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ABSTRACT:

Introduced as a non-traditional stabilizer for soil stabilization and erosion control, liquid polymer-based products have become popular in respect to cost-efficiency, ease-of-application, and fast-curing. They prevent base failure, dust pollution and soil erosion; and they increase soil shear strength and reduce permeability. A series of unconfined compression (UC), California Bearing Ratio (CBR), and cone penetrometer tests were conducted on compacted flexible base course materials with and without polymer treatment. A water-based liquid polymer admixture was used. The testing program was carried out to determine the effects of polymer admixtures on the strength properties of soils and to establish correlations between UC, CBR, and penetrometer test results. Treated specimens were prepared for three polymer environments (0.25%, 0.50%, and, 1.0% polymer by weight). The results revealed that, on average, the unconfined compressive strength with 1% polymer was 7.6 times, with 0.5% polymer was 5.7 times, and with 0.25% polymer was 3.7 times the unconfined compressive strength of untreated aggregate. On average, the CBR values with 1% polymer was 240, with 0.5% polymer was 200, and with 0.25% polymer was 177. Penetrometer results showed that there was a decrease in penetration with an increase in polymer percentage.

Strength Properties of Non-traditionally Stabilized Flexible Base Course Materials

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1 INTRODUCTION

Soil stabilization for the improvement of engineering properties of base course materials has been practiced for many years using traditional (calcium-based) and non-traditional (non-calcium based) stabilizers. Cement, lime, and fly-ash are the three most common traditional stabilizers. Research findings over the years consistently revealed that cement and lime treatment will produce significant increase in strength and durability of treated soils (TxDOT 09/2005 and NCHRP 144, 2009). With the relative lack of fines, base courses typically require less volume of stabilizer if treated with conventional stabilizers, but mechanisms of stabilizer action are similar in base courses and subgrades.

Although much research has been conducted on traditional (calcium-based) stabilizers during the past several decades, non-traditional (non-calcium based) stabilizers have been recently recommended as alternative base stabilization additives. The effectiveness of non-calcium based stabilizers for base and subgrade soils has been studied by various researchers. Some of the recommended non-traditional stabilizers include barium hydroxide and barium chloride (Ferris et al. 1991), sulfonated naphthalene to enzymes and bioenzymes (Scholen 1995 and Marquart 1995), potassium stabilizer (Addison and Petry 1998), hydrogen ion exchange chemicals (Sarkar et al. 2000), low pH solutions of sulfonated limonene (Katz et al. 2001 and Mohan et al. 2013), enzymes, lignosulfonates, petroleum emulsions, polymers and resins (Santoni et al. 2002), and chemical stabilizers (Petry and Das 2001).

Introduced as a non-traditional stabilizer, polymer-based products have become popular due to cost efficiency, ease of application, and fast curing times. Field-testing with the Texas Department of Transportation has revealed that the strength after polymer treatment is comparable to that of cement stabilization. Other tests have shown that its resistance to moisture significantly exceeds Environmental Protection Agency standards.

In this study, a series of UC, CBR and cone penetrometer tests were conducted to determine the load bearing capacity of base course materials. The UC test was carried out to determine the unconfined compressive strength and axial strain as well as the behavior of the treated and untreated specimens in failure (ASTM D2166). Developed by the California Department of Transportation, CBR is a penetration test for evaluation of the mechanical strength of road sub-grade and base aggregate. Penetrometers provide a fast and simple test method for “quick and dirty” measurement of soil properties. Penetration tests can be performed on laboratory specimens and in the field. The reliability and repeatability of penetrometer testing encouraged researchers develop correlations between penetration rate and CBR and UC test results (Smith and Pratt 1983, Webster et al. 1992, Webster et al. 1994, Coonse 1999). Wu and Sargand (2007) studied the dynamic cone penetrometer data collected from 10 road projects in Ohio and concluded that dynamic cone penetrometer sounding values correlate well with CBR and UC strength values. The standard test method for the use of the dynamic cone penetrometer in shallow pavement applications is summarized in ASTM D6951.

