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Physicochemical and microstructure evaluation in lime-treated silty soil exposed to successive wetting-drying cycles submitted to different testing conditions.

Geetanjali Das¹; Andry Razakamanantsoa²; Gontran Herrier³; Dimitri Deneele⁴

¹Ph.D student, Université Gustave Eiffel, Laboratoire GERS-GIE, F-44344 Bouguenais, France (corresponding author). ORCID: <https://orcid.org/0000-0003-0573-9077>.

E-mail : geetanjavidas55@gmail.com

²Researcher, Université Gustave Eiffel, Laboratoire GERS-GIE, F-44344 Bouguenais, France. E-mail : andry.razakamanantsoa@univ-eiffel.fr

³Formerly Senior Research Engineer, Lhoist Recherche et Développement, rue de l'Industrie 31, 1400 Nivelles, Belgium. Email : gontran.herrier@gmail.com

⁴Researcher, Université Gustave Eiffel, Laboratoire GERS-GIE, F-44344 Bouguenais, France. Researcher, Université de Nantes, CNRS, Institut des Matériaux Jean Rouxel, IMN, F-44000 Nantes, France. E-mail: dimitri.deneele@univ-eiffel.fr

Abstract

Physicochemical-and microstructural-evolution in lime-treated soil subjected to successive wetting and drying (W-D) cycles were investigated, and the relevancy of the laboratory-implemented testing condition with in-situ conditions was discussed. Lime-treated soils were exposed to 17 W-D cycles using different testing conditions. Two laboratory testing conditions were operated at laboratory temperature, consisting of W-D duration representing the saturation level close to the one experienced in in-situ soil during rainy-and drought-periods. The results obtained were interpreted with those obtained using the reference ASTM procedure, which involves oven-drying of specimens at 71°C. Drying of lime-treated soil at 71°C reduced the water content from about 20% to 0.85%. This has led to greater contact between soil particles, thus, increasing the suction from about 143.5 MPa to 270 MPa. Such a phenomenon increased the Unconfined Compressive Strength (UCS) of the oven-dried soil up to about 3 times compared to the air-dried specimen, though the available cementitious bonding reflected by the presence of pores smaller than 3000 Å was comparatively low in the former than the latter. Percentage leaching of calcium components with respect to the initial calcium content of the soil was significantly low during W-D cycles due to greater exposure of only the outer part of the compacted soil structure during wetting. However, the leaching was comparatively higher in the oven-dried soil. The implemented wetting duration and drying temperature influence the

wetting front velocity of water, which significantly affects the duration taken by infiltrated water to invade the core of an earthen structure, and hence its durability.

Keywords: Wetting and drying cycles; Unconfined compressive strength; physicochemical; microstructure; Lime-treated soil.

Introduction

The sustainability of earth structures by lime treatment was shown to improve through several laboratories (Cuisinier et al. 2011; Runigo et al. 2009; 2011; Shen et al. 2021) and a few field investigations. Some recent in-situ evidence was provided in the study reported by Akula et al. (2020) and Das et al. (2020). Akula et al. (2020) reported the behavior of the Friant-Kern Canal in California, United States, a hydraulic earthen structure built with heavy plastic clay soil. The Friant-Kern Canal suffered severe erosion and slope sliding in the early stages after construction due to the low engineering properties of the plastic soil. Several sections of the Canal were renovated with 4% quicklime during the '70s. Study of up to more than 40 years was conducted to inspect the long-term performance of the lime-treated material used for the repair and reinforcement of the bottom and blankets of the canal. The study evidenced the increased long-term strength, reduction in swelling and shrinkage potential, as well as significant resistance to erosion, thus showing the improved geo-mechanical stability of the structure. Another study, reported by Das et al. (2020), was related to the mechanical and physicochemical performance of a 2.5% quicklime-treated embankment built with silty soil after 7 years of atmospheric exposure. The embankment was exposed to the climate of Rouen, France, which experiences a mostly damp climate throughout the year due to heavy rainfall and frost. However, despite this exposure, an average UCS of $3.29 \pm (0.45)$ MPa was reported in the core of the lime-treated embankment. Additionally, the physicochemical and microstructural investigation evidences the long-term impact of lime treatment towards such significant evolution in compressive strength.

Lime, when added to soil in the presence of water, brings physical improvement in the short-term and chemical modifications in the long-term. The short-term improvement includes decreasing the plasticity of the soil, thus resulting in increased workability of the soil (Diamond and Kinter 1965; Little 1995). In the

long-term, lime undergoes pozzolanic reactions, which form cementitious compounds such as Calcium Silicate Hydrate (CSH), Calcium Aluminate Hydrate (CAH) (Ali and Mohamed 2019a; Mehenni et al. 2016). These compounds play a central role in improving the long-term hydromechanical performance of lime-treated soil.

Although several studies report the improvement brought by lime treatment; however, the performance of lime-treated soil upon its exposure to successive alterations of seasonal temperatures as well as fluctuations in water level is still a concern. Such concern varies with the climate of the specific regions in which the structure is located or constructed. Some field investigations conducted with lime-stabilized roads evidenced that a significant alteration in climatic conditions can negatively impact the performance of lime-treated soil (Cuisinier and Deneele 2008; Kelley 1977). Additionally, several laboratory studies are available that delineated the severity of wetting and drying (W-D) cycles, as well as freeze/thaw cycles on degrading the improved hydromechanical behavior of lime-treated soil (Chittoori et al. 2018; Cuisinier et al. 2020; Nabil et al. 2020). For instant, Chittoori et al. (2018) reported that lime-treated expansive soil containing higher montmorillonite content suffers premature failure during W-D cycles than the one dominant in other clay minerals. Another study reported by Nabil et al. (2020) stated that the severity of W-D cycles impact on lime-treated soil is resistible only for soil treated with greater lime content. The effect of W-D cycles in the field is explained below.

In the field, the slope of the lime-treated hydraulic earthen structure built near water bodies often suffers W-D cycles due to several fluctuations in water level (Chen et al. 2018; Jia et al. 2009; Johansson and Edeskär 2014; Xiong et al. 2019). During heavy rainy periods, due to the rise in water level in water bodies, the slope towards the base of the hydraulic structure may remain underwater for several weeks to months. Such a situation can increase the available saturation level of the soil. On the other hand, during severe drought periods, a drastic decrease in the water level might occur, thus exposing the same base level to severe drying for several months to years, which in turn can decrease the saturation level. Such a fluctuation in the saturation level can modify the mechanical resistivity of the lime-treated soil and might impact the service life of the structure. Though assessment of the durability of lime-treated soil subjected to

W-D cycles was extensively studied, of which most of the studies were made following the testing condition provided in ASTM D559 standard (ASTM 2015). According to the ASTM standard, the soil sample is alternatively immersed in water for 5 hours at laboratory temperature and then placed in the oven for 42 hours of drying at 71°C. The benefit brought by lime treatment was then shown to be partially lost under the impact of alterations of W-D Cycles either by showing the loss in mass or decrease in strength as a function of the number of cycles. However, how well this technique represents the above in-situ W-D situation is less investigated.

Recently, Cuisinier et al. (2020) demonstrated the importance of establishing a field-representative laboratory testing protocol to evaluate the W-D cycles impact on stabilized soil. The study compared results obtained from specimens subjected to W-D cycles as per ASTM standard and by drying at laboratory temperature. It showed that oven-drying and full immersion of specimens during W-D cycles conducted as per ASTM standard led to comparatively greater UCS degradation and increased the hydraulic conductivity values up to two orders in magnitude. This demonstrates the essentiality of investigating the mechanism, which has led to such differences in UCS, and hydraulic conductivity based on the implemented testing conditions.

In this context, this study focuses on analyzing the physicochemical and microstructure mechanism contributing to the evolution of UCS in compacted lime-treated cured specimens subjected to different testing conditions. It is worth noting that the previous study by Das et al. (2020) demonstrates the long-term effect of lime treatment on the physicochemical and microstructural properties of silty soil after 7 years of atmospheric exposure. This study is aimed to highlight the importance of reproduction of laboratory testing conditions close to the field's weather and soil condition, while evaluating the W-D effect on the long-term performances of lime-treated soil by comparing the UCS, physicochemical and microstructural evolution. Two laboratory testing conditions were proposed to represent the W-D cycles lime-treated soil may experience in the field. The results obtained were compared with the respective results obtained using the reference ASTM standard. The first part of the study focuses on comparing the UCS evolution and volume variation of the specimens. Later, the physicochemical and microstructure characteristics are presented. In

the end, the mechanism correlating the physicochemical and microstructure properties with the UCS evolution is explained.

Properties of Soil and Lime

The soil used was silty soil imported from Marche-Les-Dames (Belgium). The geotechnical properties of the soil, which is obtained from the study reported by Nguyen et al. (2019) are presented in Table 1. The mineralogy of the soil was obtained by X-ray diffraction, which showed the presence of Illite, Kaolinite, and Chlorite as clay minerals, along with Quartz and Feldspars (Nguyen et al. 2019).

