



Advances in ground modification with chemical additives: From theory to practice



Anand J. Puppala PhD, PE, DGE*

Distinguished Professor, Civil Engineering, University of Texas at Arlington, Arlington, TX, USA

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ABSTRACT

This keynote paper describes recent advances in chemical stabilization with a particular focus on applications related to transportation infrastructure. Chemical stabilization advances ranging from stabilization design guidelines with incorporation of fundamental soil chemistry principles to novel chemical additives for future stabilization are covered. This paper focuses on chemical treatments of shallow to moderate subgrade depths for supporting transportation pavement infrastructure. A background summary of stabilization methods along with modifications to the current design practices is presented. This section is followed by a comprehensive experimental program on chemical treatments of expansive subsoils. Both clay mineralogy influence and durability issues are fully addressed. Stabilization leachate studies and their implication in relation to real field performance are also addressed. The final outcome of this research is a more comprehensive stabilization methodology that addresses soil types and performance based testing methodologies. The last two sections cover a brief summary of new treatments of immense interest to addressing sustainable elements in ground improvement practices.

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Introduction and background

The increase in population and subsequent urbanization has often resulted in the construction of highways on soft and problematic subsoils. Stabilization of the problematic soils typically include enhancement of soil property by the addition of admixtures in the form of compaction or other means. Typically one or more properties of the soil are targeted for improvements. For soils that are soft, targeted soil properties include soil strength, compressibility and stiffness properties whereas for expansive soils, volume change is important. Both soil types cannot be dealt with successfully without a knowledge of soil plasticity properties. Among the treatment methods currently used in civil engineering practice,

chemical modification is often used due to the advantages of easy field mixing procedures that allow soil properties to be altered so as to meet required or targeted standards.

Additives based on a chemical stabilization technique is widely used in the construction of roads, airports, embankments, or canal linings by mixing chemicals with clayey soils to improve their workability, strength, stiffness, swelling characteristics and bearing capacity (Nelson and Miller, 1992; Puppala et al., 2006, 2009; De Bel et al., 2009; Pedarla et al., 2011; Yi et al., 2016). For chemical treatment, soil property enhancements usually occur through chemical gel formation and bonding among soil particles along with a reduction in soil water affinity characteristics (Jones and Holtz, 1973; Petry and Armstrong, 1989; Chittoori, 2008). Enhancement of soil plasticity, strength and stiffness properties in addition to mitigation of volume change behavior with additives has been practiced since the 1930s (Chen, 1988). Most designs could

* Fax: +1 (817) 272 2630.

E-mail address: anand@uta.edu

lead to stabilization of subgrades that will show stabilization or enhanced soil properties, but they are only sustainable for a short time. The permanency or longevity of chemical treatments usually controls the overall effectiveness of a given soil stabilization methodology at a project site. Hence, durability studies of the chemical treatment are often needed to provide a better understanding of the long term performance of chemical treatments in field conditions (Puppala et al., 2013).

This paper describes an overview of chemicals based on soil stabilization practices and advances made in this area. The first part of the paper focuses on chemical stabilization design approaches and recent advancements in these design methods. A brief review of byproduct stabilizers including chemical additives, ashes and slags is described. The second section covers a comprehensive experimental program conducted at the University of Texas at Arlington (UTA), which has resulted in many advances in chemical stabilization as well as incorporation of more performance-based durability aspects into the laboratory chemical stabilization design. Durability assessments that account for both wet-dry cycles and leachability studies are described. Test results performed on several soil types and their results are used to illustrate the improved stabilizer designs. The final outcome of this experimental design provides a flow chart that can be used to screen appropriate chemical stabilization combinations by including Montmorillonite clay minerals and performance-based durability studies.

