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Soil Shrinkage Characterization of Low Plasticty Soil using Digital Image Analysis Process

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ABSTRACT

The purpose of this paper is to understand the shrinkage behaviour of low plasticity soil, which is prevalent in Warangal, India. In this study, the shrinkage mechanism and behaviour with suction variation are characterised and described using simple and reliable experimental approaches. The findings concern the changes in suction, water content, and void ratio of soil that has been air-dried from full saturation to dryness. The proposed framework employs two simple processes: one to calculate the suction potential and the other to characterise the shrinkage mechanism. The study also highlights the use of ImageJ software to capture sample shrinkage using digital image processing (DIP). The findings confirm the absence of macro pores, and the effects of capillary suction on the shrinkage response are reiterated in volume change studies using suction as a stress-state variable.

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1. INTRODUCTION

There is extensive research to understand the volume change of expanding clay minerals. The soils of low plasticity are considered to be less prone to hydration or desoprtion and thus often neglected in volume change characterization. There are many field applications of locally available low plasticity soils, and there is no insight into the behavior of soil during desiccation [1]. There are limited works that have put emphasis on the impact of drying pertaining to geotechnical engineering application [2]. During the construction phase and the service life, compacted soil layers tend to remain in unsaturated state. This consideration necessitates the inclusion of suction existing between the soil pore spaces contributed by the water to understand the thermo-hydro-mechanical behavior [3, 4]. Based on the recognition that suction is a function of water content, shrinkage analysis in the framework of suction change and the volume of void variation has been examined by number of researchers [4-6]. The plastic strain accumulation of soil deformation under the effect of mechanical loading and the suction induced stress has been studied to incorporate constitutive relationship by numerous experimental works [7, 8]. The complex nature of soil pore structure and the physical significance of understanding the suction potential of engineered soils is explained in terms of soil water characteristic curve (SWCC) [9]. In order to determine the shrinkage character of soil from its initial state to dryness, the experimental works required the simultaneous measurements of volume changes and the water content changes [10]. The volume change will be expressed as the quantification of the void ratio induced by changing the water content subjected to various methods of drying. The water content reduction and the subsequent pore void changes are represented as the soil ashrinkage curve (SSC) [11].

The measurement of moisture change in the course of drying is very easy and can be done with the help of weight change. The complexity of framing the SSC lies in the accurate measurement of the volume of void change. The measurement of the volume change in the laboratory has progressed from the use of fluid

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displacement method with various types of fluids to the advanced method of 3D modeling using photogrammetric techniques.

The use of direct methods such as water or mercury displacement, saran resin coating, use of kerdane oil, toluene coating, rubber balloon method and flexible tape or Vernier caliper to measure the dimensional change has been widely studied [12, 13]. All these procedures have been applied primarily on soil samples obtained as clods. It has been observed that all these methods are applicable largely to sample in natural moisture conditions. The mercury displacement method and use of resins recommended in literature seems to be hazardous to health. The direct methods also possess numerous inaccuracies in the volume measurements due to the likelihood of loss of sample during coating or immersions [14].

The non-contact measurement techniques includes the use of displacement transducers [15], laser sensors [16], digital imaging with high-resolution cameras [17, 18] particle image velocimetry (PIV) technique [19] and photogrammetric technique with pin-hole cameras [20, 21]. All these techniques appear to be more sophisticated and necessitate the knowledge of coding, 3D modeling, and simultaneous use of multiple softwares to process the 3D models. Though there exists very limited research that discusses the application of non-contact techniques, they have gained attention with respect to slurry and compacted samples prone to cracking by desiccation [22]. Among these non-contact volumetric strain measurement methods, digital imaging technique which uses hand-operated digital cameras and open-source softwares such as *'ImageJ', 'Scion image'* [21-23] provides reliable results and practicable for soils that are not highly prone to volume change placed under lightly loaded structures. The soil profiles in temperate zone can be more precisely using the high-end sophisticated photogrammetric technique whereas soils prevailing in tropic zone can be studied with digital imaging process.

This work focusses on quantifying the shrinkage behavior of low plasticity in the Warangal district of India is characterized by the pore volume change. The experimental procedure aims at determining the suction potential and shrinkage induced change in the volume of voids. The study utilizes a chilled mirror hygrometer (model WP4-T Dewpoint PotentioMeter) for suction measurement and digital image analysis process for capturing the diametrical change of the drying sample. The initially saturated state is found to be an ideal approach as low plasticity soil is devoid to lesser volume change in the partially saturated condition. This initial condition is expected to simulate the worst moisture variation. The vertical deformation is measured using the caliper and the combined dimensional change is used for computation of volume. The proposed approach used in this study is rather simple and efficient in contrast to the existing procedures that required expertized assistance. This paper does not discuss the comparison of the proposed practice with other routine fluid displacement methods or photogrammetric approaches. The mechanism of shrinkage is highlighted with the use of the DIP under the framework of unsaturated soil mechanics principles.

