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Influence of environmental relative humidity on unconfined compressive strength of unsaturated residual soils

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ABSTRACT: Variations in climate in semi-arid and arid parts of the world play critical role in influencing soil-water characteristics of unsaturated residual soils and hence their mechanical properties. This paper describes the influence of environmental relative humidity on the engineering characteristics of compacted residual clayey sands of Bangalore, Karnataka, India. Results show that exposure of the unsaturated residual soil specimens to different environmental humidity (97%, 76% and 33%) led to moisture desorption through vapor transport. The consequent reduction in soil moisture content increased total suction and led to significant gain in compressive strength. Unconfined compressive strength tests showed that initial water content than dry density has profound influence on strength mobilization of the compacted clayey sand specimens upon moisture loss on exposure to relative humidity gradients.

1 INTRODUCTION

Temperature, precipitation and relative humidity are major elements of climate that regulate moisture content of soil deposits. Thornthwaite has defined moisture index (I_m) to classify the climate into different zones from arid ($-60 < I_m < -40$) to perhumid ($I_m > 100$) (Thornthwaite, 1948). Residual soils often exist where the climate is characterized by alternate wet and dry seasons and are widely found in South America, Africa, Asia, and Australia and occur in several Indian states as well (Rao 2011). The exchange of moisture across soil-air interface occurs through evaporation and infiltration. Evaporation entails removal of water in the form of vapour whereas infiltration of moisture into soil can occur as liquid and/or vapor. In semi-arid ($-40 < I_m < -20$) and arid ($-60 < I_m < -40$) regions that have low rainfall, vapour transfer is the dominant mode of liquid transfer between earth and atmosphere (Pedram et. al., 2017). The vapour concentration in atmosphere is expressed as relative humidity (RH), defined as ratio of actual vapour pressure to saturated vapour pressure at given temperature. Temperature and vapour pressure (relative humidity) gradients drive vapour transport between vadose zone soil and atmosphere (Tran et al., 2016). If the RH of atmosphere is greater than that of RH in soil pores, water vapour would intrude the soil pores and increase the moisture content. The reverse would occur if soil moisture humidity is larger than that of atmosphere. The relative humidity inside soil pores can be determined from soil suction using Kelvins equation as:

$$\psi = \frac{-RT}{v_{\omega}} \ln\left(\frac{u_v}{u_{vo}}\right) \qquad (1)$$

where ψ represents total suction, ν_w is the partial molar volume of liquid water and u_v/u_{vo} represents relative humidity inside the pores.

Several studies have been conducted to understand factors controlling moisture flux and engineering response of unsaturated soils. Blight, (1966) observed that engineering behaviour of soils in dry regions is largely dependent on the soil humidity which in turn is controlled by environmental humidity. Bruch (1993), Wilson et. al. (1997), Dunmola (2012), Fredlund et. al. (2016), conducted several studies on prediction of evaporation flux from unsaturated soils. Rao and Revanasiddappa (2000) observed that the collapse magnitude of unsaturated residual soils depend on relative compaction and external pressure at which the unsaturated soils are wetted. Wang et. al. (2016), Nowamooz and Masrouri (2010), Rao and Revanasiddappa (2005) observed that soil structure responds to changes in suction of compacted soils. Most laboratory studies on engineering response (volume change and strength) of unsaturated soils to moisture flux have used liquid (water/salt solution) to alter the moisture content status of the soil.

To gain insight into the role of vapor exchange on soil behaviour, this paper describes results of laboratory experiments that simulate interaction of unsaturated residual soils with atmospheric relative humidity, in the context of changes in moisture content, total suction and unconfined compressive strength.