Quicklime (CaO) was used for the treatment. The lime consists of 90.9% of available CaO and a reactivity (t_{60}) of 3.3 min. The Lime Modification Optimum (LMO) of the silt was determined by Eades and Grim test as per ASTM standard D 6276-99a (ASTM 2006) and was found to be 1% by weight of lime. The Lime Modification Optimum is defined as the minimum amount of lime that is essential to initiate the hydration reaction between lime and soil (Cherian and Arnepalli, 2015; Little, 1987). However, in field practice, to ensure a long-term pozzolanic reaction between lime and soil as well as the enhancement of its hydromechanical performances, the quantity of lime to be added is recommended to be higher than LMO (Runigo et al., 2001; Das et al., 2022). Thus, lime content, 1.5% higher than LMO, *i.e.*, equal to 2.5%, was used herein. Also, this 2.5% of quicklime was shown to be sufficient to bring significant long-term improvement in a full-scale experimental embankment built using the studied soil by Das et al. (2020). Besides, this embankment was previously studied by Makki-Szymkiewicz et al. (2015), where the permeability performance of the lime-treated soil is reported. Hence, 2.5% quicklime content is chosen in the present study to keep the continuation of any necessary comparison required to be made with previous studies.

Sample preparations

The maximum dry density, $\rho_{d(max)}$, and Optimum Moisture Content (OMC) of the untreated and the lime-treated silty soil were obtained as per ASTM D698-12e2 (ASTM 2012) (Table. 2).

The silt was mixed with distilled water at a water content of $1.1 \times \text{OMC}$, *i.e.*, specimens were prepared at the wet of optimum (WMC). This is because a compaction moisture content similar to the one reported by Das et al. (2020) was maintained, which involved a study regarding the performance of an in-situ embankment built with the present soil configuration. The soil mixture was then stored in sealed plastic bags to allow moisture content homogenization for about 24 hours. The soil mixture was then mixed with lime and rested for 1 hour before compaction. This process of soil preparation was as per the French GTS Technical Guide for soil treatment (GTS - LCPC-Setra Technical Guide 2000).

Cylindrical specimens of dimensions 0.10 m in height and 0.05 m in diameter were prepared by the static compaction method at WMC. The process of static compaction involves compression of the specimens from top and bottom, as demonstrated by Holtz et al. (1981). A total of 2 untreated and 14 lime-treated specimens were prepared, of which 4 lime-treated specimens were presented in Fig.1. After compaction, specimens were wrapped in plastic film and then subjected to curing at a laboratory temperature of 20 ± 1 °C. A 10 month curing time was implemented herein, considering it the longest laboratory implemented curing time to have the most suitable results in a one-year time frame.

Laboratory Experiments

This section explains the testing conditions developed, followed by tests performed successively in the study.

Testing conditions for Wetting and drying cycles

The W-D cycles were imposed as per the ASTM standard and using two laboratory-developed testing conditions. The testing condition implemented as per the procedure demonstrated in ASTM D559, which involves 5 hours of wetting at laboratory temperature followed by 42 hours of oven-drying at 71°C is denoted as AP. Fig. 2 shows the wetting and drying of the AP subjected specimens. The second and third testing conditions were proposed to represent the situation a soil might experience in the field during rainy and drought seasons, respectively.

Alteration of W-D cycles brings an increase and then decrease of the soil-saturation level, respectively. During rainy periods, when the slope towards the base of the hydraulic earthen structure remains under water for a long time, the soil can be assumed to have attained a maximum saturation level of 85-90%. Again, due to the greater frequency of precipitation during the rainy season, the soil can be assumed to have reach a saturation level not less than 65-70% during the drying period, when the water level in the water bodies decreases for a certain period. Similarly, the soil was assumed to dry up to a saturation level of 25-30% during the drought season, and considering the slightest rainfall that can probably happen during the drought period; the soil was supposed to reach a maximum saturation level of only 65-70%. For the present lime-treated soil, the duration required to attain the above assumed saturation level during rainy and drought periods was measured in the laboratory, during which the temperature and relative humidity varied from 22.1-25.2°C and Relative Humidity (RH) of 34.3-52.8%, respectively. The present study considers the laboratory temperature and RH as the reference condition to highlight the essentiality of considering the field conditions. The obtained wetting and drying duration were then used to undergo successive W-D and drying-wetting cycles to represent the rainy and drought situations, respectively. The testing conditions and the duration required to attain the assumed levels of saturation are provided in Table 3. The second and the third testing conditions, which represent the rainy periods and drought periods, respectively, are regarded as RP and DP, respectively, in the following study. It is worth noting that specimens subjected to AP and RP experience alternate W-D cycles, whereas specimens subjected to DP experience alternate drying and wetting (D-W) cycles.

The RP and DPs were conducted by a laboratory proposed device, which involves successive wetting of the specimens by soaking in water for the proposed time and then drying the same by allowing the water to move out after completion of the wetting duration. A part of the water after each wetting, *i.e.*, the effluent, was stored for chemical analysis. A total of 17 wetting-drying and drying wetting (W-D/D-W) cycles were operated using the three testing conditions. This is because, within the time frame of one year, 10 months were used for curing, and in the remaining 2 months, 17 was found to be the maximum number of cycles that can be achieved for all the testing conditions. The mass and volume of the specimens subjected to all three conditions were recorded at the end of each cycle. During these measurements, samples were carefully handled, and the excess water around the specimens was wiped off to avoid any error in the measurements. To establish the homogeneity of the specimens, they were periodically turned during the alternate cycles.

Of the 14 lime-treated specimens prepared and cured, three sets of 4 specimens were subjected to the three testing conditions, and the remaining 2 were used to evaluate the initial state of the specimen after 10 months of curing.

Unconfined Compressive Strength measurement

10 months cured specimen, *i.e.*, the initial specimen, and the specimens subjected to 5th, 9th, 13th, and 17th alternate W-D/D-W cycles in each of the three testing conditions were subjected to UCS test using a mechanical press with a load sensor of 10 KN. The load was applied to the specimens at a constant axial displacement rate of 1 mm/min.

Measurement of Physicochemical properties

The water content of each UCS-subjected specimen was measured by oven drying at 105°C (ASTM D2216-10) and was used to estimate the water content corresponding to the remaining cycles. The suction of the UCS subjected specimen was determined using the WP4C Dewpoint Potentiometer. The pH of the UCS subjected specimens was also measured. Specimens collected at the end of the UCS test were crushed and

then mixed with demineralized water in a 5:1 liquid: solid ratio for 1 hour, and then the pH of the solution was recorded (ASTM D4972-19). To have more reliable results, at least an average of the three values of preceding properties was reported.

The Electric Conductivity (EC) of the effluents collected after each wetting was determined by a Water Quality Meter. A part of the collected effluent corresponding to a certain number of wetting cycles was filtered using a 0.45 μm syringe and then subjected to Inductively Coupled Plasma Optical Emission Spectrometry (ICP OES) analysis. This was done to determine the elementary concentrations of Calcium (Ca) that have been leached from the lime-treated soil subjected to W-D/D-W cycles.

Pore structure determination

Pore Size Distribution (PSD) was analyzed by Mercury Intrusion Porosimetry (MIP) test and Barrett-Joiner-Halenda pore (BJH) method (Barrett et al. 1951). Since MIP was known to investigate macropores and BJH, the mesopores more elaboratively, as shown by Das et al. (2020); hence both the methods are used herein. The analysis was made on the freeze-dried samples gathered from the core of the 10 months cured specimen and the specimens subjected to the UCS test.

During the MIP test, mercury (Hg) was progressively intruded into freeze-dried specimens contained inside a sealed penetrometer after the evacuation of the specimen via heating. The intruded Hg volume and the corresponding applied pressure, p (MPa), were registered, using which pore sizes were obtained from the Washburn equation (Romero and Simms 2008). Similar, to the MIP test, freeze-dried samples were degassed at 50°C, and then nitrogen gas was injected during the Brunauer-Emmett-Teller (BET) test (Brunauer et al. 1938). From the isotherms obtained in the freeze-dried specimens, the BJH method analyzes the PSD using the Kelvin equation. The discussion of pore structure is presented as per the International Union of Pure and Applied Chemistry (IUPAC) (Rouquerol et al. 1994), which classifies pores based on their pore-width as macropores ($> 500 \text{ \AA}$), mesopores ($20\text{-}500 \text{ \AA}$), and micropores ($< 20 \text{ \AA}$).

Results

This section is focused on presenting the observation made with the results, and then the mechanism behind such observations is followed up in the discussion section.

W-D/D-W cycle influence on UCS evolution

The untreated compacted silty soil was destroyed when submitted to the first wetting cycle, as shown in Fig. 3; hence, no UCS test and any further tests could be conducted with the untreated specimens.

The UCS evolution of the lime-treated soil subjected to 17 W-D/D-W cycles as per the 3 testing conditions is presented in Fig. 4. The UCS of the initial specimen after 10 months of curing was measured to be 1.26 MPa. This UCS increased to 3.40 MPa after the lime-treated soil underwent 5 cycles of W-D cycles as per the AP (Fig. 4). Further increase in the W-D cycles brought a slight decrease in the UCS to about 3.26 MPa after the 9th W-D cycle compared to the UCS attained after the 5th cycle. This UCS decreased significantly to 2.28 MPa, and 1.57 MPa after the 13th, and 17th W-D cycles, respectively. Thus, the UCS of the AP-subjected soil increased significantly after the 5th and 9th W-D cycles and then decreased. However, the overall evolution of UCS throughout the 17 W-D cycles remained higher than the UCS obtained with the initial specimen.

For the RP-subjected soil, the UCS decreased slightly to 1.04 MPa after the 5th W-D cycle and then reached a value that was about 0.40 MPa higher than the initial UCS after the 9th W-D cycle. After 13th W-D cycle, the UCS again decreased to a level similar to the one attained after the 5th W-D cycle and then remained the same as the initial UCS after the 17th W-D cycle. However, compared to the initial UCS, the overall fluctuations observed in the evolution of UCS with the RP-subjected specimens were significantly less than the one attained with the corresponding AP-subjected specimens throughout the 17 W-D cycles.

