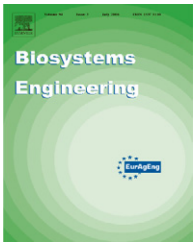
BIOSYSTEMS ENGINEERING 98 (2007) 90–101

Available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110



Research Paper: SW—Soil and Water

Suitability of pre-compression stress as the real critical stress of unsaturated agricultural soils

M.R. Mosaddeghi[a,*], *A.J. Koolen*[b], *M.A. Hajabbasi*[c], *A. Hemmat*[d], *T. Keller*[e]

[a]*Department of Soil Science, College of Agriculture, Bu-Ali Sina University, Hamadan 65174, Iran*
[b]*Soil Technology Group, Wageningen University, Technotron, Bornsesteeg 59, 6708 PD Wageningen, The Netherlands*
[c]*Department of Soil Science, College of Agriculture, Isfahan University of Technology, Isfahan 84156, Iran*
[d]*Agricultural Machinery Engineering Department, College of Agriculture, Isfahan University of Technology, Isfahan 84156, Iran*
[e]*Department of Soil Sciences, Swedish University of Agricultural Sciences, P.O. Box 7014, SE 750 07 Uppsala, Sweden*

ARTICLE INFO

Article history:
Received 17 July 2006
Accepted 8 March 2007
Available online 5 July 2007

This study was conducted to examine if the pre-compression stress σ_{pc} is the major critical stress influencing soil physical quality indices, i.e. air permeability K_g and air-filled porosity (AFP). Topoils of five soil series were collected from the Isfahan Province in central Iran. Treatments consisted of: five soil types (sandy loam to clay), four matric suctions (10, 20, 50 and 80 kPa), three values for the maximum axial stress σ_{pc} (200, 400 and 600 kPa), and three loading types with 10 loading cycles. The loading types were a confined compression test (CCT), a semi-confined compression test (SCCT) and a kneading compression test (KCT). Soil type and matric suction, loading type, maximum applied stress and number of loading cycles significantly affected log $[K_g]$, void ratio e, and AFP. The Significance of the loading cycle's number implies that though the σ_{pc} of the soil was not exceeded, the soil physical properties were considerably changed. A gradual transition from elastic-to-plastic deformation was observed on the stress–strain curves obtained from CCT. The stress–strain curves of the SCCT were sharp at σ_{pc} due to the semi-confined condition, which allows lateral deformation during loading. Cyclic loading was not always accompanied by significant irreversible strain but this could result in up to 10 times the decrease in K_g. For the fine-textured soils, CCT resulted in a significantly greater reduction in K_g, e and AFP when compared with KCT. The opposite trend was observed for the coarse-textured soils. The KCT homogenised the pore system and resulted in more decrease of K_g when compared with CCT at matric suctions of 10 and 20 kPa. However, at the matric suctions of 50 and 80 kPa, KCT created an open microstructure, which led to relatively higher values of K_g. The results show that the σ_{pc} might not be a real critical stress from a view of soil physical quality indices (i.e. K_g and AFP), especially at low matric suctions. Thus, the characterisation of soil compaction may not be completely accounted by a bulk property such as void ratio, but additional information about pore characteristics are needed to describe the effect of compaction on soil physical quality.

---

[*] *Corresponding author.*
E-mail addresses: mosaddeghi@basu.ac.ir (M.R. Mosaddeghi), jos.koolen@wur.nl (A.J. Koolen), hajabbas@cc.iut.ac.ir (M.A. Hajabbasi), ahemmat@cc.iut.ac.ir (A. Hemmat), thomas.keller@mv.slu.se (T. Keller).

doi:10.1016/j.biosystemseng.2007.03.006

1. Literature review

The development of heavier agricultural tractors and implements, and intensive agricultural activities within the last three decades, has led to the questioning of the the maximum acceptable mechanical compressibility of arable lands. Although the effectiveness of the farmer's practices increased due to improvements in farm machinery technology, the uncertainty of the sustainablity crop of production also increased. The development of techniques to identify and quantify the machinery-induced compaction of agricultural soils is the first step toward sustainable soil management.

