



Stabilization of a silty soil: Effects of disruptive salts



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ABSTRACT

Soil stabilization with lime and hydraulic binders is a widely used technique to improve the stability and the mechanical properties of soils for use in road construction. However, the presence of substances such as sulphates can induce the swelling, cracking and loss of some mechanical properties defined as disruptive behaviours. This paper analyses the disturbances on the treatment of one silty soil contaminated with sulphates, chlorides, phosphates and nitrates salts, separately then by combinations of two salts. Tests in accelerated curing conditions are used as they are the first realised by the embankments companies, before undertaking further study. The impact of each soluble salt depends on the associated anion and cation. It is not possible to establish a degree of disturbance by cation or anion type. The deleterious effects of sulphates can change if other salts coexist in the soil (i.e., Vs (Volumetric swelling) equal 7% in case of potassium sulphate contamination, whereas Vs reaches 18 and 23% with a crossed contamination of potassium-sodium sulphates and potassium sulphate-chloride respectively). The influence of complete salts, instead of anions only, should be integrated in technical guides to improve the reliability of the suitability tests they propose.

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1. Introduction

Soil stabilization is a type of engineering treatment for soils which consists of improving their geotechnical properties for road construction, especially for base and sub-base layers (Bell, 1993). From its development in the 1960s, this technique has been increasingly applied on fine grained soils (Ingles and Metcalf, 1972). Nowadays, construction projects including the excavations and transportation of soils are basically chosen according to economic and environmental criteria. To reduce the environmental impact, the project managers are increasingly forced to use the soils present on site, which however do not always have the desired geotechnical properties (Cuisinier et al., 2011).

Despite soil stabilization is a proven technique, Wang (2002) analyses multiple failures that occurred in treated soil bearing layers related to loss of strength or swelling (considered as disruptive behaviours). Other studies (LCPC-SETRA, 2000a; Cabane et al., 2004, 2005; Xing et al., 2009; Le Borgne et al., 2009, 2010) indicate that the presence of soluble minerals such as chlorides, phosphates, nitrates and more specifically sulphates, may be the cause of swelling, cracking and weakening of treated soil layers. So, they are defined as disruptive salts. The presence of sulphates in soils can ruin the efficiency of this treatment;

the contact with lime and hydraulic binders (LCPC-SETRA, 2000b; Britpave, 2011) can induce the formation of expansive minerals (calcium-sulpho-aluminate-hydrate; ettringite) causing the swelling and loss of bearing capacity (Sherwood, 1962; Hunter, 1988; Little et al., 2010; Mitchell and Dermatas, 1992; Kinuthia et al., 1999; Puppala et al., 2005; Rajasekaran, 2005; Wang et al., 2003). Sodium sulphate is proven to cause some disturbances on the treatment of soils by means of the swelling, the cracking and the loss of strength of the treated soils (Harris et al., 2004; Rajasekaran, 2005; Xing et al., 2009). Studies addressing the impact of potassium sulphate on soil stabilization are scarce (Kinuthia et al., 1999; Wild et al., 1999; Rajasekaran and Narasimha Rao, 2002) and do not focus on the treatments with hydraulic binders. For example, Kinuthia et al. (1999) discussed the effects of potassium sulphate on the soil consistency and the Atterberg limits. Some authors (Cabane, 2004; Harris et al., 2004) proposed maximum values for concentration of sulphates to avoid perturbations on soils stabilization. But those thresholds were cation-specific, ranging from 0.01 and 1% depending on the soil, treatment, curing conditions as well as on the presence of other salts in the soil. Interactions between the salts, soil and treatment might lead to synergistic or antagonistic effects (Cau Dit Coumes and Courtois, 2003). Few research investigations focused on such approach (Malone et al., 1997; Bénard, 2005; Bénard et al., 2008; Saussaye et al., 2014). In the literature, the interactions between chlorides and sulphates are studied in order to understand the impact of sulphate environments, then of seawater, on cementitious materials (Al-Amoudi et al., 1995; Abdelrazig et al., 1999; Brown and

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Table 1
Geotechnical properties of the “limon de Loucelles”.

| Properties | Units | Values |
|--|---|--------|
| Maximum grain diameter, D_{max} | mm | 50 |
| Grain size for which 80 to 99% of grains pass, D | mm | 0.200 |
| Fine fraction (0/80 μm) | % | 77 |
| Clay fraction (0/2 μm) | % | 10 |
| Methylene Blue Value (clay activity) | $\text{g} \cdot 100\text{g}^{-1}$ of dry soil | 0.80 |
| Specific gravity | – | 2.50 |
| Optimum moisture content, OMC | % | 16 |
| Maximum dry density, MDD | $\text{g} \cdot \text{cm}^{-3}$ | 1.77 |

Table 2
Salt types and notation.

| Salt | Scientific notation | Paper notation |
|--|---|----------------|
| Sodium sulphate decahydrate (mirabilite) | $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ | Na + S |
| Sodium chloride (halite) | NaCl | Na + Cl |
| Sodium hexametaphosphate | $(\text{NaPO}_3)_6$ | Na + P |
| Sodium nitrate | NaNO_3 | Na + N |
| Potassium sulphate | K_2SO_4 | K + S |
| Potassium chloride | KCl | K + Cl |
| Potassium dihydrogenophosphate | KH_2PO_4 | K + P |
| Potassium nitrate | KNO_3 | K + N |