The UCS of the DP-subjected soil showed a gradual decrease up to the 13th D-W cycle, and then after the 13th and 17th D-W cycles, the obtained UCS was almost similar.

W-D/D-W cycle influence on volume variations

The change in volume of the specimens during W-D/D-W cycles is presented as a percentage increase or decrease in the volume of respective specimens compared to the volume of the initial specimen in Fig. 5 (a-c). The presented percentage change in volume is the average of the volume change obtained during the 17 W-D cycles of the 4 specimens subjected to each RP, AP, and DP.

The amplitude of average volume changes between the wetting and drying phase and between 2 successive cycles during the W-D cycles remained less significant in the specimens submitted to the RP testing condition (Fig. 5a). A maximum increase and decrease of about 0.8% in the average volume occurred compared to the initial volume.

Compared to the initial volume of the specimen, the AP submitted specimens showed a slight increase in average volume during the 1st wetting, and then the volume decreased by about 2% after the 1st oven-drying (Fig. 5b). In the successive W-D cycles from 1st to about 8th cycles, the amplitude in average volume variations between the wetting and drying phase remained almost similar, where the increase and decrease in the average volume was less than 1% and 2%, respectively than the initial volume. The fluctuation in the average volume variation was then lowered in the following W-D cycles. However, the maximum increase in average volume during wetting remained lower by about 0.4% compared to the initial volume throughout the 17 W-D cycles.

DP-subjected soil underwent a maximum decrease in average volume during drying of about 1.5%, and the maximum increase in average volume corresponds to the initial volume from the 1st to about 7th D-W cycles. For the remaining cycles, the loss in the average volume was almost insignificant (Fig. 5c). The overall trend observed in the average volume variation between the AP, and the DP submitted specimens were almost the same. However, the percentage of average volume loss after each drying was comparatively higher in the AP compared to the DP-subjected soil. On the other hand, the percentage increase in average volume after each wetting was relatively higher in the DP than the AP-subjected soil.

W-D/D-W cycle influence on water content variations in the specimens

The water content was measured for the 10 months cured soil and for the specimen subjected to UCS test after 5th, 9th, 13th, and 17th cycles. The water content corresponding to the remaining cycles was then estimated by using the bulk mass of the soil measured after each cycle and the dry mass of the soil measured at the end of the 17th cycle. This method of back estimation was approved in ASTM D559. The evolution of average water contents is presented in Fig. 5 (d-f).

According to Fig. 5d, a maximum of 2% increase and decrease in the average water content occurred during the wetting and drying phases, respectively, at laboratory temperature in the RP-subjected soil throughout the 17 W-D cycles. This increase and decrease in the average water content were found to almost correspond with the average maximum and minimum saturation level set earlier for the RP testing condition. The global trend of average water content evolution between 2 successive wetting and drying cycles remained almost constant.

Similar to the RP-subjected soil, the overall trend in the variation of the average water content between the wetting and drying phases and between 2 successive cycles remained almost constant in the AP-subjected soil (Fig. 5e). About 1% increase in the average water content compared to the initial water content occurred during every 5 hours of wetting at laboratory temperature; however, almost a complete loss in water content occurred during each 71°C oven-drying of the AP submitted soil.

In the DP submitted soil, the increase in average water content level during each wetting remained almost at a similar level, which was equivalent to the initial water content (Fig. 5f). However, a mean loss in average water content of about 13% occurred during the D-W cycle compared to the initial water content. The increase in average water content attained during almost each wetting, though corresponds with the average saturation level set for the DP testing condition, the average saturation level has fluctuated during the drying in certain number of cycles.

W-D/D-W cycle influence on soil suction and soil pH evolution

At the end of the UCS test, the soil suction and pH of the soil were measured and presented in Fig. 6 for each testing condition, with the soil suction and soil pH recorded from the initial soil.

As expected, the soil suction of the AP submitted soil increased significantly in comparison to the initial suction of the soil due to almost total loss in water content (as seen in Fig. 5). The soil suction increased to 143.5 MPa after 5th cycle, then it increased to 270.0 MPa after 9th cycle and then remained approximately unchanged for the 13th and 17th cycles. The difference in the soil suction measured for the corresponding RP submitted soils remained less significant compared to the initial soil suction (Fig. 6a). The soil suction decreased for the DP-subjected soil up to 9th cycle, and then this decrease was slightly lowered after the 13th and 17th D-W cycles.

The pH measured for the initial specimen was 11.86. For the RP-subjected soil, this pH remained approximately unchanged up to 17th cycle (Fig. 6b). The pH of the AP-subjected soil decreased to 10 from the initial soil pH after the 5th cycle. The pH then further decreased; however, the decrease was relatively lower and remained above 9.3. Similar to the AP submitted soil, the pH of the DP submitted soil also decreased compared to the initial pH of the soil (Fig. 6b).

W-D/D-W cycle influence on Ca concentration and EC evolution in the effluents

Fig. 7 presents the concentration of *Ca* and EC measured in the effluents collected during the W-D/D-W cycles conducted as per the testing conditions. The initial CaO in the untreated silty soil was estimated as 0.5%, and 2.5% of CaO was added during specimen preparation. Thus, the lime-treated soil consists of 3% CaO before curing. The *Ca* content in the 3% of the CaO, *i.e.*, $Ca_{initial}$ was estimated, and the release of *Ca* measured in the effluent, *i.e.*, $Ca_{leached}$ was then expressed as a percentage of the former in Fig. 7a.

The percentage of *Ca* leached from the lime treated soil was observed to be extremely low in all the specimens, regardless of the testing conditions (Fig. 7a). However, the loss of *Ca* and the magnitude of EC obtained were relatively higher in AP-subjected soil compared to the corresponding RP-subjected soil throughout the W-D cycles. The trend of the loss in *Ca* concentration and the measured EC decreased during the W-D cycles for the AP-subjected soil. On the other hand, this trend remained almost constant for the corresponding RP-subjected soil.

For the specimens subjected to DP testing conditions, the leaching of Ca and EC measured remained relatively lower than both RP and AP-subjected specimens, and the overall evolution was almost similar throughout the D-W cycles (Fig. 7b).

W-D/D-W cycle influence on pore structure modifications

The PSD and cumulative pore volume evolution in the lime-treated W-D/D-W cycles subjected specimens were compared with the one obtained from the untreated and the 10 months cured soil by MIP and BJH, respectively, in Fig. 8.

Determination of PSD by MIP

Fig. 8 showed that the untreated soil exhibits greater intensities of macropores of diameter in the range of 10^4 and 10^5 Å. After lime treatment and 10 months of curing, macropores of diameter 10^5 Å evolved, a significant decrease of macropores of diameter 10^4 and 10^5 Å and an increase in pores smaller than 3000 Å occurred (Fig. 8(a-c)). Pores of diameter 10^5 Å were due to agglomeration of lime-treated soil, while pores smaller than 3000 Å evolved because of cementitious bonding as reported in previous studies (Das et al. 2021; 2022; Cuisinier et al. 2011).

On subjecting the 10 months cured lime-treated soil to the W-D cycles as per the AP testing condition, macropores of diameter 10^4 Å increased, and the broad pore peak developed in the 10 months cured soil over pores smaller than 3000 Å was narrowed down during the W-D cycles (Fig. 8a). These features remained almost similar irrespective of the number of W-D cycles the specimens were subjected. On the other hand, 10 months cured lime-treated soil, despite being subjected to over 17 cycles of W-D as per the RP, showed no significant change in the broad pore peak developed over a pore range smaller than 3000 Å (Fig. 8b). A slight insignificant rise in intensities of pores of diameter 10^4 Å occurred during the W-D cycles.

For specimens subjected to DP, pores smaller than 3000 Å were gradually decreased, and pores of diameter 10^4 Å increased with an increased number of D-W cycles (Fig. 8c).

Determination of cumulative pore volume evolution by BJH

Using the BJH method, the evolution of cumulative pore volume in the pore range 24-250 Å, which comes under the mesopores range, was analyzed and presented in Fig. 8(d-f).

According to Fig. 8(d-f), lime-treated 10 months cured soil showed a significant development of pore volume in the mesopore range 24-250 Å compared to the untreated soil.

For the AP-subjected specimens, after the 5th W-D cycles, the cumulative pore volume in the mesopore range 24-250 Å remained at a similar level to the initial 10 month cured specimen (Fig. 8d). However, after the 9th W-D, these cumulative pore volumes increased by about 1.3 times compared to the initial specimen. Further increase in W-D cycles, *i.e.*, after the 13th and 17th W-D cycles, has resulted in a decrease in the cumulative pore volume by about 1.5 to 1.6 times compared to the initial specimen.

Specimens that underwent W-D cycles as per the RP testing condition showed a minimal difference in the cumulative pore volume in the mesopore range 24-250 Å over the entire 17 W-D cycles compared to the initial specimen (Fig. 8e).

For the DP-subjected soil, the cumulative pore volume in the mesopore range 24-250 Å after the 5th D-W cycles remained at a similar level to the initial specimen (Fig. 8f). This feature then gradually decreased by about 1.1 times in the specimen that has suffered the 9th D-W cycles and by about 2 times in the specimen subjected to the 13th D-W cycles. The cumulative pore volume then remained almost similar for the 17th D-W subjected specimen with the 13th D-W subjected soil.

