Compaction and durability characteristics of polymer modified soils

Caractéristiques de compactage et de durabilité des sols modifiés aux polymères

James Hanson, Gary Welling, Nazli Yesiller
Civil and Environmental Engineering Department, California Polytechnic State University, U.S.A., jahanson@calpoly.edu

ABSTRACT: An extensive laboratory test program was undertaken to evaluate a series of engineering properties over a range of soil types; chemical addition rates; and water contents to enhance understanding of the engineering significance of polymer amendment. Test soils included a poorly graded sand and three clayey sands with gravel. Fines contents ranged from 2.5% to 41%. The polymer was an elastic copolymer and was added to the soil at rates of 0.5% to 2.5% (dry weight basis). Engineering properties determined throughout the test program included dry unit weight / water content relationships through compaction tests and durability through freeze-thaw and wet-dry tests. Tested water contents ranged from 4% dry of optimum to 4% wet of optimum. The addition of polymer significantly affected the optimum water content and to a lesser extent the maximum dry unit weight. The maximum wet-dry and freeze-thaw durability of polymer amended specimens (at 1% addition rate) ranged from 6.8 to 11.0 integrated cycles. The amount of polymer required to modify the engineering properties was directly related to specific surface of the soils.

RÉSUMÉ : Un vaste programme de tests en laboratoire a été entrepris pour évaluer les propriétés mécaniques de différents types de sols modifiés aux polymères. Différents taux d'addition chimique et teneurs en eau ont été évalués pour mieux comprendre les conséquences de l'ajout de polymères sur les sols. Les sols testés correspondent à un sable *mal classé* et trois sables argileux avec du gravier. La teneur en sédiments fins des sables est comprise entre 2,5% et 41%. Le polymère, un copolymère élastique, a été ajouté au sol à des taux de 0,5% à 2,5% (en masse sèche). Les propriétés mécaniques déterminées tout au long du programme d'essai incluaient les relations entre la masse unitaire sèche et la teneur en eau par des essais de compactage, et la durabilité par des essais de gel-dégel et de séchage-mouillage. La teneur en eau mesurée varie de 4% sec de l'optimum à 4% humide de l'optimum. L'ajout de polymère a significativement modifié la teneur optimale en eau de manière significative, et dans une moindre mesure, la masse sèche unitaire. La durabilité maximale des sols modifiés aux polymères (à un taux d'addition de 1%) a présenté une variabilité de 6,8 à 11,0 cycles intégrés de séchage-mouillage et gel-dégel. La quantité de polymère nécessaire pour modifier les propriétés mécaniques est estimée être directement liée à la surface spécifique des sols.

KEYWORDS: compaction, ground improvement, polymer, durability, freeze-thaw, wet-dry

1 INTRODUCTION

Amendment of soils with chemicals is common in ground improvement applications. Typical chemicals used for ground improvement include hydraulic cement, lime, and more recently, polymers. Polymer amendment for improvement of soils is a growing industry and has been of particular interest in recent field applications for improvement of soil strength as well as erosion and dust control (e.g., Rauch et al. 2002, Orts et al. 2007). Polymers improve the soil by providing physical stabilization through the use of binding agents. Polymers are easily manipulated; therefore, a range of polymer combinations can be prepared to modify soils. Two common polymer products used for soil stabilization are vinyl acetate and acrylic-based copolymers. These polymer emulsions typically consist of 40-50% solid particles by weight of emulsion (e.g., Tingle et al. 2007). Both vinyl acetate and acrylic copolymers have demonstrated success in bonding to silty-sand soils (Santoni et al. 2002). Tingle et al. (2007) reported that polymer amendment is better suited to granular soils than fine-grained soils. For stabilizing sand, Al-Khanbashi and Abdalla (2006) confirmed using SEM imaging of polymer-amended sand that three structural changes occurred: the development of interconnected ties between the sand particles, the development of adhesion between adjacent sand particles, and the coating of the sand particles with a thin polymer film. Because the primary stabilization mechanism associated with polymer addition is physical bonding, strength improvement depends on the ability of polymer to adequately coat the soil particles and on the physical properties of the polymer with polymers indicated to be less effectiveness for fine-grained soils due to the higher specific surface, as compared to coarse-grained soils (Tingle et al. 2007).

