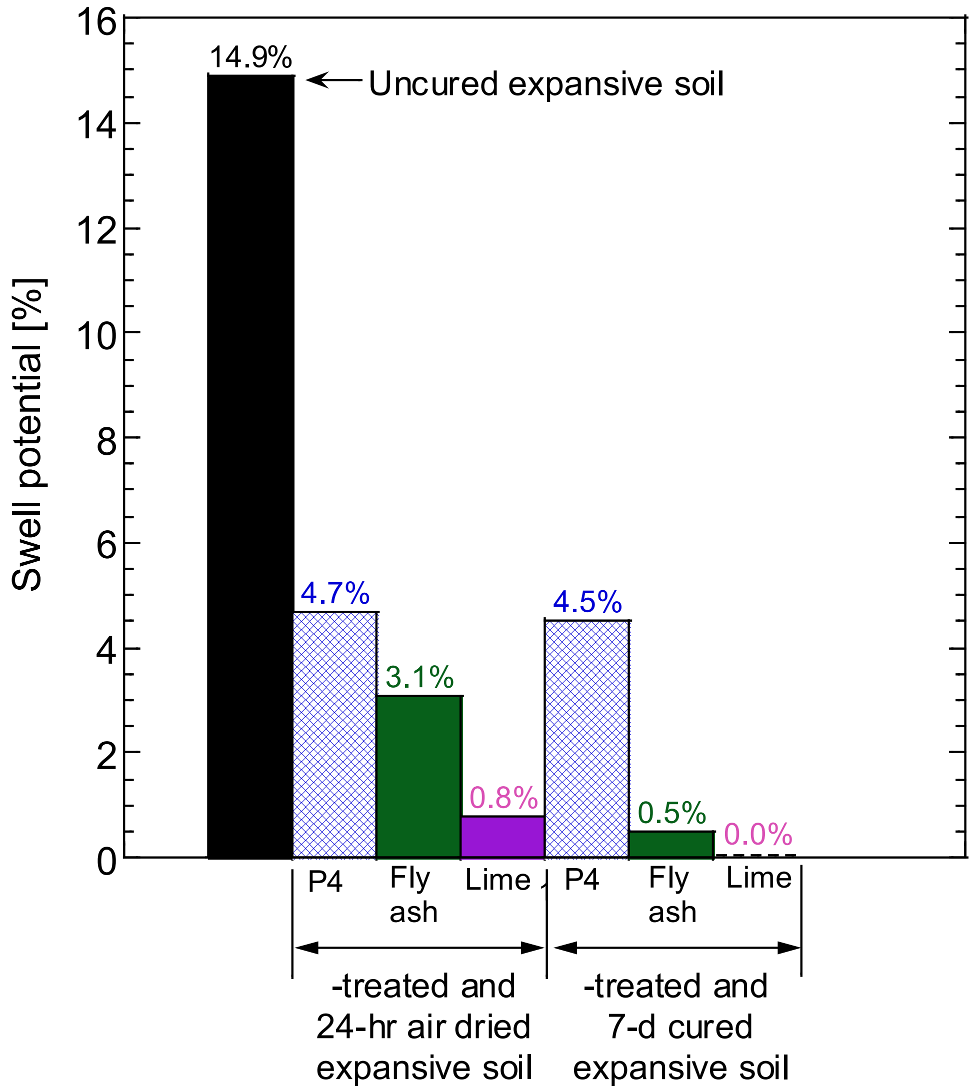

Figure 6.5 Swell potential for treated and untreated expansive soil at 24-hr air drying and 7-day curing

6.6 Polymer as a Physical Treatment

The effect of a spray-on layer of polymer (i.e., polymer coating) was used to evaluate the effectiveness of polymer "stabilizers" as a physical treatment rather than as a chemical stabilizer. Tests were conducted on base clay due to the high hydraulic conductivity of this soil relative to the expansive soil tested. Specimens were prepared by manually spraying a polymer solution across the surface of the specimen with a 500-mL plastic spray bottle. The sprayed-on surfaces were then allowed to air-dry at 20°C prior to assembly in a flexible wall permeameter and testing. The following hydraulic conductivity tests were performed: 1) untreated base clay (as a control), 2) base clay coated on bottom face (inflow end) with 2.0% P4 by solid mass, and 3) base clay coated on bottom face with 0.6% P4 by solid mass. These percentages (i.e., 2.0% and 0.6%) were calculated from the manufacturer's recommended rate of P4 volume per surface area based on use for soil stabilization (0.8 L/m^2) and dust control (0.2 L/m^2).

The results of hydraulic conductivity tests to evaluate polymer coating as a physical stabilizer are presented in Table 6.1. Specimens coated with 2.0% or 0.6% P4 had no measurable flow over one day corresponding to a maximum hydraulic conductivity 1.9×10^{-12} m/s (i.e., considering the precision of the graduated burette in the hydraulic conductivity test was $\pm$ 0.05 mL). Thus, an intact polymer coating was highly effective at reducing flow.

Table 6.1 Effect of polymer coating on water flow through base measured in a flexible wall permeameter

Coating description	Hydraulic conductivity, k [m/s]	Effective stress to swell pressure ratio, σ'/p_s [-]	Pore Volume of flow, PVF [-]	Outflow to inflow ratio, Q_o/Q_i [-]
Base clay (control)	4.5×10^{-9}	1.0	0.77	1.1
Base clay fully coated with 2.0% P4	Not measurable → no flow	1.0	0	Undefined
Base clay fully coated with 0.6% P4	Not measurable → no flow	1.0	0	Undefined

7. DISCUSSION

The objective of this study was to assess if commercially available polymer stabilizers were as effective as traditional stabilizers for expansive soil shrink-swell reduction. In terms of effectiveness as a stabilizer, polymer treatment was substantially less effective at reducing swell potential and swell pressure, and increasing unconfined compressive strength compared with fly ash treatment or lime treatment (Figures 6.3 and 4). In contrast, use of polymer as a stabilizer resulted in a smaller increase in hydraulic conductivity relative to a comparatively larger increase with fly ash and lime treatment (Figure 6.5). Furthermore, although fly ash and lime treatment substantially reduced swelling and increased strength, the compacted non-stabilized soil (analogous to over-excavation and re-compaction) was most effective at preventing moisture ingress due to the low hydraulic conductivity.

Consistent with the results of the DOT survey provided in Supplemental Material, there is no clear "superior" treatment technology. For example, while lime may substantially improve strength and reduce swelling of a treated expansive soil layer, the higher hydraulic conductivity may lead to increased percolation and swelling of underlying untreated layers. The ultimate effectiveness of a given treatment technology will depend on site-specific conditions (including runoff/run-on, evapotranspiration, and thickness of expansive soil layer).

Based on the findings in this study, practitioners working in transportation geotechnics should consider polymer-based soil additives as a candidate tool to create an encapsulating hydraulic barrier (physical stabilizer) around expansive soil to minimize moisture ingress, potential volume change, and strength reduction with wetting. Use of P4 as a coating hydraulic barrier layer enables substantial reduction in percolation, similar to the use of an encapsulating geomembrane, but unlike a geomembrane laid atop a prepared clay layer, sprayed-on polymer coating holds the advantages of perfectly intimate contact reducing the impact of any holes in the barrier (Giroud and Bonaparte 1989; Foose et al. 2001), and potentially easier installation. However, the sprayed-on polymer coating is substantially thinner than a geomembrane and is therefore more likely to be punctured, although given the intimacy of contact the effect of punctures may be minimal. The sprayed-on coating of P4 used in this study was effective under ideal conditions (in the laboratory). Use of commercially available polymer coatings for seepage mitigation warrants further investigation and should be of paramount consideration when evaluating the use of commercially available polymers for treatment of expansive soils.

The results presented are only valid for the high swelling expansive soil described in this study and laboratory tests conducted and may not represent field behavior. Given the complex interplay between moisture ingress and swelling reduction, future assessment of polymer treatment technologies should incorporate test methods that model the hydration-swell process that occurs in the field. Spraying of polymer on undisturbed soil and relying on the unconfined compressive strength of a dry(er) subgrade may also better represent field behavior but cannot be representatively tested with existing standard methods for measuring swelling pressure and swelling potential (ASTM D4546-14).

8. SUMMARY AND CONCLUSIONS

This study presents a comparative assessment of the effectiveness of commercially available polymers to reduce the swelling potential of an expansive clay relative to traditional chemical stabilizers (quicklime and Class C fly ash). A survey of state departments of transportation within the Mountain-Plains region of the United States was conducted to define the state-of-the-practice in expansive soil mitigation and identify lime and fly ash as the most common chemical stabilizers. Four commercially available polymers advertised as soil stabilizers were initially tested, and one polymer (P4) was selected for further comparative testing based on demonstrating the greatest swell reduction. The effectiveness of 3% (by mass) lime, 15% (by mass) fly ash, and 5% (by mass relative to as received polymer solution) to reduce swelling potential and swelling pressure, increase unconfined compressive strength, and impact hydraulic conductivity were measured. Tests were also performed after a 7-day cure at 40°C, with a subset of tests conducted after 24 hours of air drying at 20°C to assess curing time as an advantage of a polymer stabilizer. Finally, polymer was tested as a coating to assess the effectiveness of the polymer stabilizer as a hydraulic barrier. The followings conclusions are drawn from this study:

- The stabilizing effect of P4 was poor compared with that of lime and fly ash based on the swelling pressure, swelling potential, and unconfined compressive strength tests. P4 resulted in only a 14% reduction in swell pressure, 70% reduction in swell potential, and 46 kPa increase in unconfined compressive strength compared with 99%, 100%, and 1260 kPa for lime, and 76%, 97%, and 382 kPa for fly ash, respectively.

- Lime and fly ash treatments resulted in 52,000-times and 1,100-times increases in hydraulic conductivity, respectively, relative to untreated clay prepared in the same way (hydraulic conductivity = 2.9×10^{-11} m/s). However, P4 resulted in an approximately 400-times-lower hydraulic conductivity than fly ash treated soil and approximately 20,000-times-lower hydraulic conductivity than lime treated soil.

- Spray coating with P4 effectively restricted flow to below the measurable range of conventional flexible-wall hydraulic conductivity testing equipment (hydraulic conductivity $< 1.9\times10^{-12}$ m/s).

- Given that an ingress of moisture underlies expansive soil swelling, the results of testing did not demonstrate a clear "superior" expansive soil treatment technology. Chemical treatments (lime) and polymer treatments have different advantages. Future comparisons of polymers to conventional chemical stabilizers requires careful consideration of the differing mechanisms by which materials will reduce swelling.

In addition to distilled conclusions, the following are recommended to further investigate the effectiveness of commercially available polymers for stabilization of expansive soils.

- A method is required to test polymer treated expansive soil in a manner that is more representative of field conditions. This method should represent the coupled effects of swelling and hydraulic conductivity (i.e., water ingress and resulting swell).

- Longevity of commercially available polymers versus lime or fly ash is unknown but may warrant future study.

- Commercial polymers should be tested for soil conditions under which conventional chemical stabilizers are ineffective and compared to current dominant treatment techniques (excavate and replace or excavate and re-compact).

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APPENDIX A. DOT SURVEY RESULTS

Survey results on expansive soil identification and treatment methods used by state departments of transportation (DOTs) in five Mountain Plains region states.

1. Expansive soils identification: please list the methods your DOT uses to identify expansive soils. How does your DOT decide on the severity of expansive soils based on your identification methods?	
Colorado	We do the swell test, Atterberg limits and gradation analysis. We use AASHTO LRFD Bridge Design Table 10.4.6.3-1 to identify potentially expansive soils.
Montana	Primarily we would use lab testing (swell tests from Shelby tube samples). We might use other methods such as soil property index correlations, or even just visual observation. Severity is based up on the lab results, pavement ride data, or discussion with maintenance personnel or personal experience on the "real world feel" of the issue while driving the roadway.
South Dakota	Geographic location, laboratory testing, knowledge and experience, past performance.
Utah	We identify the expansive soils by observation of damaged pavements. Severity determined by Atterberg limits and soil swell tests.
Wyoming	Swell tests, classification, observations of roadway conditions, and maintenance records.

2. The techniques used to mitigate expansive soils: please list any remedial measures that your DOT has ever taken to eliminate or mitigate swelling problems:	
Colorado	Removal and replacement, remolding and compaction, surcharge loading, pre-wetting, horizontal barriers, lime treatment, fly ash treatment.
Montana	Removal and replacement, remolding, and compaction.
South Dakota	Removal and replacement, Remolding and compaction, lime treatment, Fly ash treatment,
Utah	Removal and replacement, lime treatment
Wyoming	Removal and replacement, pre-wetting, membrane encapsulated soil layers (MESL), lime treatment

3. Please list the mitigating techniques that have worked best, and why.	
Colorado	For shallow and lightweight structures, such as retaining walls, we recommend a deep foundation system such as piles or caissons to support the structure and prevent differential settlement. Our bridge abutments and piers are also founded on deep foundation system to prevent uplift and settlement. If feasible and not cost prohibitive, removal and replacement of expansive material is also effective. For pavement, lime and fly ash treatment are effective techniques provided that the treated soil does not contain sulfate. Remolding and compaction are common mitigation techniques in pavement construction.
Montana	Removal and replacement has worked, but we haven't really tried too many different techniques.
South Dakota	Removal and replacement - only used for isolated specific design requirements to do associated expense. Remolding and compaction - standard undercut practice utilized for all associated grading projects. Lime treatment - used extensively 1970s on during interstate construction. Results quite variable. Fly ash treatment - used on several projects to mitigate specific fault/heave traces with good results.
Utah	We haven't done much. Besides some excavation and replacement, we replaced an extensive section of rigid concrete pavement with flexible asphalt pavement and incorporated positive surface drainage.
Wyoming	Membrane.

4. Please list the techniques that have NOT worked, or that your DOT no longer uses, and why.	
Colorado	Partial removal of the expansive material and replacement with granular material does not solve the heave problem. Bath tub situation is created with this mitigation technique and the heave problem persists.
Montana	N/A
South Dakota	Limited use of lime treatment due to previous results.
Utah	Deep dynamic compaction (DDC). The soil was thought to be collapsible when it was actually expansive. DDC did not work at all.
Wyoming	Disruption of shale layers with explosives.

5. Please provide the names or links of the document guidelines that your DOT uses in dealing with expansive soils.

Colorado	CDOT Materials Manual and AASHTO LRFD Bridge Design Manual.
Montana	We generally follow FHWA guidelines such as the soil stabilization manual or textbooks on expansive soils. We may also research journal articles.
South Dakota	N/A
Utah	None
Wyoming	FHWA/WY-94/05

6. Does your DOT use polymer as a stabilization technique? If yes, please explain why? What is the manufacturer/company that provides the Polymer for your DOT?

Colorado	I am not aware of.
Montana	Not yet
South Dakota	No
Utah	No
Wyoming	No

7. Please provide any additional comments/suggestions.

Colorado	Draining surface water away from structures using flexible and rigid membranes is a CDOT standard.
Montana	-
South Dakota	-
Utah	-
Wyoming	-

APPENDIX B. EXPERIMENTAL RESULTS

B.1 Specific Gravity Test

Tables B.1 – B.3 report the G_s of NFC.

Table B.1. *First specific gravity test.*

Specific Gravity (Gs) Test #1 for NFC	Weight/Gs
Weight of the flask filled with 500 ml of water (w1)=	668.12 g
Weight of the flask filled with 500 ml of water and soil (w2)=	746.63 g
Weight of dry soil (w3)=	123.86 g
Gs at 22.5°C=	2.7312
Gs at 20°C=	2.73

Table B.2. *Second specific gravity test.*

Specific Gravity Test #2 for NFC	Weight/Gs
Weight of the flask filled with 500 ml of water (w1)=	665.82
Weight of the flask filled with 500 ml of water and soil (w2)=	699.00
Weight of dry soil (w3)=	52.57
Gs at 24.3°C=	2.7112
Gs at 20°C=	2.71

Table B.3. *Average specific gravity test.*

GS (average)=	2.72

B.2 Atterberg Limit Tests

B.2.1 NFC Liquid Limit and Plastic Limit Test Results

B.2.1.1 Liquid Limit of NFC

Table B.4. *Liquid limit of NFC.*

Liquid Limit (LL) Test						
Test no.	1	2	3	4	5	6
LL [%]	29.6	30.1	30.1	32.7	32.0	31.6
LL [%] (Average)=	31.0					

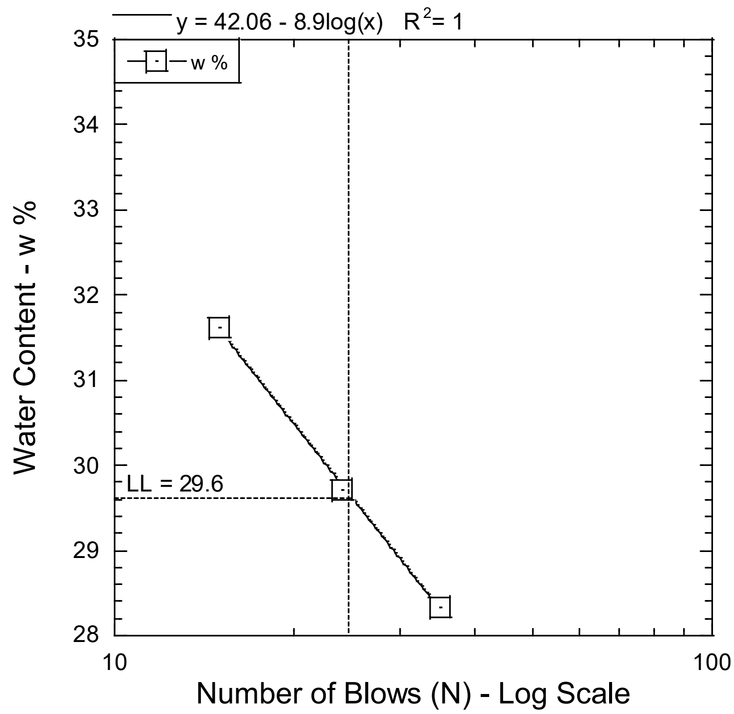


Figure B.1. *Liquid Limit test results for NFC – test number one.*

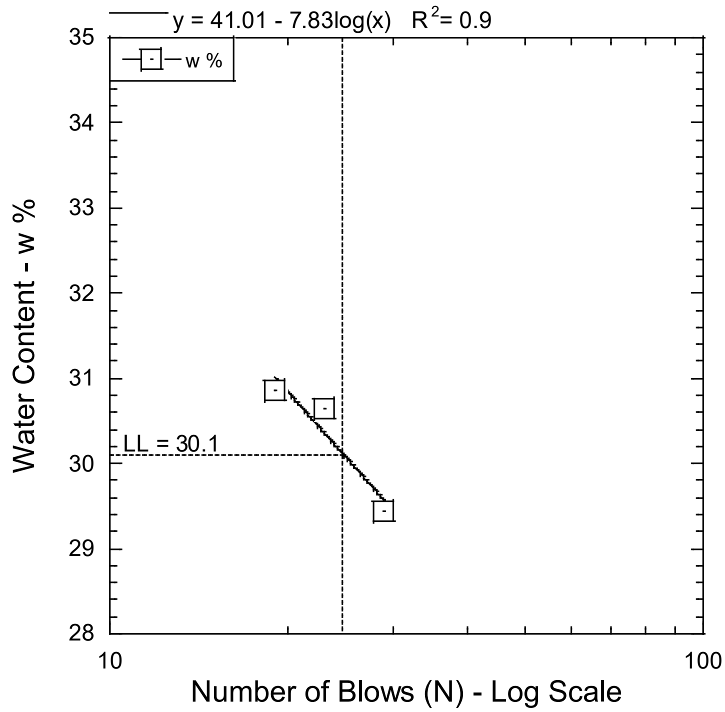


Figure B.2. *Liquid limit test results for NFC – test number two.*

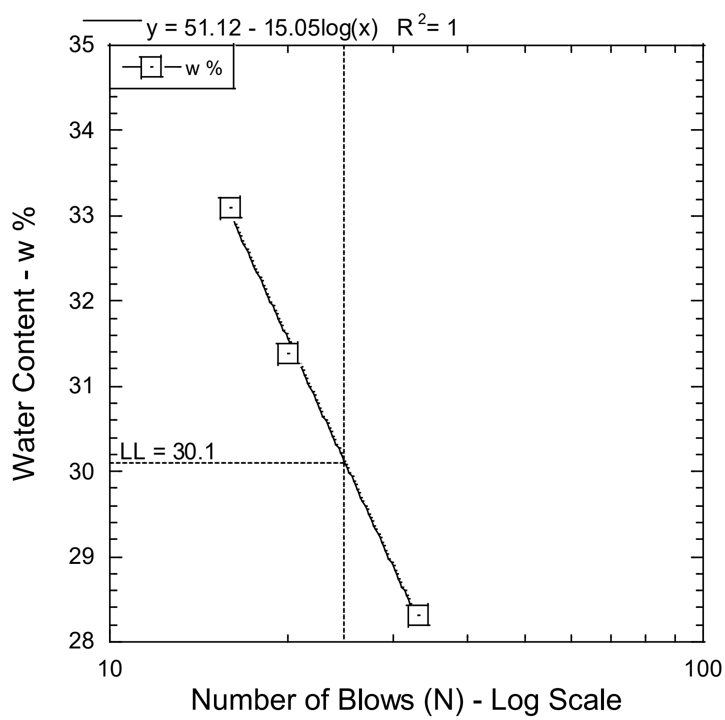


Figure B.3. *Liquid Limit test results for NFC – test number three.*

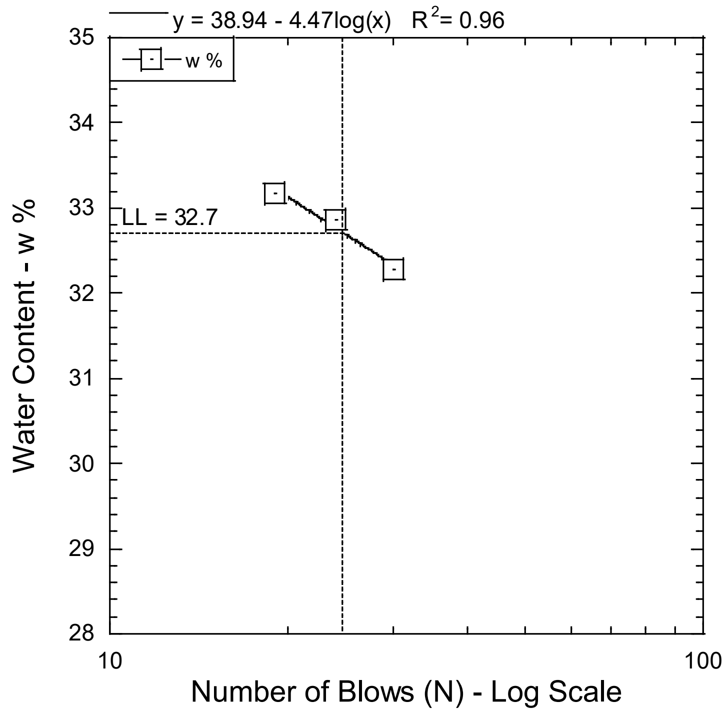


Figure B.4. *Liquid limit test results for NFC – test number four.*

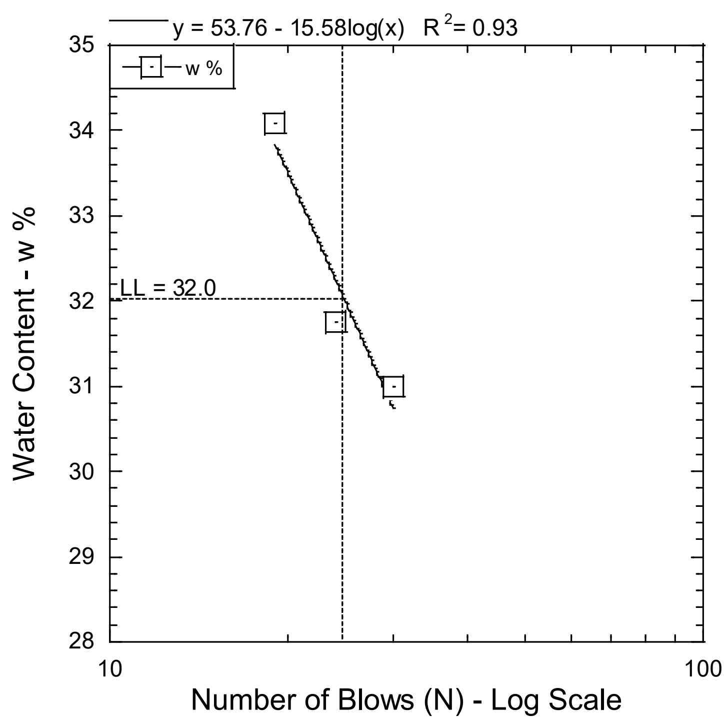


Figure B.5. *Liquid limit test results for NFC – test number five.*

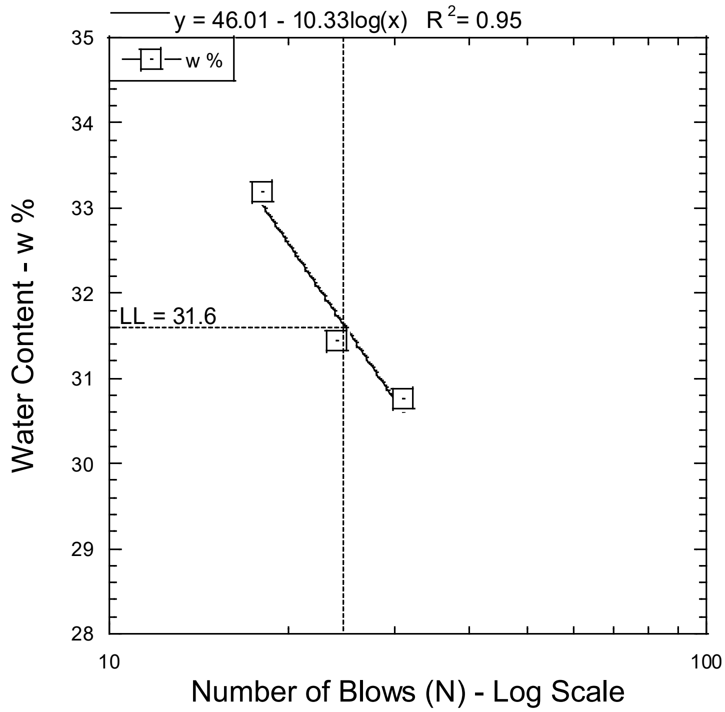


Figure B.6. *Liquid limit test results for NFC – test number six.*

B.2.1.2 Plastic Limit and Plasticity Index of the NFC

Table B.5. *Plastic limit of NFC.*

Plastic Limit (PL) Test			
Test no.	1	2	3
PL [%]	18.66	17.81	17.79
PL [%] (Average)=		18.1	

Table B.6. *Plasticity index (PI) of NFC.*

LL [%] (Average)	31.0
PL [%] (Average)	18.1
PI [%] =	12.9

B.2.2 Expansive Soil (85% NFC + 15% Bentonite) Liquid Limit and Plastic Limit Test Results

B.2.2.1 Liquid Limit of Expansive Soil

Table B.7. *Liquid limit of expansive soil.*

Liquid Limit (LL) Test		
Test no.	1	2
LL [%]	76.7	74.8
LL [%] (Average)=		75.8

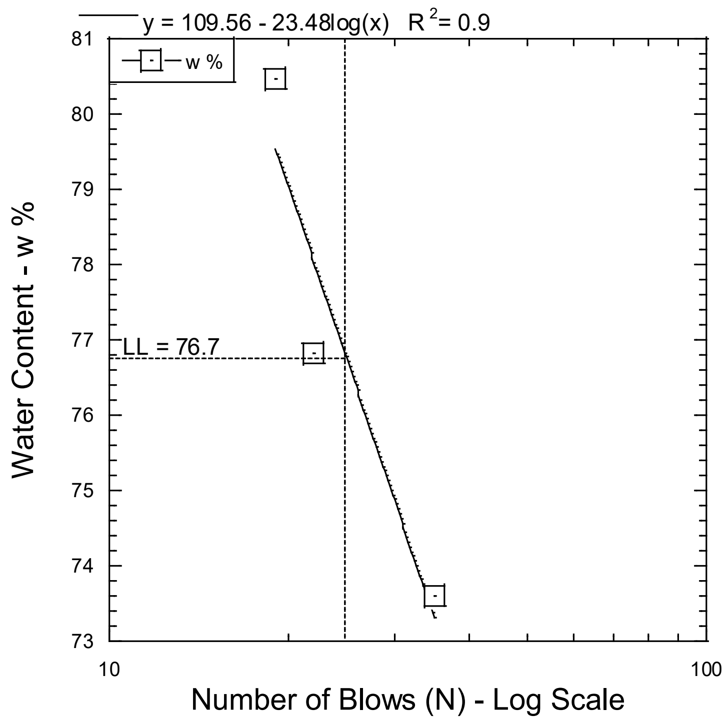


Figure B.7. *Liquid limit test results on expansive soil – test number one.*

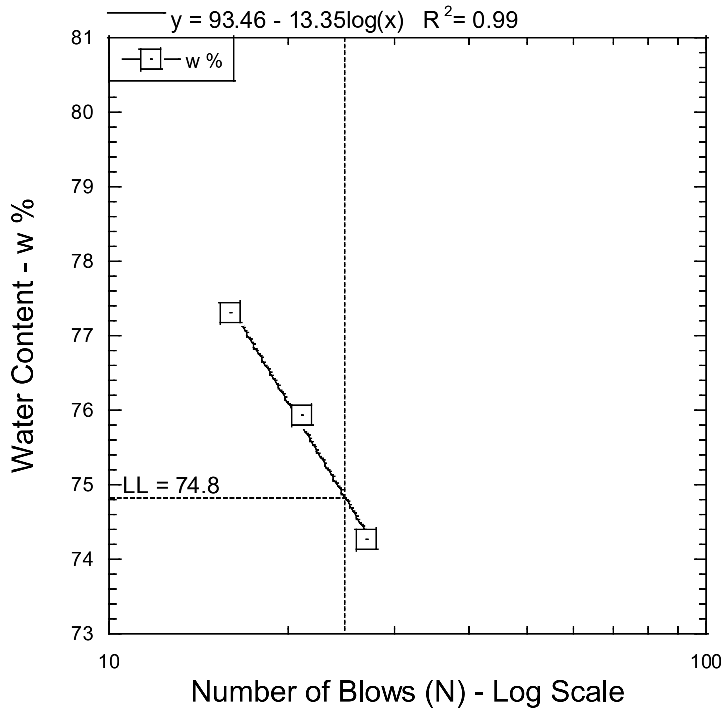


Figure B.8. *Liquid limit test results on expansive soil – test number two.*

B.2.2.2 Plastic Limit and Plasticity Index of Expansive Soil

Table B.8. *Plastic limit of expansive soil*

Plastic Limit (PL) Test			
Test no.	1	2	3
PL [%]	18.86	17.02	17.35
PL [%] (Average)=		17.7	

Table B.9. *Plasticity index (PI) of expansive soil*

LL [%] (Average)=	75.8
PL [%] (Average)=	17.7
PI [%] =	58.0

B.2.3 Fly Ash Treated (85% NFC + 15% Bentonite + 15% Fly Ash) LL and PL Tests

B.2.3.1 Liquid Limit Test of the Fly Ash Treated

Table B.10. *Liquid limit of fly ash treated soil.*

Liquid Limit (LL) Test		
Test no.	1	2
LL [%]	56.0	57.0

LL [%] (Average)=	56.5

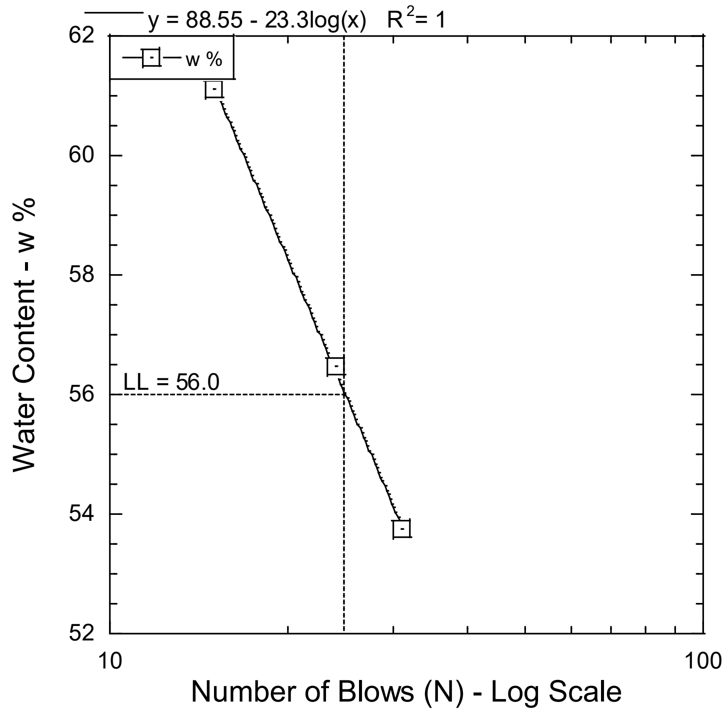


Figure B.9. *Liquid limit test results on fly ash treated soil – test number one.*

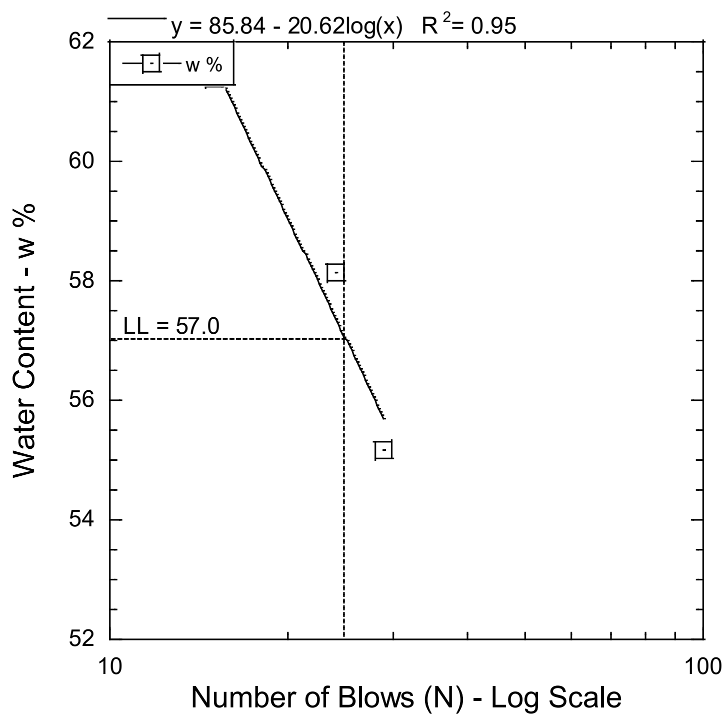


Figure B.10. *Liquid limit test results on fly ash treated soil – test number two.*