Discussions

The UCS of a lime-treated soil is the resistance to deformation of the compacted soil structure under unconfined compression. This resistance is a resultant of the inter-and intra-aggregates modifications, which are influenced by the water content (Yin et al. 2018) and cementitious compounds (Little 1995). Thus, during these W-D/D-W cycles, a significant loss or gain in water can modify the inter-aggregate structure of the compacted soil. In the present study, subjecting the lime-treated soil to high drying temperature (71°C

in oven) as per AP testing condition resulted in accelerated pozzolanic reactions between soil minerals and lime (Little 1995; Wang et al. 2017). Concurrently, a total loss of moisture content occurred as measured at the end of each AP's W-D cycle (Fig. 5e). Again, the development of pozzolanic reactions is dependent on water availability (Diamond and Kinter 1965; Little 1995). Hence, the loss in water content and the necessity of water for pozzolanic reactions possibly have created a competition between the pozzolanic reaction and soil suction evolution during the cycles. However, Fig. 6(a) presents a significant increase in total suction of the AP-subjected soil compared to the initial soil suction, and the AP-subjected soil did not show significant evolution of cementitious compounds during the W-D cycle as reflected by the difference in the generation of pores smaller than 3000 Å in Fig. 8a & d. Thus, it can be derived that the high UCS developed in the AP-subjected soil was mostly contributed by the high soil suction generated due to induced contact between soil particles because of water loss. The preceding statement is supported by the less significant evolution of soil suction (Fig. 6a) and UCS (Fig. 4) in the specimens with similar configurations but was subjected to air-drying as per RP and DP testing conditions. Thus, the soil suction developed in the lime-treated soil during successive W-D/D-W cycles possibly contributes to the evolution of UCS.

The insignificant soil suction generated in the RP-subjected soil (Fig. 6a) during the W-D cycle compared to the initial suction is attributed to only 2% average water content loss during every 17 hours of air-drying at 22.1-25.2°C (Fig. 5d). However, though the average water content loss after each air-drying was higher in the DP-subjected soil compared to the RP-subjected soil, due to the longer air-drying of the DP-subjected soil (Figs. 5d & f), the suction evolution was comparatively lower in the former than the latter (Fig. 6a). This was due to the presence of higher water content in the DP-subjected soil, as the soil suction was measured after the wetting phase of the D-W cycles, while suction measurement was conducted after the drying phase of the W-D cycles in the AP-and RP-subjected soil.

The amplitude of the average volume variations between wetting and drying phases and the overall trend of average volume changes in the specimens over the 17 W-D cycles evolved based on the temperatures and durations of wetting and drying applied as per the three different testing conditions (Fig. 5 (a-c)). However, the overall trend of average volume variations was insignificant. Such an observation

can be due to the absence of smectite as a clay mineral in the present silty soil, which is mainly responsible for the volume change behavior of soil (Das and Bharat 2016; Gapak et al. 2017). Also 2.5% quicklime treatment might have subsided the possible ability of the soil to show considerable volume change (Chittoori et al. 2013, 2018). For the RP-subjected soil, owing to the air-drying at 22.1-25.2°C, which caused a minimum loss in average water content, the amplitude of average volume change in each cycle remained almost insignificant compared to the initial volume of the specimen (Fig. 5a). Though DP-subjected soil was also air-dried at 22.1-25.2°C, however, due to 70 hours of drying, which was 53 hours higher than the RP-subjected soil, the amplitude of average volume change was comparatively higher (Fig. 5c). However, the complete evaporation of water in the AP-subjected soil caused the maximum average volume loss of the specimen during each oven-drying (Fig. 5b).

Durability of a hydraulic earth structure is interlinked with the ability of water to flow into the structure. Water flow level can be quantified by the rate at which the wetting front developed during the infiltration of water into the soil (Johnson 1963; Kirkham 2014). This velocity of the wetting front can be said to vary based on W-D cycles created by the in-situ water fluctuations. Thus, a greater wetting front velocity can increase the dampness of the structure and causes the structure to collapse due to loss in mechanical strength (Jia et al. 2009; Johansson and Edeskär 2014). Besides, lime-treated soil is prone to leach more lime if subjected to a greater wetting front velocity (Chittoori et al. 2013; Hara et al. 2008). Thus, considering the wetting front velocity of water as an important parameter, the same was estimated herein for the specimens subjected to W-D/D-W cycles as per the different testing conditions. Using the average increase in the volume of the specimens during each wetting of the W-D/D-W cycles, the average volume flow rate of water (Q) was calculated. From the Q , the average velocity of wetting front (W_f) into the specimens was estimated as per Eq. 1.

$$W_f = Q/A = V_i/A \times t \quad (\text{Eq. 1})$$

where Q is the average volume flow rate of water into the specimens in m^3/s ; V_i is the increase in the average volume of the specimens during each wetting in m^3 ; t is the duration of wetting during each cycle in s; W_f is the average wetting front velocity of water in m/s ; A is the total surface area of cylindrical specimen in m^2 . Since the flow of water into the specimen occurred from all directions during wetting hence, the total surface area of the cylindrical specimen was considered.

Table 4 presents the average of the estimated average W_f of water into the specimens subjected to W-D/D-W cycles as per the different testing conditions. Using the estimated average velocity of W_f , the duration required by the infiltrated water to flow to the center of an in-situ structure of reference thickness 1m was obtained (see Table 4).

The average W_f caused during wetting of the W-D/D-W cycles was maximum for the DP- followed by AP-, and then RP-subjected soil. Correspondingly, the duration estimated for the water to invade the center of an in-situ structure was maximum for RP- followed by AP-, and then DP-subjected soil. Thus, Table 4 evidence that lime-treated soil exhibiting similar configuration on being subjected to W-D/D-W cycles conducted as per different testing conditions can show different W_f which can lead to a difference in the durability of the structures. However, interestingly, the W_f was higher in the DP-subjected soil compared to the AP-subjected soil, though the AP-subjected soil underwent complete evaporation of water during each drying (Fig. 5e). Such an evolution was noticed due to greater amplitude of average volume increase, *i.e.*, swelling during wetting in the DP-compared to the AP-subjected soil (Fig. 5b & c). Studies have reported that oven-drying of soil cause soil aggregation and loss in plasticity, thus, resulting in a reduction of the swelling potential of soil (Basma et al. 1994; Sunil and Deepa 2016). Thus, in the present case, it might be probably due to the preceding statement the swelling was relatively lowered in the AP-subjected soil due to oven-drying. Since the W_f was estimated based on the increase in volume during each wetting thus, it occurred to be lower in the AP- than the DP-subjected soil. Thus, oven-drying of soil may cause an underestimation of the W_f .

Specimens subjected to W-D/D-W cycles showed Ca leaching, which was significantly lower than the Ca content estimated to be present in the soil during sample preparation (Fig. 7a). This is attributed to

the consumption of *Ca* by the pozzolanic reactions during the 10 months curing, thus, probably leaving a limited soluble *Ca* in the soil. Also, the limited contact of the soil structure with water during wetting, which mostly exposes the outer layer of the compacted soil to leach a comparatively higher amount of minerals than the internal soil structure, has led to the presence of such lower *Ca* concentration in the effluent. However, despite the fact that the RP-subjected soil was exposed to longer wetting hours than the corresponding AP-subjected soil, the leaching of *Ca* and EC measured was comparatively higher in the latter than the former (Figs. 7a & b). Such an evolution was due to the complete drying of the AP-subjected soil because of oven-drying, thus, making the soil more vulnerable to loss of minerals during wetting. However, due to only 2 hours of contact of the specimens with water during each wetting as per the DP testing condition, the loss in *Ca* and the measured EC remained relatively lower (Figs. 7a & b).

Additionally, according to Figs. 7a & b, the trend observed in the evolution of *Ca* and EC was almost equivalent. Fig. 9 presents the obtained linear trend for the *Ca* and EC evolution in the W-D/D-W subjected specimens. Such an observation demonstrates the important role of *Ca* component on controlling the EC evolution of the lime-treated soil. Thus, EC can be used as an important parameter to assess the leaching process of *Ca* occurring during the W-D/D-W cycles.

The above discussion shows that specimens subjected to RP testing condition exhibited an insignificant change in soil suction (Fig. 6a), minimum volume and water content variations (Figs. 5a & d), minimum *Ca* loss, and EC evolution (Fig. 7). Thus, the soil pH remained almost unchanged compared to the initial soil pH (Fig. 6b), despite being subjection of the specimens to 17 W-D cycles. The preceding feature favored the conservation of cementitious bonding formed in the 10 months cured soil as evidenced by the almost similar presence of smaller pores lower than 3000 Å (Fig. 8b) and mesopores volume (Fig. 8e) in the RP-subjected soil. On the other hand, a gradual loss in soil pH up to less than 10 from the initial soil pH 11.86 (Fig. 6b) occurred in the AP-and DP-subjected specimens. Fig. 8a & c showed that the significant evolution of pores smaller than 3000 Å in the initial specimen decreased, and macropores at 10⁴ Å increased. The former feature evidenced the possible loss in cementitious bonding, which contributed to the decrease in soil pH, and the latter was probably due to soil shrinkage, thus, inducing crack and increasing

the macropores. In addition to the loss in cementitious bonding, the observed loss in soil pH in the AP and DP submitted soil could also be a consequence of possible carbonation, as reported in previous studies (Deneele et al. 2021; Xu et al. 2020).