The first objective of this study was to determine how the use of polymer admixtures can improve the strength properties of base materials. To achieve this objective a laboratory shear strength testing program was conducted where polymer treated aggregate mixtures were prepared using polymer percentages of 0.25%, 0.5%, and 1% by weight. The laboratory program included compaction, UC, CBR, and penetrometer tests performed on treated and untreated specimens. The second objective of the study was to establish correlations between UC, CBR, and penetrometer test result. These correlations can serve as fast and practical tools to evaluate the in-situ strength characteristics of stabilized soils using the results of field penetrometer tests.

2 MATERIALS

2.1 POLYMER

A water-based TSW liquid polymer was used. The polymer was in the form of aqueous dispersion. The pH value was around 4.5 – 5.5 and the density was around 0.9982 g/cm3 (68 °F (20 °C)) (data for Water (7732-18-5)). The specific

Gravity (Relative density) was around 0.95 - 1.10, Water=1 (liquid). The polymer was provided by Terra Pave International which is located at the University of Texas at Austin.

2.2 BASE COURSE MATERIAL

The base course material for all specimens was a crushed limestone with a percentage passing 40-mesh (i.e. soil binder) of around 23%. It was not possible to roll soil samples into 1/8'' diameter threads (i.e. Non-plastic). Based on the compaction test series performed at various moisture content values, the optimum moisture content and the maximum dry density were determined to be around 10.5% and 121 pcf. In this study, it was assumed that the same compaction curve was applicable for all polymer environments. The rationale behind this assumption was that polymer was also in liquid form and similar to the water in the polymer – water dilution also would act as softening (lubricating) agent during compaction.

3 TEST PROCEDURES

All specimens were compacted at the optimum moisture content of 10.5%. UC and CBR tests were performed using a Tinius Olsen 400 kip Super “L” universal tension-compression testing machine. Following TxDOT specifications (TxDOT Tex-117-e, 2005), the loading rate for UC test was selected as 0.1 in/min (i.e. 2.0% strain per minute). UC tests were performed on extruded specimens. The specimen sizes did not meet the typical UC test H : D ratio of 2.0; however, the strength results were not directly compared to other databases and the same specimen size was consistently used throughout the laboratory testing program. It was therefore assumed that the specimen size did not have a significant effect on the observations and interpretation of the results. CBR tests were conducted on specimens inside the mold (not extruded) at a rate of around 0.05 in/min (ASTM D1883-14).

As shown in Figure 1, the penetrometer assembly consisted of a 10.0-lbs sliding hammer and modular extensions of a nail, a cone, and a cylinder. The upper stop and washer were placed to keep the hammer inside the 1 inch-long shaft. The cylinder extension continued with the same shaft diameter (i.e. 1 inch) for a height of 4 inches below the washer. The nail diameter and nail height were 0.2 inch and 4 inches, respectively. The cone height and cone diameter were 4 inches and 1 inch, respectively, corresponding to a cone angle of 83 degrees. The cylinder extension was recommended for relatively softer soils whereas the nail extension was recommended for relatively harder soils. The penetrometer test procedure was such that the sliding hammer was released from a standard drop height of 1 foot and the total penetration for a given number of blows was recorded.

Figure 1. Penetrometers with a nail, cone, and cylinder extensions

4 RESULTS

A total of 12 UC, 18 CBR, and 17 penetrometer tests were carried out to evaluate the strength behavior of polymer-treated and untreated specimens. Polymer-treated specimens were prepared for three polymer environments (i.e. 0.25%, 0.50%, and, 1.0% polymer by weight). Control specimens with no additives were also prepared for reference.

4.1 UNCONFINED COMPRESSION TESTS

As displayed in the UC stress – strain plots in Figure 2, the unconfined compression strength increases with polymer percentage. On average, the unconfined compressive strength with 1% polymer was 7.6 times, with 0.5% polymer was 5.7 times, and with 0.25% polymer was 3.7 times the unconfined compressive strength of untreated aggregate.