2. EXPERIMENTAL DETAILS

2. 1. Materials and Specimen Preparation

The soil was mixed with distilled water and placed in airtight press bags to reach equilibrium for 24 hours. The mellowed soil was statically compacted to thickness of 20mm and diameter 70mm such that dry unit weight is 17.12 kN/m^3. The specimen for measuring suction was extracted for a of size 30 mm diameter and 10 mm height using a dedicated metal ring (see Figure 1).

Secondly, to measure shrinkage potential, the dry so passing through 0.075mm IS sieve was mixed with water content excess to its liquid limit (LL) to obtain a slurry. The slurry was placed in a grease coated aluminum cup of diameter 42 mm and depth 10 mm. It was placed in the laboratory to simulate the evaporation by air-drying.

2. 2. Measurement

2. 2. 1. Suction Potential

Dewpoint PotentioMeter (model WP4-T, Decagon Devices, USA)

TABLE 1. Properties of soil sample

Soil Property	Unit	Value
Liquid Limit	%	42
Plastic Limit	%	31
Plasticity Index	%	11
Specific Gravity	--	2.61
Maximum dry unit weight	kN/m^3	17.12
Optimum moisture content	%	15.5
USCS		CL

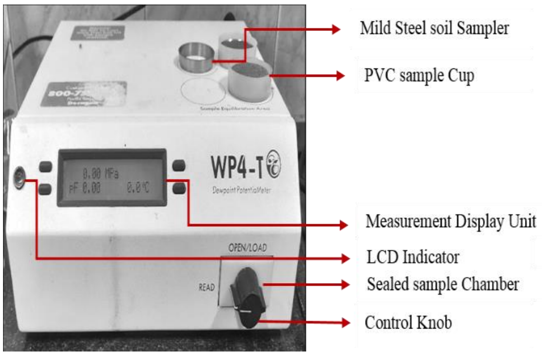

Figure 1. WP4-T Dewpoint PotentioMeter

(Figure 1) was used for the total suction measurement of the compacted specimen. The device measures the relative moisture of air above the soil sample in a sealed chamber and uses the principle of chilled mirror hygrometer. The accuracy is ±0.1 MPa for measurements from 0 to -10 MPa and ±1% for measurements from -10MPa to -300 MPa. The testing protocol followed as mentioned in ASTM D6836-16 [24]. The measurement takes time of about 5 -10 minutes and the instrument was operated at 20±2°C with their actual range of maximum 40°C. The SWCC is plotted by fitting the experimental data using the equation proposed by Fredlund and Xing [25] to obtain the complete curve.

$$W(\psi) = W_s\left[1-\frac{ln\left(1+\frac{\psi}{h_r}\right)}{ln\left(1+\frac{10^6}{h_r}\right)}\right]\langle\left\{ln\left[exp(1)+\left(\frac{\psi}{a_f}\right)^{n_f}\right]\right\}^{m_f}\rangle^{-1} \quad (1)$$

In Equation (1) W (ψ) is the moisture content corresponding to suction value ψ, a_f, n_f & m_f are fitting parameters and h_r is the residual suction in kilo-Pascal (kPa).

2. 2. 2. Shrinkage Characterization Shrinkage behavior was measured by allowing the slurry to dry placed open to the atmosphere exposed on its top surface. The research is limited to the examination of samples with sizes that are equivalent to those used in the mercury displacement method of shrinkage limit test. The other reason is that larger sizes may necessitate the use of high-resolution cameras fixed in varying positions to capture complete soil behaviour. The shrinkage of the soil was recorded by still image capture technique at regular time intervals (Figure 2). The captured image was analyzed and processed using the *'ImageJ'* software to quantify the radial shrinkage.

The mass of the specimen was measured to an accuracy of 0.01g and terminated when the difference in the mass was almost negligible. The specimen was subjected to a drying regime by containing it in constant temperature facility to achieve a gradual decrease in water content. The thickness change was measured using Vernier calipers such that loss of sample is minimal.

