1 Soil treatment with organic non-traditional additives for the improvement of earthworks

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17 Abstract

18 The aim of this study was to characterise the technical and environmental implications of
19 non-traditional treatments of a low-plasticity compacted silt ($PI = 14$) and to investigate their
20 actions both at the micro- and macro-structural scales. Three non-traditional additives
21 derived from industrial vegetal by-products were studied. These additives are classified as an
22 acid solution (AS), an enzymatic solution (ES) and calcium lignosulfonate (LS). The first step
23 was to characterise the effects of these treatments on Proctor compaction, bearing capacity,
24 unconfined compressive strength and stiffness. The index properties of the treated samples
25 were also measured to assess changes in the interaction between soil minerals and the
26 additives. These experimental results showed that the 0.002% ES and 2.0% LS treatments
27 were the most effective at improving the soil dry density and allowing the soil to reach
28 optimum density using 3% less water or 25% less compaction energy. In a second step the
29 mechanisms involved by the treatment were investigated. A microscopic study was
30 conducted including scanning electronic microscopy (SEM) and mercury injection porosity
31 (MIP) tests, measurements of the surface tension of non-traditional additives mixed with
32 water completed the study and demonstrated that the ES treatment has the same surfactant
33 properties as sodium dodecyl sulfate, a common surfactant. Compaction tests confirmed that
34 the behaviours of the soil after ES and sodium dodecyl sulfate treatments were similar.

35 Key words: Soil treatment, non-traditional additives, compaction, bearing capacity, surfactant

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1. INTRODUCTION

In earthworks, sustainable development will play a larger role in future project design and the assessment of technical solutions by contractors. Currently, the reduction of the environmental impact of earthworks is a growing issue. One of the major challenges facing earthworks companies is the need to use a majority of natural materials extracted within the construction site, including materials with very low geotechnical characteristics. The common industry solution is to use lime, cement or fly ash to improve the soil geotechnical properties; however, sustainable development principles also require a reduction in the consumption of water and non-renewable energies as a way to limit greenhouse gas emissions. In this context, soil treatment with various non-traditional additives has been tested. These additives are diverse in nature and some of them derive from the industrial transformation of renewable raw materials. Due to their organic nature, some products are biodegradable. Thus, the treated soils can recover their untreated composition after the end of the biodegradation process. These products are also beneficial due to their efficiency at low dosages, thereby limiting the environmental impact and cost of their use. Various additives have been tested for improving the compaction of dry soils to avoid dust generation and for increasing the durability of uncovered roads [5, 22, 24, 27]. Additionally, additives have been tested to stabilise erodible soils [33]. Mechanical properties, such as the unconfined compressive strength [23, 28] or the swelling potential of plastic soils [11, 19], have also been studied.

Tingle and Santoni [28] listed seven non-traditional categories based on the major active component and classified them as salts, acids, enzymes, lignosulfonates, petroleum emulsions, polymers and tree resins. Acids are low pH aqueous solutions containing sulfonated molecules such as naphthalene or limonene [13]. The presence of proteins in enzymatic solutions was confirmed by Velasquez et al. [32]. Lignosulfonates are organic

polymers derived from lignin extracted by the sulfite processing of cellulose in the wood-pulp and paper industries. According to Tingle et al. [30], petroleum emulsions contain asphalt or synthetic iso-alkane fluids suspended in emulsions by a surfactant, polymer emulsions contain vinyl acetates or acrylic copolymers and tree resins are diverse emulsified by-products of the timber and paper industries. Nevertheless, many of these products also include secondary additives such as surfactants or ultraviolet inhibitors, which may react with the soil minerals or modify the soil water properties and thus influence the mechanical behaviour of the treated soils [30]. The emphasis of this study was put on non-traditional additives that would lower the environmental impact of soil treatment in the earthworks industry. Therefore, this study focused on the following products which are derived from the transformation of renewable organic matters: acids, enzymes and lignosulfonates. For each of these categories, a review of the literature concerning the effects on geotechnical properties and suspected mechanisms is presented. Then, geotechnical properties such as compaction, bearing capacity, unconfined compressive strength and stiffness were investigated to define the potential application of these treatments. In the last part, the action of the treatments on the microstructure of the soil was studied by performing scanning electronic microscopy (SEM) and mercury injection porosity (MIP) tests to identify the mechanisms involved by the different products.