B.2.3.2 Plastic Limit and Plasticity Index of Fly Ash Treated Soil

Table B.11. *Plastic limit of fly ash treated soil.*

Plastic Limit (PL) Test			
Test no.	1	2	3
PL [%]	17.56	17.99	17.21
PL [%] (Average)=		17.6	

Table B.12. *Plasticity index (PI) of fly ash treated soil.*

Plasticity Index (PI) Result	
LL [%] (Average)=	56.5
PL [%] (Average)=	17.6
PI [%] =	38.9

B.2.4 Lime Treated (85% NFC + 15% Bentonite + 3% Lime) LL and PL Test Results

B.2.4.1 Liquid Limit of Lime Treated Soil

Table B.13. *Liquid limit of lime treated soil.*

Liquid Limit (LL) Test		
Test no.	1	2
LL [%]	50.7	49.7
LL [%] (Average)=		50.2

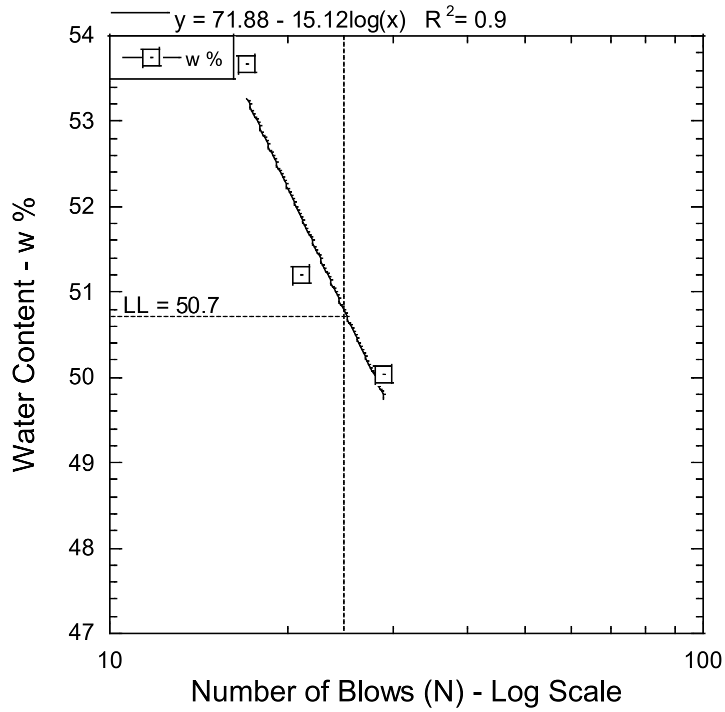


Figure B.11. *Liquid limit test results on lime treated soil – test number one.*

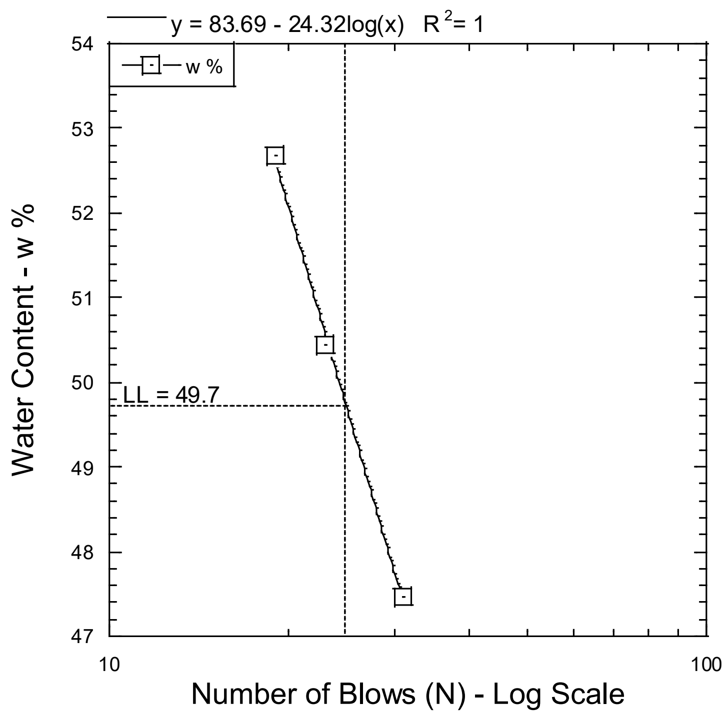


Figure B.12. *Liquid limit test result on lime treated soil – test number two.*

B.2.4.2 Plastic Limit and Plasticity Index of Lime Treated Soil

Table B.14. *Plastic limit of lime treated soil.*

Plastic Limit (PL) Test			
Test no.	1	2	3
PL [%]	31.8	32.0	33.8
PL [%] (Average)=		32.6	

Table B.15. *Plasticity index (PI) of lime treated soil.*

LL [%] (Average)=	50.2
PL [%] (Average)=	32.6
PI [%] =	17.6

B.2.5 P4 Treated (85% NFC + 15% Bentonite + 5% P4) LL and PL Tests Results

B.2.5.1 Liquid Limit of P4 Treated Soil

Table B.16. *Liquid limit of P4 treated soil.*

Liquid Limit (LL) Test		
Test no.	1	2
LL [%]	69.6	70.6
LL [%] (Average)=		70.1

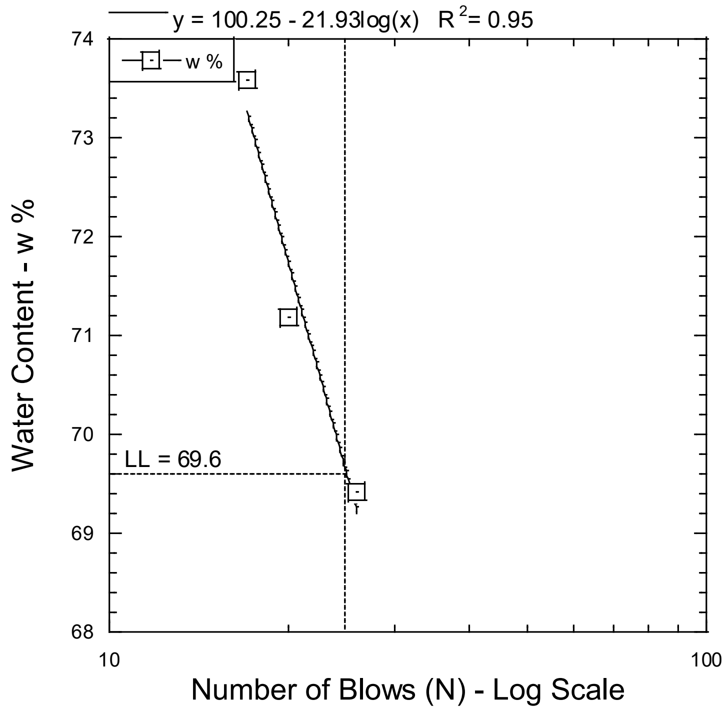


Figure B.13. *Liquid limit test results on P4 treated soil – test number one.*

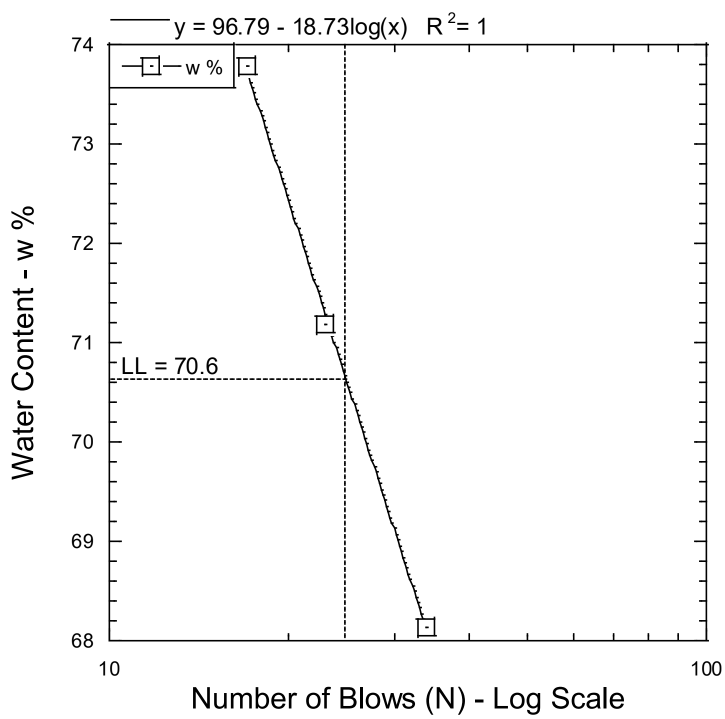


Figure B.14. *Liquid limit test results on P4 treated soil – test number two.*

B.2.5.2 Plastic Limit and Plasticity Index of P4 Treated Soil

Table B.17. *Plastic limit of P4 treated soil.*

Plastic Limit (PL) Test			
Test no.	1	2	3
PL [%]	18.2	20.0	20.2
PL [%] (Average)=		19.5	

Table B.18. *Plasticity index (PI) of P4 treated soil.*

LL [%] (Average)=	70.1
PL [%] (Average)=	19.5
PI [%] =	50.6

B.2.6 Maximum P4 Treated (Expansive Soil + 27% P4) LL and PL Test Results

B.2.6.1 Liquid Limit of Maximum P4 Treated Soil

Table B.19. *Liquid limit of P4 treated soil.*

Liquid Limit (LL) Test	
Test no.	1
LL [%]	66.9
LL [%] (Final Result)=	66.9

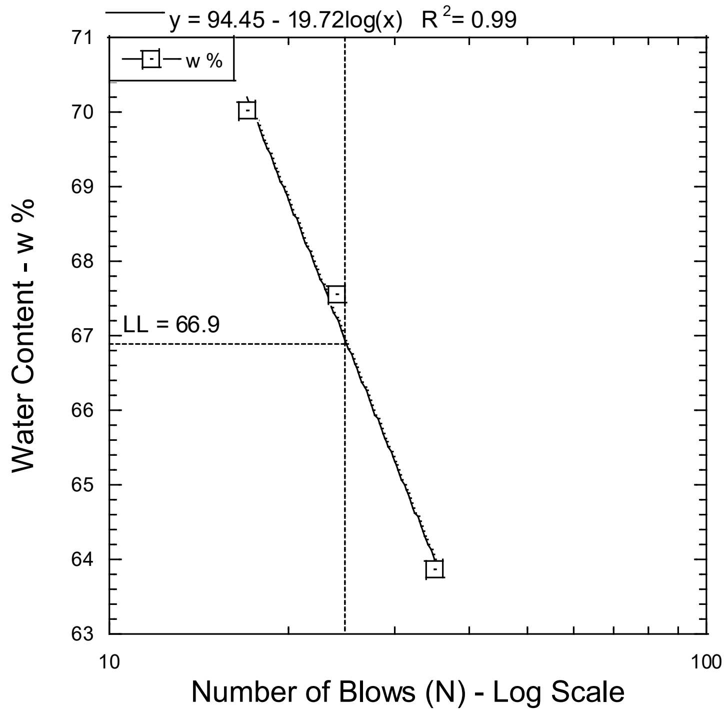


Figure B.15. *Liquid limit test results on maximum (27%) P4 treated soil.*

B.2.6.2 Plastic Limit and Plasticity Index of Maximum P4 Treated Soil

Table B.20. *Plastic limit of 27% P4 treated.*

Plastic Limit (PL) Test			
Test no.	1	2	3
PL [%]	32.1	32.2	32.4
PL [%] (Average)=		32.2	

Table B.21. *Plasticity index (PI) of 27% P4 treated.*

LL [%] (Average)=	66.9
PL [%] (Average)=	32.2
PI [%] =	34.7

B.3 Standard Compaction Tests

B.3.1 The Standard Compaction Tests on NFC

Table B.22. *Standard compaction tests on NFC.*

Optimum Water Content (w [%]) and Maximum Dry Unit Weight (γdmax [lb/ft3])		
Test No.	1	2
w [%]	16.1	16.1
γdmax [lb/ft3]	112.9	111.5
Average w [%] =	16.1	
Average γdmax [lb/ft3] =	112.2	

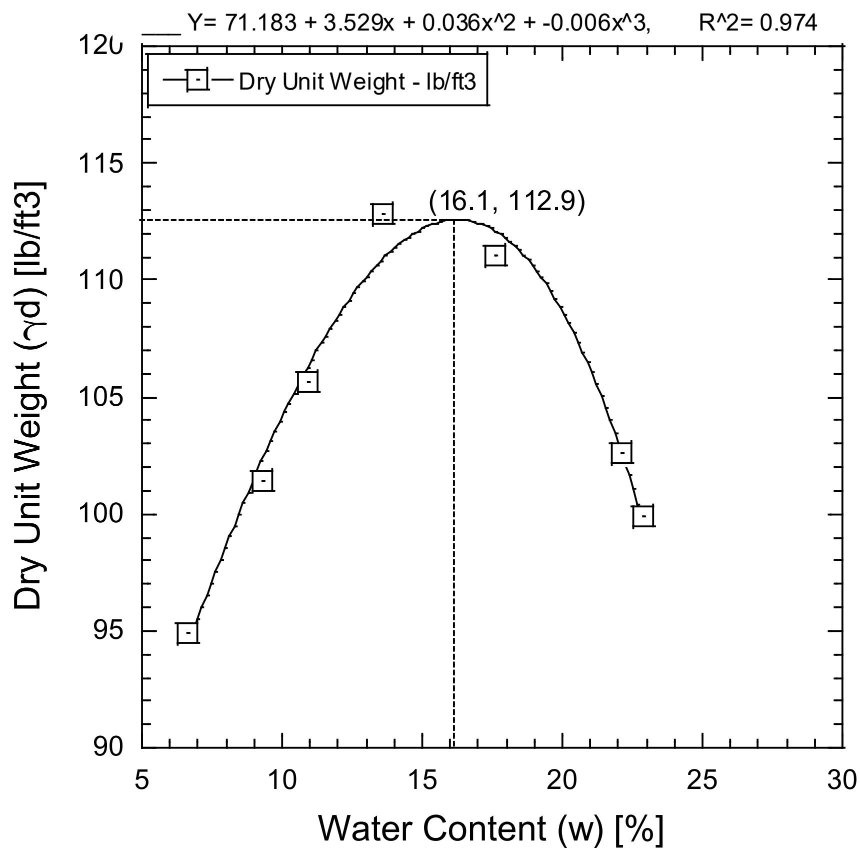


Figure B.16. *Standard compaction results on NFC – test number one.*

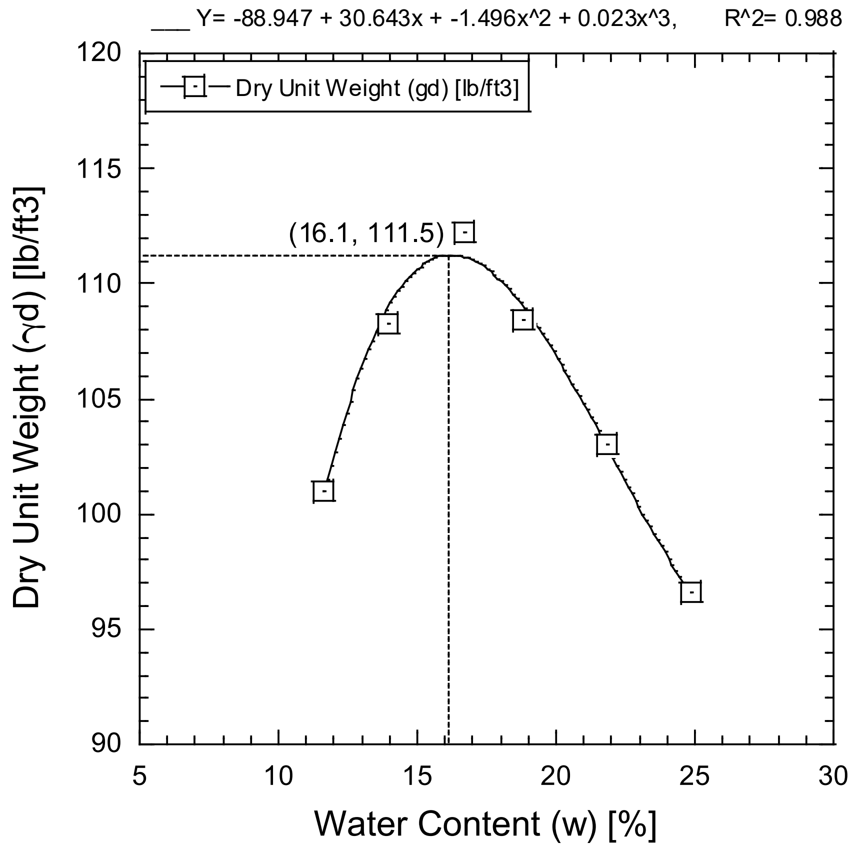


Figure B.17. *Standard compaction test results on NFC – test number two.*

B.3.2 The Standard Compaction Test on Expansive Soil

Table B.23. *Standard compaction tests on expansive soil.*

Optimum Water Content (w [%]) and Maximum Dry Unit Weight (γdmax [lb/ft3])		
Test No.	1	
w [%] =	18.4	
γdmax [lb/ft3] =	105.0	

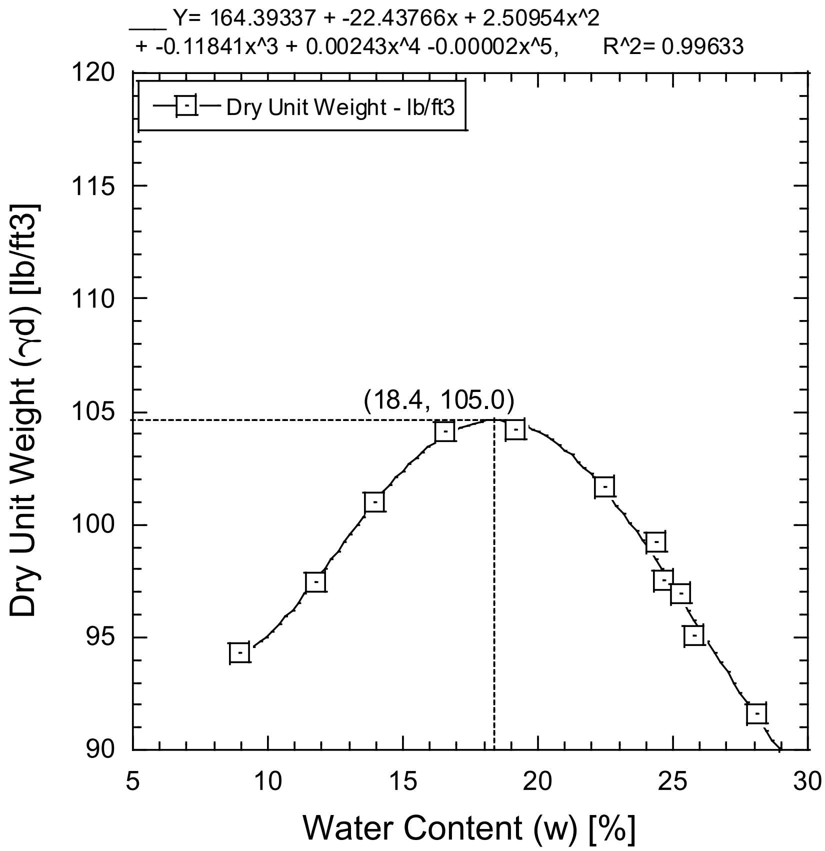


Figure B.18. *Standard compaction test results on expansive soil.*

B.3.3 Standard Compaction Test on Fly Ash Treated

Table B.24. *Standard compaction tests on fly ash treated soil.*

Optimum Water Content (w [%]) and Maximum Dry Unit Weight (γdmax [lb/ft3])		
Test No.	1	2
w [%]	17.0	18.0
γdmax [lb/ft3]	103.0	103.0
Average w [%] =	17.5	
Average γdmax [lb/ft3] =	103.0	

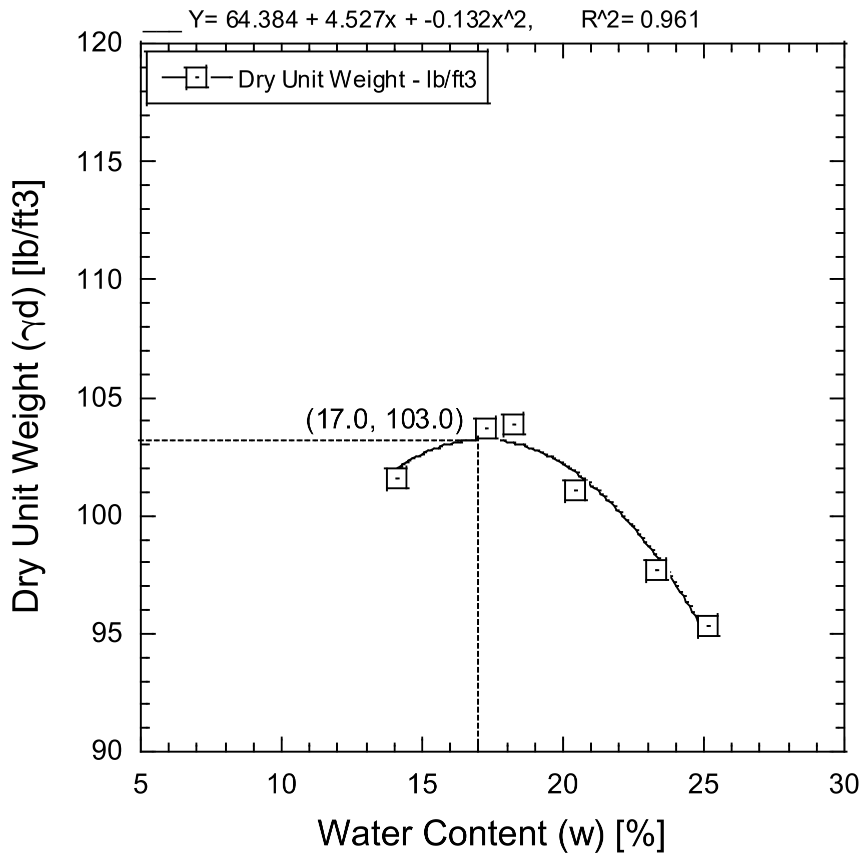


Figure B.19. *Standard compaction test results on fly ash treated soil – test number one.*

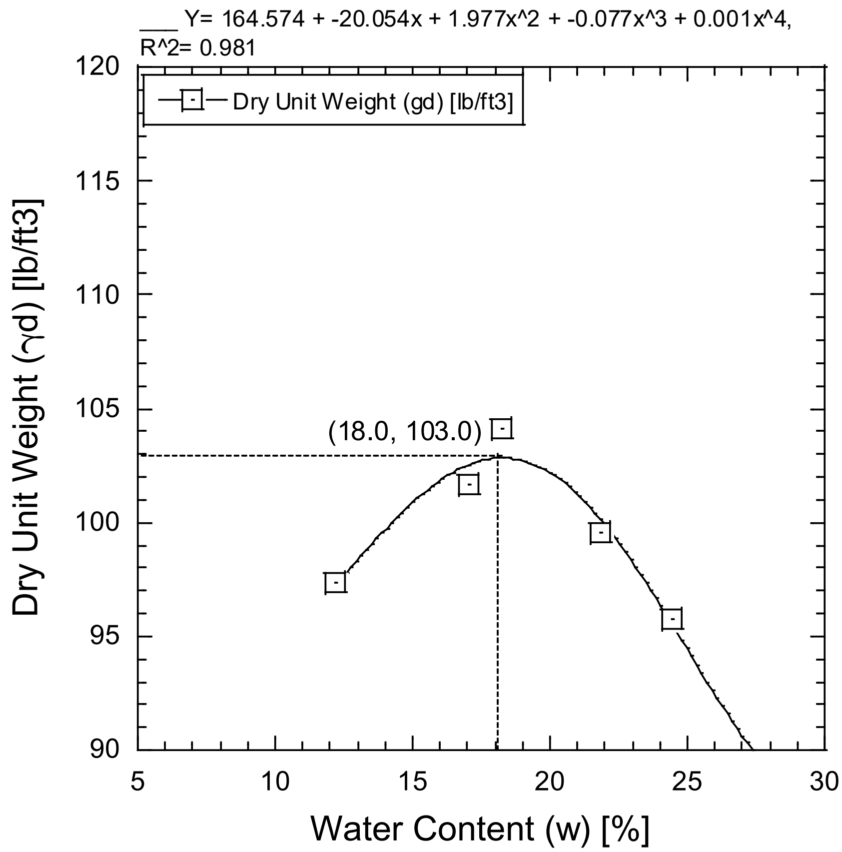


Figure B.20. *Standard compaction test results on fly ash treated soil – test number two.*

B.3.4 Standard Compaction Test of Lime Treated Soil

Table B.25. *Standard compaction tests on lime treated.*

Optimum Water Content (w [%]) and Maximum Dry Unit Weight (γdmax [lb/ft3])	
Test No.	1
w [%] =	20.0
γdmax [lb/ft3] =	101.1

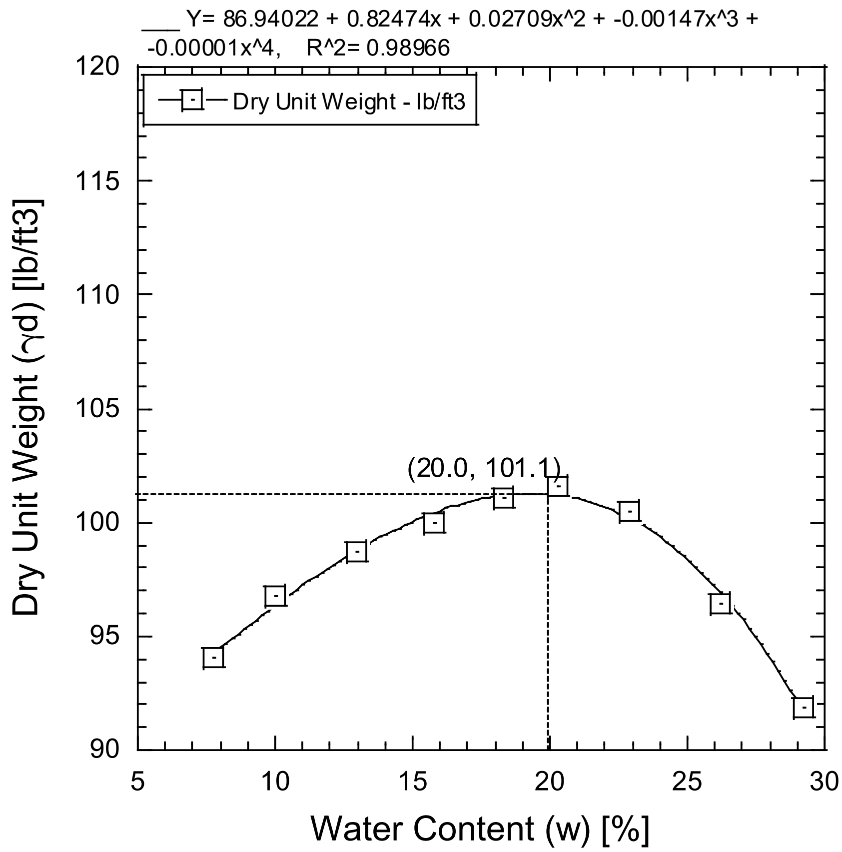


Figure B.21. *Standard compaction results on lime treated soil.*

B.3.5 Standard Compaction Test on P4 Treated Soil

Table B.26. *Standard compaction test on P4 treated soil.*

Optimum Water Content (w [%]) and Maximum Dry Unit Weight (γdmax [lb/ft3])	
Test No.	1
w [%] =	19.4
γdmax [lb/ft3] =	103.5

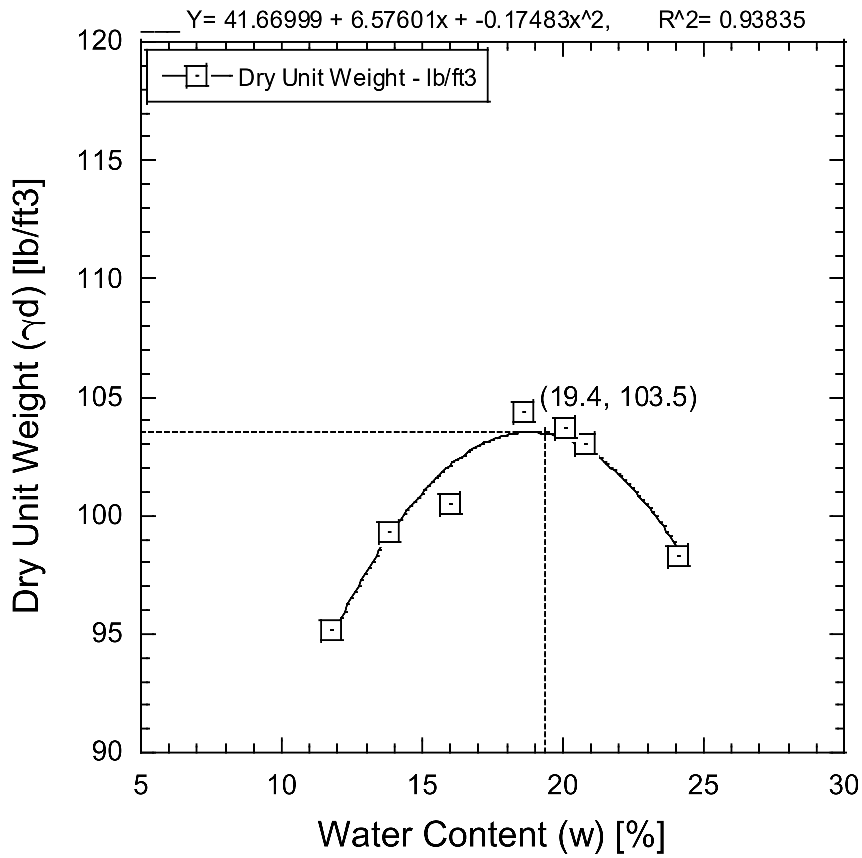


Figure B.22. *Standard compaction test results on P4 treated soil.*

B.4 Swell Tests

B.4.1 NFC Swell Test

B.4.1.1 Swell Test Under 1 kPa

Table B.27. *Swell test under 1 kPa on NFC.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two Inch
Cell height, h=	25.4	mm	One inch
Cell weight=	558.5	g	
Water content, w%=	16.1	%	Optimum Water Content
Soil Total weight, Wt=	147	g	
Volume of soil, V=	80439.8	mm3	
Weight of solids, Ws=	126.6	g	
Height of solids, hs=	14.8	mm	
Compression prior to wetting, dh1=	-0.130	mm	Immediately before wetting
Specimen height prior to wetting, h1=	25.3	mm	Immediately before wetting
Swell/Collapse caused by wetting dh2=	0.085	mm	Linear swell
Swell/Collapse= 100 x dh2/h1=	0.34	%	% swell

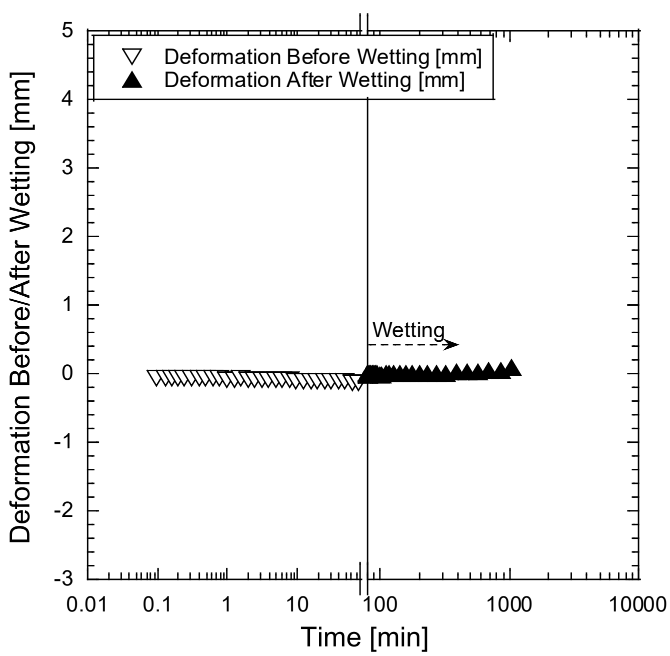


Figure B.23. *Swell test under 1 kPa on NFC.*

B.4.1.2 Swell Test Under 20 kPa

Table B.28. *Swell test under 20 kPa on NFC.*

Swell Test	Values	Units	Comments
Pressure to be applied=	20	kPa	
Load to be placed=	809.45	g	Arm= 10x
Cell diameter, d=	71.1	mm	More than Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	348.5	g	
Water content, w%=	16.1	%	Optimum Water Content
Soil Total weight, Wt=	195.9	g	
Volume of soil, V=	100966.1	mm^3	
Weight of solids, Ws=	168.7	g	
Height of solids, hs=	19.7	mm	
Compression prior to wetting, dh_1=	-0.974	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	24.5	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	-0.116	mm	Linear Collapse
Swell/Collapse= 100 x dh_2/h_1=	-0.47	%	% Collapse

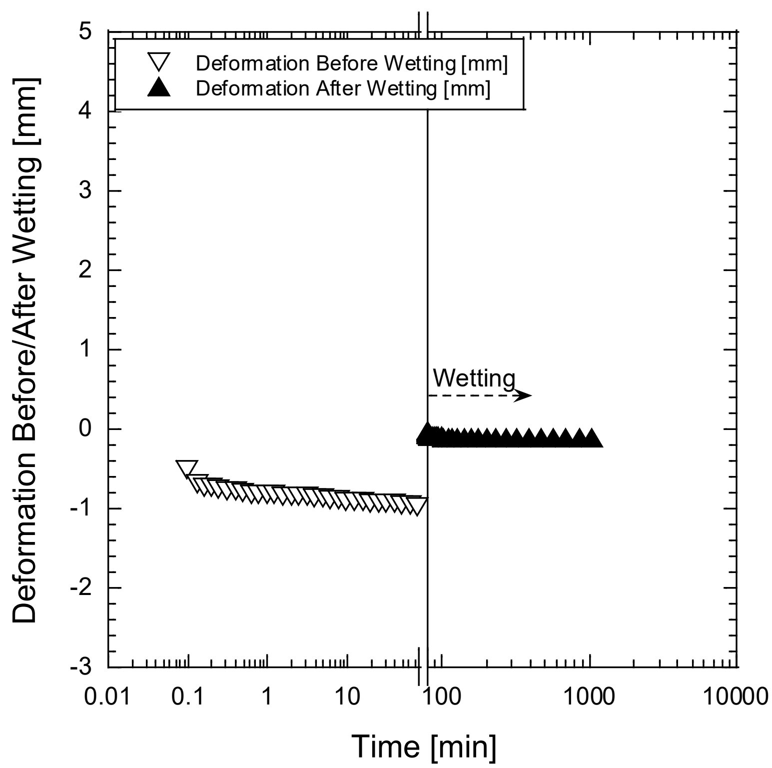


Figure B.24. *Swell test under 20 kPa on NFC.*

B.4.1.3 Swell Test Under 50 kPa

Table B.29. *Swell test under 50 kPa on NFC.*

Swell Test	Values	Units	Comments
Pressure to be applied=	50	kPa	
Load to be placed=	1606.0	g	Arm= 10x
Cell diameter, d=	63.34	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	524	g	
Water content, w%=	16.1	%	Optimum Water Content
Soil Total weight, Wt=	152.3	g	
Volume of soil, V=	79877.4	mm^3	
Weight of solids, Ws=	131.2	g	
Height of solids, hs=	15.3	mm	
Compression prior to wetting, dh_1=	-2.164	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	23.2	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	-0.079	mm	Linear Collapse
Swell/Collapse= 100 x dh_2/h_1=	-0.34	%	% Collapse

