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Physico-chemical aspects of cementitious slurry design for the stabilisation of reactive soils

Aspects physico-chimiques des coulis de ciment pour la stabilisation des sols réactifs

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ABSTRACT

The physico-chemical implications of cementitious stabilisation across a range of soil geochemical conditions have been addressed to rationalise the current state of practice. The processes that influence the gain in soil characteristics include the short-term flocculation of clay particles that stabilises the expansive nature of moisture-sensitive soils, and the occurrence of pozzolanic reaction to give cementitious products. The proposed approach to slurry design is based on assessing the potential for these two processes in the soil chemistry and mineralogy and matching a complementary cementitious additive type and concentration. Ten soils have been collected and assessed using the Unified Soil Classification System and the Great Soil Group Classification System. The former classification system is used to express the plasticity characteristics of the soil deposit. The latter system is used by agricultural scientists to express the profile development of soil deposits, and provides a convenient source for gaining an appreciation of site geochemistry without deferring to expensive laboratory tests. The two systems can be used to determine an appropriate slurry composition to affect a desired geotechnical response. This will improve the efficiency of the stabilisation routine.

RÉSUMÉ

Les implications physico-chimiques de la stabilisation au ciment à travers une gamme des états géochimiques de sol ont été adressées pour rationaliser l'état actuel de la pratique. Les processus qui influencent le gain dans les caractéristiques de sol incluent la floculation à court terme des particules d'argile qui stabilise la nature expansible des sols sensibles à l'humidité, et l'occurrence de la réaction pozzolanique. L'approche proposée à la conception du coulis est basée sur l'évaluation du potentiel de ces deux processus du point de vue chimique (du sol) et minéralogique et assortir un type et une concentration additifs de ciment complémentaires. Dix sols ont été rassemblés et évalués en utilisant le système de classification unifié de sol et le grand système de classification de groupe de sol. L'ancien système de classification est employé pour exprimer les caractéristiques de plasticité du dépôt de sol. Le deuxième système est employé par les agronomes pour exprimer le développement de profil des dépôts de sol, et fournit une source commode pour gagner une appréciation de la géochimie du site sans se reporter aux essais en laboratoire onéreux. Les deux systèmes peuvent être employés pour déterminer une composition appropriée du coulis pour affecter une réponse géotechnique désirée. Ceci améliorera l'efficacité de la routine de stabilisation.

1 INTRODUCTION

In geotechnical engineering, lime stabilisation of clay soils has received much attention over the last few decades. This is primarily owing to the significant physico-chemical and microstructural developments that can be achieved through this process (Eades & Grimm 1960, Locat et al. 1990, Boardman et al. 2001). It is accepted that the principal mechanisms of soil-structure alteration include:

- (1) cation-exchange driven flocculation and aggregation of the soil microstructure within moments of lime application, and;
- (2) eventual dissolution of alumino-silicious clay minerals and formation of cementitious products in pozzolanic reaction.

Early research directed in this field focussed mainly on monomineralic soils (typically kaolin or montmorillonite) stabilised by a specific additive (Eades & Grimm 1960; Herzog & Mitchell 1962; Willoughby et al. 1968). They demonstrated the practicality of X-ray diffraction methods in the identification of neofomed cementitious products and use of the scanning electron microscope for recognition of the altered soil microstructure. Similar methods have been employed for studies on a range of natural soils to explore the variables likely to affect the performance of lime stabilisation in the field (Locat et al. 1990). It was established that the different clay minerals can yield different reaction products, which affect engineering properties of soils although the reaction mechanisms remain similar. In the short term montmorillonite has great susceptibility to floccula-

tion/aggregation due to a higher Cation Exchange Capacity (CEC) and specific surface area. Strength gain in the long term is due to the formation of Calcium Silicate Hydrate (CSH) gel and stable phases. Kaolin is more likely to form Calcium Aluminate Hydrate (CAH) due to the higher proportion of accessible aluminium in the clay lattice.

Other studies adopted similar methods to trace the development of cementitious elements for a broad range of geotechnical parameters (Rajasekaran & Rao 2000; Chew et al. 2004). Permeability, consolidation, and Atterberg tests were conducted for a single soil type and a specific stabilising agent. It was proved that the stabilised soils become less permeable, stiffer and are less sensitive to changes in moisture content with morphological development of the soil mineralogy.

A range of soil type, additive composition and additive concentration on geotechnical characteristics have been discussed in recent years (Ahnberg et al. 2003; Puppala et al. 2003). They establish that no individual binder would produce similar results across a range of soils. This emphasises a desire to tailor design cementitious slurry to meet site conditions for the requirements of performance and economy.