2. LITERATURE REVIEW

2a. Acid solutions

Rauch et al. [20] studied the effects of an acid product on the index properties of three pure clay phases (kaolinite, illite and montmorillonite) and two plastic soils. They concluded that the acid treatment had little effect on soil plasticity, swelling potential and shear strength. The authors explained that the observed modifications were induced by initial differences in properties of the compacted samples. Tingle & Santoni [28] and Santoni et al. [23] tested the

application of an acid solution to three soils ranging from non-plastic to highly plastic in nature. They found no change in the unconfined compressive strength. The authors determined that the acid treatment had no effect on the compaction properties of the soils. However, another study [21] showed that changes in the compaction properties of acid-treated soils can occur. Scholen [24] reported in situ studies undertaken by the US Forest Service between 1991 and 1993 which tested the addition of acid solutions. In 1995, no particular failure or degradation of the treated sections was reported. Scholen [24] proposed that acidic non-traditional additives act by altering the electrolyte concentration of the pore fluid, thereby reducing the double layer thickness of clay minerals. Cation exchange was also suspected to occur and to flocculate the clay minerals. Moreover, important lowering of the pH of a soil can also lead to the dissolution of clay minerals [26, 36]. For example, to start the dissolution of kaolinite, the pH values have to be lower than 2 [16, 35]. However, the X-ray diffraction, specific surface area and cation exchange capacity were not modified by the treatments, even for dosages as high as 50% [13, 21]. Scanning electron microscope pictures obtained by Katz et al. [13] showed similar structures for the acid-treated and untreated soils. According to the literature, acid solutions modify the compaction and bearing capacity properties of treated soils without modifying the soil mineralogy.

2b. Enzymatic solutions

For enzymatic treatments, Rauch et al. [20, 21] concluded that most of the variations in the Atterberg limits they observed were insignificant compared to the typical variations of such measurements. Unconfined Compressive Strength (UCS) tests of the treated soils demonstrated modifications from -30 to +80%, depending on the product and soil tested [18, 28]. Velasquez et al. [32] mentioned an increase in shear strength resistance of 9 to 39% for two enzymatic treatments but detailed analysis of samples properties showed that modifications can be attributed to differences in water content and dry density after

treatment. For some enzymatic solutions, limited changes in the compaction references were found [19, 21]. Tingle and Santoni [28] considered that the modifications in the compaction properties after enzymatic treatments were too small to be significant; however, Velasquez et al. [32] mentioned that samples treated with enzymatic solutions achieved a higher density for the same compaction energy. In two of the three field studies reported by Scholen [24], the treated section of uncovered forest roads showed less degradation than untreated sections. Visser [34] performed in situ California Bearing Ratio (CBR) measurements on four soils ranging from sandy to clayey treated with an enzymatic solution. CBR improvement occurred in 4 cases out of 8. For enzymatic treatment, Scholen [24] hypothesised that enzymes bond the organic matter of the soil with clay minerals. These additional bonds should reduce the water affinity of the clay and limit the swelling potential of the soil. However, Harris et al. [11] showed that the 3-D swelling potential of a plastic clay (PI = 51) was not modified by the addition of 0.07% of an ES treatment. Another stabilisation mechanism was suggested by Velasquez et al. [32], who observed that an ES could have surfactant properties and thus stabilise the soil by improving its compaction ability. This property was confirmed by Berney et al. [4] and Park et al. [17], who showed that the dry density of compacted soils is improved by the addition of surfactants. In conclusion, ES seems to induce compaction modifications, but the stabilisation mechanisms of this family of products remain in question.

2b. Lignosulfonates

The addition of lignosulfonates modified the index properties of treated soils in different ways. Lambe [14] showed that small quantities of calcium lignosulfonate (< 0.5%) reduce the liquid limit of a low-plasticity soil. Gow et al. [10] treated a silty sand with 0.25 to 1.0% of lignosulfonate and observed that the plastic limit was reduced when the dosage increased, but no consistent trend was found for the liquid limit. A maximum improvement in the UCS

was observed for the addition of 5% of lignosulfonates [23, 28]. Compaction properties were also affected by the treatment. Gow et al. [10] showed that the optimal water content of a compacted soil was reduced and the maximum dry density increased especially for dosages between 0.5 and 1.5%. CBR values measured for each dosage at optimal water content and maximum dry density were improved in comparison to untreated samples but decreased with increased dosages. In situ evaluations of the mechanical performances of the lignosulfonate treatment are limited. Surdahl et al. [27] mentioned a stiffness improvement of a granular soil after treatment. Lignosulfonates are thought to stabilise the soil by coating together its particles [30, 33]. However, lignosulfonates also have surfactant [31] and dispersive properties [14, 25]. Thus, the stabilisation mechanism of lignosulfonates is not yet well understood.

