The effect of water-based Acrylic polymers on the soil properties

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by

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Dedicated To My loving family …

Who supported me in all tough moments…

Abstract

The focus of this Ph.D. project is on the effect of some characteristics of polymer latexes, including glass transition temperature (Tg), particle size, additives, monomer type, and surfactant charge on the physical, mechanical, thermal, and electrical properties and microstructure of polymer-stabilized soils.

Poly (methyl methacrylate-co-butyl acrylate) with three different Tg, and poly (styrene-co-butyl acrylate), were synthesized and a commercially produced poly (vinyl acetate) were regarded as different monomer types. Various polymer additives consisting of thickeners, wetting agents, antifoaming agents, and buffers were also used. A series of geotechnical laboratory tests, including compaction, Atterberg, UCS, DS, Triaxial, Consolidation, and swelling, as well as thermal conductivity, CEC, electrical resistivity, and pH control tests were carried out on different mixtures of polymer-stabilized sand and kaolinite. Five different curing methods were considered to evaluate the optimum condition for soil strength-gaining.

The results showed a considerable improvement in the UCS value and cohesion of both soils considering the air-drying condition. The polymer with a near-to-ambient Tg made a more notable enhancement. Samples stabilized with a polymer having the lowest Tg have displayed more compression index and higher plasticity. The swelling parameters (i.e., swelling index and pressure) decreased slightly with increasing Tg. Samples stabilized with poly (vinyl acetate) have the highest strength. The plasticity index and swelling parameters are increased compared to the unstabilized soil. The samples stabilized with poly (methyl methacrylate-co-butyl acrylate) have shown a better performance from the perspective of both reducing swelling and increasing strength. Thickeners have shown a significant positive influence on the UCS while enhancing the ductility. Acidic pH has led to UCS up to 2.5 times than the alkaline media. The higher anionic wetting agent (i.e., SDS) amount resulted in a higher failure strain and reduced UCS. Polymer addition also affects the electrical behavior of soil. However, regarding the trivial variation of EC by adding different polymers, monomer type and Tg have a minor effect on the total electrical behavior of the soil-polymer mixture. Tg and monomer type also influence the thermal behavior of the soil-polymer mixture. Lower Tg has also reduced the polymer thermal conductivity. Overall, the polymers used in this study showed promising results in improving the soil properties subjected to different loading conditions.

Keywords: soil stabilization, waterborne latex, glass transition temperature, monomer type, thickeners, pH control agent, surfactant, antifoaming agent

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Table of Content

Figure List

Table List

List of Abbreviations

Tg	Glass transition temperature
PI	Plasticity index
LL	Liquid limit
PL	Plastic limit
UCS	Unconfined compressive strength
DS	Direct shear
MBA	Poly (methyl methacrylate-co-butyl acrylate)
LT	Poly (methyl methacrylate-co-butyl acrylate) with low Tg
MT	Poly (methyl methacrylate-co-butyl acrylate) with Tg near ambient
HT	Poly (methyl methacrylate-co-butyl acrylate) with high Tg
PVAc	Poly (vinyl acetate)
STBA	Poly (styrene-co-butyl acrylate)
FTIR	Infrared Fourier transform spectroscopy
DSC	Differential scattering calorimetry
DLS	dynamic light scattering
DMTA	Dynamic mechanical thermal analysis
K	Kaolinite
S	Sand
C	Cohesion
φ	Internal friction angle
MDD	Maximum dry density
OMC	Optimum moisture content
MT (N)	Poly (methyl methacrylate-co-butyl acrylate) synthetized with nonionic surfactant
MT (AA)	Terpolymer of methyl methacrylate, butylacrylate, and acrylic acid
SDS	Sodium dodecyl sofunate
KPS	Potassium persulfate
Kenon	Nonyl phenol ethoxylates
PVOH	Poly vinyl alcohol
CMC	Critical micelle concentration
CMC	Carboxy methyl cellulose
EC	Electrical conductivity
CEC	Cation exchange capacity
R_E/ρ	Electrical resistivity
R_T/λ	Thermal resistivity
TC	Thermal conductivity
CTAB	Cetrimonium bromide

