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Soil & Tillage Research 70 (2003) 53–64

Soil & Tillage Research

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Pre-compression stress and its relation with the physical and mechanical properties of a structurally unstable soil in central Iran

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Received 18 April 2002; received in revised form 25 September 2002; accepted 9 October 2002

Abstract

Pre-compression stress approach as a mean of assessing compressive nature of soils has received more attention nowadays. A pot experiment of a silty clay loam soil (fine-loamy, mixed, thermic Typic Haplargids, USDA; Calcaric Cambisols, FAO) was conducted to examine the effect of internal forces upon drying on pre-compression stress. The pots were saturated by flood irrigation. Bulk density (BD), water content (θ_m), matric suction ($-\psi_m$), cone index (CI), unconfined compressive strength (UCS), indirect tensile strength (ITS) and pre-compression stress (σ_{pc}) were measured at different water contents/matric suctions during soil drying. It was found that σ_{pc} prediction using BD as strain-related property in functional relationship with logarithm of major principal stress ($\sigma_{pc(BD)}$) is higher compared with σ_{pc} prediction using e (void ratio) ($\sigma_{pc(e)}$) by a factor of 1.3. Because the non-linear function of BD vs. e can affect the curvature of the stress–strain relationship and therefore the σ_{pc} determination. Pre-compression stress ($\sigma_{pc(e)}$) was strongly affected by θ_m, but the packing state of the soil, i.e. BD had a weaker effect on $\sigma_{pc(e)}$. Pre-compression stress ($\sigma_{pc(e)}$) increased linearly with effective stress for $0 < \sigma' < 100$ kPa (wet moisture range), after which the relation deviated from the linear line. The internal forces are the major source of hardening in this structurally unstable soil. Pre-compression stress ($\sigma_{pc(e)}$) was predicted fairly well by using the UCS and the ITS data. However, a very close linear relationship was obtained between $\sigma_{pc(e)}$ and CI. The results may be useful for rapidly predicting the $\sigma_{pc(e)}$ of the soil. It is indicated that UCS and ITS can be used to predict one another.

Keywords: Structurally unstable soils; Pre-compression stress; Effective stress; Cone index; Unconfined compressive strength; Indirect tensile strength

1. Introduction

Compressive behaviour of a soil is expressed in terms of the relationship between stress (σ) and strain (ε) or some parameters regarding the packing state of soil, most often void ratio (e) or bulk density (BD). When no prior stress has been applied, the relationship is usually linear with drawing ε, e or BD vs. the logarithm of σ. The linear relationship indicates the compressive behaviour of soil under major principal stress (σ_1), in uni-axial confined compression, often defined as normal or virgin consolidation or compression line (NCL or VCL). When soil experienced previous stresses (over-consolidated or pre-compacted), the relationship becomes curvilinear. In this case, pre-consolidation/pre-compression stress (σ_{pc}) corresponds to the stress, which divides the soil

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0167-1987/02/$ – see front matter
PII: S0167-1987(02)00120-4

compression curve into a region of small elastic deformation and a region of plastic deformation (NCL or VCL) (Horn and Lebert, 1994; Koolen, 1994). By limiting the load to below σ_{pc}, the risk of additional soil compaction can be minimized (Alexandrou and Earl, 1998).

Soil pre-compression can be due to its previous geological history or to mechanically applied load (Alexandrou and Earl, 1998). In unsaturated agricultural soils, many factors such as soil matric suction or water content, effective stress caused by drying or freezing and organic matter (OM) contribute to σ_{pc}. Other factors that contribute to σ_{pc} are inorganic stabilizing materials, aggregate formation, drying and wetting processes, soil settlement, cropping and/or tillage systems, age-hardening and hardsetting behaviour (Dexter, 1988; Horn, 1988; Horn and Lebert, 1994; McBride and Joosse, 1996).

In the absence of age-hardening and structural changes of soil after pre-loading, σ_{pc} is equal to the maximum previously applied compaction stress provided that the water content is the same (Dexter, 1988). Drying of soil can also cause compaction through the action of soil water potential generating effective stresses (Towner and Childs, 1972). When σ_{pc} of a soil is exceeded, it deforms plastically and similarly, when pre-desiccation stress of a soil is exceeded, then there is also irreversible deformation in the soil due to particle rearrangement. Therefore, σ_{pc} may represent the greatest effective stress that a soil has been subjected to in the past, irrespective of the causes (external or internal) (Baumgartl and Horn, 1999). No attempt has been made so far in linking the effective stress theory to σ_{pc} approach in structurally unstable soils.

In structurally stable soils, it is expected that soil strength is not strongly dependent on the change of effective stress (Mullins, 2000). The effective stress is the dominant factor in determining strength of single-grain soils (Towner and Childs, 1972), artificial sand–clay mixtures (Mullins and Panayiotopoulos, 1984) and soils with low structural stability (Mullins, 2000). Soils with low structural stability have high amount of unstable and fine aggregates ($<$0.125 mm) (Mullins, 2000).

An indication of σ_{pc}, predicted from easily measurable soil properties, provides a useful measure of the mechanical state of soils for use in the management and planning of agricultural mechanization systems (Alexandrou and Earl, 1998). Burger et al. (1988) showed σ_{pc} variation with depth is comparable with cone index (CI) variation. Culley and Larson (1987) presented a correlation between σ_{pc} and fall-cone penetration index. Kirby (1991) used 180 soils from Queensland, Australia, and reported that liquidity index is a good predictor of σ_{pc} rather than water content/suction. Multiple regressions were also used to relate σ_{pc} to shear strength parameters (Lebert and Horn, 1991). McBride and Joosse (1996) reported that by using three pedotransfer functions, σ_{pc} could be predicted by in situ BD, organic carbon, and some other properties in Ontario, Canada. Alexandrou and Earl (1998) suggested regression equations for predicting σ_{pc} using BD and volumetric water content in plate sinkage test.