In general, soil treatment with non-traditional additives can improve the engineering properties of soils; however, these results vary depending on the tested products, soil nature and at times, the dosages. According to Rauch et al. [20] the variability of the engineering properties may be due to the modification of the optimal density and water content of compacted soils. Thus, as for traditional treatments such as lime or cement, the addition of chemical additives may induce modifications of maximum dry density and optimal water content, which must be determined for accurate field applications. Moreover, the strengthening mechanisms of non-traditional treatments are not yet well understood and where data are available, no correlations between microscopic and macroscopic observations have been established. Therefore, some experiments were conducted to identify the mechanisms of each additive.

3. MATERIALS AND METHODS

3a. Non-traditional additives

The acid solution (AS) tested in this study was a concentrated solution of sulfuric acid mixed with D-limonene, a by-product of citrus processing. For this kind of products, typical dosages tested in the literature are comprised between 0.01 and 0.2%. As shown by different authors, UCS, compaction and clay mineralogical properties were not affected by dosage increase [13, 21, and 28]. Thus, a dosage of 0.01% of concentrated product by dry weight of soil was tested in this study (Tab. 1).

The tested enzymatic solution (ES) is a biodegradable brown aqueous solution with an acidic pH of 4.6. For this type of product, typical dosages are comprised between 0.002% and 0.1%. However, according to Tingle & Santoni [28] and Velasquez et al. [32], the geotechnical properties of soils treated with an enzymatic additive were independent of the dosage. Therefore a dosage of 0.002% was selected.

The tested lignosulfonate (LS) was a biodegradable, organic, water soluble calcium salt used in powder form. The insoluble components were less than 0.5%, the moisture content was approximately 7% and the reducing sugar content was approximately 7% by dry weight of product. Experimental results indicated an optimal additive content of 5% [23, 28] for improving the UCS. On the other hand, Gow et al. [10] had demonstrated that maximum density and bearing capacity values were obtained for a dosage of 0.5%. For that reason, three dosages (0.5, 2.0 and 5.0%) were tested.

The tested surfactant was a powder with a SDS content of more than 95 % by dry weight. The required quantity of SDS for a 0.01% dosage was diluted in distilled water and then added to the soil during mixing operations.

3b Tested soil

A natural fine-graded silt of low plasticity often encountered in earthworks projects in the Paris Basin was tested in this study (Tab. 2). X-ray diffraction investigations indicated that the main minerals were quartz and calcite (8.0% by weight determined by calcimetry). The <2 µm fraction contains quartz and clay minerals (chlorite, illite, kaolinite and smectites) and the sulphur content of the soil was less than 0.02%.

Before testing, the soil was dried at 60°C and pulverised to pass through a 2 mm sieve. Depending on the liquid or solid nature of the treatment product, a specific protocol was followed to ensure the application was representative of field application procedures. For the AS and ES treatments, the initial quantity of water was mixed with the dry soil material to achieve a water content 3% lower than the target moisture content for compaction. The samples were placed in a container at 20°C for 24 hours to reach the equilibrium of moisture content. Then, the additive was mixed with the quantity of water required to obtain the total desired water content and added during the mixing operation. For LS treatment, the soil was directly brought to the desired water content and set aside for 24 hours to equilibrate. Finally, the powder was added to the soil during mixing. For all treatments, a curing time of one hour in sealed containers was chosen before conducting further tests.

4. ALTERATION OF GEOTECHNICAL CHARACTERISTICS AFTER TREATMENT

4a. Index properties

The liquid limit (LL) and plastic limit (PL) of the treated soil were determined (Tab. 3). For the AS, ES and SDS treatments, the Atterberg limits were not modified; however, a reduction in the LL and PL occurred after the addition of lignosulfonate (LS) at dosages of 2.0 and 5.0%. Despite these changes in the consistency limits, the plasticity index remained constant for all tested treatments and dosages.