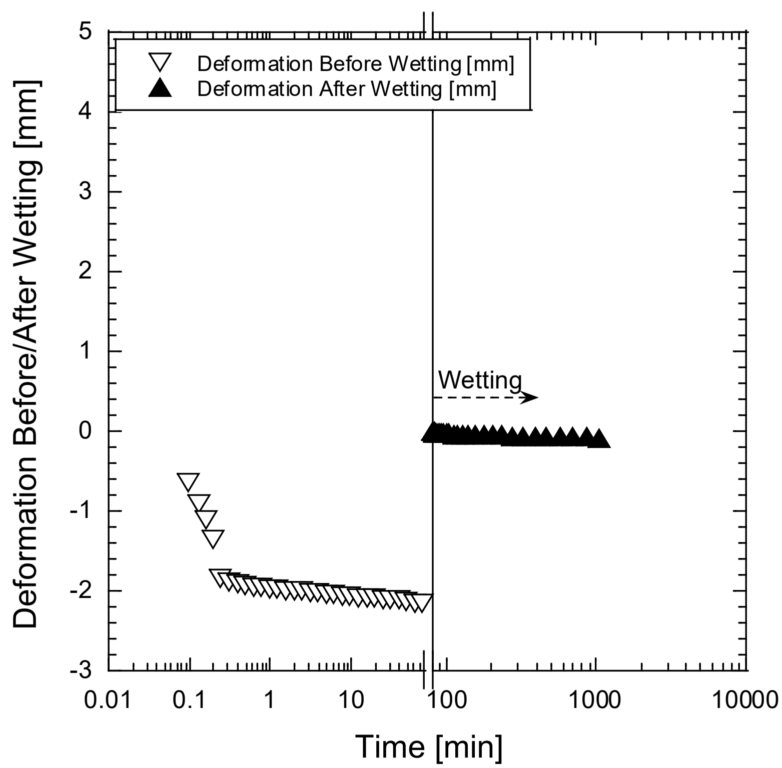


Figure B.25. *Swell test under 50 kPa on NFC.*

B.4.1.4 Swell Test Under 100 kPa

Table B.30. *Swell test under 100 kPa on NFC.*

Swell Test	Values	Units	Comments
Pressure to be applied=	100	kPa	
Load to be placed=	3223.2	g	Arm= 10x
Cell diameter, d=	63.45	mm	Two inches
Cell height, h=	25.3	mm	One inch
Cell weight=	520	g	
Water content, w%=	16.1	%	Optimum Water Content
Soil Total weight, Wt=	160.1	g	
Volume of soil, V=	79965.4	mm^3	
Weight of solids, Ws=	137.9	g	
Height of solids, hs=	16.1	mm	
Compression prior to wetting, dh_1=	-2.968	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	22.3	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	-0.093	mm	Linear Collapse
Swell/Collapse= 100 x dh_2/h_1=	-0.42	%	% Collapse

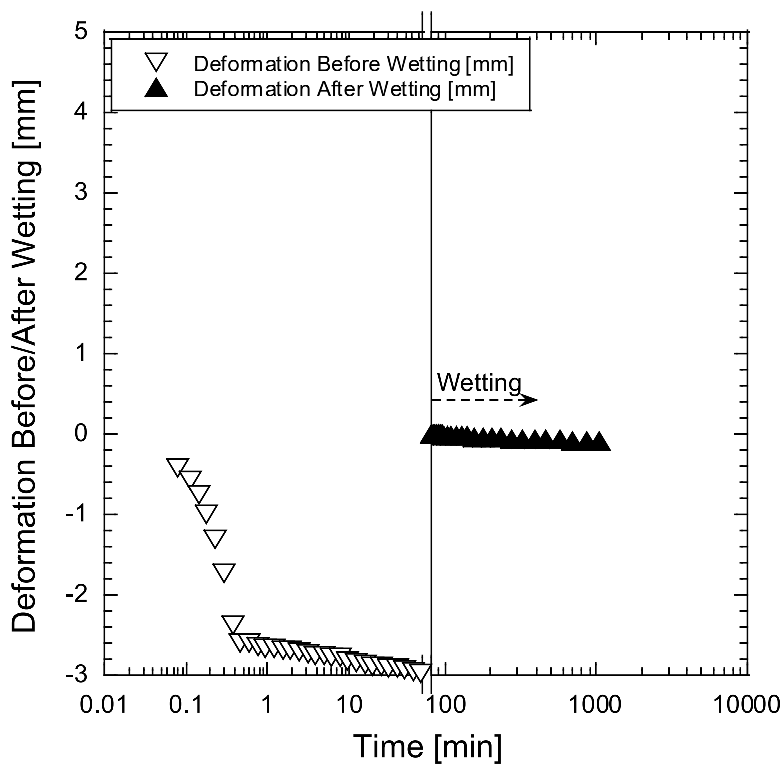


Figure B.26. *Swell test under 100 kPa on NFC.*

B.4.1.5 Swell Pressure and Swell Potential:

Table B.31. *Swell pressure and swell potential of NFC.*

Swell Pressure [kPa]	Swell Potential [%]
1	0.3
20	-0.5
50	-0.3
100	-0.4

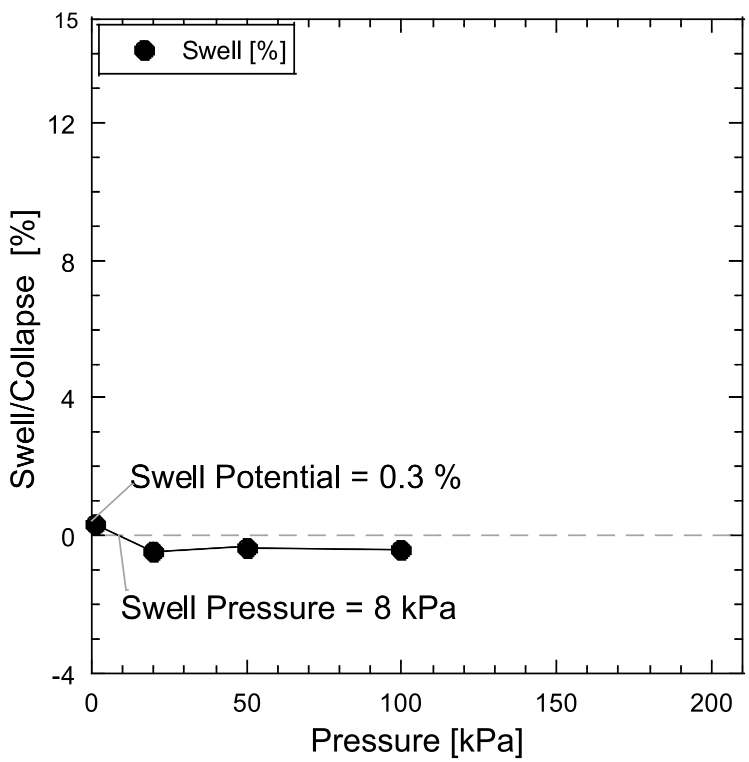


Figure B.27. *Swell pressure and swell potential of NFC.*

B.4.2 Expansive Soil Swell Test

B.4.2.1 Swell Test Under 1 kPa

Table B.32. *Swell test under 1 kPa on expansive soil.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	30.0	g	Arm= 10x
Cell diameter, d=	61.19	mm	Two inches
Cell height, h=	25.6	mm	One inch
Cell weight=	558.5	g	
Water content, w%=	17.18	%	~Optimum water content
Soil Total weight, Wt=	150	g	
Volume of soil, V=	75370.2	mm^3	
Weight of solids, Ws=	128.0	g	
Height of solids, hs=	15.0	mm	
Compression prior to wetting, dh_1=	-0.011	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.6	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	3.828	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	14.9	%	% swell

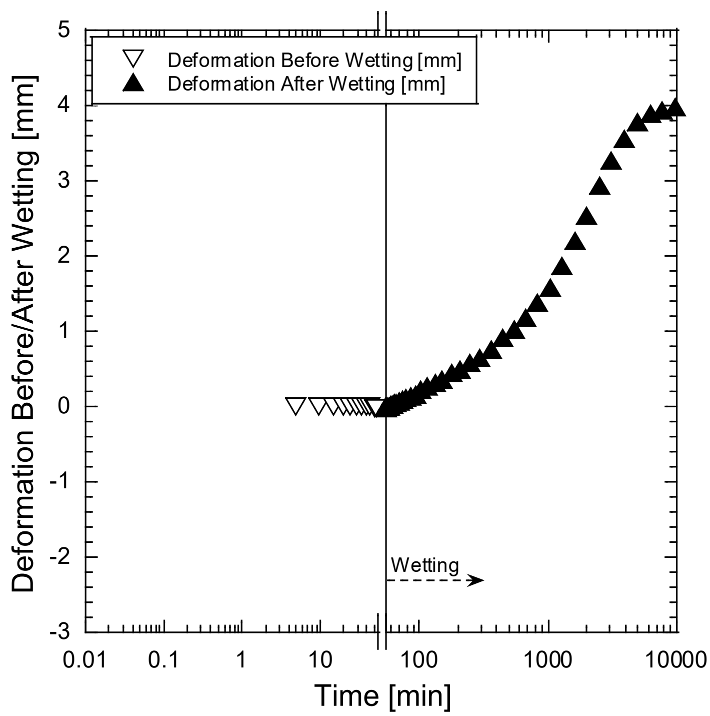


Figure B.28. *Swell test under 1 kPa on expansive soil.*

B.4.2.2 Swell Test Under 10 kPa

Table B.33. *Swell test under 10 kPa on expansive soil.*

Swell Test	Values	Units	Comments
Pressure to be applied=	10	kPa	
Load to be placed=	321.6	g	Arm= 10x
Cell diameter, d=	63.38	mm	Two inches
Cell height, h=	25.3	mm	One inch
Cell weight=	519	g	
Water content, w%=	17.18	%	~Optimum water content
Soil Total weight, Wt=	158	g	
Volume of soil, V=	79820.6	mm3	
Weight of solids, Ws=	134.8	g	
Height of solids, hs=	15.8	mm	
Compression prior to wetting, dh1=	-0.169	mm	Immediately before wetting
Specimen height prior to wetting, h1=	25.1	mm	Immediately before wetting
Swell/Collapse caused by wetting dh2=	1.389	mm	Linear swell
Swell/Collapse= 100 x dh2/h1=	5.5	%	% swell

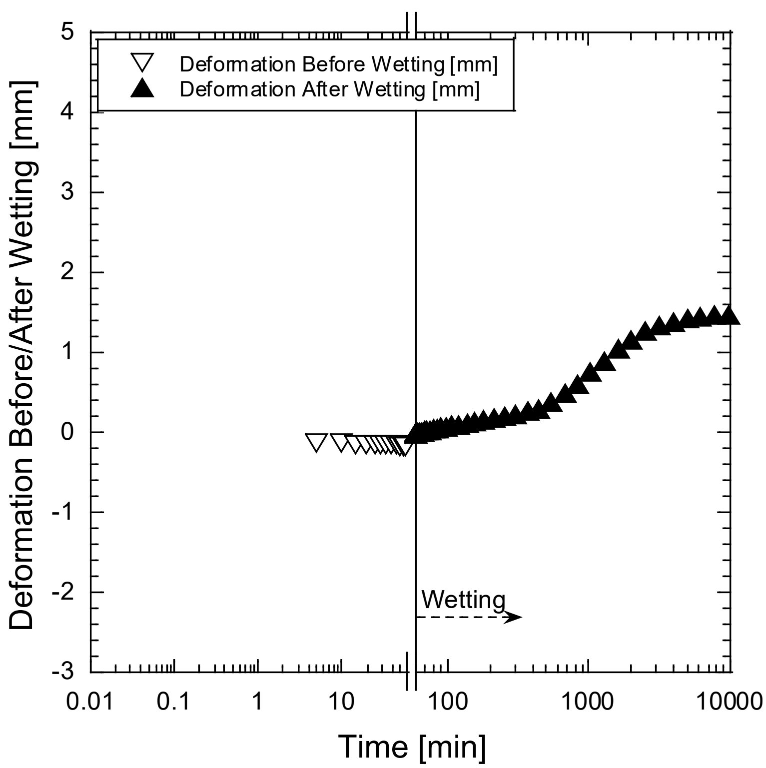


Figure B.29. *The swell test under 10 kPa on expansive soil.*

B.4.2.3 Swell Test Under 50 kPa

Table B.34. *Swell test under 50 kPa on expansive soil.*

Swell Test	Values	Units	Comments
Pressure to be applied=	50	kPa	
Load to be placed=	1606.0	g	Arm= 10x
Cell diameter, d=	63.34	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	524	g	
Water content, w%=	17.18	%	~Optimum water content
Soil Total weight, Wt=	152.3	g	
Volume of soil, V=	79877.4	mm^3	
Weight of solids, Ws=	130.0	g	
Height of solids, hs=	15.2	mm	
Compression prior to wetting, dh_1=	-0.238	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.1	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.367	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	1.5	%	% swell

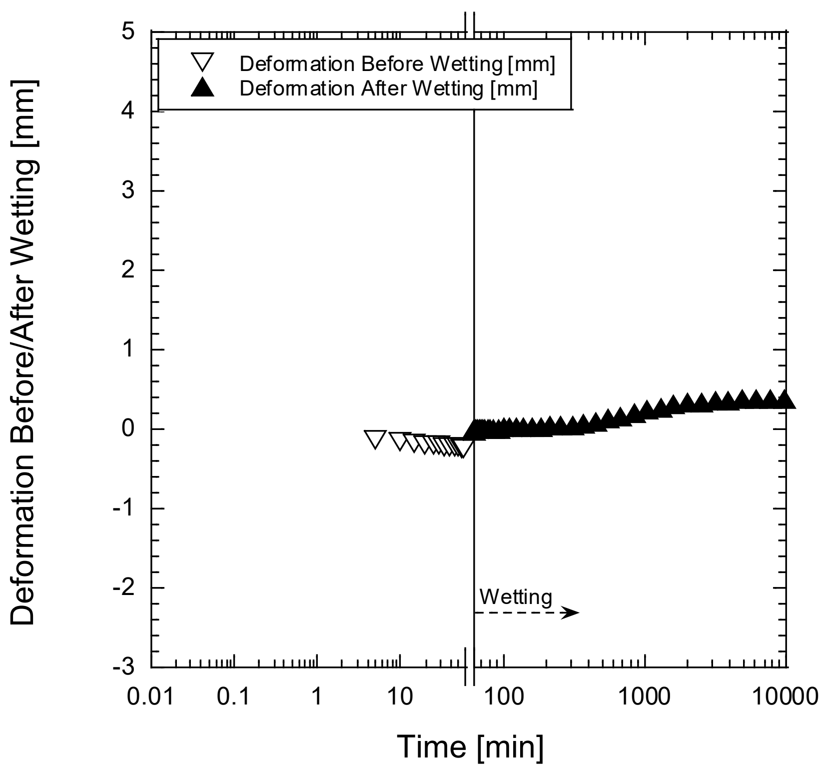


Figure B.30. *Swell test under 50 kPa on expansive soil.*

B.4.2.4 Swell Test Under 100 kPa

Table B.35. *Swell test under 100 kPa on expansive soil.*

Swell Test	Values	Units	Comments
Pressure to be applied=	100	kPa	
Load to be placed=	3223.2	g	Arm= 10x
Cell diameter, d=	63.45	mm	Two inches
Cell height, h=	25.3	mm	One inch
Cell weight=	520	g	
Water content, w%=	17.18	%	~Optimum water content
Soil Total weight, Wt=	160.1	g	
Volume of soil, V=	79965.4	mm^3	
Weight of solids, Ws=	136.6	g	
Height of solids, hs=	16.0	mm	
Compression prior to wetting, dh_1=	-1.116	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	24.2	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.095	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.4	%	% swell

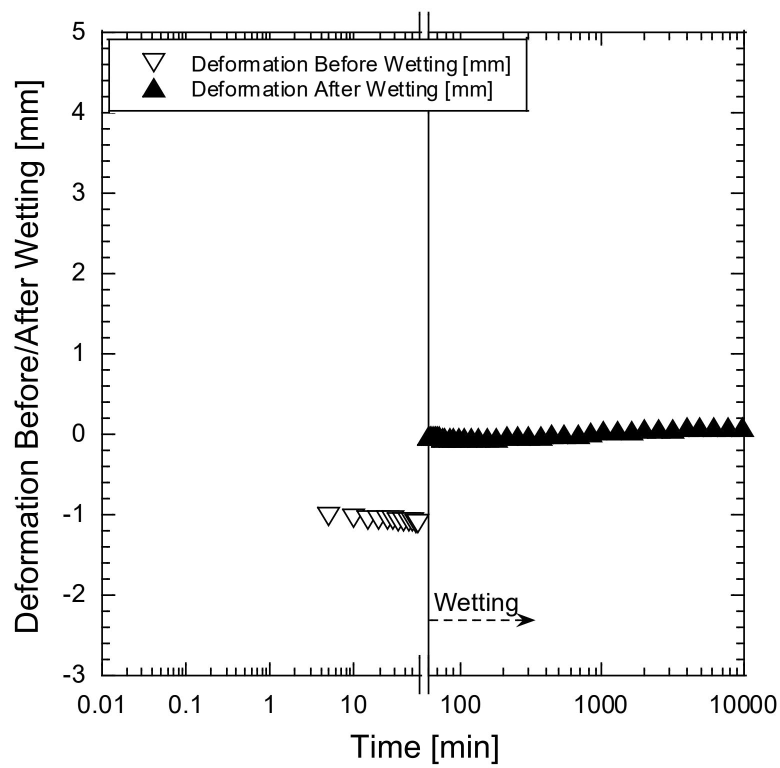


Figure B.31. *Swell test under 100 kPa on expansive soil.*

B.4.2.5 Swell Test Under 207.3 kPa

Table B.36. *Swell test under 207.3 kPa on expansive soil.*

Swell Test	Values	Units	Comments
Pressure to be applied=	207.27	kPa	
Load to be placed=	6657.5	g	Arm= 10x
Cell diameter, d=	63.34	mm	Two inches
Cell height, h=	25.5	mm	One inch
Cell weight=	520	g	
Water content, w%=	18.4	%	~Optimum water content
Soil Total weight, Wt=	161.5	g	
Volume of soil, V=	80192.5	mm^3	
Weight of solids, Ws=	136.4	g	
Height of solids, hs=	15.9	mm	
Compression prior to wetting, dh_1=	-0.804	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	24.6	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	-0.143	mm	Linear Collapse
Swell/Collapse= 100 x dh_2/h_1=	-0.6	%	% Collapse

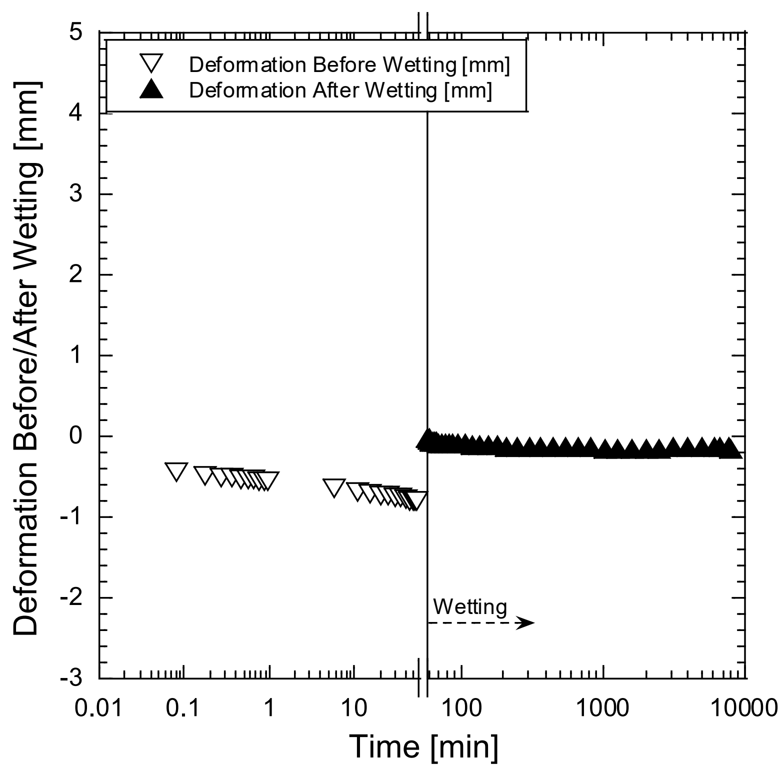


Figure B.32. *Swell test under 207.3 kPa on expansive soil.*

B.4.2.6 Swell Pressure and Swell Potential

Table B.37. *Swell pressure and swell potential on expansive soil.*

Swell Pressure [kPa]	Swell Potential [%]
1	14.9
10	5.5
50	1.5
100	0.4
207.3	-0.6

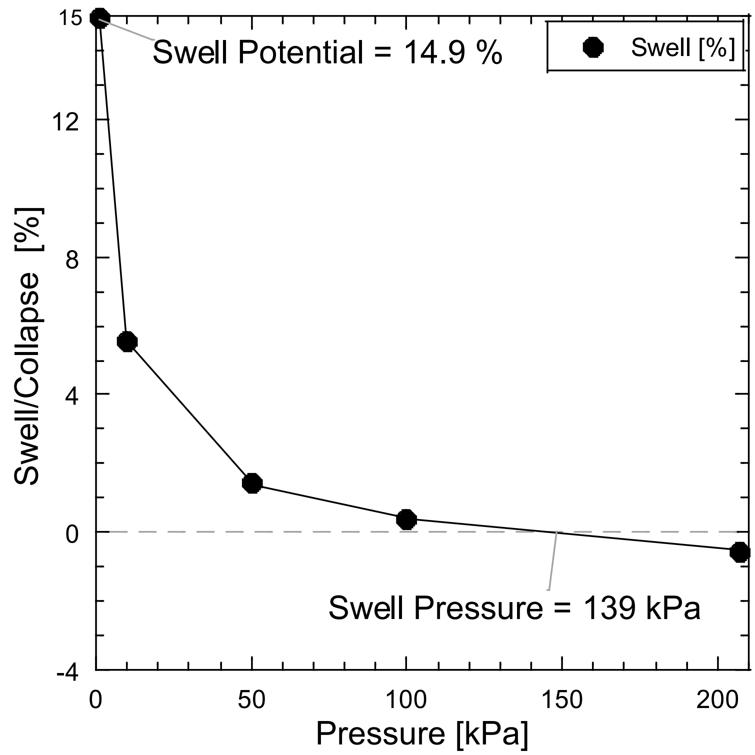


Figure B.33. *Swell test under different pressures.*

B.4.3 Fly Ash Treated Soil Swell Test (15%)

B.4.3.1 Swell Test Under 1 kPa

Table B.38. *Swell test under 1 kPa on fly ash treated soil.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	30.0	g	Arm= 10x
Cell diameter, d=	61.19	mm	Two inches
Cell height, h=	25.6	mm	One inch
Cell weight=	558.5	g	
Water content, w%=	17.18	%	~Optimum water content
Soil Total weight, Wt=	152.5	g	
Volume of soil, V=	75370.2	mm^3	
Weight of solids, Ws=	130.1	g	
Height of solids, hs=	15.2	mm	
Compression prior to wetting, dh_1=	-0.070	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.6	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.115	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.5	%	% swell

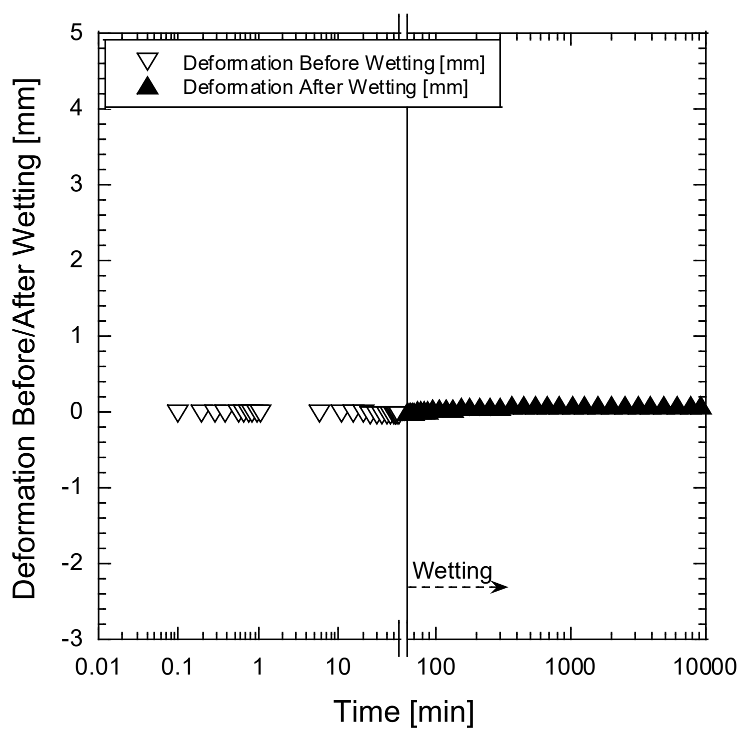


Figure B.34. *Swell test under 1 kPa on fly ash treated soil.*

B.4.3.2 Swell Test Under 10 kPa

Table B.39. *Swell test under 10 kPa on fly ash treated soil.*

Swell Test	Values	Units	Comments
Pressure to be applied=	10	kPa	
Load to be placed=	321.6	g	Arm= 10x
Cell diameter, d=	63.38	mm	Two inches
Cell height, h=	25.3	mm	One inch
Cell weight=	519	g	
Water content, w%=	17.18	%	~Optimum water content
Soil Total weight, Wt=	158	g	
Volume of soil, V=	79820.6	mm^3	
Weight of solids, Ws=	134.8	g	
Height of solids, hs=	15.8	mm	
Compression prior to wetting, dh_1=	-0.037	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.3	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.099	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.4	%	% swell

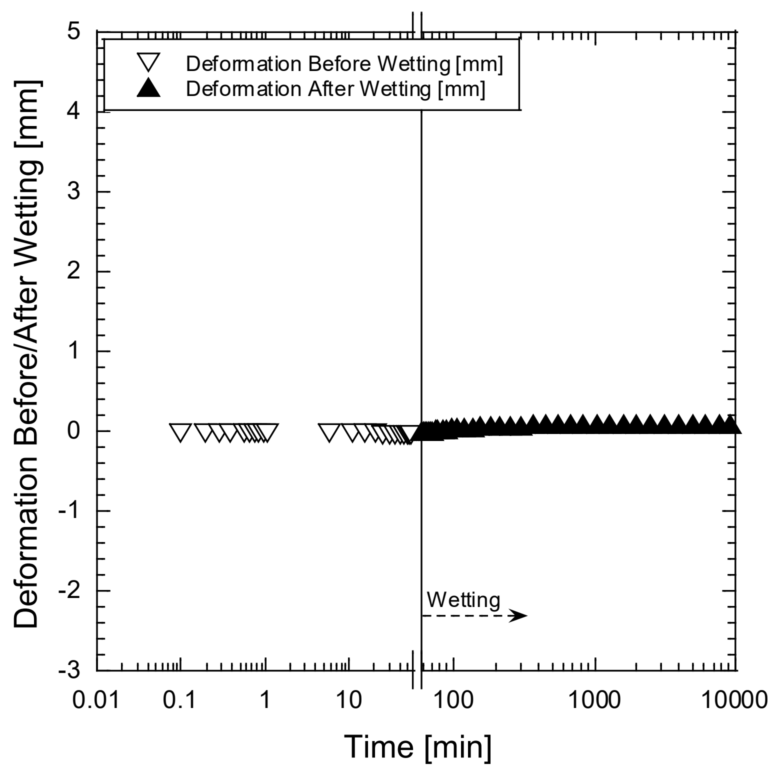


Figure B.35. *Swell test under 10 kPa on fly ash treated soil.*

B.4.3.3 Swell Test Under 50 kPa

Table B.40. *Swell test under 50 kPa on fly ash treated soil.*

Swell Test	Values	Units	Comments
Pressure to be applied=	50	kPa	
Load to be placed=	1606.0	g	Arm= 10x
Cell diameter, d=	63.34	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	524	g	
Water content, w%=	17.18	%	~Optimum water content
Soil Total weight, Wt=	152.3	g	
Volume of soil, V=	79877.4	mm^3	
Weight of solids, Ws=	130.0	g	
Height of solids, hs=	15.2	mm	
Compression prior to wetting, dh_1=	-0.110	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.2	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	-0.104	mm	Linear Collapse
Swell/Collapse= 100 x dh_2/h_1=	-0.4	%	% Collapse

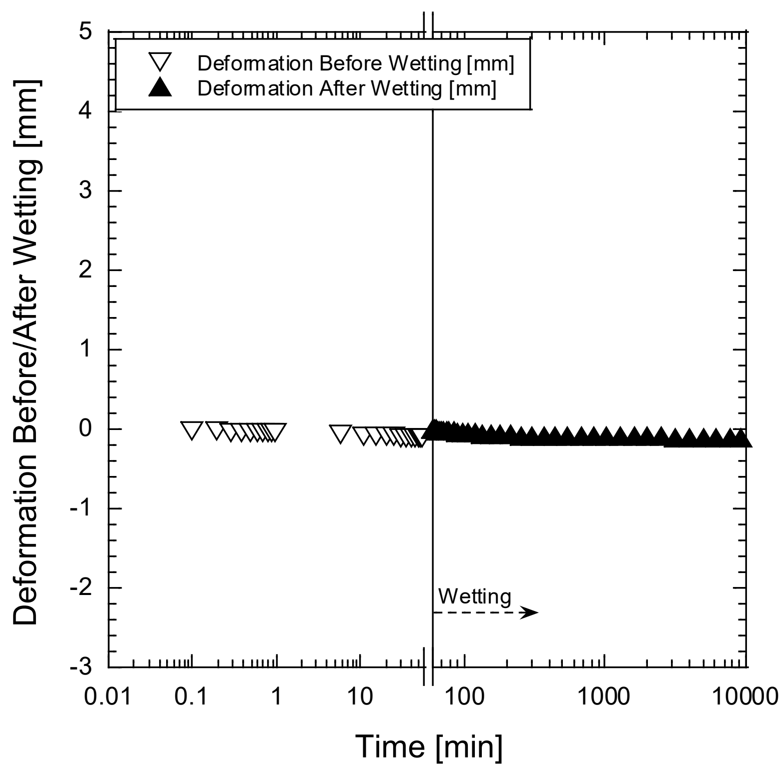


Figure B.36. *Swell test under 50 kPa on fly ash treated soil.*

B.4.3.4 Swell Test Under 100 kPa

Table B.41. *Swell test under 100 kPa on fly ash treated soil.*

Swell Test	Values	Units	Comments
Pressure to be applied=	100	kPa	
Load to be placed=	3223.2	g	Arm= 10x
Cell diameter, d=	63.45	mm	Two inches
Cell height, h=	25.3	mm	One inch
Cell weight=	520	g	
Water content, w%=	17.18	%	~Optimum water content
Soil Total weight, Wt=	160.1	g	
Volume of soil, V=	79965.4	mm^3	
Weight of solids, Ws=	136.6	g	
Height of solids, hs=	16.0	mm	
Compression prior to wetting, dh_1=	-1.348	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	23.9	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	-0.618	mm	Linear Collapse
Swell/Collapse= 100 x dh_2/h_1=	-2.6	%	% Collapse

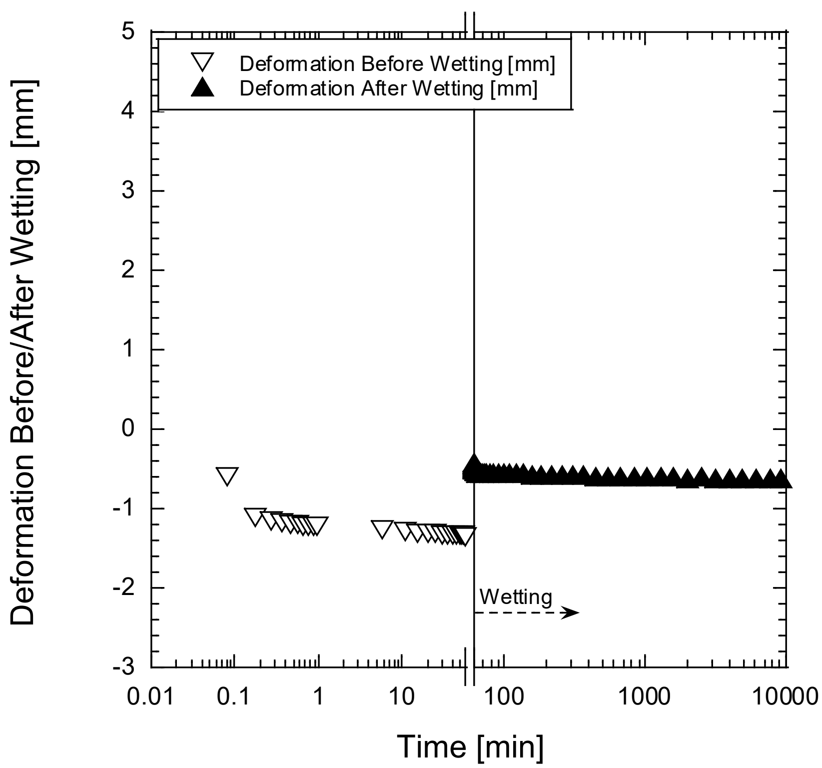


Figure B.37. *Swell test under 100 kPa on fly ash treated soil.*

B.4.3.5 Swell Pressure and Swell Potential

Table B.42. *Swell pressure and swell potential on fly ash treated soil.*

Swell Pressure [kPa]	Swell Potential [%]
1	0.5
10	0.4
50	-0.4
100	-2.6

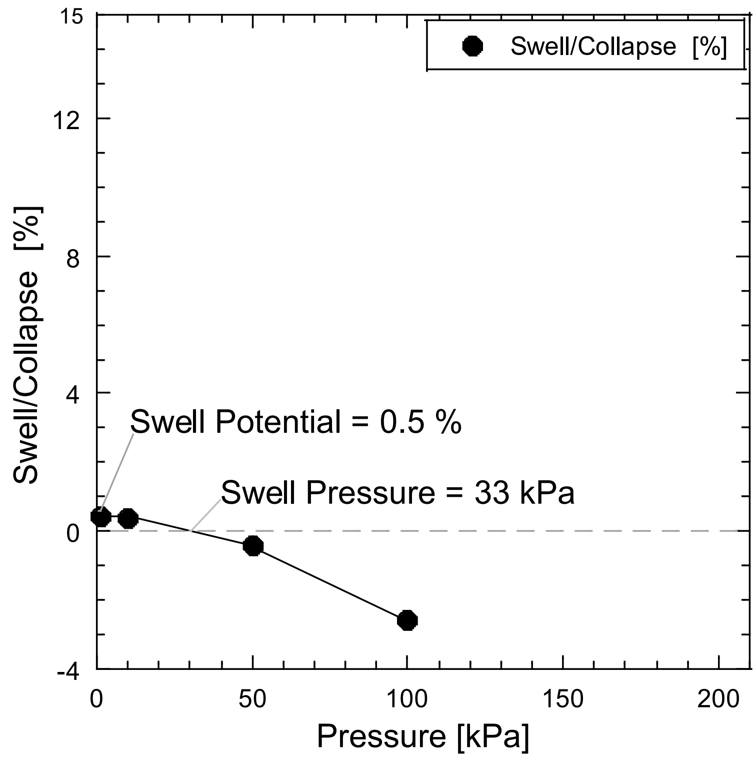


Figure B.38. *Swell pressure and swell potential of fly ash treated soil.*

B.4.4 Fly Ash Treated Swell Test - Additional Tests

B.4.4.1 Swell Test Under 1 kPa

Table B.43. *The swell test under 1 kPa on fly ash treated soil – additional tests.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.2	g	Arm= 10x
Cell diameter, d=	63.4	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	558.5	g	
Water content, w%=	17.18	%	~Optimum water content
Soil Total weight, Wt=	152.5	g	
Volume of soil, V=	80186.7	mm^3	
Weight of solids, Ws=	130.1	g	
Height of solids, hs=	15.2	mm	
Compression prior to wetting, dh_1=	-0.038	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.014	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.1	%	% swell