Despite the recent interest in polymer amended soils, limited research has been conducted to determine fundamental engineering behavior. Most laboratory and field experiments to date have focused on performance evaluation rather than evaluation of the mechanism constituting change in the performance of amended soils. A systematic evaluation of polymer-amended soils is needed to establish a basis for comparison between response of various soils to different chemical treatments and to determine underlying mechanisms associated with polymer treatment of soils. A thorough investigation was conducted to evaluate engineering performance of polymer-amended soils in comparison to control conditions and in comparison to conventional chemical amendments (cement and lime) (Welling 2012). The compaction and durability (both wet-dry and freeze-thaw) components of this broad test program are presented herein for polymer-amended soils.

2 EXPERIMENTAL TEST PROGRAM

An extensive laboratory test program was undertaken to evaluate engineering properties over a range of soil, polymer, and water mixture ratios to enhance understanding of the engineering significance of polymer modification. Polymer was tested at amendment rates of 0.5% to 2.5% (on dry weight basis). Engineering properties reported herein include dry unit weight – water content relationships through the use of compaction tests; and durability through the use of freeze-thaw and wet-dry tests. Four test soil mixes were designed and prepared by combining individual soil constituents in established mixture ratios. Test soils included a poorly graded sand with minimal fines (SAND) and three clayey sands with gravel (LCL, LCH, HCH). The three clayey sands had varying percentages of fines and varying values of plasticity. The nominal maximum diameter of the test soils was 9.5 mm. The specific surface of each test soil was calculated based on idealized spherical soil particles and diameters from the grain size distribution. A summary of the characteristics of the test soils is provided in Table 1.

Table 1. Test soils.

Parameter	SAND	LCL	LCH	HCH
D_{60} (mm)	3.30	1.10	1.06	0.66
D_{30} (mm)	0.61	0.32	0.23	0.03
D_{10} (mm)	0.28	0.06	0.14	0.001
C_c	0.40	1.55	0.35	0.93
C_u	12	18	8	522
% Fines	2.5	17.0	17.6	40.8
PL	NP	17	12	13
LL	NP	27	34	42
PI	NP	10	22	29
G_s	2.68	2.66	2.63	2.68
Specific Surface (m^2/kg)	4	52	54	141
USCS Classification	SP poorly graded sand	SC clayey sand with gravel	SC clayey sand with gravel	SC clayey sand with gravel
AASHTO Classification	A-1-a(1)	A-2-4(0)	A-2-6(0)	A-7-6(6)

For polymer treatment, a proprietary elastic co-polymer was used. The polymer was received as an aqueous solution comprised of 65% polymer and 35% water by weight. The polymer was diluted for use in the mixes to be consistent with field applications. Polymer addition rates (PARs) of 0.5%, 1%, and 1.5% for SAND, LCL, and LCH and 0.5%, 1%, 1.5%, 2%, and 2.5% for HCH on dry weight bases were applied. Each test soil was evaluated without chemical amendment to provide baseline/control conditions.

An overview of the testing program is presented in Table 2. Water contents are reported with respect to optimum water content, which was determined for each test soil/polymer amendment rate combination. The compaction tests were conducted in accordance with ASTM D698 (standard compaction effort). Compaction tests were conducted on 101.6-mm-diameter specimens using a combination of manual and mechanical rammers. The wet-dry and freeze-thaw durability tests were conducted in accordance with ASTM D559 and ASTM D560, respectively. The durability specimens were prepared using the same method as compaction specimens and then allowed to cure for a 7-day period (± 8 hours) at laboratory temperature. Durability tests included conditioning and scratching phases. Wet-dry conditioning involved 5-hour water submersion and 42-hour drying in a convection oven at 60°C. Freeze-thaw conditioning involved a 24-hour freeze period at −23°C and a 23-hour thaw period at 21°C and 100% humidity. After conditioning, controlled abrasive scratching was applied to the specimens using a large-format stiff steel brush. The mass of the test specimens was measured after each cycle. Twelve cycles were used for both wet-dry and freeze-thaw tests.