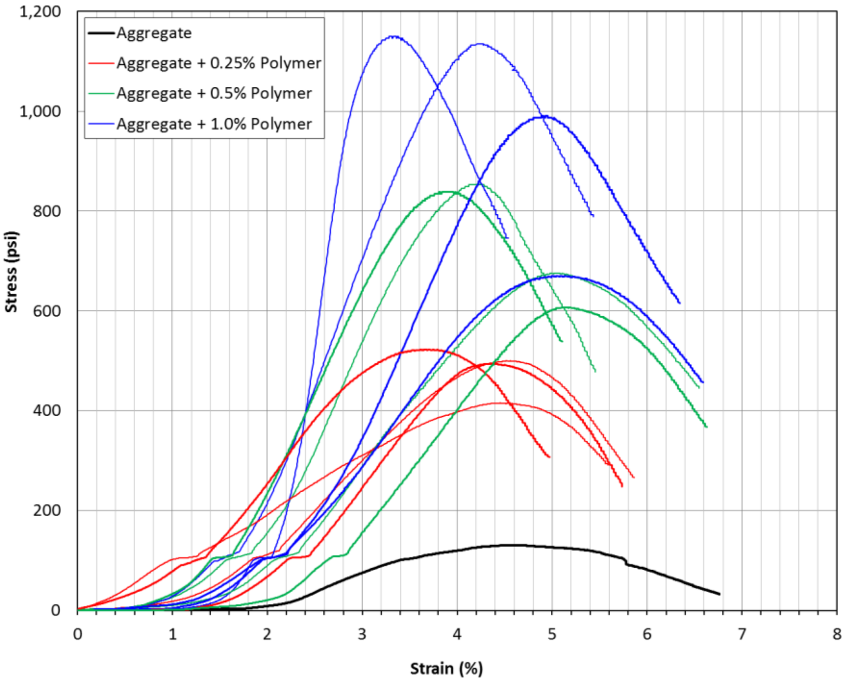

Figure 2. Stress – Strain plots from unconfined compression tests

4.2 CBR TESTS

The average CBR value on two compacted untreated specimens was approximately 123 indicating that the surface of the untreated base material used in this laboratory testing program was harder than the standard material for the CBR test, i.e. California Crushed Limestone. Figure 3 shows the histogram of average CBR values at various polymer environments and Figure 4 displays the individual CBR test results. Out of all polymer-treated specimens, aggregates with 1% polymer had the highest average CBR values whereas the aggregates with 0.25% polymer had the lowest average CBR values. CBR test results revealed a relatively large variation but, the overall trend in the data suggested that CBR values increased with polymer percentage. On average, the CBR with 1% polymer was 240, with 0.5% polymer was 200, and with 0.25% polymer was 177.