In the central parts of Iran, the soils are generally low in OM content but they are intensively tilled. Consequently, these soils tend to have unstable structure (Eghbal et al., 1996; Hajabbasi and Hemmat, 2000). Eghbal et al. (1996) reported the formation of crust after the first irrigation of the soil of this study. The surface horizon with higher silt content was more susceptible to physical deterioration and crust formation. High exchangeable sodium together with physical deterioration of surface structure due to a long period of mechanized cultivation on this soil created a suitable condition for crust formation and soil compaction.

Mosaddeghi et al. (2000) showed that when the soil is at the plastic limit (PL), passage of a tractor causes about 7 cm deep rut due to sinking and side-flowing of the soil. They, however, found negligible sinking of the soil at 0.6 PL. This behaviour can be related to abrupt change in strength and compactibility of the soil with water content. In a clay loam arid soil, application of a no-till system resulted in an increase in soil OM and thus larger aggregates. However, the initial heavy soil texture and low initial OM of the soil necessitates the use of tillage implements to maintain crop productivity (Hajabbasi and Hemmat, 2000). Shirani et al. (2002) indicated that there was no significant difference on soil physical properties and corn yield among tillage systems. A. Hemmat (personal communication) studied the variation of CI after conventional tillage system during a growing season and observed that CI increased to about the initial pre-tillage state.

There is little scientific or quantitative information on compaction and its causes, compactibility and bearing capacity of soils in the region. Therefore, it is necessary to study this aspect of soil physical quality. It is required to measure how much natural processes of wetting/drying cycles cause soil densification especially in regions with structurally unstable soils that can be dominant in arid and semiarid regions.

Drawing upon the results from previous studies, our hypothesis in this research is that internal or hydric forces are among the main causes of soil compaction in the region. We assume that σ_{pc} of an unstable soil is reset to very low value when the soil is cultivated at the start of the growing season and saturated by surface irrigation. Soil drying can leave the soil compacted to a level of σ_{pc} equal to the maximum level of effective stress applied due to internal forces.

The objectives of this study are to: (i) measure variation of σ_{pc} upon soil drying after surface irrigation, (ii) apply effective stress theory to predict σ_{pc}, and (iii) identify relationships of σ_{pc} with soil physical and mechanical properties.

2. Materials and methods

2.1. Study site and soil

The soil for the experiment was collected from the Isfahan University of Technology Research Station farm (32°32′N; 51°23′E; 1630 m a.s.l.) in Isfahan (central Iran). The mean annual precipitation and temperature at the station are 140 mm and 14.5 °C, respectively. The soil (fine-loamy, mixed, thermic Typic Haplargids, USDA system; Calcaric Cambisols, FAO system) is formed by the alluvial sediments of the Zayandeh Roud river (Lakzian, 1989). It is initially low in OM and has a history of intensive conventional cultivation and cropping of cereals, hay, and silage corn (*Zea mays* L.) in rotation. According to qualitative assessment of Lakzian (1989), the dominant clay minerals are in decreasing order of micas/illite, smectites, palygorskite and kaolinite.

2.2. Sample preparation

Pre-test composite samples of topsoil (0–20 cm) were obtained, air-dried and grounded to pass a 2 mm sieve for the determination of soil physical properties. Particle size distribution was determined using the pipette method. Organic matter (OM) content was determined using the wet digestion method. Field capacity (FC) and permanent wilting point (PWP) were obtained using soil water characteristic curve (SWCC). The SWCC was determined from the readings of tensiometer and TDR (up to matric potential of −0.8 bar) as mentioned in experimental procedure section. Lower than matric potential of −0.8 bar, the SWCC was determined using the pressure plate. Atterberg limits, viz., liquid limit (LL); plastic limit (PL) and shrinkage limit (SL) were determined, respectively, by the three-point Casagrande method, the 3 mm rod formation and shrinkage mould techniques (McBride, 1993). The differences between LL and PL, and between PL and SL were defined as plastic index (PI) and friability index (FI), respectively. Critical water content (CWC) and maximum dry bulk density (MDBD) were defined by using the results from a proctor test. Particle density (PD) was measured by using the pycnometer method. Mean weight diameter (MWD) of aggregates was determined by the wet sieving method. The values of some physical and mechanical properties of the topsoil are given in Table 1.

The experiment was conducted with topsoil (0–20 cm) samples in laboratory. Enough soil was collected from the ploughed layer having suitable water content (i.e. between PL and SL) by composite sampling and great care was taken not to crush soil clods and aggregates during sampling. The samples were air-dried and passed through 8 mm sieve. Plastic pots with diameter and height of 30 cm were chosen. In order to drain the soil, gravel was placed at the perforated bottom of the pots. The soil was poured and knocked gently to achieve 20 cm thickness and uniform soil packing state (BD of 1.2 Mg m^{-3}) with depth. It was assumed this packing state and size range are ideal for a seedbed after primary and secondary tillage practices.