2 MATERIALS AND METHODS

2.1 *Soil Description*

Representative sample of residual soil was obtained from 1m deep pit at IISc campus, Bangalore (locally known as red soil). The residual soil profile in Bangalore District can be divided into three zones: 1) the upper zone - a crust of stiff red sandy clays, 2) the intermediate zone - a thick bed of loose to firm micaceous sandy silts and silty sands, 3) the partially weathered zone - the transition to unweathered rock consisting of gravelly silty sands with lenses of relatively sound rock (Rao and Revanasiddappa, 2005)

The representative soil classifies as clayey sand (SC). The specific gravity and Atterberg limits of the soil were determined as per IS 2720-1980, Parts 3 and 5 respectively. Grain size analysis of the soil was obtained as per Indian standard IS 2720-1980 Part 4. The standard Proctor test (IS 2720-1980, Part 7) was performed to determine maximum dry density (MDD) and optimum moisture content (OMC) of the soil. Index properties and compaction characteristics of the soil are given in Table 1. X-ray diffraction analysis had shown that the soil contained kaolinite and montmorillonite as its major and minor clay minerals, while quartz, mica, and feldspar minerals composed the non-clay mineral fraction (Rao and Revanasiddappa, 2003).

2.2 *Specimen preparation and equilibration with environmental RH*

The representative soil was air dried and pulverized to pass 2 mm sieve. Soil batches were mixed at water contents of 11 and 16 % and kept for 24 hours in air-tight container for moisture equilibration. Specimens (7.6 cm length and 3.8 cm diameter) were statically compacted to dry density-compaction water content combinations of 1.69 Mg/m^3-11% (series A); 1.78 Mg/m^3-11% (series B); and 1.78 Mg/m^3-16% (series C). The void ratio and degree of saturation (S) of as-compacted, series A, B and C specimens correspond to 0.57, 0.49, 0.49 and 51%, 59%, 86% respectively.

The compacted specimens were placed in vacuum desiccators containing saturated K_2SO_4, NaCl and $MgCl_2.6H_2O$ solutions that maintained relative humidity of 97%, 76% and 33% respectively (Young, 1967). Nine specimens of each series were placed in desiccator containing given saturated salt solution [K_2SO_4/NaCl/$MgCl_2.6H_2O$]. Thus, each compaction series was exposed to three RH environments, namely, 97, 76, 33 % respectively for 7, 14 and 28 days respectively. The unconfined compression strength (UCS) tests were performed as per IS 2720-1973, Part 10. UCS test was selected so as to capture the influence of soil suction on the compression strength. After 0 (as-compacted), 7, 14 and 28 days of equilibration, three specimens of each series were subjected to volumetric measurements (mass and volume) and then subjected to UCS tests. Average of three strength measurements is reported at each equilibration period. Water contents of failed specimens were determined. Knowing water content (after strength determination), and dry density (before measurement of strength), the degree of saturation of specimens were obtained.

2.3 *Soil Water Characteristic Curve (SWCC)*

The equilibrium (gravimetric) water contents attained by the specimens on exposure to different environmental RH for given period (0/7/14/28 days) are converted to S (degree of saturation) from mass-volumetric relations. The specimens were additionally exposed to RH of 7 % (saturated NaOH solution) and 64.4 % (saturated $NaNO_2$ solution) to obtain supplementary data points for SWCC plots. Total suction of the soil specimens is obtained from Kelvin's equation (Fredlund et al., 2012). Fredlund-Xing (F-X) model is used to fit the experimental data (Sillers et al., 2001). The F-X curve fitting parameters (a, n and m) for series C specimens correspond to 2.48, 1.21 and 1.51 respectively.

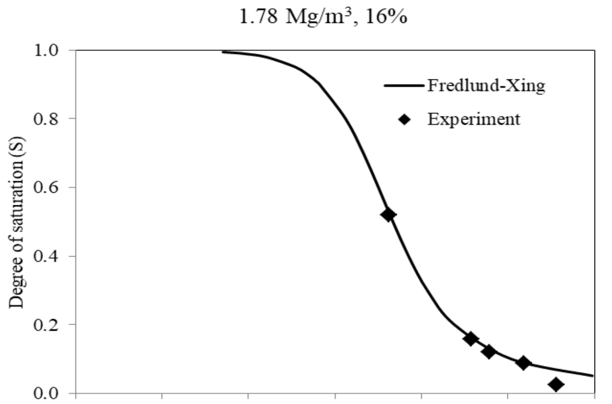


Figure 1. Experimental and predicted (Fredlund-Xing) SWCC plot of series C specimens.