Table 2. Testing program.

Test	Soil	Amendment and Addition Rate	Water Content
Compaction	SAND LCL LCH	Control P: 0.5%, 1%, 1.5%	Opt. − 2% Opt. − 4% Opt. Opt. + 2% Opt. + 4%
	HCH	Control P: 0.5%, 1%, 1.5%, 2%, 2.5%	Opt. − 2% Opt. − 4% Opt. Opt. + 2% Opt. + 4%
Durability (Wet-Dry and Freeze-Thaw)	SAND LCL HCL HCH	Control P: 1%	Opt. − 2% Opt. − 4% Opt. Opt. + 2% Opt. + 4%

3 RESULTS AND DISCUSSION

3.1 *Compaction*

A summary of the compaction test results is presented in Table 3. Compaction test results, when plotted as dry unit weight versus water content, were generally bell-shaped. The maximum dry unit weights ranged from 19.2 to 19.4 kN/m^3; 20.1 to 20.4 kN/m^3; 19.1 to 19.5 kN/m^3; and 18.4 to 18.7 kN/m^3 for SAND, LCL, LCH, and HCH, respectively. Optimum water content (w_{opt}) ranged from 4.8 to 9.7%; 8.2 to 9.3%; 9.8 to 10.7%; and 9.7 to 12.3% for SAND, LCL, LCH, and HCH, respectively.

Table 3. Compaction test results.

Soil	PAR (%)	w_{opt} (%)	γ_{dmax} (kN/m^3)	Leading Slope ((kN/m^3)/%w)	Trailing Slope ((kN/m^3)/%w)
SAND	0	9.7	19.24	0.30	N/A
SAND	0.5	5.9	19.18	0.50	-0.40
SAND	1	4.8	19.37	0.80	-0.40
SAND	1.5	5.2	19.31	0.73	-0.37
LCL	0	9.3	20.37	0.44	-0.44
LCL	0.5	8.2	20.19	0.33	-0.43
LCL	1	8.2	20.2	0.37	-0.43
LCL	1.5	8.2	20.07	0.43	-0.36
LCH	0	10.4	19.51	0.46	-0.40
LCH	0.5	10.7	19.27	0.27	-0.25
LCH	1	10.4	19.12	0.37	-0.27
LCH	1.5	9.8	19.41	0.50	-0.34
HCH	0	9.7	18.72	0.37	-0.18
HCH	0.5	11.4	18.49	0.29	-0.15
HCH	1	12.3	18.44	0.26	-0.22
HCH	1.5	10.6	18.62	0.24	-0.20
HCH	2	10.7	18.39	0.31	-0.20
HCH	2.5	10.1	18.25	0.40	-0.14

The sensitivity to changes in water content on resulting dry unit weight were determined by calculating the slope of the leading (i.e., dry of optimum) and trailing (i.e., wet of optimum) portions of the compaction curves. In comparison to control conditions, polymer amended SAND specimens demonstrated increased sensitivity on the dry side of optimum (i.e., steeper leading slope), while the other specimens maintained a similar sensitivity as control conditions. Trailing slopes were not highly sensitive to PAR.

The normalized maximum dry unit weight (calculated as the quotient of maximum dry unit weight for given polymer addition rate and maximum dry unit weight for control conditions) with polymer addition rate is presented in Figure 1. Maximum dry unit weight was not highly sensitive to polymer addition rate. The maximum dry unit weight remained relatively similar for SAND with polymer addition whereas the maximum dry unit weight generally decreased with increasing polymer addition rate for clayey sands. The small increase in dry unit weight with polymer addition for SAND was attributed to improved particle packing arrangement and the decreases for the other soils to a combination of bulking and the relatively low specific gravity of polymer solids compared to soil solids.