4b. pH

The pH of the treated soil was determined according to ISO 10390 [12]. Measured values showed that the pH of the AS and ES treated soil was not affected despite the acidic features of both products. This phenomenon might be related to the high dilution of the products combined with the increased buffering capacity of the soil due to the presence of calcium carbonate. In contrast, the addition of the LS treatment reduced the pH by approximately one pH unit for the 5.0% dosage. This action is due both to the acidic carboxylic and sulfonate functions of lignosulfonate and to the high dosages.

4c. Compaction

Compaction tests were performed according to ASTM D 698-91 [1] using a standard Proctor test. After compaction, the instant bearing index (IPI) was measured following the same procedure as for the un-soaked Californian bearing ratio (ASTM D 1883-92 [2]) but without placing surcharge weights. A penetration piston of 49.6 mm diameter is used to apply the load on the compacted soil. The penetration rate was 1.27 mm/min. The compaction and instant bearing index curves are plotted in Fig. 1 for AS and ES treated soil. Fig. 2 shows the results for the addition of LS at 0.5, 2.0 and 5.0%. The optimum water content (w_{opt}) and the maximum dry unit weight (γ_{dmax}) for each treatment are summarised in Tab. 4.

Fig. 1 shows that for the AS treatment, no changes in the compaction and IPI curves occurred. After ES treatment, the maximum dry unit weight increased and the optimum water content reduced from 18.2 kN/m³ and 15.5% to 18.6 kN/m³ and 14.5%, respectively. On the dry side of the compaction curve, a maximum increase in the dry unit weight of 0.8 kN/m³ was measured. This means that the compaction ability of the treated soil was improved over a range of water contents from 8 to 15.5%. The IPI curve was also affected by the treatment and shifted towards lower water contents. Thus, the bearing capacity of the soil was reduced

for water contents in the vicinity of w_{opt} . However, the measured IPI at the respective optimum water content for both ES treated and untreated soil were roughly equal (Tab. 4). Fig. 2 shows that the LS treatment increased the dry unit weight and reduced the optimum water content of the soil for the three dosages. A maximum densification was obtained with the addition of 2.0% LS, which corresponded to a reduction of 2% in the optimum water content (13.5% for 2.0% LS treatment as compared to 15.5% for untreated soil). For this same treatment, dry unit weights were increased on the dry side of the compaction curve and γ_{dmax} increased from 18.2 to 18.5 kN/m³. Despite an improvement in density, the addition of lignosulfonate reduced the IPI at constant water content, and the IPI reduced further with higher doses of LS. If the soil was compacted at w_{opt} to reach the maximum dry density, the IPI measured for the 2.0% LS treatment was 14, compared to a value of 15 measured at w_{opt} for the untreated soil (Tab. 4). These results illustrate the importance of considering the entire compaction curve when assessing the effects of ES and LS treatments.

After 0.002% ES and 2.0% LS treatments, an increase in dry unit weight and a reduction in w_{opt} were observed, implying that a minimum dry density may be achieved for lower water contents. For example, the γ_{dmax} of untreated soil may be achieved at 3% lower water content. Moreover, both treatments could also reduce the energy needed to compact the soil to a minimum desired density. An estimation of the potential energy savings was made according to the results and is presented on Figs 3 and 4. These graphs show the compaction and bearing capacity curves for the ES and LS treated soil compacted at 100% and 75% of the standard Proctor energy. For samples compacted on the dry side of the compaction curve, the measured dry unit weights were the same as for untreated soil despite the 25% energy reduction. For the ES and LS treatments, however, the bearing capacity of the soil compacted at 75% of the standard Proctor energy was reduced compared to the untreated soil.

4d. Unconfined compressive strength

To study the evolution of the mechanical behaviour of treated soil, UCS values were determined at 7 and 28 days for samples compacted at their respective w_{opt} and γ_{dmax} after treatment (Tab. 4). Three replicate samples were statically compacted in one layer in a cylindrical mould 100 mm high and 50 mm in diameter. Samples were wrapped in a plastic film, covered by an aluminium sheet and stored in a plastic container at 20°C. Geometrical parameters, sample weight and water content were controlled after the sample compaction and just before testing. The results of the UCS tests at 7 and 28 days are presented in Fig. 5. In comparison with the untreated soil, the resistance of the AS and 2.0% LS treated soil was not significantly modified. The UCS of ES treated soil was slightly improved due to a higher maximum dry unit weight obtained after treatment, but the addition of 0.5 and 5.0% of lignosulfonate reduced the unconfined compressive strength by 20 and 50%, respectively. Moreover, UCS values only displayed minor changes as a function of curing time, implying that the treatments mainly have short term effects. For samples compacted at w_{opt} and γ_{dmax} determined for each treatment after 7 days of curing, the mean modulus for untreated, ES and 2.0% LS treated soils were respectively 13, 15 and 22 MPa (Tab. 5). Samples were also compacted at a target water content of 12.5% and a dry unit weight of 18.5 kN/m³. The results showed that only the 2.0% LS treatment significantly reduced the stiffness of the soil.