Table 1. Index and compaction properties of red soil.

Index property	
Standard compaction tests	
Maximum dry density (Mg/m^3)	1.78
Optimum moisture content (%)	16
Grain size distribution	
Sand content (%)	52
Silt content (%)	25
Clay content (%)	23

Specific gravity	2.66
Atterberg limits	
Plastic limit (%)	18
Liquid limit (%)	34
Plasticity index (%)	16
Unified soil classification system (USCS)	Clayey sand

3 RESULTS AND DISCUSSION

All graphs pertain to series C specimens and similar trends are observed for series A and B specimens.

3.1 *Influence of environmental Relative Humidity on soil moisture*

Figure 2 presents time dependent water content variations of series C specimens on exposure to environmental RH of 97 to 33 %. As, RH in soil pores exceed the environmental RH, moisture desorption occurs from the specimens. As RH gradient between soil pores and environment increases (i.e., soil is exposed to lower environmental RH), greater amount of moisture loss occurs from soil specimens. Exposure of specimens for 28 days to environmental RH of 97% reduces the gravimetric water content from 16.02% to 12.66%. At RH=76%, water content reduces from 15.96% to 4.08% and at RH=33%, it reduces to 1.64% from 15.93% after 28 days of exchange.

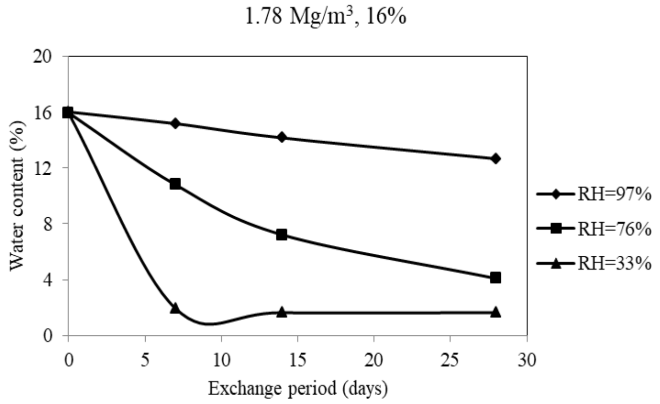


Figure 2. Moisture desorption plots of series C specimens exposed to environmental RH of 97%, 76% and 33%.

3.2 *Influence of environmental relative humidity on soil suction*

The moisture loss experienced by the specimens on exposure to environmental RH (97% to 33%) increased their total suction (ψ) values (example, Figure 3). The total suction at each exchange period is determined from SWCC plot (Figure 1) using its corresponding S value, which is in turn is calculated from void ratio and gravimetric water content of the specimen at concerned exchange period. On exposure to different relative humidity conditions, the diameter and length of series A to C specimens marginally reduced by 0.4-1.2% and 0.5-1.2%. Hence volume change experienced by the specimens during moisture exchange is not considered while calculating the degree of saturation. After 28 days, moisture loss at 97 % RH, increased total suction of series C specimens from 907 kPa (as-compacted value) to 2301 kPa. Total suction increased from 928 kPa to 20170 kPa at RH of 76 % and from 939 kPa to 151779 kPa at RH of 33 % after 28 days of moisture-exchange.