Badger, 2000; Dehwah et al., 2003; Mohammed et al., 2004; Shayan et al., 2010). The formation of ettringite is supposed reduced by the formation of Friedel's salt ($3\text{CaOAl}_2\text{O}_3\text{CaCl}_2 \cdot 10\text{H}_2\text{O}$) resulting from the interactions between the chloride ions and C3A. However, Revertegat et al. (1997) observed an increase of the swelling caused by favouring the alumina-sulphate reaction. Jallad et al. (2003) reported interactions between phosphates and sulphates by altering the formation of thaumasite ($\text{CaCO}_3\text{CaSO}_4\text{CaSiO}_3 \cdot 15\text{H}_2\text{O}$); at pH levels < 11 thaumasite reacted with KH_2PO_4 and Na_2HPO_4 and some conversions to calcium phosphate, calcium silicate and calcium carbonate were detected. Kordlaghari and Rowell (2006) showed that, in a soil, the presence of gypsum interacted with KH_2PO_4 through the formation of calcium phosphate. The interactions between nitrates and sulphates were rarely studied and were limited to the farming sector (Miller, 1988).

The aim of this study is to investigate the combined effects of some soluble salts on a soil treated with lime and hydraulic binders, and focuses on the influence of sulphate salts, alone or co-added with another salt. Indirect tensile strength and volumetric swelling are measured after accelerated curing, as applied by embankments companies as a prerequisite to advanced treatment study. The approach “by salts” should increase the reliability of the conclusions of the usual suitability tests.

2. Materials and methods

2.1. Soil

The selected soil is a silt from the Lower Normandy Region known as “limon de Loucelles”. The main properties of the soil are reported in Table 1. It is classified as ML according to the Unified Soil Classification System.

Table 3
Main properties of the quicklime Proviacal® DS (Lhoist, Neau factory).

| Lime CaO (%) | Free CaO (%) | Magnesium oxide MgO (%) | Sulphite SO_3 (%) | Anhydrite CaSO_4 (%) | Passing through 2 mm (%) | Bulk density ($\text{g} \cdot \text{cm}^{-3}$) | Reactivity t_{60} (min) |
|--------------|--------------|-------------------------|----------------------------|-------------------------------|--------------------------|--|---------------------------|
| 93.00 | 87.90 | 1.10 | 0.30 | 0.50 | 100 | ≈ 1.00 | <1 |

2.2. Soluble salts

This paper focuses on the disturbances caused by sulphates on the stabilization of the soil and the effects of other existing salts such as chlorides, nitrates and phosphates. Two approaches are chosen:

- addition of each salt individually at different concentrations (3, 5, 7 and 10 g of anion per kg of dry soil) in order to observe the effect of each salt on the studied soil. Added concentrations have been selected in the context of a global study on the chemical stabilization disturbances of soils treated with hydraulic binders (Saussaye, 2012). Anion concentrations are higher than general natural concentrations in soils (Calvet, 2003; Saussaye et al., 2013, 2014, 2015). Salt notations are reported in Table 2.
- contamination of the soil with two salts with a total anion concentration of $10 \text{ g} \cdot \text{kg}^{-1}$ (combinations of 3 g of $\text{SO}_4^{2-} \cdot \text{kg}^{-1}$ + 7 of other anion noted 3/7, 5 g of $\text{SO}_4^{2-} \cdot \text{kg}^{-1}$ + 5 of other anion noted 5/5 and 7 g of $\text{SO}_4^{2-} \cdot \text{kg}^{-1}$ + 3 of other anion noted 7/3);

Once the behaviour of the treated soil with each type of salt is known, the contamination of the treated soil with a combination of two of them seeks to understand:

- the influence of two different sulphates salts (different cation) on the treated soil (combination named (Na/K) + S);
- the influence of two different anions associated with the same cation on the treated soil (combination named Na + (S/Anion) or K + (S/Anion)).

Solution of the soluble salts (using ultrapure water and analytical grade salts) are added to the soil before the soil treatment, just as Guichard (2006) and Le Borgne (2010) previously performed. This method might be far from real conditions, compared to Cabane (2004) who worked with natural soils, but it allows to set concentrations and to perform combinations between anions. Moreover the addition of solutions before stabilization treatment, allows to control the concentrations of potentially disruptive anions (Guichard, 2006; Le Borgne, 2010).

The salt solution is added to the dried soil to obtain a moisture content of 18%. The soil and the salt solution are mixed and sealed in airtight bags during seven days in order that moisture and salts spread over the sample.

2.3. Lime and cement

The stabilization consists of a soil treatment with 1% of quicklime (Proviacal® DS quicklime, from the Neau factory, produced by Lhoist) (Table 3) and 6% of hydraulic road binder (HRB) (ROLAC® 645, from Le Havre St-Vigor factory, produced by Lafarge) (Table 4). The mixing is performed according to the NF P94-093 standard. HRB is added 1 h after the lime, response time necessary to the reaction between quicklime and soil, for moisture content decrease or clay inhibition. During the treatment, the moisture content is reduced to 16% due to the water consumption of the quicklime, which corresponds to the Optimum Moisture Content (OMC) of the treated soil without any addition of any salt (noted control soil hereafter).

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