However, the observed decrease in pores smaller than 3000 Å compared to the one available in the 10 months cured soil was more significant in the DP-compared to the AP-subjected soil during the D-W and W-D cycles, respectively. Owing to the subjection of specimens to high temperature during each drying, accelerated-pozzolanic reactions were induced (Little 1995; Wang et al. 2017), which probably have resulted in the presence of more pores smaller than 3000 Å in the AP-subjected soils. The preceding statement was evidenced by the pore structure analyzed by both MIP and BJH in Fig. 8a & d, where the pores smaller than 3000 Å increased after the 9th cycle in the AP-subjected soil. Such a feature was missing in the specimens subjected to other testing conditions. Thus, such a phenomenon explains that 5 hours of wetting duration followed by oven-drying at 71°C provides sufficient water to reactivate the generation of cementitious compounds in the AP-subjected soil. Thus, such evolution can overestimate the actual cementitious compounds that can be expected from an in-situ lime-treated soil subjected to W-D cycle.

Additionally, the gradual decrease in pores smaller than 3000 Å with increased D-W cycles in the DP-subjected soil can be attributed to only 2 hours of contact of the lime-treated soil with water during each wetting (Fig. 8c & f). This is evident from the maintenance of cementitious compounds in the RP-subjected soil (Fig. 8b & e), which was subjected to 5 hours of wetting under the same testing environment (temperature and RH), as the DP-subjected soil. Thus, the duration of wetting hours implemented during the W-D/D-W cycles significantly influence the maintenance of cementitious compounds.

Conclusions

The physicochemical properties and microstructure modification that underlines the mechanism governing the UCS evolution in lime-treated soil subjected to W-D/D-W cycles as per different testing conditions were evaluated. Following conclusions were derived based on the evaluations:

1) The soil suction generated in the lime-treated soil during successive W-D/D-W cycles contributes towards the UCS evolution. Lime-treated soil subjected to W-D/D-W cycles did not show any significant generation of cementitious compounds compared to the one that evolved during curing time. However, the total loss in water content during the oven-drying of the AP-subjected soil induced a greater soil-particles contact, which increased the soil suction and resulted in up to about 3 times greater UCS in the AP-subjected soil. At the same time, the corresponding UCS and suction evolution remained insignificant in the soil subjected to testing conditions that represent a situation close to the field condition.

2) Wetting front velocity of water in specimens during W-D/D-W cycles is an important index to estimate the duration taken by infiltrated water to invade an in-situ hydraulic structure, which is interlinked with the durability of such structure. Soil subjected to W-D/D-W cycles as per different testing conditions exhibited different wetting front velocities. DP-subjected soil showed 3 times greater wetting front velocity than the AP-subjected soil. At the same time, RP-subjected soil showed 3 times lower wetting front velocity than the AP-subjected soil.

3) The leaching of calcium from specimens exposed to W-D/D-W cycles is mainly regulated by the exposure of the soil structure to the water during wetting. Since such exposure was mainly limited to the external surface of the specimens thus, the overall leaching of calcium remained significantly low, regardless of the testing conditions they are subjected to.

4) Oven-drying of AP-subjected soil at 71 °C makes the soil comparatively more prone to leach minerals during the wetting phase. Thus, the leaching of calcium and the electric conductivity measured in the effluent obtained from the AP-subjected specimens was comparatively higher than the specimens subjected to the RP testing condition.

5) A similar trend of *Ca* and EC evolution occurred in the lime-treated soil submitted to the W-D/D-W cycles, thus, demonstrating *Ca* as a controlling component on the EC evolution of the lime-treated soil. Thus, EC can be used as an important parameter to assess the leaching process of *Ca* occurring during the W-D/D-W cycles.

6) Re-wetting of lime-treated soil followed by oven-drying at 71°C during each cycle of the W-D cycles induced pozzolanic reactions, which potentially overestimates the actual cementitious compounds that can be expected from an in-situ lime-treated soil subjected to W-D cycle. As a result, though the loss of calcium and soil pH in the AP-subjected soil was comparatively higher, pores smaller than 3000 Å, which evolved due to lime treatment, seems to be less affected.

7) The maintenance of cementitious compounds in lime-treated soil subjected to W-D/D-W cycles is significantly influenced by the wetting hours implemented under the same testing environment (temperature and RH). RP-subjected soil being in contact with water for 7 hours, maintained the cementitious bonding formed during the 10 months curing, while the same was gradually lost in the DP-subjected soil during the successive D-W cycles, which remained only for 2 hours in contact with water.

The results emphasized the fact that based on the type of testing conditions implemented at a laboratory for conducting W-D/D-W cycles, the physicochemical and microstructural modifications occur, which brings a considerable change in the UCS evolution of lime-treated soils. Thus, consideration of the temperature, RH, and wetting and drying durations based on soil saturation level is essential while evaluating the impact of W-D/D-W cycles on the long-term performances of soil.

The present study is conducted under laboratory temperature, RH, and using an assumed saturation level; however, in the field, based on the weather conditions of the in-situ project locations, these parameters will vary. Also, the curing time implemented is 10 months, the difference in which can bring a variation in the presently reported properties of the lime-treated soil. The selection of the convenient curing time is fundamental as it ensures continuous contact between the soil, water, and the binder. Hence, further studies should focus on reproducing a laboratory environment that resembles the actual temperature, RH, soil saturation level of the targeted project sites, and intended curing time of the land infrastructure. This would provide a more accurate representation of the expected long-term hydromechanical performance of the soil structure under consideration.

Besides, additional studies should also be made (i) to evaluate the influence of the W-D/D-W cycle on lime-treated soil that represents a situation similar to the one produced by wave effects on harbors, levees,

etc. during boat movements (ii) to investigate how such a difference in testing condition can affect the carbonation of the lime-treated soil. However, based on the present results, it can be said that lime-treated structures can maintain a longer durability in regions exhibiting longer rainy periods compared to the ones with longer dry periods.

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Data Availability Statement

Data generated or analyzed during the study is included in the submitted manuscript.

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Table 1. Geotechnical properties of soil studied (Nguyen et al. 2019)

Clay fraction (< 0.002mm) (%)	Fraction (< 0.08 μ m) (%)	Methylene Blue Value (g/100g)	Atterberg's limit			USCS Classification
			PL (%)	LL (%)	PI (%)	
24	99	2.4	23.2	30.1	7	ML

Table 2. Maximum dry density and OMC of untreated and lime-treated silty soil

Soil	$\rho_{d(max)}$ (kN/m ³)	OMC (%)
Untreated silty soil	18.4	14.3
Silty soil treated with 2.5% lime	17.1	18.5

Table 3. Presentation of testing conditions

Designation	Testing conditions			Sequence of cycles	Number of specimens
	Wetting hours	Drying hours	Temperature (°C)		
AP (ASTM standard)	5	43	22.1-25.2 (wetting) 71 (drying)	Wetting then drying (W-D)	4
RP (to represent in-situ rainy situation)	7	17	22.1-25.2	Wetting then drying (W-D)	4
DP (to represent in-situ drought situation)	2	70	22.1-25.2	Drying then wetting (D-W)	4

Table 4. Estimated average velocity of wetting front and duration required by infiltrated water to flow to the center of a reference in-situ structure

Testing conditions	Average W_f (m/s)	Duration to reach the center of a 1m reference thickness in-situ structure (years)
AP	3×10^{-09}	05
RP	1×10^{-09}	13
DP	9×10^{-09}	02

Figure Captions List

Fig.1. Statically compacted lime-treated specimens.

Fig. 2. Immersion of specimens during wetting (a) and oven-drying of specimens at 71 °C (b) as per ASTM procedure.

Fig. 3. Appearance of compacted untreated silty soil after the 1st wetting cycle

Fig. 4. UCS evolution in the lime-treated specimens subjected to W-D/D-W cycles as per AP, RP, and DP testing conditions

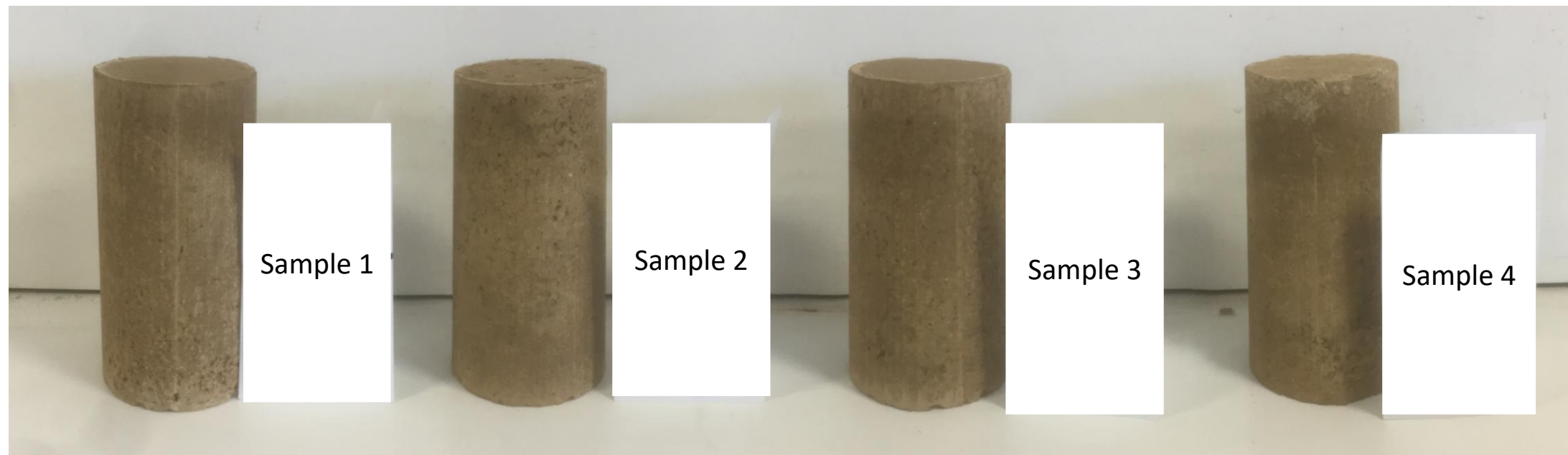
Fig. 5. Average volume variations (a-c), and water content variations (d-f) measured in the specimens subjected to W-D/D-W cycles as per AP, RP, and DP testing conditions

Fig. 6 Suction (a) and pH (b) measured in the initial and UCS subjected specimens during W-D/D-W cycles as per AP, RP, and DP testing conditions.