2.3. Experimental procedure

Water having an electrical conductivity (EC × 10^3) of 0.56 and sodium adsorption ratio (SAR) of 0.77 was applied to the corner of each pot. A small flow of water was maintained by a water spreader against the walls of the pots. This prevented particle washing and scouring and buoyancy effect on soil surface. Enough water was applied to saturate the soil completely all

Table 1
Some physical and mechanical properties of topsoil (0–20 cm)[a]

Sand ($g\,kg^{-1}$)	Silt ($g\,kg^{-1}$)	Clay ($g\,kg^{-1}$)	Texture	OM ($g\,kg^{-1}$)	LL ($kg\,kg^{-1}$)	PL ($kg\,kg^{-1}$)	PI ($kg\,kg^{-1}$)	SL ($kg\,kg^{-1}$)	FI ($kg\,kg^{-1}$)	FC ($kg\,kg^{-1}$)	PWP ($kg\,kg^{-1}$)	CWC ($kg\,kg^{-1}$)	MDBD ($Mg\,m^{-3}$)	PD ($Mg\,m^{-3}$)	$CaCO_3$ ($g\,kg^{-1}$)	MWD (mm)
158	494	348	SiCL	10	0.306	0.191	0.115	0.086	0.105	0.258	0.102	0.170	1.72	2.73	450	0.7

[a] USDA textural classification—SiCL: silty clay loam; OM: organic matter; LL: liquid limit; PL: plastic limit; PI: plastic index; SL: shrinkage limit; FI: friability index; FC: field capacity; PWP: permanent wilting point; CWC: proctor critical water content; MDBD: proctor maximum dry bulk density; PD: particle density; MWD: mean weight diameter of aggregates by wet sieving.

through the depth. The buriable wire of TDR (model Truse) was immediately inserted horizontally across a pot through a hole in depths of 4 and 12 cm after the start of ponding. The perimeters of the holes were carefully sealed to prevent evaporation. Tensiometers were also installed in depths 4 and 12 cm of the pot. The pots were then allowed to drain and also to dry by a low rate of surface evaporation. Meanwhile, soil water content (θ_m), matric potential (ψ_m), dry BD, CI, unconfined compressive strength (UCS), indirect tensile strength (ITS) and pre-compression stress (σ_{pc}) were measured on the soil during and after watering times including different water contents/suctions.

2.4. Soil measurements

Bulk density was determined by core sampling from each pot. The diameter and height of the core sampler were 4 and 30 cm, respectively. The sampler had been cut longitudinally to facilitate separating and dividing "undisturbed" soil core in two increments of 8 cm (0–8 and 8–16 cm depths). As these cores were also used for ITS and UCS, the samples were weighed before the tests. After the tests, the samples were oven-dried at 105 °C for 48 h and the BD and θ_m calculated. The θ_m of each pot was also measured by TDR. Matric potential (ψ_m) was measured directly from tensiometers located at the depths 4 and 12 cm, which are midpoints of 0–8 and 8–16 cm soil increments, respectively. Cone index was measured using a digital cone penetrometer (model Rimik CP20) in increments of 2.5 cm near the region that was to be sampled for BD, UCS, ITS and σ_{pc} tests and averaged for the depths 0–7.5 and 7.5–15 cm. The cone had tip angle and diameter of 30° and 12.8 mm, respectively. It was attempted to have a constant inserting speed of 2 m min^{-1} (ASAE Standards, 1999). Using a PC-based software, the data was easily transferred to a personal computer for further analysis.

A compression test machine (ELE) was used for the UCS and ITS tests at a deformation rate of 1 mm min^{-1}. During the tests, stress and strain were recorded manually in deformation increments of 0.1 and 0.5 mm for ITS and UCS, respectively.

The ITS tests were performed by applying load along the cores in between two flat parallel plates according to the indirect Brazilian test described by Dexter and Kroesbergen (1985). Failure occurred when fracture was observed at both ends of the sample. The ITS was calculated from a modified equation proposed by Frydman (1964)

$$\mathrm{ITS} = \frac{2Fg(x)}{\pi dl} \quad (1)$$

where F is the polar force required to fracture the core, d and l representing sample diameter and length, respectively. Flattening coefficient ($g(x)$) was defined as suggested by Frydman (1964)

$$g(x)=\left(-\frac{d}{2a}\right)\left\{2x - \sin 2x - \left(\frac{2y}{d}\right)\ln\left(\frac{\pi}{4}+\frac{x}{2}\right)\right\} \quad (2)$$

where x is the flattening ratio such that $x = a/y$, and a the width of the flattened portion and y the distance between the flattened portions at failure. Frydman (1964) suggested that Eq. (2) may be used as long as $g(x)$ is greater than 0.9.

The UCS testing was carried out in a similar way as the ITS, but in this case, the load was applied across the ends of the sample. The UCS was calculated as the load at failure divided by the sample's cross-sectional area at failure (A_f), which was estimated as (Koolen and Kuipers, 1983)

$$A_f = A_0(1 - \varepsilon_f) \quad (3)$$

where A_0 and ε_f represent initial cross-sectional area and longitudinal strain at failure, respectively. Failure was assumed to have occurred when an abrupt and permanent decrease of applied load was observed.

