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Capillary Rise Experiment to Assess the Effectiveness of an Enzyme Soil Stabilizer

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1 ABSTRACT

2 An experimental program to assess of the attributes of an enzyme soil stabilizer is described.

3 The focus of the program were two one-year capillary rise experiments designed to test the

4 influence of the soil additive on the soil's adsorption of water. The enzyme additive is typically

5 applied to marginal clay-based soils to improve the performance of road subgrades. The study

6 investigated the potential increase in shear strength and the reduction in swelling. The two long-

7 term soil column tests were conducted to measure water absorption due to capillary rise with,

8 and without, enzyme treatment. The test results demonstrated that the addition of the enzyme

9 soil additive had the effect of reducing water retained in the pore spaces of a partially-saturated

10 soil. The soil treated with the enzyme additive absorbed a lower quantity of water in the

11 capillary rise test, and at a slower rate of absorption. The results from a concurrent suite of tests

12 suggested that partially-saturated clay having lower moisture content was linked to an increase in

13 shear strength.

14

15 Keywords

16 Enzyme additive, capillary rise, water adsorption, subgrade stabilization, laboratory testing

1. Introduction

Red River valley soils are rich in clay and silt. While this may be beneficial for agricultural uses, fine-grained soils can be problematic as construction materials for roads and foundations. Clay soils, owing to their molecular structure, have an affinity for water making them weaker during wet weather. Clay often experiences considerable swelling and shrinkage in response to moisture changes, and if silt is present, can be prone to frost heaving in the winter. A number of solutions are available to mitigate potential construction problems, ranging from replacing the fine-grained soil with granular material and/or the use of geosynthetic reinforcement to the use of soil additives. Demonstrating an economically viable improvement of marginal subgrade soils, by application of soil improvement additives, would have a benefit for roadway construction.

An emerging category of soil additives are the natural organic, bio-degradable multi-enzyme products. Enzymes are natural organic compounds, which act as catalysts. Enzyme products can also include biodegradable surfactants to reduce the surface tension and promote enzymatic reactions. Marasteanu et al. (2005) report that enzymes have been applied with success to road and highway projects in over forty counties since the 1970s. Although this type of additive has been applied to stabilizing soils for decades (Khan and Sarker 1993) there is still very little information in the technical literature describing its use in road construction.

Different theories have been espoused in the literature as to how enzymes improve soil performance. These theories are documented in Section 8 of this paper with reference to the results of the current research. To summarise, enzymes are believed to combine with large organic molecules that are adsorbed to the clay surfaces, they act as catalysts for cation

exchange, they may improve chemical bonding, and/or they include proteins that act as surfactants reducing the surface tension in the water surrounding the clay particles. Enzyme products have no negative environmental affects, as might be the case with lime, cement, bitumen, chlorides, synthetic polymers, or acid-based additives. Anecdotal evidence from applications around the world suggests that adding the enzyme stabilizer to predominantly clay-based road sub-grade material enhances the material's bearing capacity. This affect is most apparent when the soil is less than saturated.

The primary incentive for using enzyme additives would for be its positive environmental attributes. Also, since only 1 L of enzyme treatment is added to about 30 m³ of compacted soil, enzyme treatment is less expensive when compared with cement additives or other hydraulic binders. In addition, enzyme treated clay remains flexible and elastic, whereas cemented soils are rigid and once they crack are not fixable. Enzyme treated clay soils retain their self-healing qualities. A disadvantage for enzyme stabilization is that, to be effective, the soil must be at or below its optimum moisture content when treated. The enzyme treated soil must then be allowed to adequately dry to obtain best results. The paucity of documented case studies or laboratory testing results, relative to the information available for hydraulic binders, can also be seen as a disadvantage when considering enzymes for use in road improvement projects. In particular, there is little discussion in the literature on the effectiveness of enzyme treatment in response to drying and wetting cycles.

