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# Effect of laboratory compaction mode, density and suction on the tensile strength of a lime-treated silty soil

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A R T I C L E I N F O

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A B S T R A C T

Facing the need to adopt a laboratory compaction method of natural or lime-treated soils which is repeatable and representative of real in-situ compaction conditions for dike or road constructions, the effects of compaction mode, dry density and suction on the tensile strength of natural and lime-treated silty soil compacted in laboratory have been investigated in a systematic way. Soil specimens were prepared from three different modes of compaction: the static kneading compaction, the standard Proctor compaction and a dynamic in-mold compaction. For kneading and Proctor compaction, small cylindrical samples were extracted at different locations in larger compacted specimen with a milling machine controlled by computer. On the contrary, the so-called "in-mold compaction" consists in compacting the soil in a mold with the final required dimensions. The small cylindrical samples were then submitted to various suctions from 0 to 2000 kPa during seven days. At the end, dry density of samples was measured with a 3-dimensionnal scanner and tensile strength was determined from indirect (Brazilian) tensile tests. The same investigation was also performed, with similar number of specimens, on untreated soil. In-mold compaction provides the best repeatability of obtained tensile strength (essentially because of the controlled and uniformly distributed dry density though the specimen) but is not representative of real compaction condition. Also, it is observed that the tensile strength of untreated soils is strongly affected by suction level and slightly by dry density. At the opposite, for lime-treated soil, little variations of dry density may have a significant impact on the tensile strength while suction plays a secondary role. This study reveals that, when compacted lime-treated soils are used as a bearing element (like in road subgrades or subbases), a particular attention must be paid on the quality of compaction process to avoid under-compacted zones that could lead to material weakness.

## Introduction

Infrastructure geotechnics for transportation (road, railway, pavements, …) or hydraulics works (dikes, dams, impervious barriers, …) requires the use and the implementation of earth materials with suitable mechanical properties, in terms of strength and stiffness. In that framework, dynamic compaction and lime-treatment are amongst the best practices to reach adequate mechanical performance of the ground [9].

Various techniques are used in laboratory to reproduce compacted soil samples in order to obtain geotechnical properties as the ones observe in field. Whether standard or modified, the Proctor compaction is the mostly used laboratory dynamic compaction method [1,2,30]. However, to obtain specimen of required sizes, the sample must then be reshaped from a larger sample (corresponding to the dimension of CBR – Californian Bearing Ratio – or Proctor mold). An alternative is to compact dynamically a wet mass of soil in a mold with the required dimensions [13]. This method ensures a fine control of the dry bulk density $\gamma_d$ because a given mass of soil is compacted in a target volume, oppositely to Proctor compaction for which the soil is compacted at a controlled energy, but not at imposed volume or mass. For in-mold compaction, possible sizes of the samples are limitless since only depending on the size of the mold. These two laboratory methods of compaction present however a significant problem because they are not representative of the in-situ conditions of compaction [5,35]. In order to answer to this particular issue, Kouassi et al. [20] developed a static compaction process reproducing, in laboratory conditions, the effect of a real sheepsfoot roller. This method is called the kneading compaction

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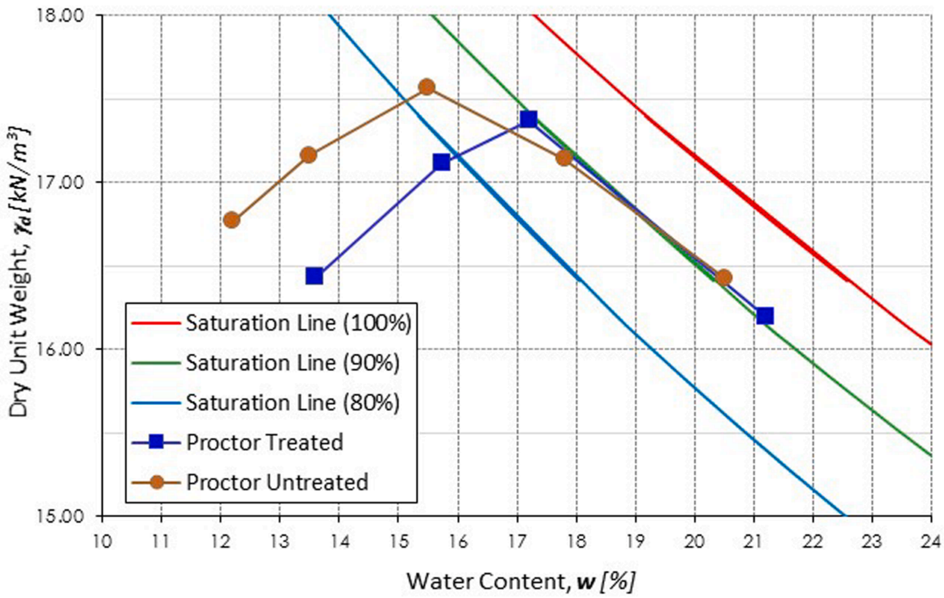



**Fig. 1.** Proctor curves (standard compaction energy) for both untreated and lime-treated (with 2% of lime) soils and saturation lines.

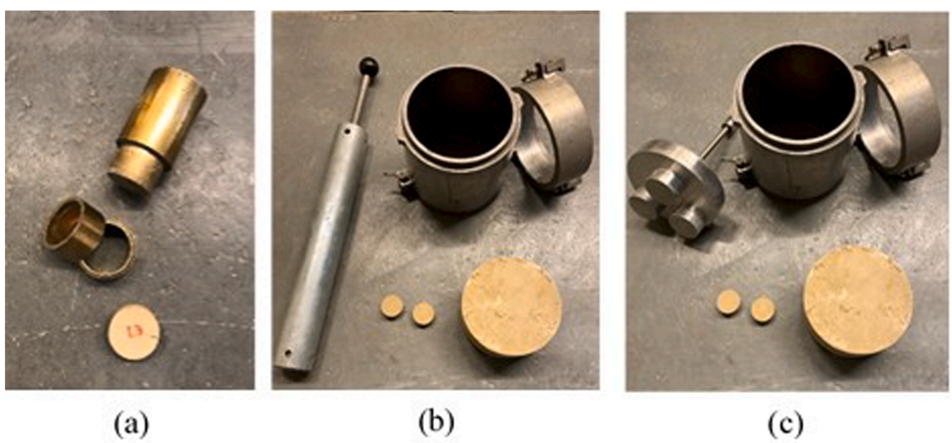



**Fig. 2.** The different methods of compaction used: (a) in-mold compaction, (b) Proctor compaction and (c) kneading compaction.

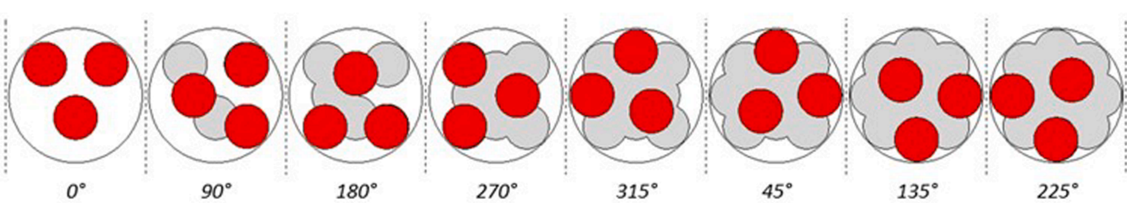



**Fig. 3.** Eight steps compaction sequence of each layer for the kneading compaction process.

according to its kneading effect of the soil. Recently, Das et al. [10] demonstrates the important benefits provided by the kneading compaction on the strength of lime-treated fine-grained soils. Kneading action during compaction undergoes better lime-dispersion which favours the long-term pozzolanic-reactions. Through Scanning Electron Microscope investigation on the microstructure of untreated and lime-treated silty soil, compacted through a standard Proctor method and a kneading compaction method, Deneele [12] clearly highlighted a significant reduction of the amount of macropores induced by the kneading compaction that can be beneficial for the strength of the material. This reduction of macropores is still enhanced when the soil is compacted on the wet side of optimum (i.e. for water content higher than optimum water content).