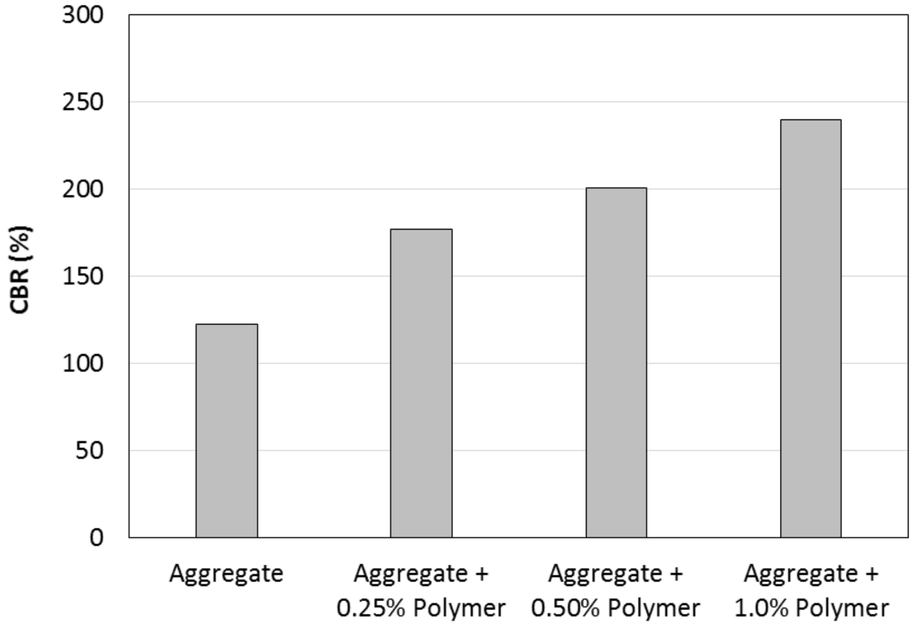

Figure 3. Summary of CBR tests

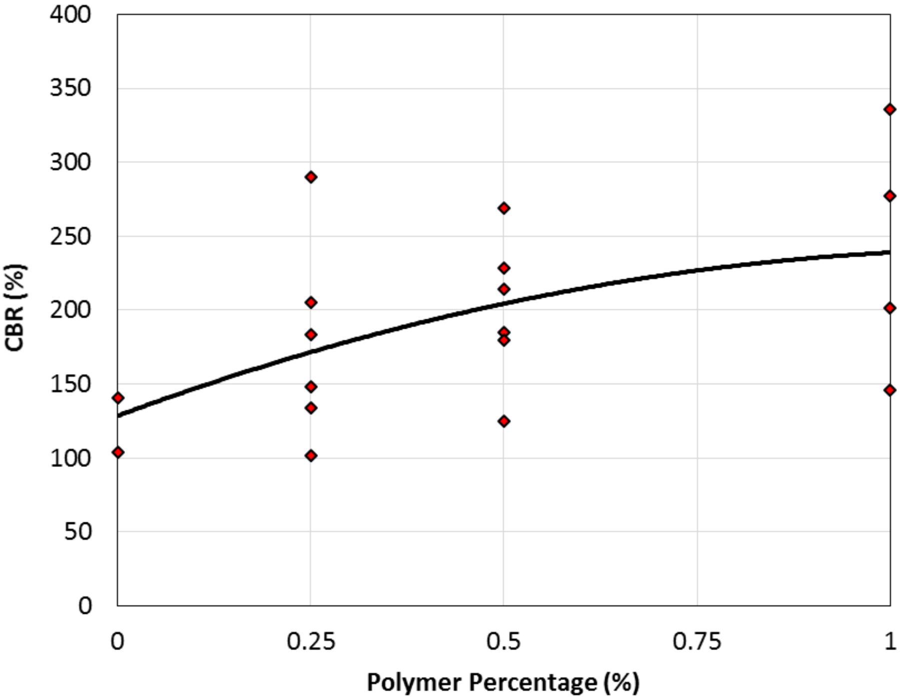

Figure 4. Individual CBR test results

4.3 PENETROMETER TESTS

The cone extension was used for the penetrometer tests. In Figure 5, the number of blows and corresponding penetrations were displayed for various polymer environments. The general trend of the data suggested that there was a decrease in penetration with an increase in polymer percentage. The figure also displays the functional forms of cubic polynomial trend lines representing different polymer environments. A third order polynomial was used to achieve best fit of data points (especially the data points at the beginning). Measuring the compatibility of the fit, the R^2 values of the trend lines were ranging between 0.97 and 0.99.