Fig. 7. Calcium concentration (a) and Electric Conductivity (b) measured in the effluents collected from the specimens subjected to W-D/D-W cycles as per AP, RP, and DP testing conditions

Fig. 8. Comparative PSD by MIP (a-c), and Cum. (cumulative) pore volume evolution by BJH (d-f) between untreated and 10 months cured lime-treated specimen with the lime-treated specimens subjected to W-D/D-W cycles as per AP, RP, and DP testing conditions

752 **Fig. 9.** Comparative evolution of calcium concentration and electric conductivity in the specimens subjected
753 to W-D/D-W cycles



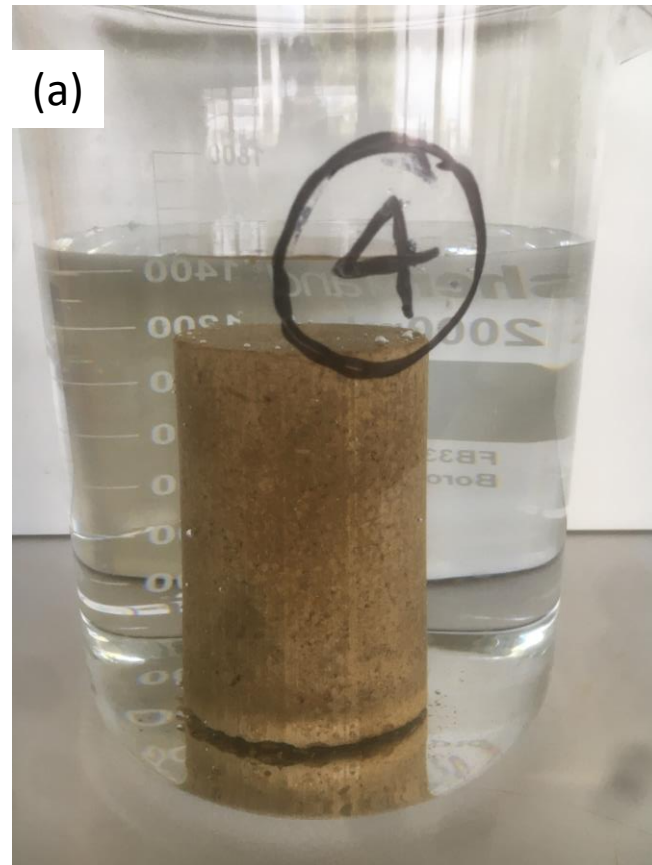


Fig. 3



Fig. 4

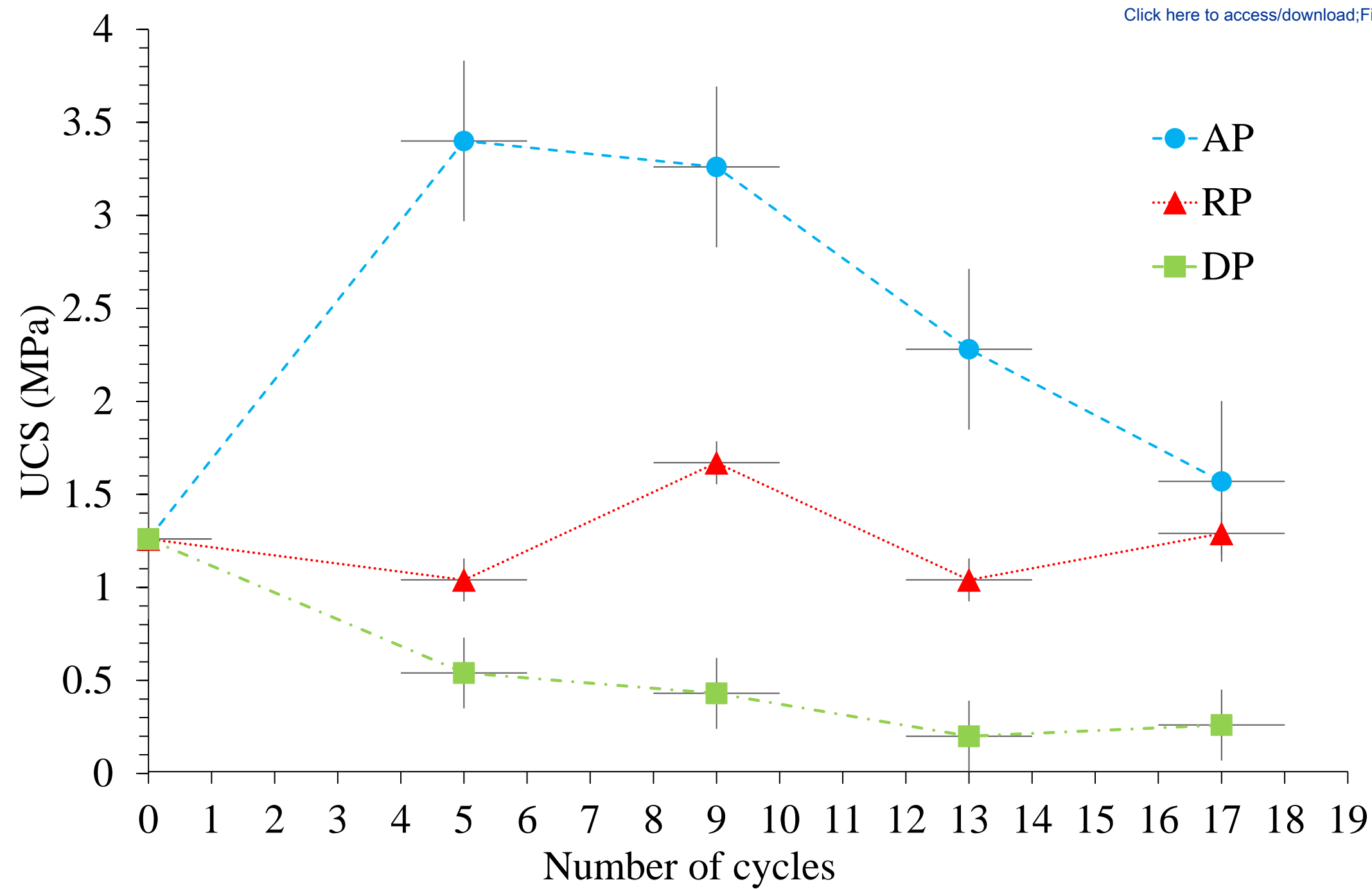


Fig. 5

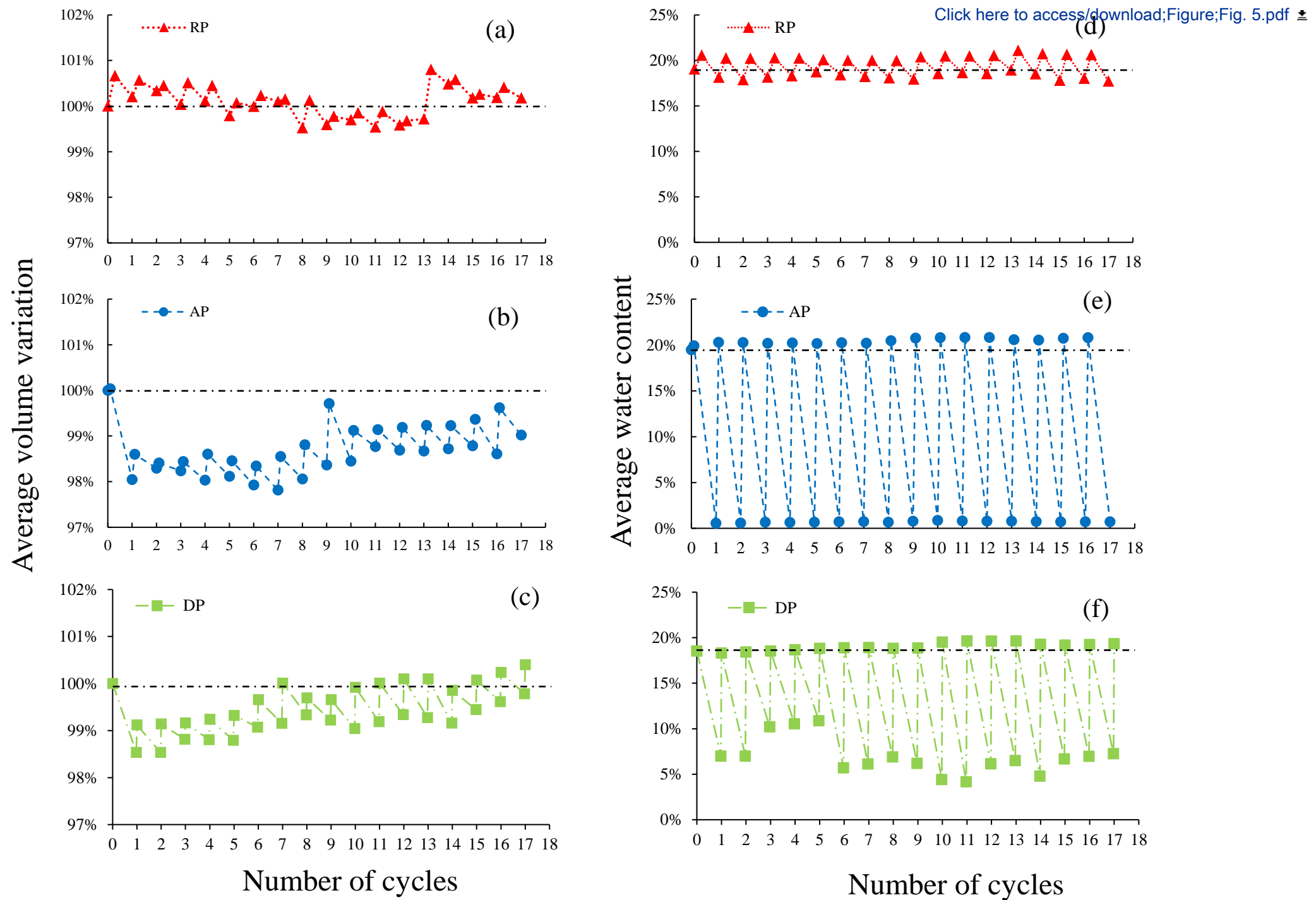


Fig. 6

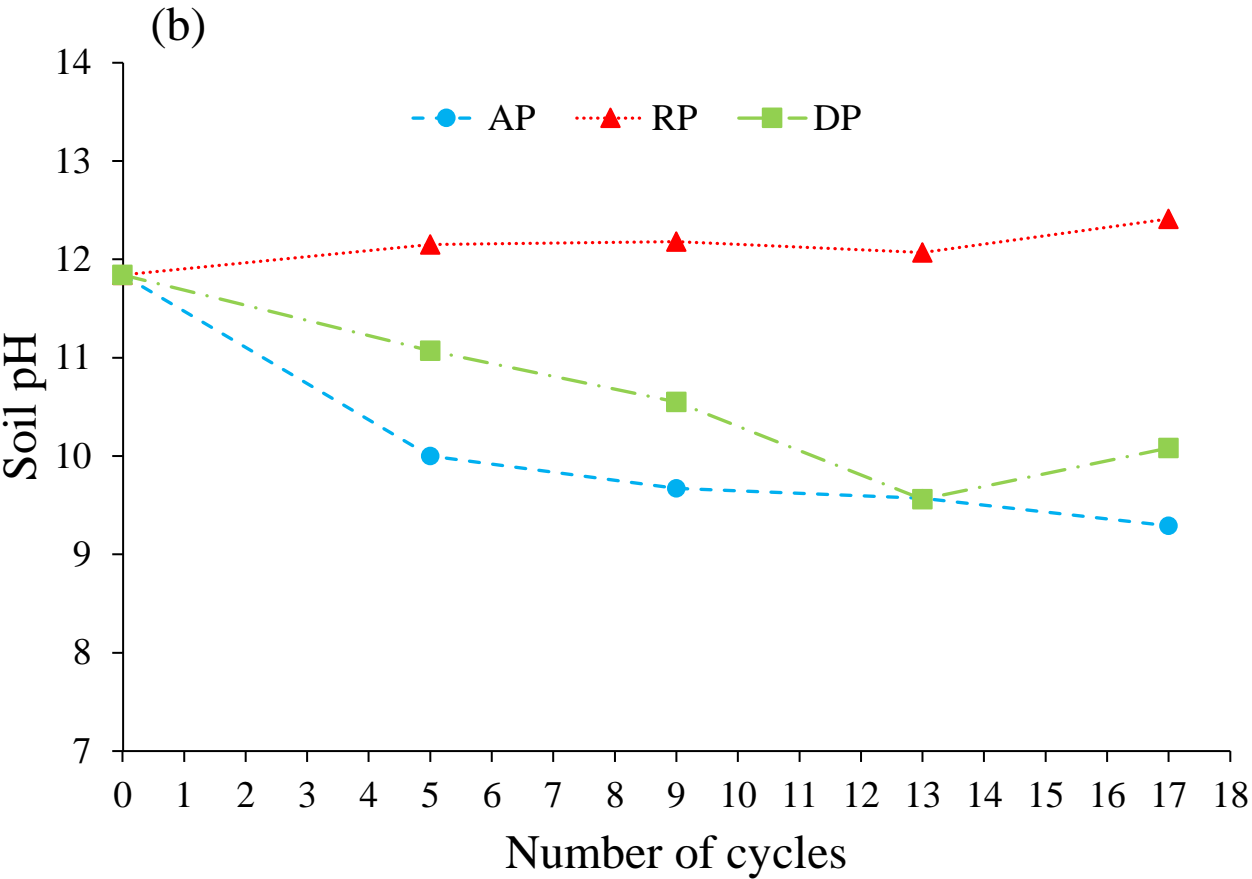
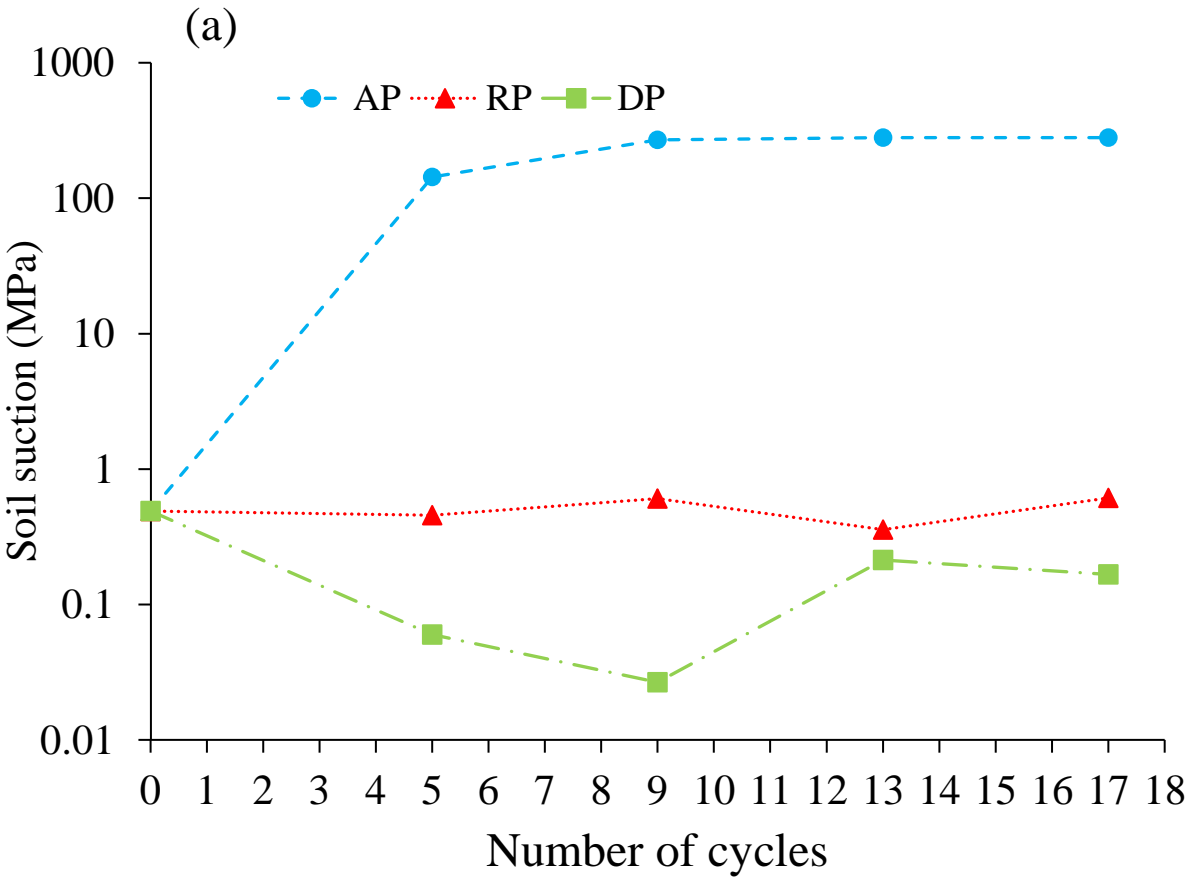