Uni-axial confined compression test (CCT) was performed to characterize σ_{pc} (Koolen, 1987). Core samples (diameter 10 cm and height 7.3 cm) were taken from 0–7.5 to 7.5–15 cm depths. Particular care was taken to obtain the "undisturbed" samples. After inserting the core samplers, the walls of the pots were carefully cut and then a sharp knife was used to separate the bottom of the sample of 0–8 and then 8–16 cm depth. A California Bearing Ratio (CBR) machine was used for the tests at a deformation rate of 1 mm min^{-1}. A plate having a diameter of a little less than that of the core samplers was mounted between the loading ram and the soil sample. During testing, major principle stress (σ_1) and major principle strain (ε_1) were recorded manually in deformation increments of 0.5 or 1 mm depending on the changes of stress during loading. The test was continued up to a maximum of 20 mm sinkage.

2.5. Effective stress calculation

In unsaturated soil and in cases where the externally applied stresses are absent as in the present study, there are two forces which generate effective stress, viz. a component caused by the matric potential and a component caused by the surface tension in the water menisci (Towner and Childs, 1972). As the data used concern the degrees of saturation (S) more than 0.3 (wet moisture range), we ignored the contribution of surface tension (Towner and Childs, 1972 and personal communications with Prof. A.R. Dexter and Dr. A.J. Koolen). Therefore, only the matric potential component ($-\chi\psi_m$) was used as effective stress (σ'), where χ was assumed to be equal to S and ψ_m represents matric potential. Validity of the assumption has been justified for granular material (Towner and Childs, 1972), sand–kaolin mixtures (Mullins and Panayiotopoulos, 1984) and structurally unstable soils (Mullins, 2000) like this soil. Matric potential up to -0.8 bar and the corresponding S values were read from tensiometers' and TDR readings, respectively. Those lower than -0.8 bar were inferred from the SWCC.

2.6. Determination of pre-compression stress (σ_{pc})

Following the procedure of Dawidowski and Koolen (1994), Casagrande's (1936) method was used in a computer programme written in MATLAB. The computer programme has the flexibility to accept all kinds of stress–strain pairs, stress or force vs. sinkage, ε_1, e or BD and can calculate σ_{pc} for any of these combinations. The computer programme can reduce and filter the data in order to cope with the ever-present small fluctuations in the experimental results and determine the data pair for which the smallest radius of curvature has occurred in the plot of ε_1, e or BD vs. $\log\sigma_1$. Then, it characterizes the bisector line between tangential line on curve in the point of smallest radius and horizontal line. Finally, threshold value (σ_{pc}) can be found by stress ordinate of intersection of the bisector and the extension of the VCL.

3. Results and discussion

Soil settlement measurement after watering shows that the soil shrank rapidly within the first few hours of drainage. Consolidation of the soil starts with structural break down followed by slumping and shrinkage during drying. It was observed that the BD of the soil changed from 1.2 Mg m^{-3} (initial BD) to an average value of 1.5 Mg m^{-3} after flood irrigation and subsequent drying (Mosaddeghi et al., 2003). Studies of Hajabbasi et al. (1999) on the soil showed that there was no significant difference between BD and physical properties under no-tillage and conventional tillage systems at the end of growing season and the soil approached pre-tillage state irrespective of the management systems. This is in agreement with Bennie and Krynauw (1985) report that flood irrigation and wetting of a silt loam soil to LL caused consolidation to a higher density. Kuipers and van Ouwerkerk (1963) also showed important impact of rainfall on consolidation process in silty clay loam soil.

3.1. Pre-compression stress vs. bulk density and water content

In the wet range of water contents, some water was squeezed out of the soil during the CCT and therefore, σ_{pc} was considered as the pre-consolidation stress in these cases. The results showed that the value of σ_{pc} was non-unique and dependent upon whether e, sinkage, ε_1 or BD was used as packing state of the soil in order to predict σ_{pc}. However, the predicted values of σ_{pc} using sinkage or ε_1 was similar to the one predicted using e as dependent variable. In Fig. 1, it can be seen that σ_{pc} prediction using BD, as strain-related property vs. stress ($\sigma_{pc(BD)}$) is higher than that obtained using e ($\sigma_{pc(e)}$) by a factor of 1.3. As we know, BD is not a linear function of e (i.e. $\mathrm{BD} = \mathrm{PD}/(e+1)$). Thus it is reasonable to expect different values of σ_{pc} using e or BD as strain input. We assume that this non-linear function of BD vs. e can affect the curvature of the stress–strain relationship and therefore the σ_{pc} determination. The magnitude of the change in the value of σ_{pc} as a result of the use of BD as the strain-related property is determined by the curvature of the plot of e vs. $\log\sigma_1$ of the soil at a particular θ_m. This might be related to the contributive effect of non-linearity in e vs. BD compared with

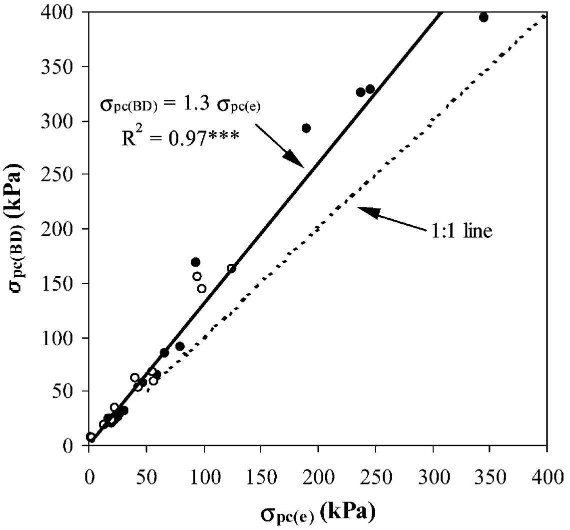

Fig. 1. Interrelationship of pre-compression stress calculated using BD-log σ_1 ($\sigma_{pc(BD)}$) and e-log σ_1 ($\sigma_{pc(e)}$) and comparison with 1:1 line. Solid and open symbols represent values from 0–8 and 8–16 cm depths, respectively.