In the following, the three investigated modes of compaction will be named: “in-mold compaction” for the dynamic compaction in mold with final required dimensions, “Proctor compaction” for the conventional dynamic laboratory compaction Proctor method using standard effort size and “kneading compaction” for the static compaction with sheeps-foot roller effect.

In the other hand, in combination with dynamic compaction, lime-treatment is an efficient way to significantly improve the engineering properties of fine-grained compacted soils [4,26,32] with applications in road subgrades [7,24,31] or hydraulic works [18,17,23]. Concerning the stabilization of the soil, lime reacts mostly with the clay fraction

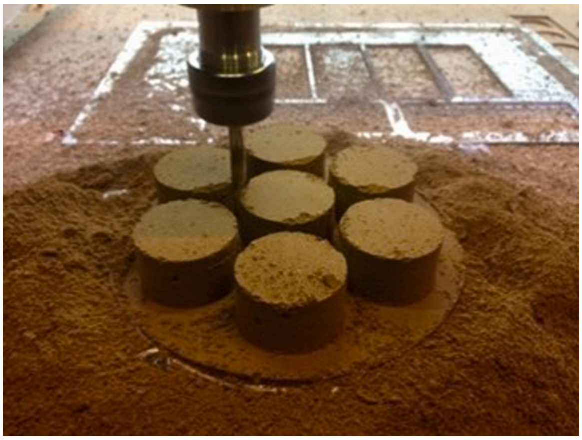
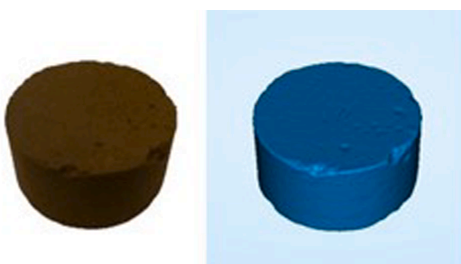


**Fig. 4.** Tensile strength sample shaping from CBR sample with a milling machine controlled by computer. The final dimensions of the specimens are D = 36 mm and H = 18 mm.



(a) (b)

**Fig. 5.** Real sample (a) and its 3D digital model obtained from the 3D scan (b).

[16]. The reaction influences the soil behaviour on two time-scales: a first quick reaction with the clay mineral fraction of the soil leading to the flocculation of the soil structure and then, the soil stabilisation effect corresponding to long-term pozzolanic reactions [19,22]. Consequently, the lime-treatment enhances the mechanical properties of soil, including its tensile strength.

Treated or not, compacted soils used in civil engineering infrastructures are often submitted to the atmospheric conditions, including drying process. Simulated by the application of various suction level in laboratory, this process can lead to desiccation cracking, a major problematic on road embankments or on earthen hydraulic structures (dikes, levees or earth dams). For instance, Wang et al. [34] noticed that, despite shrinkage cracking is one of the primary distresses found in cementitious stabilized layers (CSL) of pavements, the current methodology for analysis and performance prediction of CSL pavements does not account for the prediction of shrinkage cracking. The first step

**Table 1**
Van Genuchten parameters for both untreated and treated soils after 7 days of curing.

| | $P_r$ *[Pa]* | *n [-]* |
|---|---|---|
| Untreated soils | 120 000 | 1.18 |
| Lime treated soils | 75 000 | 1.25 |

**Table 2**
Number of samples studied in the 30 different configurations (UT: Untreated; T: Lime-treated).

| | | Compaction mode | | | | | |
|---|---|---|---|---|---|---|---|
| | | Mold | | Proctor | | Kneading | |
| Treatment | | UT | T | UT | T | UT | T |
| Applied suction [kPa] | 120 | 25 | 12 | 6 | 4 | 24 | 28 |
| | 500 | 3 | 3 | 6 | 4 | 12 | 6 |
| | 1000 | 3 | 3 | 6 | 4 | 9 | 6 |
| | 1500 | 3 | 3 | 5 | 5 | 4 | 6 |
| | 2000 | 3 | 3 | 5 | 5 | 3 | 5 |
| Total | | 37 | 24 | 28 | 22 | 52 | 51 |
| | | 61 | | 50 | | 103 | |
| | | 214 | | | | | |

**Table 3**
Initial (before suction application) dry bulk density and standard deviation of treated and untreated samples, according to the mode of compaction.

| Dry bulk density $\rho_{d\text{-}i}$ *[g/cm$^3$]* | Untreated | | | Treated | | |
|---|---|---|---|---|---|---|
| | Mold | Proctor | Kneading | Mold | Proctor | Kneading |
| Target | 1.71 | 1.74 | 1.71 | 1.64 | 1.68 | 1.64 |
| Min | 1.73 | 1.77 | 1.76 | 1.63 | 1.67 | 1.59 |
| Max | 1.75 | 1.91 | 1.94 | 1.67 | 1.79 | 1.73 |
| Average | 1.74 | 1.85 | 1.81 | 1.66 | 1.72 | 1.66 |
| Standard deviation σ | 0.006 | 0.034 | 0.052 | 0.010 | 0.023 | 0.031 |