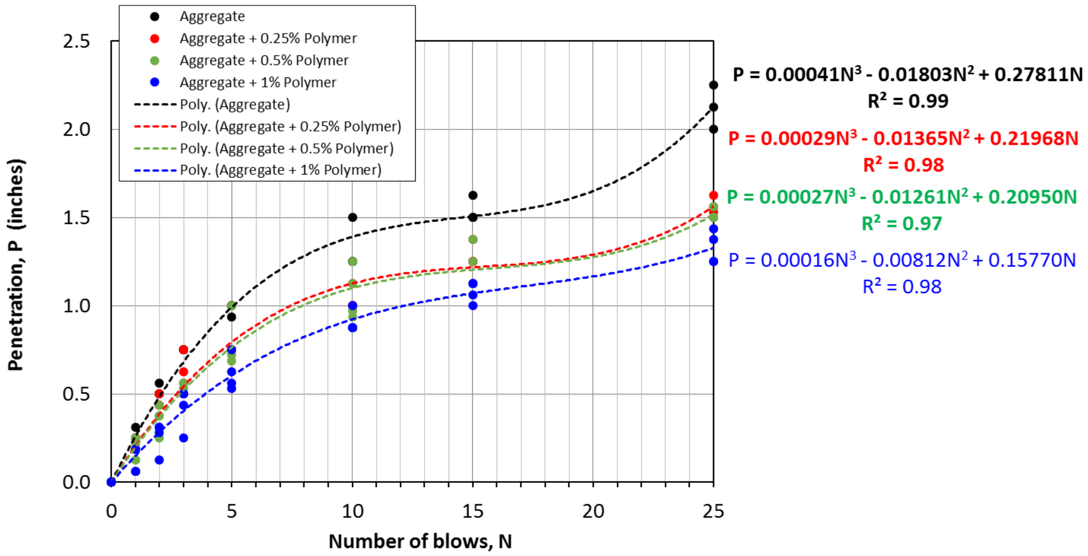

Figure 5. Penetrometer results

4.4 CORRELATION BETWEEN UNDRAINED SHEAR STRENGTH AND CBR

Using the average undrained shear strength (s_u) and CBR values of three polymer environments summarized in Table 1, Equation 1 was proposed for the relationship between su and CBR values. Indicating an almost perfect fit with an R^2=0.9997, this empirical relationship takes into account of the polymer percentage in aggregate mixtures.

$$s_u \text{ (psi)} = \text{CBR (\%)} \times (-2.2974 \times PP^2 + 3.8122 \times PP + 0.5385) \qquad (1)$$

Where s_u is the undrained shear strength in psi and PP is the polymer percentage.

Table 1 Average undrained shear strength (s_u) and CBR for various polymer environments

Mix	Average s_u (psi)	Average CBR (%)
Aggregate	65	123
Aggregate with 0.25% polymer	251	177
Aggregate with 0.5% polymer	372	200
Aggregate with 1.0% polymer	493	240

In Figure 6, the predictions of the model were compared to the average values of the test results for the polymer environments tested. The figure revealed that both su and CBR increased with an increase in polymer percentage. The rate of increase in su was greater than that of the CBR; therefore, the s_u / CBR ratio increased with increasing polymer percentage.

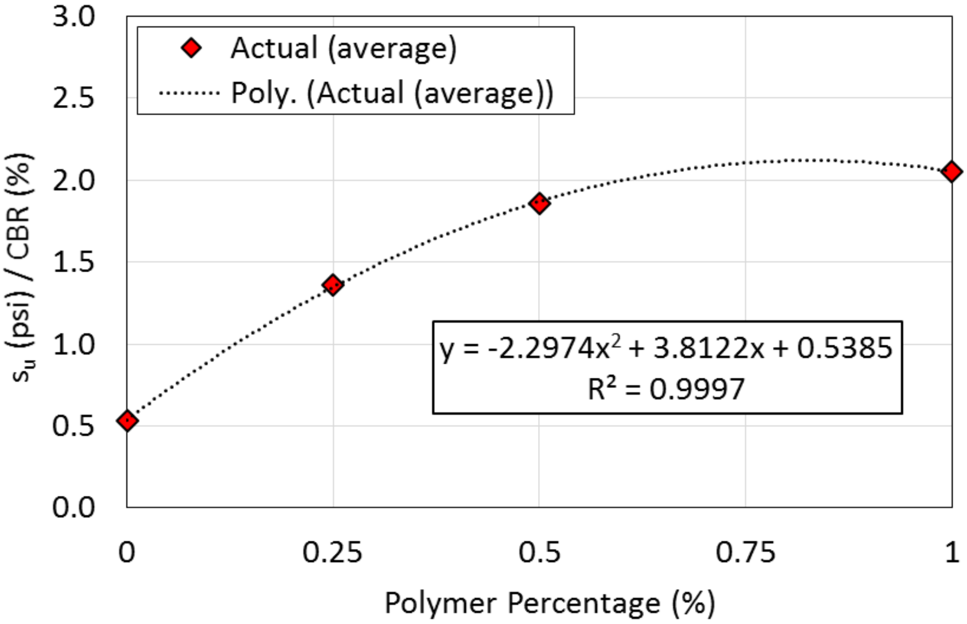

Figure 6. Correlation between undrained shear strength and CBR

To establish a correlation between the undrained shear strength and penetrometer results, it was assumed that (i) peak compressive stress corresponded to the penetration at 25 blows and (ii) there was a linear relationship between the undrained shear strength and penetration. Using the penetration and number of blows relationships displayed in Figure 5, predictive models for the equivalent undrained shear strength values as a function of number of blows are proposed in Equation 2. The predictions of Equation 2 are shown in Figure 7.