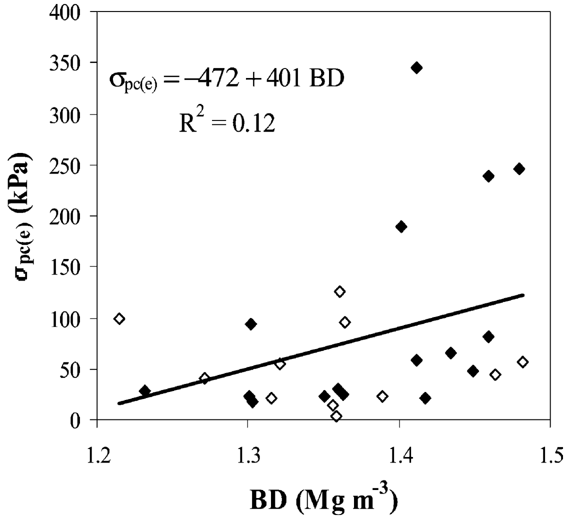

Fig. 2. Pre-compression stress ($\sigma_{pc(e)}$) vs. dry bulk density (BD) of the soil. Solid and open symbols represent values from 0–8 and 8–16 cm depths, respectively.

the curvature of stress–strain curve depending on the slope of over-consolidation and virgin compression regions and the sharpness of pre-compression region on stress–strain curves. It is recommended to use $\sigma_{pc(e)}$ for the analysis, as Casagrande (1936) in his standard method used e as strain-related property and the values are on the safe side compared with $\sigma_{pc(BD)}$ from the view of soil bearing capacity against external stresses. Pre-compression stress values are identified within the range of sinkage from 0.5 to 3 mm as reported earlier by Dawidowski and Koolen (1994).

As there was no abrupt difference between variation tendencies of $\sigma_{pc(e)}$ with θ_m for 0–8 and 8–16 cm soil layers, we pooled the data from both depths for the analysis. The relationships of $\sigma_{pc(e)}$ vs. initial BD and θ_m are plotted in Figs. 2 and 3, respectively. There was no significant or strong correlation between $\sigma_{pc(e)}$ and BD. Although there was a tendency for $\sigma_{pc(e)}$ to increase with BD, $\sigma_{pc(e)}$ was found to be largely independent of BD. On the other hand, Canarache et al. (2000) showed that σ_{pc} increased with increasing BD (decreasing e) in deep-ripped soils of Romania. Alexandrou and Earl (1998) using plate sinkage test results for σ_{pc} determination, found that the σ_{pc} of sand loam soil increased when BD was increased and θ_m was decreased. As for clay soil, the σ_{pc} increase was largely independent of BD. Lebert and Horn (1991) indicated that the impact of BD on σ_{pc} with increasing clay content (aggregation) diminished. For very loose soils (BD < 1.27 Mg m^{-3}), no σ_{pc} was observed by Alexandrou and Earl (1998). However, the results of this work showed that a soil with BD as low as 1.27 Mg m^{-3} had some σ_{pc} depending on θ_m (Fig. 2).

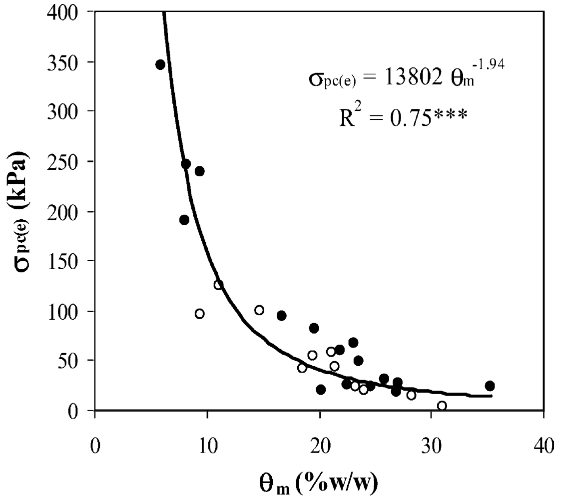

Fig. 3. Effect of soil water content (θ_m) on soil pre-compression stress ($\sigma_{pc(e)}$). Solid and open symbols represent values from 0–8 and 8–16 cm depths, respectively.

The $\sigma_{pc(e)}$ values were strongly correlated with θ_m and increased consistently for decreasing θ_m (Fig. 3). A similar trend was observed for tensile strength of structurally unstable soils (Mullins, 2000). The strong relationship between $\sigma_{pc(e)}$ and θ_m reflects the dominance of cohesion rather than friction on soil strength as reported by Alexandrou and Earl (1998) for clay soil. Despite the linear relation reported by Alexandrou and Earl (1998), our results (Fig. 3) showed a logarithmic relationship. This might be due to different ranges of θ_m studied, intrinsic soil properties and different techniques used for σ_{pc} determination. Since the soil used in this study was structurally very unstable, an abrupt change of strength as a result of soil drying was expected. The range of θ_m in our study was larger than that of Alexandrou and Earl (1998). Therefore, if one considers only the wet end, i.e. θ_m values greater than 15% in Fig. 3, one might conclude that a linear relationship exists. For structured non-plastic soils, Veenhof and McBride (1996) reported that σ_{pc} was significantly, negatively and logarithmically correlated to θ_m. Kirby (1991) reported that σ_{pc} increases in a soil that is in a more dense or drier pre-test condition and decreases with higher θ_m and lower porosity.

