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ABSTRACT

The aggregate size resulting from the construction procedure is an essential parameter that may influence the behaviour of lime-treated soils in field construction. This study aims to investigate the aggregate size effects on the compressibility and air permeability of a lime-treated soil. For this purpose, air permeability measurements in oedometer compression tests were carried out on a silt with two different maximum aggregate size (D_{max} = 5 and 0.4 mm) and treated with 2% quicklime).The tests were performed on both untreated and treated samples at various curing times (t = 7, 28, 60 and 90 days). Results showed that lime treatment significantly improves the compression behaviour of soil due to both the flocculation process and the pozzolanic reaction. The treated samples prepared with smaller aggregates have higher oedometer modulus, suggesting a better lime distribution and the production of more cementitious compounds. Air permeability of soil is strongly related to the aggregate size: the soil with smaller aggregates can have a value of one order of magnitude lower than that with larger aggregates. Further examination showed that in the case of smaller aggregates, the morphology of macro-pores and the efficiency of air flow are more sensitive to lime treatment.

KEYWORDS: aggregate size; oedometer compression; air permeability; curing time; lime treatment.

INTRODUCTION

In recent years, increasing attention has been paid to the efficiency and durability of soil stabilisation by lime in the field conditions. Studies assessing the efficiency of lime treatment in both field and laboratory conditions showed that the lime treatment in field usually exhibits a lower performance with respect to that in the laboratory. Field treatment often leads to lower strength (Kavak & Akyarh, 2007; Horpibulsuk et al., 2006), smaller moduli (Dong, 2013), higher hydraulic conductivity (Bozbey & Guler, 2006) and higher swelling potential (Cuisinier & Deneele, 2008) of soils. This can be closely related to the different aggregate sizes considered in the field and in the laboratory. Indeed, in addition to the climate conditions, the aggregate size can play an essential role in the lime treatment (Tang et al., 2011a). Generally, soil aggregates may reach several centimetres even after the scarification/pulverization processes in the field conditions. By contrast, the soil prepared in the laboratory is usually well ground into few millimetres before treatment. To the authors' knowledge, there are a few studies on the aggregate size effects. Tang et al. (2011a) and Dong (2013) studied the aggregate size effect on the stiffness of lime-treated soils during curing and concluded that the treated soils with larger aggregates exhibit a lower small-strain shear modulus and lower resistance to wetting/drying cycles. Wang et al. (2015) reported a relatively higher water retention capacity for the treated soil with smaller aggregates.

Numerous studies dealing with the compression behaviour of lime-treated soils showed that lime treatment effectively improves the unconfined compression strength of soils (Al-Mukhtar et al., 2012; Pakbaz & Farzi, 2015; Yunus et al., 2015). In addition, significant reduction in compressibility for lime-treated samples was also reported in previous studies

(Nalbantoglu and Tuncer, 2001; Di sante et al., 2014; Makki-Szymkiewicz et al., 2015; Jha and Sivapullaiah, 2016). However, less attention has been paid to the effect of aggregate size on the compressibility of lime-treated soils.

Lime treatment can also significantly influence the air permeability. Previous studies reported that air permeability was strongly related to the air-filled porosity, macro-pore space and soil structure (Blackwell *et al.* 1990; Delage *et al.*, 1998; Poulsen *et al.* 2001; Tang *et al.* 2011b). Some studies analysed the effects of soil deformation induced by the mechanical process on air permeability (Blackwell & Kirby, 1998; Moon *et al* 2008). Furthermore, air permeability can be used to assess the saturated hydraulic conductivity of soil when the direct measurement of hydraulic conductivity is found difficult (Blackwell & Kirby, 1998; Ghanbarian et al., 2014; Huang et al., 2016). This is particularly the case for lime-treated soils because pozzolanic reactions can be accelerated during the measurement with water flow, leading to changes in hydraulic conductivity.

In this study, the air permeability of a lime-treated silty soil was determined at each loading step in oedometer compression tests. Two different maximum aggregates sizes (D_{max} = 5 and 0.4 mm) were considered before lime treatment. The obtained results allowed the effects of aggregate size on the compressibility and the air permeability of lime-treated soil to be analysed.

MATERIALS AND METHODS

The soil used (27 % of clay-size fraction) was taken from a site in Héricourt, France. This soil can be classified as a silt of high plasticity (MH) following the Unified Soil Classification

System (USCS). Natural soil was first air-dried, ground then passed through two target sieves (D_{max} equal to 5 and 0.4 mm, respectively), to obtain two different soil powders S5 and S04 with two different maximum aggregate diameters: D_{max} = 5 mm and D_{max} = 0.4 mm (see Figure 1). All the samples were prepared following the same procedure. A dosage of 2% quicklime by dry weight of soil was applied. Soil powder was first thoroughly mixed with lime and then humidified with distilled water (at a target water content w = 17 %). After a mellowing time of 1 h, static compaction was performed for the sample remoulding. Note that a 'Tritest 50 compaction' machine was used in this study, and the compaction rate adopted was 0.3 mm/min. The finale dimensions of the sample are 50 mm in diameter and 20 mm in height with a controlled dry unit mass ρ_d = 1.65 Mg/m^3. After compaction, they were covered by wax and cured in a chamber at a temperature of 20±2 °C for 7, 28, 60 and 90 days, respectively. More details about the geotechnical properties of this silt and the detailed procedure of samples' preparation can be found in Wang *et al.* (2015; 2016).