Aggregate:	s_u (psi) = $0.0128\times N^3 - 0.5628\times N^2 + 8.68160\times N$	(2a)
Aggregate with 0.25% polymer:	s_u (psi) = $0.0488\times N^3 - 2.2968\times N^2 + 36.9643\times N$	(2b)
Aggregate with 0.5% polymer:	s_u (psi) = $0.0598\times N^3 - 2.7925\times N^2 + 46.3933\times N$	(2c)
Aggregate with 1.0% polymer:	s_u (psi) = $0.0564\times N^3 - 2.8619\times N^2 + 55.5813\times N$	(2d)

Where s_u is the undrained shear strength and N is the number of blows.

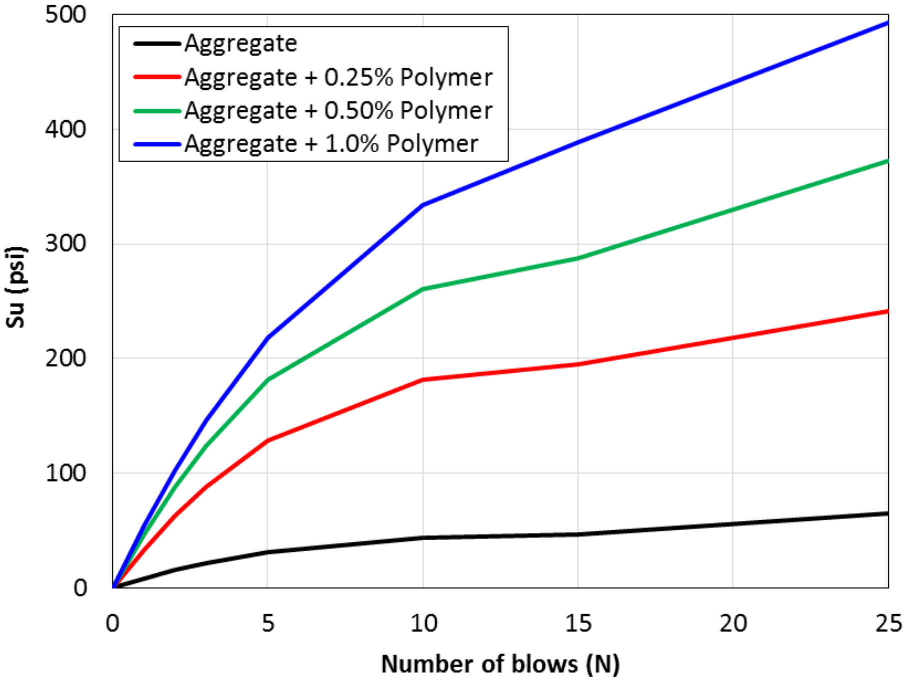

Figure 7. Correlation between undrained shear strength and penetrometer results

4.5 CORRELATION BETWEEN CBR AND PENETROMETER RESULTS

A regression analysis was performed for CBR where CBR was defined a function of the number of blows required for 1-inch penetration and the polymer percentage. The proposed predictive model for CBR is in Equation 3. The model had R^2 of 0.98. As displayed in Figure 8, CBR values increased with an increase in polymer percentage and the number of blows required for 1'' penetration. This trend was in accordance with the aforementioned results.

$$\text{CBR (\%)} = 83.856 + 9.746 \times N_1 + 45.292 \times PP \tag{3}$$

Where N_1 is the number of blows required for 1 inch penetration and PP is the polymer percentage.

