Effects of the maximum soil aggregates size and cyclic wetting-drying on the stiffness of a lime-treated clayey soil

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Abstract

Lime treatment is a well-known technique to improve the mechanical response of clayey subgrades of road pavements or clayey soils used for embankment. Several studies show that lime treatment significantly modifies the physical and hydro-mechanical properties of compacted soils. Nevertheless, studies on the scale effect under climatic changes are scarce. Actually, wetting-drying cycles might significantly modify the microstructure of treated soils, giving rise to changes in hydro-mechanical properties. This modification could be dependent on the size of soil aggregates before lime treatment. In the present work, this scale effect was studied by investigating the stiffness of a compacted lime-treated clayey soil using bender elements. The studied soil was first air-dried and ground into a target maximum soil aggregates size (D_{max}). For each aggregates size, the soil was humidified to reach the target water contents w_i, then mixed with 3% of lime powder (mass of lime divided by mass of dried soil) prior to the static compaction at a dry density of 1.60 Mg/m^3. Two initial water contents (w_i = 14 and 18%) and four maximum soil aggregates sizes (D_{max} = 0.4, 1.0, 2.0 and 5.0 mm) were considered. After the compaction, the soil specimen (50 mm in diameter and 50 mm in height) was covered by plastic film in order to prevent soil moisture changes. The soil stiffness was then monitored at variable time intervals until reaching stabilisation. Afterwards, the soil specimen was subjected to full saturation followed by air-drying to come back to its initial water content. The results show that: i) the soil stiffness after lime-treatment is significantly dependent on the aggregates size: the finer the aggregates the higher the soil stiffness; ii) the effect of initial water content on the stiffness is negligible and iii) the wetting-drying cycles seem to slightly increase the soil stiffness in the case of lime-treated specimens and decrease the soil stiffness in the case of untreated specimens. Furthermore, when an intensive drying was applied reducing the soil water content lower than the initial one, the soil stiffness decreased drastically after the subsequent wetting.

Keywords: Fabric/structure of soil; Laboratory tests; Soil stabilisation; Stiffness; Suction; Time dependence.

Introduction

Lime stabilisation is a well-known technique in civil engineering applications such as road construction, embankments, slab foundations and piles. After Boardman *et al.* (2001), adding lime to clayey soils leads to various reactions such as cation exchange, flocculation, carbonation and pozzolanic reaction. When quicklime (CaO) is added into a soil-water system, a highly exothermic hydration reaction occurs forming $Ca(OH)_2$. The water consumed in the hydration reaction (and that removed from the soil system via evaporation) can give rise to significant change in soil hydro-mechanical properties. At the same time, hydration reaction results in higher concentration of Ca^{2+} and OH^- ions in the soil pore water. The immediate cation exchanges induce then an apparently dried and more friable material. Beside the cation exchange, reaction also occurs between silica and some alumina of the lattices of the clay minerals. As a result, the pozzolanic reactions create hydrated cementation and flocculation by bonding adjacent soil particles together. Such pozzolanic reactions are time dependent, the strength developing gradually over a long period (Bell, 1996), with the general effect of improving the soil hydro-mechanical properties. Indeed, the treatment reduces the swelling potential (Tonoz *et al.*, 2003; Al-Rawas *et al.*, 2005), increases the shear strength (Bell, 1996; Osinubi & Nwaiwu, 2006; Sivapullaiah *et al.*, 2006; Consoli *et al.*, 2009), increases the elastic modulus (Bell, 1996; Rogers *et al.*, 2006; Sakr *et al.*, 2009) and modifies the compaction properties (Bell, 1996; Osinubi & Nwaiwu, 2006; Consoli *et al.*, 2009). The water retention properties of clays can be also modified by the lime treatment (Clare & Cruchley, 1957).

Microstructural investigations on lime-treated clays show that the treatment changes the soil fabric significantly (Cai *et al.*, 2006; Russo *et al.*, 2007; Shi *et al.*, 2007; Le Runigo *et al.*, 2009; Sakr *et al.*, 2009). Moreover, the above studies have shown that the effects of lime treatment depend on lime content, soil water content, soil type, curing time, temperature, stress state, etc.

Even though numerous studies have been performed to analyse the effect of lime treatment, almost all works have involved soil specimens prepared in the laboratory, while investigations of the lime-treated soil specimens taken from the field still remain rare. Bozbey & Guler (2006) investigated the feasibility of using a lime-treated silty soil as landfill liner material by conducting tests on both laboratory and field scales. They found that the hydraulic conductivity measured on the specimens prepared in the laboratory was one order of magnitude lower than that of undisturbed samples taken from the field. Kavak & Akyarh (2007) investigated the improvement of road by lime treatment based on both laboratory and field CBR tests. They concluded that the soaked CBR values obtained in the laboratory increased significantly (16 – 21 times) 28 days after the treatment while that obtained from field CBR tests increased slightly (2 times). Cuisinier & Deneele (2008) performed suction-controlled oedometer tests on soil samples taken from an embankment three years after the construction. They also performed the same tests on un-treated soil and treated specimens prepared in the laboratory. The results show that the swelling potential of the lime-treated samples taken from the field is significantly larger than that prepared in the laboratory, but still remains lower than that of the un-treated samples. They attributed the loss of stabilization efficiency observed in field conditions to the effects of drying-wetting cycles related to climatic changes. Rao *et al.* (2001), Guney *et al.* (2007) and Khattab *et al.* (2007) also reported a reduced efficiency of lime treatment with wetting-drying cycles.

One of the main reasons explaining the difference between lime-treated soil samples prepared in the laboratory and the treated soil samples taken from the field could be the difference in soil aggregates size. Indeed, prior to compaction in the laboratory, the soil is usually ground at a few millimetres and then mixed with lime. On the contrary, in the field, the dimension of clay clods may reach several centimetres before the treatment.

The present work aims at investigating the effects of soil aggregates size on the efficiency of lime treatment under cycles of wetting and drying. For this purpose, air-dried soils were ground at four values of maximum sieve dimensions (0.4, 1.0, 2.0 and 5.0 mm) prior to lime treatment and compaction. The shear moduli of soil specimens were monitored using the bender elements method. When reaching the stabilization of the shear moduli, wetting-drying cycles were applied in order to simulate the weathering effects.