The concept of pre-consolidation stress originated in civil engineering soil mechanics in relation to the slow consolidation of saturated homogenised clayey soils (Casagrande, 1936). In agriculture, the concept is applied to quick compression of unsaturated soils simulating the loading by soil running gears and wheels, and has been given a variety of names such as: pre-compaction stress, equivalent pre-compaction stress, pre-compression stress, critical stress, preload, bearing capacity and compaction resistance (Koolen & Kuipers, 1989; Dawidowski & Koolen, 1994; Koolen & van den Akker, 2000; Horn & Baumgartl, 2001; Keller, 2004; Mosaddeghi *et al.*, 2006, 2007).

When a soil is pre-compressed, i.e. it has a pre-compression stress σ_{pc} greater than zero, a 'knee' discontinuity is expected on the stress–strain curve partitioning the curve into two regions: an elastic or over-compacted section, and a plastic or virgin compression section. The elastic region is usually approximated by the re-compression line (RCL), while the plastic region is characterised by the virgin compression line (VCL). The σ_{pc} is defined as the stress value at the intersection of the less steep RCL and the steeper VCL. Principally by limiting the imposed stress to below σ_{pc}, the risk of soil compaction (i.e. plastic deformation) and undesirable changes of soil structure could be minimised (Dawidowski & Koolen, 1994; Horn & Lebert, 1994).

Pre-compression stress is an important input parameter in the modelling of soil tillage and compaction problems (Koolen & van den Akker, 2000). Römkens and Miller (1971) reported that σ_{pc} is a predictor of the critical strength at which root elongation ceases, indicating that soils with considerable σ_{pc} are more likely to reduce root growth. Watts *et al.* (1999) declared that σ_{pc} could be linked to soil biological properties, e.g. soil respiration. Horn (2000) stated that σ_{pc} is a critical stress for changes in soil physical, chemical and biological properties but the evidence is limited.

The concept of σ_{pc} is based on non-significant reversible or elastic strain (in the over-compacted region, i.e. at stresses $<\sigma_{pc}$) and significant irreversible or plastic strain (at stresses $>\sigma_{pc}$) of the soil (Koolen, 1987; Horn & Lebert, 1994; Alexandrou & Earl, 1995). However, Koolen and Kuipers (1989) mentioned that there might be significant strain even in the over-compacted region depending on the initial soil conditions. They assumed that the concept was more valid for structurally stable, dry and fine-textured soils. For structurally unstable soils and sandy soils, however, the transition from the over-compacted to the virgin compression part might be rather gradual than sharp, and therefore, it might be difficult to identify the exact position of σ_{pc} on the stress–strain curve. Trautner (2003) observed that plastic deformation took place when the stress applied by wheels was lower than σ_{pc}. He believed that σ_{pc} is applicable for homogeneous civil soils but that it is not a reliable index of soil strength against external stresses of heterogeneous, aggregated agricultural soils.

For root growth, however, soil physical properties and pore characteristics should be included in addition to soil deformation for the assessment of compaction. Studies of Canarache *et al.* (2000) on deep-ripped soils in Romania showed that crop yields were not significantly correlated with σ_{pc} or compression index. They showed that other soil physical properties should be considered that directly affect root growth in order to assess compaction of agricultural soils. An important question is: "what are the relevant quantities that must be considered to obtain the most useful relationship between compaction and soil physical effect?" (Koolen, 1994). The term soil qualities are designated for those physical properties that are relevant to agricultural uses of the soil (Koolen, 1987).

The quantification of compaction using the concept of soil qualities is an attempt to widen the usefulness of the information obtained for integrated soil, crop-and machine-related disciplines (Koolen, 1987; Lerink, 1994). Dawidowski and Koolen (1987) and Lerink (1990) reported that soil qualities decline during deformation even at constant soil volume. Normal and shear stresses could extensively affect soil pore size distribution, hydraulic conductivity and air permeability at constant pore volume (Horn, 2002). Thus, we may not limit ourselves to strain-related properties as the dependent variable for the determination of σ_{pc}, but should also consider further soil quality attributes.