The $\sigma_{pc(e)}$ values could be categorized based on the classification of Horn and Fleige (2000) and predict $\sigma_{pc(e)}$ using θ_m as an easily measurable property. Based on this classification, the soil has very low $\sigma_{pc(e)}$ (<30 kPa) at θ_m higher than PL and extremely high values (>150 kPa) at θ_m lower than SL. This sharp change of compactibility state is unique and is in agreement with the findings of Mosaddeghi et al. (2000). They reported that soil sinkage and side-flowing are caused by traffic at PL and little compaction at 0.6 PL. However, studies by Dias Junior (1994) on the σ_{pc} of structurally stable soils with high OM under long-term tillage treatments showed a slight change of σ_{pc} with θ_m.

3.2. Pre-compression stress vs. matric suction and effective stress

There is a significant non-linear relationship between $\sigma_{pc(e)}$ and matric suction ($-\psi_m$) that can be utilized in the prediction of $\sigma_{pc(e)}$ provided that ψ_m is available (Fig. 4). Studies of Horn et al. (1994) confirmed that the σ_{pc} value is very close to that of ψ_m of wet homogenized soil. Wulfsohn et al. (1996) observed significant changes in ψ_m when the applied load exceeded some transition stress related to the value of soil ψ_m.

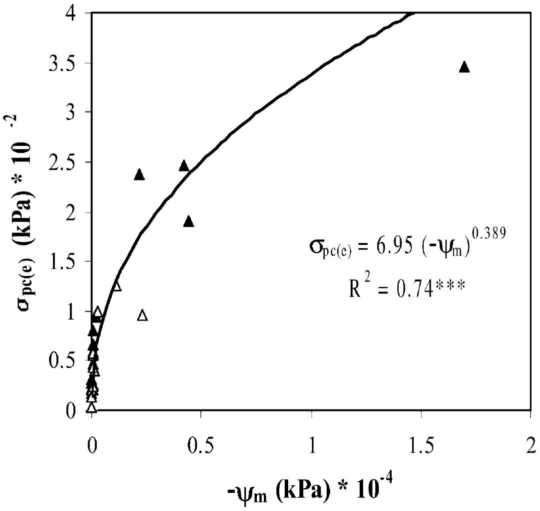

Fig. 4. Effect of matric suction ($-\psi_m$) on soil pre-compression stress ($\sigma_{pc(e)}$). Solid and open symbols represent values from 0–8 and 8–16 cm depths, respectively.

Linear relationship of $\sigma_{pc(e)}$ with effective stress (σ') was observed in the range of 0–100 kPa (wet moisture range) (Fig. 5). This implies that in the absence of external loads $\sigma_{pc(e)}$ of the soil is determined mainly by $-\chi\psi_m$ and the derived equation can be used for predicting $\sigma_{pc(e)}$, if ψ_m and S are known. The intercept of the fitted line (14.5 kPa) represents $\sigma_{pc(e)}$ value for saturated state. In agreement with Canarache et al. (2000), it was found that effective stress due to soil drying was the main cause of increase in σ_{pc}. In other words, with soil drying, transition from over-consolidated range to VCL (as calculated using σ_{pc}) occurred at a higher stress. The slope of the fitted equation was near one and showed that $\sigma_{pc(e)}$ is closely related to σ'. In this regard, Horn et al. (1994) also showed that for homogenized soils, value of σ_{pc} corresponds to that of σ'. Mullins (2000) reported a similar relation for tensile strength and CI of some hardsetting soils. At higher effective stresses (>100 kPa), the relation deviated from a linear line. This might be due to development of micro-cracks (weak spots) in the soil upon drying that could decrease σ_{pc} when compared to the theoretical value.

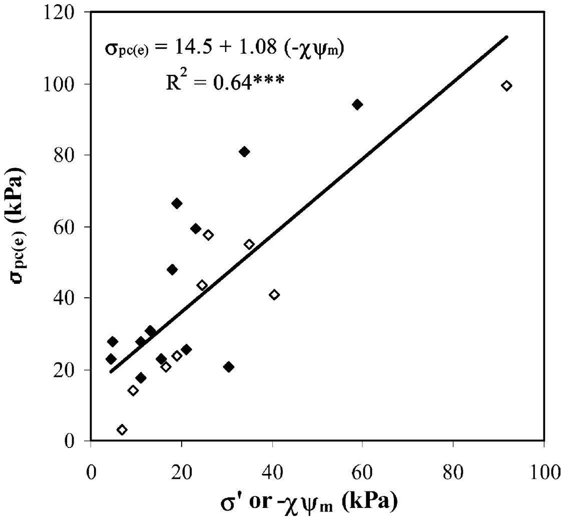

Fig. 5. Pre-compression stress ($\sigma_{pc(e)}$) vs. effective stress (σ' calculated as $-\chi\psi_m$). Solid and open symbols represent values from 0–8 and 8–16 cm depths, respectively.

