Chemical Stabilization of Inherently Weak Subgrade Soils for Road Construction – Applicability in Canada

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Abstract

Chemical soil stabilization has been widely practiced in many European countries and numerous states in the US. The process involves the incorporation of hydraulic binders: namely, lime and cement, which in turn enhance the physical properties of the host soil. Soils best suited to the process typically incorporate clay and silt, and are prone to losing strength properties as the water content increases. Once treated with lime and/or cement, the improvements to the properties of the soil are numerous. Some of the most significant enhancements include: strength increase, decreased susceptibility to water ingress and volume changes, and improved durability.

Chemical stabilization of a soil eliminates the need to remove an inherently weak soil subgrade and replace it with a quarried, processed granular material. This process is not only cost effective, but it also lessens the demand on non-renewable resources and reduces the environmental footprint of a road construction project. Although the technology is proven and widely adopted around the world, the process is not widely utilized in Canada.

This paper describes the soil stabilization process, including the physical alterations to the soil and the design process. The paper also presents case studies where chemical soil stabilization has been utilized as an alternative to “remove and replace” processes. Finally, the applicability of chemical soil stabilization techniques within Canada is discussed.

1 Introduction

The successful construction of highways requires the construction of a structure that is capable of carrying the imposed traffic loads. One of the most important layers of the road is the actual foundation, or subgrade. Where the subgrade is founded in an inherently weak soil, this material is typically then removed and replaced with a stronger granular material.

This "remove and replace" technique can be both costly and time consuming. Where aggregates are scarce, the use of these non-renewable resources is viewed as non-sustainable, particularly if haulage distances are significant. In the EU, an aggregate tax and landfill tax is applied to construction projects, thereby making the "remove and replace" option less economically viable.

An alternative to the "remove and replace" option is to chemically stabilize the host material. This eliminates the requirement to replace the material, and ensures the engineering characteristics and performance of the host material is enhanced to allow for its use within the pavement structure. Chemical stabilization is a process by which hydraulic binders are introduced and intimately mixed into the soil. Hydraulic binders are defined as those that – when mixed with an appropriate quantity of water – will form cementitious hydrate gels. Commonly utilized hydraulic binders include quicklime (CaO), hydrated lime $Ca(OH)_2$, Portland cement, fly ash and cement kiln dust (CKD). Fly ash and CKD are typically used as a partial replacement for the more expensive binders (i.e., lime and Portland cement). Once mixed into the soil, a chemical reaction occurs that both modifies and stabilizes the host material.

Chemical soil stabilization has been utilized for many centuries. The Romans were one of the first to utilize a chemical stabilization process. Weak soils were mixed with pozzolana (volcanic ash containing alumina and silica) and lime to improve its bearing capacity. The modern day treatment of soils started in the late 1950s in the US where weak clays were treated with hydrated lime. The development and improvement of construction equipment since these early days has seen significant utilization of the process globally. In particular, countries that have developed the process include the US, France, Australia, New Zealand, South Africa, the United Kingdom, Germany and Sweden. Although a widely used process with a good history of success, the utilization of chemical soil stabilization has been limited in Canada. Except for some early experiences in Alberta, Saskatchewan and Prince Edward Island, soil stabilization processes are not currently adopted or even favoured within Canada for highway construction.

2 Soil Stabilization – The Chemical Reaction

Hydraulic binders are most effective when inherently weak materials would normally be removed and replaced with materials that have superior engineering characteristics. The soil type and mineralogy of the soil will dictate the binder that is utililized. Where significant quantities of clay and silt are present, the favoured stabilizing additives are either lime (either hydrated or quicklime) or a combination of lime and Portland cement. Where a much coarser material is present, additives such as Portland cement, fly ash and CKD are preferable. To identify binder type and concentration, laboratory mix designs are performed. This ensures the optimum addition of a binder in order to meet the desired end performance criteria. The mix design process is discussed in detail in Section 3.

When a hydraulic binder is mixed with a soil in the presence of adequate water, the following chemical reactions occur:

- Cation exchange: replacement of exchangeable cations held by the host soil by higher valiancy calcium ions, which are held by the lime.
- Flocculation/agglomeration of the host soil particles and an increase in the effective grain size.
- Pozzolanic reaction: a long-term reaction producing cementitious materials, typically calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) gels.