Another important aspect is that the direction of the principal stresses changes in a soil–wheel system. When a wheel passes over soil, the directions of principal stresses will rotate continuously. These changes in stress directions may be simulated by kneading types of compaction (Söhne, 1958; Mosaddeghi *et al.*, 2007). However, information about the effect of diverse loading conditions on different soils is limited.

The hypothesis in this study was that soil physical quality will not change significantly during loading under the stresses lower than or equal to the value of σ_{pc} provided that σ_{pc} is a critical stress for agricultural soils. The objectives of this study were: (i) to use the different compaction tests to assess the response of five agricultural soils from central Iran when compacted at different normal stresses and soil matric suctions and (ii) to evaluate if the pre-compression stress is a critical stress from a view of soil physical quality.

2. Materials and methods

2.1. Soil properties

Topsoils (0–20 cm) of five different soil series were collected from the Isfahan Province in central Iran. The soils are typical soil series in the region. The mean annual precipitation and temperature at the region are about 160 mm and 16 °C, respectively.

Prior to compaction tests, soil samples were air-dried and grounded to pass a 2 mm sieve for measuring physical and mechanical properties. Classification and some physical and mechanical properties of the soils are given in Table 1.

2.2. Sample preparation

The experiment was conducted on soil samples in laboratory. Sufficient amount of soil was collected from the ploughed layer at suitable water content (i.e. between plastic limit and shrinkage limit) by composite sampling and great care was taken not to crash soil aggregates during sampling. The samples were air-dried and passed through 10 mm sieve. Soil was poured and knocked slightly into cylinders with diameter and height of 9.9 and 5 cm, respectively in order to achieve a uniform initial dry bulk density of 1.2 Mg m^{-3}. The initial bulk density for soils nos 4 and 5 (coarse-textured soils) were higher than 1.2 Mg m^{-3} due to unstable structure and lack of aggregates. The inner wall of the cylinder was lubricated with oil before filling to decrease friction between soil particles and the cylinder wall. Cloth pieces were tightened under the cylinders before soil filling. It was assumed that this packing state and size range are ideal for a seedbed after primary and secondary tillage practices.

The prepared soil cylinders were wetted slowly, and then left at saturation for 2 days and weighed for saturated water content. Then, the soil cylinders were placed on sandbox (0–10 kPa) or sand–kaolin box (20–100 kPa) for adjusting matric suctions to values of 10, 20, 50 and 80 kPa. The equilibrium time of 2 and 5 days were found to be satisfactory for sandbox and sand-kaolin box, respectively. The soil cores then were weighed and loaded while tightly fitted in sample holder of a kneading apparatus as explained in Section 2.3. After compaction processes, the soil cylinders were oven-dried for 48 h at 105° C to calculate soil water content and void ratio *e*.

2.3. Loading characteristics

Compaction of the soil cores was accomplished using a Zwick Universal Testing Machine. The machine was fully controlled by a PC. The master program of *hysteresis* and its option *cyclic loading* was used to collect the data on loading, unloading and reloading paths. Pre-load pressure, pre-load speed, and loading speed were set to 5 kPa, 50 mm min^{-1}, and 10 mm min^{-1}, respectively, for all the tests. These values were found to be the best based on some preliminary tests on a loamy soil with moderate water content. The strain rate of 10 mm min^{-1} is about one order of magnitude slower than strain rates under normal agricultural practices (Koolen, 1987; Keller *et al.*, 2004). Loading speed of 10 mm min^{-1} was the highest one that did not cause significant noise or change of stress during constant cyclic loading. Upper and lower reversal points were adjusted to 200, 400 or 600 and 5 kPa, respectively. Ten loading cycles were applied for each maximum stress. So the maximum stress (200 kPa) was constant for the *first* 10 cycles and was increased to 400 and 600 kPa for the *second* and *third* 10 cycles, respectively. Ground pressures from tractors and harvesting machines commonly range from 50 to 300 kPa. Koolen and Kuipers (1983) proposed axial stress of 400 kPa to be applied in CCT for simulation of field traffic by normal tires.