4e. Swelling potential and hydraulic conductivity

The determination of one dimensional free swell potential of treated soil was carried out on samples of 70 mm diameter and 15 mm thickness statically compacted in oedometric cells at different initial compaction states. The samples were saturated with distilled water.

Fig. 6 shows the one dimensional swelling potential ($\Delta H/H_0$) for untreated, 2.0% LS and ES treated samples. For each treatment, at optimal conditions of compaction, the swelling

potentials were not significantly modified. Moreover, when the untreated soil was compacted at the same dry density and initial water content than treated samples, the swelling potentials were of the same order of magnitude. Therefore, it could be concluded that the studied products did not significantly alter the swelling potential of the tested soil.

After the stabilisation of swelling, the saturated hydraulic conductivities of the samples were determined (Fig. 7). Treated samples compacted at their respective maximum dry densities showed a small decrease of the hydraulic conductivity. For treated and untreated samples on the dry side of the compaction curves, the hydraulic conductivities were very similar.

This section showed that the non-traditional additives led to several modifications of the geotechnical behaviour of the tested material. The modifications did not appear to be time-dependant since no significant modification of unconfined compressive strength occurred over the curing period considered. Nevertheless, a key question is the permanence of the improvement brought by these products over a long period of time. In this context, the interaction mechanisms between the soils particles and the additives were investigated.

5. THE STUDY OF INTERACTION MECHANISMS

5a. Microstructure of compacted soil

The investigation of the microstructure of compacted soil was conducted using a scanning electron microscope equipped with an energy dispersive X-ray spectrometer (EDS). Images obtained by collecting the secondary electrons were taken at different magnifications between 100 and 10,000x. All samples were compacted at their respective optimum water content and maximum dry unit weight. After compaction, they were wrapped in a plastic film, covered by an aluminium sheet and stored in a plastic container at 20°C for 28 days. Then, samples 2 to 3 cm³ in volume were carefully extracted and freeze-dried to remove the water

and minimise sample deformation. Fragments of the freeze-dried samples were extracted and coated with gold before the SEM analyses.

To study the organisation of the internal structure of the compacted soil, SEM investigations were conducted with mercury injection porosity (MIP) tests. Tests were conducted on freeze-dried samples compacted at the maximum dry density and optimal water content for each treatment following the same procedure as for SEM preparation. The pore size distribution is obtained by derivation of the injected mercury volume (V_{inj}) function. To compare the four samples, the injected volume was normalised such that the surface under the pore size distribution curve was equal to 1. The void ratio investigated by the mercury (e_{inv}) can be defined as the ratio between the injected volume of mercury and the volume of solids. When e_{inv} is equal to e_{tot} , the entire porosity of the sample is filled by mercury. Thus, the calculated e_{inv} (Tab. 6) reveals that the majority of the existing pores in the samples were filled with mercury during MIP tests.

Fig. 8 shows the surface of the untreated soil. The mineralogical nature of the bigger grains, generally measuring 10 to 50 μm , was determined by the EDS. These grains were identified to be quartz associated with smaller clay minerals of 1 to 5 μm diameter. No preferential orientations of the clay minerals were detected. MIP results indicated that the pore size of untreated soil presents a uni-modal distribution with a dominant radius of 0.6 μm .

Results obtained by SEM showed a slightly more aggregated structure and a face to edge organisation of clay minerals for the soil treated with 0.01% AS (Fig. 9). Individual clay minerals are less visible but inter-aggregates pores size remained similar after treatment as confirmed by MIP data (Figs 12 and 13). Therefore, the structure of the treated soil was not significantly altered in this case.

After 0.002% ES treatment, the same structure as for the untreated soil is observed from the SEM images (Fig. 10). The MIP study (Fig. 12) showed that less mercury was injected in the ES treated sample. This phenomenon is linked with the higher dry unit weight of the ES treated sample, which reduced its total void ratio (e_{tot}) and thus the total injected volume (V_{inj}). This result is associated to a reduction of the amount of pores comprised between 3 and 10 μm (Fig. 13).