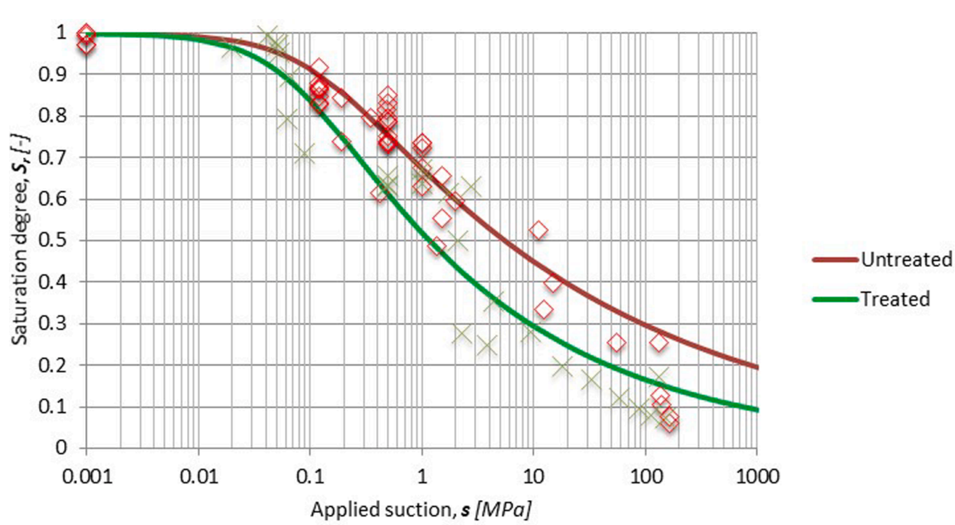



**Fig. 6.** Water retention curve (WRC) of both treated and untreated soils.

**Table 4**
Final (after suction application) dry bulk density and standard deviation of treated and untreated samples.

| | Dry bulk density $\rho_{d\text{-}f}$ [g/cm$^3$] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Untreated | | | | | Treated | | | | |
| suction | 120 | 500 | 1000 | 1500 | 2000 | 120 | 500 | 1000 | 1500 | 2000 |
| | **Mold** | | | | | | | | | |
| Min | 1,74 | 1,76 | 1,78 | 1,78 | 1,79 | 1,66 | 1,67 | 1,68 | 1,69 | 1,69 |
| Max | 1,76 | 1,77 | 1,79 | 1,80 | 1,81 | 1,67 | 1,68 | 1,68 | 1,70 | 1,70 |
| Average | 1,75 | 1,77 | 1,79 | 1,80 | 1,80 | 1,66 | 1,68 | 1,68 | 1,70 | 1,70 |
| Standard deviation σ | 0,009 | 0,005 | 0,004 | 0,010 | 0,008 | 0,005 | 0,003 | 0,000 | 0,003 | 0,008 |
| | **Proctor** | | | | | | | | | |
| Min | 1,81 | 1,80 | 1,81 | 1,89 | 1,88 | 1,71 | 1,73 | 1,71 | 1,73 | 1,72 |
| Max | 1,91 | 1,93 | 1,98 | 1,99 | 1,97 | 1,76 | 1,76 | 1,77 | 1,79 | 1,79 |
| Average | 1,87 | 1,88 | 1,91 | 1,94 | 1,93 | 1,73 | 1,74 | 1,74 | 1,75 | 1,75 |
| Standard deviation σ | 0,035 | 0,045 | 0,056 | 0,034 | 0,037 | 0,022 | 0,015 | 0,026 | 0,021 | 0,028 |
| | **Kneading** | | | | | | | | | |
| Min | 1,73 | 1,71 | 1,78 | 1,85 | 1,85 | 1,61 | 1,63 | 1,63 | 1,59 | 1,63 |
| Max | 1,86 | 1,94 | 1,94 | 1,91 | 1,91 | 1,71 | 1,70 | 1,69 | 1,70 | 1,70 |
| Average | 1,80 | 1,85 | 1,86 | 1,88 | 1,88 | 1,66 | 1,66 | 1,66 | 1,64 | 1,67 |
| Standard deviation σ | 0,039 | 0,077 | 0,051 | 0,027 | 0,031 | 0,027 | 0,028 | 0,024 | 0,039 | 0,032 |

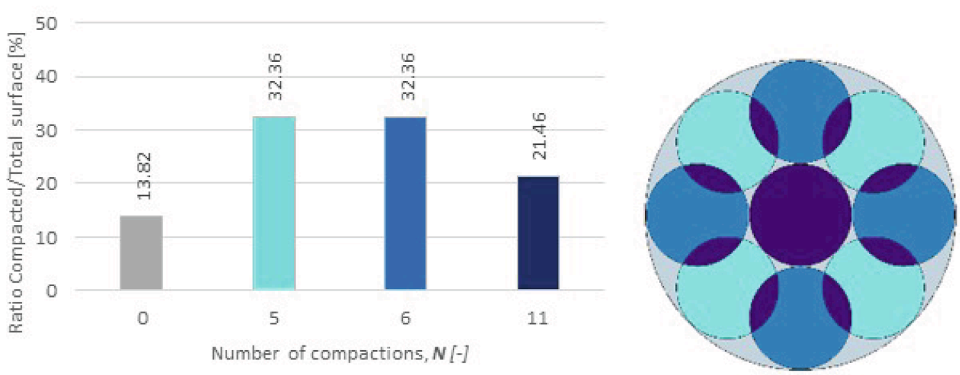



**Fig. 7.** Analysis of the Proctor compaction process on one layer. Number of passes per layer as a function of the location.

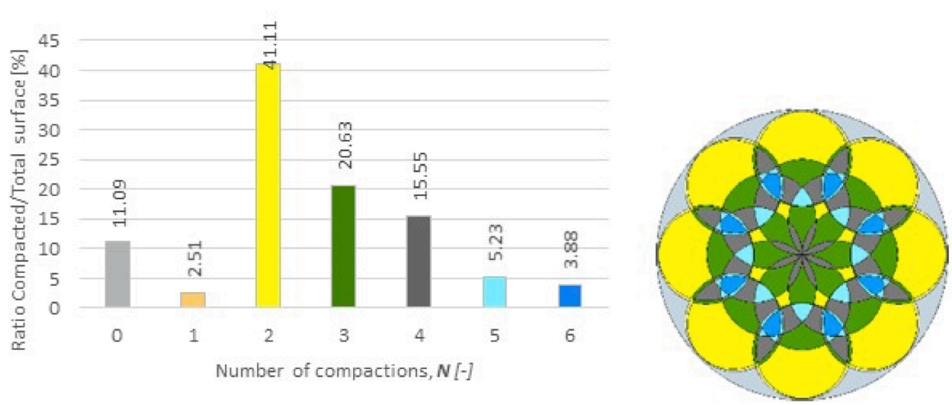



**Fig. 8.** Analysis of the kneading compaction process on one layer. Number of passes per layer as a function of the location.

to determine the propensity of desiccation crack occurrence is to characterize the tensile strength of soils at different suctions and for various dry densities. A weak tensile strength may facilitate the initiation of desiccation cracking and lead to accelerated degradation of the earth structure. In that sense, Poncelet et al. [29] concluded that lime treatment of a silty clay soil (with 2% of lime) postpones (in terms of suction levels) the triggering of desiccation cracks due to a combination of a change of water retention properties and of tensile strength induced by the lime treatment.

In order to understand the reason of high variability of measured tensile strength of lime-treated silty soil compacted in laboratory, the effects of compaction mode, dry density and suction on its tensile strength are investigated in a systematic way. Static kneading compaction, dynamic Proctor compaction and dynamic in-mold compaction are first studied on “as compacted” naturel (untreated) or treated samples. Here, “as compacted” means “at the water content of compaction”

**Fig. 9.** Texture of samples coming from in-mold compaction (left) or Proctor and kneading compaction (right).

**Table 5**
Additional samples of the in-mold compaction mode tested at as-compacted suction (120 kPa). The exact distribution of obtained dry density is visible Figs. 10 and 11 (“in-mold” points).

| | | Untreated | Treated |
|---|---|---|---|
| Additional samples | | 22 | 9 |
| Dry bulk density $\rho_{d\text{-}f}$ [g/cm$^3$] | min | 1,48 | 1,43 |
| | max | 1,76 | 1,67 |

without any control of suction. The first goal is to evaluate the effect of the compaction mode and treatment on the tensile strength of soil. To obtain the required samples with precise dimensions from the samples obtained after the Proctor and kneading compaction processes in CBR mold, a particular sampling method using a milling machine controlled by computer have been developed and used.

In addition, the effect of soil suction, from 120 kPa (as compacted) to 2000 kPa, has been investigated, by a fine control of suction through the osmotic technique. After suction equilibrium, taking less than 7 days to reach a constant mass of the sample, the tensile strength was evaluated by indirect tensile tests. Those tests, performed on relatively small samples (Height = 1.8 cm and Diameter = 3.6 cm), enables to tackle local heterogeneities of soil density inside the CBR specimen.

## Materials and experimental methods

### *Soil properties*

The soil used for this study is a silty clay soil (CL, according to the Unified Soil Classification System - USCS) that has been used for the construction of a prototype dike in the South of France [27]. Its liquid limit ($w_L$) and plasticity index ($I_P$) are respectively equal to 33.6 % and 14.8%. The clayey fraction (<2 μm) represents 22 % while the silty one (between 2 μm and 60 μm) is about 60 % and the sandy one (>60 μm) is about 18 %. This material has shown its relevance to be treated with lime, essentially due to its relatively large clay fraction. According to the lime fixation point, as determined through the method described by ASTM D6276, also called the Eades and Grim technique [14], the soil has been treated with 2% of lime.

As presented on Fig. 1, optimum normal Proctor conditions have been determined at $w_{opt} = 15.5$ % and $\gamma_{d,opt} = 17.6$ kN/m$^3$ for untreated soil and $w_{opt} = 17.2$ % and $\gamma_{d,opt} = 17.4$ kN/m$^3$ for soil treated with 2% of lime. The method for the sample preparation, including lime mixing with soil is detailed in Section ‘Sample preparation’.