The last two sections of the paper describe non-traditional, and byproduct-based stabilizers with a particular focus on geopolymers and low energy binder treatments. The final section briefly introduces and describes the sustainability enhancements and how they can be evaluated as a part of stabilization design methods. It should be noted that the majority of the material covered here mostly comes from comprehensive experimental studies conducted by the author and his research group at the University of Texas at Arlington (UTA). In the case of novel treatment methods, a brief overview of only a few methods are presented. This list cannot possibly represent all of advancements, especially those innovative treatments that are currently taking place throughout the world.

Chemical stabilizers and mix design

Chemical Stabilizers

Traditional stabilizers typically depend on pozzolanic and cationic exchange reactions to modify and stabilize soils (NCHRP 114 2009). Pozzolanic reactions occur when siliceous and aluminous materials react chemically with calcium hydroxide at regular temperatures to form cementitious compounds or gels. Cation exchange also occurs when the soil is able to exchange free cations available in exchange locations (Mitchell and Soga, 2005; Chittoori and Puppala, 2011a). Lime, cement, and fly ash are the most frequently used chemical additives in soil stabilization practices.

Lime has been known to reduce the swelling potential, liquid limit, plasticity index and maximum dry density of

the soil, and increase its optimum water content, shrinkage limit and strength (Croft, 1967). It improves the workability and compactability of subgrade soils (Jung et al., 2008). When clay soil is treated with lime and reacts in the presence of water, new compounds are formed through the processes of cation exchange, flocculation, carbonation and pozzolanic reaction (Al-Rawas et al., 2005). These processes can vary with their time of completion depending on the type of clay being treated. Therefore, lime-treated soil is allowed one to four days for mellowing, which helps establish a consistent or homogeneous mixture (Al-Rawas et al., 2005; Puppala et al., 2006; Chittoori et al., 2013).

Lime stabilization is a widely used means of chemically transforming unstable soils into structurally sound construction foundations. Lime stabilization enhances engineering properties in soils by improving strength, improving resistance to fracture, fatigue, and permanent deformation, improving resilient properties, reduced swelling, and resistance to the damaging effects of moisture. The most substantial improvements in these properties are seen in moderately to highly plastic clays (Little, 1999; Puppala et al., 2006, 2013). When lime is combined with water and the soluble silica and alumina present in clay, a chemical reaction occurs, resulting in the formation of new compounds. During this reaction, the primary function of lime is alteration of particle structure and increased resistance to shrink-swell and moisture susceptibility. A secondary result is an increase in strength caused by the binding of particles through chemical gels including formed tobermorite gels (Al-Rawas et al., 2005). Tobermorite gels are typically formed due to hydration of calcium silicates and this gel formation results in hardening of treated soils. Since alteration of particle structure occurs slowly, depending upon the type of clay present, a mellowing period of one to four days is allowed to obtain a homogeneous, friable mixture. Many researchers have used lime as a stabilizer with an appreciable amount of success to modify soils and enhance their soil properties.

Portland cement production begins with two essential raw ingredients: a calcareous material and an argillaceous material. Limestone, chalk, and oyster shells are examples of calcareous materials, primarily containing calcium oxide. On the other hand, argillaceous material is a combination of silica and alumina that can be found in clay, shale, and blast furnace slag. These materials are crushed through a grinding mill using either a wet or dry process and then stored in silos until needed. The raw materials are then melted in a kiln at temperatures ranging from 1400 °C to 1650 °C (2500°F to 3000°F) to form cement clinkers, which are then cooled and stored. The last step in the process involves grinding the clinker into a fine powder (Mamlouk and Zaniewski, 2011).

As previously noted, cement is a compilation of various minerals—typically composed of calcium, silica, alumina, and iron compounds. When water is mixed with cement, hydration occurs, meaning cementing compounds of calcium-silicate-hydrate (C-S-H) and calcium-aluminate-hydrate (C-A-H) are formed and an excess of calcium hydroxide (CaOH) is released, approximately 31% by weight. (Parsons and Milburn, 2003) C-S-H and C-A-H occurs when crystals begin forming a few hours after the

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