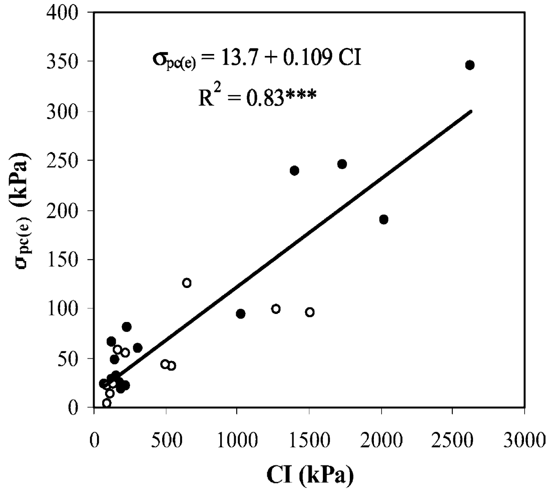

Fig. 6. Prediction of soil pre-compression stress ($\sigma_{pc(e)}$) by cone index (CI). Solid and open symbols represent values from 0–8 and 8–16 cm depths, respectively.

It can be assumed that the first period of flood irrigation brings soil to saturation (zero ψ_m and consequently σ' become zero) and causes collapse slaking and disruption of unstable bonds between particles. As the soil is high in silt and has unstable aggregates and low OM (Table 1), under this condition, finer particles (silt and clay) can be released and are free to be randomly arranged and be pulled by water menisci to points of contact between larger particles. Subsequent shrinkage of soil causes mineral particles to be bonded together by capillary forces through effective stress, which results in an increase in the number of contact point and a higher σ_{pc}. In addition, with such high carbonate content (Table 1), solution of carbonates upon saturation and subsequent precipitation during drying might be expected. As the soil dries, the concentration of carbonates in solution increases toward maximum. When water menisci retreats to points of contact, it is reasonable to expect carbonates to precipitate in these menisci and act as a cement and contribute in strengthening the soil.

It is also believed that dense agricultural subsoils are caused by secondary compression (realignment of clay particles during long time periods under constant overburden pressures) occurring simultaneously with primary compression under increased effective stress from desiccation (Hartge, 1986).

3.3. Pre-compression stress vs. cone index

Cone index is an easily measurable soil attribute and was found to have high correlation with $\sigma_{pc(e)}$ (Fig. 6). The derived equation is very similar to that of Canarache et al. (2000) ($\sigma_{pc} = 11 + 0.115\,\mathrm{CI}$, $R^2 = 0.90^{**}$) for σ_{pc} of deep-ripped soils of Romania. These equations approached a 1:10 regression of $\sigma_{pc(e)}$ vs. CI. As a first approximation, well-known critical CI of 2 MPa for root growth corresponds to a $\sigma_{pc(e)}$ of 200 kPa. Culley and Larson (1987) obtained a highly significant correlation between $\sigma_{pc(e)}$ and undrained fall-cone strength. Dias Junior (1994) also found significant correlation between σ_{pc} and unconfined strength measured by pocket penetrometer in soils under long-term tillage systems. However, Lebert and Horn (1991) used multiple regressions where CI, soil physical and Mohr–Coloumb mechanical properties were included as independent variables for prediction of σ_{pc} of structurally stable soils of Germany.

3.4. Pre-compression stress vs. unconfined compressive strength and indirect tensile strength

Due to high flattening of wet and moist samples during loading in ITS test, in some cases, $g(x)$ was smaller

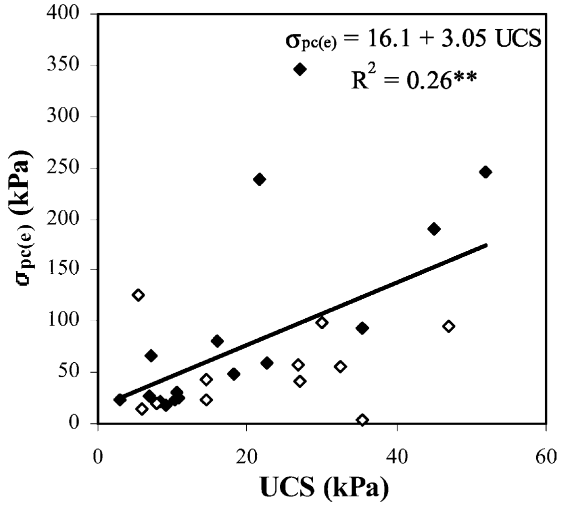

Fig. 7. Relation between soil pre-compression stress ($\sigma_{pc(e)}$) and unconfined compression strength (UCS) of the soil. Solid and open symbols represent values from 0–8 and 8–16 cm depths, respectively.

than 0.9 (the complete range of $g(x)$ was 0.85–0.99). However, having no alternative, Eq. (2) was used for calculating ITS.

A high correlation between $\sigma_{pc(e)}$ and UCS or ITS was expected. However, as is shown in Figs. 7 and 8,

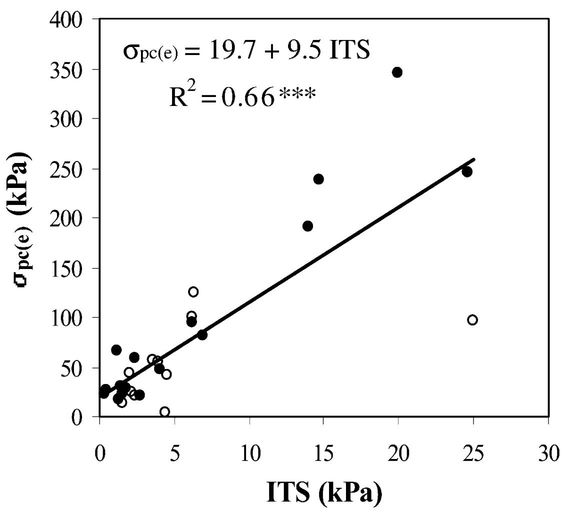

Fig. 8. Relation between pre-compression stress ($\sigma_{pc(e)}$) and indirect tensile strength (ITS) of the soil. Solid and open symbols represent values from 0–8 and 8–16 cm depths, respectively.