The experimental setup for measuring the compressibility and the air permeability of soil was developed based on the systems proposed by Yoshimi & Osterberg (1963) and Delage *et al.* (1998), as shown in Figure 2. Before placing the sample in a standard oedometer cell, high vacuum silicone grease was applied on its side surface to prevent any air leakage between the sample and the inner side of the cell. First of all, an air pressure lower than 8 kPa was applied in the air tank (Delage *et al.* 1998). At the beginning of the test (t = 0), the valve which connects the bottom of oedometer cell to the air tank was open, inducing an air flow through the sample accompanied by a decline of air pressure over time. The air permeability (k_a) can be deduced from this result of air pressure evolution (Yoshimi & Osterberg, 1963).

When the sample was installed in the oedometer cell, a vertical stress, σ_v, of 23 kPa was applied through the piston prior to the first measurement of air permeability. Then, σ_v was incrementally increased to 42, 89, 179, 372, 750, 1500 and 2730 kPa. When the stabilisation is reached at each loading step, air permeability measurement was performed. The sample height change at each stress level was calculated based on the records of vertical displacement. Two samples were used in each case to duplicate the tests. For the safe of clarity, a unique name was given for each category of samples. For instance, in the naming of "S5L2_7d", "S5" stands for D_{max} = 5 mm, "L2" for 2% lime treatment (while untreated sample was named as "L0"), "7d" for a curing time of 7 days.

RESULTS

The compression curves of untreated and lime-treated soils are plotted in Figure 3. Note that only the mean values of two duplicated samples are presented because the two results show a good repeatability. The last vertical stress applied on the untreated soils is around 1500 kPa since the compression was stopped when limited airflow was observed at this load level. Other tests on the treated soils were stopped at the load level of 2730 kPa. The result indicates that the yield stress of untreated sample is lower than that of lime-treated sample (see Figure 3a and Figure 3b). For example, the yield stress of untreated sample S5L0 is around 300 kPa; lime treatment substantially increases the yield stress up to 1000 kPa. The similar results can be obtained for the samples prepared with smaller aggregates (S04), as shown in Figure 3b. However, it appears that samples S04 have less volume change than samples S5, especially at the last stress level.

For further analysis on the compression behaviour, these compression curves are used to determine the compressibility parameters such as volumetric strain (ε_v) and oedometer modulus (E_{oed}), which are respectively defined as follows:

$$\varepsilon_v = \frac{\Delta e}{1+e_0} \tag{1}$$

$$E_{oed} = \left(d\sigma_v / d\varepsilon_v\right) = h_i\left(d\sigma_v / dh\right) \tag{2}$$

where h_i is the initial height of the sample, dh is the height change under an increment of vertical stress $d\sigma_v$. Figure 3c and Figure 3d plot the volumetric strain (ε_v) versus vertical stress (σ_v) in a semi-logarithmic scale for both soils S5 and S04. Lime treatment effectively reduces the volumetric strain ε_v for both small and large aggregates. For lime-treated soil S5, ε_v is similar when σ_v is lower than 750 kPa; however, lower ε_v is observed for lime-treated S5 which was cured for a longer time. For example, at σ_v = 2730 kPa, ε_v decreases from 0.063 for treated soil S5 at 7-day curing to 0.05 for the sample at 90-day curing (a decrease of 20.6 %). More significant curing time effect is observed for soil S04 as shown in Figure 3d. About 26 % reduction of ε_v is obtained for the treated soil S04 at 90-day curing compared to that at 7-day curing. Furthermore, compared to S5, slightly lower ε_v is observed for S04 at a given stress level for each curing term.

The oedometric modulus (E_{oed}) is primarily dependent on σ_v, and lime treatment contributes to a substantial increase of E_{oed}. As presented in Figure 3e, E_{oed} of untreated soil S5 is only about 14.3 MPa at σ_v = 1127 kPa. By comparison, E_{oed} of lime-treated soil S5 cured at t = 7 days is about threefold larger (E_{oed} = 56.3 MPa) than that of untreated soil and it continues to increase up to 76.6 MPa at 90-day curing. Then, E_{oed} of treated soils decreases slightly at the highest vertical stress. The similar results are obtained for lime-treated soil S04 with more significant gains from curing (Figure 3f). E_{oed} of S04 at 7-day curing is 74.8 MPa and it increases to 113.2 MPa at 90-day curing, which are about 280 % and 480 % higher than that of untreated soil, respectively. Obviously, S04 has a higher value of E_{oed} than S5. This is consistent with the results obtained by Tang *et al.* (2011a) who reported a higher small-strain shear modulus for the lime-treated soil with smaller aggregates.

Figures 4a and 4b present the air permeability (k_a) of both soils S5 and S04, against vertical stress. All results for the two duplicated samples are shown because large difference can be obtained, in particular for the untreated samples. Note that only one result is obtained for the treated samples S5L2_60d and S5L2_90d respectively, as seen in Figure 4a because the uncertain damage of particular samples. Generally, k_a decreases with increasing vertical stress. However, some points show that k_a increases at the beginning of the compression for some samples. This will be further discussed in the following section. Compared to the treated samples, the untreated ones (both S5L0 and S04L0) exhibit more significant reduction of k_a at high σ_v. However, no airflow is observed for S5L0 when σ_v = 1500 kPa is loaded. The air permeability k_a of samples S5 mainly ranges from 0.02 to 0.14 μm², while the data of samples S04 are even one order of magnitude lower, from around 0.002 to 0.01 μm².