Soil studied and experimental techniques

The soil used in this study was taken at a site near Tours, a city in central France. Its main geotechnical properties are reported in Table 1. The grain size distribution, as obtained by dry sieving method after washing (Afnor, 1996) for elements larger than 80 μm and by hydrometer method (Afnor, 1992) for elements smaller than 80 μm, is shown in Figure 1 (curve 'After washing'). The curve shows that washing has disaggregated the soil particles into small dimensions and almost all soil aggregates became smaller than 1 mm, with a clay fraction (< 2 μm) of 26%.

To prepare the soil samples, the air-dried soil was first ground and passed through one of the four target sieve sizes (D_{max} = 0.4, 1.0, 2.0 and 5.0 mm). The soil aggregates which did not pass through the sieve were ground again. The procedure was repeated until all the soil aggregates passed through the sieve except some large stones. The grading curves (obtained by sieving) of the four soil sub-series having different maximum soil aggregates diameter are also shown in Figure 1. This procedure allows preparing the soils with the same mineral composition and various values of soil clusters D_{max}. Comparison between the curve 'After washing' and that 'D_{max} = 0.4 mm' shows that washing preserved the portion of soil aggregates larger than 0.4 mm (about 20%), while the preparation of 'D_{max} = 0.4 mm' crushed this portion.

After grinding, the soil was humidified by spraying distilled water to reach prescribed initial moisture contents and sealed in plastic box for at least 48 h for moisture content homogenization. For each D_{max}, 14% and 18% water contents were considered. Prior to compaction, the moist soil was thoroughly mixed with lime and then poured into a mould of 50 mm in diameter. The lime content studied was 3% (mass of lime divided by mass of dried soil). Static compaction was then carried out to reach a dry density of 1.60 Mg/m^3 with a final height of the soil specimen of 50 mm. After the compaction, the soil specimen was taken out of the mould and wrapped by plastic film in order to avoid any moisture exchange between soil and atmosphere. The initial dimensions and the basic properties of the compacted soil specimen are presented in Table 2.

In Figure 2 the Standard Proctor compaction curves of lime treated and untreated soils are presented. The after-compaction conditions studied are also shown in the figure. It can be observed that the compaction curve of lime-treated soil is quite different from the untreated one. The dry density chosen for the present study (1.60 Mg/m^3) corresponds to the maximum dry density of lime-treated soil obtained by the Standard Proctor compaction. The mentioned water content values (14 and 18%) both correspond to the dry side of the compaction curve and were chosen in order to preserve the soil aggregates. Indeed, Delage *et al.* (1996) showed that compaction on dry side leads to a microstructure characterised by an assembly of aggregates whereas compaction on wet side leads to a more homogeneous microstructure without apparent aggregates.

The bender element was used to monitor the small strain shear modulus. The experimental set-up is shown in Figure 3. The soil specimen was put in contact with two bender elements: the transmitter one embedded in the top base and the receiver one embedded in the bottom base. Both bender elements were connected to a control and data logging system. A triggered sinusoidal signal was then sent to the transmitter, recording the response of the receiver at the specimen base. An example of the time-domain records collected is reported in Figure 4, together with the indication of travel time (Δt). Considering the travel length, l, assumed equal to the specimen height (50 mm) minus the protrusions of the bender transmitter and receiver into the soil specimen (2 mm), the shear wave velocity was then calculated as $V_s = l/\Delta t$. The soil mass density (ρ) was verified after each V_s measurement by weighing the soil specimen and was used for the determination of the small strain shear modulus: $G_{max} = \rho V_s^2$. This experimental technique is similar to that recently used by Puppala *et al.* (2006) when monitoring the shear modulus of chemically treated sulphate-bearing expansive soils and previously used by several other authors.

Once the stabilization of G_{max} was reached, the soil specimen was first wetted, Adding water with a sprayer and monitoring the change in the specimen weight until a water content of 21% (corresponding to a degree of saturation S_r = 82%) was obtained. Adding more water to the soil specimen would lead to water drainage from its bottom, indicating that the water content of 21% corresponds to the maximum value that the soil specimen can retain. After reaching the target water content value and prior to the G_{max} measurements, the soil specimen was wrapped by plastic film (for at least 24 h) for moisture Homogenisation. To achieve drying, the soil specimen was air-dried until the target water content was reached. Afterwards, it was wrapped by plastic film to achieve 'water content' equalisation. During wetting and drying, the water content of the soil specimen (w) was controlled by monitoring the changes of its mass (m) by the equation $w = (1+w_i)\times m/m_i-1$, where w_i and m_i are respectively the initial water content and the initial mass of the soil specimen. The changes in the dimensions of the specimen, as measured by calliper after wetting and drying stages, were found negligible and for this reason were ignored when calculating both V_s and the mass density. Five wetting-drying cycles were applied for each treated soil specimen. For the untreated specimens, the number of cycles was varied from two to five. The soil specimen was removed systematically from the testing device after each measurement of V_s. The bender elements were always installed in the same slots during the measurement of V_s.

Summarising, in this study two moulding water contents (14 and 18%) and four maximum soil aggregates size (D_{max} = 0.4, 1.0, 2.0 and 5.0 mm) were considered. In each case, both treated and untreated specimens were tested. Moreover, for each test three identical specimens were investigated for replicate. That corresponds to 48 soil specimens in total.

Experimental results

Changes of small strain shear modulus (G_{max}) after compaction

After compaction, the small strain shear modulus G_{max} was monitored in order to follow its changes versus time. In Figure 5, the mean value of G_{max} (measured on three identical specimens) is plotted against time. For the untreated soil passed through 0.4 mm sieve (Figure 5*a*), immediately after the compaction G_{max} was equal to 65 MPa and 44 MPa for an initial water content of 14% and 18% respectively. The values increased slightly with time and stabilized after 100 h at 73 MPa and 50 MPa, respectively. In the case of treated specimens, G_{max} was equal to 108 MPa for w_i = 14% and 80 MPa for w_i = 18%. Comparison with the values of untreated specimens shows that the lime treatment has a significant effect on G_{max} immediately after the compaction. With time, G_{max} increased and stabilized after 200 h at about120 MPa for both values of w_i . The time increase of G_{max} was more significant in the case of the higher water content (w_i = 18%). Interestingly, the stabilized G_{max} value has been found independent of the initial water content.