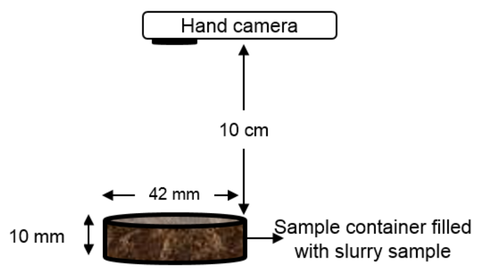

Figure 2. Experimental set-up for digital imaging capture process

The image capturing was done only to capture the radial deformation of the drying sample with a concentration on the open-top face of the shrinkage dish. The soil shrinkage curve was plotted with gravimetric water content variation agreeing to the void ratio of tested specimen assuming constant volume condition and the curve was categorized based on the shrinkage phases exhibited. The experimental data of the void ratio corresponding to water content variation is fitted with the hyperbolic equation proposed by Fredlund et al. [26]. A non-linear least square algorithm with the fit Equation (2) was be used to fit the experimental data.

$$e(w) = a_{sh}\left[\frac{w^{c_{sh}}}{b_{sh}^{c_{sh}}}+1\right]^{\frac{1}{c_{sh}}} \quad (2)$$

$$\frac{a_{sh}}{b_{sh}} = \frac{G_s}{S} = \text{Constant} \quad (3)$$

where S represents the degree of saturation, G_s is the specific gravity of soil sample, a_{sh} is the minimum void ratio (e_{min}), b_{sh} is the slope of the tangent line and c_{sh} is the curvature of shrinkage curve. Equation (3) is a constant for a specific soil which shows that on determining the minimum void ratio of the soil sample, the slope of the tangent drawn to the shrinkage curve can be obtained. The shrinkage curve parameter c_{sh} was determined by the consistency observed in the experimental study conducted by Fredlund et al. [26] based on the initial condition of the test sample (i.e. compacted, slurry or undisturbed). The c_{sh} parameter for an initially slurry sample was determined as 25.31 with a standard deviation of ± 25.41. In this study, to perform the fit, the c_{sh} value suggested by Fredlund method had found to be satisfying. To observe and quantify the radial shrinkage of the saturated slurry sample at net zero stress condition, 12 Megapixel (MP) camera was mounted in position as shown in Figure 2. The images were captured every 3 hours in the day time between 930 h to 1800 h for 5 days represented according to the military time system. The average maximum daily temperature in the course of the testing which lasted for 5 days was found to be 32.3℃. At the end of 5^{th} day, the sample was placed in the oven maintained at 60 ℃ for 24h to determine the dry weight of the soil sample. Final weight and volume observations were used along with the observations made during the entire test period of 5 days. The processing of images captured through standard arrangement was processed further to obtain the radial variation which is discussed in detail in the next section.

2. 2. 3. Digital Image Analysis The identification of the shrinkage response of saturated soil specimens subjected to desaturation is carried out by extracting the dimensional change information from the digital images captured. The captured images were processed further to acquire the required volumetric change information of the shrinking soil sample. In this study, the qualitative, as well as quantitative characterization of the two-dimensional image, is done using the image processing software '*ImageJ 1.52a*' software developed at the University of Wisconsin. This software helps in spatial as well as grayscale calibration that makes it more reliable to measure distances and calculate area and pixel value by simulating real-time dimensional measurements. The threshold processing of the image will be followed up to segment it from 8-bit grayscale to an image of 2 colors, in general black and white based on the clustering concept.

3. RESULT AND DISCUSSIONS

The suction potential of soil in the desorption phase obtained from the Chilled mirror hygrometer was plotted against the corresponding gravimetric water content of the soil sample and represented as the SWCC as shown in Figure 3. The dataset obtained from the experiment was fit with Fredlund and Xing (F&X) model [25] which resulted in the air-entry value (AEV) of 220 kPa corresponding to a saturated water content of 18.82% and the residual water content value was obtained as 10.42 %.

The AEV represents the suction beyond which air starts receding into the pores of the sample and residual suction represents the region where further increase in suction will not result in reduction of water from the pores [27]. The F&X model was found to be the best fit for a comprehensive range of suction values and thus the model was chosen to fit the measured data to obtain the suction potential of soil specimen with varying water content. The volume change response of the specimen during testing was assumed to be nil as the dry density of the compacted specimen remained constant. The fit of the experimental data with Equation (1) was performed using the program "SWRC fit" which accomplishes nonlinear fitting [28]. As seen from the graph plotted in Figure 3, there is a negligible decrease of water content up to a suction increase of about 220 kPa and this was an indication that constant water content was observed in the range of low suction. The results adhere to the understandings that there is restricted water flow from the intra-aggregate pore spaces which are typically a property of the adsorption water layer [29]. There was a gradual decrease in the water content retention behavior of soil with suction increase beyond the air entry value. The residual water content from the graph indicated that with a further increase in the suction potential, there was no variation in the retention water. This gave an indirect assessment of the pore size distribution of the compacted specimen thus the interrelation between the retention water and the pore size characterization became an important facet to be concerned. The inter-aggregate pore water held under capillary pressure was removed with a suction increase up to the residual value and beyond this, there was no water-volume loss.