Fig. 7

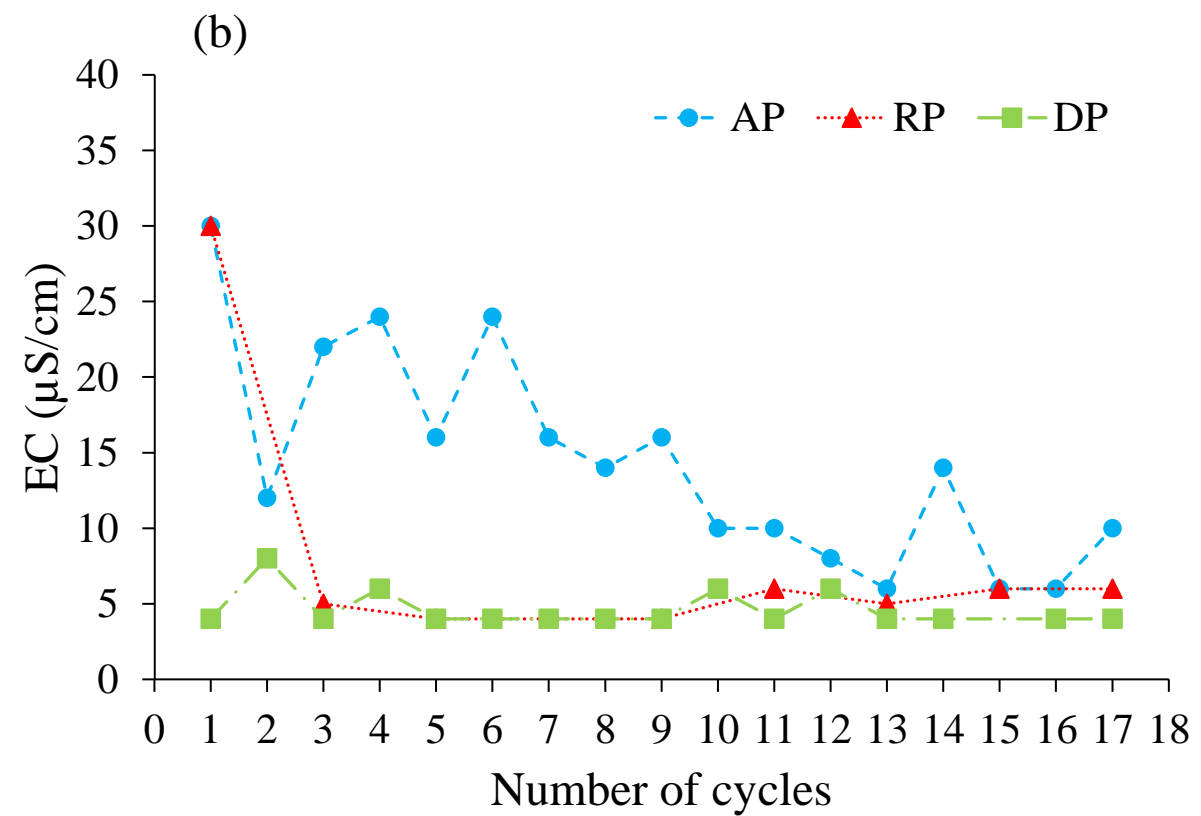
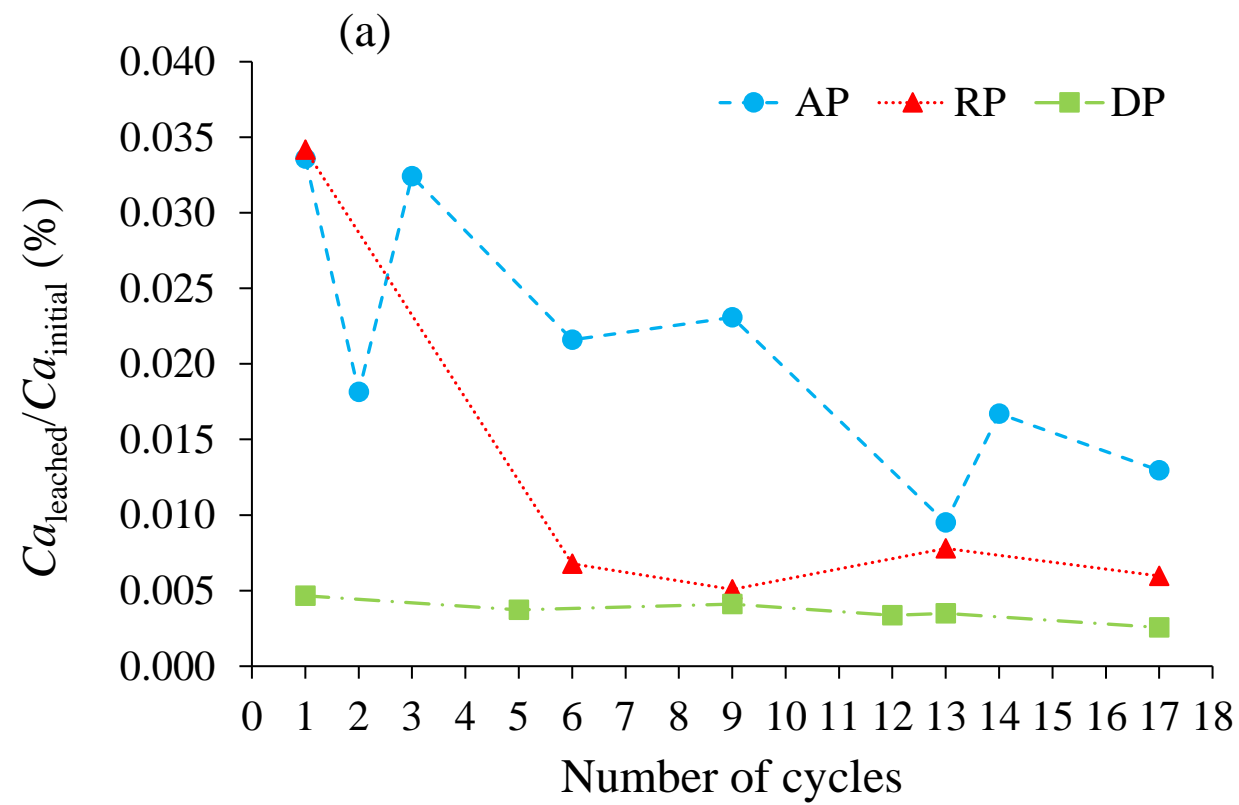
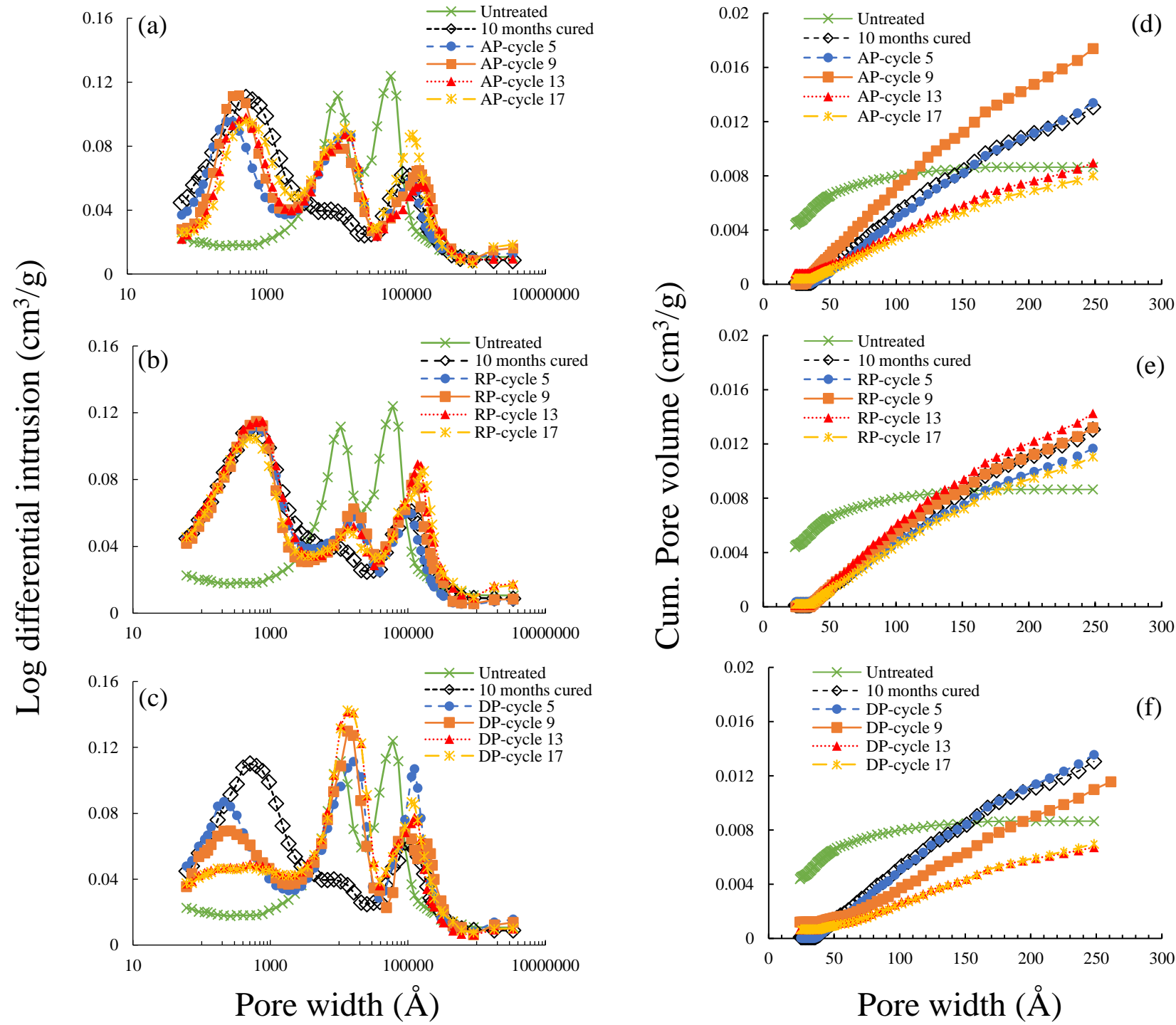


Fig. 8

[Click here to access/download;Figure;Fig. 8.pdf](#)