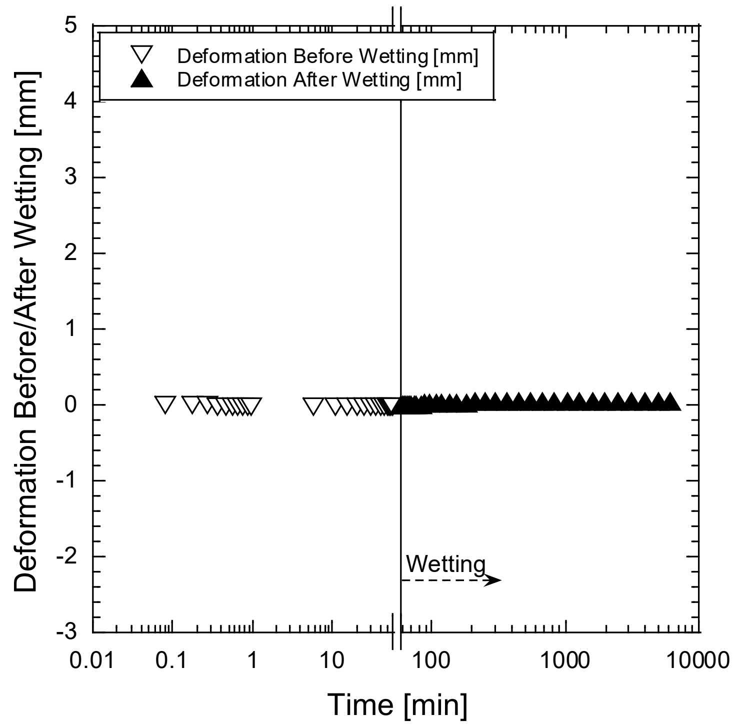


Figure B.39. *Swell test under 1 kPa on fly ash treated soil – additional tests.*

B.4.4.2 Swell Test Under 10 kPa

Table B.44. *Swell test under 10 kPa on fly ash treated soil – additional tests.*

Swell Test	Values	Units	Comments
Pressure to be applied=	10	kPa	
Load to be placed=	321.6	g	Arm= 10x
Cell diameter, d=	63.38	mm	Two inches
Cell height, h=	25.3	mm	One inch
Cell weight=	519	g	
Water content, w%=	17.18	%	~Optimum water content
Soil Total weight, Wt=	158	g	
Volume of soil, V=	79820.6	mm^3	
Weight of solids, Ws=	134.8	g	
Height of solids, hs=	15.8	mm	
Compression prior to wetting, dh_1=	-0.029	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.3	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.048	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.2	%	% swell

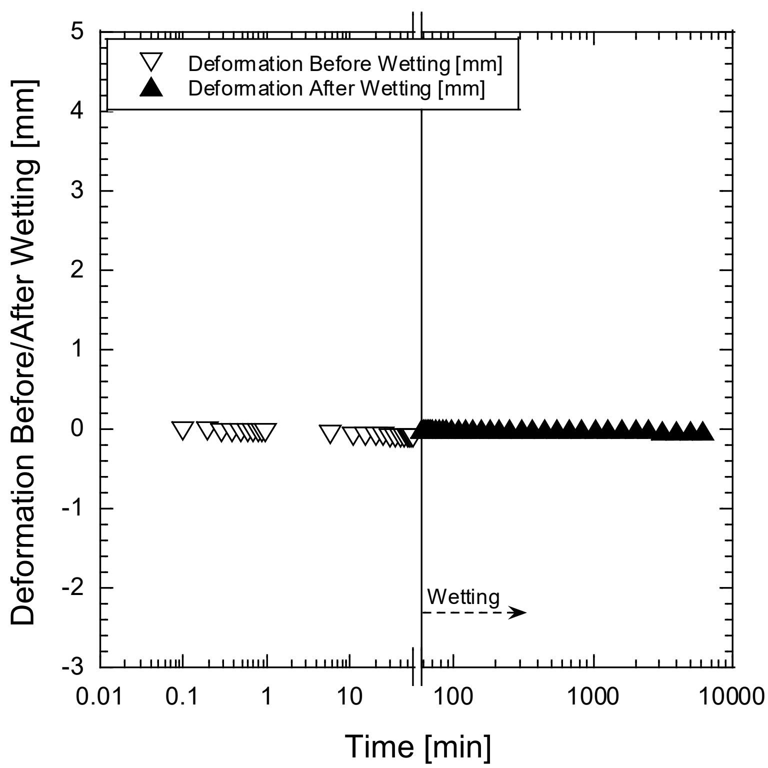


Figure B.40. *Swell test under 10 kPa on fly ash treated soil – additional tests.*

B.4.4.3 Swell Test Under 50 kPa

Table B.45. *Swell test under 50 kPa on fly ash treated soil – additional tests.*

Swell Test	Values	Units	Comments
Pressure to be applied=	50	kPa	
Load to be placed=	1606.0	g	Arm= 10x
Cell diameter, d=	63.34	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	524	g	
Water content, w%=	17.18	%	~Optimum water content
Soil Total weight, Wt=	152.3	g	
Volume of soil, V=	79877.4	mm^3	
Weight of solids, Ws=	130.0	g	
Height of solids, hs=	15.2	mm	
Compression prior to wetting, dh_1=	-0.119	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.2	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	-0.016	mm	Linear Collapse
Swell/Collapse= 100 x dh_2/h_1=	-0.1	%	% Collapse

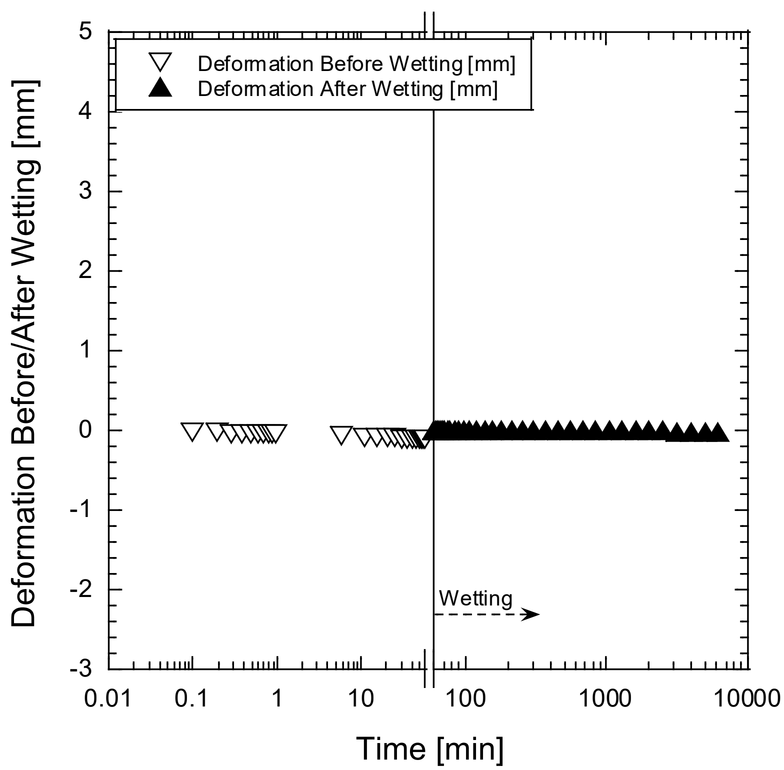


Figure B.41. *Swell test under 50 kPa on fly ash treated soil – additional tests.*

B.4.4.4 Swell Test Under 100 kPa

Table B.46. *Swell test under 100 kPa on fly ash treated – additional tests.*

Swell Test	Values	Units	Comments
Pressure to be applied=	100	kPa	
Load to be placed=	3223.2	g	Arm= 10x
Cell diameter, d=	63.45	mm	Two inches
Cell height, h=	25.3	mm	One inch
Cell weight=	520	g	
Water content, w%=	17.18	%	~Optimum water content
Soil Total weight, Wt=	160.1	g	
Volume of soil, V=	79965.4	mm^3	
Weight of solids, Ws=	136.6	g	
Height of solids, hs=	16.0	mm	
Compression prior to wetting, dh_1=	-1.228	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	24.1	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	-0.681	mm	Linear Collapse
Swell/Collapse= 100 x dh_2/h_1=	-2.8	%	% Collapse

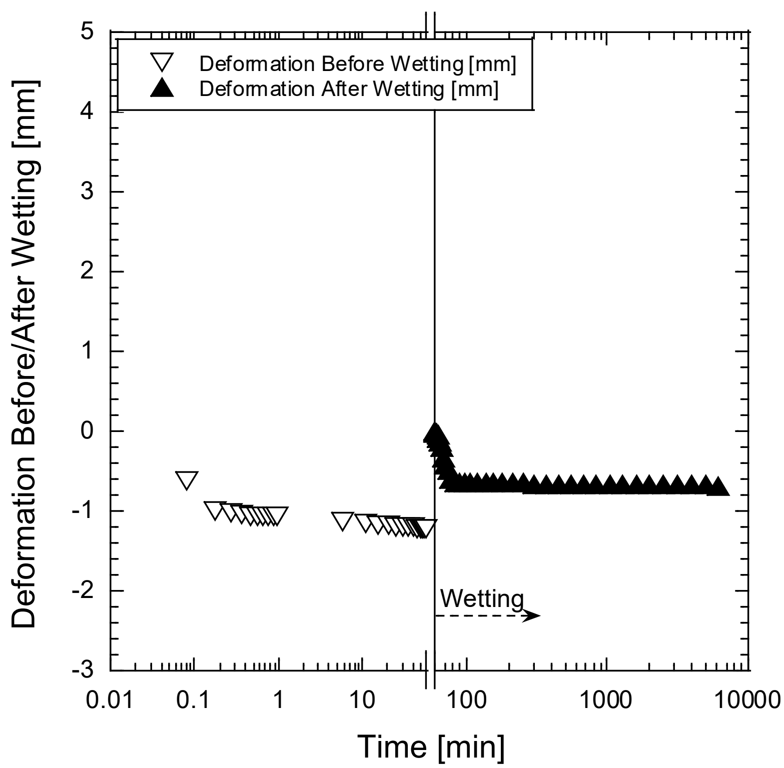


Figure B.42. *Swell test under 100 kPa on fly ash treated soil – additional tests.*

B.4.4.5 Swell Pressure and Swell Potential

Table B.47. *Swell pressure and swell potential on fly ash treated soil – additional tests.*

Swell Pressure [kPa]	Swell Potential [%]
1	0.1
10	0.2
50	-0.1
100	-2.8

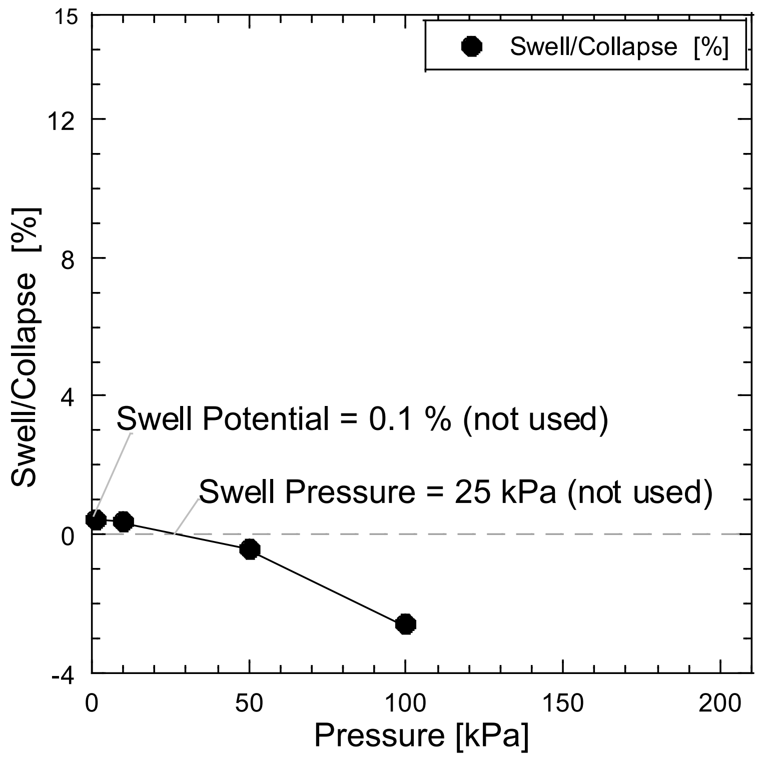


Figure B.43. *Swell pressure and swell potential of fly ash treated soil – additional tests.*

B.4.5 Swell Tests for Determining Optimum Fly Ash Content

B.4.5.1 Fly Ash Content of 9%

Table B.48. *Swell test under 1 kPa on soil treated with 9% fly ash.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	521.1	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	162.54	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	138.3	g	
Height of solids, hs=	16.2	mm	
Compression prior to wetting, dh_1=	-0.007	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.183	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.7	%	% swell

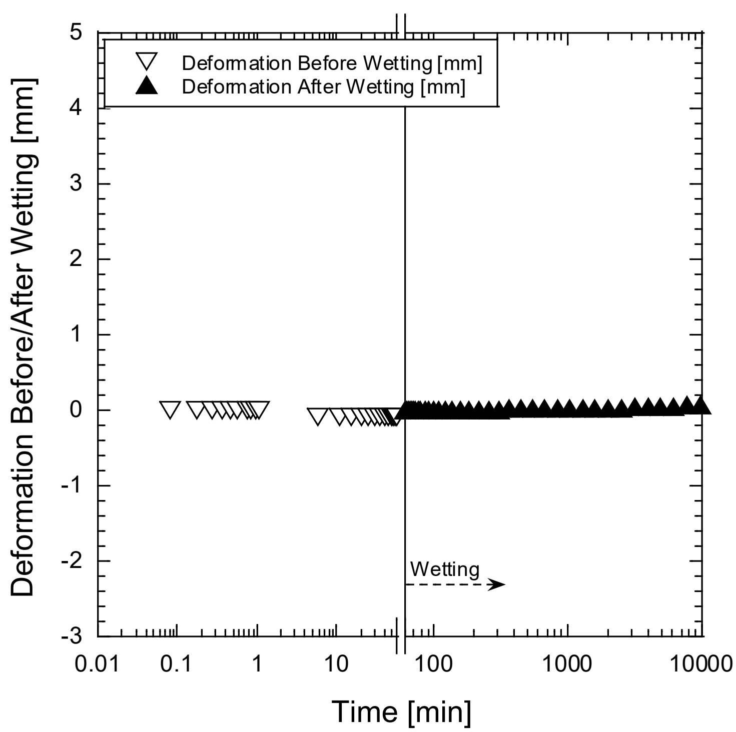


Figure B.44. *Swell test under 1 kPa on soil treated with 9% fly ash.*

B.4.5.2 Fly Ash Content of 11%

Table B.49. *Swell test under 1 kPa on soil treated with 11% fly ash.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	519	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	161.26	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	137.2	g	
Height of solids, hs=	16.0	mm	
Compression prior to wetting, dh_1=	-0.088	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.3	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.061	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.2	%	% swell

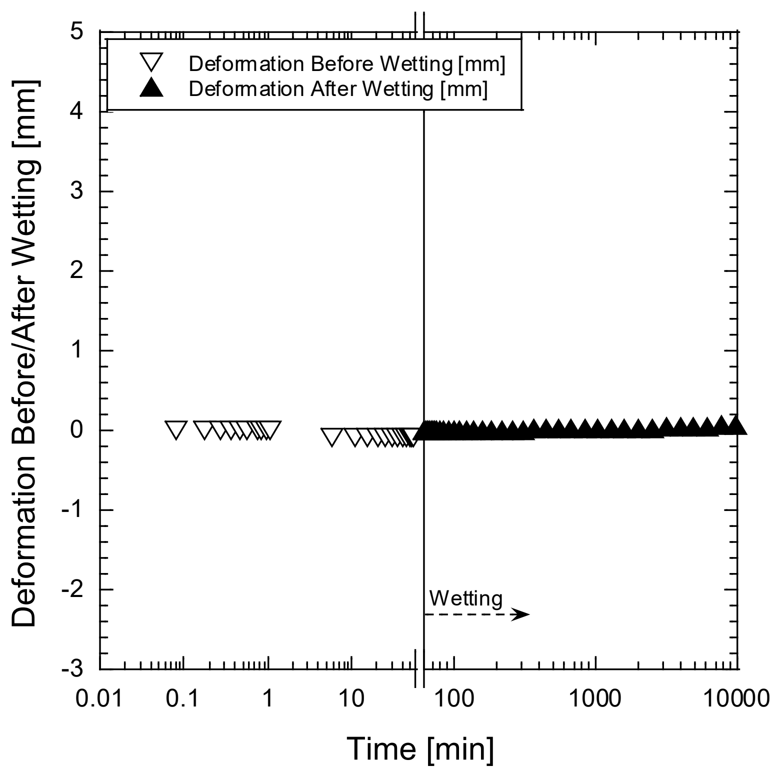


Figure B.45. *Swell test under 1 kPa on soil treated with 11% fly ash.*

B.4.5.3 Fly Ash Content of 11% - Second Trial

Table B.50. *Swell test under 1 kPa on soil treated with 11% fly ash – second trial.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	0	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	164.66	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	140.1	g	
Height of solids, hs=	16.4	mm	
Compression prior to wetting, dh_1=	-0.007	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.127	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.5	%	% swell

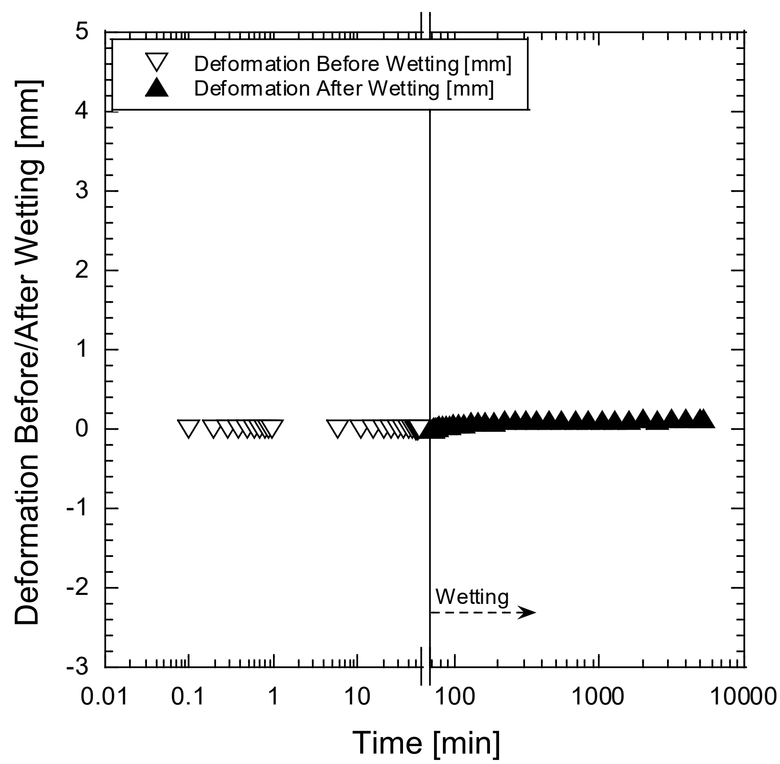


Figure B.46. *Swell test under 1 kPa on soil treated with 11% fly ash – second trial.*

B.4.5.4 Fly Ash Content of 13%

Table B.51. *Swell test under 1 kPa on soil treated with 13% fly ash.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	523.24	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	162.3	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	138.1	g	
Height of solids, hs=	16.1	mm	
Compression prior to wetting, dh_1=	-0.003	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.040	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.2	%	% swell

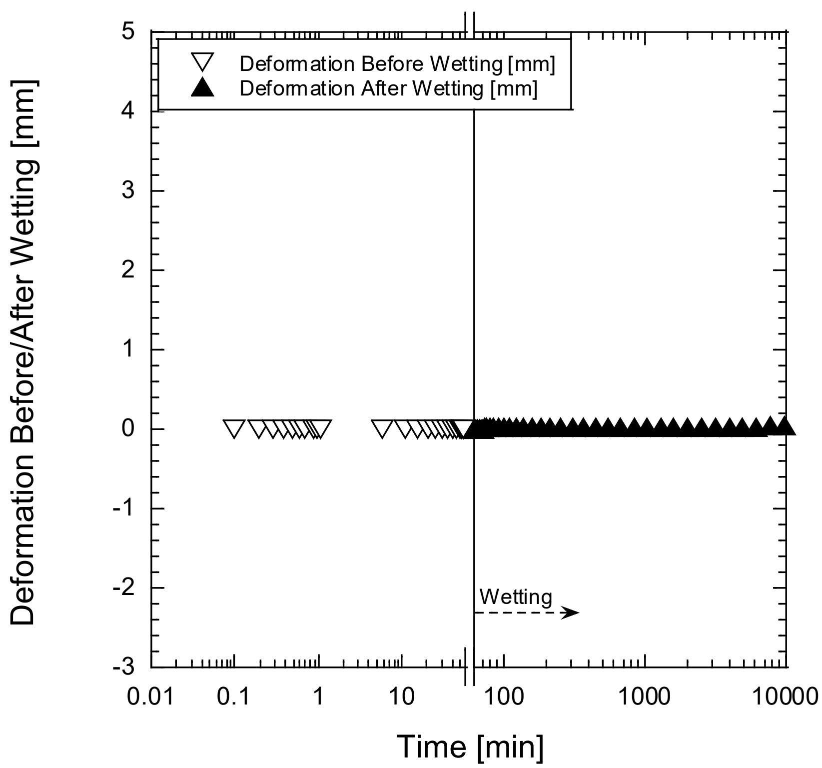


Figure B.47. *Swell test under 1 kPa on soil treated with 13% fly ash.*

B.4.5.5 Fly Ash Content of 15% - Second Trial

Table B.52. *Swell test under 1 kPa on soil treated with 15% fly ash - second trial.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	519.74	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	160.52	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	136.6	g	
Height of solids, hs=	16.0	mm	
Compression prior to wetting, dh_1=	-0.020	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.172	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.7	%	% swell

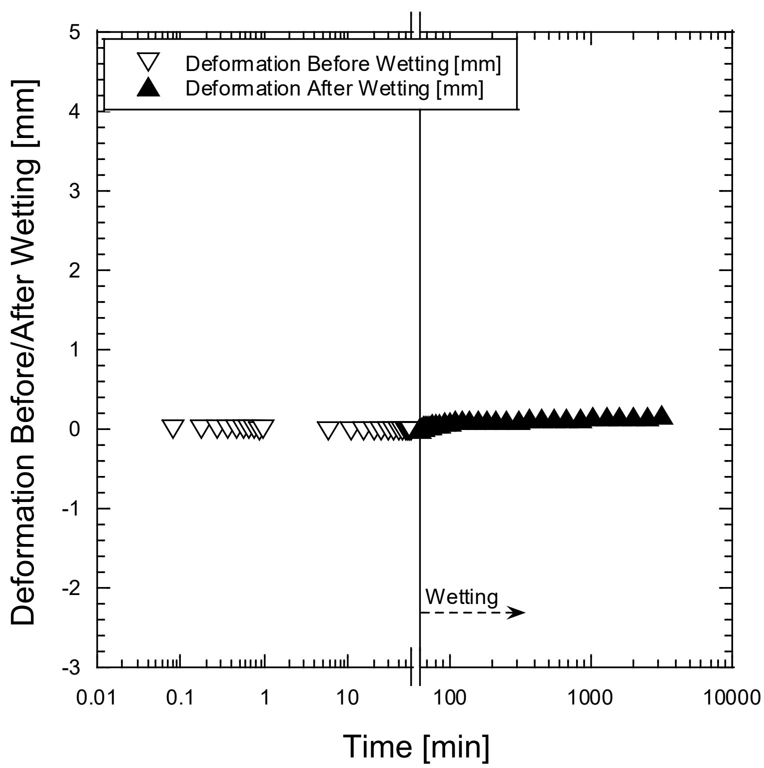


Figure B.48. *Swell test under 1 kPa on soil treated with 15% fly ash - second trial.*

B.4.5.6 Fly Ash Content of 15% - Third Trial

Table B.53. *Swell test under 1 kPa on soil treated with 15% fly ash - third trial.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	519	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	165.08	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	140.5	g	
Height of solids, hs=	16.4	mm	
Compression prior to wetting, dh_1=	-0.013	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.017	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.1	%	% swell

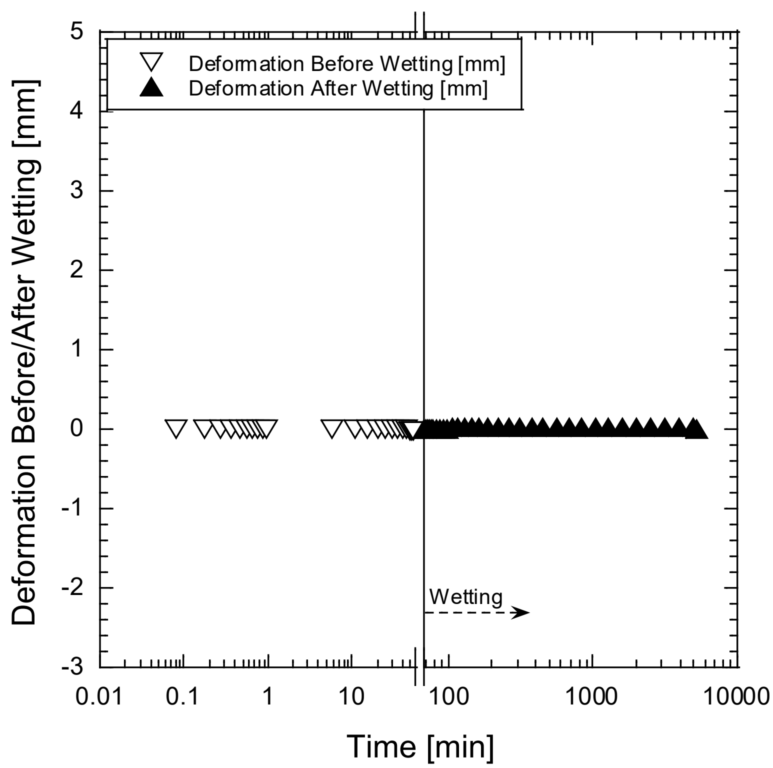


Figure B.49. *Swell test under 1 kPa on soil treated with 15% fly ash - third trial.*

B.4.5.7 Fly Ash Content of 17% - First Trial

Table B.54. *Swell test under 1 kPa on soil treated with 17% fly ash - first trial.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	*Leaking problem*
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	525.81	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	156.43	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	133.1	g	
Height of solids, hs=	15.6	mm	
Compression prior to wetting, dh_1=	-0.034	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.080	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.3	%	% swell

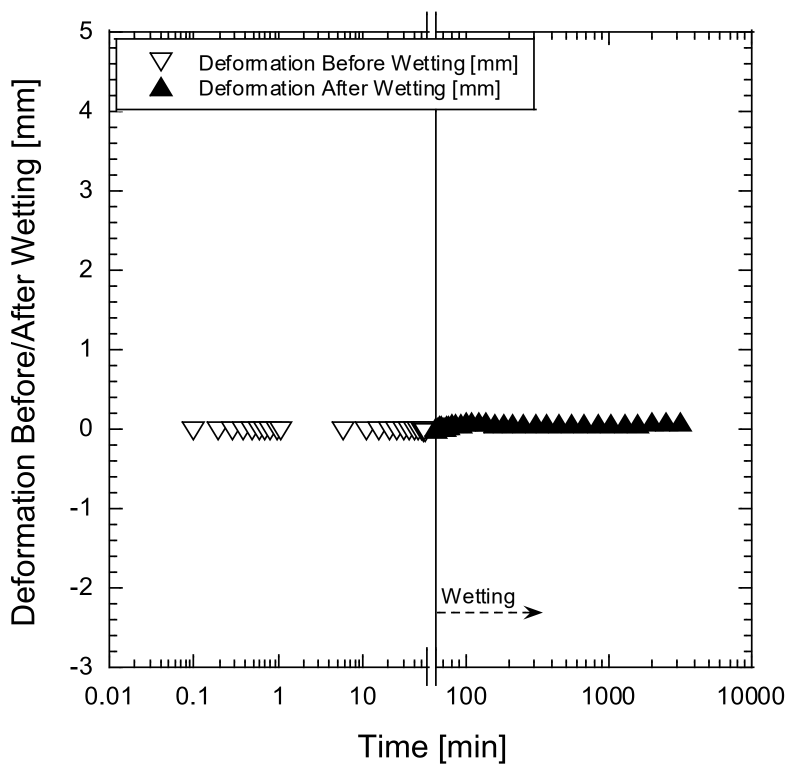


Figure B.50. *Swell test under 1 kPa on soil treated with 17% fly ash - first trial.*

B.4.5.8 Fly Ash Content of 17% - Second Trial

Table B.55. *Swell test under 1 kPa on soil treated with 17% fly ash - second trial.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	523.24	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	165.5	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	140.9	g	
Height of solids, hs=	16.5	mm	
Compression prior to wetting, dh_1=	-0.019	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.033	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.1	%	% swell

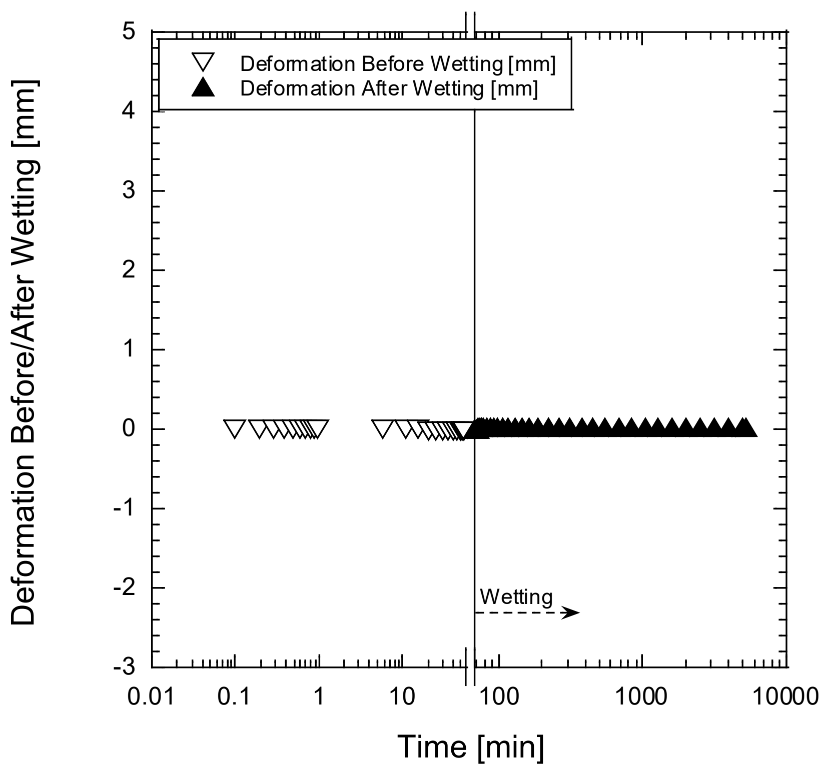


Figure B.51. *Swell test under 1 kPa on soil treated with 17% fly ash - second trial.*

B.4.5.9 Fly Ash Proportion vs. Swell Potential

Table B.56. *Fly ash proportion vs. swell potential.*

Fly Ash Proportion [%]	Swell Potential [%]
9	0.7
11	0.2
11	0.5
13	0.2
15	0.5
15	0.1
15	0.7
17	0.3
17	0.1

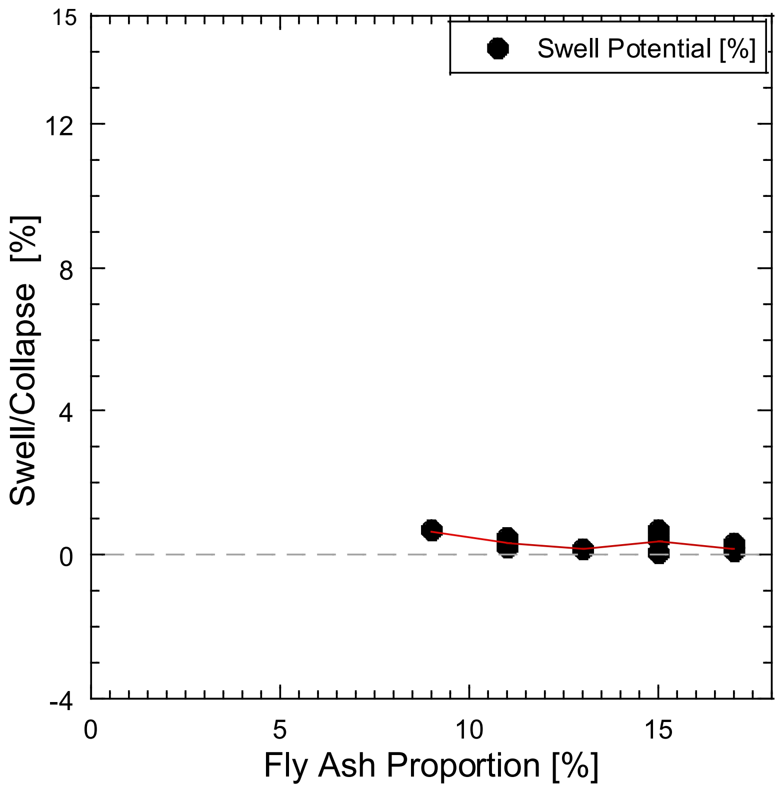


Figure B.52. *Fly ash proportion vs. swell potential.*

B.4.6 Lime Treated Soil Swell Test (3%)