Three loading-type tests of confined (CCT), semi-confined (SCCT) and kneading (KCT) compression tests were performed in Lerink's kneading apparatus (Fig. 1). The kneading apparatus was installed into the testing machine. The apparatus is fully described by Lerink (1990). It was designed in principle for kneading distortion on wet soil samples without any volume change. The apparatus consisted of a sample holder, a piston–annulus unit (with a diameter of 9.8 cm) and an adaptor (Lerink, 1990). The piston–annulus unit applied load on the surface of the sample. The piston had a diameter of 5 cm to apply stress on the centre of the soil core. The annulus was to apply stress on the surrounding soil. The adaptor would change the stress application between piston and annulus areas. The prepared soil cylinders were tightened in the sample holder by three screws. For the CCT, the soil was

Table 1 – Classification and some physical and mechanical properties of the studied soils

Soil number	1	2	3	4	5
Soil classification[a]	Aquic Haplocalcids	Typic Haplargids	Fluventic Haplocambids	Typic Torrifluvents	Not Available
Sand, g kg^{-1}	127	158	240	532	432
Silt, g kg^{-1}	348	502	472	301	396
Clay, g kg^{-1}	525	348	288	167	172
Texture[a]	Clay	Silty clay loam	Clay loam	Sandy loam	Loam
Organic matter, g kg^{-1}	20	10	14	9.3	8
Liquid limit, g kg^{-1}	483	306	360	NP[b]	NP
Plastic limit, g kg^{-1}	240	191	181	NP	NP
Shrinkage limit, g kg^{-1}	136	86	105	75	81
Field capacity, g kg^{-1}	293	258	269	155	171
$CaCO_3$ content, g kg^{-1}	301	450	341	328	316

[a] USDA classification.

[b] NP means non-plastic behaviour.

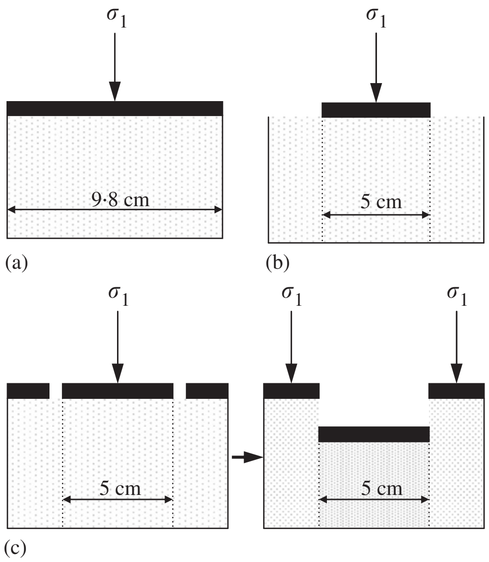


Fig. 1 – Schematic of the loading types; confined compression test (a), semi-confined compression test (b), and kneading compression test (c); σ_1, compressive stress.

compacted in the rigid cylindrical sampler under a steadily downward-moving plate (with a diameter of 9.8 cm) fitting inside it until a certain σ_{pc} achieved. The piston stroke was used for the SCCT. Alternative strokes of piston and annulus were applied for the KCT. The piston–annulus unit was lubricated before starting the tests to decrease friction among piston and annulus as well as their frictions with the soil.

2.4. *Measurements of soil physical properties*

During the tests, force as a function of plate sinkage was measured for further analysis. From the output data, stress–strain curves were calculated by dividing the measured force by the loading area and the sinkage by the initial height of the sample. It should be mentioned that for the SCCT and the KCT, the calculated vertical strain is an *apparent* strain since it includes axial and lateral deformations due to unconfined condition of the loaded soil.

From the soil sample height, and wet and dry weights, *e* and water content were calculated for the CCT and the KCT. Air-filled porosity (AFP) was computed as the difference between soil porosity and volumetric water content. Air permeability K_g was measured by the constant pressure method proposed by Kmoch and Hanus (1965).