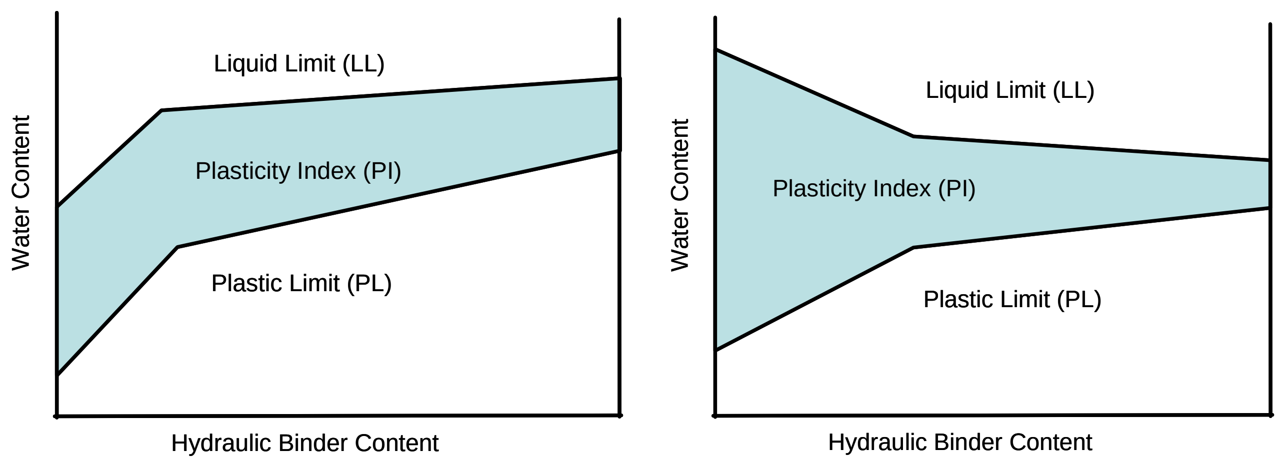
Of these reactions, the first two are immediate and result in a **modification** of the host soil. Modification is more rapid when lime is added to a soil, as more calcium ions are present compared to those present in Portland cement, fly ash and CKD. Providing an adequate concentration of binder has been introduced to the host soil and an alkaline environment has been maintained after modification, a pozzolanic reaction will occur. This reaction process is very time dependant and can continue over a long period of time. The reaction phase is generally referred to as **stabilization** of the soil.

2.1 Modification of the soil

During the modification process numerous alterations to the host soil occur. These alterations include dramatic reductions to the plasticity (and shrinkage characteristics) of a fine-grained soil, alteration of compaction characteristics, and increases to the stability of the host soil. These reactions occur immediately upon addition of a hydraulic binder and are typically complete within a 48-72 hour timeframe.

Changes to the plasticity of the soil are a result of the cation exchange resulting in particle flocculation and aggregation. This increases the effective particle size of the fine-grained soil resulting in a more silt-like material. This typically increases the plastic limit and decreases the liquid limit, *Thompson (1967) and TRB (1987).* In some instances the soil may even become non-plastic. For some soils the liquid limit may actually increase with lime concentration. Research tends to suggest that this is clay mineral dependant; *Rowlands et al (1987), Cobbe (1988) and Thompson (1967)* all reported increases in liquid limit in soils where illite was the predominant clay mineral. Even with an increase in liquid limit, the accompanying increase in plastic limit is always greater – thus resulting in a net reduction in the plasticity index of the soil. Both of these reactions are graphically represented in Figure 1.

Figure 1 Effect of hydraulic binder on the plasticity of soils



The addition of hydraulic binders alters the compaction characteristics of the host soil. The maximum dry density (MDD) decreases and the optimum moisture content (OMC) increases. Typically, the higher the concentration of binder, the greater the alterations to the compaction characteristics are. The OMC increases due to the hydration effect and the affinity for more moisture during this reaction process. Decreases in density are directly attributed to the flocculation/aggregation and the formation of weak cementitious products. Flocculation/aggregation of the soil offers greater resistance to densification at a given level of compactive effort. The net result is a reduction in the MDD. The effect of binder addition to a soil is graphically represented in Figure 2.

In addition to the above, minor improvements to the stability and strength of the soil can also be observed, *Van Ganse (1973/74) and Neubauer and Thomson (1972)*. These immediate strength gains can generally improve adverse soil conditions, when soft, wet and highly plastic soils are encountered (Figure 3). Once treated, construction processes can be expedited and a satisfactory subgrade support can be achieved for construction traffic within several hours after binder application.