### *Sample preparation*

The soil being prepares in order to satisfy the required properties (especially a low water permeability) to be used for the construction of a prototype dike, it was decided to compact the untreated soil at water content close to optimum water content (i.e. 15.5%) while the treated soil was compacted with a water content 2% higher than optimum water content (17.2% + 2% = 19.2%), because it is generally accepted that the compaction on wet-side of optimum significantly reduces the water permeability under saturated conditions [21,25]. For the soil preparation, the dry soil is mixed with the required quantity of water to reach an initial water content of 16% for untreated soil and 21.5% for treated soil (knowing that the lime reaction consumes around 2% of water content). After wetting the soil at targeted water content, wet soil is sealed in plastic buckets during at least 24 h to achieve a homogeneous water content in all the soil mass.

For the treated soil, the quantity of lime is then added (under wet conditions) to the natural soil in a food cutter to maximize the efficiency of the mixing. Then, after addition of 2% of lime, the treated soil loses approximately 1.7% of water content to reach the targeted initial water content of 19.8%, corresponding to the wet side of optimum (wOPN + 2%). Treated soil is then sealed in a bucket during one hour before compaction.

The three different compaction methods are then used. The first is one of the most common method used in laboratory investigation. It consists to compact dynamically a wet mass of soil in a mold having precise dimensions, corresponding to the final dimension of the tested specimen (Fig. 2.a). The second compaction method is based on the standard Proctor test, performed in the CBR mold (diameter 152 mm; height 127 mm) (Fig. 2.b). The last compaction mode is the kneading compaction, also performed in the CBR mold, as developed by Kouassi et al. (2000) in order to simulate the in-situ compaction condition. Unlike the two first ones, this method is a static compaction process using a three kneading feet tool (Fig. 2.c).

ASTM standard D698-00a (2000), corresponding to the standard effort, is used to obtain the CBR sample with the Proctor mode, compacting the soil in three layers. During the compaction, the volume of soil is split in five equal masses to proceed to the compaction by five different layers. On each layer, a standardized hammer 2.49 kg is dropped 55 times from a height of 305 mm to obtain a total volumetric energy of 0.531 MJ/m$^3$. For the kneading compaction, the total soil volume needed to achieve the CBR sample is divided in five layers. Each of them is compacted with an eight steps compaction sequence detailed on Fig. 3.

The target values of the dry bulk density $\rho_d$ are respectively 1,71 g/cm$^3$ and 1,64 g/cm$^3$ for untreated and lime-treated soil. This target density is obtained or approached differently depending on the method of compaction. For the first method (in-mold compaction), the corresponding mass of wet soil is inserted in the mold and then compacted. For the second mode of compaction (the normal Proctor compaction), the target density is approached by the optimum normal Proctor for untreated and treated soil respectively. It is to note that the optimum proctor dry densities (respectively 1,74 g/cm$^3$ and 1,68 g/cm$^3$ for untreated and lime-treated) soil slightly differ from the dry density targeted for in-mold and kneading compactions (respectively 1,71 g/cm$^3$ and 1,64 g/cm$^3$ for untreated and lime-treated soil). For the last method, the stress applied on the layers during each compaction step has been adjusted to reach the target density and is equal to 0.45 MPa for the untreated and 0.65 MPa for the treated soil.

The in-mold compaction gives directly the size of the samples needed for the indirect tensile test while for the two other methods, the soil is first compacted in CBR molds, and reshaped in a second step. In order to avoid soil damaging during sample re-shaping and to obtain precise sample dimensions, specimen have been milled with a milling machine controlled by computer (Fig. 4). The small specimens were extracted at various locations across the cross-section and the height of the big specimen in order to catch the heterogeneous distribution of the dry density inherent to the kneading compaction process. The final specimens have a diameter of 36 mm and a height of 18 mm.

Each sample is then measured with a *Einscan-S* 3D scanner to deduce its volume and is weighted in order to determine its bulk density. The water content is measured at the end of the test by a wet weighing and a dry weighing after 24 h in an oven at 105 °C, such that the dry density can be deduced.


**Fig. 10.** Degree of saturation as a function of suction for all the tested specimens, for the different modes of compaction, for untreated (left) and lime-treated (right) soils. The results are split into different ranges of dry bulk density in order to analyse the effect of dry bulk density on the water retention curve.

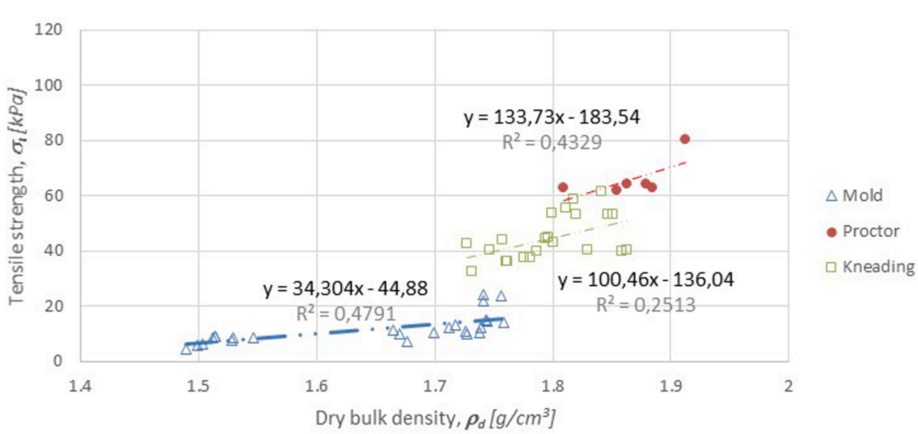



**Fig. 11.** Tensile strength results of untreated as-compacted samples in function of the compaction mode and the dry bulk density. The trend line is discussed in Section 'Result analysis'.

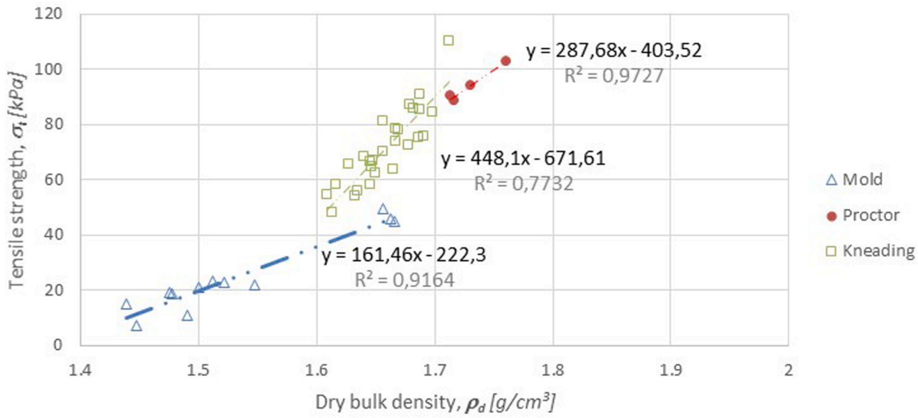



**Fig. 12.** Tensile strength results of treated as-compacted samples, after 7 days of curing, in function of the compaction mode and the dry bulk density. The trend line is discussed in Section 'Result analysis'.

The 3D scanner is also particularly useful to determine the size variation during all the steps of the study. A 3D digital model of each sample is indeed created (Fig. 5) at the different steps.

### *Water retention properties*

Water retention curves (i.e. degree of saturation versus suction) of untreated and treated compacted soils were determined on centimeter-scale fragments of soil compacted with the kneading compaction techniques. To do so, two different techniques to control the suction were used. To ensure a fine control for suctions lower than 1 MPa, the osmotic technique was used [11]. For greater suction, samples are dried under free air conditions during various elapses of time (from a couple of minutes to several hours) and then placed during 24 h in a hermetically sealed container to obtain a global homogenization of water distribution in the sample. They are then inserted in a dewpoint potentiometer to measure their total suction. The corresponding degree of saturation is then obtained by volume and mass measurements of the soil fragments with a 3D scanner.