B.4.6.1 Swell Test Under 1 kPa

Table B.57. *Swell test under 1 kPa on lime treated soil.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	523.2	g	
Water content, w%=	19.86	%	~Optimum water content
Soil Total weight, Wt=	158.7	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	132.4	g	
Height of solids, hs=	15.5	mm	
Compression prior to wetting, dh_1=	-0.006	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.006	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.0	%	% swell

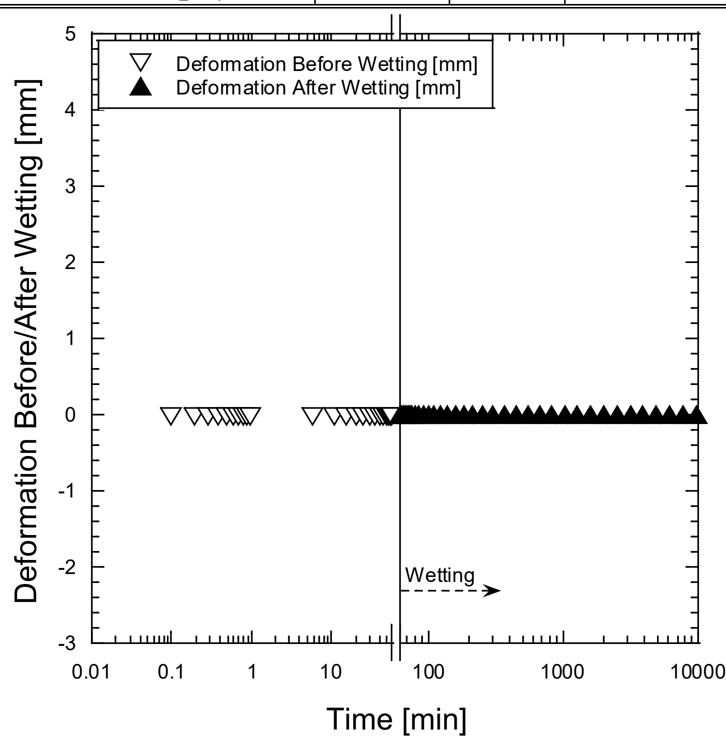


Figure B.53. *Swell test under 1 kPa on lime treated soil.*

B.4.6.2 Swell Test Under 1 kPa – Second Trial

Table B.58. *Swell test under 1 kPa on lime treated soil – second trial.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	521.05	g	
Water content, w%=	19.91	%	~Optimum water content
Soil Total weight, Wt=	161.1	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	134.4	g	
Height of solids, hs=	15.7	mm	
Compression prior to wetting, dh_1=	-0.022	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.005	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.0	%	% swell

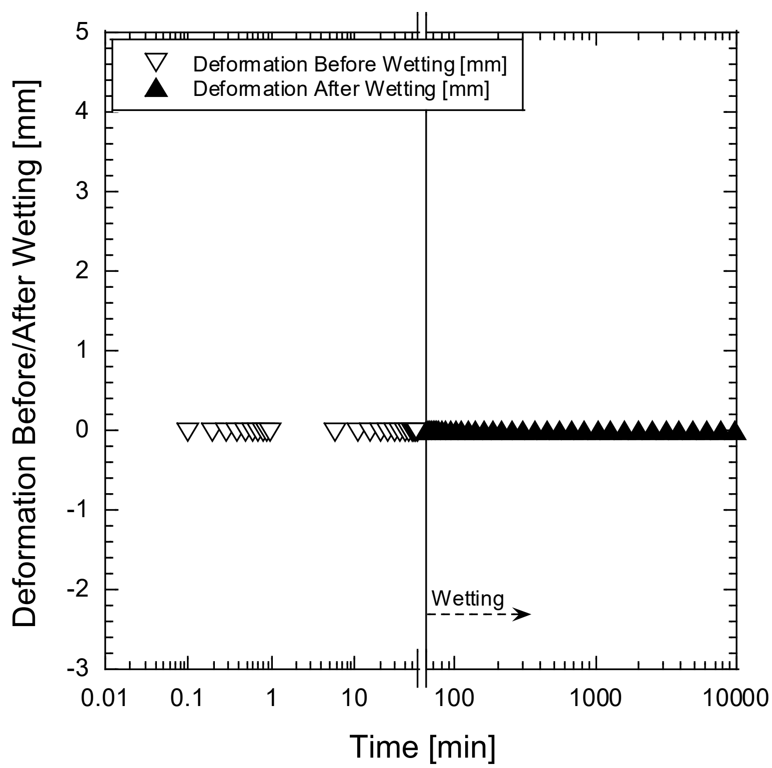


Figure B.54. *Swell test under 1 kPa on lime treated soil – second trial.*

B.4.6.3 Swell Test Under 10 kPa

Table B.59. *Swell test under 10 kPa on lime treated soil.*

Swell Test	Values	Units	Comments
Pressure to be applied=	10	kPa	
Load to be placed=	322.8	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	519.69	g	
Water content, w%=	19.77	%	~Optimum water content
Soil Total weight, Wt=	158.56	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	132.4	g	
Height of solids, hs=	15.5	mm	
Compression prior to wetting, dh_1=	-0.044	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	-0.072	mm	Linear Collapse
Swell/Collapse= 100 x dh_2/h_1=	-0.3	%	% Collapse

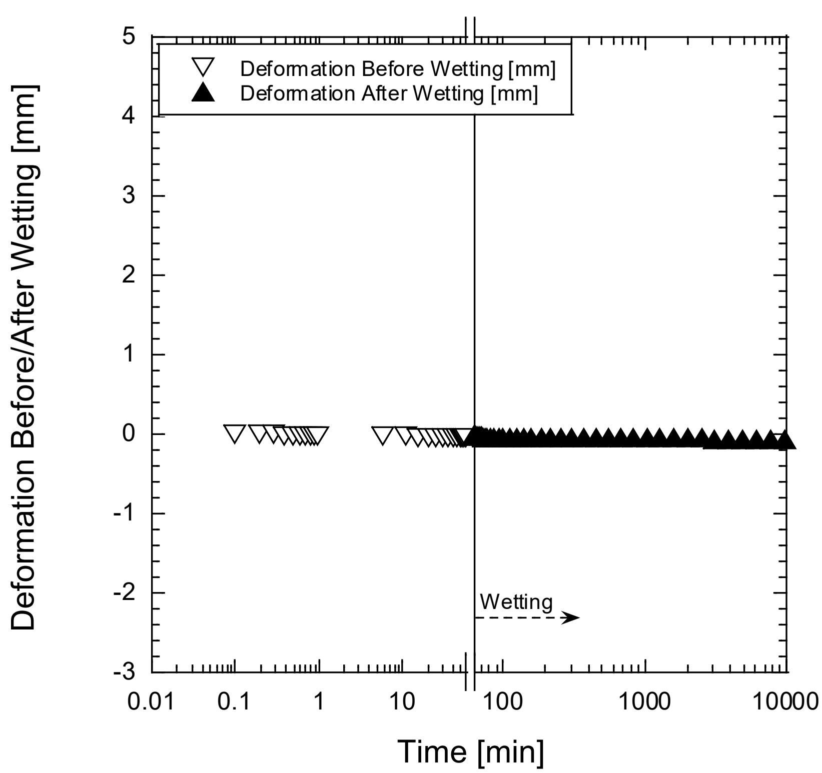


Figure B.55. *Swell test under 10 kPa on lime treated soil.*

B.4.6.4 Swell Test Under 50 kPa

Table B.60. *Swell test under 50 kPa on lime treated soil.*

Swell Test	Values	Units	Comments
Pressure to be applied=	50	kPa	
Load to be placed=	1614.1	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	518.13	g	
Water content, w%=	19.73	%	~Optimum water content
Soil Total weight, Wt=	158	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	132.0	g	
Height of solids, hs=	15.4	mm	
Compression prior to wetting, dh_1=	-0.172	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.2	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	-0.002	mm	Linear Collapse
Swell/Collapse= 100 x dh_2/h_1=	0.0	%	% Collapse

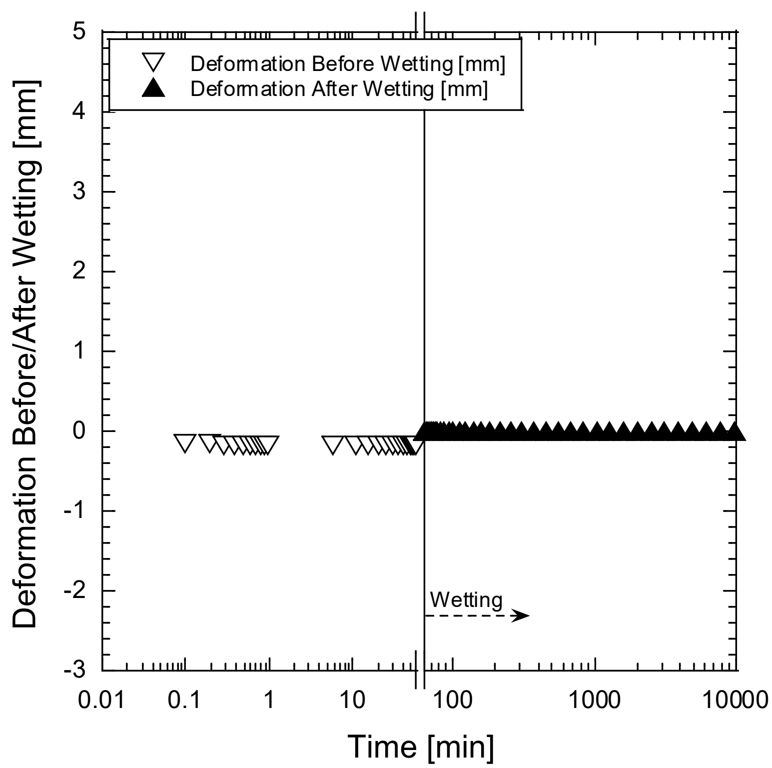


Figure B.56. *Swell test under 50 kPa on lime treated soil.*

B.4.6.5 Swell Test Under 100 kPa

Table B.61. *Swell test under 100 kPa on lime treated soil.*

Swell Test	Values	Units	Comments
Pressure to be applied=	100	kPa	
Load to be placed=	3228.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	525.77	g	
Water content, w%=	19.46	%	~Optimum water content
Soil Total weight, Wt=	160.28	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	134.2	g	
Height of solids, hs=	15.7	mm	
Compression prior to wetting, dh_1=	-0.215	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.2	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	-0.016	mm	Linear Collapse
Swell/Collapse= 100 x dh_2/h_1=	-0.1	%	% Collapse

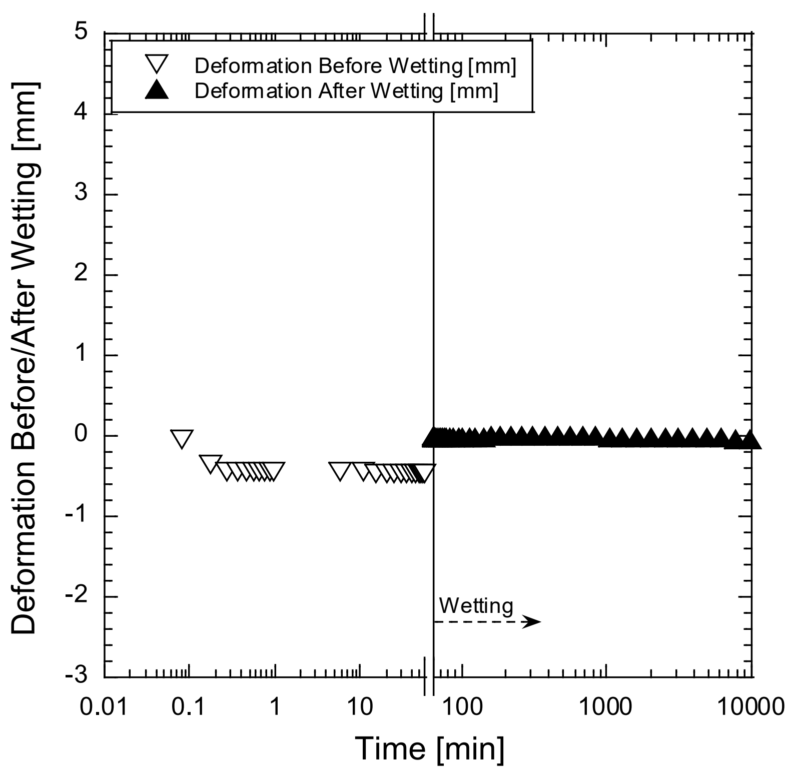


Figure B.57. *Swell test under 100 kPa on lime treated soil.*

B.4.6.6 Swell Test Under 207.3 kPa

Table B.62. *Swell test under 207.3 kPa on lime treated soil.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	518.21	g	
Water content, w%=	20.24	%	~Optimum water content
Soil Total weight, Wt=	160.61	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	133.6	g	
Height of solids, hs=	15.6	mm	
Compression prior to wetting, dh_1=	-0.473	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	24.9	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	-0.041	mm	Linear Collapse
Swell/Collapse= 100 x dh_2/h_1=	-0.2	%	% Collapse

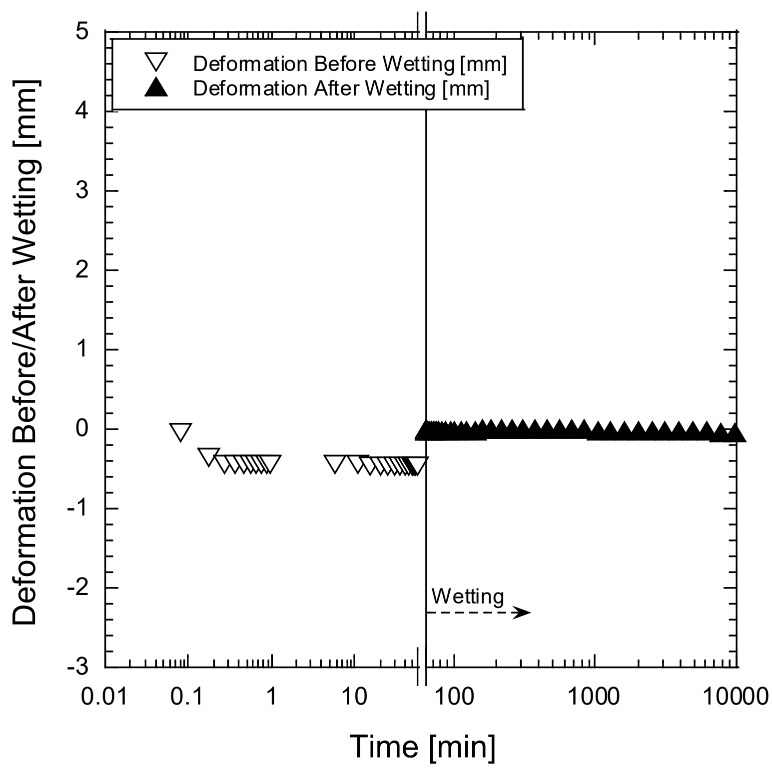


Figure B.58. *Swell test under 207.3 kPa on lime treated soil.*

B.4.6.7 Swell Pressure and Swell Potential

Table B.63. *Swell pressure and swell potential of lime treated soil.*

Swell Pressure [kPa]	Swell Potential [%]
1	0.0
1	0.0
1	0.0
10	-0.3
50	0.0
100	-0.1
207.3	-0.2

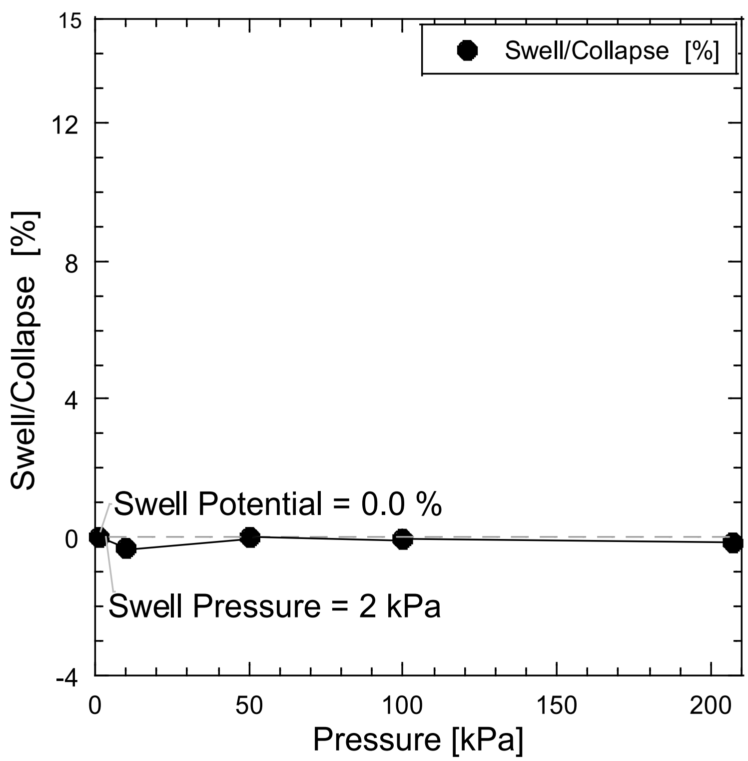


Figure B.59. *Swell pressure and swell potential of lime treated soil.*

B.4.7 Swell Tests for Determining Optimum Lime Content

B.4.7.1 Lime Content of 2%

Table B.64. *Swell test under 1 kPa on soil treated with 2% lime.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	0	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	156.18	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	132.9	g	
Height of solids, hs=	15.5	mm	
Compression prior to wetting, dh_1=	-0.012	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.031	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.1	%	% swell

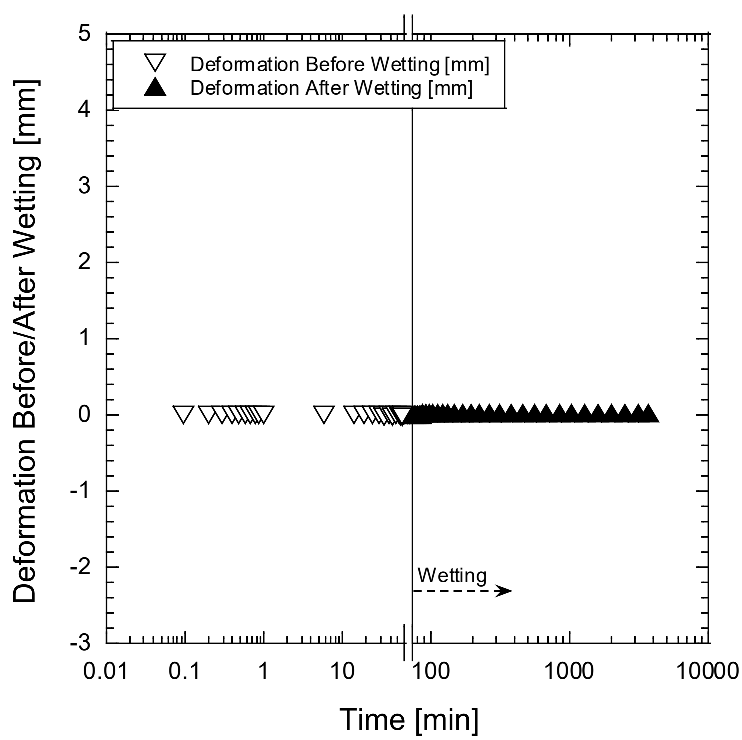


Figure B.60. *Swell test under 1 kPa on soil treated with 2% lime.*

B.4.7.2 Lime Content of 3% - Second Trial

Table B.65. *Swell test under 1 kPa on soil treated with 3% lime – second trial.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	519	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	155.11	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	132.0	g	
Height of solids, hs=	15.4	mm	
Compression prior to wetting, dh_1=	-0.005	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.001	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.0	%	% swell

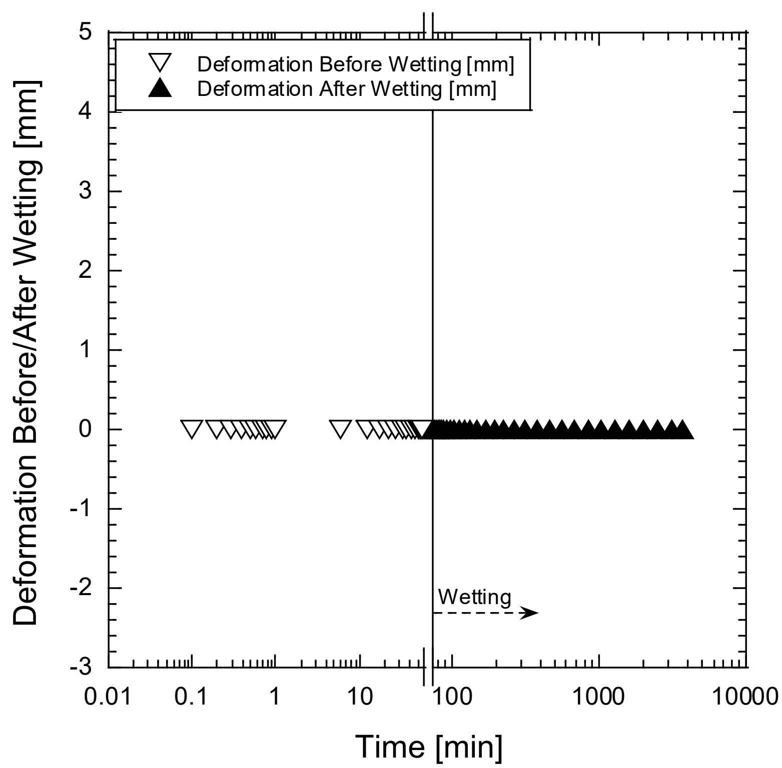


Figure B.61. *Swell test under 1 kPa on soil treated with 3% lime – second trial.*

B.4.7.3 Lime Content of 4%

Table B.66. *Swell test under 1 kPa on soil treated with 4% lime.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	518.34	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	153.07	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	130.3	g	
Height of solids, hs=	15.2	mm	
Compression prior to wetting, dh_1=	-0.007	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.012	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.0	%	% swell

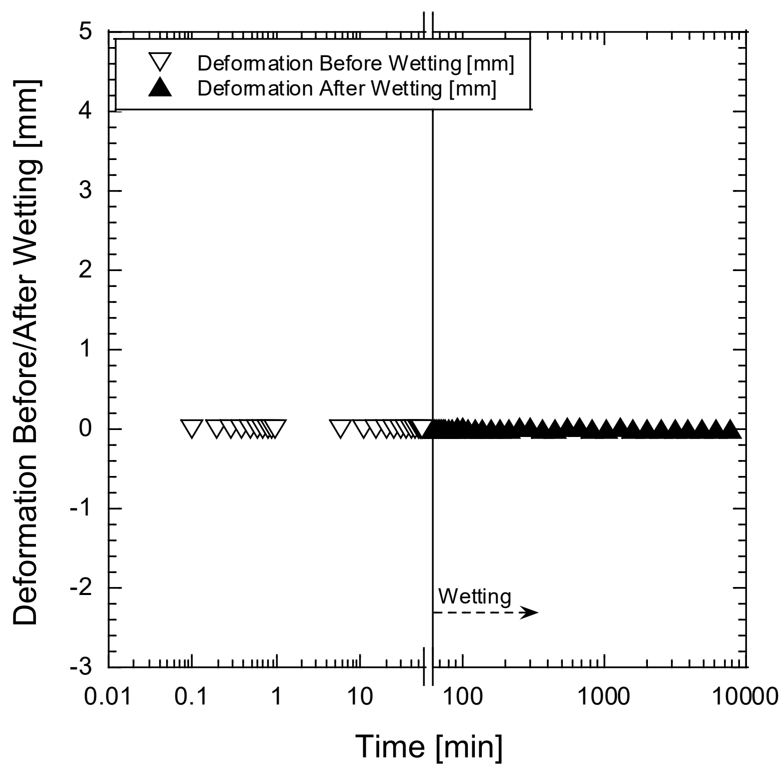


Figure B.62. *Swell test under 1 kPa on soil treated with 4% lime.*

B.4.7.4 Lime Content of 5%

Table B.67. *Swell test under 1 kPa on soil treated with 5% lime.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	523.24	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	150.74	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	128.3	g	
Height of solids, hs=	15.0	mm	
Compression prior to wetting, dh_1=	-0.003	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.004	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.0	%	% swell

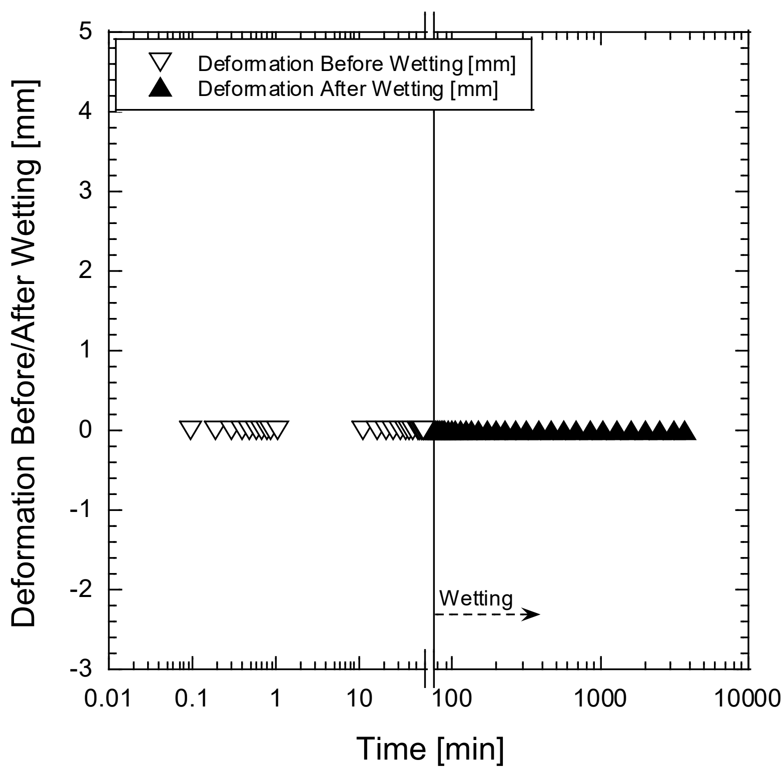


Figure B.63. *Swell test under 1 kPa on soil treated with 5% lime.*

B.4.7.5 Lime Content of 6%

Table B.68. *Swell test under 1 kPa on soil treated with 6% lime.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	523.24	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	151.34	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	128.8	g	
Height of solids, hs=	15.1	mm	
Compression prior to wetting, dh_1=	-0.013	[-]	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.001	[-]	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.0	%	% swell

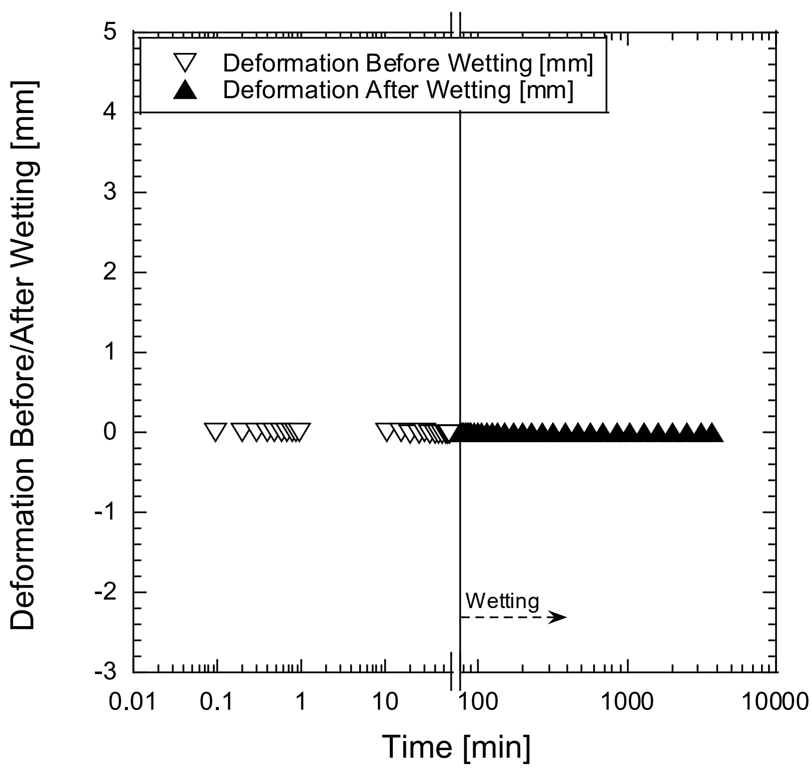


Figure B.64. *Swell test under 1 kPa on soil treated with 6% lime.*

B.4.7.6 Lime Proportion vs. Swell Potential

Table B.69. *Lime proportion vs. swell potential.*

Lime Proportion [%]	Swell Potential [%]
2	0.1
3	0.0
3	0.0
4	0.0
5	0.0
6	0.0

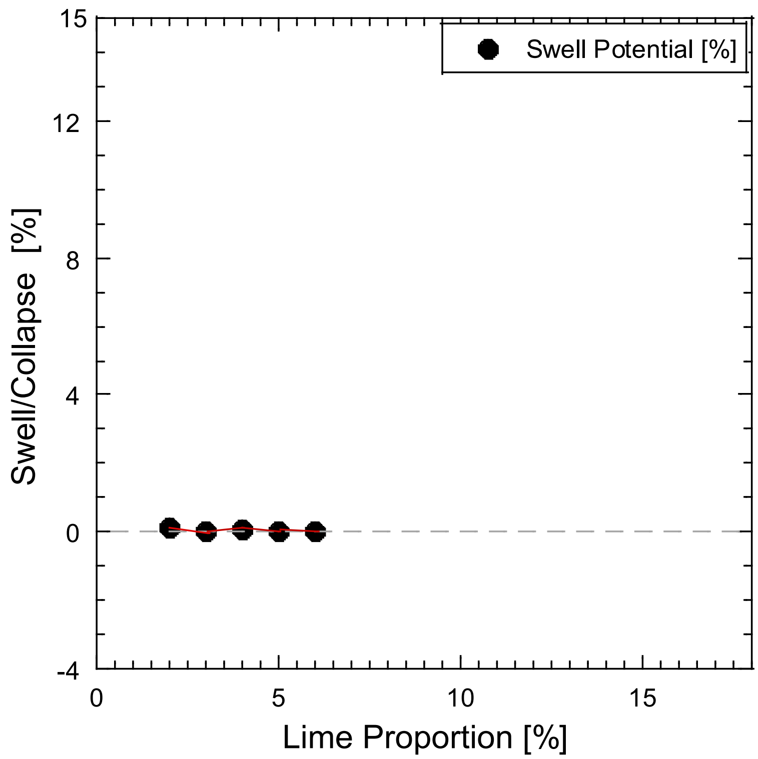


Figure B.65. *Lime proportion vs. swell potential.*

B.4.8 Swell Potential for Analyzing Variability of P1 Polymer Content – 7-d Curing

B.4.8.1 Swell Potential of Expansive Soil

Table B.70. *Swell test under 1 kPa on expansive soil with seven days of curing.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	523.2	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	160.52	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	136.6	g	
Height of solids, hs=	16.0	mm	
Compression prior to wetting, dh_1=	-0.019	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	1.030	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	4.1	%	% swell

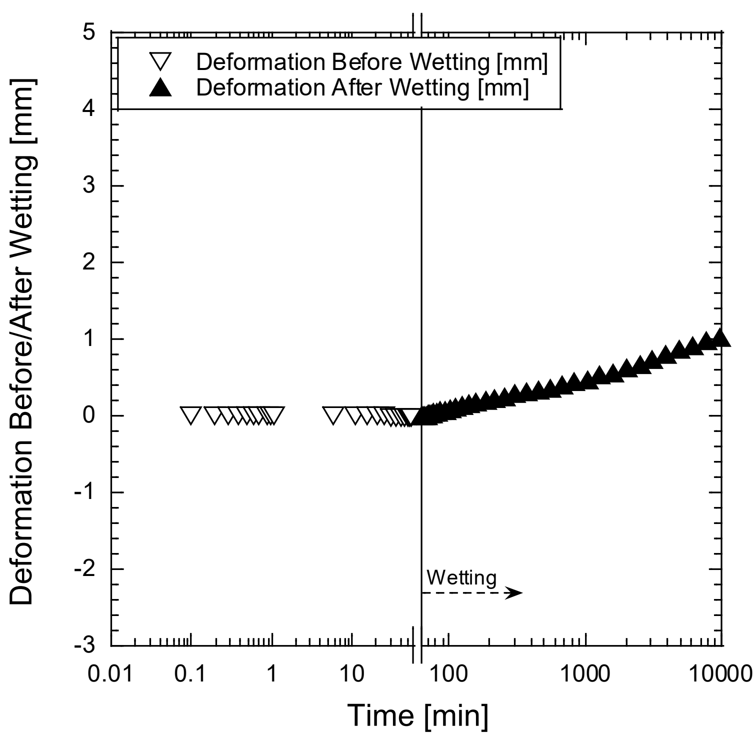


Figure B.66. *Swell test under 1 kPa on expansive soil with seven days of curing.*

B.4.8.2 Swell Potential of the Fly Ash Treated Soil

Table B.71. *Swell test under 1 kPa on fly ash treated soil with seven days of curing.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	519.69	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	162.96	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	138.7	g	
Height of solids, hs=	16.2	mm	
Compression prior to wetting, dh_1=	-0.016	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.024	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.1	%	% swell

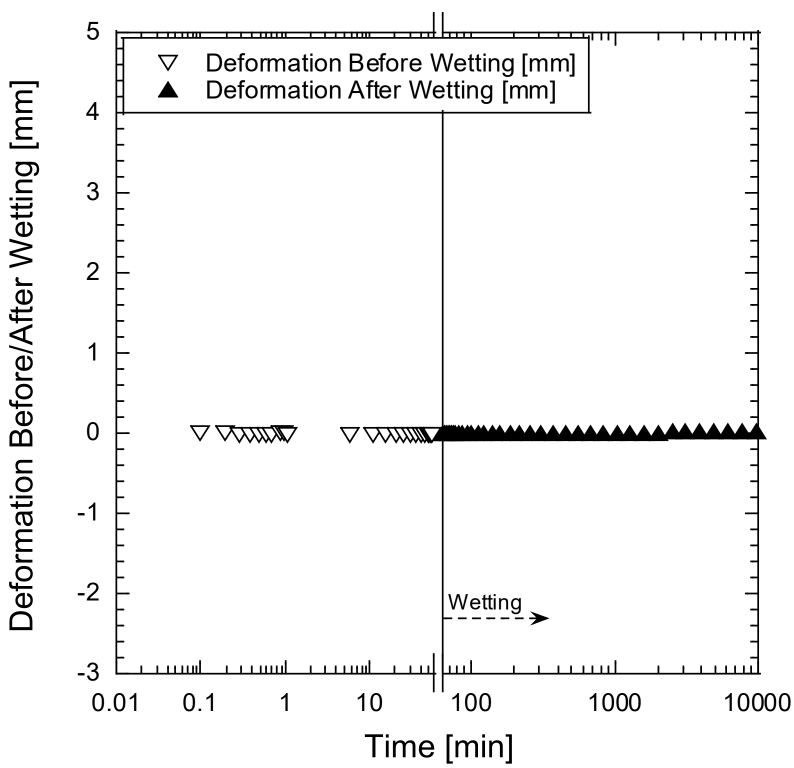


Figure B.67. *Swell test under 1 kPa on fly ash treated soil with seven days of curing.*