2. Review of previous laboratory studies

A few laboratory studies into the effectiveness of enzyme additives to improve soil properties have been performed. However, the experimental findings have been inconsistent. Tingle and Santoni (2003) tested four enzyme products with two products producing a 30% gain in unconfined compressive strength of high-plastic clay, while the other two products produced no strength gain at all. A low plastic material with less than 27% clay-size particles had almost no strength gain when treated with any product. Rauch et al. (2002) also provided varied results and concluded that the as-prepared moisture content had as great effect on the strength data as the application of the enzymes. Velasquez et al. (2006) concluded that one of the two enzyme additives tested greatly increased the elastic resilient modulus of a high plastic clay making it much stiffer under dynamic loading. Mgangira (2009), Venkatasubramanian and Dhinakaran. (2011), Eugene et al. (2014) and Agarwal and Kaur (2014) all observed an increase in strength with curing time for most of the enzyme products tested, while Parsons and Milburn (2003) found no significant increase in soil strength with enzyme treatment. Common themes in most publication were that the enzyme additive worked better on higher plasticity soils with greater clay content, that the product reduced the soils affinity for water, and that not all enzyme products produce positive results in the laboratory. Inconsistency of results from one researcher to the next may be due, in part, to differences in specimen preparation and curing methodology.

The study described in this paper was performed at the Robert Kwok Memorial Lab at Red River College in Winnipeg, Manitoba. The purpose of the study was to compare properties of a local soil treated with an enzyme additive to those of the same untreated soil. The experimental protocol was developed to test the hypothesis that the enzyme additive affects a clay soil's ability to absorb water or release it to evaporation. The central components of the experimental program were two year-long capillary rise tests to assess water adsorption with and without the

enzyme additive. Tests were also concurrently carried out to compare strength and swelling.

The contents of this paper will summarise the results from strength and swelling tests, with the capillary absorption tests described in greater detail.

3. Soil characteristics and specimen preparation

The soil was chosen at random from the Winnipeg region. The intent was to obtain sufficient soil with consistent properties from the lacustrine sediments of the Red River flood plain in the Lake Agassiz Basin. Although regional fine-grained soils are similar in appearance throughout Southern Manitoba, soil plasticity, fine particle size distribution, and compaction characteristics can vary significantly from location to location. About 100 kg of clay soil was collected from one site to be used for all the soil tests. Only one enzyme product (Earthzyme) was used in the study¹.

EarthZyme is a product that is added to clay-based soils. Its use is intended to increase soil compaction and consequently bearing capacity for roadway construction. EarthZyme consists of three primary elements: (1) an ionic solution that interacts with clay minerals and reduces the thickness of the water layer bound to the clay particles, (2) a surfactant to reduce the water viscosity, and (3) a combination of enzymes that facilitate ion exchange between clay particles and the ionic solution.

The soil had a liquid limit of 85, a plastic limit of 37 and a plasticity index of 47. On the plasticity chart, the soil characteristics plot just above the A-Line (the boundary between MH

¹ Earthzyme is a product of Cypher Environmental Ltd.(1149 St. Matthews Ave, Winnipeg, Manitoba), and was used exclusively in this study.

111 and CH) and so would be classified as a high plastic clay (CH). The grain size analysis indicated
112 that the soil contained 73% clay-sized particles (< 0.002 mm), 24% silt-sized particles and 3%
113 sand (retained on the No. 200 sieve). The soil's specific gravity was measured to be 2.72. The
114 soil could be compacted to a dry density of approximately 1450 kg/m^3 at moisture contents
115 between 15 and 20%. The clays of the Red River basin typically swell significantly when
116 inundated with water. This soil was no different, experiencing 11% volume increase in free
117 swell tests for specimens prepared at densities near the MDD.