Figure 2 Effect of hydraulic binder on compaction characteristics

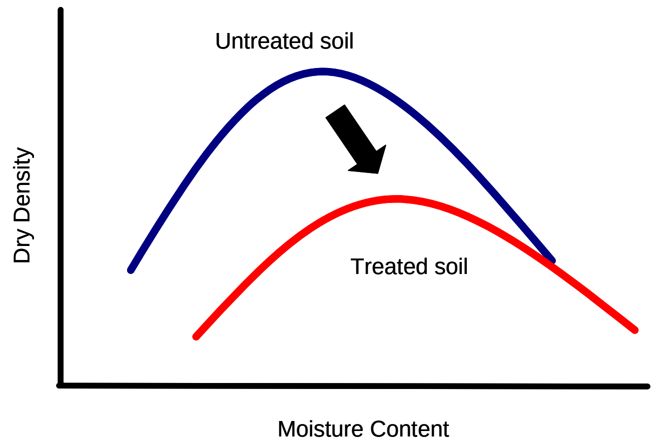


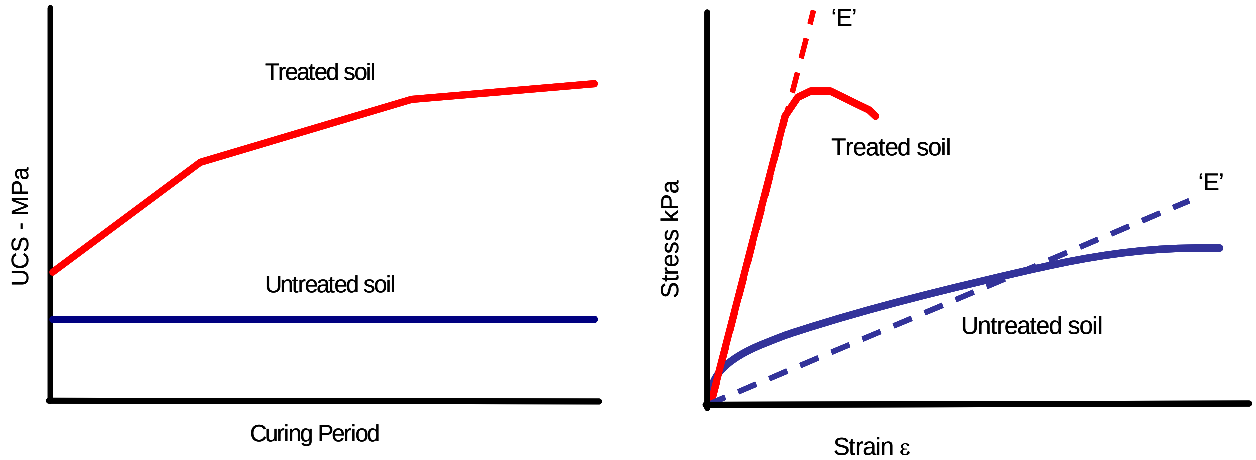
Figure 3 Site prior to stabilization (left) and after (right) stabilization

2.2 Stabilization of the soil

After a soil has become modified, and providing sufficient available calcium and hydroxyl ions are present after modification, stabilization of the soil will occur. Stabilization involves the reaction of calcium ions, alumina and silica (either dissolved from the host material or present within the binder) and water. These ingredients form calcium silicate hydrate and calcium aluminate hydrate gels. These gels are similar to those produced in the production of concrete and will enhance the strength, bearing capacity and durability characteristics of the treated soil.

Stabilization of a soil is commonly assessed in terms of strength gain over a certain period of time (cure). Strength gain is typically assessed by unconfined compressive strength (UCS) shear strength testing. The effect of binder addition to the UCS and shear strength is graphically represented in Figure 4.

Figure 4 Effect of hydraulic binder on strength properties



3 Soil Stabilization – The Mix Design Process

Where soil stabilization is considered for the treatment of an unsuitable subgrade, the mix design typically, as a minimum, considers the following:

- Alteration to compaction characteristics after binder addition.
- Improvement in strength with time.
- Resistance to water.
- Resistance to frost (only considered in colder climates).

All the above tests should be performed on representative soil samples retrieved from the proposed area of treatment.