The water retention curves of both treated and untreated materials are reported in Fig. 6. They have been determined on small fragments of soils, compacted through the kneading compaction techniques. The relative scattering of experimental points could be explained by the variability of the dry density of soil fragments, extracted from soil specimen obtained through kneading compaction (as reported in Table 3). Later in this study (see Section 'Water retention curve'), the effect of dry density on the water retention curve will be addressed. The experimental points are fitted with the Van Genuchten model using equation (1) [33]:

$$S_r = \left[1 + \left(\frac{s}{P_r}\right)^n\right]^{\left(1-\frac{1}{n}\right)} \tag{1}$$

where $S_r$ is the degree of saturation and s the suction. The parameters n and $P_r$ are given in Table 1 for both untreated and lime-treated soils.

It is to note that the initial suction measured after compaction, through the filter paper technique [3,8], were randomly distributed in a range from 80 kPa to 200 kPa, without any clear distinction as a function of the compaction methods (the three methods were investigated) and the lime-treatment. As a consequence, in the following, the average value of 120 kPa will be considered as the as-compacted suction.

### *Drying process*

Samples are then dried at various suction levels going from 120 kPa (as-compacted suction), 500 kPa, 1000 kPa, 1500 kPa and 2000 kPa. The osmotic technique is used to insure a fine control of the applied suction. During this process, samples are sealed in an osmotic membrane and submerged in polyethylene glycol (PEG) solutions at various concentrations in order to obtain the desired suction [11]. To keep on homogeneous PEG concentration, solution is mixed continuously with a magnetic agitator at slow RPM. The mass of the sample is measured at regular time interval until reaching an equilibrium. This constant mass is obtained after 3 to 6 days depending on the applied suction level.

### *Experimental program*

In order to evaluate the effect of the compaction mode, the applied suction, the dry density and the lime-treatment on the tensile strength of the samples, 30 different configurations for a total of 214 samples have been investigated as detailed in Table 2.

After the mass equilibrium of the samples subjected to drying for untreated samples, or at a curing time of 7 days for lime-treated samples, the samples are submitted to indirect tensile test following the French standard NFP98-232-3 [28] for roads design. This test being performed on a relatively small specimen (diameter = 3.6 cm; height = 1.8 cm), it allows to investigate the local mechanical properties inside a larger sample (compacted in CBR model), by opposition to uniaxial compression test or Californian bearing ratio which involves larger soil volume.

The tensile strength $\sigma_t$ is obtained using Equation (2), where P is the maximum loading force, D and t are respectively the diameter and the thickness of the sample.

$$\sigma_t = \frac{2P}{\pi D t} \tag{2}$$

## Results

### *Initial dry bulk density*

Initial (before suction application) and final (after suction application) dry bulk density $\rho_{d\text{-}i}$ and $\rho_{d\text{-}f}$ of the samples compacted at the target value respectively with the in-mold, Proctor and kneading compaction modes is given in Tables 3 and 4. In these tables, the minimum, maximum and averages values obtained on all the set of samples are given. The standard deviation σ is also given in order to evaluate the variability of the parameter.

In Tables 3 and 4, we observe a clear influence of the compaction mode on the dry bulk density. The in-mold compacted samples present a small variability of the dry density which is equal or very close to the target value. The variability increases when samples are compacted with the Proctor method and the situation is even worse with the kneading compaction. For these two compaction modes, the global dry bulk

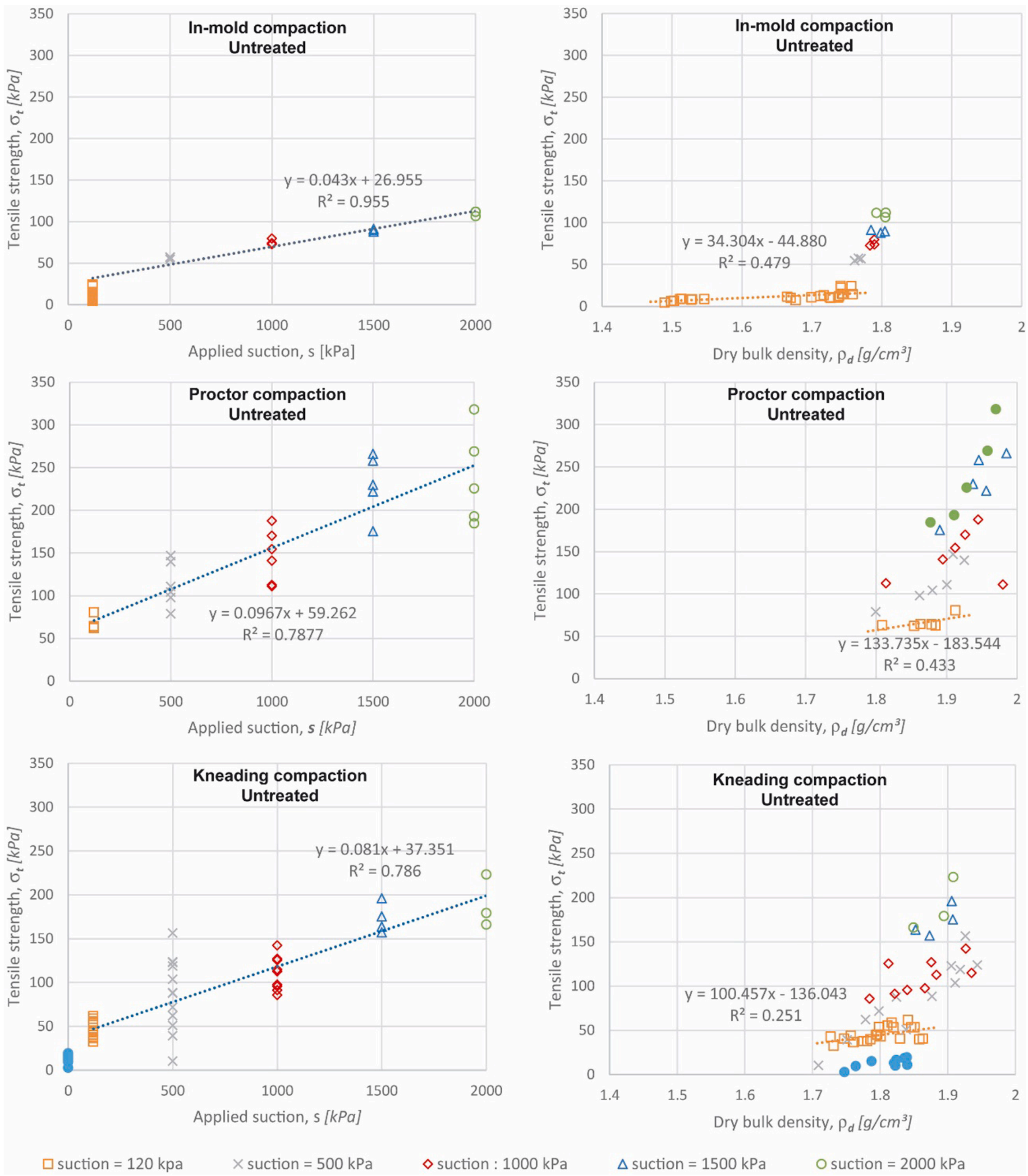



**Fig. 13.** Tensile strength of the untreated samples in function of the compaction mode, the applied suction and the dry bulk density.

density of the initial CBR sample is however equal to the target value. Even if the global dry density at the scale of the CBR mold is repeatable, the bulk density inside the CBR sample varies significantly depending on the position of the extracted small sample.