In Figure 5, the air permeability of soils S5 and S04 is plotted against the air-filled porosity (V_a/V). Upon compression, k_a of both soils S5 and S04 generally decreases with the reduction of V_a/V. Specifically, at the beginning of compression, a slight reduction of k_a with the decrease of V_a/V is observed for most samples. Then, k_a decreases at a greater rate with the decrease of V_a/V. It is worth noting that the treated samples S04 apparently show lower k_a compared to the untreated ones at given value of V_a/V. However, there is no significant difference in V_a/V between the treated samples S5 and the untreated S5.

As the organisation of macro-pores induced by soil aggregate size, rather than the total volume, plays a major role in the air permeability, in the further analysis, both the organization of macro-pores (*O*) which includes the size, shape, tortuosity and the arrangement of macro-pores are taken into account. The macro-pores organization (*O*) was defined by Blackwell et al. (1990) as follows:

$$O = k_a / (V_a / V) \tag{3}$$

The relationship between *O* and V_a/V of both samples S5 and S04 are plotted in Figures 6a and 6b, respectively. When the vertical stress is low, *O* remains nearly constant: *O* of all the samples S5 is at a stable level of 1 μm² as V_a/V decreases from 0.12 to 0.08, while *O* of samples S04 remains near the value of 0.1 μm² as V_a/V decreases from 0.12 to 0.07. With higher vertical stress, *O* decreases progressively.

Furthermore, the efficiency for airflow *E* is also introduced to describe the key feature of macro-pore shape (Blackwell et al., 1990):

$$E = \log(O) / (V_a / V) \tag{4}$$

where *E* represents the magnitude of the slope of *O* - V_a/V curve.

Figure 7a presents the relationship between *E* and k_a of both untreated samples S5L0 and S04L0 in semi-logarithmic scale. Generally, the data of samples S5L0 and S04L0 merge rather well on a unique curve. This indicates that *E* of untreated soils with different aggregates sizes (D_{max} = 5 and 0.4 mm) is strongly related to k_a. Figure 7b shows that samples S5 with larger aggregates have the values of *E* ranging from -9 to 2.4 log (μm²). Moreover, the lime-treated samples S5 have a similar behaviour with untreated samples: all the data of samples S5 are located on a unique curve. Figure 7c shows that the untreated S04 samples have the values of E lower than -9 log (µm²). However, the lime-treated S04 samples behave a little differently: the points of treated samples S04 do not seem to be located on a unique curve.

DISCUSSION

By comparing the compression curves of lime-treated with those of untreated soils, it appears that lime treatment substantially reduces the compressibility of soil. The yield stress is also increased by lime treatment. This can be related to the fundamental processes occurring during lime treatment. Firstly, the short-term flocculation/aggregation caused by cation exchanges decreases the plasticity of soil, leading to an increase of yield stress (Nalbantoglu & Tuncer, 2001) and a decrease of compression index (C_c) (Rajasekaran & Rao, 2002). Secondly, the cementitious compounds produced in the long-term pozzolanic reactions greatly modify the compression behaviour of treated soil (Nalbantoglu & Tuncer, 2001; Rajasekaran & Rao, 2002; Rao & Shivananda, 2005). These cementitious compounds coat the surface of soil particles, and bond them together, reducing the soil compressibility. Thus, both the short-term and long-term lime treatment explains the decrease of ε_v and the increase of E_{oed} over curing time.

As far as the aggregates size effect on the compression behaviour is concerned, the treated soil with smaller aggregates (S04) exhibits lower ε_v and higher E_{oed} compared to that with larger aggregates (S5) at the same stress level. Moreover, more significant improvement in terms of oedometric modulus E_{oed} is observed over curing time in the case of smaller aggregates. This can be explained by the larger quantity and the more homogeneous distribution of cementitious compounds with smaller aggregates (Wang et al., 2017). At longer curing time, this aggregate size effect becomes more significant, because of the more cementitious compounds created in the soil with smaller aggregates.

The compression process by increasing vertical stress (σ_v) decreases the void ratio (e) and air-filled porosity (V_a/V), modifying the air permeability of soil. The results obtained show that at the beginning of compression when the stress is lower than the yield stress, k_a remains almost constant with a very small slope of plot k_a-σ_v. Under further loading, irrecoverable plastic strain occurs by significant modification of soil structure. Therefore, k_a is greatly affected by the modification of soil structure. The particular increase observed during compression can be attributed to possible openings of some macro-pores which were formed during the sample preparation. Furthermore, it is also noticeable that no airflow can be detected for sample S5L0 at σ_v = 1500 kPa, and sample S04L0 at σ_v = 2730 kPa. However, all the treated samples (both S5 and S04) still allow airflow after application of the greatest stress. This suggests that in the case of untreated samples, the compressibility is larger and the pores available for airflow are quickly collapsed when the stress reach a certain level. By contrast, some pores can still be preserved for the treated samples at the same stress level, allowing further airflow.

Basically, the air permeability of soil is mainly influenced by the structure of macro-pores. It is observed that the air permeability of the samples prepared with large aggregates (D_{max} = 5 mm) is generally one order of magnitude higher than that of the samples prepared with smaller aggregates (D_{max} = 0.4 mm). This can be ascribed to the larger macro-pores of samples S5 (Wang et al., 2015). Even though the samples prepared with different sizes of aggregates present the same air-filled porosity (V_a/V), they have different pore size distributions and different shapes: in the case of S5, the large macro-pores form a better pore continuity leading to a higher air permeability, while in the case of S04, the smaller macro-pores form a more complex arrangement and lower continuity, resulting in a much lower air permeability.