One of the most important aspects of the mix design is determining the OMC of the treated mix. As discussed in Section 2, compaction characteristics are altered due to a chemical reaction. This alteration is more significant for fine-grained (clay and silt) soils compared to coarse-grained (sand) soils. The treated soil should be compacted as close to the OMC as possible. Ideally the water content of the treated soil should be slightly wet of the modified OMC, as this will ensure enough water is present for the hydration process and subsequent production of cementitious products. Compaction at or slightly wet of the OMC also reduces the concentration of air voids, and ensures the material is not sensitive to water ingress and frost-heave action.

UCS tests are performed to determine the concentration of a hydraulic binder required to achieve the desired engineering properties. The engineering properties are a function of the proposed end utilization. In many parts of the world where soil stabilization techniques are prevalent, the treated soil can be utilized as a modified subgrade or a sub-base replacement *(Chaddock and Atkinson [UK], Setra [France], NAASRA [Australia] and Texas DoT [USA]).*

As an example of sub-base stabilization, in 2001 the Highways Agency in the UK *(WRAP – AggRegain 2002)* proposed a stabilized sub-base alternate design for the Polegate By-pass, a 2.7km new construction with a traffic count of 23,500 vehicles per day. The road design comprised the replacement of a 300mm layer of Type 1 crushed aggregate with a 255mm in-situ stabilized layer of clay. The design requirement for the stabilized layer was a soaked CBR strength of 50% after a 7 day cure. Once stabilized, a 300mm asphalt base and wearing surface was then placed. To achieve the required design, the in-situ clay was firstly treated with 2% quicklime to modify the characteristics of the clay. After a 24 hour "mellowing" period, an additional 6% Portland cement was then added to achieve the desired strength requirements.

It should be noted that a strength criteria for soil stabilization is not universal, and is dependent upon the type of soil being treated, where the soil is being treated, and the proposed end use of the stabilized layer. Different jurisdictions will specify different criteria based on past experiences. For example, *Indiana Department of Transport (2008)* specifies that for a stabilized subgrade, the strength gain of a lime stabilized soil must be at least 0.35 MPa greater than the untreated soil after a 48 hour cure at 50^{o}C. Conversely, in the UK a minimum CBR strength of 15%, after a 28 day cure, is recommended for a stabilized subgrade soil, according to the *Department of Transport, UK (2007)*.

In addition to strength assessment, it may also be a necessary to assess the durability of the treated soil. This typically, takes the form of assessing resistance to excessive moisture and/or a freeze-thaw action. Moisture resistance typically requires immersion of a cured specimen in water for a prescribed period. Strength assessment is then undertaken and differences between a soaked and an unsoaked strength are reported. Where soil stabilization is performed in colder climates, it is important to assess resistance to freeze-thaw cycles. Varied and numerous testing methodologies exist whereby frost susceptibility is assessed; these are discussed in detail later in this paper.

4 The Treatment Process

Once the mix design has been developed the construction process is relatively simple. The treatment process comprises the following phases:

- Preparation of soil (if required).
- Spreading of the hydraulic binder on the soil to be treated.
- Mixing of the hydraulic binder into the soil at a prescribed depth.
- Compaction of the treated material at the appropriate water content and grading to final level.

Depending upon initial site conditions it may be necessary to grade the site prior to treatment.

4.1 Preparation of soil

The in-situ soil to be treated should be brought to the approximate proposed final grade prior to stabilization activities. This minimizes the final grade work required after treatment and compaction, and reduces the risk of removing stabilized material to achieve the desired grade. When preparing the soil for treatment, consideration should be given to the potential of bulking after treatment. This is caused by the chemical reaction process that lowers the density of the soil at any given moisture content compared to the untreated soil. Bulking can be minimized or even eliminated by ensuring that enough water is present during the stabilization process. Typically, the water content should be slightly higher than the OMC of the treated soil.

4.2 Spreading of hydraulic binders

Hydraulic binders are spread onto the surface of the soil to be treated in a controlled manner. Generally, the hydraulic binders are spread as a dry powder directly onto the surface of the soil (Figure 5). However, in urban areas hydraulic binders can be distributed in a slurry form to eliminate the potential for dust generation (Figure 5).

Hydraulic binders are added to the soil as a percentage of the weight of material that is to be treated. Spread rates are typically calculated on a weight distributed over a square metre as a function of the depth of treatment.