Similar observation can be made from the results of soil ground to 1.0 mm (Figure 5*b*), 2.0 mm (Figure 5*c*) and 5.0 mm (Figure 5*d*) in terms of: (*i*) immediate effect of lime treatment after compaction, characterised by a significant increase of G_{max}; (*ii*) slight increase of G_{max} with time for untreated specimens; (*iii*) increase of G_{max} with time for treated specimens especially in the case of the higher water content (w_i = 18%) and (*iv*) stabilization of G_{max} about 200 h after the treatment, with similar final values for both water contents.

In order to analyse the effect of maximum soil aggregates size on G_{max}, the mean final values of G_{max} and the range measured on three identical specimens are compared in Figure 6 as a function of D_{max}. For the treated soil compacted at w_i = 14% (Figure 6*a*), G_{max} was found to be decreasing with D_{max}, showing the highest value of 120 MPa for D_{max} = 0.4 mm and the lowest of 103 MPa for D_{max} = 5.0 mm. Similar observation can be made for the treated soil compacted at w_i = 18% (Figure 6*b*), indicating that the larger is the maximum soil aggregate size the lower is the value of G_{max}. For the untreated specimens, the G_{max} versus D_{max} data show a less clear trend for the w_i = 14% case and indicates almost constant G_{max} for the w_i = 18% case.

Changes of small strain shear modulus G_{max} under cyclic wetting-drying

Cyclic wetting-drying was carried out by controlling the water content of the soil specimen. In Figure 7, the G_{max} versus time data of the soil aggregates ground to 0.4 mm are presented. The corresponding water content at each measurement is also indicated. The starting points (t = 0) correspond to the last points shown in Figure 5. At the initial water content w_i = 14% (the corresponding degree of saturation is S_{ri} = 55%), G_{max} was equal to 73 MPa (Figure 7*a*) for the untreated specimen. Wetting to a water content of 21% (S_r = 82%) decreased G_{max} to 28 MPa. The subsequent drying to the water content of 14% (at t = 100 h) increased G_{max} to 50 MPa. On subsequent wetting and drying cycles, cracks progressively developed until the bender elements signal was no longer transmitted through the soil sample. The soil may be then considered as profoundly fissured after two wetting-drying cycles. The two following parameters are proposed to characterise the changes of G_{max} under cyclic wetting-drying for untreated soils: (*i*) the decrease of G_{max} during the first wetting path, ΔG_{max1}; (*ii*) the number of wetting-drying cycles causing cracking, N_f. Note that another parameter $\Delta G_{max1}/G_{max\ i}$ alternative to ΔG_{max1} can be used, where $G_{max\ i}$ is the initial value obtained in the wetting-drying tests. In the case of the untreated samples having D_{max} = 0.4 mm, these parameters are ΔG_{max1} = 45 MPa ($\Delta G_{max1}/G_{max\ i}$= 62%), N_f = 2.

For the specimen treated at the initial water content of 14% (Figure 7*a*), wetting to a water content of 21% decreased slightly G_{max} from 121 to 114 MPa. Nevertheless, when this high value of water content was maintained, G_{max} was increasing and reached 127 MPa after 100 h. The subsequent wetting and drying only induced slight changes of G_{max}. For the last drying stage (at t = 580 h), the water content was finally reduced to 11%. This intensive drying resulted in a significant decrease of G_{max} when the soil was wetted again to a water content of 21%; G_{max} decreased from 134 to 97 MPa. This can be explained by the development of micro-cracks observed on the specimen surface. Beside the parameter ΔG_{max1} described above, the decrease of G_{max} during the last wetting path (ΔG_{maxf}) can be also proposed to describe the behaviour of treated soils under wetting-drying path. In the case of the treated samples having D_{max} = 0.4 mm, these parameters are ΔG_{max1} = 7 MPa ($\Delta G_{max1}/G_{max\ i}$= 6%) and ΔG_{maxf} = 37 MPa.

For the soil specimen compacted at the initial water content of 18%, micro-cracks appeared on the untreated specimens after three wetting-drying cycles, leading to no bender elements vibration transmission (Figure 7*b*). For the treated specimens, the phenomena were similar to that observed for a water content of 14%: i) slight increase after the first wetting; ii) small changes upon cyclic wetting-drying; iii) drastic decrease due to development of micro-cracks after an intensive drying with the water content decreased to 11%.

The changes of G_{max} upon wetting-drying for other maximum soil aggregate sizes show similar trends. The main parameters of all samples are reported in Table 3, including $\Delta G_{max1}/G_{max\ i}$. The untreated specimens compacted at a drier state (initial water content of 14%) also show diffused cracking after three wetting-drying cycles. This is not the case for the untreated specimens compacted at a wetter state (i.e., w_i = 18%) except the specimens having D_{max} = 0.4 mm (Figure 7*b*). For the lime-treated specimens, wetting-drying cycles only induced small changes of G_{max}, becoming significant only on wetting stage following an intensive drying. This effect seems to be more significant for the drier specimen (i.e., w_i = 14%). The effect of D_{max} upon cyclic wetting-drying was found insignificant as the behaviour of the soil specimens having different D_{max} was quite similar. Comparison of the $\Delta G_{max1}/G_{max\ i}$ data with the ΔG_{max1} data indicates that the wetting-drying effect is more clearly evidenced by the $\Delta G_{max1}/G_{max\ i}$ parameter with

$\Delta G_{max1}/G_{max\ i} \geq 38\%$ for untreated specimens and $\Delta G_{max1}/G_{max\ i} \leq 12\%$ for treated specimens.