Fig. 11 shows the soil after the addition of 2.0% of lignosulfonate. In the picture, additional structures can be observed. These structures resemble fibres and are probably lignosulfonate associations forming a network between the soil minerals (arrows). Point 1 on Fig. 11 was identified by the EDS to be a clay mineral, but as the fibres were too small to be analysed by the EDS, their exact nature is unknown. The SEM results also showed larger inter-aggregates pores, large clay minerals were organised in face to face structures orientated in the plane of the picture. Compared to untreated samples, MIP results confirmed the increase of the frequency of pores having radii between 0.3 and 5 μm and also showed a reduction of pores with a radius $<0.3 \mu\text{m}$. The increase in larger pores radius might be caused by aggregation of clay mineral and dispersion of the created structure due to adsorption of lignosulfonates molecules. The reduction in intra-aggregates pores may be explained by the clogging of the smallest pores by lignosulfonates.

5b. Comparison of the treatment additives with a common surfactant

Some authors, for example, Velasquez et al. [32] demonstrated that enzymatic solutions could have surfactant properties. As enzymatic solutions, lignosulfonates also have surfactant properties, which could alter the mechanical behaviour of soils [10, 31]. To determine if the tested non-traditional additives have surfactant properties, the surface tension was measured using the Du Noüy ring method [9]. The results were compared with

the surface tensions obtained for aqueous solutions of sodium dodecyl sulfate (SDS) (Fig. 14).

Similar to SDS, low dosages of the enzymatic solution reduced the surface tension of the water. At a concentration of 1.0 g/L the surface tension was reduced by more than 50%. Lignosulfonate also exhibited surfactant properties, but the additive was less efficient in reducing the surface tension of the solution. At higher concentrations, the surface tension of the LS solution stabilised approximately 42 mN/m. Only the acid additive did not exhibit any surfactant properties.

To study the influence of the addition of a surfactant on the compaction behaviour, 0.01% of SDS by dry matter weight was added to the soil (Fig. 15). The required quantity of SDS was first diluted in water, and the same protocol used for liquid non-traditional treatments was followed. The resulting compaction and IPI curves were compared to those obtained after the ES treatment.

With regard to the ES treatment, the SDS addition improved the dry unit weight on the dry side of the compaction curve. The IPI curve for the SDS-treated soil was also slightly shifted towards smaller water contents as was observed after the ES-treatment. Thus, the SDS and ES treatments have a similar effect on the mechanical behaviour of soils. This finding implies that both products may utilise the same stabilisation mechanism. Indeed, the reduction of the surface tension of the soil's interstitial water should lower the matrix suction according to the Jurin law.

The suction of the treated soil was investigated for the three non-traditional treatments. The filter paper methodology was used to measure matrix suction of compacted soil according to ASTM D 5298-94 [3]. After compaction of two 70 mm diameter for 15 mm thickness samples, three filter papers were inserted between each sample. Thereafter, the samples were kept in

sealed container for 7 days to achieve the suction equilibrium. As the calibration curve of the filter paper was known, the measurement of its water content gave the matrix suction of the soil.

The results showed that the acid solution (AS) did not change the suction of the soil. This is consistent with the absence of surfactant features of the additive.

As ES treatment has surfactant properties, a reduction of the suction could be expected. In this work, the addition of the enzymatic solution (ES) did not lead to suction modifications (Tab. 7). This can be explained by the biodegradability of the additive. An equilibrium period of seven days may allow the additive to be totally degraded before suction measurements.

The LS treatment led to an increase in the matrix suction of the soil. As LS is an organic calcium salt, the increase of the suction might be explained by the hygroscopic nature of lignosulfonates.

6. DISCUSSIONS

Herein, the effects, mechanisms and applications of the three studied treatments are discussed.

AS treatment did not change geotechnical properties of the soil but small modifications in the clay minerals organisation were observed in SEM pictures (Fig 9). The observed modifications could be due to changes in the ionic composition of the pore fluid after addition of the product since this parameter is known to induce fabric changes according to the literature [6-8, 15, 16]. No particular application was evidenced for AS treatment of the studied soil.