118

119 A combined total of 43 specimens were prepared for unconfined compression, unconsolidated-
120 undrained, consolidated-undrained, swelling pressure and tempe cell tests. All specimens were
121 pre-mixed to an average moisture content of 28% (with a 2.5% standard deviation) by weight
122 with an average dry density of 1510 kg/m^3 (with a 57 kg/m^3 standard deviation). To prepare the
123 treated soil, 0.6 mL of Earthzyme was added to 4 kg of water before mixing with 25 kg of dry
124 soil (1 L treatment for 30 m^3 of compacted soil). Remolded specimens for strength and swelling
125 tests were compacted in layers inside a steel mold using a Proctor hammer, employing the same
126 compaction energy as in a Proctor test. The strength and swelling pressure soil specimens were
127 trimmed to size, wrapped in newsprint, and allowed to dry for usually seven days. The drying
128 stage was incorporated to allow the soil-enzyme mixture to cure under conditions representative
129 of those in the field. The purpose of the newsprint was to slow the rate of drying in order to
130 prevent splitting due to shrinkage. The ambient relative humidity in the laboratory was an
131 average of 32% and the residual moisture content of the fully-dried soil was 9% on average (with
132 a standard deviation of 3.3%). Specimens air-dried in the lab would achieve the residual
133 moisture after about one week following preparation, although some variability in the final
134 moisture content was recorded. Owing to shrinkage during drying, the dry density of the air-

dried soil increased, on average, to 1870 kg/m^3 (with a standard deviation of 48 kg/m^3). The treated and untreated specimens were both prepared at the same time, using the same specimen preparation methods and cured in the same temperature and humidity environment. The exception being the soil column capillary absorption tests, which had to be performed sequentially owing to material and equipment limitations.

4. Strength and swelling

Unconfined compression tests and California Bearing Ratio (CBR) tests were conducted following ASTM procedures. Drying and curing for one week tended to produce very strong unconfined compression specimens. The seven day duration of the drying stage was subsequently reduced to allow the specimens to be tested at higher moisture contents. Fig. 1 illustrates a typical unconfined compression tests result. The enzyme treated soil was usually dryer and slightly denser than the untreated specimen. As a consequence, the treated soil was usually stronger than untreated soil and an average of 60% stiffer as evidenced by a steeper slope on the stress-strain diagram. The observation that treatment with enzymes produced a stiffer soil is in keeping with the findings of Velasquez et al. (2006) that enzyme treatment produced a soil with a higher resilient modulus. The compilation of data in Fig. 2 suggests that soil strength was more dependent more upon moisture content than on soil treatment with the enzyme additive. It is important to note that even the wettest specimen in Fig. 2 (a volumetric moisture of 32% or gravitational moisture of 18%) had experience considerable drying shrinkage during the curing period. As a consequence, all the unsaturated dried/cured specimens would be expected to be much stronger than remolded specimens tested without drying, with or without treatment. Vanapalli et al. (1996) document the theoretical relationship between increasing soil strength,

159 decreasing moisture content and increasing soil-water suction, supporting the concept that
160 strength increases for dryer soils. In the current study, the treatment of the soil with the enzyme
161 additive produced a dryer and consequently stronger material, provided it was cured for the same
162 duration as the untreated specimen. Fig. 3 illustrates the increase in soil dry density as a function
163 of curing time. The presumption is that decreased moisture leads to shrinkage and density
164 increase with a consequent increase in strength.

165

166 The California Bearing Ratio (CBR) test uses a volume of soil more than twelve times larger
167 than the unconfined compression specimen, with less overall drying occurring during the one
168 week of curing. The CBR test is the standard test method for determination of the strength of
169 sub-grade material for use in road construction. CBR test data for treated and non-treated soils
170 are provided in Fig. 4. ASTM D1833 (2014) requires the CBR value at 5.0 mm of penetration to
171 be used if the value at 5 mm is consistently greater than the value at 2.5 mm. The treated CBR
172 value of 28 compared with the untreated CBR of 21 suggests a 38% increase in bearing strength
173 when the soil is treated with the enzyme additive.