The soil sample height and K_g were determined before the compaction process, between the first and the second cycles and after the tenth cycle of each 10 cycles. This means that after the first loading cycle and measuring the soil properties, the loading with constant upper reversal stress was continued for nine more cycles. Due to uneven surface of the soil compacted by KCT, the soil height $h_{average}$ that was used for calculation of *e* was computed by a weighted formula. Because the loaded volume of the annulus was three times larger than that of the piston, $h_{average}$ was calculated as

$$h_{average} = (h_{piston} + 3h_{annulus})/4, \quad (1)$$

where h_{piston} and $h_{annulus}$ are the heights of the soil under piston and annulus, respectively. Because of heterogeneity of compaction processes in the SCCT, *e* and K_g were not measured in this test.

The soil height was determined using a caliper. The software of the testing machine could determine total, plastic and elastic sinkages from the measured force–sinkage curves. The decrease of soil height in the CCT, as measured by the caliper, was checked by the registered plastic sinkage. However, pure compaction did not happen in the KCT so that the soil height was only determined by the caliper.

The K_g was considered as a quantitative measure of soil microstructure, physical quality and continuity of air-filled pores. The virgin compression lines (VCL) of *e* (*e* vs. logarithm of axial stress) and K_g (logarithm of K_g vs. logarithm of axial stress) were plotted in order to compare the effect of different treatments on soil behaviour and physical quality.

2.5. *Statistical analyses*

The experiment was a complete randomised factorial design with two replicates. The treatments consisted of five soil types, four matric suctions, three maximum stress or σ_{pc} values, three loading types with 10 loading cycles. Due to the difficulties mentioned in Section 2.4, the results of SCCT were not included in the statistical analysis so that the total analysed soil samples were 480 ($5 \times 4 \times 3 \times 2 \times 2 \times 2$). The dependent soil properties for the statistical analyses were log [K_g]), *e* and AFP. For some treatments, K_g was too low to be measured; in these cases K_g was set to a very low value of $10^{-6}\,\mu m^2$ to have a definite value of log [K_g]. The mean comparisons were established using the Duncan new multiple range test for probability $P<0.05$. All the statistical analyses were undertaken using the SAS statistics software (Helwig & Council, 1982).

3. Results and discussion

3.1. *Air permeability, void ratio and air-filled porosity as affected by soil and loading conditions*

Analysis of variance showed that the effects of soil type, soil matric suction, loading type, maximum applied stress and number of loading cycles as well as the majority of their on soil physical properties (log [K_g], *e* and AFP) were significant ($P<0.01$).

The differences between the soils with respect to the measured physical properties were significant (Table 2). This implies that the intrinsic soil properties (e.g. texture and organic matter content) are important concerning soil behaviour under a load. Sanchez-Giron *et al.* (1998) and Mosaddeghi *et al.* (2007) also observed that soil textural and intrinsic properties would affect the soil compressibility. The lowest and highest values of K_g and AFP were recorded for soil no. 1 and soil no. 4, respectively. The higher number of macropores of the coarse-textured soil (soil no. 4) might be the reason for its highest value of K_g. The lowest value of *e* (i.e. the highest compressibility) was observed for soil no. 2 which was low in organic carbon and structural stability (Table 2). The K_g was stronger correlated with AFP rather than with *e*. O'Sullivan (1992) reported that K_g of compacted soil samples had a significant power relation with AFP but he did not find a significant relation with *e*; sometimes even a low K_g was recorded on a sample with high *e*.

The K_g and AFP of the compacted samples continuously increased as the soils became drier. However, *e* attained its lowest values for the intermediate matric suctions (Table 3). Void ratio did not highly decrease for the matric suction of 80 kPa, due to soil resistance originated from the internal stress, respectively. This suggests

Table 2 – Mean comparisons of the influence of soil type on air permeability K_g, void ratio *e* and air-filled porosity (AFP)

Soil number	log [K_g, μm^2]	*e*, cm^3 cm^{-3}	AFP, cm^3 cm^{-3}
1	-2.497^{d}	0.742^{a}	0.049^{d}
2	-2.130^{bc}	0.633^{e}	0.060^{c}
3	-2.229^{c}	0.728^{b}	0.061^{c}
4	-1.243^{a}	0.695^{c}	0.161^{a}
5	-1.983^{b}	0.649^{d}	0.101^{b}

Numbers followed at least by one same lower case letter in each column are statistically similar.CCT, confined compression test; KCT, kneading compression test.