This density heterogeneity can be explained by the sequence of compaction. Figs. 7 and 8 propose an analysis of the compaction mode respectively for the Proctor and the kneading compaction. The number of compaction passes is plotted as a function of the position on the cross section of the CBR samples. For the Proctor compaction mode, 55 blows are given on the sample on each layer. 13.85% of the total surface is not directly compacted (on the side of the sample), 32.36% are compacted 5 times and 6 times while only 21.46% are compacted 11 times. For the kneading compaction, each layer is compacted in an eight-step procedure. For each layer, soil is compacted between 0 and 6 times depending on the location. This strong variability in the number of compactions per zone explains the heterogeneity in the dry bulk density of the samples extracted from the CBR sample.

Also, in addition to the position of the extracted small sample in the horizontal plane, the vertical position has also an effect, the bottom layer being more intensively compacted than the top layer. Consequently, there is a density gradient through the height of the CBR specimen.

The standard deviation of the obtained dry bulk density is higher for kneading compaction because the number of compactions per zone is also more variable.

Despite this variability in the obtained dry bulk density, kneading and Proctor compactions bring an advantage in terms of the homogeneity of the obtained soil structure caused by their kneading effect. As shown on Fig. 9, samples coming from the in-mold compaction mode present a heterogeneous texture including particle clustering (aggregates) surrounded by big voids while the samples extracted from the CBR mold (compacted with the Proctor and kneading modes) present a

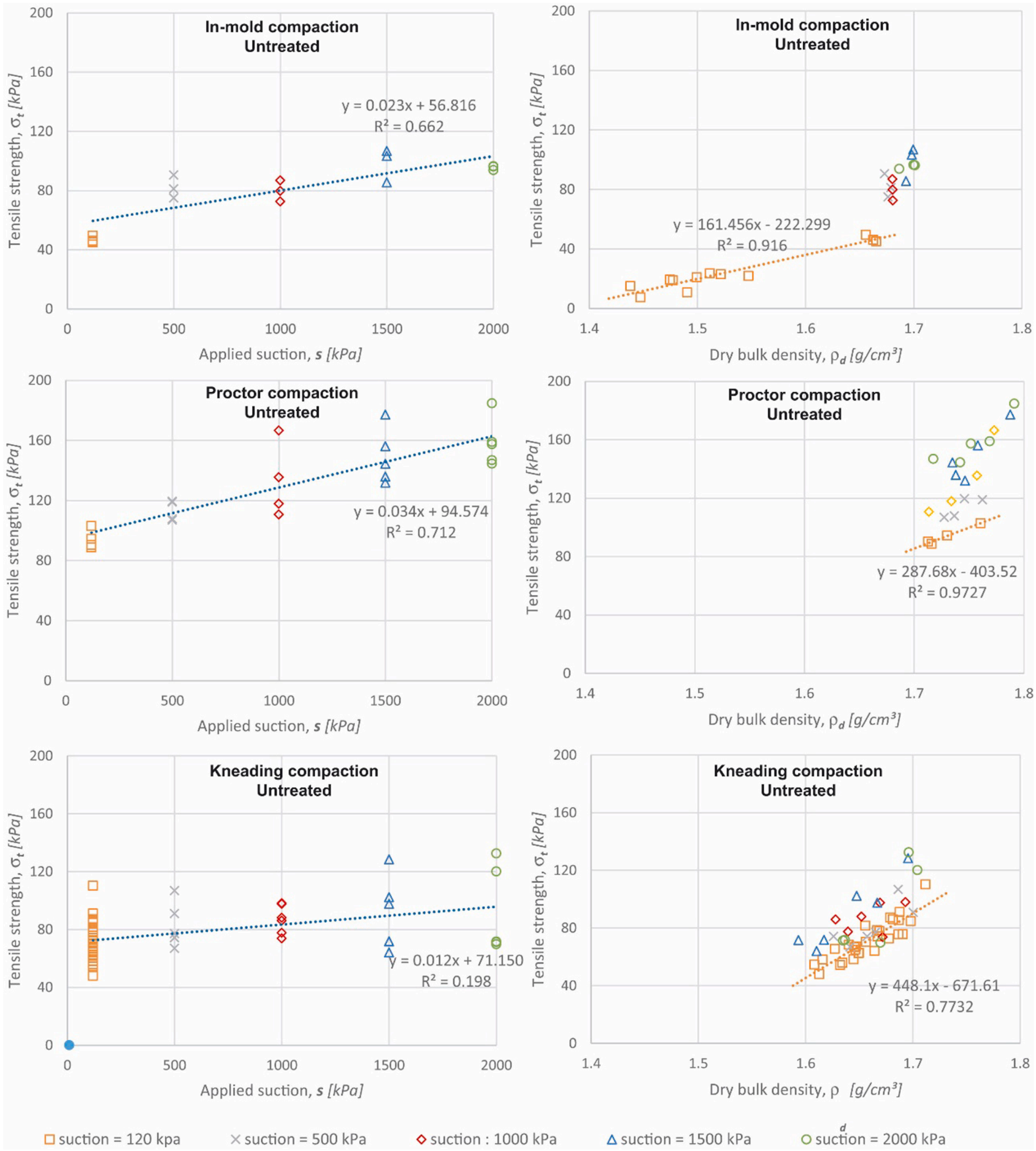



**Fig. 14.** Tensile strength of the treated samples in function of the compaction mode, the applied suction and the dry bulk density.

more uniform (homogeneous) texture. For in-mold compacted samples, big voids around the aggregates are preferential path for cracks to propagate which may induce early failure. This is particularly the case for untreated specimen for which the aggregates are not bounded together.

Because of this dry density variability, and in addition to the mode of compaction, the lime treatment and the applied suction, the dry bulk density of the samples is considered as a parameter to investigate in the study of the tensile strength of the samples. A larger range of dry density value is therefore also investigated for the in-mold compacted samples under as-compacted suction. The total number of additional samples and their minimum and maximum dry bulk density $\rho_{d\text{-}f}$ are detailed in Table 5.

It is here important to note that this large range of dry density obtained from the in-mold compaction is imposed artificially and does not follow from an intrinsic variability of dry density due to the compaction technique.

*Water retention curve*

Due to the application of the different suction levels, the specimens experience volumetric variations. The volume of the specimens is measured, with the 3D scanner, after suction equilibrium. The water content, the density of solid particles and the dry bulk density (deduced from volume and mass measurements) allows to determine the degree of saturation of each specimen. Fig. 10 reports the obtained degree of saturation with respect to applied suction, for the 6 different sample conditions (i.e. the three modes of compaction, for untreated and lime-treated soils). The results are split into different ranges of dry bulk density in order to analyse the effect of dry bulk density on the water retention curve.