Chapter 1. Introduction

1.1 Background and Motivation

1.1.1 Soil stabilization

From a civil engineering perspective, proper soil is defined as discrete material with adequate compressive and shear strength to bear construction. However, as a heterogeneous material and due to increasing demands for construction, it is hardly possible to find the originally suitable subgrade without modification to withstand the building loads. It is even more unattainable when the project faces problematic soils such as organic soils, expansive soils, and liquefiable soils. On the other hand, many geotechnical projects confront new challenges in buried facilities such as high-voltage cables, geothermal energy systems, and third rail technology of railway system, affecting the electrical, mechanical, and thermal properties of soils.

Many soil stabilization methods were invented to respond to the challenges of limited resources, project costs, material availability, and sustainable infrastructure as a viable political issue for developed and developing countries. Soil stabilization is a technical term used to improve the soil to meet the desired purpose. This mainly includes increasing unit weight, strength, bearing capacity, and reducing settlement, swelling potential, and porosity from a geotechnical perspective. However, the geotechnical design criteria consisting of loading, type of foundation, desired bearing capacity, allocated budget, and instability severance has to be considered to choose whether the soil has to be replaced or stabilized.

Soil stabilization techniques can be categorized into various ways, including physical, mechanical, chemical, and biological stabilization (Ingles and Metcalf, 1973). It is realized via rearranging, bonding together, or even waterproofing soil particles to enhance stability facing loading and water (Makusa, 2012). Physical stabilization is defined as changing the physical state of soil via heating or freezing procedure (Chang and Lacy, 2008). The mechanical stabilization is simply obtained by mostly increasing the soil density using mechanical forces or external intruders like geosynthetics and nailing. The most well-known mechanical methods are roller-compaction and drainage, vibration or dynamic compaction, stone column, preloading consolidation, geosynthetic reinforcement, and deep soil mixing; some of them have been depicted in Figure 1-1.

(a) (b) (c)

Figure 1-1. Some of the soil stabilization methods, (a) Geocell, (b) surface chemical stabilization, (c) deep mixing method

However, soil properties need other amendments when the intrinsic structure is too weak and unstable, like high swelling potential. These can be responded to by using some chemical binders such as lime, cement, and polymers (Alazigha et al., 2016; Turkoz et al., 2015; Rao and Anusha, 2011).

Chemical stabilization is defined as binding soil particles by chemical reaction of additives with soil substance. Various additives have been applied to the soil, from rice husk to microbially induced cementitious materials. For instance, Ghasemzadeh and Modiri (2020) investigated soil stabilization using a novel Persian gum, and their results showed a significant improvement in the UCS and microstructure of soil. Lu et al. (2014b) studied the effect of rice husk and coal fly ash on expansive clayey soil, and their findings revealed that the combination of carbon atoms with clay minerals led to a lower plasticity index.

Chemical additives can be classified into two groups of traditional and nontraditional additives (Marto et al., 2014). Traditional binders are mainly included cement, lime, fly ash, and bitumen. However, these stabilizers have negatively affected the environment and shown weak long-term performance. As an example of the weak points, cement is the source of 5 percent of global Co_2 emissions based on the Carbon dioxide information analyses center (2017). Besides, the shrinkage cracking resulted from hydration and cement drying process, brittleness, and swelling are other drawbacks of cement stabilization. These flaw points decrease the ultimate strength and performance of the soil-cement mixture (Rezaeimalek et al., 2017c; Sebesta and Scullion, 2004; George, 1973). Hence, engineers tend to replace innovative methods and binders in order to reduce the side effects of the previous ones.