Treatment with ES demonstrated an increase in the compaction ability of the soil. The increase in maximum dry density induced small modifications of the UCS, stiffness, swelling

potential and permeability of the soil. Moreover, the microstructure of the soil was not modified. Therefore, it can be concluded that the observed hydro-mechanical modifications are mostly related to the effect of treatment on compaction behaviour of the soil. This hypothesis was confirmed by the absence of pH and index properties changes. As shown on the Fig. 15, the compaction behaviour of the ES treated soil is similar to the behaviour observed after a treatment with a surfactant. Results shown on Fig. 3 indicated that treated soil had a smaller bearing capacity than the untreated soil at given water content and dry density. This phenomenon may be explained by the surfactant properties of the ES. Strong modifications of the surface tension for low additive dosages may also explain why the compaction ability of the ES treated soil was improved despite a low dosage (0,002%). As the enzymatic solution is biodegradable, the product has disappeared in a few days. During the degradation stage of the ES product, increase in bearing capacity may be expected and after degradation of the additive, no long term modifications are expected beyond those caused by the initial densification. According to the experimental results, the ES treatment can be used to increase the compaction ability on the dry side of the compaction curve and thus compact the soil at higher densities for lower water contents.

LS treatment reduced the pH and modified the pore-fluid composition, thus, the organisation and interactions between soil particles were changed as shown by mechanical results and SEM pictures. Experimental results showed dosage dependent effects on geotechnical characteristics. The 2% amount of lignosulfonate added to the soil also reduced the stiffness and the index properties. This observation is consistent with dispersive properties of lignosulfonates which tend to increase repulsive interactions between soil constituents [5, 14, 25]. LS treatment also reduced the friction between the grains of the soil, which facilitate its deformation under loading, and thus explain the observed reduction in bearing capacity (Figs. 2 and 4). However, surfactant properties and suction modification after treatment cannot explain alone why the bearing capacity was reduced by an increase in the

lignosulfonate dosage (Fig. 2). This observation is probably due to the formation of an organic film increasing lubrication between the particles after the addition of lignosulfonate [9]. An increase in dosage led to thicker films, reducing the bearing capacity of the LS treated soil by facilitating the deformation under loading. As for ES, addition of the product modified the behaviour of the soil during the compaction. Nevertheless, field and laboratory testing confirmed the ability of lignosulfonate to be leached out of the soil [11, 22, 27]. So, it is to be expected that the soil will recover its initial characteristics after a certain period of time. The uses of LS treatment are similar to those of ES but higher dosages are needed and attention must be paid on bearing capacity which is altered by the treatment.

7. CONCLUSION

This paper presented an experimental multi-scale study of a low-plasticity soil treated with three non-traditional organic products classified as an acid solution, an enzymatic solution and lignosulfonate. Hydro-mechanical investigations including compaction, bearing capacity, UCS, free swelling and hydraulic conductivity tests were conducted. The effect of the treatments on the microstructure of the compacted soil was investigated using SEM and MIP tests. The study also proposed a reflexion on the modification of the interactions between soil particles induced by the treatments. The following conclusions can be drawn based on the obtained results.

- To evaluate the performances of non-traditional products used for soil treatment, it is important to consider the entire compaction and bearing capacity curves and not only the values obtained at the optimal conditions. In fact, the water content of compacted soil has a strong influence on the dry unit weight obtained after treatment.
- The ES and LS treatments reduced the optimal water content and increased the dry density of the compacted soil allowing the use of 3% lower water content and a 25%

reduction in the compaction energy, required to achieve the same density when compared to untreated soil. Therefore, the treatments can improve the environmental impact of earthwork projects and are particularly well suited for dry soil compaction in areas where the access to water resources is limited.

- Before in situ applications, careful laboratory investigations should be conducted to determine if the treatment genuinely improves the soil behaviour; some non-traditional products have little or no impact on the mechanical properties of treated soils. The changes in compaction parameters must be characterised to determine the optimal application conditions in terms of dosage, desired water content and bearing capacity.

- Treatments with organic products have showed immediate modification of the compaction parameters; however, no evolution of the resistance of the soil over time was observed. Thus, treatments essentially act through a physical modification of the soil behaviour. Moreover, as AS and ES were added at low dosages and were biodegradable, intrinsic characteristics of the soil are not changed and the long term behaviour of the soil should not be modified. For LS treatment, leaching of the additive can be expected in case of water transfer in the compacted structure.