Discussion

The bender elements method is often used to monitor the changes in shear wave velocity in triaxial cell under stress confined conditions. In this case, good contact between the bender elements and the soil specimen can be ensured (Leong *et al.*, 2009; Ng *et al.*, 2009). Application of this method is much more difficult in the case of the present study where the evolution of G_{max} needs to be monitored during several days and on a large number of soil specimens. For this reason, in this work the bender elements were put in contact with the soil specimen only during the measurement and no confining pressure was applied. In order to analyse the test scattering, three specimens were tested for each D_{max} and w_i. The results showed a good repeatability of the procedure used (see Figure 7).

The changes of G_{max} with time of the compacted soil specimens were monitored until reaching the stabilization. A slight increase of G_{max} with time was observed for the untreated specimens and is attributed to aging effects of compacted clay soils. It is worth noting that Delage *et al*. (2006) observed significant changes in microstructure of a compacted expansive soil after compaction. These authors attributed the mentioned changes to increase in the intra-aggregate porosity caused by exchange of water between the inter-aggregate and intra-aggregate pores. Tang *et al*. (2008) also observed this phenomenon characterised by a slight increase of soil suction after compaction. The effect of suction on G_{max} was also evidenced in the present study as untreated specimens compacted at lower water contents (higher suction) have higher G_{max}. Such behaviour was also observed by Sawangsuriya *et al*. (2008).

For the treated specimens, G_{max} obtained immediately after the compaction has been found to be significantly higher than that of untreated specimens prepared at the same moulding water content. The values of G_{max} of treated specimens range between 80 and 130 MPa. This result is similar to that obtained by Rogers *et al*. (2006) from cyclic triaxial tests on compacted clay treated with 2.5% of lime. The immediate increase of G_{max} with lime-treatment can be partly explained by the increase of suction caused by decrease of water content after treatment due to hydration and evaporation (Boardman *et al.*, 2001), and to the cation exchanges which increase the flocculation of mineral particles.

It is worth noting that the final values of G_{max} after compaction are independent of the initial values of water content considered (14% and 18%) despite the above-mentioned effect of initial water content immediately after the treatment (Figure 5). As described by Bell (1996), pozzolanic reactions, which take place over a long period, induce bonding between adjacent soil particles. The different evolution over time of G_{max} at different water contents (shown in Figure 5) can be then explained as follows: the small-strain shear modulus (G_{max}) of compacted soil is mainly governed by the contacts between adjacent soil particles; immediately after the compaction, the contacts are mainly governed by the capillary suction: the higher the suction (or the lower the water content) the higher the G_{max}; over a long period, due to pozzolanic reactions in lime-treated soil, cementation develops increasing gradually G_{max}; when stabilization is reached, G_{max} is governed mainly by the cementation bonds and the effect of suction (or water content) becomes less significant. The evolution of the G_{max} with time can be also explained from a microstructural point of view. Russo *et al.* (2007) studied the time-dependency of the microstructure of lime-stabilised soil samples by means of Mercury Intrusion Porosimetry (MIP) tests. The results show significant effects of moulding water content on the pore size distribution immediately after the compaction. Nevertheless, after a curing time of 28 days the lime-stabilized samples show a very similar pore size distribution, irrespective of the moulding water content adopted. This evolution of microstructure is also similar to that observed on G_{max} in the present study.

As far as the effect of the maximum soil aggregate size (D_{max}) is concerned, the results of the treated specimens showed a lower value of G_{max} for a larger value of D_{max}. This effect was not observed for the untreated specimens. Actually, for a smaller D_{max}, the total surface of aggregates was larger and therefore more soil-lime reaction can be expected. Note that this observation is of importance from a practical point of view, since laboratory tests are usually performed on small soil aggregates size (less than few millimetres) while in the field they may reach several centimetres. As a consequence, particular attention should be paid when using the parameters determined in laboratory for field application design.

As far as the effects of cyclic wetting-drying on G_{max} are concerned, data presented indicate that wetting induced a decrease and drying induced an increase of G_{max}. This can be explained by the effect of suction: wetting decreased the soil suction thus the soil stiffness while drying increase the soil suction thus the soil stiffness. The same phenomenon was observed by Ng *et al*. (2009) when performing measurements of G_{max} in a suction-controlled triaxial cell. Vassallo *et al.* (2007*a*) used suction-controlled resonant column torsional shear cell to study the effect of net stress and suction history on G_{max} of a compacted clayey silt. The experimental results show that G_{max} depends significantly on mean net stress and matric suction as well as stress history. Modelling criteria were proposed by Vassalllo *et al.* (2007*b*) to describe the observed soil behaviour. In the present work, comparison between the treated specimens and untreated specimens shows that the effect of suction change on G_{max} of treated specimens is less significant than that of untreated specimens. This shows that lime-treatment reinforces the soil and makes it less sensitive to ’weathering’.

The significant decrease of G_{max} during the last wetting path after an intensive drying (up to a water content of 11%) observed in this work could be explained within the framework of unsaturated soil mechanics where the soil suction is usually considered as a stress variable. Actually, after the lime treatment, cementation bonds were progressively created under a humidity condition corresponding to the initial water content (14% or 18%). During the first wetting-drying cycle, the water content was varied in the range from w_i to the maximum value (21%). Thus, the soil suction remains lower than its maximum value (reached after the stabilization of G_{max}). The soil state moves inside the ‘elastic’ zone (see Alonso *et al*, 1990; Cui & Delage, 1996) and the bonds between particles are relatively well preserved. On the contrary, on intensive drying (water content decreased to 11%), the soil suction exceeded its maximum value: large elasto-plastic deformations and significant damage of bonds are thus induced as for the case of Pinyol *et al.* (2007). This damage of bonds would result in micro-cracking and therefore in decrease of G_{max}. On the other hand, the drying increased the soil suction thus increasing

G_{max}. The fact that a slight increase of G_{max} was observed during the drying shows that the suction effect prevailed on the bonds damages. During the subsequent wetting, as the suction effect was removed, the damage effect was finally evidenced. It is also interesting to note that the decrease of G_{max} for treated samples during the last wetting path is similar to the decrease observed on untreated samples from the beginning of wetting-drying cycles. This seems to confirm the onset of severe bonds damages of the treated samples on intensive drying.