B.4.8.3 Swell Potential of the Lime Treated Soil

Table B.72. *Swell test under 1 kPa on lime treated soil with seven days of curing.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	518.13	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	162.46	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	138.3	g	
Height of solids, hs=	16.2	mm	
Compression prior to wetting, dh_1=	-0.002	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	-0.007	mm	Linear Collapse
Swell/Collapse= 100 x dh_2/h_1=	0.0	%	% Collapse

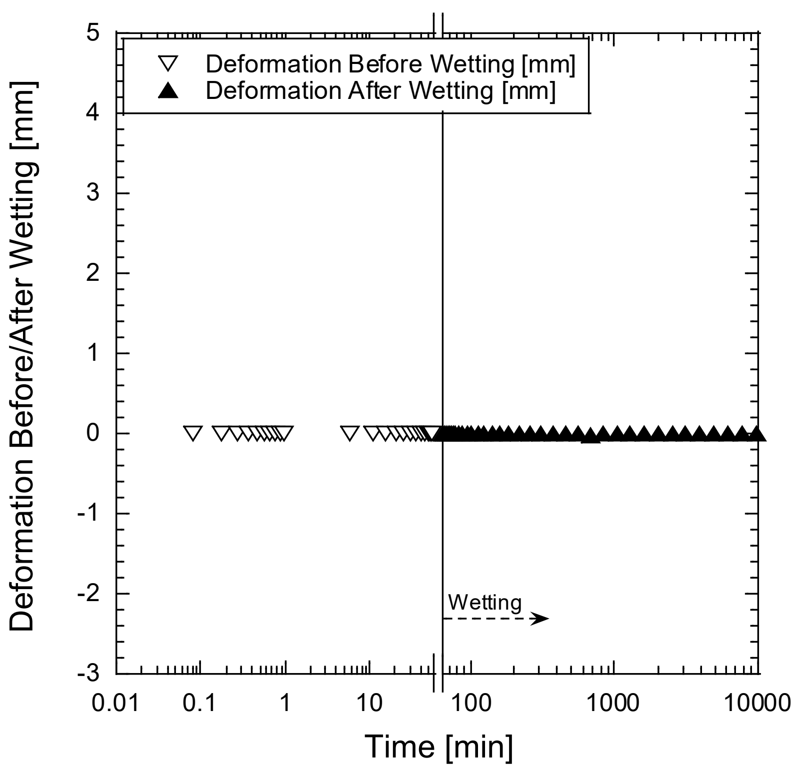


Figure B.68. *Swell test under 1 kPa on lime treated soil with seven days of curing.*

B.4.8.4 Swell Potential of 18.4% P1 Treated Soil

Table B.73. *Swell test under 1 kPa on 18.4% P1 treated soil with seven days of curing.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	525.77	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	149.17	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	127.0	g	
Height of solids, hs=	14.8	mm	
Compression prior to wetting, dh_1=	0.002	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.438	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	1.7	%	% swell

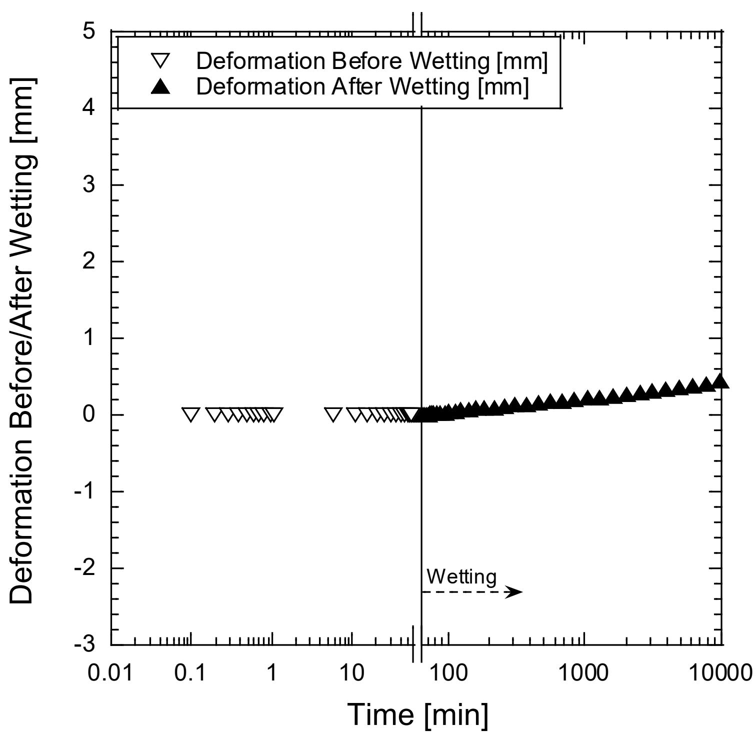


Figure B.69. *Swell test under 1 kPa on 18.4% P1 treated soil with seven days of curing.*

B.4.8.5 Swell Potential of 9.2% P1 Treated Soil

Table B.74. *Swell test under 1 kPa on 9.2% P1 treated soil with seven days of curing.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	518.21	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	154.77	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	131.7	g	
Height of solids, hs=	15.4	mm	
Compression prior to wetting, dh_1=	0.032	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	1.326	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	5.2	%	% swell

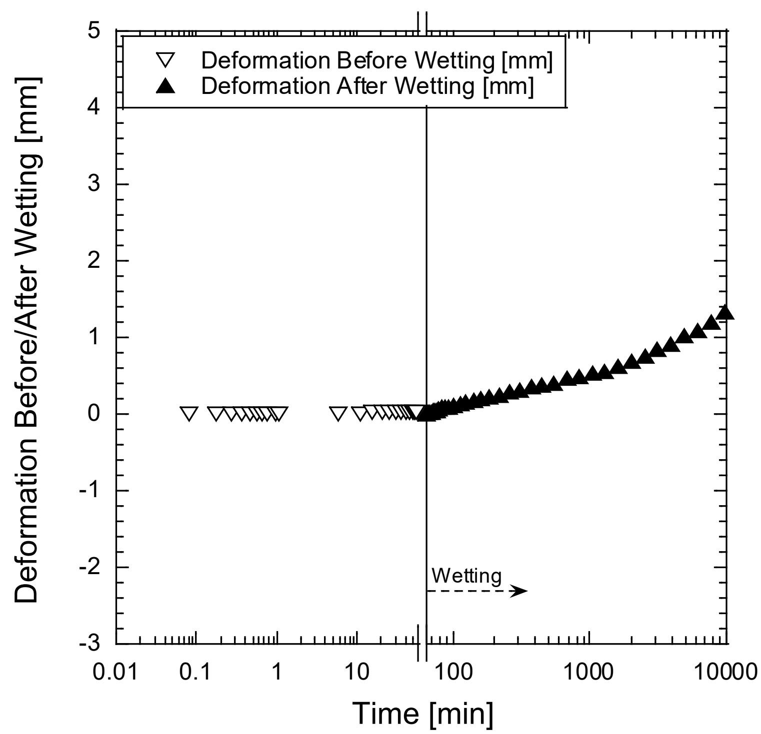


Figure B.70. *Swell test under 1 kPa on 9.2% P1 treated soil with seven days of curing.*

B.4.8.6 Swell Potential of 4.6% P1 Treated Soil

Table B.75. *Swell test under 1 kPa on 4.6% P1 treated soil with seven days of curing.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	521.05	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	156.51	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	133.2	g	
Height of solids, hs=	15.6	mm	
Compression prior to wetting, dh_1=	0.002	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.669	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	2.6	%	% swell

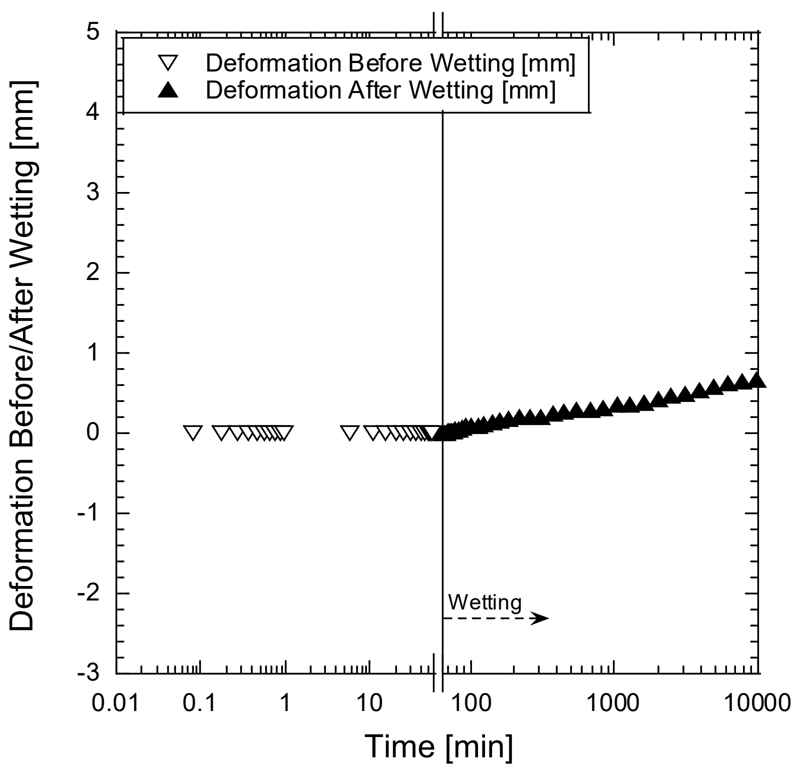


Figure B.71. *Swell test under 1 kPa on 4.6% P1 treated soil with seven days of curing.*

B.4.8.7 Effect of P1 Compared with Lime, Fly Ash, and Expansive Soil

Table B.76. *Effect of P1 compared with lime, fly ash, and expansive soil.*

	P1 9.2% Treated	P1 4.6% Treated	P1 18.4% Treated	Fly Ash 15% Treated	Lime 3% Treated
Swell Potential [%]	5.2	2.6	1.7	0.1	0.0

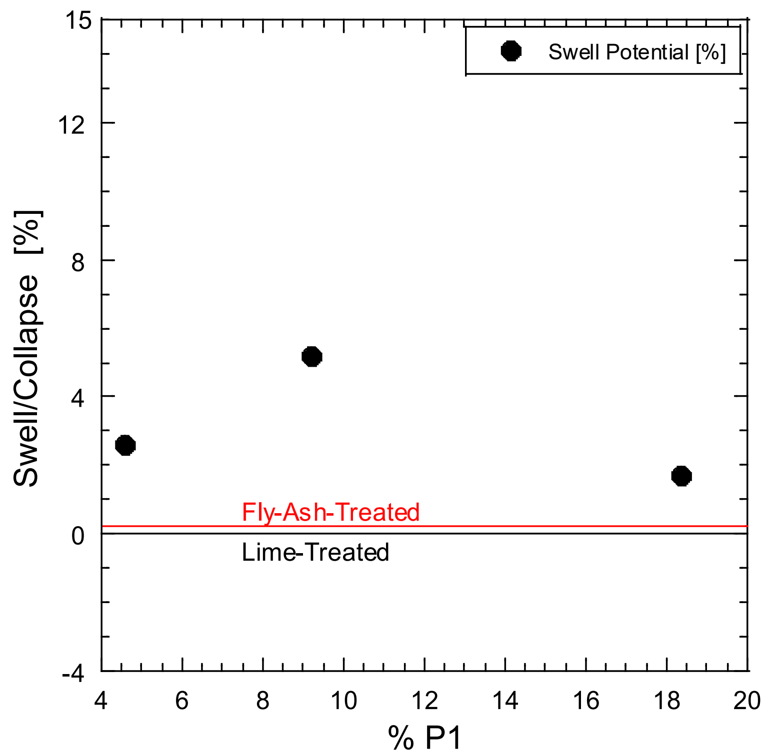


Figure B.72. *Effect of P1 compared with lime, fly ash, and expansive soil.*

B.4.9 Swell Potential for Assessing Four Polymer Types with 24 Hour Evaporation

B.4.9.1 Swell Potential of the Fly Ash Treated Soil

Table B.77. *Swell test under 1 kPa on fly ash treated soil with 24 hours of air-drying.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	523.2	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	155.15	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	132.0	g	
Height of solids, hs=	15.4	mm	
Compression prior to wetting, dh_1=	0.000	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.787	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	3.1	%	% swell

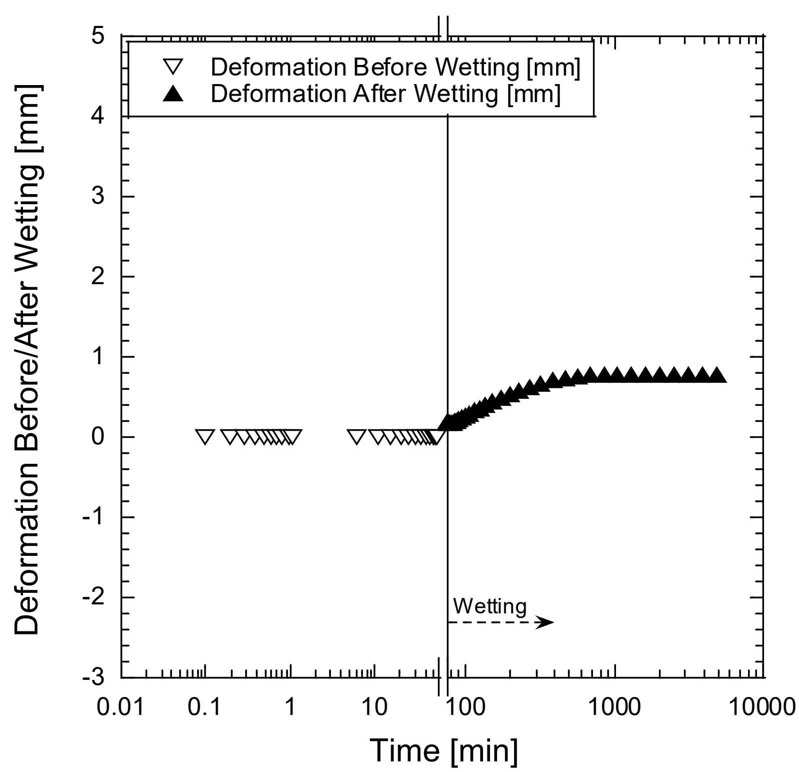


Figure B.73. *Swell test under 1 kPa on fly ash treated soil with 24 hours of air-drying.*

B.4.9.2 Swell Potential of the Lime Treated Soil

Table B.78. *Swell test under 1 kPa on lime treated soil with 24 hours of air-drying.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	519.69	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	148.6	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	126.5	g	
Height of solids, hs=	14.8	mm	
Compression prior to wetting, dh_1=	0.000	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.196	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.8	%	% swell

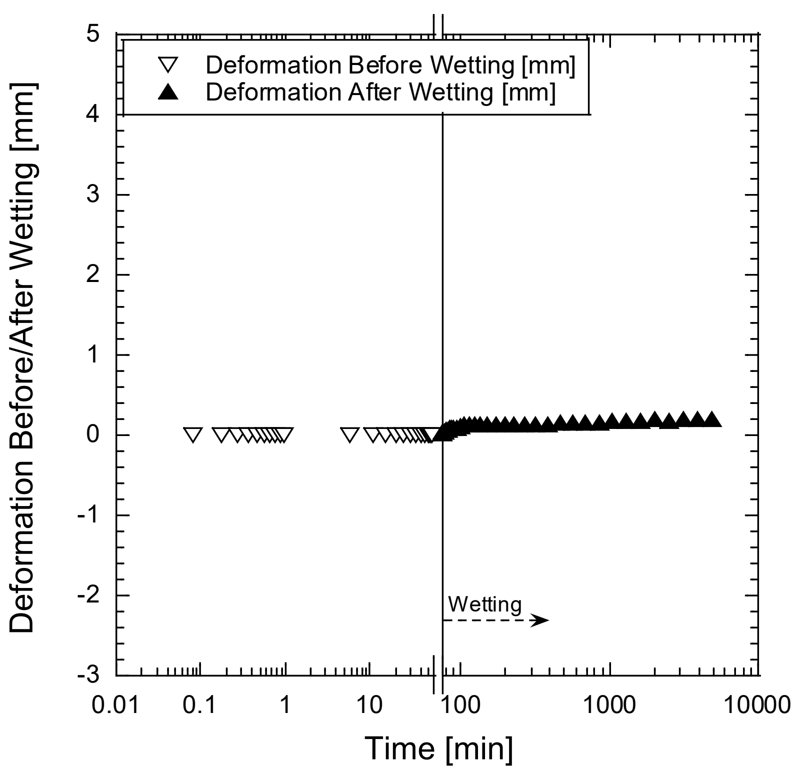


Figure B.74. *Swell test under 1 kPa on lime treated soil with 24 hours of air-drying.*

B.4.9.3 Swell Potential of the 4.6% of the P1 Treated Soil

Table B.79. *Swell test under 1 kPa for the 4.6% on P1 treated soil with 24 hours of air-drying.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	518.13	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	152.26	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	129.6	g	
Height of solids, hs=	15.1	mm	
Compression prior to wetting, dh_1=	-0.039	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	2.207	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	8.7	%	% swell

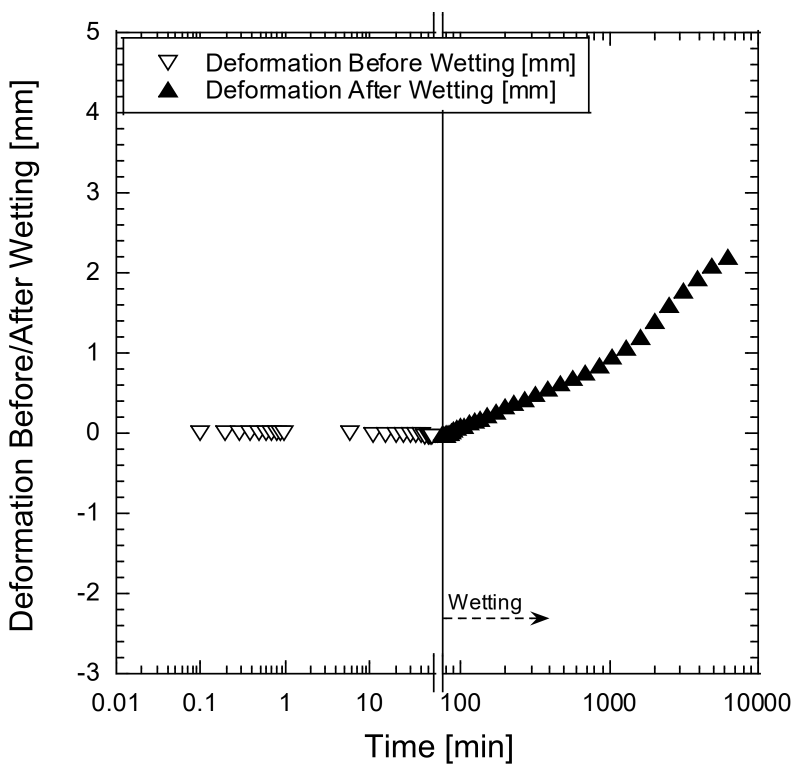


Figure B.75. *Swell test under 1 kPa on 4.6% P1 treated soil with 24 hours of air-drying.*

B.4.9.4 Swell Potential of the 4.6% of P2 Treated Soil

Table B.80. *Swell test under 1 kPa on 4.6% P2 treated soil with 24 hours of air-drying.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	525.77	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	153.55	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	130.7	g	
Height of solids, hs=	15.3	mm	
Compression prior to wetting, dh_1=	0.000	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	2.040	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	8.0	%	% swell

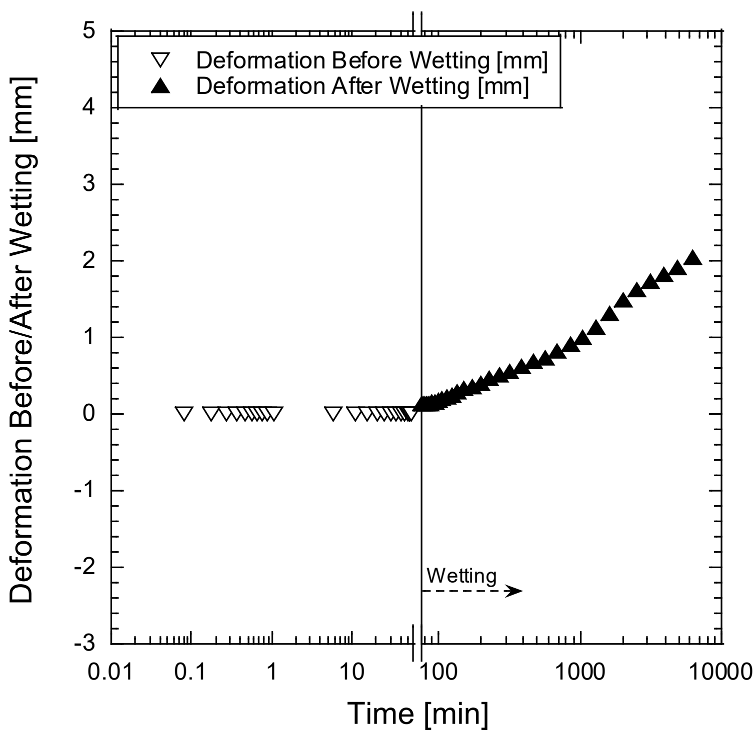


Figure B.76. *Swell test under 1 kPa on 4.6% P2 treated soil with 24 hours of air-drying.*

B.4.9.5 Swell Potential of 4.6% P3 Treated Soil

Table B.81. *Swell test under 1 kPa on 4.6% P3 treated soil with 24 hours of air-drying.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	518.21	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	150.7	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	128.3	g	
Height of solids, hs=	15.0	mm	
Compression prior to wetting, dh_1=	0.000	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	2.013	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	7.9	%	% swell

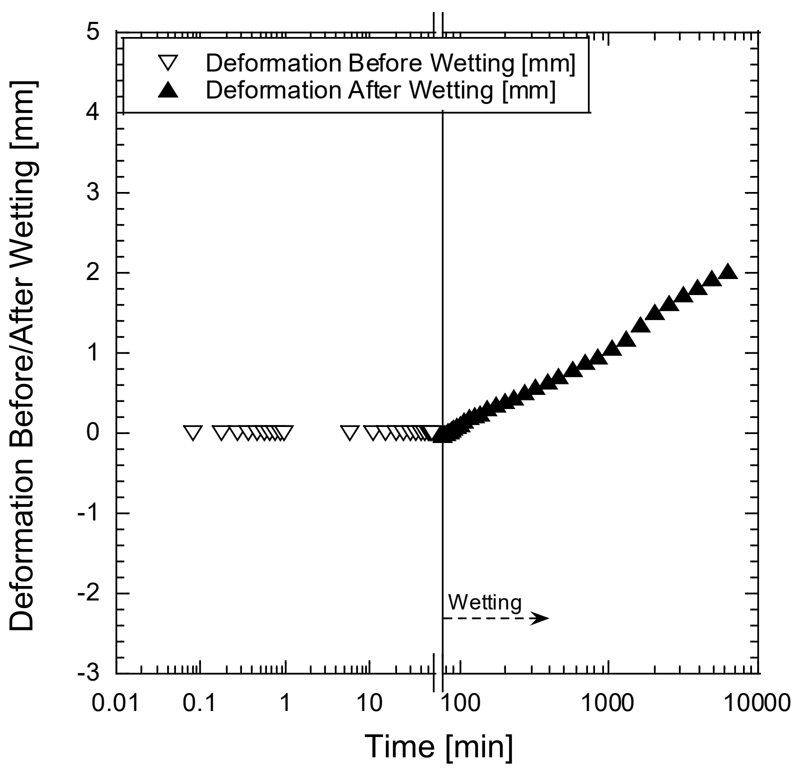


Figure B.77. *Swell test under 1 kPa on 4.6% P3 treated soil with 24 hours of air-drying.*

B.4.9.6 Swell Potential on 4.6% P4 Treated Soil

Table B.82. *Swell test under 1 kPa on 4.6% on P4 treated soil with 24 hours of air-drying.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	521.05	g	
Water content, w%=	17.5	%	~Optimum water content
Soil Total weight, Wt=	152.62	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	129.9	g	
Height of solids, hs=	15.2	mm	
Compression prior to wetting, dh_1=	-0.007	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	1.203	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	4.7	%	% swell

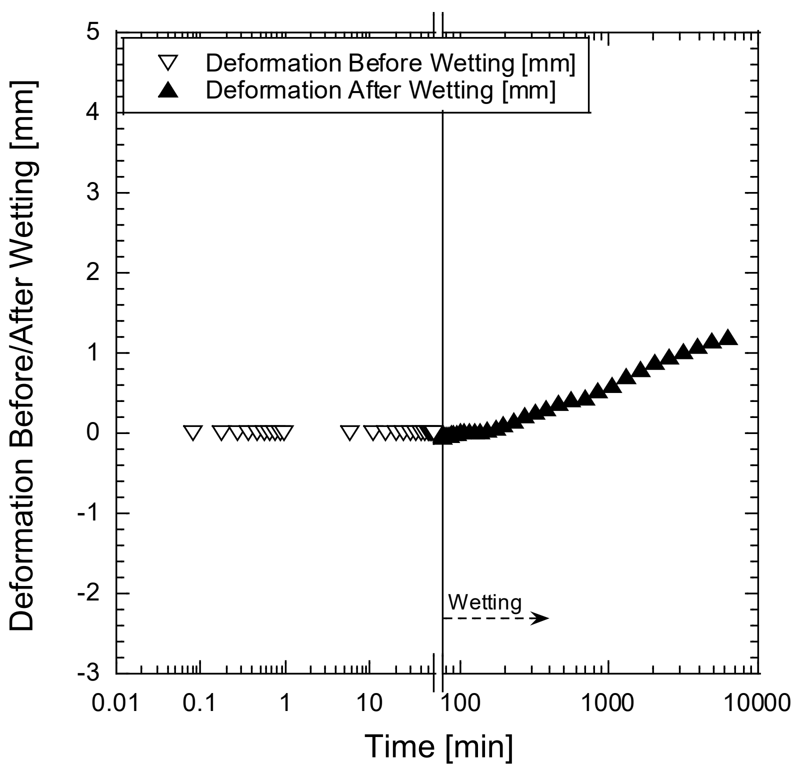


Figure B.78. *Swell test under 1 kPa on 4.6% P4 treated soil with 24 hours of air-drying.*

B.4.9.7 Effect of Four Polymer Types Compared with Lime and Fly Ash with 24 Hours of Evaporation

Table B.83. *Effect of four polymer types compared with lime and fly ash with 24 hours of air-drying.*

	P1 4.6% Treated	P2 4.6% Treated	P3 4.6% Treated	P4 4.6% Treated	Fly Ash Treated	Lime Treated
Swell Potential [%]	8.7	8.0	7.9	4.7	3.1	0.8

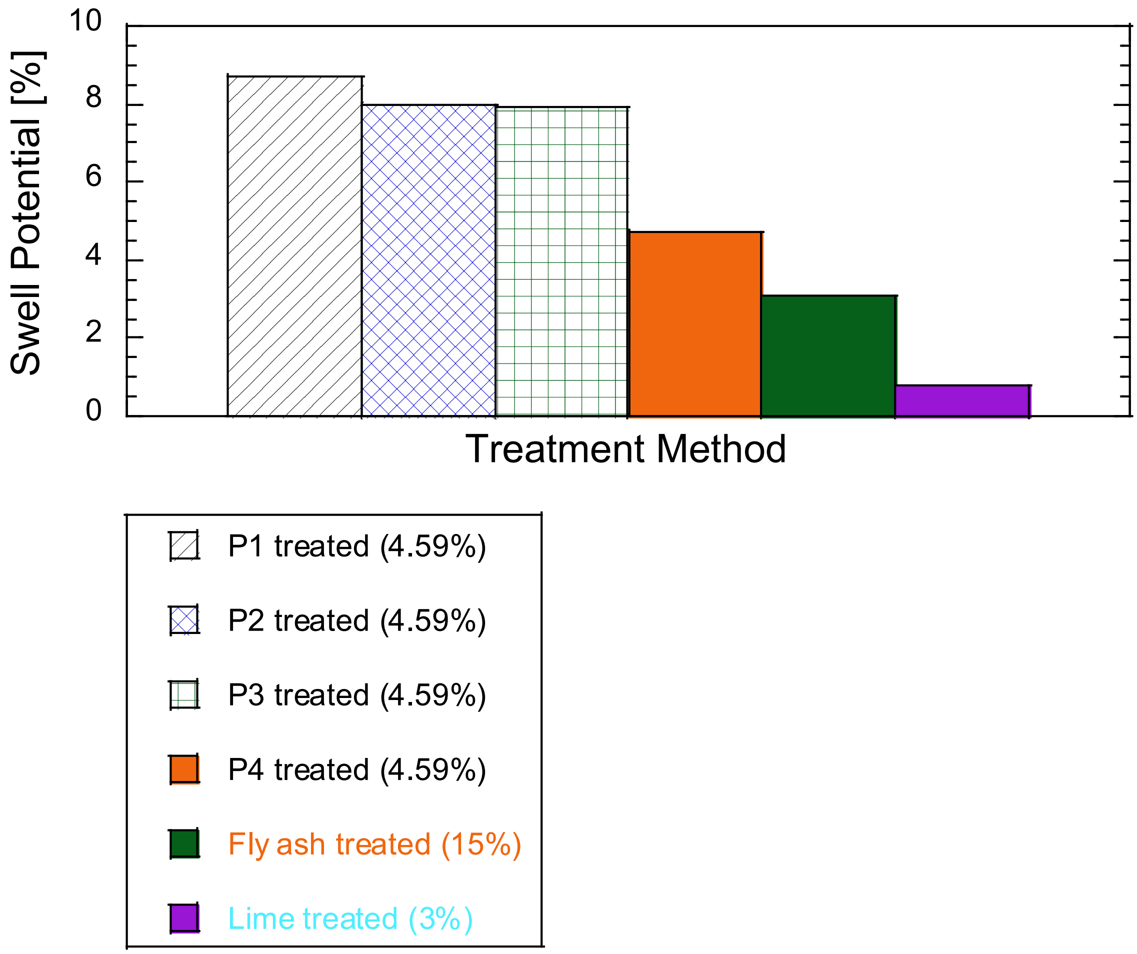


Figure B.79. *Effect of four polymer types compared with lime and fly ash with 24 hours of air-drying.*

B.4.10 P4 Treated Swell Test (5%)

B.4.10.1 Swell Test Under 1 kPa

Table B.84. *Swell test under 1 kPa on P4 treated soil.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	523.2	g	
Water content, w%=	20.2	%	~Optimum water content
Soil total weight, Wt=	154.15	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	128.2	g	
Height of solids, hs=	15.0	mm	
Compression prior to wetting, dh_1=	-0.036	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	1.247	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	4.9	%	% swell

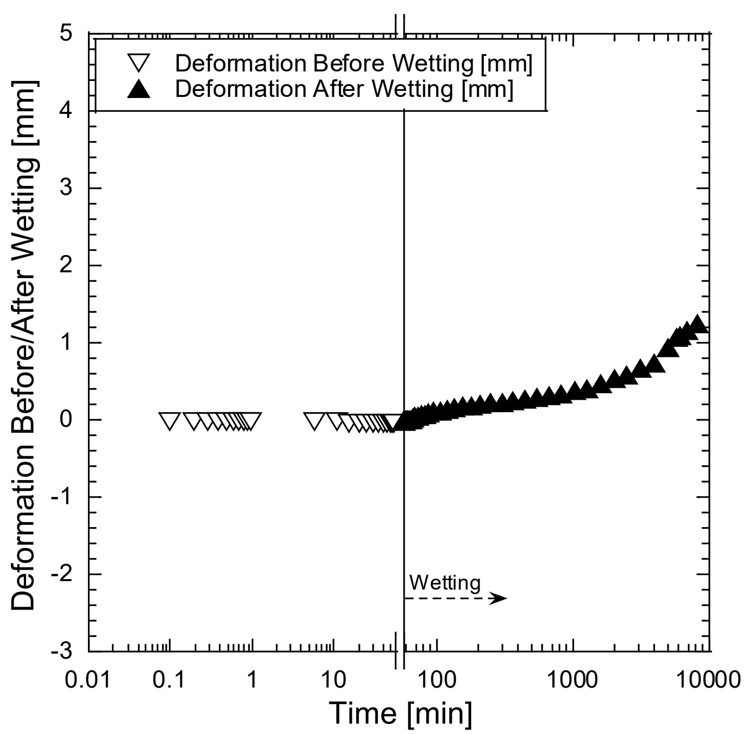


Figure B.80. *Swell test under 1 kPa on P4 treated soil.*

B.4.10.2 Swell Test Under 1 kPa – Second Trial

Table B.85. *Swell test under 1 kPa on P4 treated soil – second trial.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	521.05	g	
Water content, w%=	19.53	%	~Optimum water content
Soil Total weight, Wt=	156.75	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	131.1	g	
Height of solids, hs=	15.3	mm	
Compression prior to wetting, dh_1=	-0.031	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	1.012	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	4.0	%	% swell

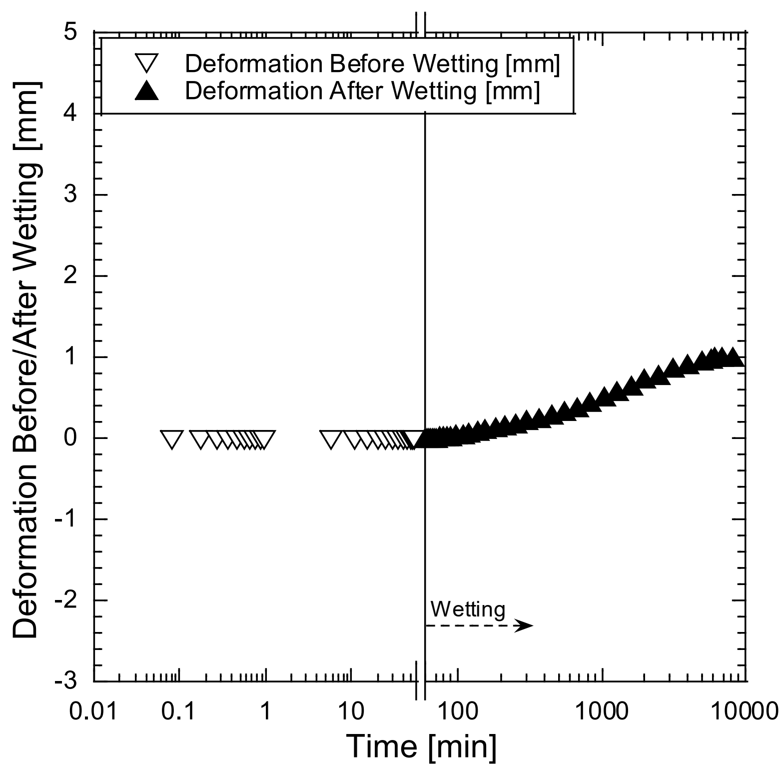


Figure B.81. *Swell test under 1 kPa on P4 treated soil – second trial.*

B.4.10.3 Swell Test Under 10 kPa

Table B.86. *Swell test under 10 kPa on P4 treated soil.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	519.69	g	
Water content, w%=	19.18	%	~Optimum water content
Soil total weight, Wt=	155.31	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	130.3	g	
Height of solids, hs=	15.2	mm	
Compression prior to wetting, dh_1=	-0.067	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.3	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.251	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	1.0	%	% swell