Parameter E is used to describe the efficiency for airflow, which mainly represents the dominant morphology of macro-pores. Generally, data of untreated samples S5L0 and S04L0 merge rather well on a unique curve in E-k_a plot. This curve indicates the evolution of E-k_a relationship upon the compression process. The dominant morphology of the macro-pores in samples S04L0 at the beginning of compression is close to that in samples S5L0 under the last applied load. To some extent, the aggregate size effect on the E-k_a relationship is more like the effect of compression. In the case of lime-treated samples with large aggregates (D_{max} = 5 mm) an E-k_a relationship similar to that of untreated sample S5L0 is identified. This suggests that lime treatment has less effect on the airflow efficiency in the samples prepared with large aggregates. This can be explained by the large macro-pores in the samples with D_{max} = 5 mm. Lime-treatment slightly reduces the entrance size of both macro-pores and micro-pores, without significantly modifying the efficiency for air transfer. By contrast, the lime-treated samples prepared with smaller aggregates (D_{max} = 0.4 mm) show a relatively lower E value with lower corresponding k_a in comparison with the untreated samples at the beginning of compression. This suggests that the dominant morphology of macro-pores with small entrance size can be more sensitive to lime treatment. Besides, more cementitious compounds are expected in the case of smaller aggregates, leading to the decrease of the efficiency of airflow.

CONCLUSION

This study investigates the compression behaviour and air permeability of a lime-treated soil, with emphasis put on the effects of aggregate size. Based on the results obtained, some conclusions can be drawn, as follows:

- Lime treatment reduces the soil compressibility and increases the oedometer modulus E_{oed} of soil due to both the flocculation/agglomeration and the production of cementitious compounds. Furthermore, aggregate size significantly influences E_{oed}: smaller aggregates present higher E_{oed} due to a better lime distribution and more production of cementitious compounds.
- The air permeability of soil with large aggregates is one magnitude larger than that of soil with smaller aggregates at a given value of V_a/V. This is due to the different modal sizes and the different dominant morphology of macro-pores.
- Lime treatment has less impact on the organization of macro-pores and efficiency of airflow for larger aggregates; by contrast, lime treatment substantially modifies both the size and the morphology of macro-pores for smaller aggregates, suggesting more cementitious compounds produced and the high sensibility of the smaller macro-pores to airflow in this case.

ACKNOWLEDGEMENTS

The support from China Scholarship Council (CSC) and Ecole des Ponts ParisTech are gratefully acknowledged.

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List of Figures

Figure 1 Grain size distribution of natural silt and aggregate size distributions of soils S5 and S04

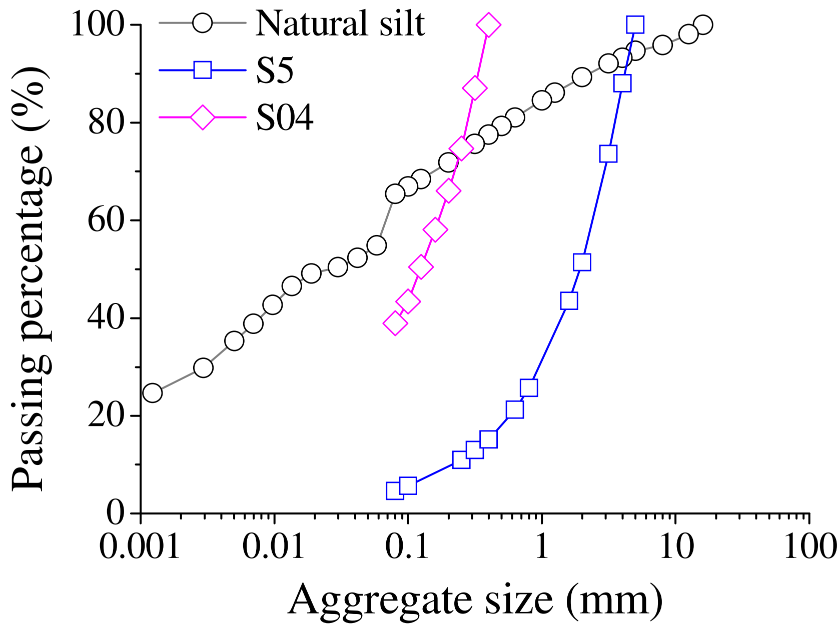


Figure 2 Sketch of the air permeability measurement system (after Yoshimi and Osterberg, 1963 and Delage *et al.*, 1998)