- Some non-traditional products act like surfactants. This property appears to be an important parameter of the effectiveness of non-traditional products when they are used as compaction aids.

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1 **Tab. 1** Dosages tested for the three non-traditional additives

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Non-traditional additives	Dosages by dry weight of soil
Acid solution (AS)	0.01%
Enzymatic solution (ES)	0.002%
Calcium lignosulfonate (LS)	0.5 ; 2.0 and 5.0%

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5 **Tab. 2** Properties of the tested soil

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Property	Low plastic clay
Passing 2 mm (%)	100
Passing 80 µm (%)	87
Passing 2 µm (%)	19
Specific gravity	2.67
Liquid limit (%)	34
Plastic limit (%)	20
Plasticity index	14
pH	9.2

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9 **Tab. 3** Index properties and pH of the treated soil

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Treatment	pH (+/- 0.1)	PL (%)	LL (%)	PI
Untreated	9.2	20	34	14
0.01% AS	9.2	19	33	14
0.002% ES	9.3	19	33	14
0.5% LS	8.8	19	32	13
2.0% LS	8.4	17	30	13
5.0% LS	8.1	13	27	14
0.01% SDS	9.1	19	34	15

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14 **Tab. 4** Geotechnical properties of the treated soil

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Treatment	w _{opt} (%)	γ_{dmax} (kN/m ³)	IPI at w _{opt}	UCS (MPa)	
				7 days	28 days
Untreated	15.5	18.2	15	0.44	0.46
0.01% AS	15.0	18.3	19	0.40	0.41
0.002% ES	14.5	18.6	14	0.53	0.54
0.5% LS	15.0	18.4	13	0.36	0.40
2.0% LS	13.5	18.5	14	0.45	0.49
5.0% LS	14.0	18.3	5	0.22	0.24

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19 **Tab. 5** Deformation modulus at 50% of maximal strength

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Treatment	w (%)	γ_d (kN/m ³)	E ₅₀ (MPa)	Standard deviation (MPa)
Untreated	15.0	18.2	13	2
	12.5	18.4	56	7
0.002% ES	14.0	18.5	15	1
	12.5	18.3	50	4
2.0% LS	12.7	18.5	22	2

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24 **Tab. 6** Total void ratio for the compacted samples and calculated mercury investigated
25 maximum void ratio during the MIP tests

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Treatment	e_{tot}	e_{inv}	γ_d (kN/m ³)
Untreated	0.47	0.44	18.3
0.01% AS	0.46	0.44	18.3
0.002% ES	0.43	0.42	18.7
2.0% LS	0.44	0.41	18.6

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29 **Tab. 7** Matrix suction of treated soil

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Treatment	w (%)	γ_d (kN/m ³)	Matrix suction (kPa)
Untreated	14.7	18.0	56
0.01% AS	15.4	18.0	54
0.002% ES	14.7	18.2	58
2.0% LS	15.2	18.2	225

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Fig. 1 Compaction and IPI curves for the untreated, 0.01% AS and 0.002% ES treated soil

Fig. 2 Compaction and IPI curves for the LS treatment at 0.5, 2.0 and 5.0%

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13 **Fig. 3** Compaction and IPI curves of the ES treatment at 75 and 100% of the standard
 14 Proctor energy

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Fig. 4 Compaction and IPI curves of the 2.0% LS treatment at 75% and 100% of the standard Proctor energy

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24 **Fig. 5** Unconfined compressive strength at 7 and 28 days for the studied non-traditional
 25 treatments compacted at their respective optimum Proctor

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Fig. 6 One-dimensional free swelling potential for the ES and LS treatments at different initial compaction states

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34 **Fig. 7** Hydraulic conductivity coefficient for the ES and LS treatments in different initial
35 compaction states

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40 **Fig. 8** SEM image of the untreated soil

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45 **Fig. 9** SEM image of the 0.01% AS treated soil

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49 **Fig. 10** SEM image of the 0.002% ES treated soil

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55 **Fig. 11** SEM image of the 2% LS treated soil

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60 **Fig.12** Injection curves for the untreated, 0.01% AS, 0.002% ES and 2.0% LS treated soil

Fig. 13 Pore size distribution for the untreated, 0.01% AS, 0.002% ES and 2.0% LS treated soil

Fig. 14 Surface tension of the three non-traditional additives and SDS in aqueous solution

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74 **Fig. 15** Compaction and IPI curves for 0.01% SDS and 0.002% ES treated soil

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