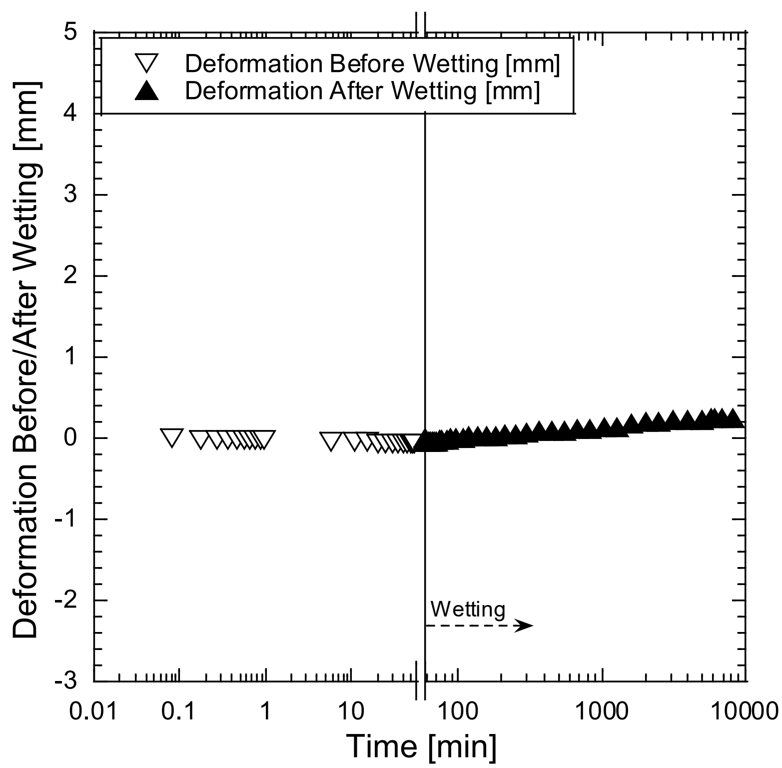


Figure B.82. *Swell test under 10 kPa on P4 treated soil.*

B.4.10.4 Swell Test Under 50 kPa

Table B.87. *Swell test under 50 kPa on P4 treated soil.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	518.13	g	
Water content, w%=	18.87	%	~Optimum water content
Soil Total weight, Wt=	155.76	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	131.0	g	
Height of solids, hs=	15.3	mm	
Compression prior to wetting, dh_1=	-0.330	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	25.1	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.142	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.6	%	% swell

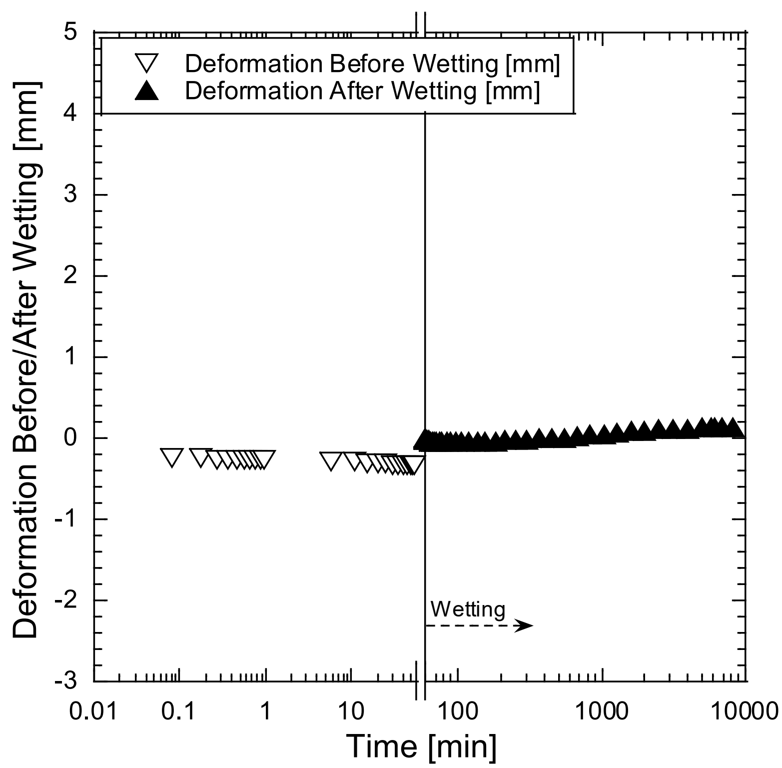


Figure B.83. *Swell test under 50 kPa on P4 treated soil.*

B.4.10.5 Swell Test Under 100 kPa

Table B.88. *Swell test under 100 kPa on P4 treated soil.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	525.77	g	
Water content, w%=	19.1	%	~Optimum water content
Soil total weight, Wt=	156.85	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	131.7	g	
Height of solids, hs=	15.4	mm	
Compression prior to wetting, dh_1=	-0.631	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	24.8	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	0.030	mm	Linear swell
Swell/Collapse= 100 x dh_2/h_1=	0.1	%	% swell

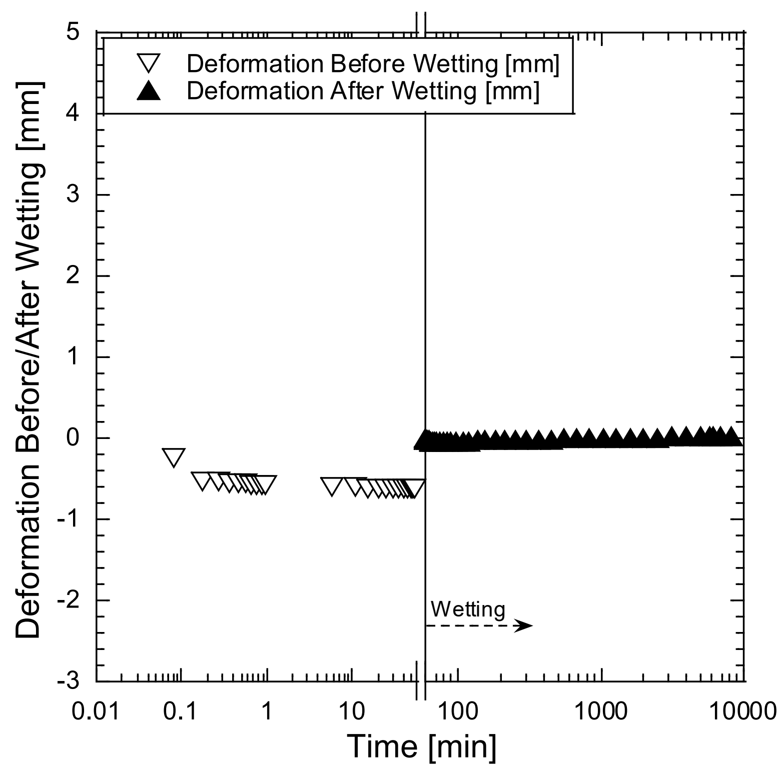


Figure B.84. *Swell test under 100 kPa on P4 treated soil.*

B.4.10.6 Swell Test Under 207.3 kPa

Table B.89. *Swell test under 207.3 kPa on P4 treated soil.*

Swell Test	Values	Units	Comments
Pressure to be applied=	1	kPa	
Load to be placed=	32.3	g	Arm= 10x
Cell diameter, d=	63.5	mm	Two inches
Cell height, h=	25.4	mm	One inch
Cell weight=	518.21	g	
Water content, w%=	18.84	%	~Optimum water content
Soil Total weight, Wt=	156.56	g	
Volume of soil, V=	80439.8	mm^3	
Weight of solids, Ws=	131.7	g	
Height of solids, hs=	15.4	mm	
Compression prior to wetting, dh_1=	-1.025	mm	Immediately before wetting
Specimen height prior to wetting, h_1=	24.4	mm	Immediately before wetting
Swell/Collapse caused by wetting dh_2=	-0.145	mm	Linear Collapse
Swell/Collapse= 100 x dh_2/h_1=	-0.6	%	% Collapse

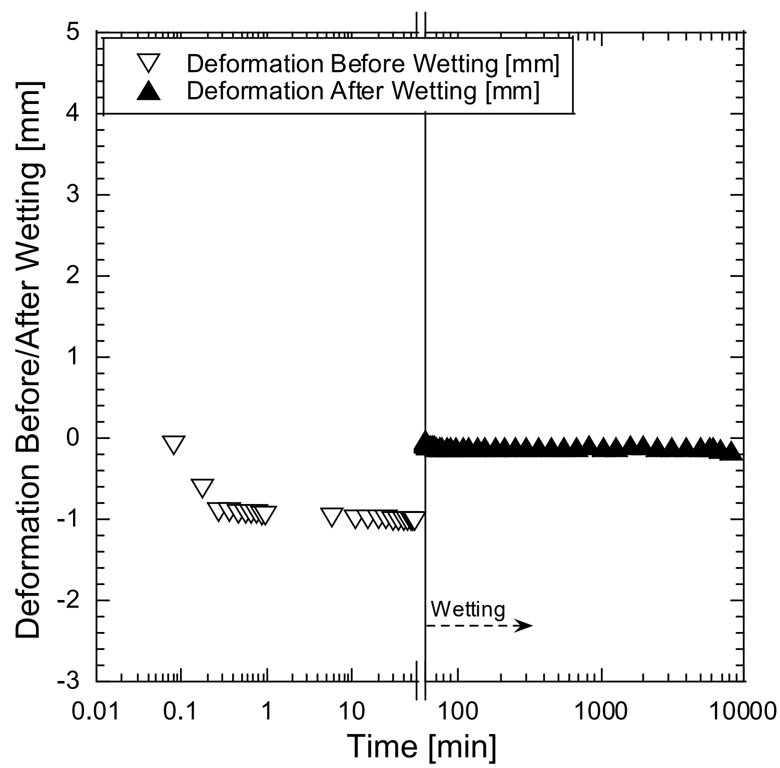


Figure B.85. *Swell test under 207.3 kPa on P4 treated soil.*

B.4.10.7 Swell Pressure vs. Swell Potential

Table B.90. *Swell pressure vs. swell potential on P4 treated soil.*

Swell Pressure [kPa]	Swell Potential [%]
1	4.9
1	4.0
10	1.0
50	0.6
100	0.1
207.3	-0.6

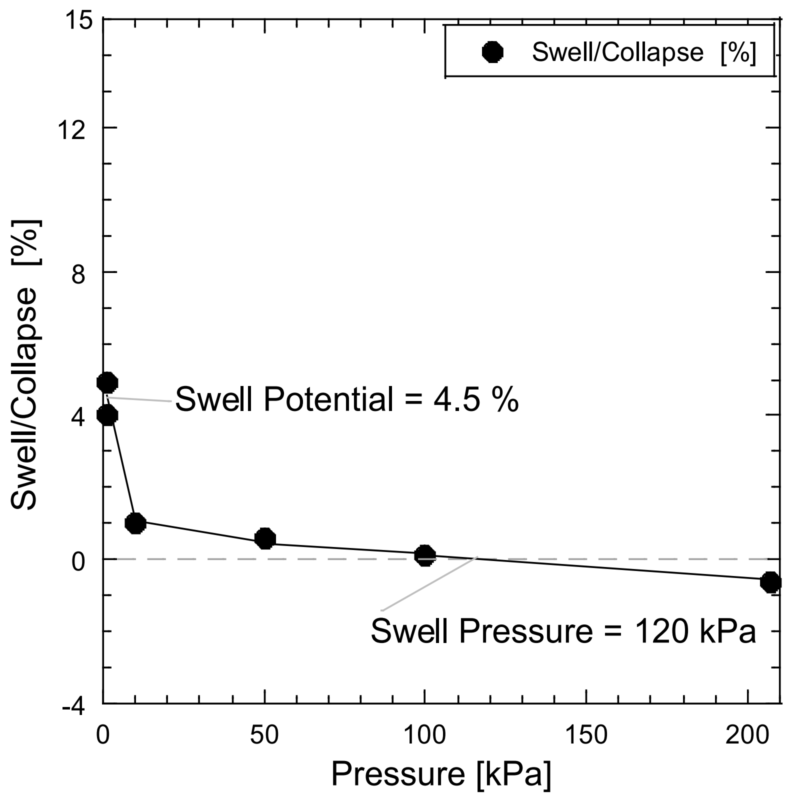


Figure B.86. *Swell pressure vs. swell potential for the P4 treated soil.*

B.5 Hydraulic Conductivity Tests

B.5.1 Expansive soil hydraulic conductivity

Table B.91. *Hydraulic conductivity test on expansive soil.*

Hydraulic Conductivity Test	Values	Units	Comments
Volume of soil, V=	429.27	mm^3	Compacted with 1 layer & 19 blows
Water content, w%=	18.4	%	~Optimum water content
Specimen height, h=	29.3	mm	
Specimen diameter, d=	101.6	mm	
Diameter of Influent pipet d_i=	10.52	mm	
Correction factor, influent pipet, CF_i	1.135	[-]	
Diameter of effluent pipet d_o=	10.52	mm	
Correction factor, effluent pipet, CF_o	1.134	[-]	
Degree of saturation, S=	64.0	%	
Hydraulic gradient, i=	30.2	[-]	
Cell pressure applied, Pc=	75.0	psi	
Head backpressure applied, Ph=	55.4		
Tail backpressure applied, Pt=	54.2		
Average effective stress, σ'=	20.2	psi	to prevent swelling
Average effective stress, σ'=	139.3	kPa	~Swell pressure
Hydraulic conductivity=	2.9E-11	m/s	

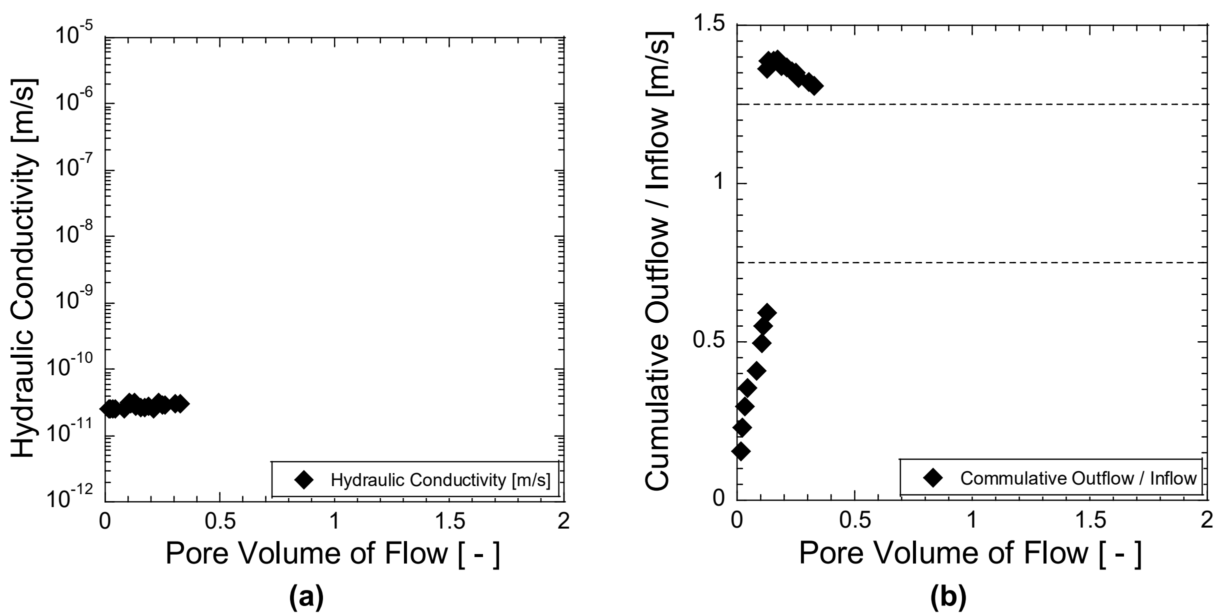


Figure B.87. *Hydraulic conductivity of expansive soil; (a) hydraulic conductivity vs. pore volumes of flow, and (b) cumulative outflow /inflow vs. pore volumes of flow.*

B.5.2 Fly Ash Treated Hydraulic Conductivity Test (15%)

Table B.92. *Hydraulic conductivity of fly ash treated soil.*

Hydraulic Conductivity Test	Values	Units	Comments
Volume of soil, V=	436.72	mm^3	Compacted with 1 layer & 19 blows
Water content, w%=	17.6	%	~Optimum water content
Specimen height, h=	29.15	mm	
Specimen diameter, d=	101.6	mm	
Diameter of Influent pipet d_i=	10.3	mm	
Correction factor, influent pipet, CF_i	1.1428	[-]	
Diameter of effluent pipet d_o=	10.1	mm	
Correction factor, effluent pipet, CF_o	1.1561	[-]	
Degree of saturation, S=	65.5	%	
Hydraulic gradient, i=	9.6	[-]	
Cell pressure applied, Pc=	75.0	psi	
Head backpressure applied, Ph=	70.4		
Tail backpressure applied, Pt=	70.0		
Average effective stress, σ'=	4.8	psi	to prevent swelling
Average effective stress, σ'=	33.1	kPa	~Swell pressure
Hydraulic conductivity=	3.1E-08	m/s	

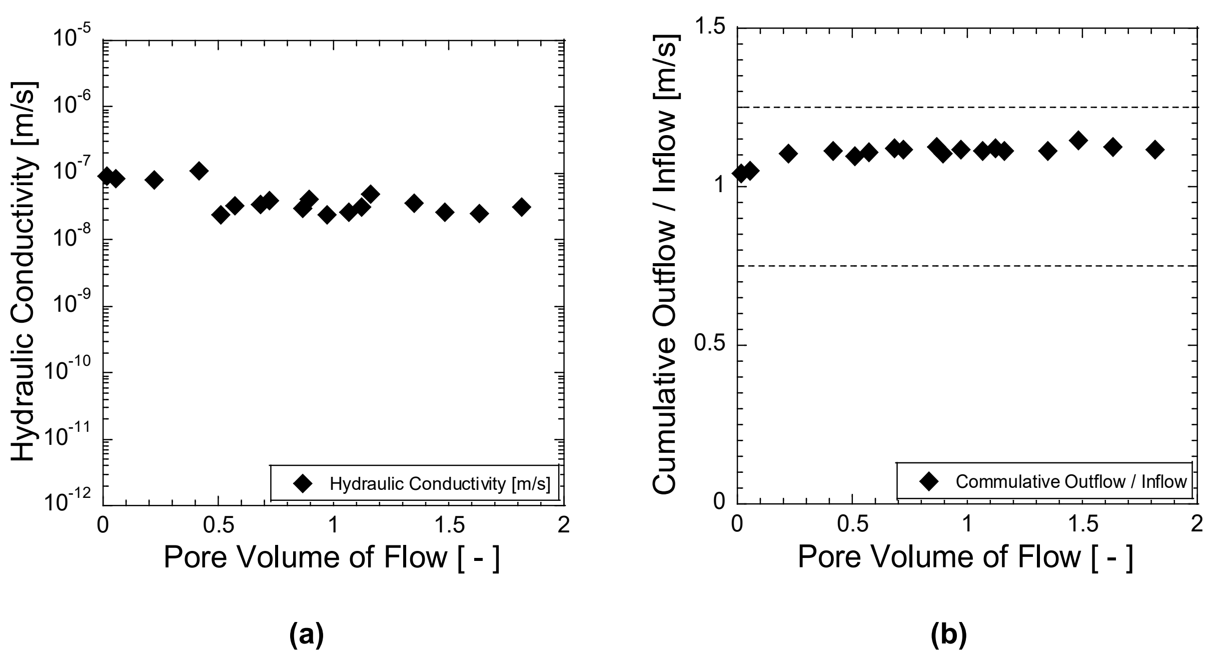
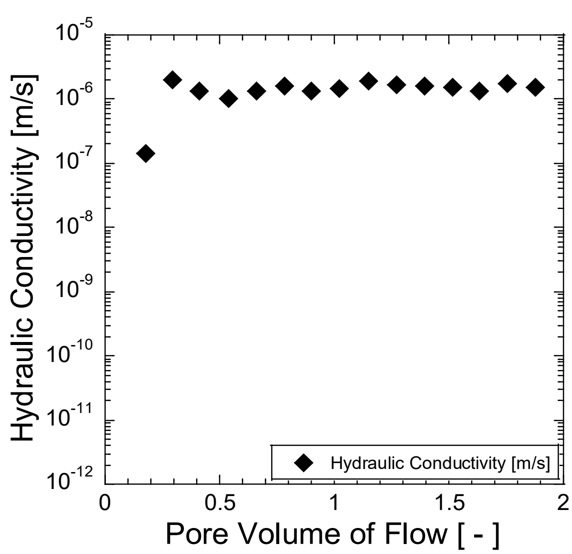


Figure B.88. *Hydraulic conductivity of fly ash treated soil; (a) hydraulic conductivity vs. pore volumes of flow, and (b) cumulative outflow /inflow vs. pore volumes of flow.*

B.5.3 Lime Treated Hydraulic Conductivity Test (3%)

Table B.93. *Hydraulic conductivity of the lime treated soil.*

Hydraulic Conductivity Test	Values	Units	Comments
Volume of soil, V=	451.5	mm^3	Compacted with 1 layer & 19 blows
Water content, w%=	19.96	%	~Optimum water content
Specimen height, h=	29.3	mm	
Specimen diameter, d=	101.6	mm	
Diameter of Influent pipet d_i=	10.3	mm	
Correction factor, influent pipet, CF_i	1.1428	[-]	
Diameter of effluent pipet d_o=	10.1	mm	
Correction factor, effluent pipet, CF_o	1.1561	[-]	
Degree of saturation, S=	75.8	%	
Hydraulic gradient, i=	4.8	[-]	
Cell pressure applied, Pc=	71.1	psi	
Head backpressure applied, Ph=	70.2		
Tail backpressure applied, Pt=	70.0		
Average effective stress, σ'=	1	psi	almost no swelling
Average effective stress, σ'=	6.9	kPa	~Swell pressure
Hydraulic conductivity=	1.5E-06	m/s	



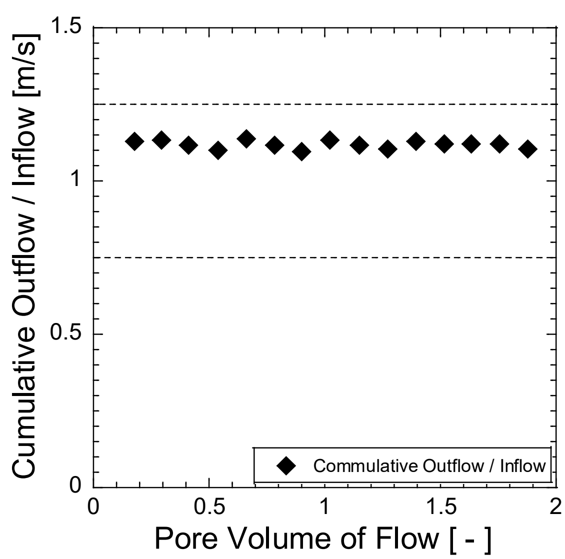


Figure B.89. *Hydraulic conductivity of lime treated soil; (a) hydraulic conductivity vs. pore volumes of flow, and (b) cumulative outflow /inflow vs. pore volumes of flow.*

B.5.4 P4 Polymer Treated Soil Hydraulic Conductivity Test (5%)

B.5.4.1 Assumed Swell Pressure

Table B.94. *Hydraulic conductivity of P4 treated soil with assumed swell pressure.*

Hydraulic Conductivity Test	Values	Units	Comments
Volume of soil, V=	456.14	g	Compacted with 1 layer & 19 blows
Water content, w%=	18.55	%	~Optimum water content
Specimen height, h=	29.3	mm	
Specimen diameter, d=	101.6	mm	
The influent and effluent pipet diameters and correction factors are the same as Table B.93			
Degree of saturation, S=	74.3	%	
Hydraulic gradient, i=	28.8	[-]	
Cell pressure applied, Pc=	75.0	psi	
Head backpressure applied, Ph=	65.6		
Tail backpressure applied, Pt=	64.4		
Average effective stress, σ'=	**10**	psi	to prevent swelling
Average effective stress, σ'=	68.9	kPa	~Swell pressure
Hydraulic conductivity=	9.4E-11	m/s	

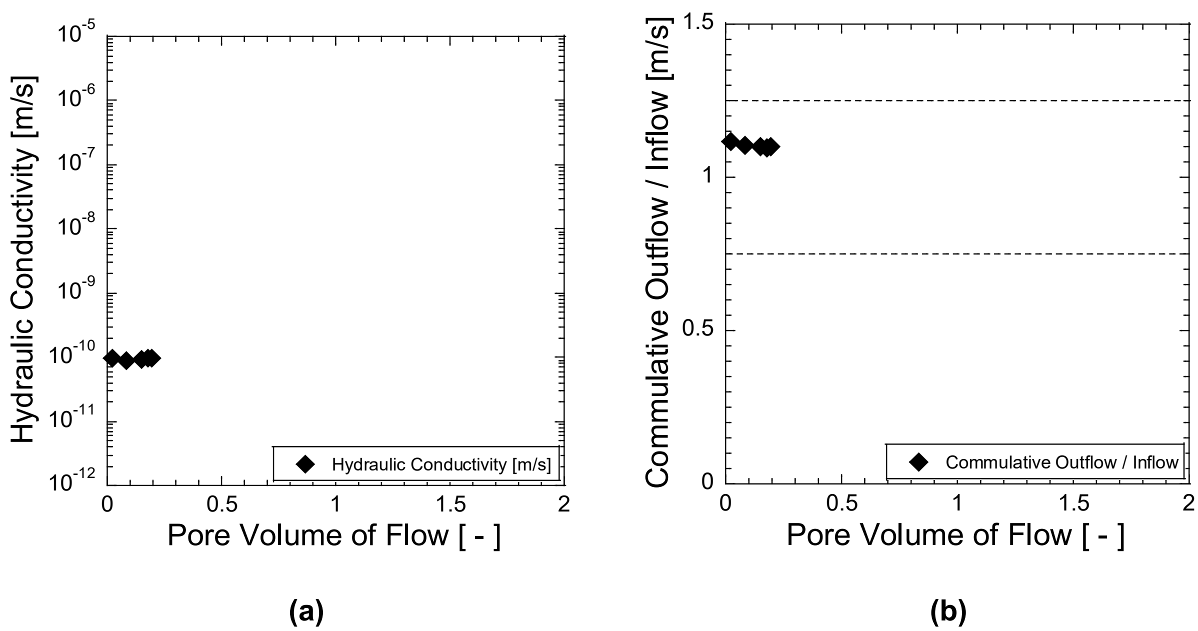


Figure B.90. *Hydraulic conductivity of P4 treated soil with assumed swell pressure; (a) hydraulic conductivity vs. pore volumes of flow, and (b) cumulative outflow /inflow vs. pore volumes of flow.*

B.5.4.2 Measured Swell Pressure

Table B.95. *Hydraulic conductivity of P4 treated with actual swell pressure.*

Hydraulic Conductivity Test	Values	Units	Comments
Volume of soil, V=	456.14	g	Compacted with 1 layer & 19 blows
Water content, w%=	18.55	%	~Optimum water content
Specimen height, h=	29.3	mm	
Specimen diameter, d=	101.6	mm	
The influent and effluent pipet diameters and correction factors are the same as Table B.93			
Degree of saturation, S=	74.3	%	
Hydraulic gradient, i=	28.8	[-]	
Cell pressure applied, Pc=	77.4	psi	
Head backpressure applied, Ph=	60.6		
Tail backpressure applied, Pt=	59.4		
Average effective stress, σ'=	**17.4**	psi	to prevent swelling
Average effective stress, σ'=	120.0	kPa	~Swell Pressure
Hydraulic conductivity=	7.2E-11	m/s	

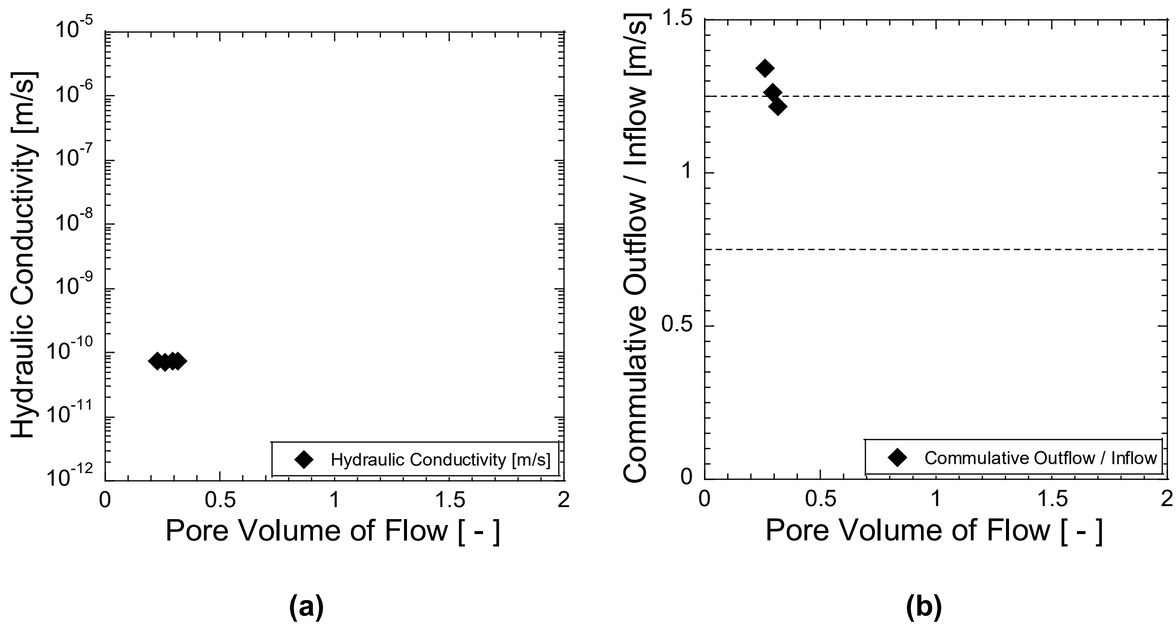


Figure B.91. *Hydraulic conductivity of P4 treated soil with measured swell pressure; (a) hydraulic conductivity vs. pore volumes of flow, and (b) cumulative outflow /inflow vs. pore volumes of flow.*

B.5.4.3 Combined Assumed and Measured Swell Pressure Hydraulic Conductivities

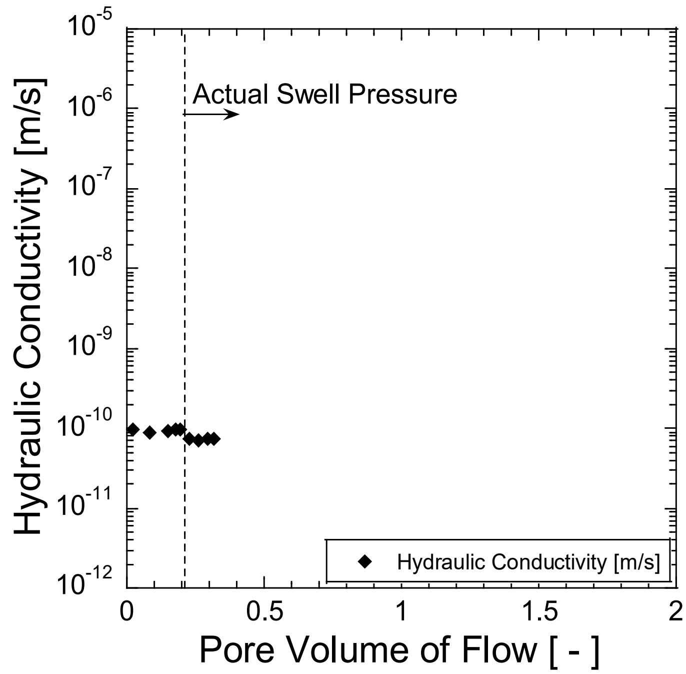


Figure B.92. *Combined hydraulic conductivity results for P4 treated soil.*

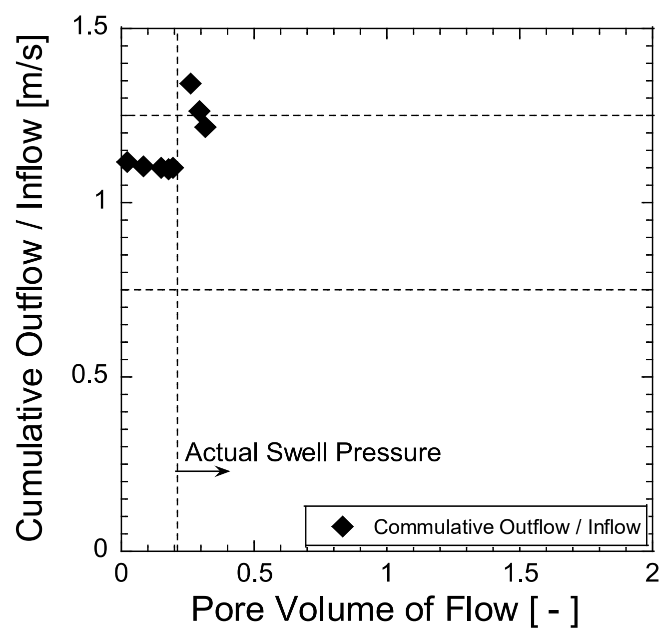


Figure B.93. *Combined hydraulic conductivity results for P4 treated soil.*

B.6 Unconfined Compressive Strength (UCS) Tests

B.6.1 Expansive soil UCS Tests

B.6.1.1 Unsoaked UCS Test

Table B.96. Unconfined compressive strength of expansive soil – all tests unsoaked.