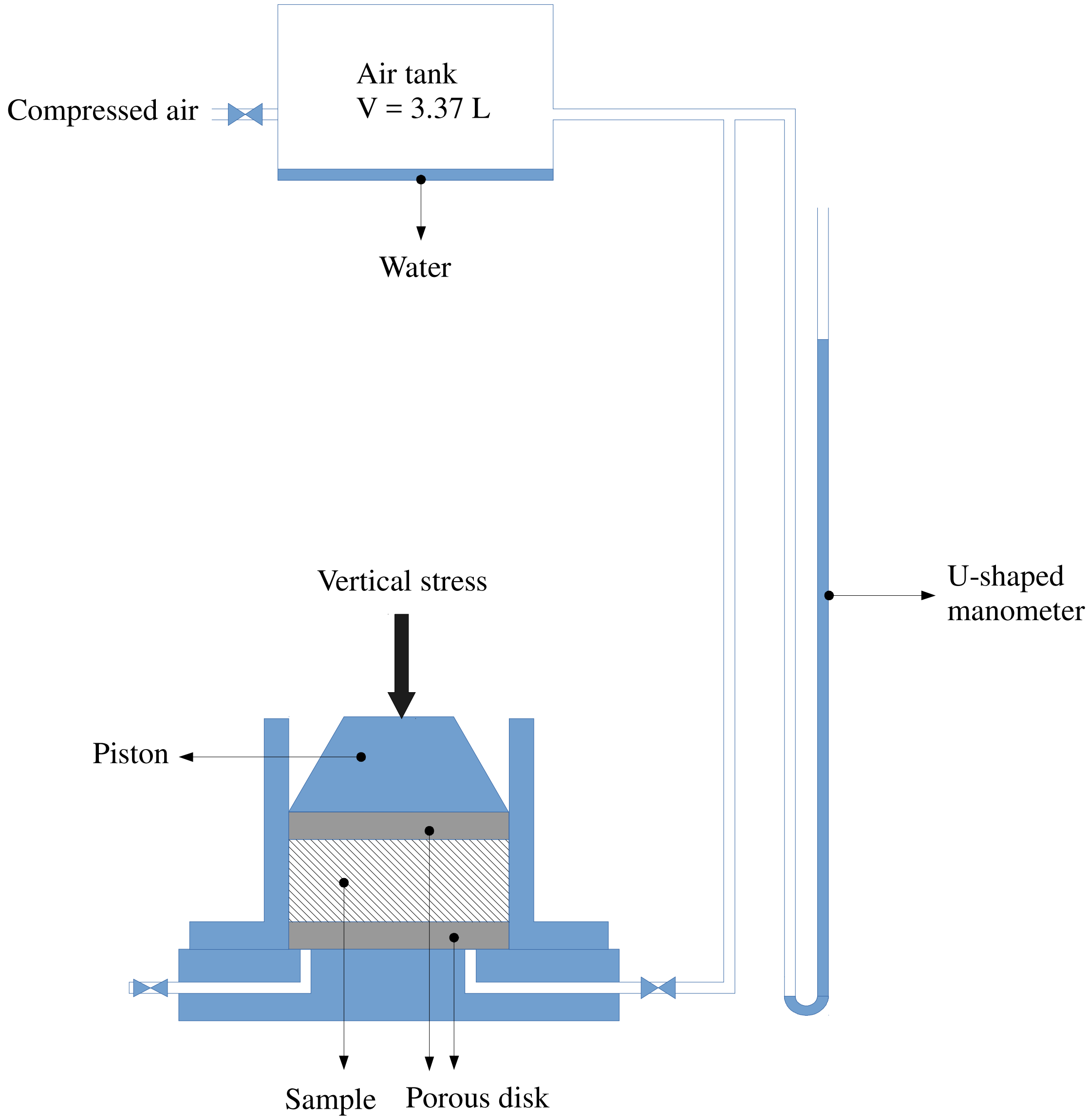


Figure 3 Compression curves of lime-treated and untreated soils: (a) plot e-σ_v of S5; (b) plot e-σ_v of S04; (c) plot ε_v-σ_v of S5; (d) plot ε_v-σ_v of S04; (a) plot E_{oed}-σ_v of S5; (b) plot E_{oed}-σ_v of S04