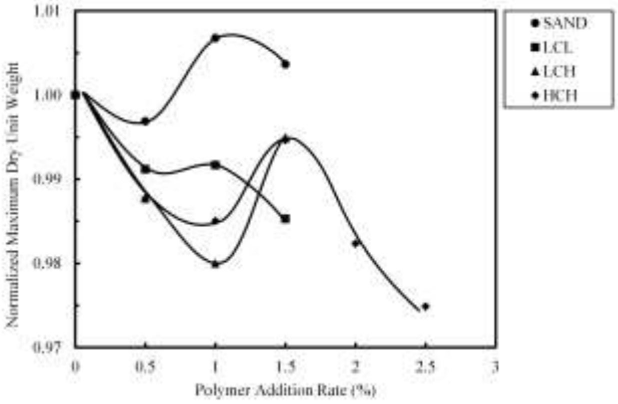

Figure 1. Normalized maximum dry unit weight with addition rate.

The variation of w_{opt} as a function of polymer addition rate is presented in Figure 2. The results are presented as normalized w_{opt}, which was calculated as the quotient of w_{opt} (associated with a given polymer addition rate) and w_{opt} for control conditions. Significant variation in normalized w_{opt} was observed for SAND where the w_{opt} decreased with increasing polymer addition. In general, less variation in w_{opt} was observed for the clayey sands with the highest variation measured for HCH (Figure 2). For all soils, the addition of polymer resulted in greatest modification to w_{opt} at 0.5% or 1% PARs.

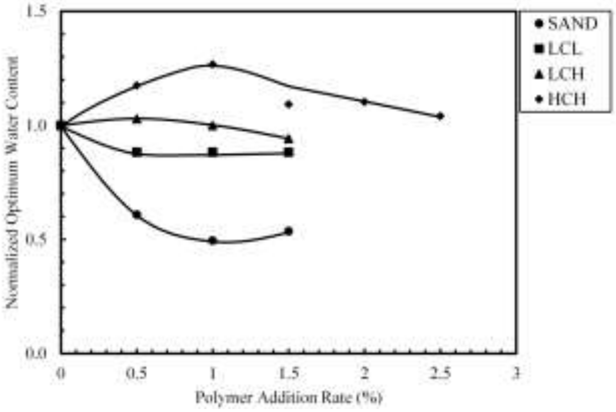

Figure 2. Normalized w_{opt} with polymer addition rate.

The average normalized w_{opt} for all polymer addition rates was plotted against specific surface of each test soil (Figure 3). An increase in normalized optimum water content was observed with increased specific surface of the test soils. Polymer was able to enter the relatively large pore sizes of SAND (i.e., low specific surface) at low moisture content allowing for coating of particles and providing lubrication. For the clayey sands, especially HCH (high specific surface), extra moisture was required for polymer to enter small pores and coat the fine-grained particles.

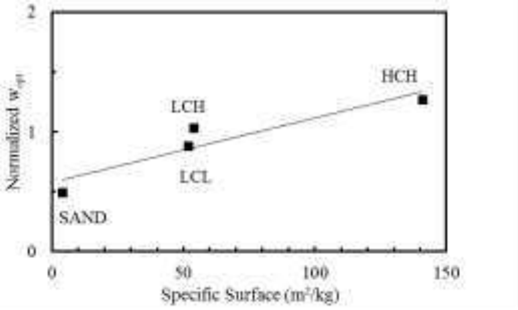

Figure 3. Normalized w_{opt} with specific surface.