The advent of nontraditional stabilizers such as enzymes, polymers, biopolymers, microbial induced cement, or wastes have shown successful results in the literature (Chen et al., 2019a; Kang et al., 2019b; Hamdan and Kavazanjian, 2016; Smith et al., 2001), worth focusing literally and practically.

1.1.2 Novel chemical additives

The use of nontraditional additives seems to be a new subject of interest, through world war II, due to the emergency need of the US Army for rapid soil improvement, and a great effort performed to find new chemical additives as a concept of nontraditional stabilizers (Kinter, 1975),

Most nontraditional stabilizers are divided into ionic, enzymes, salts, oil derivative resins, polymers, and biopolymers (Tingle et al., 2007). However, other innovative, more environmentally-respectful materials like wastes (Eshghinezhad et al., 2020; Bekhiti et al., 2019; Attom and Al-Sharif, 1998), rice husk (Lu et al., 2014b), and carpet fiber (Mirzababaei et al., 2013) have been investigated but less practically used. It should be noted that nontoxicity is the most important characteristic that should be considered in choosing the proper materials. The stabilizing mechanisms of nontraditional binders are mostly introduced as filling, particle covering, or chemical reaction by ion-exchange. These mechanisms depend on the material and soil surface charge. For instance, ionic stabilizers such as acids and alkaline have been reported to cause a reduction in the double layer through cation exchange, while lignin is mostly bridging between particles due to electrostatic attractions. However, filling the voids is mostly mentioned since these agents' molecules are supposed to bind the soil particles through physical or chemical adhesion (Kushwaha et al., 2019; Rodriguez et al., 2018; Lu et al., 2014a). This microscopic viewpoint has led to a better understanding of stabilized soil meso- and macro-scale behavior with nontraditional additives.

Plenty of successful application of novel additives is reported in the literature (Collins et al., 2015; Marto et al., 2014; Cuisinier and Masrouri, 2013). However, some studies have shown incompatibilities between the manufacturer claim and experimental results (Kolay et al., 2016; Mousavi et al., 2014). On the other hand, the product chemical components have mostly not been revealed due to the company's policy. Therefore, it is hardly possible to determine the optimum condition, material concentration, and soil particle interaction for each product.

1.1.3 Polymer- soil composite

Polymers are defined as giant molecules made up of a thousand repetitive units called a monomer. These materials have almost high molecular weights (from 1000 to 1 billion) and high stability under ambient environment. Polymers have been introduced to geotechnical engineering with the advent of geosynthetics by 1980 as polymeric sheets to enhance slope stability.

Various types of polymers have been introduced and utilized for geotechnical engineering soil improvement. Vinyl polymers have been found practical for improving the mechanical properties of both fine and coarse-grain soils. These polymers are non-toxic, inexpensive, and categorized as environmental-friendly water-based soil stabilizers that guarantee ease of a mixing procedure with soil (Fungaroli and Prager, 1969). The polymer's sticky features result in binding soil grains and developing larger-size aggregates with a higher compressive and shear strength (Mirzababaei et al., 2009).

However, despite considering the effect of using vinyl polymers as soil conditioners in most previous studies, the influence of polymer characteristics on the chemical and mechanical behavior of the subsequent soil-polymer mixture is almost neglected. Hence, identifying the impact of polymer characteristics such as chemical structure, electrical charge, solvent type, and density on the physical, mechanical, thermal, and electrical properties of soil needs a precise insight into polymer science and soil mechanics. This is necessary to promote the polymeric soil additives in case of compatibility and better interaction.