Waste by-products such as fly ash and Ground Granulated Blast Furnace Slag (GGBFS) can be used to improve the economy of slurry design and the quality of cementitious products. These products are alumino-silicates which will preferentially dissolve in an alkaline environment. The nature of these desired effects and the range of secondary products that will be formed depend on the specific geochemical environment for which the process is employed.

In Australia, cementitious slurry stabilisation is being applied by the railway industry across a range of soils that generally exhibit highly compressive or reactive (shrink/swell) geotechnical characteristics. Slurry injection stabilisation is the process used to introduce lime and pozzolanic additives to rehabilitate the geotechnical characteristics of problematic subgrades. Australian rail infrastructure passes through a diverse range of terrain and climate, reflecting a wide range of pedogenic environments and natural soil profiles. The operating environment offers further complications to the curing of stabilised soils with cyclical ambient temperatures, seasonal ground-moisture fluctuation and imposed dynamic stresses. The selection of lime to additive proportion should address specific site conditions and the range of factors that affect the development of geotechnical characteristics. This requires an investigation into the consequence of soil stabilisation by lime, fly ash and GGBFS and the formation of new microstructural elements.

This paper addresses the physico-chemical mechanisms and factors that affect the performance of the stabilisation procedure. It also offers a new approach to cementitious slurry design based on in-situ soil conditions.

2 CEMENTITIOUS ADDITIVES

The aim of exposing a problematic soil to a cementitious additive is to eliminate excessive volumetric instability and to enhance engineering properties such as stiffness. A reduction in permeability will stabilise the formation from ground-moisture fluctuation. This is achievable with the use of cementitious slurry products such as lime supplemented with fly ash or GGBFS.

In the short-term the particulate slurry additives can act as a microfiller, accumulating in the voids of the soil and increasing the interparticle contacts (Sherwood 1993). This increases the friction of the system and soil strengthens. High concentrations of calcium ions present in the lime slurry will displace the native cations on the exchangeable sites of the clay soil. The increased charge density on clay particle surfaces then cause the particles to form flocs leading to soil aggregations. The potential for this mode of improvement is driven by the CEC of the clay particle surface, the specific surface area (which itself is often directly related to CEC) and the soil pH. In the geotechnical context, this mode of improvement dramatically reduces the plasticity of the soil and associated swell characteristics. The consequence of particle aggregation is an open pore-structure with increased saturated permeability.

In an alkaline environment the long-term pozzolanic reaction of aluminosilicate minerals of both clay and additive will increase the engineering characteristics of the soil mass. This reaction is governed by chemical-thermodynamics and stoichiometry, where crystalline phases are generated from relative concentrations of soluble materials (Kulik & Kersten 2001). A solution of high pH will dissolve the aluminium and silicon from slurry additive and clay lattices to form metastable Calcium Aluminate Hydrate (CAH) gel and Calcium Silicate Hydrate (CSH) gel. These gels will develop into reticular CSH and plate-like CAH crystalline phases respectively (Chew et al. 2004). Under certain conditions secondary reaction products, such as expansive carbonates and ettringite, can also enhance or degrade the engineering characteristics (Nontananandh & Kamon 1996). Consequently, the soil will exhibit reduced permeability as the pore spaces are occupied with reaction products and increased stiffness as crystalline products are formed. The soil generally develops a more stable and rigid structure with time.

3 CHARACTERISTICS OF NATURAL SOILS

The parent material and multitude of processes which form an indigenous soil will affect the potential for stabilisation in the field. It is important to consider the problematic soil as a three dimensional pedological unit with geochemical and mineralogical features that may vary dramatically with depth. To reduce the abundant level of uncertainty the factors that affect the potential for stabilisation can be assessed independently. Such factors include clay mineralogy, additional mineral components, organic content and porewater quality. For instance, pozzolanic reaction and the formation of new cementitious elements will be dependant on the composition of these soluble phases within the soil mass (Stronach & Glasser 1997).

3.1 Clay Mineralogy

Simplistically, the clay particle is a combination of silica tetrahedral and aluminium or magnesium octahedral sheets. They have a surface charge derived from an immense specific surface area and unresolved negative charges at particle surfaces and edges. Cations are drawn to these negative charge sites to give the clay a stable electrostatic configuration. The arrangement of silica and aluminium (or magnesium) sheets and the species of inter-layer and surficial cations governs the clay particle interaction and ultimately controls the macro-scale volumetric response to changes in moisture content. Clay minerals with cations of low ionic potential and high specific surface areas, such as Na-Montmorillonites, have a large diffuse water layer and relatively weak interparticle contacts, compared to relatively stable kaolinite.