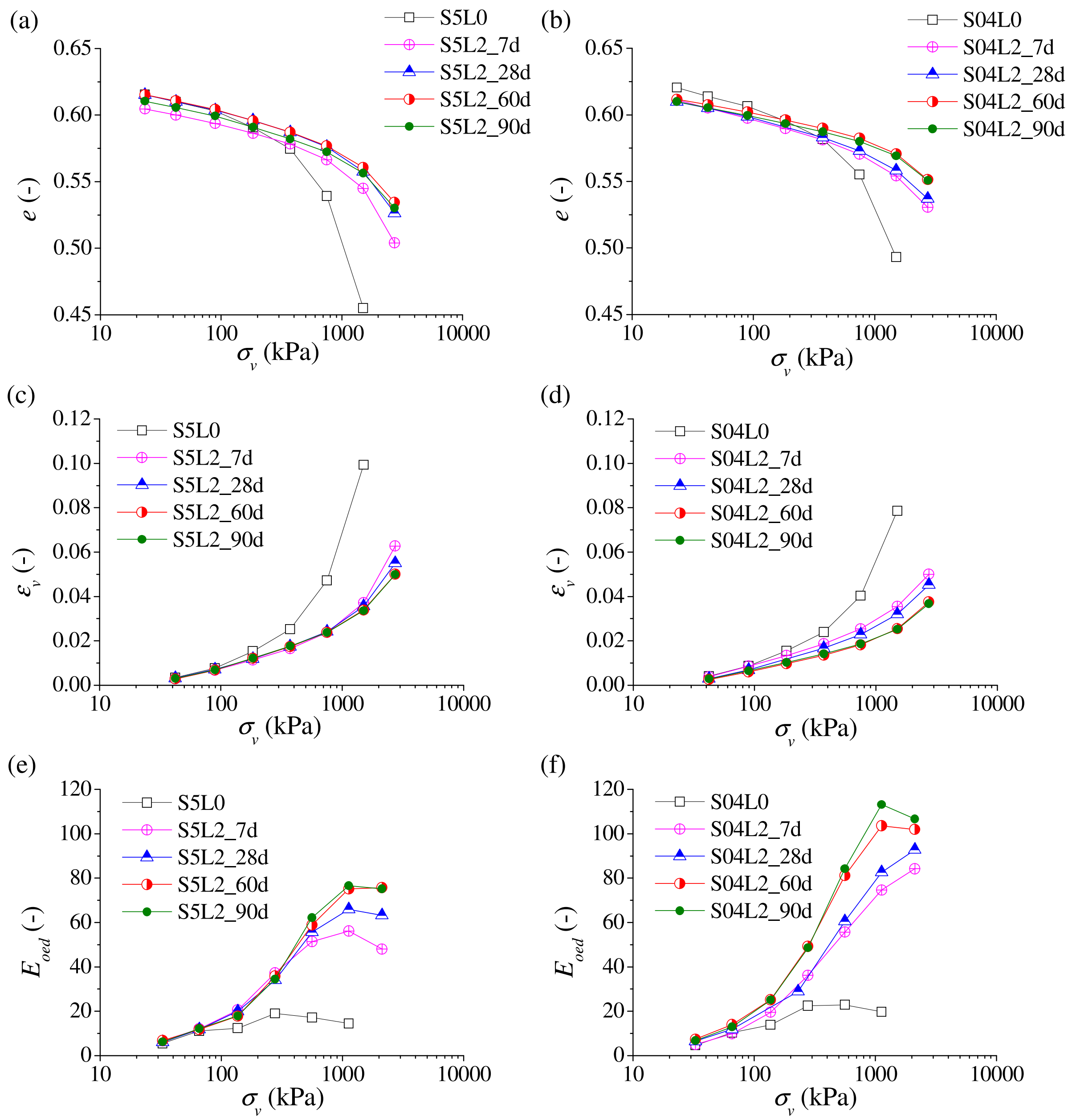


Figure 4 Air permeability versus vertical stress for S5 (a) and S04 (b)

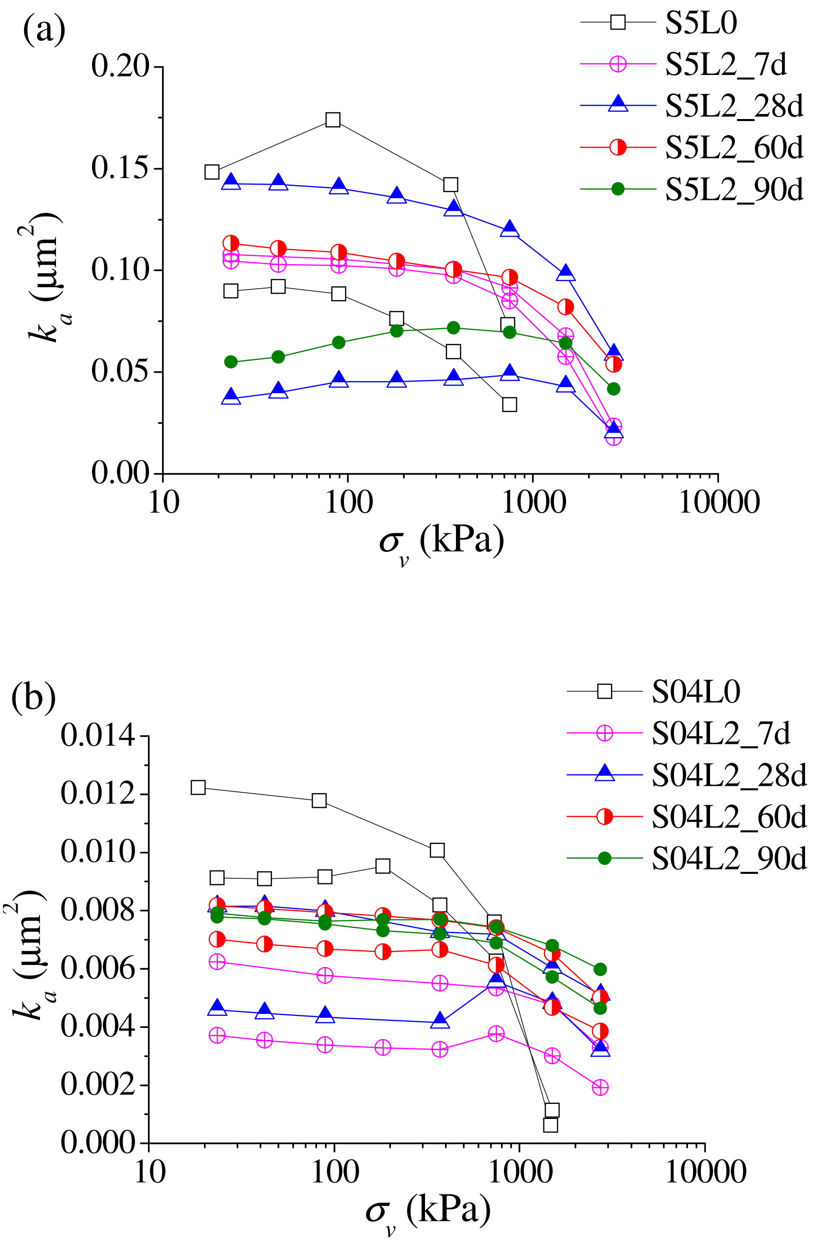


Figure 5 Air permeability versus air-filled porosity for S5 (a) and S04 (b)