The following features can be observed from Fig. 10:

- The lime-treated specimens show globally a lower retention capacity than the untreated soils. At a same suction, the degree of saturation

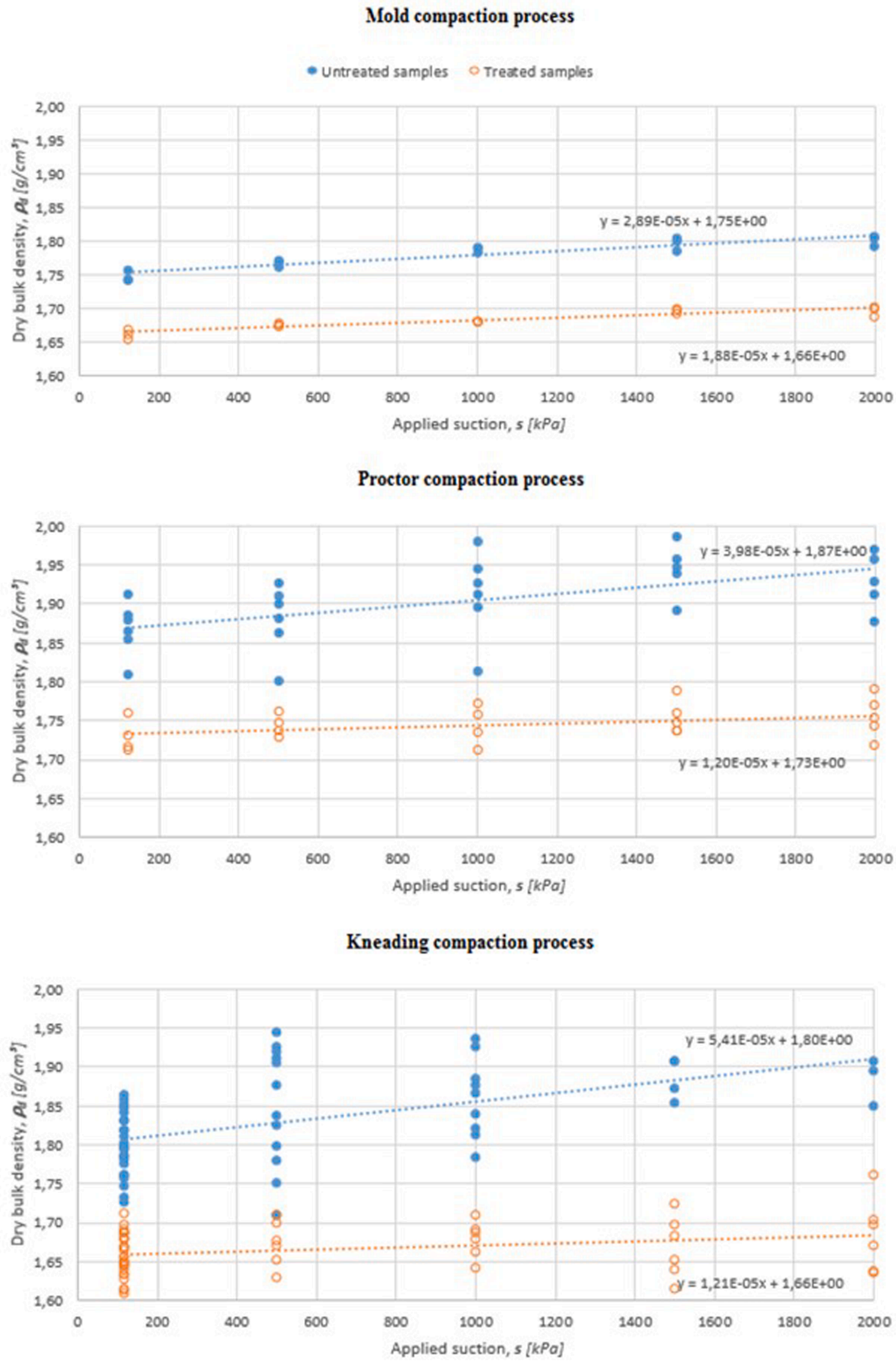



**Fig. 15.** Final dry bulk density $\rho_{d\text{-}f}$ in function of the applied suction s, treatment and compaction mode.

of lime-treated soils is lower than the one of treated soil. This is consistent with the water retention curve shown in Fig. 6 where the curve of lime-treated soil is below the curve of untreated soil.

- An increase of the dry bulk density induces an increase of the degree of saturation for a same suction. This is in agreement with the well-known effect of the density on the water retention capacity of soils [15].
- When comparing the different modes of compaction, in-mold compaction induces the lowest water retention capacity. It may be explained by the presence of macro-voids induced by the in-mold compaction process (as illustrated in Fig. 9). Those macro-voids have low water retention capacity, leading to the drainage of water from those macro-voids at relatively low suction [6]. The comparison of the water retention curves between Proctor compaction and kneading compaction is not really possible because they do not refer to the same ranges of dry bulk density. Water retention capacity appears relatively similar between those two modes of compaction but specimens prepared from Proctor compaction have an high bulk density. So, at equal dry bulk densities, we can suppose that the water retention capacity of specimen obtained from kneading compaction would have a higher water retention capacity.

**Table 6**
Values of α, β, γ and δ in function of the compaction mode and treatment.

| | Mold | | Proctor | | Kneading | |
|---|---|---|---|---|---|---|
| | UT | T | UT | T | UT | T |
| α *[kPa/kPa]* *($\Delta\sigma_t$ / $\Delta s$)* | 0,043 | 0,023 | 0,097 | 0,034 | 0,081 | 0,012 |
| β *[g/ ($cm^3$kPa)]* *($\Delta\rho_d/\Delta s$)* | $2,9\ 10^{-5}$ | $1,9\ 10^{-5}$ | $4,0\ 10^{-5}$ | $1,2\ 10^{-5}$ | $5,4\ 10^{-5}$ | $1,2\ 10^{-5}$ |
| γ *[($cm^3$kPa)/ g]* *($\Delta\sigma_t/\Delta\rho_d$)* | 34,3 | 161,5 | 133,7 | 381,2 | 100,5 | 381,2 |
| δ *[kPa/kPa]* *($\Delta\sigma_t$ / $\Delta s$)* | 0,042 | 0,020 | 0,092 | 0,031 | 0,076 | 0,008 |

This can be due to the kneading effect that reduces the amount of macropores.

As a conclusion, Fig. 10 demonstrates that the water retention curve (i.e. degree of saturation with respect to suction) is affected by the soil treatment, the global dry bulk density of the specimen and the mode of compaction (that modifies the soil textures), kneading compaction leading to the reduction of the amount of macro-voids and so, to an higher water retention capacity.

### *Tensile strength*

Figs. 11 and 12 present respectively the tensile strength of untreated and treated samples as a function of their dry bulk density $\rho_{d\text{-}f}$ only for the as-compacted conditions (suction = 120 kPa).

Figs. 11 and 12 show, first, that the increase of the dry bulk density induces an increase of the tensile strength in any cases. The magnitude of the increase is however greater for the treated samples than for the untreated ones. Secondly, in-mold compaction seems to produce samples having lower tensile strength than samples compacted with Proctor and kneading methods. Because Proctor and kneading compaction methods lead to samples developing similar trends of tensile strength with respect to dry density, they have been merged in a single trend line.

In addition to those results, the effects of the applied suction *s* on the tensile strength are now detailed on the Figs. 13 and 14 respectively for the untreated and treated samples. The same scale for the tensile strength (Y-axis) has been used in each figure to allow a better comparison of the influence of the studied parameters. The results are expressed in function of the applied suction *s* and the dry bulk density $\gamma_d$ for each compaction mode. They present also trend lines of tensile strength *vs* suction (whatever the dry density) and tensile strength *vs* dry density (under as-compacted suction) to feed the developments of Section 'Result analysis'.

Whatever the compaction mode, for the untreated soil, a clear increase of the tensile strength is observed with increasing applied suction. On the other hand, the increase of the suction induces an increase of the dry bulk density. Still for the untreated soil, the compaction mode affects tensile strength value. The in-mold compaction gives the smallest strength while the Proctor compaction gives the greatest ones, close to the value obtained with the kneading compaction. For treated soil, the suction seems to have a more limited effect on the tensile strength. Similarly to untreated soil, the in-mold compaction mode gives the smallest tensile strength while Proctor and kneading compaction gives similar trend. The highest tensile strength obtained with the Proctor compaction mode (with respect to kneading compaction) is essentially due to the highest target dry bulk density.