3.2 Mineral Compounds

Most soil deposits comprise of mixed clay mineralogy and additional compounds, which may interact with the stabilisers. These include carbonates, sulphurous compounds and sesquioxides. The presence of carbonates such as calcium carbonate is not detrimental to the stabilised product, but may act as a reaction inhibitor (Locat et al. 1990). Sulfides can oxidise to sulphates which may then, under certain environmental conditions, form highly expansive ettringite in the presence of calcium (Mitchell & Dermatas 1990; Sherwood 1993). Sesquioxides are compounds of iron and aluminium that complicate the exchange complex of the soil mass and detrimentally lower the soil pH. They do, however, add material for pozzolanic reaction (Sherwood 1993; Young & Young 2001).

3.3 Organic Content

Organic matter has a role in the stabilisation process: organic polymers can form interparticle bonds that increase the stability of the soil structure; humus has a cation exchange capacity far exceeding that of most clay minerals, and; the pH of the soil is lowered in the presence of organic acids. This means the efficiency of the stabilising procedure may be reduced if the organic matter acts as a buffer to the clay minerals.

3.4 Porewater

The moisture content of a soil has qualitative as well as quantitative implications for the soil characteristics. Soil suction and volumetric change are directly associated with the moisture content and the relative scale of diffuse water on the clay particles. The quantity of diffuse water that the clay can accommodate is related to the net negative charge on the clay particles. This is variable with the water electrolyte type, concentration and ambient pH. The flow of groundwater through soil pores creates a dynamic chemical and hydro-mechanical state. It can fuel redox reaction and displace cations. Hydrodynamic dispersion

and chemical diffusion can also transport the solute stabiliser to a greater zone of influence within the soil mass.

4 SITE CLASSIFICATION

Soil samples have been collected from 10 sites across Australia where slurry injection stabilisation has been carried out. The location of each site is indicated in Figure 1. The soils have been classified according to the Unified Soil Classification System (USCS) as well as the Great Soil Group (Stace et al. 1968). The first system is familiar to geotechnical engineers and is based on the plasticity of cohesive soils. The latter classification system is used in the field of agricultural science and addresses profile development of soil deposits. The use of these systems will form the basis of site assessment for cementitious stabilisation.

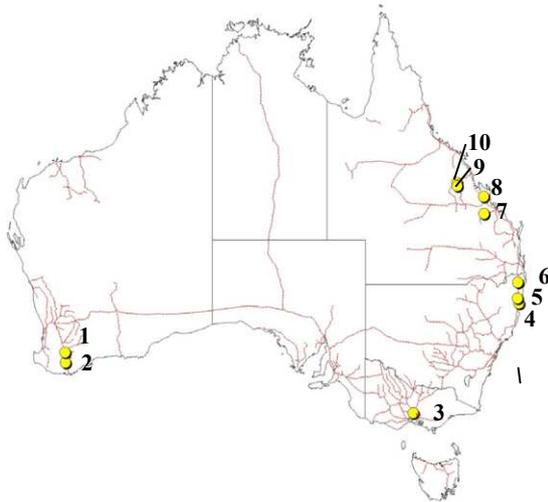


Figure 1: Rail Infrastructure of Australia and site locations of stabilised soils (Geoscience, 2004)

The results of plasticity tests are shown in Table 1 and Figure 2. This demonstrates that a wide range of soils are currently being stabilised by cementitious slurry injection from high plasticity clays (CH) to low plasticity silts (ML). It is apparent that soils which have high plasticity, giving rise to shrink/swell behaviour, are not the only soils gaining the attention of this operation. There are additional geotechnical and operational parameters that are critical in the degradation of railway subgrades.

Table 1: Plasticity characteristics of stabilised sites.

Site Id.	PL (%)	LL (%)	PI (%)	LS (%)	In situ M.C. (%)	% <2µm	Activity
1	19.0	54.3	35.4	15.0	17.8	42.0	0.8
2	28.0	67.8	39.9	13.4	21.5	42.0	0.9
3	32.0	101.9	68.8	25.6	31.4	40.0	1.7
4	24.4	55.4	31.1	13.4	22.4	17.4	1.8
5	25.1	52.7	27.7	14.6	18.5	22.0	1.3
6	25.1	73.0	47.9	18.5	37.6	31.4	1.5
7	18.6	57.0	38.4	17.3	13.2	33.2	1.2
8	22.3	69.6	47.3	20.1	12.2	29.8	1.6
9*	-	22.8	-	4.3	4.0	16.6	-
10*	-	36.5	-	8.1	7.9	17.3	-