For the untreated specimens, it has been observed that wetting-drying cycles resulted in a decrease of G_{max}, especially for drier specimens (see Figure 7 and Table 3). This can be explained by the generation of micro-cracks by cyclic wetting-drying under unconfined conditions (Yesiller *et al.*, 2000). In the works of Vassallo *et al.* (2007*a*) and Ng *et al.* (2009), the generation of micro-cracks was avoided as the tests were performed under confined conditions. For the treated specimens, the first wetting path equally induced a decrease of G_{max}. Nevertheless, after this decrease, the value of G_{max} increased slightly. The immediate decrease of G_{max} can be explained by the effect of suction, while the subsequent increase of G_{max} after wetting can be attributed to the onset of various reactions by water addition. This explains why Kavak & Akyarh (2006) recommended watering the lime-treated soil one week after the treatment.

Conclusion

The small strain shear modulus G_{max} of compacted lime-treated soil was investigated using bender elements. The following conclusions can be drawn:
i) the lime treatment significantly increases G_{max} of the soil, giving rise to G_{max} values independent of the moulding water content about 200 h after lime treatment;
ii) for the four maximum soil aggregates sizes D_{max} considered, it has been observed that the larger is the value of D_{max} the lower is the value of G_{max}. This observation is interesting from a practical point of view for earthworks involving lime-treated soils. Indeed, the results obtained show that designing earthworks based on the parameters determined from laboratory tests can be misleading, because the maximum aggregate size of the soil tested in the laboratory is usually less than few millimetres while clay aggregates in the field may reach the dimension of several centimetres;
iii) due to the appearance of micro-cracks, cyclic wetting-drying induced significant decrease of G_{max} of untreated specimens. For treated specimens, the changes of G_{max} during wetting-drying cycles are less significant. Only an intensive drying to water content very much lower than the initial one can induce micro-cracks and thus decrease of G_{max};
iv) for the treated specimens, only the first wetting induced a decrease of G_{max}. On the contrary, the subsequent cycles induced a slight increase of G_{max}. If the decrease due to wetting can be explained by the suction effect, the slight increase by further wetting-drying cycle should be attributed to the onset of various physico-chemical reactions within the soil.

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Table 1. Geotechnical properties of the studied soil

Soil properties	**Value**
Liquid limit, w_L (%)	45
Plastic limit, w_p (%)	21
Plasticity Index, I_p (%)	24
Value of blue of methylene,*VBS*	4.86
Carbonates content (%)	0.35
Specific gravity, G_S	2.70

Table 2. Dimensions and basic properties of soil specimens

Dimensions/Basic properties	**Value**
Height (mm)	50
Diameter (mm)	50
Dry density (Mg/m^3)	1.60
Initial water content (%)	14 and 18
Lime content (%)	3
Maximum soil aggregates size (mm)	0.4; 1.0; 2.0; and 5.0

Table 3. Results obtained during the wetting-drying cycles (ΔG_{max1}: decrease of G_{max} during the first wetting path; $\Delta G_{max1}/G_{max\,i}$: ratio of ΔG_{max1} to the initial value of G_{max} during the wetting-drying tests; N_f: number of cycles inducing failure; ΔG_{maxf}: decrease of G_{max} during the last wetting path)

D_{max} (mm)	w_i (%)	Lime-treatment	ΔG_{max1} (MPa)	$\Delta G_{max1}/G_{max\,i}$ (%)	N_f	ΔG_{maxf} (MPa)
0.4	14	Yes	7	6	-	37
0.4	14	No	45	62	2	-
0.4	18	Yes	10	8	-	25
0.4	18	No	19	38	3	-
1.0	14	Yes	8	7	-	36
1.0	14	No	44	70	3	-
1.0	18	Yes	4	4	-	13
1.0	18	No	19	41	> 5	
2.0	14	Yes	13	12	-	38
2.0	14	No	36	64	3	-
2.0	18	Yes	5	5	-	15
2.0	18	No	31	63	> 3	-
5.0	14	Yes	9	9	-	44
5.0	14	No	47	73	3	-
5.0	18	Yes	4	4	-	22
5.0	18	No	23	49	> 3	-

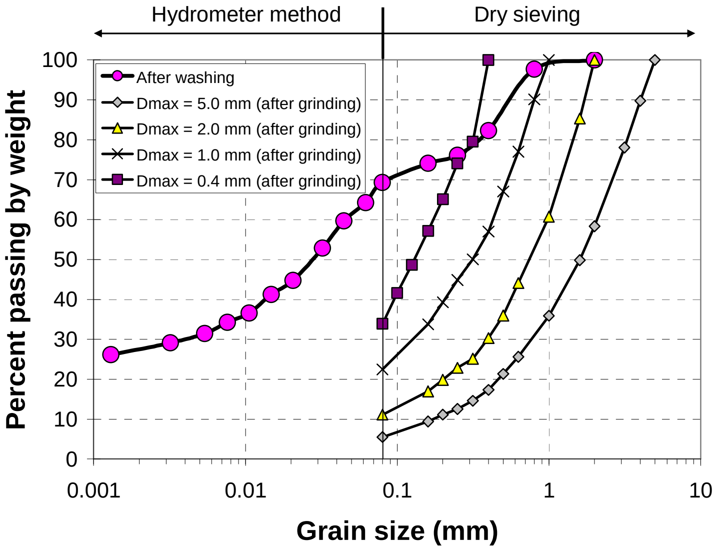

Figure 1. Grain size distributions of the studied soil prepared by various methods