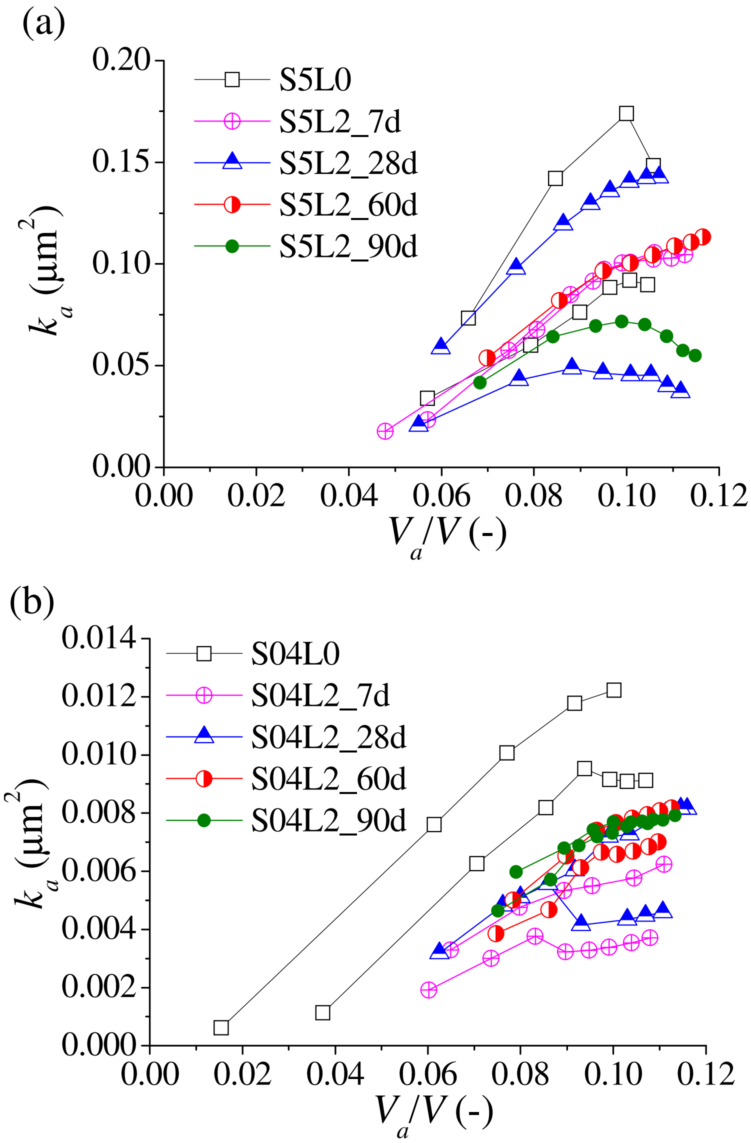


Figure 6 (a): Organization (*O*) versus air-filled porosity for S5 (a) and S04 (b)