3.2 *Durability*

Durability test results are typically plotted as percent original mass versus number of cycles, which provides an indication of the rate of loss of specimen mass with conditioning. Wet-dry test results for control and 1% polymer amended LCL are presented in Figure 4 for specimens with water contents ranging from 4.8 to 12.2% (w_{opt} = 9.3% for control and 8.2% for 1% polymer amended). Overall, the polymer amended specimens had higher durability than the control specimens, yet the rates of loss of specimen mass (once loss of mass commenced) as indicated by the slope of the durability curves in Figure 4, were greater for polymer amended specimens than for control specimens. An integrated area method is introduced herein to summarize the durability of a specimen as a single numerical value. The concept of this method is presented in Figure 5, wherein the area under the curve of percent original mass versus cycles is calculated. This value provides an indication of overall durability accounting for number of integrated cycles survived as well as rate of progressive erosion of the specimen.

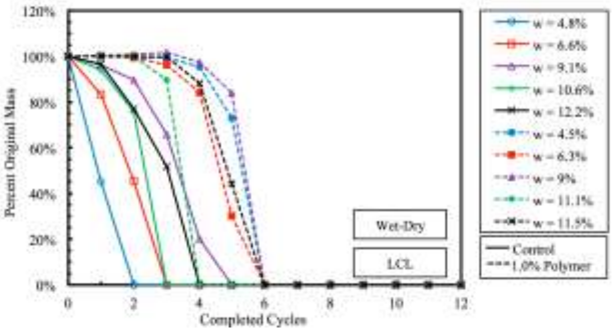

Figure 4. Example durability test results.

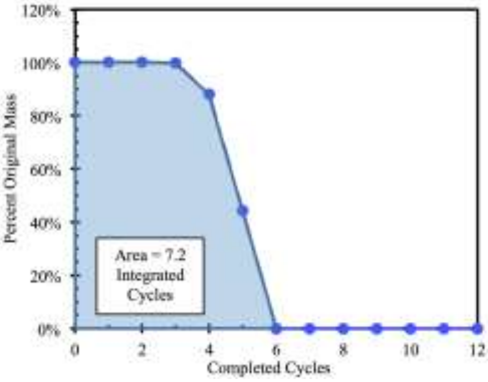

Figure 5. Schematic of integrated area calculation.

Summaries of durability test results using the integrated area approach are presented in Tables 4 and 5. Results are reported as a function of nominal water content relative to w_{opt}. Wet-dry durability of the test specimens ranged from 0 (consistent with specimen not surviving the first cycle of conditioning – the case for many control specimens, especially for wet-dry durability tests) to 11.0 integrated cycles, depending on tested condition. For the soils tested, maximum durability ranged from 6.8 to 11.0 integrated cycles. For a given soil at the 1% polymer addition rate, the wet-dry and freeze-thaw durabilities were variable with water content. For HCH, the peak wet-dry and freeze-thaw durability values were observed at wet of optimum compaction conditions. The other test soils demonstrated maximum durability at or near optimum compaction conditions. The greatest benefit of polymer addition (calculated as difference in durability between control and polymer amended conditions) was observed for SAND soil at dry of optimum and optimum conditions and LCH across a wide range of water contents for wet-dry durability and was observed for SAND at optimum conditions and LCH at dry of optimum conditions for freeze-thaw durability.

Table 4. Wet-dry durability test results.

Condition	SAND	LCL	LCH	HCH
[Opt.−4%] Control	0	0	0	0
[Opt.−4%] Polymer	0	5.7	11.0	1.3
[Opt.−2%] Control	0	0	0.3	0
[Opt.−2%] Polymer	7.4	7.3	10.0	2.6
[Opt.] Control	0	0	0.4	0
[Opt.] Polymer	7.4	7.3	11.0	6.7
[Opt.+2%] Control	0	0	0	0
[Opt.+2%] Polymer	0	7.3	11.0	6.8
[Opt.+4%] Control	0	0	0.4	0
[Opt.+4%] Polymer	0	7.2	10.0	6.8

Table 5. Freeze-thaw durability test results.