Unconfined Compressive Strength Test	Values	Units	Comments
Volume of soil, V=	18581.4	mm^3	Compacted with 6 layer & 25 blows
Water content, w%=	18.4	%	~Optimum water content
Specimen height, h=	232.86	mm	
Specimen diameter, d=	101.6	mm	
Speed of strain control=	2.0	% / min	2% as assumed brittle
Speed of strain control=	4.7	mm / min	
Unconfined Compressive Strength, qu=	242.7	kPa	Only unsoaked was doable
Undrained shear strength, Su=	121.3	kPa	

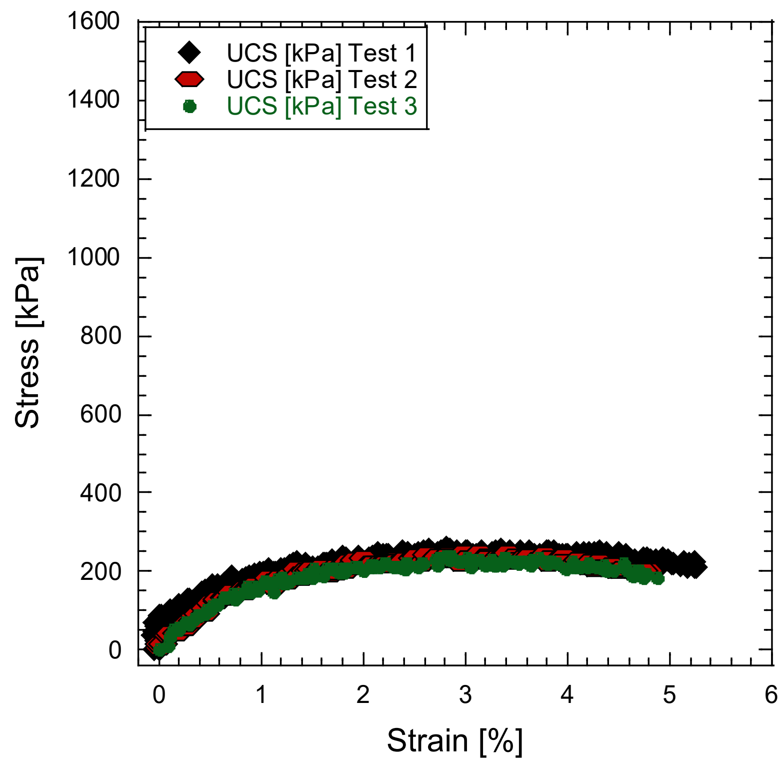


Figure B.94. *Unconfined compressive strength of expansive soil - all tests unsoaked.*

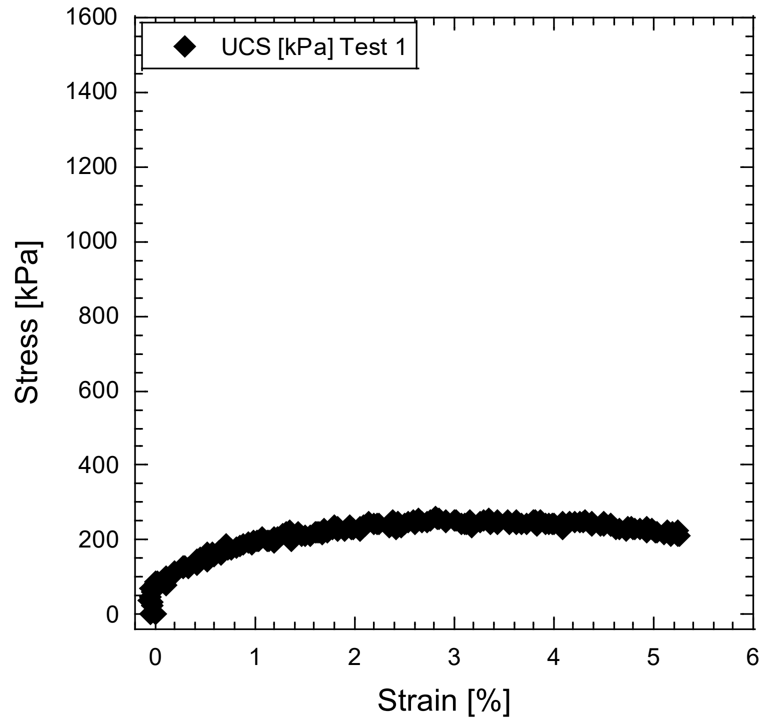


Figure B.95. *Unconfined compressive strength of expansive soil – test 1 unsoaked.*

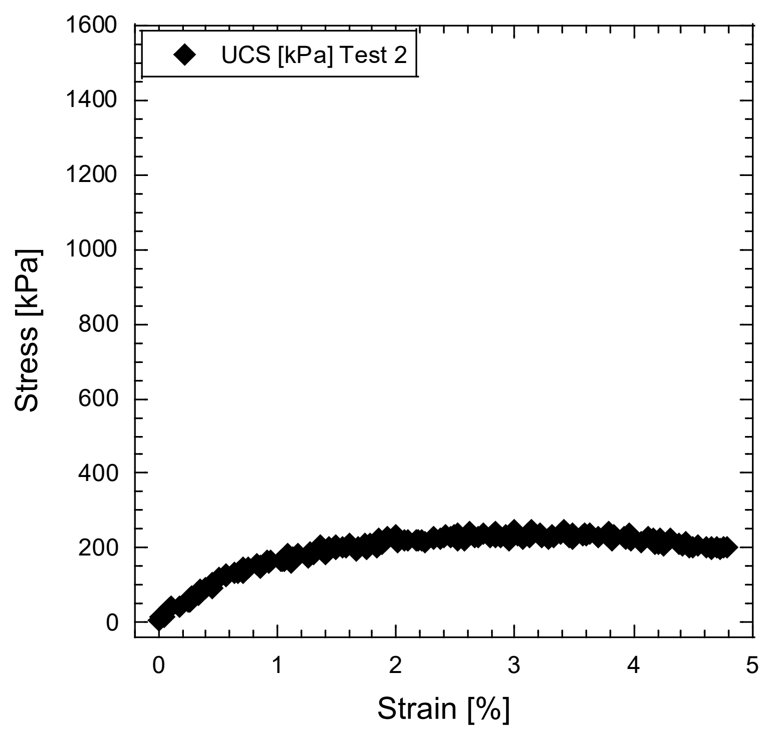


Figure B.96. *Unconfined compressive strength of expansive soil – test 2 unsoaked.*

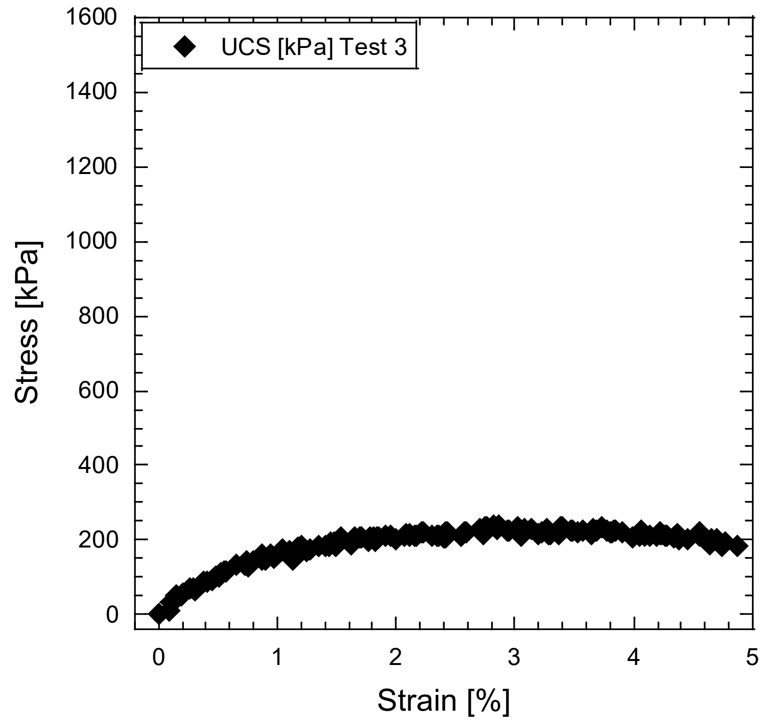


Figure B.97. *Unconfined compressive strength of expansive soil – test 3 unsoaked.*

B.6.1.2 Soaked UCS Test

Test could not be completed. The soaked specimen could not be moved and placed under the UCS machine because of the weakness of the specimen caused by excessive swelling. The result of the UCS is assumed to equal zero.

B.6.2 Fly Ash Treated UCS Tests (15%)

B.6.2.1 Combined Soaked and Unsoaked UCS Tests

Table B.97. *Unconfined compressive strength of fly ash treated soil.*

Unconfined Compressive Strength Test	Values	Units	Comments
Volume of soil, V=	18581.4	mm^3	Compacted with 6 layer & 25 blows
Water content, w%=	18.4	%	~Optimum water content
Specimen height, h=	232.86	mm	
Specimen diameter, d=	101.6	mm	
Speed of strain control=	2.0	% / min	2% as assumed brittle
Speed of strain control=	4.7	mm / min	
Unconfined Compressive Strength, qu=	547.0	kPa	unsoaked
Undrained shear strength, Su=	273.5	kPa	
Unconfined Compressive Strength, qu1=	380.0	kPa	soaked
Unconfined Compressive Strength, qu2=	335.0	kPa	soaked
Unconfined Compressive Strength, qu3=	430.0	kPa	soaked
Unconfined Compressive Strength, qu_{ave}=	381.7	kPa	soaked
Undrained shear strength, Su=	191.0	kPa	soaked

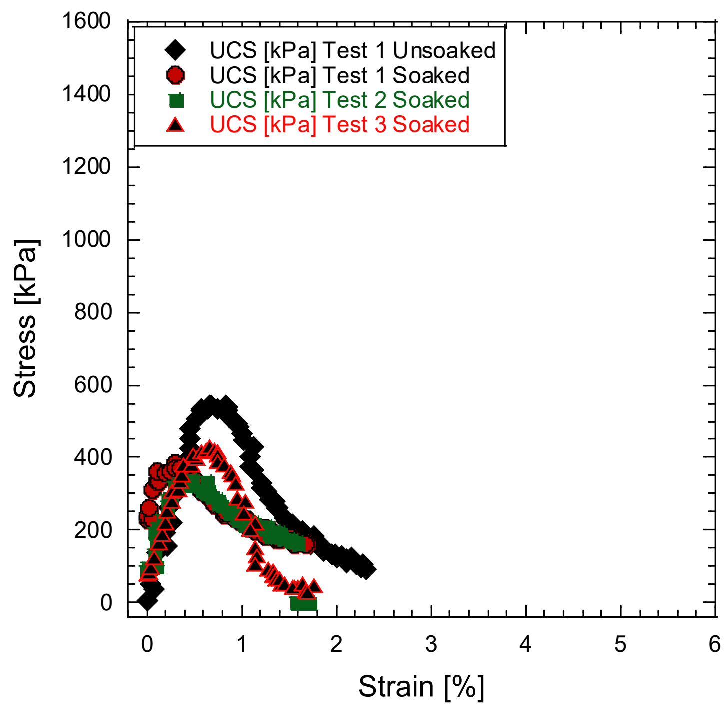


Figure B.98. *Unconfined compressive strength of fly ash treated soil – all tests.*

B.6.2.2 Unsoaked UCS Tests

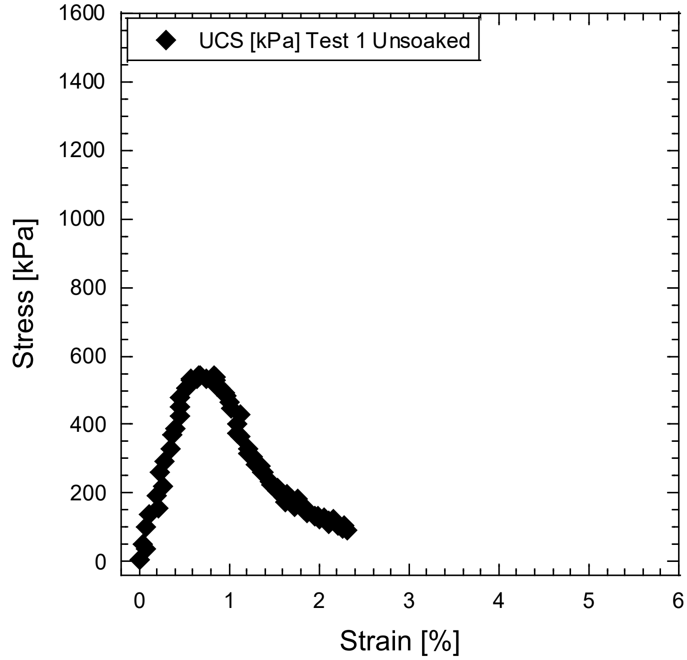


Figure B.99. *Unconfined compressive strength of fly ash treated soil – test 1 unsoaked.*

B.6.2.3 Soaked UCS Tests

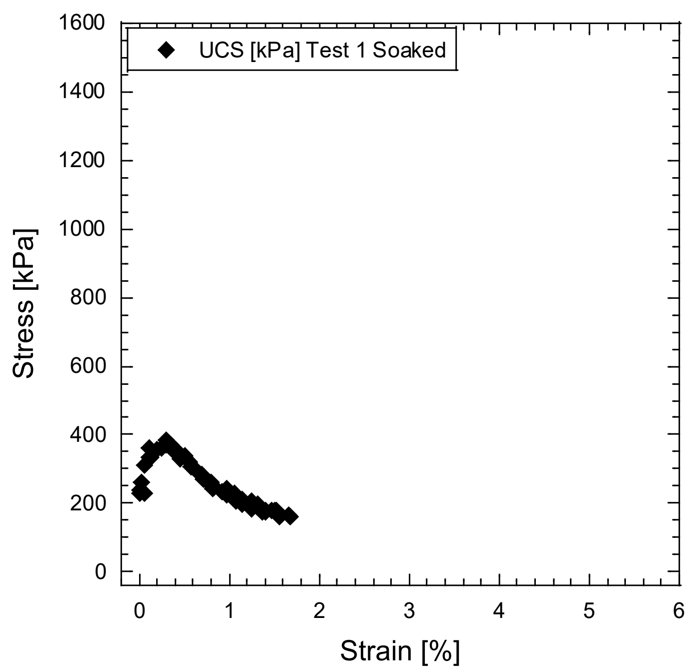


Figure B.100. *Unconfined compressive strength of fly ash treated soil – test 1 soaked.*

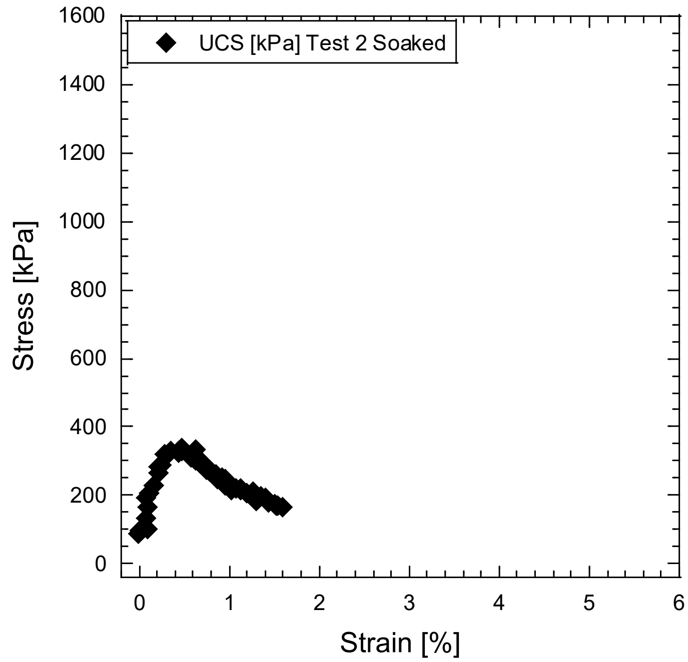


Figure B.101. *Unconfined compressive strength of fly ash treated soil – test 2 soaked.*

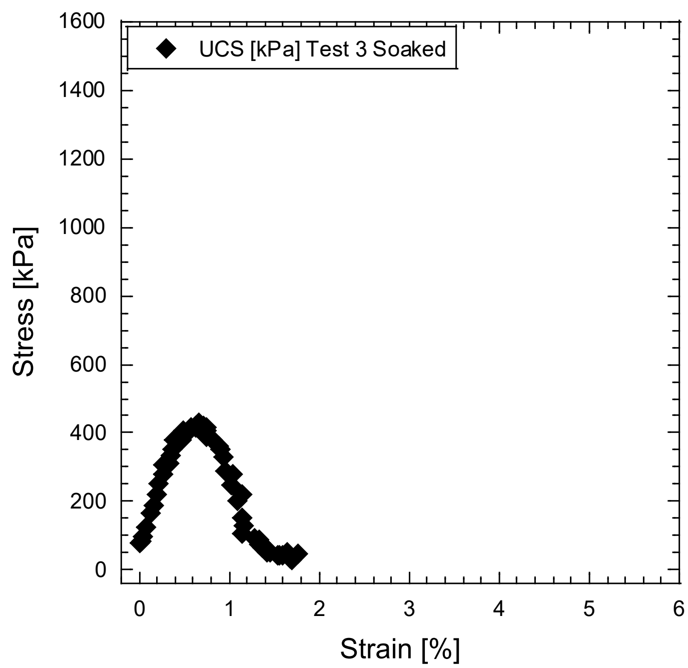


Figure B.102. *Unconfined compressive strength of the fly ash treated soil – test 3 soaked.*

B.6.3 Lime Treated UCS Tests (3%)

B.6.3.1 Combined Soaked and Unsoaked UCS Tests

Table B.98. *Unconfined compressive strength of lime treated soil.*

Unconfined Compressive Strength Test	Values	Units	Comments
Volume of soil, V=	18581.4	mm^3	Compacted with 6 layer & 25 blows
Water content, w%=	18.4	%	~Optimum water content
Specimen height, h=	232.86	mm	
Specimen diameter, d=	101.6	mm	
Speed of strain control=	2.0	% / min	2% as assumed brittle
Speed of strain control=	4.7	mm / min	
Unconfined Compressive Strength, qu=	1600.0	kPa	unsoaked
Undrained shear strength, Su=	800.0	kPa	
Unconfined Compressive Strength, qu1=	1160.0	kPa	soaked
Unconfined Compressive Strength, qu2=	1300.0	kPa	soaked
Unconfined Compressive Strength, qu3=	1320.0	kPa	soaked
Unconfined Compressive Strength, qu_{ave}=	1260.0	kPa	soaked
Undrained shear strength, Su=	630.0	kPa	soaked

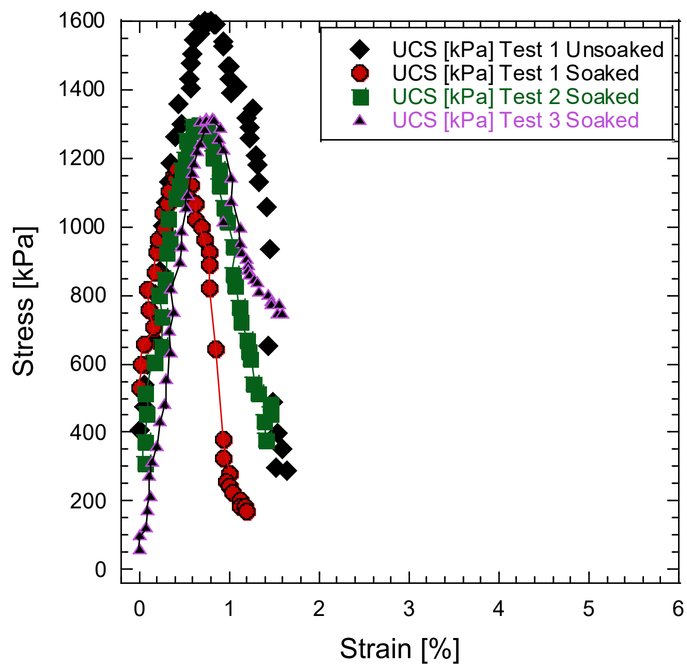


Figure B.103. *Unconfined compressive strength of lime treated soils – all tests.*

B.6.3.2 Unsoaked UCS Tests

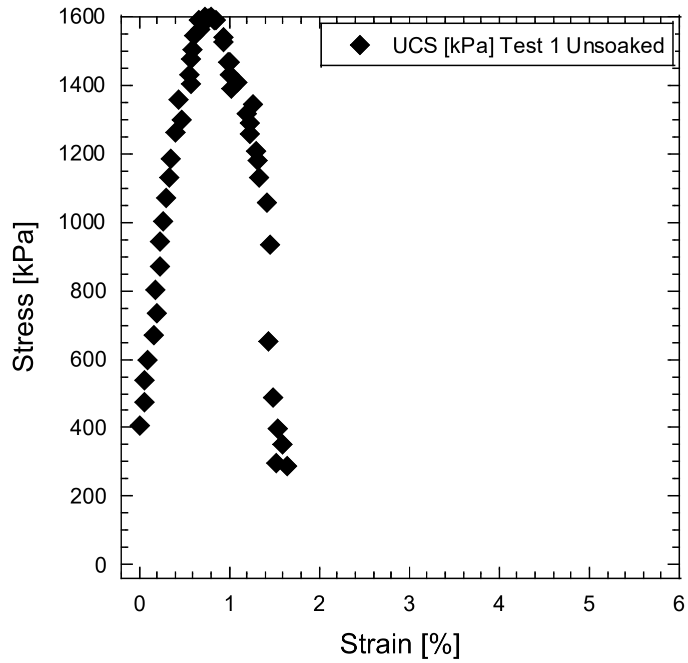


Figure B.104. *Unconfined compressive strength of lime treated soil – test 1 unsoaked.*

B.6.3.3 Soaked UCS Tests

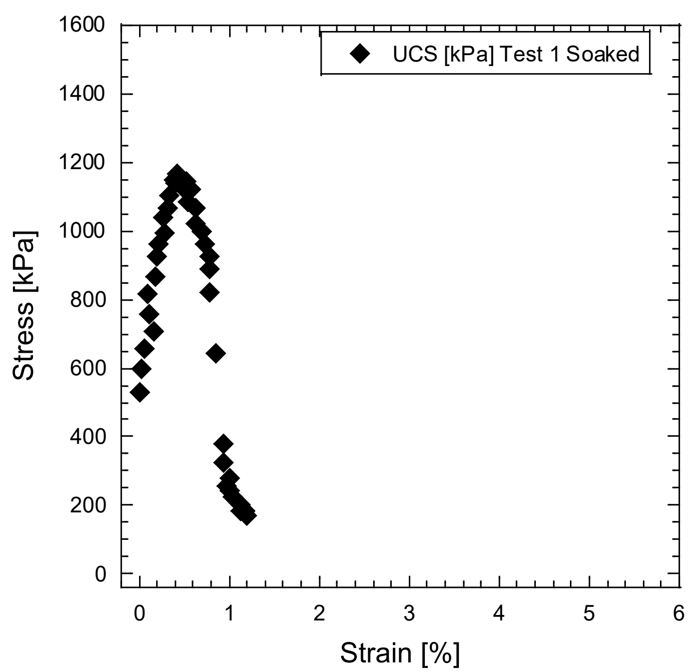


Figure B.105. *Unconfined compressive strength of lime treated soil – test 1 soaked.*

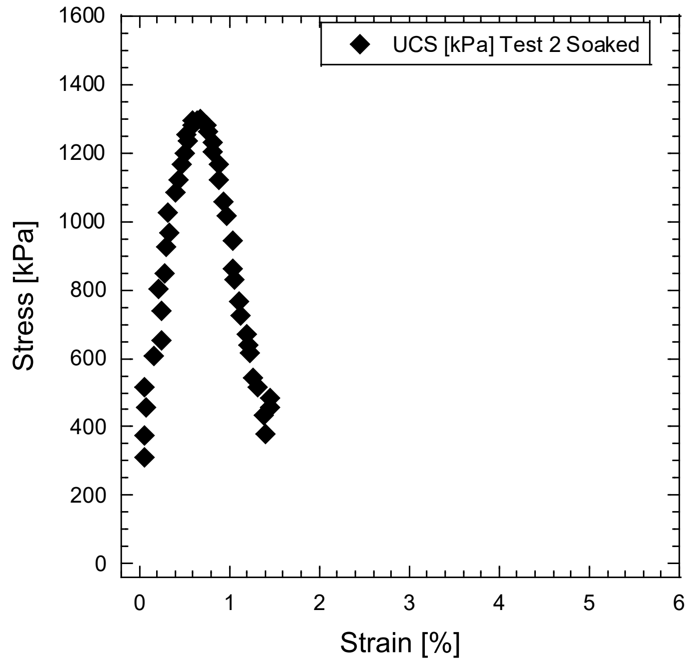


Figure B.106. *Unconfined compressive strength of lime treated soil – test 2 soaked.*

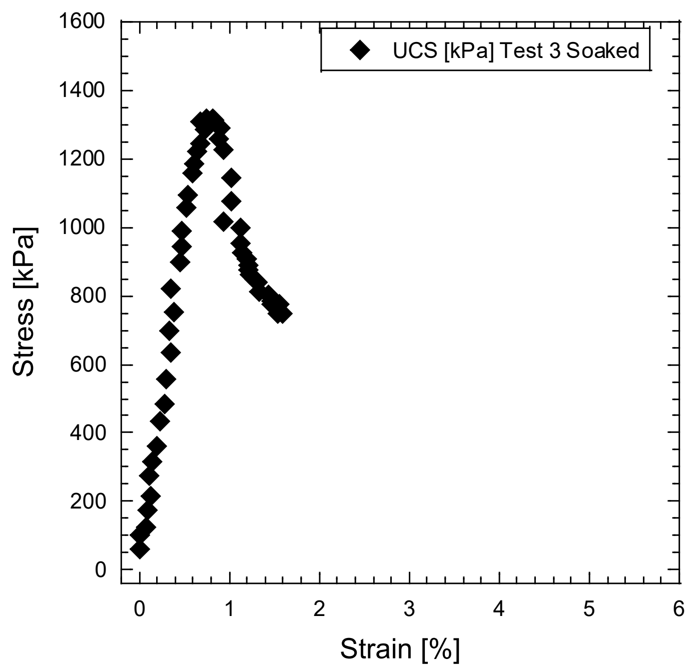


Figure B.107. *Unconfined compressive strength of lime treated soil – test 3 soaked.*

B.6.4 P4 Treated UCS Tests (5%)

B.6.4.1 Combined Soaked and Unsoaked UCS Tests

Table B.99. *Unconfined compressive strength of the P4 treated soil.*

Unconfined Compressive Strength Test	Values	Units	Comments
Volume of soil, V=	18581.4	mm^3	Compacted with 6 layer & 25 blows
Water content, w%=	18.4	%	~Optimum water content
Specimen height, h=	232.86	mm	
Specimen diameter, d=	101.6	mm	
Speed of strain control=	2.0	% / min	2% as assumed brittle
Speed of strain control=	4.7	mm / min	
Unconfined Compressive Strength, qu=	260.0	kPa	unsoaked
Undrained shear strength, Su=	130.0	kPa	
Unconfined Compressive Strength, qu1=	20.0	kPa	soaked
Unconfined Compressive Strength, qu2=	62.0	kPa	soaked
Unconfined Compressive Strength, qu3=	56.0	kPa	soaked
Unconfined Compressive Strength, qu_{ave}=	46.0	kPa	soaked
Undrained shear strength, Su=	23.0	kPa	soaked

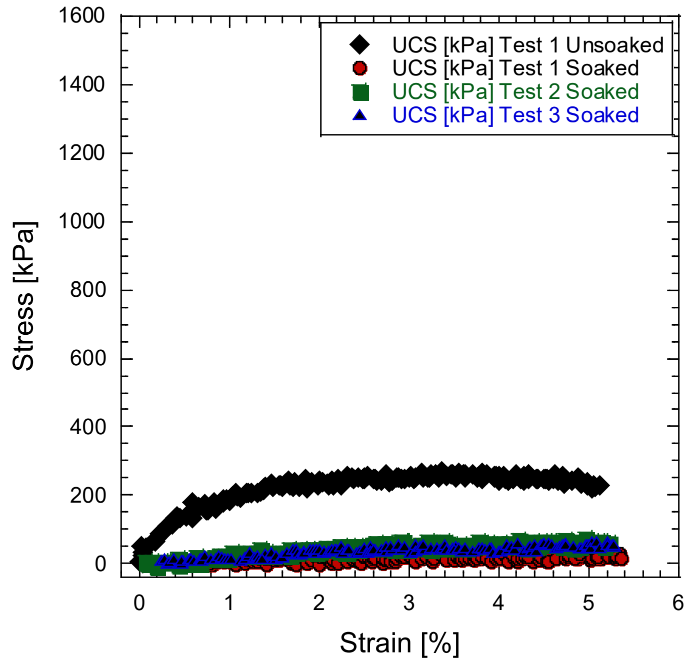


Figure B.108. *Unconfined compressive strength of P4 treated soil – all tests.*

B.6.4.2 Unsoaked UCS Tests

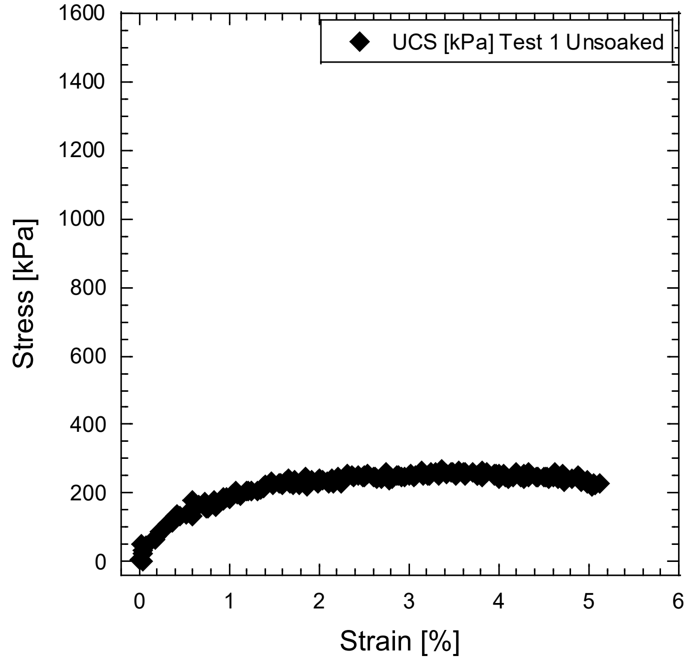


Figure B.109. *Unconfined compressive strength of P4 treated soil – test 1 unsoaked.*

B.6.4.3 Soaked UCS Tests

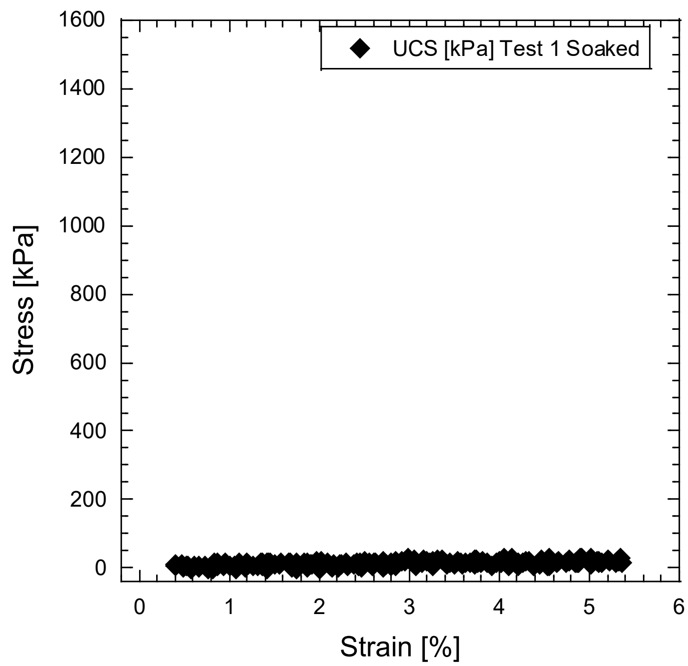


Figure B.110. *Unconfined compressive strength of P4 treated soil – test 1 soaked.*

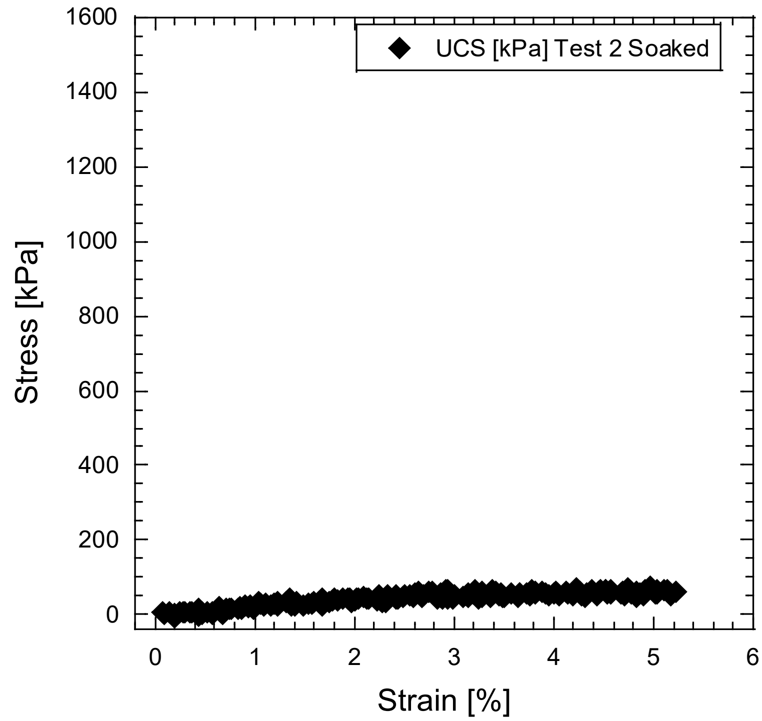


Figure B.111. *Unconfined compressive strength of P4 treated soil – test 2 soaked.*

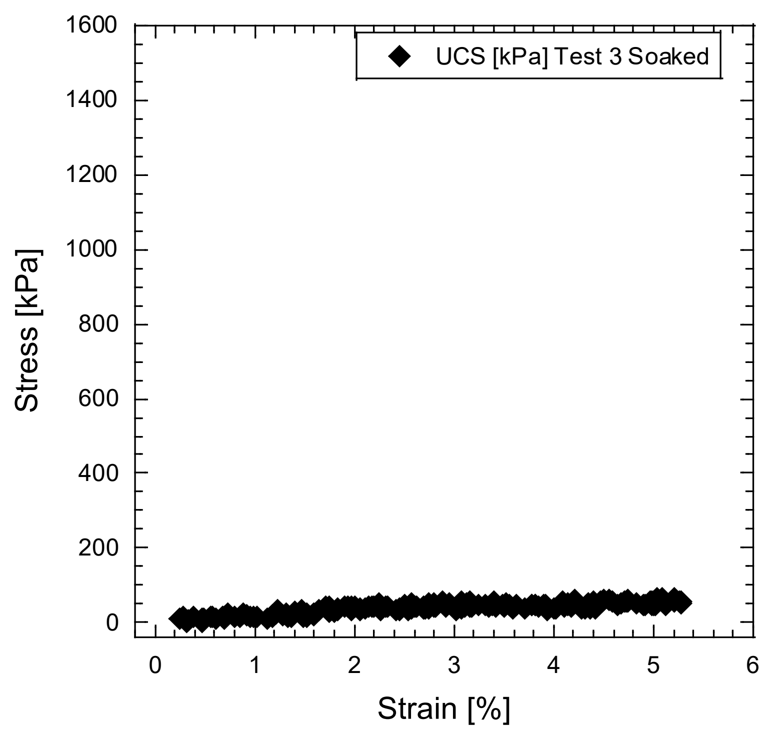


Figure B.112. *Unconfined compressive strength of P4 treated soil – test 3 soaked.*