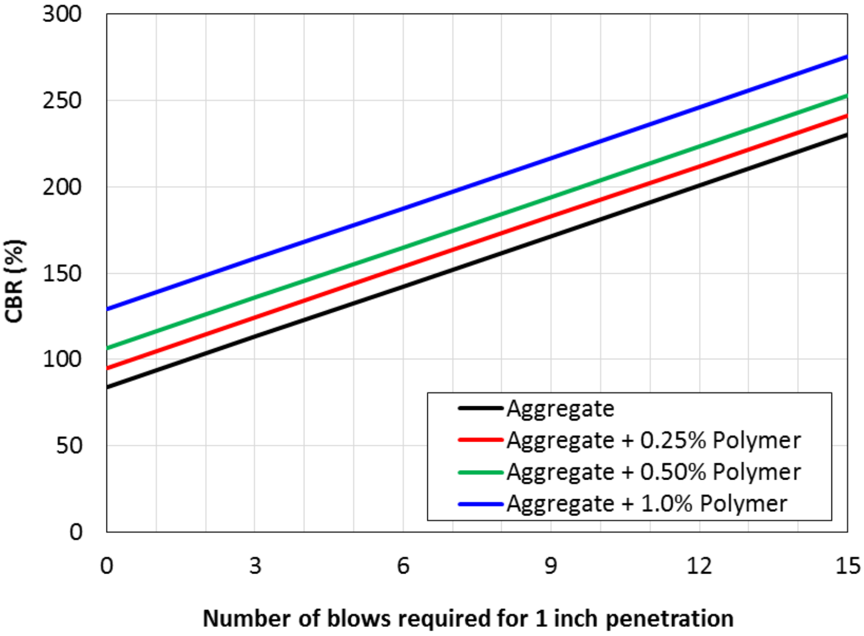

Figure 8. Correlation between CBR and penetrometer results

5 RESULTS

As displayed in Figure 9, a UC test measures the overall load bearing capacity of the specimen, a CBR test evaluates the surface hardness, and a penetrometer test measures the soil's resistance to dynamic loading conditions. The results; however, revealed that UC, CBR, and penetrometer tests provided an efficient and effective means of shear strength and failure mechanism assessment as they were able to capture the effects of very small amounts of polymer admixtures (i.e. 0.25%, 0.5%, and 1% by weight) on the shear strength of specimens.

Figure 9. Specimens after (a) UC, (b) CBR, and (c) penetrometer tests

Being a manually operated test technique, penetrometer tests can suffer from the operator inconsistency on the vertical shaft orientation and penetration recording; however, it’s a low-cost, reliable, and repeatable alternative to UC and CBR tests. Also, the high-mobility of the penetrometer apparatus makes it a suitable tool for developing correlations between the laboratory and in-situ strength of materials under field conditions. As shown in Figure 9, penetrometer and CBR tests were carried out on compacted laboratory specimens that were kept inside 6-inch diameter molds. Further research is warranted to explore the possible mold boundary effects.

Penetrometer test results were based on the modular cone extension (Figure 1). When the cylinder extension was used, it was observed that specimens were broken and no significant penetrations were achieved. Therefore, it’s recommended that cylinder extension is suitable for relatively softer specimens. On the other hand, the nail extension is recommended for relatively harder soils. However, it is important to note that the abrupt change in the cross-sectional area from a 1-inch shaft diameter to a 0.2-inch nail diameter causes wave reflections. Therefore, this connection becomes the weakest link in the assembly.

6 CONCLUSIONS

UC, CBR, and Penetrometer tests have been commonly used for the assessment of the undrained strength of base and subgrade layers; however, very little work has been carried out in the literature on the development of relationships between the strength values. In this study, these tests were performed on treated and untreated compacted specimens that were prepared for three polymer environments. The results of the laboratory testing program on crushed limestone revealed that these aforementioned test results are strongly correlated (i.e. high R-square values). The proposed correlations make it possible for researchers to estimate and make quality assurance of UC and CBR values using the results of the Penetrometer tests that (1) are simple and quick to use, and (2) allow repeated testing to minimize interpretation errors.

Further research is recommended for testing the applicability of the proposed correlations on different soil types. In essence, a comprehensive testing program needs to be followed to develop reliable relationships considering a variety of soil types and moisture conditioning (e.g. low/high of optimum). For the given conditions and specimens, the study revealed the following results:

- UC strength of treated soils with 1% polymer was 7.6 times, with 0.5% polymer was 5.7 times, and with 0.25% polymer was 3.7 times the UC strength of untreated soils.

- CBR values of treated soils with 1% polymer was 240, with 0.5% polymer was 200, and with 0.25% polymer was 177. The average CBR on two untreated soils was 123.

- Penetrometer tests showed a decrease in penetration with an increase in polymer percentage.

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