Figure 5 Spreading of hydraulic binder as a powder and as a slurry

4.3 Mixing of hydraulic binders

Once the hydraulic binder has been spread on the soil, an appropriate level of mixing and pulverization must occur in order for the process to be successful. Where the host soil is a low plastic material, mixing and pulverization can occur as a single-stage process. Where heavy, more plastic clays are encountered, a two-stage process may be required.

Where a two-stage process is utilized, it is common practice to treat the highly plastic clay soil with a small addition of lime (1-3%). Once treated, the soil is lightly compacted, to protect the surface from heavy precipitation, and then allowed to "mellow". The duration of the mellowing period is typically 24-48 hours and is dependant upon the initial moisture content and plasticity of the host clay soil. During the mellowing period the plasticity of the clay soil alters significantly and the soil becomes more friable; thus, a much finer material is generated after pulverization. This modification of the soil allows for better mixing of the hydraulic binders during the second stage of mixing. Typically, during the second stage of mixing, Portland cement is added to ensure adequate strength gain is achieved. During this second stage it is important to remember to add sufficient water to ensure compaction at the modified OMC. The OMC not only increases with binder concentration, but will also further increase with prolonged mellowing, *Holt and Freer-Hewish (1998).*

Whether using a single or a two-stage process, mixing is performed by specialist pulverizing/mixing equipment. This equipment comprises a rotating drum with teeth that is hydraulically forced into the soil. As the equipment moves forward the rotating drum mixes the soil and hydraulic binder together. Figure 6 depicts modern self-powered rotary mixers. During mixing sufficient water must be introduced to ensure compaction at the appropriate moisture content. This is achieved by directly spraying water into the drum of the mixing unit (Figure 7) or by spraying water directly onto the surface of the treated soil (Figure 7).

Figure 6 Self-powered rotary mixers blending host soil and hydraulic binders

Figure 7 Water addition while mixing and/or directly after binder spreading

4.4 Compaction and final grading

For maximum development of strength and durability it is important that the stabilized material is properly compacted. Compaction occurs immediately after mixing to ensure water is not evaporated from the treated soil. This ensures appropriate curing and hydration of water. Where thick lifts (200-300mm) of treatment have been undertaken it is common practice to firstly compact with a sheep foot roller followed by a steel wheel vibratory roller (Figure 8). Where only thin lifts (<200mm) of treatment occur a steel wheel vibratory roller is often only required to achieve the desired level of compaction. Once compacted, it may be necessary to grade the treated layer to ensure compliance with level and cross-fall requirements.

Figure 8 Initial compaction (pad foot) followed by final compaction (steel wheel)

Once fully compacted and graded, it is essential to allow the treated material to cure. This will ensure that water is hydrated to produce the cementitious material essential for the enhancement of strength and durability. Adequate curing is typically achieved by performing one of the following:

- Continually spraying water on the compacted surface until the next layer is placed.
- Spraying a bituminous membrane directly onto the treated surface.

5 Applicability in Canada

Soil stabilization has been utilized in Canada in the past to a limited extent; the author is aware of the process being utilized in Alberta, Saskatchewan and Prince Edward Island. Limited literature or data exists to confirm either the utilization or the success of the process. Nevertheless, some research has been undertaken in the past in Canada to confirm the validity of the process. In particular, work undertaken at the University of Saskatchewan (*Sweeney et al 1988 and Sweeney et al 1989*) and the University of Laval (*Choquette, et al 1987*).

A major concern with the efficacy of soil stabilization in Canada relates to the long-term durability of the material during harsh winter conditions. Most provinces experience winters where sub-zero temperatures are experienced for long periods resulting in deep frost penetration. In addition, numerous freeze-thaw cycles can occur within the winter season.

For subgrade improvement for major highway construction projects, freeze-thaw is typically not a problem as the thickness of the overlying structure is sufficient to eliminate frost penetration into the treated subgrade. However, for subgrade treatment of access/haul roads, parking lots, and minor highway works frost can – and will – penetrate the stabilized layer.

Where frost penetration is expected, appropriate freeze-thaw tests should be performed to assess the durability of the stabilized soil. Several methodologies exist whereby the freeze-thaw resistance of a stabilized soil can be measured.

ASTM 560, AASHTO T216-83 and *Transportation Alberta Test Method TLT-504 (02)* all provide similar methodologies by which specimens are prepared, exposed to freeze-thaw cycles and then exposed to brushing action. All three test methodologies are very similar. A weight before and after brushing is recorded; thus, a weight loss can be calculated. A weight loss of less than 10% (by weight) suggests adequate resistance to freeze-thaw cycles.