Condition	SAND	LCL	LCH	HCH
[Opt.−4%] Control	0	0.2	0.8	0
[Opt.−4%] Polymer	0	4.2	6.1	1.6
[Opt.−2%] Control	0	0.9	4.8	0
[Opt.−2%] Polymer	0	3.6	7.5	1.6
[Opt.] Control	0	2.2	5.6	0
[Opt.] Polymer	7.3	4.3	9.0	3.5
[Opt.+2%] Control	0	1.2	5.4	1.3
[Opt.+2%] Polymer	5.4	3.8	10.3	3.1
[Opt.+4%] Control	0	1.8	4.3	0
[Opt.+4%] Polymer	0	2.4	7.8	2.8

4 CONCLUSIONS

Based on the experimental investigation, the following conclusions were drawn:

1) Polymer addition affected optimum moisture content to a greater extent than maximum dry unit weight.

2) The maximum dry unit weight remained relatively similar for SAND and the maximum dry unit weight generally decreased for clayey sands with increasing polymer addition rate.

3) For SAND, the w_{opt} decreased with increasing polymer addition. Less variation in w_{opt} was observed for the clayey sands with the highest modification observed for HCH.

4) For the polymer amended specimens, the normalized optimum water content increased with increasing specific surface of the test soils.

5) Wet-dry durability and freeze-thaw durability increased with polymer addition. LCH demonstrated the greatest improvement in wet-dry durability with polymer addition and SAND and LCH demonstrated the greatest improvement in freeze-thaw durability with polymer addition.

5 ACKNOWLEDGEMENTS

Partial funding for the investigation was provided by the Global Waste Research Institute and by Terratech, Inc. Andrew Cirillo, Aaron Fortier, Dustin Lee, Justin Martos, Renee Morales, Ryan Owens, Clayton Proto, Maura Ruffatto, Tim Robison, and Brad Stirling assisted with the experimental testing program.

6 REFERENCES

Al-Khanbashi, A. and Abdalla, S.W. 2006. Evaluation of three waterborne polymers as stabilizers for sandy soil. *Geotechnical and Geological Engineering* 24: 1603–1625

ASTM D559-03. 2011. Standard test methods for wetting and drying compacted soil-cement mixtures. *Annual Book of ASTM Standards*, ASTM International, West Conchohocken, PA, DOI 10.1520/D0559-03.

ASTM D560-03. 2011. Standard test methods for freezing and thawing compacted soil-cement mixtures," *Annual Book of ASTM Standards*, ASTM International, West Conchohocken, PA, DOI 10.1520/D0560-03.

ASTM D698-07. 2011. Standard test methods for laboratory compaction characteristics of soil using standard effort (12400 ft-lbf/ft3 (600 kN-m/m3))," *Annual Book of ASTM Standards*, ASTM International, West Conchohocken, PA, DOI 10.1520/D0698-07E01.

Ingles, O.G., and Metcalf, J.B. 1973. *Soil stabilization: principles and practice*, John Wiley & Sons, Inc., New York.

Orts, W.J., Roa-Espinosa, A., Sojka, R.E., Glenn, G.M., Imam, S.H., Erlacher, K., and Pedersen, J.S. 2007. Use of synthetic polymers and biopolymers for soil stabilization in agricultural, construction, and military applications. *Journal of Materials in Civil Engineering* 19 (1): 58-66.

Rauch, A.F., Harmon, J.S., Katz, L.E., and Liljestrand, H. M. 2002. Measured effects of liquid soil stabilizers on engineering properties of clay. *Transportation Research Record: Journal of the Transportation Research Board,* 1787: 33–41.

Santoni, R.L., Tingle, J.S., and Webster, S.L. (2002). Stabilization of silty-sand with nontraditional additives. *Transportation Research Record: Journal of the Transportation Research Board,* 1787: 61-70.

Tingle, J.S., Newman, J.K., Larson, S.L., Weiss, C.A., and Rushing, J.F. 2007. Stabilization mechanisms of nontraditional additives. *Transportation Research Record: Journal of the Transportation Research Board* 2 (1989), 142-153.

Welling, G.E. 2012. Engineering performance of polymer amended soils, M.S. Thesis, Civil and Environmental Engineering, California Polytechnic State University.