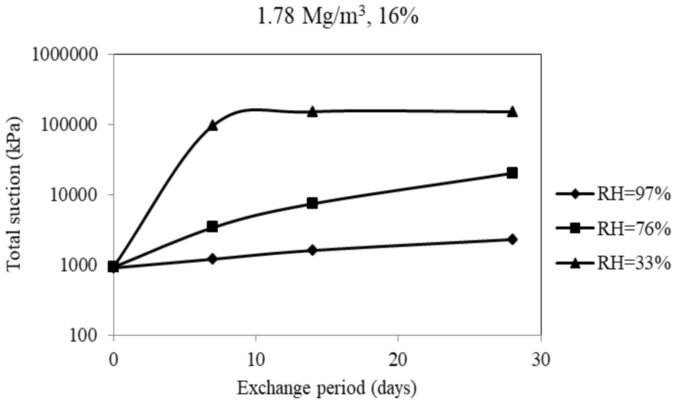
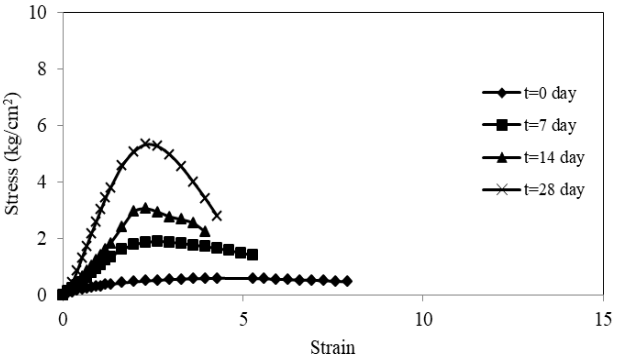


Figure 3. Variation of total suction with exchange period of series C specimens exposed to environmental RH of 97, 76 and 33 %

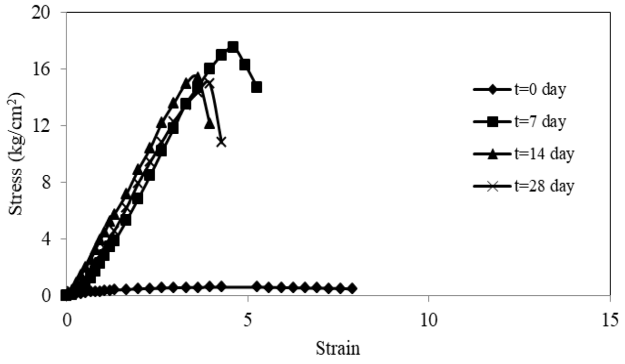
3.3 *Influence of environmental relative humidity on undrained strength*

Figures 4 (a) to 4 (c) plot stress-strain curves of series C specimens exposed to given environmental RH for various periods. The figures show that on exposure to given RH, the strength and stiffness of the residual soil specimen increases with exchange period. For example, the compressive strength of the compacted residual soil increases from 58 (as-compacted) to 531 kPa and 2504 kPa on exposure to RH of 97 and 33 % for 28 days. Likewise the initial tangent modulus (ITM) increases from 3.55 MPa (as-compacted) to 27.56 MPa and 43.77 MPa after 28 days of exposure to RH of 97 and 33 % respectively. Along with exchange period, strength and stiffness of the compacted specimens are also affected by environmental RH (Figure 5). This figure shows that series C specimens exposed to RH gradients of 97% develop compressive strength and ITM of 180 kPa and 6.13 MPa after 7 days, while specimens exposed to RH of 33% develop compressive strength and ITM of 2243 kPa and 92.65 MPa after 7 days.

(a) 1.78 Mg/m^3, 16% - RH=97%



(b) 1.78 Mg/m^3, 16% - RH=76%



(c) 1.78 Mg/m^3, 16% - RH=33%

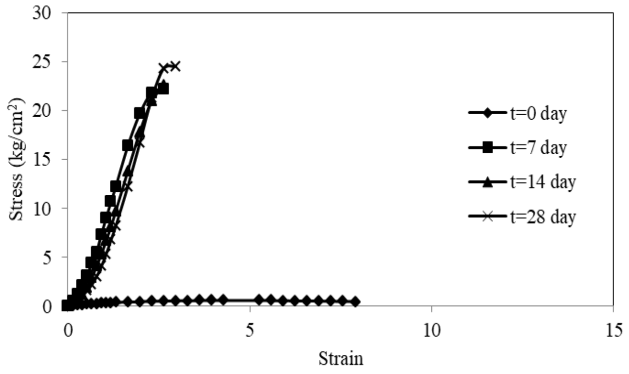


Figure 4. Stress-strain curves of series C specimens exposed to (a) RH=97% (b) RH=76% and (c) RH=33%