174

175 Consolidated-undrained triaxial compression tests were also performed on saturated treated and
176 untreated soil specimens at confining pressures up to 280 kPa with 140 kPa internal pore
177 pressure (back pressure) at the start of each test. The effective cohesion and effective angle of
178 internal friction were determined for both treated and untreated soil. The effective cohesion was
179 determined to be zero for both, while the effective angle of internal friction was approximately
180 34° for both treated and untreated soil. There was no apparent improvement to effective strength
181 properties of this soil when the soil was saturated. Published research results are inconsistent
182 with respect to strength gain while saturated. Some researchers measured no increase (Parsons

and Milburn 2003) while others observed a strength increase if the enzyme additive was allowed to cure in saturated soil for 28 days (Venkatasubramanian and Dhinakaran 2011). Results from the current study, for the specific soil used, indicate that the strength gain occurs when the soil is only partially-saturated. However, no soaked CBR tests were performed on the test material. Soaked CBR tests on some other enzyme treated soils have shown modest strength gains.

The ASTM procedure for swelling pressure measurement (ASTM D4546) provides three methods for determining swelling pressure using consolidation test equipment. The “loading after wetting” method was used in this study. The soil specimen was cut to the size of the consolidation ring before being allowed to dry (cure) for seven days. The slightly smaller cured specimens were returned to the fixed-diameter molds before being inundated with water and allowed to free swell. The initial dry density after curing, and prior to inundation, for both the treated and untreated soils was 1880 kg/m^3 , which due to curing-related shrinkage, was higher than the as-prepared dry density. The moisture content at the end of the seven day curing period varied between 5 and 8% by weight. The specimens were allowed to expand freely for several days until swelling stopped. The vertical applied load was increased daily and the vertical compression was measured. The compression data (in mm) was converted to dry density. The vertical applied pressure was considered to be the swelling pressure. The swelling pressure as a function of dry density for the treated and untreated specimens is provided in Fig. 5. The test results from three treated specimens and three untreated specimens indicate that both the free swell expansion and the swelling pressure are reduced for treated soils when compared with untreated soils. Given that volume expansion is related to the increase in the water content, the tests indicated that the untreated soil took on more water than the treated soil when an unlimited supply of water was available.

5. Water absorption and summary of mechanical testing

The strength and swelling test results indicated that the addition of an enzyme additive produced a material that lost water to evaporation more quickly during drying than untreated specimens. For a given drying time the treated soil was slightly more dense, had a greater stiffness and a higher bearing strength than the untreated soil. Inundation of the fully dried swelling pressure specimens resulted in less absorbed water for the treated soil than for the untreated soil. A lower quantity of absorbed water manifested itself as lower swelling pressures for the treated soil. The implication from the data was that addition of the enzyme soil additive resulted in a decrease in the soil's affinity for water. The enzyme additive includes a surfactant. Therefore, it is possible that the additive reduced the surface tension along air-water interfaces within the partially-saturated pore spaces. The reduced surface tension resulted in lower pore-water suction and a corresponding decrease in the water content. The relationship between the volumetric water content and pore-water suction is referred to as the Soil-Water Characteristic Curve (SWCC). Theory suggests that the addition of the enzyme shifted SWCC towards a lower volumetric water content at any given value of suction. Measurement of the SWCC using Tempe cells and vapour equilibrium was attempted for the soil used in the experiments. The inability to obtain usable results from these tests was attributed to equipment limitations, such as the ceramic air entry value, and considerable data scatter.

6. Soil column tests

The purpose of the soil column tests was to compare the water adsorption of compacted clay material with, and without, enzyme treatment. The soil was compacted in a 150 mm diameter fixed wall plastic tube to a dry density of 1350 kg/m^3 at moisture contents between 15.5 and 17.5%. The soil was compacted in place using a proctor hammer and the same lift thickness and compaction energy as used in preparing the CBR tests, although the as-placed density in the plastic tube was slightly less than the 1380 to 1450 kg/m^3 achieved in compaction molds. The two soil columns were 1170 and 1100 mm in height. Five Decagon moisture sensors were compacted inside the soil column. The lower 75 mm of the soil column was submerged in a water bath and the soil column was allowed to absorb water through capillary action for approximately one year. The upper surface of the column was open to the atmosphere. The ambient air near the upper soil surface had a relatively constant temperature of 25°C and relative humidity of 32%. The test configuration diagram and photograph are provided in Fig. 6ab.