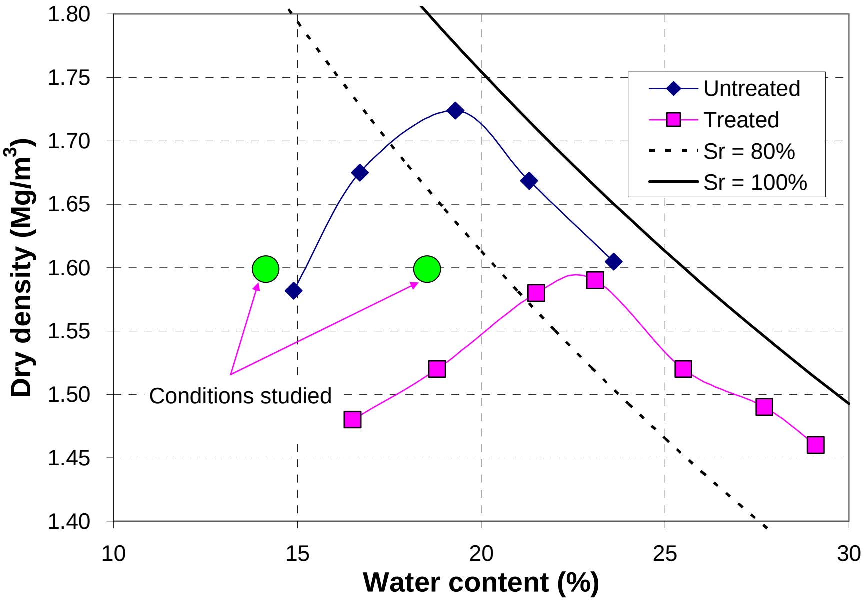

Figure 2. Standard Proctor compaction curves and conditions studied

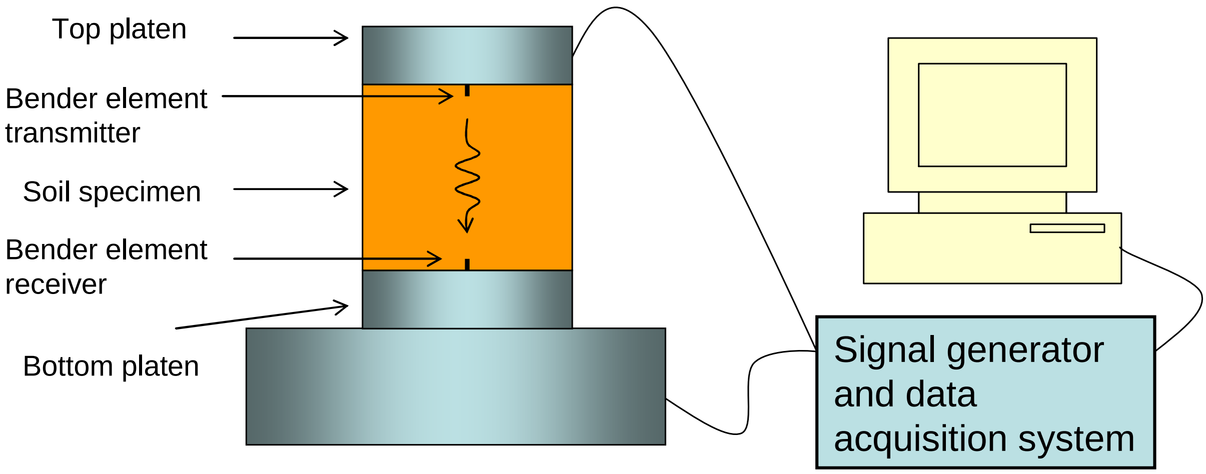

Figure 3. Experimental setup – bender elements test

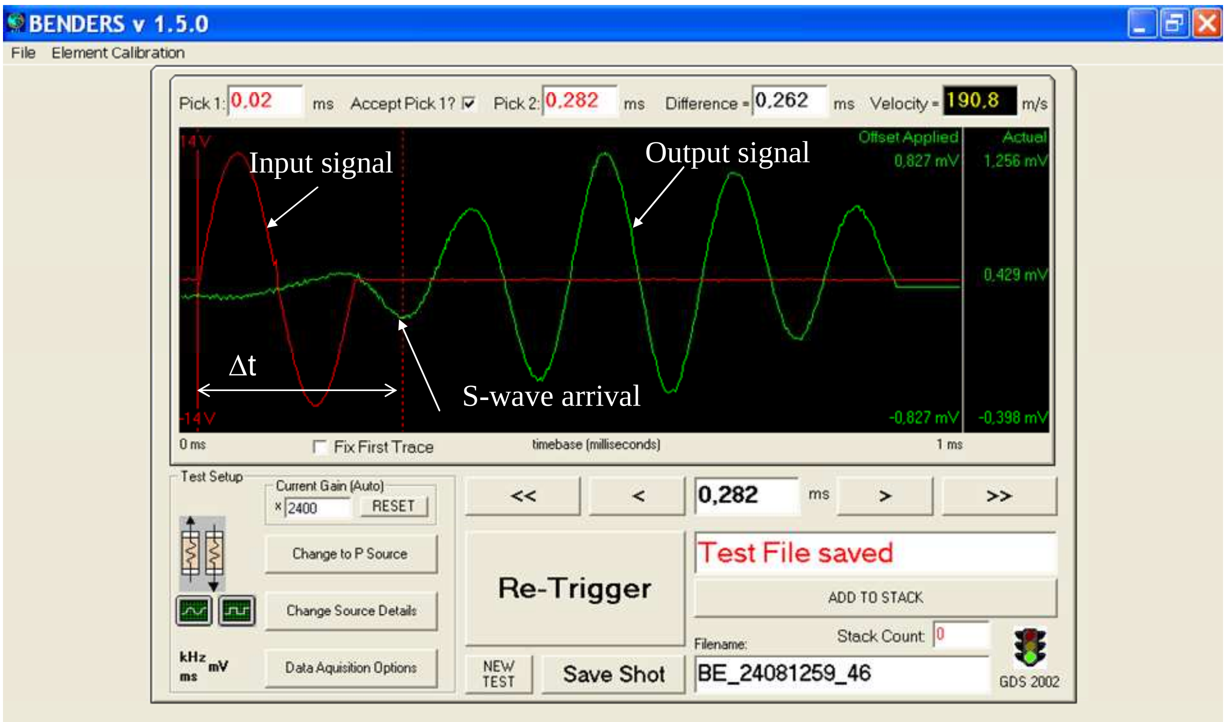

Figure 4. Response of shear wave for the soil sample treated with 3% of lime, D_{max} = 5 mm, w_i = 14%, 886 h after the treatment