these are not so good predictors of $\sigma_{pc(e)}$ as CI is. This might be due to the fact that soil is to some extent similarly confined under CCT and cone penetrometry. Thus, the values for $\sigma_{pc(e)}$ and CI correlated more (Fig. 6). On the other hand, in unconfined compressive and tensile tests, the soil is unconfined and the resultant values (UCS and ITS) might not be completely related to $\sigma_{pc(e)}$. Soil compression under cofined condition (e.g. CCT) is a stable mechanical process that causes soil homogenization (Koolen, 1987) and the soil strength, i.e. σ_{pc} is determined by cumulative effects of weak and strong spots in the soil mass. But in unstable processes like unconfined compression and tensile tests, weak spots (e.g. micro-cracks generated upon drying) in the soil mass determines the represented soil strengths (Koolen, 1987). In addition, $\sigma_{pc(e)}$ is the critical stress value at which the soil behaviour changes from elastic to plastic deformation, whereas UCS and ITS are related to the stress values at which failure occurs in the sample.

3.5. Interrelationship between unconfined compressive strength and indirect tensile strength

Studying the relations between soil mechanical properties is useful in estimating the appropriate property that should be used in specific situations. This relation was also obtained for lower range of UCS (0–40 kPa) and ITS (0–7 kPa) of the studied soil and compared with the theoretical equation (Fig. 9). At the upper ranges, there was high variability in UCS and ITS values. According to the Griffith's crack theory for brittle materials (e.g. dry soil), the slope of the line should be 8 (UCS = 8 ITS) (cited in Koolen and Vaandrager, 1984). The deviation from theory was expected because the theory was developed for homogenized and isotropic materials and not heterogeneous and anisotropic materials like agricultural soils. In addition, in contrast to the UCS test, the orientation and position of the failure in the ITS test was predefined in the sample. This is not the case in "true" tensile tests (Young and Mullins, 1991). Panayiotopoulos (1996) also reported change of slope of the equation for stable Alfisols with θ_m. However, the derived slope was similar to the value 6.3 which is usually obtained for soils with low structural stability (Young and Mullins, 1991). The derived equation can

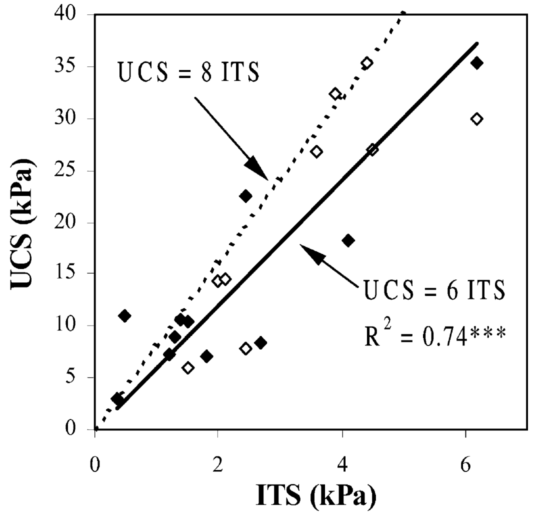

Fig. 9. Relation between unconfined compressive strength (UCS) and indirect tensile strength (ITS). Solid and open symbols represent values from 0–8 and 8–16 cm depths, respectively. The line for UCS = 8 ITS is the expected theoretical line (Koolen and Vaandrager, 1984).

be used interchangeably to predict the required values of UCS or ITS.

4. Conclusions

(1) The data supported the hypothesis that strength in this unsaturated structurally unstable soil as a typical soil of the region was controlled by the history of the soil water stress. Previous desiccation affected the extent of the over-consolidated region and pre-compression stress.
(2) The increase in soil strength defined by pre-compression stress due to soil water suction might be explained in terms of effective stress. Soil drying could leave the soil compacted to about a level of σ_{pc} equal to the maximum level of effective stress applied due to internal forces.
(3) Prediction of pre-compression stress from the soil properties (θ_m and CI) was possible. Cone penetrometer might be useful for rapidly determining pre-compression stress of the soil without the need to carry out CCT.
(4) UCS and ITS could be used to predict one another.

Acknowledgements

This study is a part of the author's original Ph.D. dissertation. The authors would like to thank Isfahan University of Technology (IUT), Iran, for the financial support of the study. Also, we are thankful to Soil Mechanics Laboratory Staff, College of Civil Engineering, IUT, Iran, for their sincere cooperation. Our special appreciation is extended to Mr. M. Cheshomi for his intensive effort and patience in developing the package of pre-compression stress calculation in MATLAB. Useful comments of Prof. A.R. Dexter from Institute of Soil Science and Plant Cultivation (IUNG), Poland, and Dr. A.J. Koolen from Soil Technology Group of Wageningen University, The Netherlands, are very appreciated. Last but not the least, our special thanks go to Mr. V. Sarami from Iran Language Institute (ILI) in Isfahan for his critical proof reading and editing of the paper.

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