Soil was compacted in 60 mm thick lifts using 56 blows per lift from a standard proctor compaction hammer. In mixing the soil, 4 kg of water was added to 25 kg of dry soil. The treated soil included 0.6 mL of the enzyme soil additive. The compacted soil column sat for one week before water was added to the reservoir. Decagon moisture sensor data was recorded every hour.

The Decagon moisture sensors measure the dielectric constant using capacitance/frequency domain technology. The sensors were calibrated to the volumetric moisture content of the compacted soil as used in the test. Prior to test assembly, the sensors were inserted into six compacted soil specimens at volumetric water content between 15 and 40% (corresponding to 11 to 30% gravimetric moisture). Upon final disassembly of each test, the moisture and density

were determined at each sensor location. The end-of-test data from the five sensor readings for both tests provided an additional 10 data points for calibration. The relationship between volumetric water content and sensor reading is provided Fig. 7.

The volumetric moisture content is the volume of water per unit total volume of soil, expressed as a percent. The relationship between volume moisture (w_{vol}) and gravimetric moisture (w) is as follows:

$$[1] \quad w_{vol} = w \frac{\rho_{dry}}{\rho_w},$$

where ρ_{dry} is the dry density and ρ_w is the density of water. The change in moisture content as measured by the five moisture sensors from the treated test is provided in Fig. 8. The rate of change of moisture content (gravimetric moisture), as measured by sensors at 26 and 50 cm above the water level, are provided in Fig. 9 for both treated and untreated tests.

The first conclusion drawn was that capillary rise takes a long time to achieve moisture equilibrium. Both the treated and untreated tests were disassembled after approximately twelve months of operation. The analysis of capillary rise in sandy silt by Lu and Likos (2004) showed that up to two years may be required for a partially-saturated soil to come into capillary equilibrium. It is possible that the one-year tests described here were not completely stabilized. Nonetheless, the soil column treated with the enzyme soil additive absorbed water at a slower rate than the untreated soil and absorbed less water after approximately one year of capillary rise.

The soil columns were dismantled at the conclusion of each test. The end-of-test soil density and moisture contents were determined at the location of each original lift. The soil was visibly much wetter on the lower end and was hard and dry nearer the upper surface, as indicated in the

photographs in Fig. 10. The individual compaction lifts were not discernible in the lower and wetter portion of each test (Fig. 10a). Color change indicated an apparent water line at about one-third of the way up the soil columns or approximately 30 cm above the waterline. The soil easily broke apart along lift lines in the upper half of both treated and untreated columns (Fig. 10b).

Pre- and post-test density determinations allowed a comparison between the initial and final densities for both tests. The initial density was calculated by using the before and after lift elevations that were measured after a known mass of soil had been compacted in place. The post-test density measurements are likely more accurate than the pre-test measurements since 1 to 2 mm of uncertainty in as-placed lift elevation measurement represents about 50 kg/m³ in calculated density. The pre-test measurements were averaged over two lifts to provide less scatter. A decreasing density during wetting would indicate swelling and an increasing density during drying would indicate shrinkage. The dry density results from the treated test are shown in Fig. 11, with both the treated and untreated tests providing similar data. The comparison suggests that no swelling occurred in the lower portion of the test where the soil was getting wetter, but shrinkage occurred near the top to the test where the soil dried out.

Gravimetric moisture content of each lift was determined by oven drying. The density of each lift was used to calculate the volumetric water content (Equation 1). The density of the wetter soil was determined by pushing a 63 mm diameter steel ring into the exposed base of each lift. Determining the mass of the soil in the ring divided by the known volume provided the bulk density. The dryer soil broke apart when attempts were made to push the ring into it. The density of the dry soil was obtained by the wax density method. Gravimetric moisture content

302 and measured dry density was converted to volumetric water content. The end-of-test volume
303 water content was plotted as a function of distance above the water line for both the treated and
304 untreated tests in Fig. 12. The volume moisture content indicated that the soil closer to the
305 waterline eventually became saturated, regardless of whether or not the soil was treated with the
306 enzyme product. The saturation volumetric water content at the as-placed density was 50%.