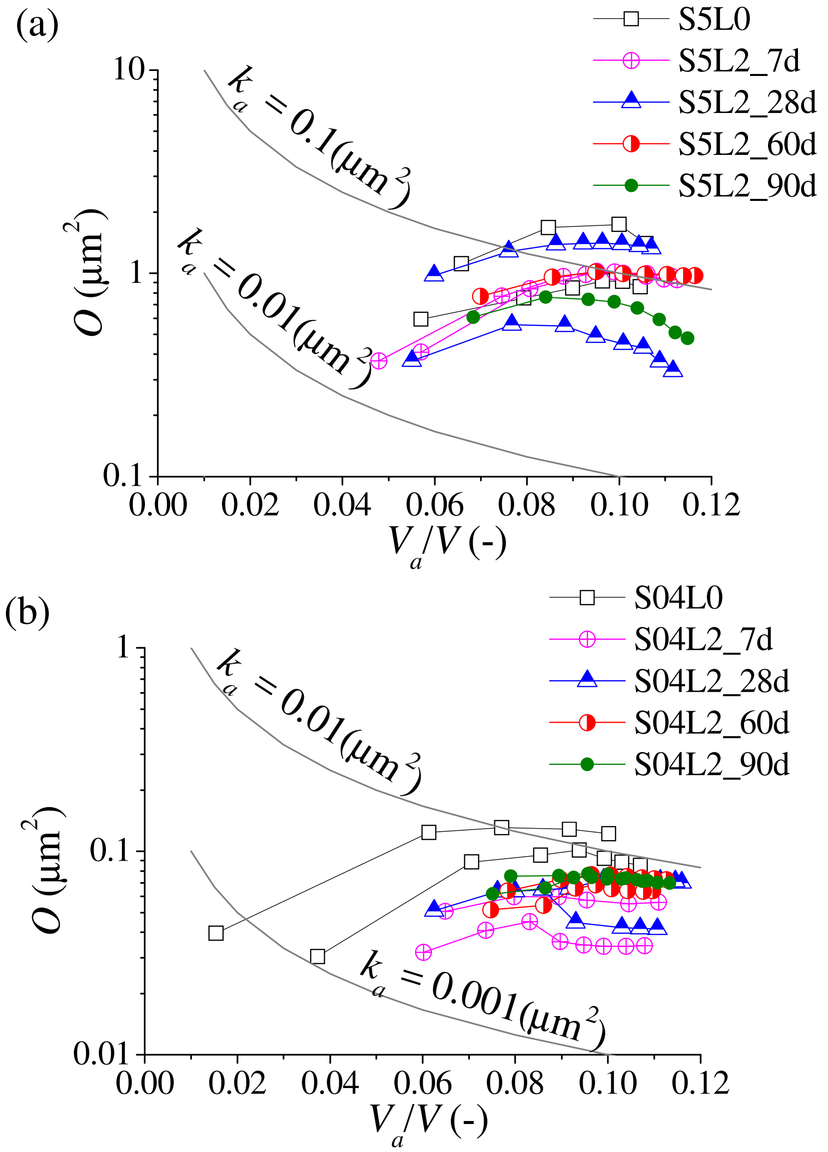
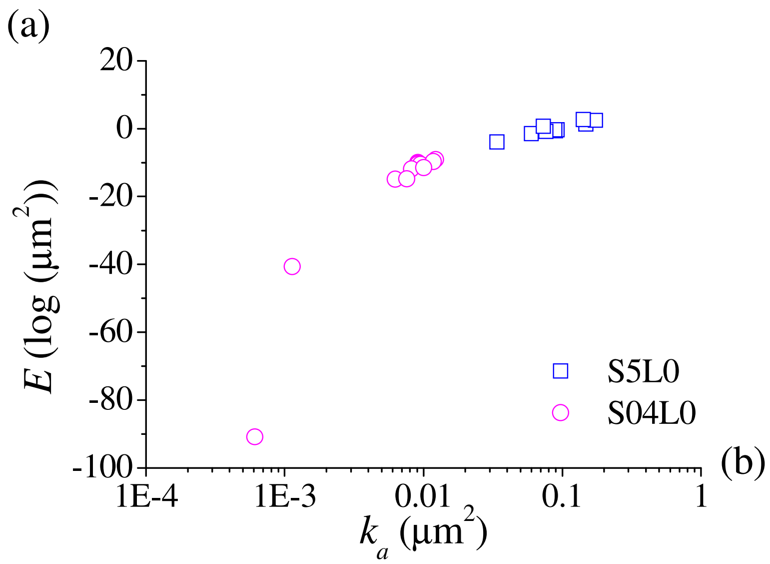
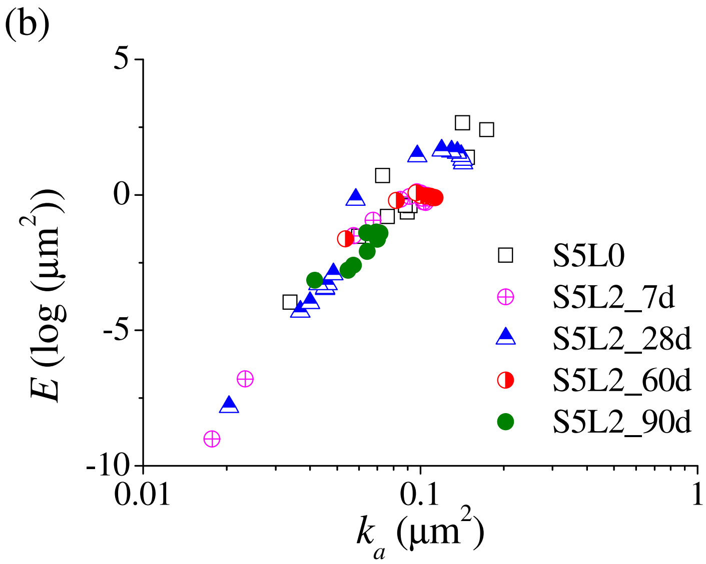
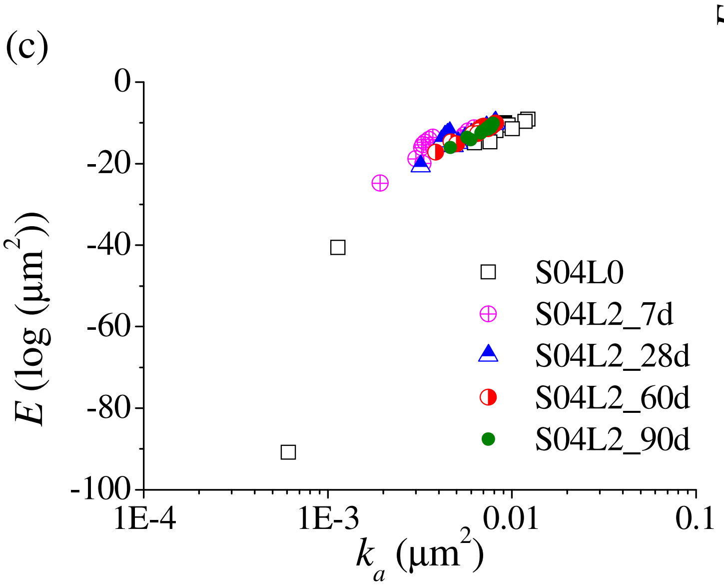


Figure 7 Efficiency of the organization of the pore space (*E*) versus air permeability for untreated soils (a),


(a)
20
0
-20
-40
-60
-80
-100
E (log (μm²))
1E-4
1E-3
0.01
0.1
1
k_a (μm²)
S5L0
S04L0


(b)
5
0
-5
-10
E (log (μm²))
0.01
0.1
1
k_a (μm²)
S5L0
S5L2_7d
S5L2_28d
S5L2_60d
S5L2_90d

S5 (b) and S04 (c)


(c)
0
-20
-40
-60
-80
-100
E (log (μm²))
1E-4
1E-3
0.01
0.1
k_a (μm²)
S04L0
S04L2_7d
S04L2_28d
S04L2_60d
S04L2_90d