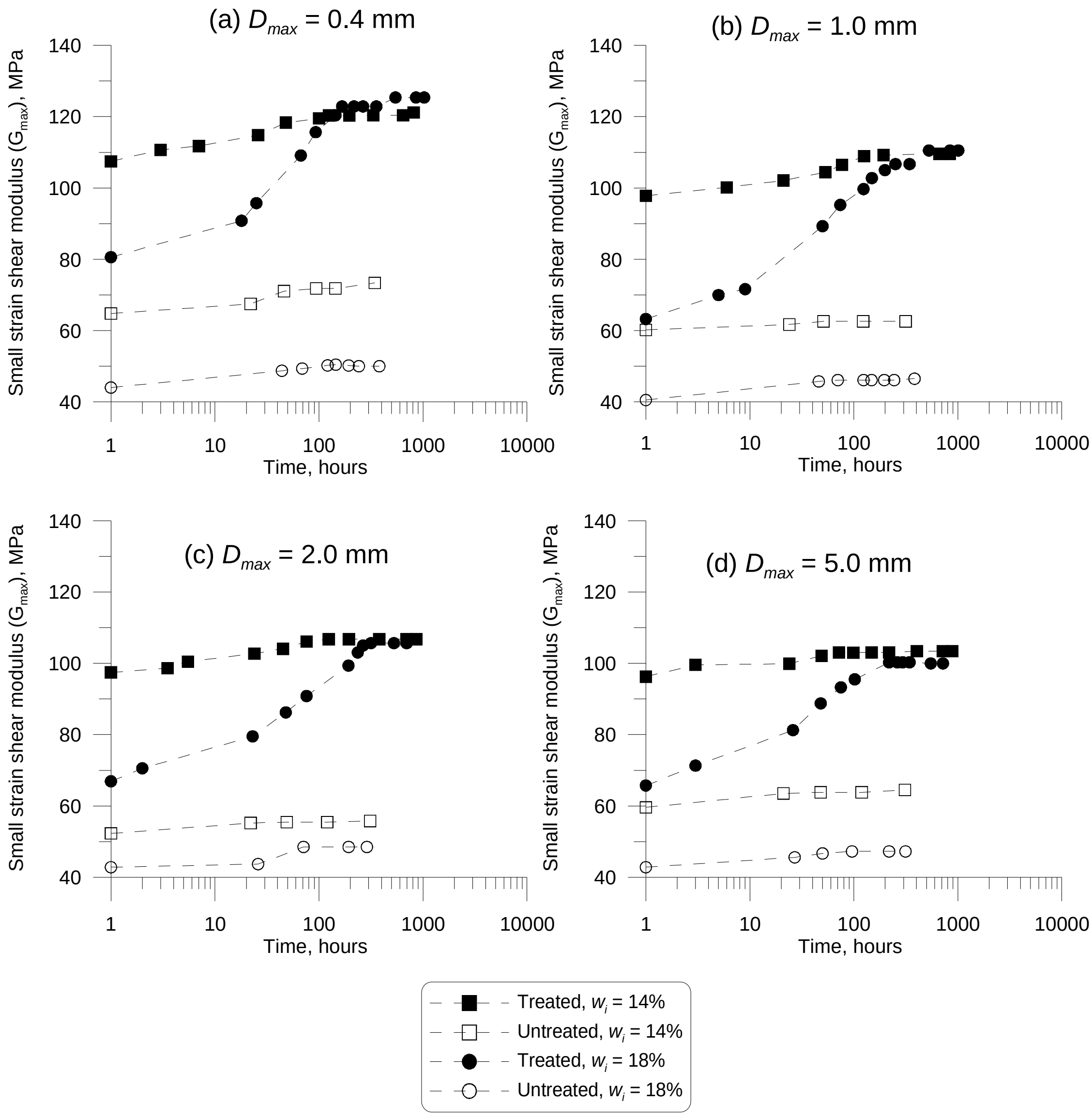

Figure 5. Small strain shear modulus versus time after compaction

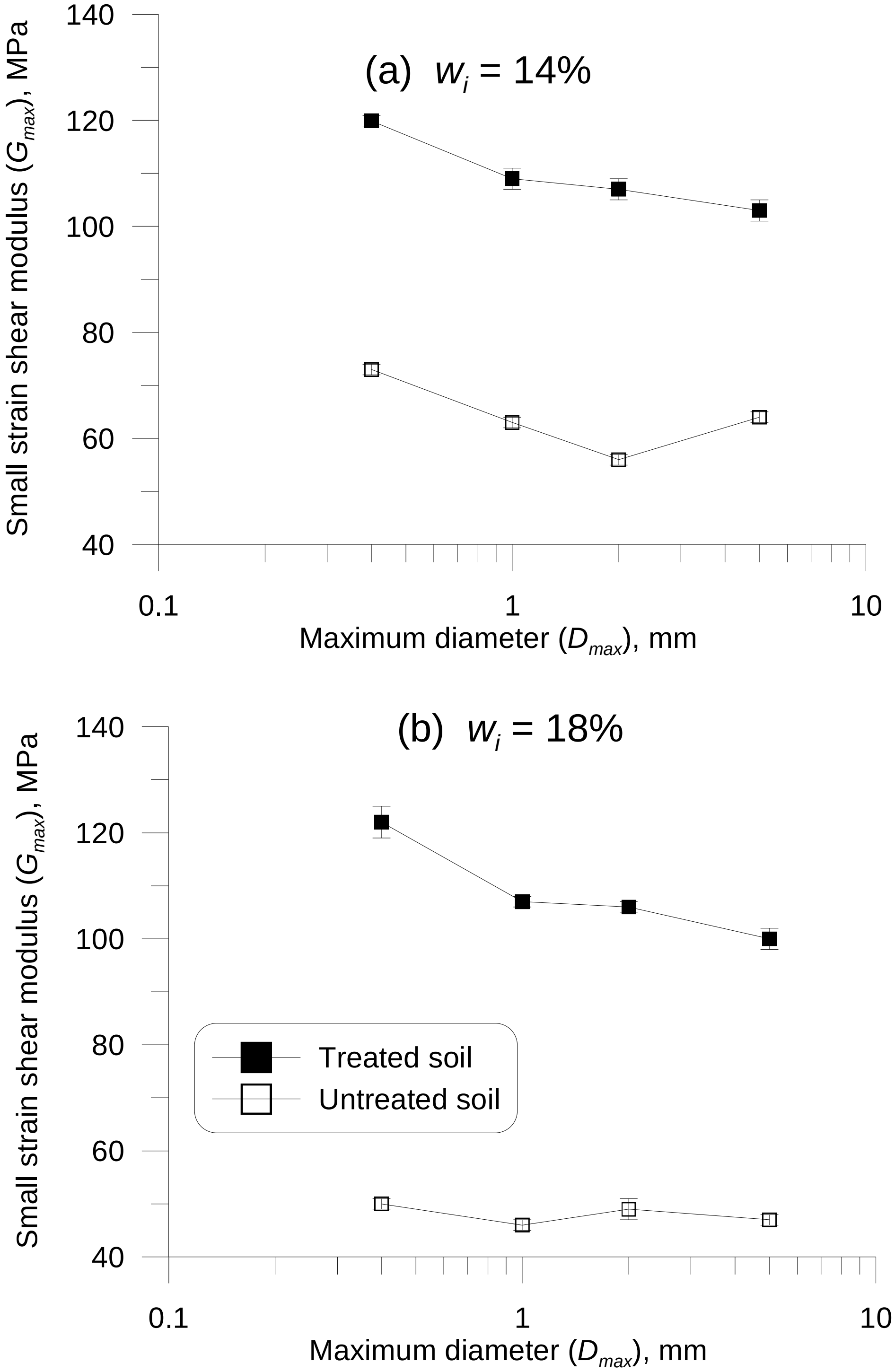

Figure 6. Small strain shear modulus after stabilization versus maximum aggregates diameter