PL = Plastic Limit; LL = Liquid Limit; PI = Plasticity Index;

LS = Linear Shrinkage

*: These are silts with an indeterminate plastic limit, and hence, plasticity index

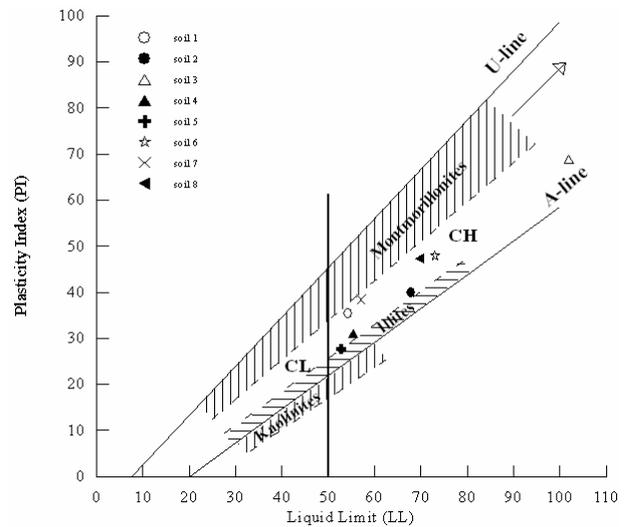


Figure 2: Casagrande plasticity chart of stabilised soils.

By observation, deduction and reason it is possible to predict dominant clay mineralogy in a body of soil. Cross-reference of the engineering behaviour, such as activity of the tested soils, to the knowledge of parent material will enable initial estimates of mineralogy. These estimates can be bolstered by the details of published studies on similar materials. The soils of this study have been correlated to the Australian Great Soil Group Classification. These soil groups indicate the profile development and elements of soil chemistry.

Table 2: Great soil group classification of stabilised sites.

Site Id.	USCS	Great Soil Group Classification
1	CH	Solodized Solonetz and Sodic Soils
2	CH	Solodized Solonetz and Sodic Soils
3	CH	Red-Brown Earths
4	CH	Siliceous Sand
5	CH	Soloth
6	CH	Grey, Brown and Red Clay
7	CH	Chernozem
8	CH	Solodized Solonetz and Sodic Soils
9	ML?	Solonetz
10	ML?	Non-calcic Brown Soil

It is also possible to infer soil chemistry from the published results of soil tests which have been compiled in the field of agricultural science. These studies detail the geochemistry and mineralogy of natural soils. For example, a similar profile to that at Site 3 has been assessed by Stace et al. 1968 in a detailed study of geochemistry in the Australian environment. These results are given in Table 3. It can be seen that the pH is moderately alkaline; this is reflected in a high carbonate and low organic content. The required proportion of lime to bring the soil to a highly alkaline state favouring pozzolanic reaction will be economically reduced in this environment. The CEC is particularly high also. This means that this site would stand to gain significant volumetric stability in the short-term from particle rearrangement if the native cations are in low concentration and are of lower ionic valence than the introduced species. Long term development of cementitious elements will also imbue the soil with considerable strength. It is likely that CSH phases will extensively form in pozzolanic reaction with the dominant clay fraction.

Table 3: Chemical Analysis of Soil at Site 3 (Stace et al. 1968)

Soil Id.	pH	CaCO ₃ (%)	Org. Mat. (%)	Eff. CEC meq/100g
3	8.2	0.9	0.7	32

This study shows that there are a diverse range of soils that are attracting the attention of Slurry Injection Stabilisation concerning both engineering and geochemical characteristics. Further studies are required into the relative influence of these identified key chemical features of natural soils over the set of cementitious additives. The results can be modeled with chemical thermodynamics. This will be the first step in specifying cementitious slurry components to achieve a desired geotechnical response in a problematic soil through physico-chemical and pozzolanic reaction.

5 CONCLUSIONS

Slurry Injection Stabilisation is being used across a range of Australian soils to enhance the strength and control the volumetric instability of railway subgrades. This technique incorporates lime, fly ash and GGBFS additives in proportions that are currently based on matching slurry specific gravity to soil moisture. This process seems arbitrary and it is proposed that soil chemistry/mineralogy can be used as the basis for establishing design criteria for slurry additive composition. The quality of cementitious products and achievable performance can then be estimated.

This approach also requires further attention to various aspects of the injection process. It assumes an intimate mix (perfect efficiency) of slurry with soil which is unrealistic in the field. Therefore, an evaluation of the overall performance should address the injection procedure, slurry rheology and soil structure in determining mix efficiency.

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