The *National Lime Association (2006)* proposes a methodology whereby specimens are prepared, cured and exposed to either 3, 7 or 10 freeze-thaw cycles. After the freeze-thaw cycles have been completed, the specimens are tested for unconfined compressive strength. Minimum strengths are recommended based on the type of pavement to be constructed.

A state-of-the-art practice report *(TRB 2005)* suggests that *ASTM D5918* can be utilized to assess freeze-thaw durability. This test standard assesses the frost heave and thaw weakening susceptibility of soils. Samples are prepared and subjected to two freeze-thaw cycles over a 24 hour period. Samples can either be tested at the expected soil moisture content or in a saturated condition, depending upon likely site conditions. During the test period heave measurements are made. Based upon these measurements, a susceptibility rating is allocated ranging from negligible to very high. Furthermore, bearing ratio tests can also be performed on specimens after thawing, typically the CBR test

It is commonly accepted that frost action will affect the stabilized material and reduce its load bearing capacity. However, increased binder addition will render the soil less or non-frost susceptible. Where freezing action is anticipated it is important that laboratory mix designs assess freeze-thaw effects. It should be noted that most frost susceptibility tests are performed on specimens that have undergone minimal curing, typically no longer than 7 days. This is a short cure period and enhancements in strength and durability continue with prolonged curing. In some cases, improvements have been reported up to 14 years after treatment, *Dawson and McDowell (1961)*. This continued enhancement in strength will ensure that the stabilized material is less susceptible to freeze-thaw cycles.

Many northern and mid-western states in the US experience winter conditions similar to those in Canada. Table 1 below tabulates states within the US that experience similar winter conditions to Canada and that still utilize soil stabilization for the construction of highway pavements.

Table 1 Winter temperature variation for states that utilize soil stabilization

State	Average Winter Temperature Range	Coldest Temperature Recorded
Colorado	-20^{o}C to -30^{o}C	-52^{o}C
Illinois	-1^{o}C to -12^{o}C	-38^{o}C
Iowa	-9^{o}C to -15^{o}C	-44^{o}C
Montana	-3^{o}C to -30^{o}C	-57^{o}C
Nebraska	-7^{o}C to -12^{o}C	-44^{o}C
Ohio	-6^{o}C to -15^{o}C	-39^{o}C
Wisconsin	-7^{o}C to -12^{o}C	-48^{o}C
Wyoming	-10^{o}C to -15^{o}C	-54^{o}C

Given the experience and continued success of the process in the states listed in Table 1, there is significant potential for the process to be utilized more prevalently across Canada. Nonetheless, for the process to be successful, appropriate construction specifications will have to be developed, including appropriate types of testing to be performed in a laboratory mix design. Reliance on current best practices used globally will make the development of such specifications relatively simple, and will guarantee the best end-product that is both strong and durable.

6 Chatham Wind Power Project, Southwestern Ontario – Case Study

Kruger Energy is currently expanding a wind power project in the Chatham area of southwestern Ontario. Expansion includes the construction of additional 44 turbines to the already existing 44. The development of these additional wind turbines requires the construction of access roads; these are typically constructed perpendicular to the existing road network

Soil conditions in the area – a plastic clay – overlaid by a minimal layer of topsoil required significant imported granular material was in order for access roads to withstand construction loading. The original design considered the removal of the weak in-situ soil and replacement with approximately 350-400mm depth of granular import. In addition, the construction of the access roads had to be below the existing grade of the surrounding agricultural land.

As an alternative to a “remove and replace” strategy, in-situ soil stabilization was investigated as a potential option for the construction of the necessary access roads. The perceived advantages of soil stabilization over “remove and replace” were as follows:

- Minimal soil removal to ensure appropriate grade: the soil stabilization option required windrowing of approximately 100mm of the topsoil, whilst the “remove and replace” strategy required the removal of at least 400mm of soil.

- Expedited construction of haul roads: the soil stabilization option provided less disruption as a result of inclement weather and minimized soil movement.

- In-situ stabilization offers a more sustainable approach: namely, there is a reduced carbon footprint as considerably less quarried material is required.

To verify the suitability of the soil stabilization option, laboratory testing of representative samples was undertaken. Tests performed included: compaction testing and UCS testing. Results are presented below. Note that the percentage and types of binders have been omitted from the data and that only a mix design designation is denoted.