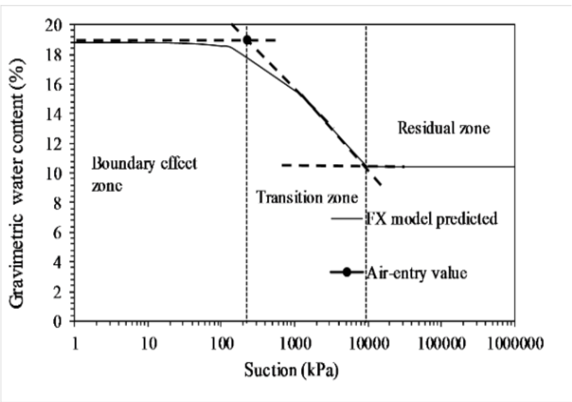

Figure 3. Soil water characteristic curve of test specimen

The radial shrinkage of the saturated sample was studied by allowing the sample to air-drying in the laboratory ambiance. The mass of the sample experienced changes as the temperature was varying. The sample was initially placed open to the atmosphere subjected to an average maximum daily temperature of 33°C. When it was confirmed that sample mass reduction is in a lower range based on observations, as they were placed in a temperature controlled set-up under 60°C for about 24 h . The sample imaging began and continued till it was transferred to the oven for complete desaturation. After removal of the sample from the oven, the final imaging to confirm the radial deformation was captured. As the sample was placed in a confined container, the vertical variation of the sample dimension was obtained using the Vernier caliper, and owing to the small size of the sample, handling was relatively easier. The captured images were analyzed and processed as the threshold images using the *'ImageJ'* software as shown in Figures 4 and 5. The image processing was done by the cluster method of thresholding the grayscale image at an initial threshold value of 8-bit. It was ensured to provide adequate lighting and negligible glaring to capture digital still images such that good contrast existed between background and foreground. This condition helped in assuring the best effect of an 8-bit threshold limit to perform better for all the captured images. This method backed an inaccurate measurement of the dimensional variation observed in the sample due to shrinkage. This imaging technique was found to be more reliable when the sample is experiencing shrinkage without being accompanied by cracking. Thus for soils with less expansive mineralogical composition, this approach is highly recommended. There exist limited studies that have used this *'ImageJ'* software for volume determination of expansive soils subjected to wet-dry cycles of moisture variation and that needs further explicit research to confirm the reliability of this imaging

Figure 4. Sequence of image processing

technique [22]. The variation of radial shrinkage observed in the specimen was quantified to be 15% of the initial sample size.

The processed threshold image of the slurry sample subjected to drying regime as shown in Figure 5.

The average vertical shrinkage of the sample subjected to gradual evaporation was about 17%. Proportional or primary shrinkage of compacted soil specimens was calculated using Equation (4). The dominant proportional shrinkage phase of this soil sample as shown in Figure 6 was quantified to be about 13%. This shrinkage refers to the phase where the volume of water loss is equal to the volume of void change which is predominantly due to the loss of moisture from the soil macropore and this phase is generally linear.

$$\text{Primary Shrinkage}, PS = \frac{(e_{is} - e_{ps})}{1 + e_{is}} \, x \, 100 \qquad (4)$$

where e_{is} and e_{ps} represent the void ratio at the initiation and end of primary shrinkage, respectively (see Figure 6). The plot was made using the variation of the water content measured from the mass variation of sample and the void ratio was calculated corresponding to the varying water content. The shrinkage curve was identified to be with no inflection point and the wetting and drying side maximum curvature. This indicates the absence of intra-aggregate pores thus there exists no adsorption suction phase in this soil. The lack of residual shrinkage phase which possesses the character of reduced void volume compared to the water volume loss is also observed. The fitting parameters used in Equation (3) were determined as a_{sh} =0.91, b_{sh} = 0.35 and c_{sh}= 25.31 using the graphical plot made for the experimental data. The fitted curve is a linear proportional shrinkage phase and it can be categorized as Type D (SSC with phase II shrinkage) and the results are similar reported by Peng