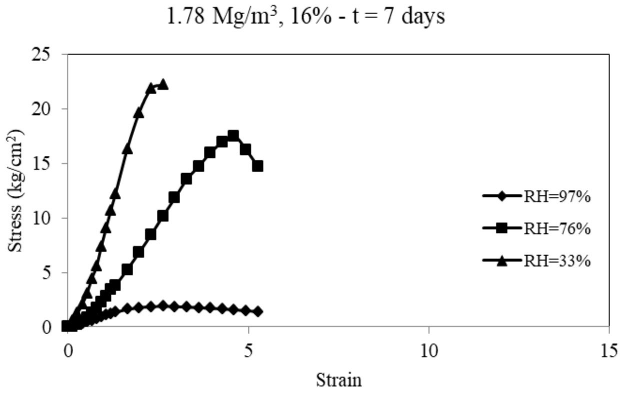


Figure 5. Stress-strain curves of series C specimens after moisture exchange for 7 days with environmental RH of 97, 76 and 33%.

Table 2 summarizes the percent increase in compressive strength (with respect to as-compacted strength) of the residual soil specimens on exposure to given RH for 28 days. Compressive strength of series C specimens increase by 800, 2436 and 4144% on exposure to environmental RH of 97%, 76% and 33% respectively. Similarly, compressive strengths of series A specimens increase by 428%, 460%, and 650% on exposure to RH of 97%, 76% and 33% respectively. Compressive strengths of series B specimens increase by 338%, 483% and 601% on exposure to RH of 97%, 76% and 33% respectively. The trends of results indicate that the initial or natural water content of the soil specimen has profound influence on magnitude of strength gain on moisture exchange under RH gradients. Series C specimens are characterized by larger initial water content of 16% and experience greater moisture loss and strength gains (800 to 4144 %). In comparison, Series A and B specimens are characterized by lower initial moisture content of 11% and lose lesser amount of moisture and gain lesser strengths (337 to 650%) on exposure to similar RH gradients. Results also imply that initial water content than dry density has larger impact on strength gain from moisture loss under RH gradients. Though series B specimens are more densely compacted than series B specimens, both series experience similar range of strength gains as they were characterized by same initial water content of 11 %.

Table 2. Percent increase in compressive strength of residual soils upon moisture exchange

	% increase in compressive strength		
Series	RH=97%	RH=76%	RH=33%
A	428%	460%	650%
B	338%	483%	601%
C	800%	2436%	4144%

4 CONCLUSIONS

Residual soil specimens compacted at dry of optimum (11 %) and at optimum water content (16 %) were exposed to environmental relative humidity of 33, 76 and 97 % for varying periods (0 to 28 days). As, RH in soil pores exceed the environmental RH, moisture desorption occurs from the clayey sand specimens. Reduction in moisture content was more severe, when the specimens were exposed to low environmental relative humidity (example, 33 %). The moisture loss under relative humidity gradients increased total suction of the specimens by 2 to 167 folds in comparison to their as-compacted values. UCS test revealed that moisture loss under RH gradients improved the strength and stiffness of the clayey sand specimens. Specimens compacted at optimum moisture content (16 %) experienced 800 to 4144 % increase in compressive strength from moisture loss after 28 days of moisture exchange. In comparison, specimens compacted at dry of optimum (11 %), experienced much lesser gain in strength (338 to 650 %) from moisture loss during 28 days of moisture exchange.

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