307
308 Inspection of the moisture sensors during dismantling indicated that the sensors were in close
309 contact with the soil and the soil was uniformly compacted around the sensors during
310 installation. These observations suggested that the moisture content indicated by the sensors was
311 representative of the moisture content of the soil at that depth in the test. The end-of-test
312 moisture sensor readings are also provided in Fig. 12.

313
314 The vertical line on Fig. 12 at a volume moisture content of 22% represents the approximate as-
315 placed volumetric moisture. Soil to the right of this line had become wetter through adsorption
316 of water from below due to capillary rise. Soil to the left of the line had lost moisture through the
317 upper surface due to evaporation into the relatively dry (32% relative humidity) ambient air.
318 Water was drawn up to a height of about 800 mm above the water line for the untreated soil,
319 while only up to a height of 500 mm for the treated soil. Soil with moisture content greater than
320 45% indicated a degree of saturation that was over 90%, and both the treated and untreated soil
321 columns approached saturation water contents at heights just above the waterline.

322
323 The treated soil column was slightly shorter than the untreated column owing to material
324 shortage during preparation of the second test. The soil near the exposed surface was very dry
325 for both tests and had a degree of saturation of 17% (w_{vol} of about 8.5%) regardless of whether or

not the soil was treated. The treated soil throughout the central region of the test had a volume moisture content that was about 5% lower throughout than the untreated soil. The five percent decrease in moisture content represents 50 kg less water for every cubic metre of soil. Density determination inaccuracy is speculated to be the reason for the anomaly at 600 mm above the water line in the untreated data.

7. Interpretation of results

The data throughout this study consistently suggests that, for the soil type tested, the addition of the enzyme additive resulted in lower amount of water absorbed by the clay particles. The soil column test demonstrated that both the total quantity of water absorbed and the rate of water absorption are reduced by the enzyme additive. The addition of the enzyme did not affect the strength of the saturated soil, nor did it reduce the residual moisture content of the fully-dried soil. The addition of the enzyme reduced the absorption of moisture for soil that was less than saturated, but not quite fully dried-out.

The addition of the enzyme to compacted soil had the effect of achieving a lower water content compared with untreated soil specimens after a similar drying time. The consequence of greater shrinkage associated with increased water loss produced a higher density material. The dryer and denser treated soil had a higher bearing strength compared to untreated soil dried under the same environmental conditions. Upon rewetting, the treated soil took in less water and incurred a lower swelling volume change and generated lower swelling pressure than the untreated soil.

349 Evidence from California Bearing Ratio tests indicated that treated soil had greater bearing
350 strength than untreated soil when it was allowed to dry or “cure” for seven days. The unconfined
351 compression test data indicated that the moisture content of the soil correlated well with strength.
352 The soil column tests suggested that treated soils above the water table would have about 5% less
353 water than untreated soils. The relationship between water content and unconfined strength
354 (Fig. 2) indicated that 5% volumetric water content decrease would result in 2000 kPa strength
355 increase, which is significant if the unsaturated soil has an unconfined strength of about 5000
356 kPa. (Recall that these large strength values are for soil that has experience considerable drying
357 shrinkage). The strength gain for the treated soil in the unconfined compression or CBR tests
358 would occur for soil that was less than saturated, but not fully dried-out.

359
360 The capillary rise soil column tests confirmed that the treated soil took on less water and that
361 wetting due to capillary rise occurred at a slower rate. The transient moisture content change
362 was monitored over two consecutive one-year testing period using Decagon moisture sensors,
363 which were calibrated to the volumetric water content of the soil. The long time required to
364 achieve capillary rise equilibrium was unexpected when the test was assembled. The slow rate
365 of water movement was probably related to the low saturated hydraulic conductivity of the
366 compacted clay material (8×10^{-11} m/s).