1.1.4 Novelty of research

Among the nontraditional additives, polymers (mostly water-based resins) are more of interest due to their low cost, ease of application, and less curing time. Although many pieces of research have been done in the area of soil stabilization by polymers, most of them have been focused on the effect of polymer application, while identifying the mechanism of stabilization with such polymers has not been fully overviewed. It is even more complicated, referring to various polymer types and their use prescription for different soil classification. The interaction of soil particles and polymer molecules is highly dependent on chemical components and synthesis of polymer and soil type and minerals. For instance, the glass transition temperature (Tg) is one of the main characteristics influencing plenty of polymers' rheological and mechanical properties. It is defined as the temperature range where the polymer form changes from a brittle material to a soft and rubbery state without phase changing (Nielsen and Landel, 1993). Considering main properties, including Tg, rheology, chemical structure, and particle size, these key factors are less regarded in the last research pieces due to commercial privacy, where the chemical composition has been refused to reveal. However, the successful development of the optimum values of polymer characteristics can help to design optimum water-based polymers for different soils and application conditions

Therefore, this study represents one of the first attempts to understand the soil interaction with polymers dealing with their main properties. Three different emulsion vinyl polymers, including poly (vinyl acetate), poly (styrene-co-butyl acrylate), poly (methyl methacrylate-co-butyl acrylate), and various types of polymer additives such as rheology agents, have been applied to cohesive and non-cohesive soils.

This research applies the concept of considering the main characteristics of polymer to soil-polymer interaction and investigating their chemical, physical, and mechanical performance via several laboratory tests and microfabric structure perspective.

1.2 Aims and objectives

This research aims to enhance polymer performance as a soil additive by understanding the effect of each property of poly (vinyl acetate), poly (styrene-co-butyl acrylate), poly (methyl methacrylate-co-butyl acrylate) on soil stabilization and interactions. As inspired by and intended to develop the prior studies, the objectives of this study are:

1. To understand the effect of Tg (by choosing below, above, and near ambient temperature) on the UCS, cohesion, internal friction angle, elastic modulus, and wetting-drying durability of sand (as non-cohesive soil) and Kaolinite (as cohesive soil), as well as swelling parameters, compression index, void ratio, durability,

electrical conductivity, cation exchange capacity, electrical resistivity, thermal resistivity, and microstructure change of Kaolinite;

2. To investigate the impact of the chemical structure of monomers on the UCS, cohesion, internal friction angle, elastic modulus, and wetting-drying durability of sand (as non-cohesive soil) and Kaolinite (as cohesive soil), as well as swelling parameters, compression index, void ratio, durability, electrical conductivity, cation exchange capacity, electrical resistivity, thermal resistivity, and microstructure change of Kaolinite;
3. To evaluate the conventional polymer additives, including rheological (Xanthan gum, CMC, and Tylose), pH control (ammonia), wetting (SDS, CTAB, and Kenon), and an antifoaming agent (silicone-based antifoam) used in the UCS value and strain energy of the clay-polymer mixture
4. To assess the different preparation and curing conditions such as temperature, moisture, and time (ambient temperature for seven days, oven drying, remoistening, and moisture remaining) on the vinyl polymer efficiency as a soil additive on the UCS value and strain energy.

Ultimately, this research aims to promote water-based polymeric soil stabilizers by providing insight into the effect of the main polymer characteristics on the soil-polymer mixture properties.

1.3 Thesis outline

This thesis has been arranged into eight chapters. **Chapter 1** introduces the background of the problem, the purpose, and the aims and scopes. **Chapter 2** presents a thorough critical literature review. The state of the artwork done by other researchers on the soil-polymer mixture and its performance subjected to different conditions is discussed, as well. Besides, the key factors affecting the polymer characteristics are investigated in detail. **Chapter 3** characterizes the materials and experimental tests used in the study and the synthesizing process of used polymers. **Chapter 4** covers the investigation of the glass transition temperature on different soil-polymer mixtures properties via laboratory tests. **Chapter 5** describes the monomer type effect of the properties of the polymer and soil-polymer composites. The use of different polymer additives has been investigated on the soil UCS in **chapter 6**. **Chapter 7** is dedicated to the effect of the main characteristics of polymer (i.e., Tg and chemical structure) on the electrical and thermal resistivity of fine-grained soil. Finally, it concludes the thesis by summarizing the main findings of this research and offers recommendations for future work in **chapter 8**.