## Result analysis

Figs. 13 and 14 show the key role of suction *s* and the dry bulk density $\rho_d$ on the tensile strength of the untreated and lime-treated soils for the different modes of compaction. The trends show that suction impacts significantly the strength of untreated soil while dry bulk density has a greater effect on the treated soil. However, dry bulk density is also directly linked to the suction level (due to the shrinkage induced by drying). It is proposed here to quantify the relative effect of suction and dry bulk density on soil tensile strength for the 6 different conditions (3 compaction modes for untreated and treated soils).

Equation (3) decomposes the variation of tensile strength with suction $\left(\alpha = \frac{\partial\sigma_t}{\partial s}\right)$ as a combination of the intrinsic effect of suction on tensile strength (at constant dry bulk density) $\left(\delta = \frac{\partial\sigma_t}{\partial s}\Big|_{\rho_d=cst}\right)$ and the indirect effect of suction due to the suction-induced densification of the material $\left(\gamma.\beta = \frac{\partial\sigma_t}{\partial\rho_d}.\frac{\partial\rho_d}{\partial s}\right)$.

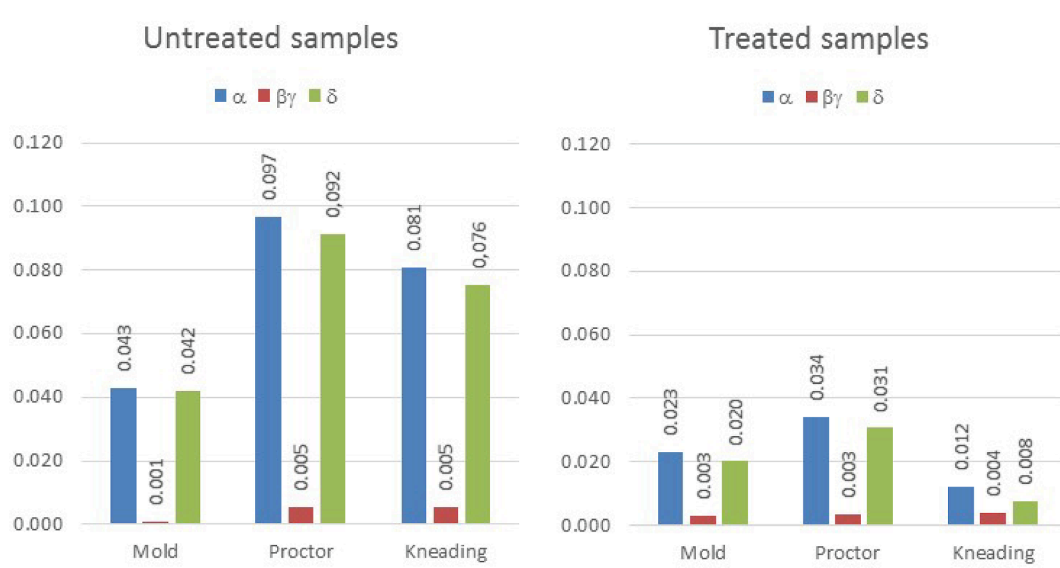



**Fig. 16.** Split of the suction effect on tensile strength (α) into the intrinsic effect of suction (δ) and the indirect effect of suction due to the suction-induced densification of the material (βγ), for untreated (left) and treated (right) samples and for the three modes of compaction.

$$d\sigma_t = \left( \frac{\partial \sigma_t}{\partial s}\bigg|_{\rho_d=cst} + \frac{\partial \sigma_t}{\partial \rho_d}\bigg|_{s=cst} . \frac{\partial \rho_d}{\partial s} \right).ds \quad (3)$$

$$\alpha = \delta + \gamma.\beta$$

It is assumed here that those evolutions are linear in the range of considered suctions and dry bulk densities. Consequently, the coefficients are constant and are obtained using a linear regression of their evolution. For the 6 cases (3 compaction modes for untreated and treated soils), parameters α and γ are directly deduced from the Figs. 13 and 14 while Fig. 15 gives the value of the parameters β. It is to note that the parameter γ was determined at a suction of 120 kPa (as-compacted conditions) because it is the suction with the highest number of results with a large spreading of dry density.

The direct effect of suction on tensile strength (parameter δ) cannot be determined from experimental results because it would require isolating the result at constant dry bulk density. However, according to Equation (3), knowing α, β and γ, δ can be obtained by subtracting the indirect effect of suction related to the density change (product of γ and β) from the total effect (parameter α). Table 6 resumes all the obtained values.

Fig. 16 splits the global effect of suction on the tensile strength of untreated and treated soils into the direct effect of suction (parameter δ) and the indirect effect of suction due to the suction-induced densification of the material (product of γ and β). As already observed by comparing Figs. 13 and 14, the global effect of suction on tensile strength (parameter α) is strongly reduced by the lime treatment. However, Fig. 16 reveals that the indirect effect of suction on the tensile strength, due to the suction-induced densification, (product of γ and β), is almost unaffected by the treatment. Consequently, the strong reduction of the suction effect on tensile strength due to the treatment is essentially due to the reduction of the intrinsic suction effect (parameter δ). In other words, in lime-treated soils, the capillary strengthening is negligible with respect to the particle bounding induced by the lime treatment, at least for the range of considered suction (until 2000 kPa).

## Conclusion

To insure the most representative value of tensile strength of compacted soil sample in laboratory, a particular attention has to be given on the laboratory compaction mode. The in-mold compaction, even if it is the most common used method in laboratory, induces some bias on the measured tensile strength due to an aggregated structure of the soil leading to some internal preferential paths of cracks between aggregates. The kneading effect observed with the normal Proctor and the kneading compaction modes permits to obtain samples having a more homogeneous structure without the occurrence of preferential failure paths. However, at the scale of a CBR mold, the specimen exhibits a relatively large variability of dry bulk densities, especially in the case of the kneading compaction which represents better the in-situ compaction mode.

A systematic analysis of the tensile strength as a function of applied suction, dry bulk density and compaction method was carried out on lime-treated and untreated silty soil. The effects of the suction have been split to ensure a strong comparison in function of the treatment. On one hand, the densification generated by the application of the suction induces similar effect on the tensile strength for both untreated and lime-treated the samples. On the other hand, the intrinsic effect of suction, leaving aside the suction-induced densification, is significantly reduced in the case of the treated materials.

At the end, it is concluded that in addition to the compaction mode that plays a significant role on tensile strength, suction has major effect on the tensile strength of untreated samples while for treated sample, it is mainly the initial dry bulk density that plays a key role on their tensile strength. Consequently, the heterogeneity of dry bulk density observed in Proctor and kneading compaction may have a strong impact on the tensile strength of lime-treated soils. It may be noted that those conclusions can not be extrapolated for suctions and dry densities outside of the ranges investigated in this study. In particular, the suction was limited to 2000 kPa, which remain relatively low with respect to suction that can be induced during dry period in the summer. Also, suction lower than 120 kPa (saturated conditions, for instance) were not investigated.

This study provides an insight on the detrimental effects of the deficiency in the compaction process of natural (i.e. untreated) or lime-treated fine-grained soils. That is of paramount importance in civil engineering infrastructure, like for base and subbase pavements, that must reach a targeted mechanical performance. That emphasizes the need for a good control of the compaction mode on site. To diminish the risk of failure triggered in weaker zone, it could be advised to highly compact the soil to obtain the desired tensile strength on the entire soil volume. Also, the sensitive role of suction (especially for untreated soil) has been highlighted. For a pragmatic approach, the worst scenario, combing the lowest suction combined with lowest dry density, can be considered. On site, suction can be deduced from the degree of saturation and the water retention curve of the material.

*CRediT authorship contribution statement*

**Nicolas Poncelet:** Conceptualization, Formal analysis, Investigation, Methodology, Resources, Software, Writing – original draft. **Bertrand François:** Methodology, Funding acquisition, Project administration, Supervision, Validation, Visualization, Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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