367
368 Although the soil column tests provided the most compelling evidence that the addition of an
369 enzyme additive reduced the rate and quantity of water absorption of a compacted clay soil, the
370 test took too long to run to be practical for future tests. The soil column test is very similar to
371 ASTM C-1585 (2013) a procedure used to determine the water “sorptivity” of concrete. The
372 mass of absorbed water in a 400 cm^3 cylindrical concrete disc is recorded manually over three

days. A similar method could be used for compacted clay. Another possibility for testing the capillary adsorption of water by treated soil would be a hanging column test, similar to the one outlined in ASTM D6836 (2002).

8. Enzyme stabilization process

Rauch et al. (2002) identified various obstacles preventing enzyme-based additives from becoming more widely used. Included among these obstacles were the lack of standard methods for either field application or laboratory testing of the product's effectiveness and that lab evidence is often inconclusive or contradictory. Understanding the reason for the soil strength improvement would benefit the development of laboratory test protocol. However, there are conflicting theories put forward in the literature regarding the stabilization mechanism. The predominant theory is that enzymes combine with large organic molecules that surround clay particles and these positively charged molecules are adsorbed to the clay surface. The molecules displace water within the diffuse double layer and neutralise the net charge on the clay surface reducing the affinity of the clay for absorbed water (Rauch et al. 2002; Tingle et al. 2007). A second theory is that the enzymes catalyze the reactions between clay and organic cations, which in turn accelerates cation exchange without becoming part of the end product (Venkatasubramanian and Dhinakaran 2011; Agarwal and Kaur 2014). A third theory suggests that the enzymes improve chemical bonding and pull the soil particles closer together (Taha et al. 2013; Rajoria and Kaur 2014). Many researchers acknowledge that enzyme products are surfactants and reduce the surface tension in pore water. Velasquez et al. (2006) measured the reduction in surface tension and postulated that it was a contributing factor for strength gain.

396 Some of these proposed mechanisms are inter-related and most have a reduced affinity for
397 adsorbed water as a consequence.
398

399 A useful explanation of the diffuse double layer of water is provided by Kirkham and Powers
400 (1972). The diffuse double layer of water surrounding negatively charged clay particles includes
401 the Stern layer, a layer of water with immobile cations adsorbed to the surface of the clay, and
402 the diffuse layer having a high concentration of mobile cations. There is an electro-chemical
403 potential that draws the cations to the charged clay surface, but which decreases with distance
404 from the clay particles. This attractive force is affected by the concentration of solutes, the type
405 of solutes in solution, the type of cations adsorbed on the clay surface and the molecular
406 structure of the clay. The thickness of the diffuse layer of water will depend on how quickly the
407 electro-chemical attraction diminishes with distance away from the clay surface. Two of the
408 prevailing theories (i) enzymes coat the soil particles displacing cations in the diffuse layer, and
409 (ii) enzymes catalyse a reaction that results in the exchange of cations on the surface or Stern
410 layer, are two different mechanisms that have a similar result. Both reduce the net negative
411 charge and consequently reduce the thickness of the diffuse double layer. A third possible
412 mechanism is that the enzyme product reduces the surface tension in the pore water of partially-
413 saturated clay. The reduction in surface tension will result in decreased pore water suction and a
414 decreased thickness of the adsorbed water layer. All three mechanisms suggest a reduced
415 affinity for water in partially-saturated clay with the addition of enzymes. Some unsaturated soil
416 researchers have lumped the soil-water forces due to hydrostatic suction, osmotic potential and
417 adhesion potential into one term, referred to by Kirkham and Powers as either capillary potential
418 or matric potential. Irrespective of whether any one of the above theories works independently,
419 or if they all contribute concurrently, the net effect of adding enzymes to the soil pore water is

the reduction of the matric potential and consequently a reduction in the thickness of adsorbed water surrounding the clay surfaces.

The suggestion that the addition of an enzyme soil stabiliser decreases a clay soil's affinity for water is supported by the results from the capillary rise tests described in this paper. In essence, the enzymes result in a decrease in the moisture content of the soil at a given pore water suction, if the soil is only partially saturated thus altering the soil water characteristic curve (SWCC).