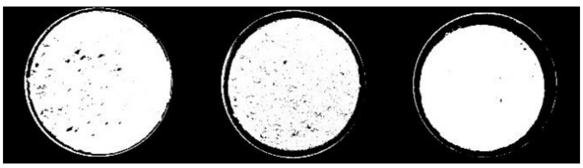

Figure 5. Threshold image of shrinkage from initial slurry state (White= soil solid)

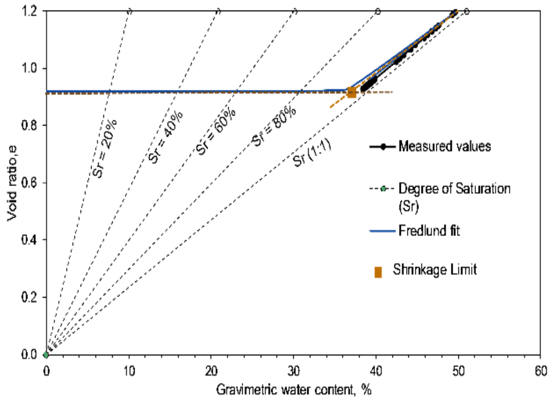

Figure 6. Soil shrinkage curve (SSC) of the sample

and Horn [6]. The presence of negligible inter-aggregate pores was attributed as the reason for the absence of a structural shrinkage phase. The existence of organic matter and the absence of clay minerals is supposed to depict this behavior and this also indicated the variation of inter aggregate pores with the variation of suction and water content. The existence of zero shrinkage phase is observed to be due to the non-existence of hydration by solid particle surfaces or the exchangeable cations [4].

The test approach can also be utilised to analyse the shrinkage behaviour of samples prepared at various initial degrees of saturation, as confirmed with Figure 6. The results of this study are limited to samples that were air dried from saturated to dry state, and more research into the effect of drying-wetting cycles and varying temperatures on shrinkage behaviour is needed to gain a better understanding of the shrinkage mechanism.

4. CONCLUSIONS

This study emphasizes the use of principles of unsaturated soil mechanics to study the drying shrinkage behavior of low plasticity soil using advanced digital imaging processes. The following conclusions are observed from the study.

a. The volume change study based on total suction is identified as an ideal approach such that the suction pressure existing in both inter and intra aggregate pore space will be considered. The silty soil considered for study undergoes the desaturation from the capillary phase (dominated in the completely water-saturated scenario) to the zero shrinkage phase where there is the nonexistence of hydrate water on the particle surface as well as lack of hydration water via the exchangeable cations.

b. The soil sample owing to its low plasticity, shows a proportional void volume change with respect to volume of water lost. This implies the absence of adsorption moisture range in the soil particle, but still an elaborate study on the wet-dry phase of moisture variation under a constant stress condition should be carried out to understand the volumetric changes. The crack initiation is restricted due to the confined small sample size used in this study and the effect of variation in area ratio of the sample should be considered for further study.

c. The *'ImageJ'* software was used to carry out the digital image analysis process and the method is observed to be easier and reliable. The analysis of small-sized sample is encouraged for image analysis technique so as to avoid optical distortions. In case of large sample sizes and for the generation of 3D volume model, photogrammetric technique which uses the pin-hole cameras will be advantageous.

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Persian Abstract

چکیده

هدف از این مقاله درک بهتر رفتار چروکیدگی خاک با خاصیت انعطاف پذیری کم است که در وارانگال هند رواج دارد. در این مطالعه ، سازوکار و رفتار چروکیدگی با تغییرات مکش با استفاده از رویکردهای آزمایشی ساده و قابل اعتماد توصیف می شود. یافته ها مربوط به تغییر مکش ، مقدار آب و نسبت درجه حرارت خاکی است که از اشباع کامل به خشکیدن در هوا خشک شده است. چارچوب پیشنهادی از دو فرایند ساده استفاده می کند: یکی برای محاسبه پتانسیل مکش و دیگری برای توصیف مکانیزم انقباض. این مطالعه همچنین استفاده از نرم افزار ImageJ را برای جمع آوری نمونه با استفاده از پردازش تصویر دیجیتال (DIP) برجسته می کند. این یافته ها عدم وجود ماکروپورها را تأیید می کند و اثرات مکش مویرگی بر پاسخ انقباض در مطالعات تغییر حجم با استفاده از مکش به عنوان یک متغیر حالت تنش تکرار می شود.