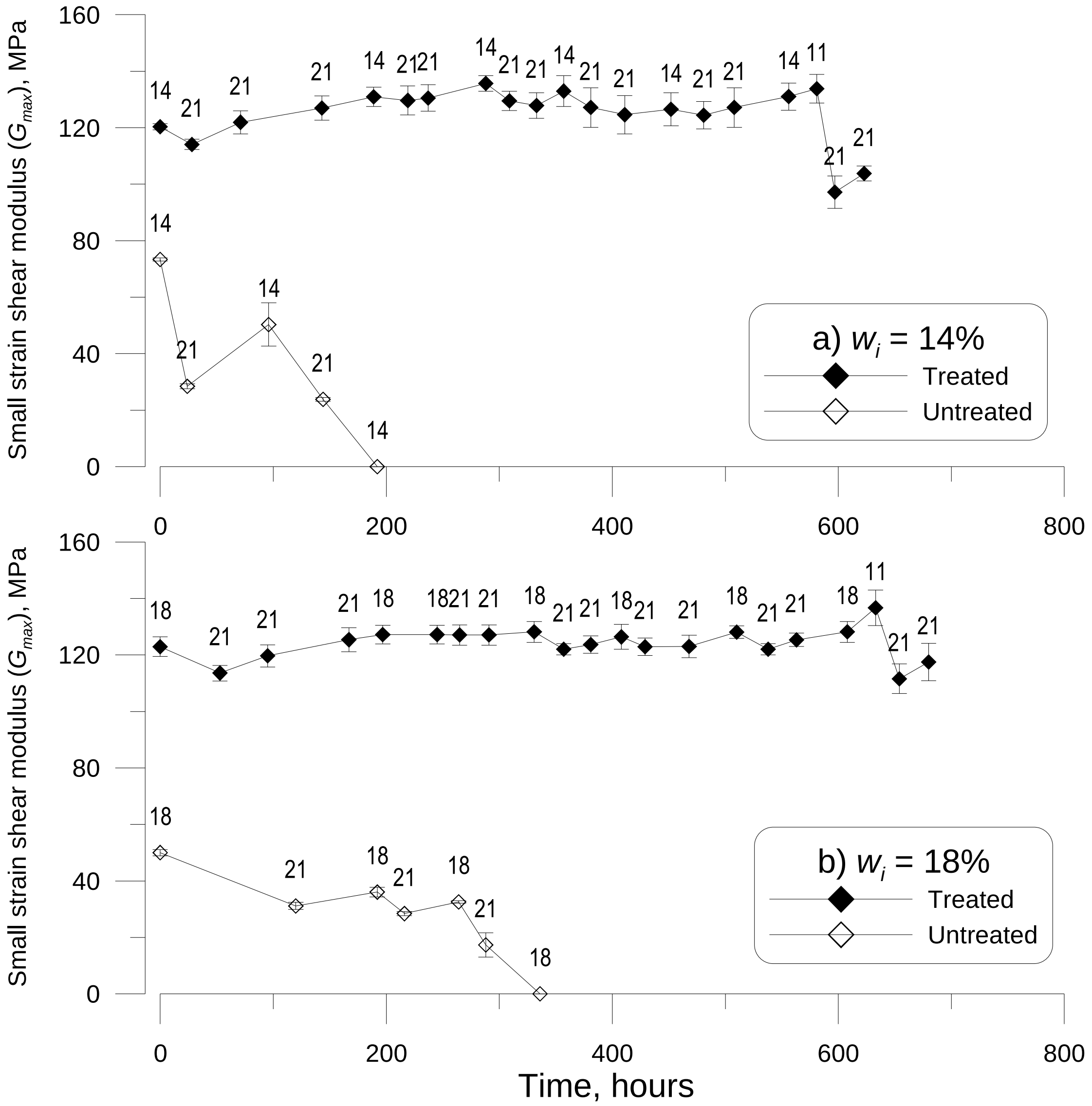

Figure 7. Changes in small strain shear modulus upon cyclic wetting/drying for D_{max} = 0.4 mm (the corresponding water content is given above each point)