Figure 9 – Summary of Compaction Results

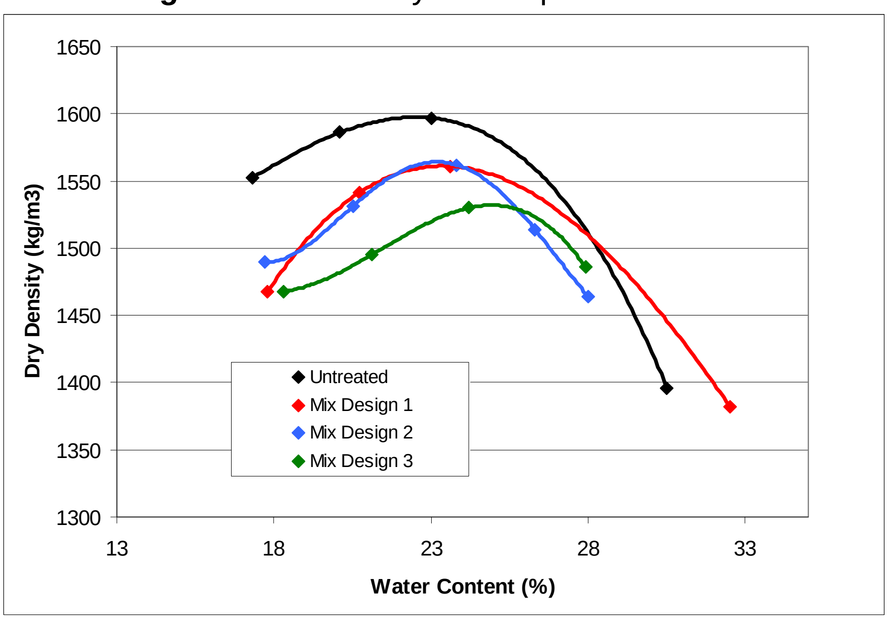


Table 2 Summary of UCS Results

Mix Design	Strength (MPa) 7 day cure	Strength (MPa) 21 day cure
Mix Design 1	0.99, 0.75 (**0.87**)	Not tested
Mix Design 2	1.43, 1.42 (**1.42**)	1.68, 2.32 (**2.00**)
Mix Design 3	1.97, 1.99 (**1.98**)	Not tested

Note: Figure in parenthesis denotes average of two values

To ensure the performance of the in-situ stabilized soil was equivalent to a granular layer, a design strength of the stabilized soil of 1.75 MPa was specified. This design strength ensured adequate load bearing capacity during wind turbine erection, and ensured that stabilized material was non-frost susceptible. Laboratory testing demonstrated the effectiveness of the process, and based on 7 day and 21 day strength testing, mix design 2 was recommended and consequently utilized in the field. Once treated, a thin layer (75-100mm) of granular material was placed on the treated material. This serves as a protective layer and a wearing surface to the access roads.

Soil stabilization operations commenced on 21st March 2010 and were successfully completed 30th April 2010. Approximately 20 km of access roads have been successfully treated. The soil stabilization option has not only been successful in stabilizing a material that would traditionally be removed and replaced, but has also reduced the construction time for the haul roads. This has enabled a greater construction window for the erection of the wind turbines. Pictures of the soil before and after treatment, together with processing, are presented in Figures 10 through 12.

Figure 10 Site prior to treatment and processing binder into the natural soil

Figure 11 Initial compaction (pad foot) and the treatment train

Figure 12 Final compaction and completed access road with granular surface

7 Conclusions

Soil stabilization with hydraulic binders offers the pavement engineer an alternative to the traditional "remove and replace" strategies commonly utilized. The process not only offers the ability to enhance the engineering characteristics of an unsuitable soil, but also offers the engineer a more sustainable approach to pavement construction.

Appropriate field investigations, material retrieval and laboratory mix design procedures are essential in ensuring the success of the process. These preliminary investigations help in providing important information for quality control during construction operations.

Soil stabilization has been successfully utilized globally, in temperate, warm and cold climates, for over 50 years. To date in Canada the process has been utilized to a limited extent. Where soil stabilization has been used, little or no data exists to suggest whether the process was successful. Recent soil stabilization operations in Chatham, Ontario have demonstrated that the process was highly successful, and, furthermore, that there is potential for widespread utilization across Canada providing appropriate procedures, design and specifications are followed.

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