Vanapalli et al. (1996) developed a model for the increase in shear strength with decrease in moisture content and the corresponding increase in suction. The increase in strength occurs within the transition phase of soil drying (or wetting) in which the soil is less than saturated but above the residual moisture content. The suggestion in the current study is that enzyme treatment lowers the clay soil's affinity for water so that the treated soil dries more quickly than an untreated soil or dries to a lower moisture content at a given humidity and temperature environment. Soil at a lower moisture content will have greater shear strength as indicated by Fig. 2.

It is apparent from the literature that not all enzyme soil stabilizers have the same effectiveness and that measured shear strength will be dependent upon the soil type and its characteristics. There is a need to be able to demonstrate the strength increase for given soil type and enzyme product. A problem with laboratory tests described in the literature is that there is not a consistent approach to specimen preparation and curing. The curing process, more so than specimen preparation, differs among researchers, with some specimens cured in wet curing rooms, others sealed to prevent moisture loss during curing, and one researcher curing specimens at constant relative humidity (Rauch et al 2002). Since benefit is gained as the soil dries but

before it dries to its residual moisture, specimens should be allowed to dry during curing but should not dry out completely. Specimens should not be sealed, nor cured in 100% humidity curing rooms. Humidity in sealed containers can be controlled using aqueous salt solutions. CBR and unconfined compression test specimens should both be cured in a controlled humidity environment to facilitate comparisons of the findings.

9. Summary

The paper describes the assessment of the attributes of an enzyme additive as applied to improving the performance of marginal clay-based soils for road subgrades. The study investigated the potential improvement to strength and the effect on swelling. Two long-term soil column tests were conducted to measure water absorption during capillary rise with, and without, enzyme treatment. The test results demonstrated that the addition of the enzyme soil additive had the effect of reducing water retained in the pore spaces of a partially-saturated soil. The soil treated with the enzyme additive absorbed a lower quantity of water in the capillary rise test, and at a slower rate of absorption.

The strength tests demonstrated that the water content of the partially-saturated soil strongly influenced strength. The soil with enzyme additive had a greater bearing strength than the untreated soil as determined using California Bearing Ratio (CBR) tests. Under similar drying times and environmental conditions the treated soil attained lower moisture content and the associated shrinkage produced a higher density material than the untreated soil. The premise is that the enzyme additive allowed the soil to lose a greater amount of pore water to evaporation. The treated soil, having a lower water content and higher dry density, consequently achieved a

greater bearing strength. The attributes of the enzyme soil additive are most apparent under partially-saturated soil conditions where the soil is neither fully-saturated nor completely dried to its residual water content. The lower rate of reabsorption of water for the treated soil had a related beneficial attribute of reducing swelling upon re-wetting.

Two one-metre high capillary rise soil column tests were each performed over a one year duration. The tests indicated a very slow rate of capillary-induced water movement in partially-saturated compacted clay for either treated or untreated soil. Results demonstrated that the soil treated with the enzyme additive absorbed less water and absorbed water at a slower rate than the untreated soil. The results from the soil column test were the strongest evidence to support the premise that the enzyme additive reduces the soil's affinity for water.

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Figure Captions:

Figure 1. Unconfined compression test data for treated and untreated specimens.

Figure 2. Unconfined strength as a function of volumetric moisture content.

Figure 3. Density increase during drying.

Figure 4. Data from CBR tests on treated and untreated specimens.

Figure 5. Swelling pressure as a function of treated and untreated soil dry density.

Figure 6. (a) Experimental arrangement for soil column capillary rise test. (b) A photograph of soil column test (right).

Figure 7. Decagon moisture sensor calibration.

Figure 8. Moisture content versus time during capillary rise for the treated soil specimen.

Figure 9. Comparison of moisture content versus time for treated and untreated soil.

Figure 10. Photographs of the soil column at the end of the test. (a) Lower, wetter soil shown on the left and (b) higher, dryer soil shown on the right.

Figure 11. As-placed and end-of-test dry density for the treated soil test.

Figure 12. Comparison of end-of-test volumetric water content as a function of distance above the waterline.

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