Table 3 – Mean comparisons of the influence of soil matric suction on air permeability K_g, void ratio *e* and air-filled porosity (AFP)

Soil matric suction, kPa	log [K_g, μm^2]	*e*, cm^3 cm^{-3}	AFP, cm^3 cm^{-3}
10	-4.624^{d}	0.684^{b}	0.014^{d}
20	-2.666^{c}	0.671^{c}	0.057^{c}
50	-0.878^{b}	0.668^{c}	0.101^{b}
80	-0.099^{a}	0.735^{a}	0.174^{a}

Numbers followed by the same lower case letter in each column are statistically similar.

Table 4 – Mean comparisons of the influence of loading type on air permeability K_g, void ratio *e* and air-filled porosity (AFP)

Loading type	log [K_g, μm^2]	*e*, cm^3 cm^{-3}	AFP, cm^3 cm^{-3}
CCT	-2.105^{b}	0.686^{b}	0.085^{b}
KCT	-1.929^{a}	0.693^{a}	0.088^{a}

Numbers followed by the same lower case letter in each column are statistically similar.
CCT, confined compression test; KCT, kneading compression test.

Table 6 – Mean comparisons of the influence of maximum applied stress on air permeability K_g, void ratio *e* and air-filled porosity (AFP)

Maximum applied stress, kPa	log [K_g, μm^2]	*e*, cm^3 cm^{-3}	AFP, cm^3 cm^{-3}
200	-0.646^{a}	0.781^{a}	0.128^{a}
400	-2.186^{b}	0.673^{b}	0.077^{b}
600	-3.220^{c}	0.614^{c}	0.054^{c}

Numbers followed by the same lower case letter in each column are statistically similar.

Table 7 – Mean comparisons of the influence of number of loading cycles on air permeability K_g, void ratio *e* and air-filled porosity (AFP)

Number of loading cycles	log [K_g, μm^2]	*e*, cm^3 cm^{-3}	AFP, cm^3 cm^{-3}
1	-1.666^{a}	0.713^{a}	0.097^{b}
10	-2.368^{b}	0.666^{b}	0.076^{a}

Numbers followed by the same lower case letter in each column are statistically similar.

Table 5 – Mean comparisons of the influence of soil matric suction-loading type interaction on air permeability K_g, void ratio *e* and air-filled porosity (AFP)

Soil matric suction, kPa	Loading type	log [K_g, μm^2]	*e*, cm^3 cm^{-3}	AFP, cm^3 cm^{-3}
10	CCT	-4.578^{e}	0.690^{c}	0.014^{f}
10	KCT	-4.671^{e}	0.677^{d}	0.013^{f}
20	CCT	-2.584^{d}	0.669^{ef}	0.059^{d}
20	KCT	-2.747^{d}	0.673^{de}	0.054^{e}
50	CCT	-1.320^{c}	0.663^{f}	0.099^{c}
50	KCT	-0.436^{b}	0.673^{de}	0.103^{c}
80	CCT	0.062^{a}	0.722^{b}	0.167^{b}
80	KCT	0.138^{a}	0.748^{a}	0.182^{a}

Numbers followed by the same lower case letter in each column are statistically similar. CCT, confined compression test; KCT, kneading compression test.

that although the soil compactness *e* did not greatly decrease at higher water contents, the soil physical quality decreased significantly. The mean comparisons for the interaction between soil type and matric suction showed that the rate of increase in K_g with soil drying is higher for the coarse-textured soils. Fine-textured soils would preserve their plastic and compressible behaviour. Therefore, the highest and lowest values of K_g were recorded for soil no. 4 at matric suction of 80 kPa and soil no. 5 at matric suction of 10 kPa.

Comparisons between the loading types are presented in Table 4. The CCT generally resulted in lower soil physical properties when compared with KCT. During compression process in the CCT, the pores become aligned in a direction perpendicular to the applied load, i.e. parallel to the soil surface (Kooistra & Tovey, 1994). These horizontally orientated pores are not vertically continuous and therefore the conductivity in the direction of load application is very low. In comparison, the pores have a more random arrangement and irregular shape in non-compacted soil (Pagliai, 1987). The

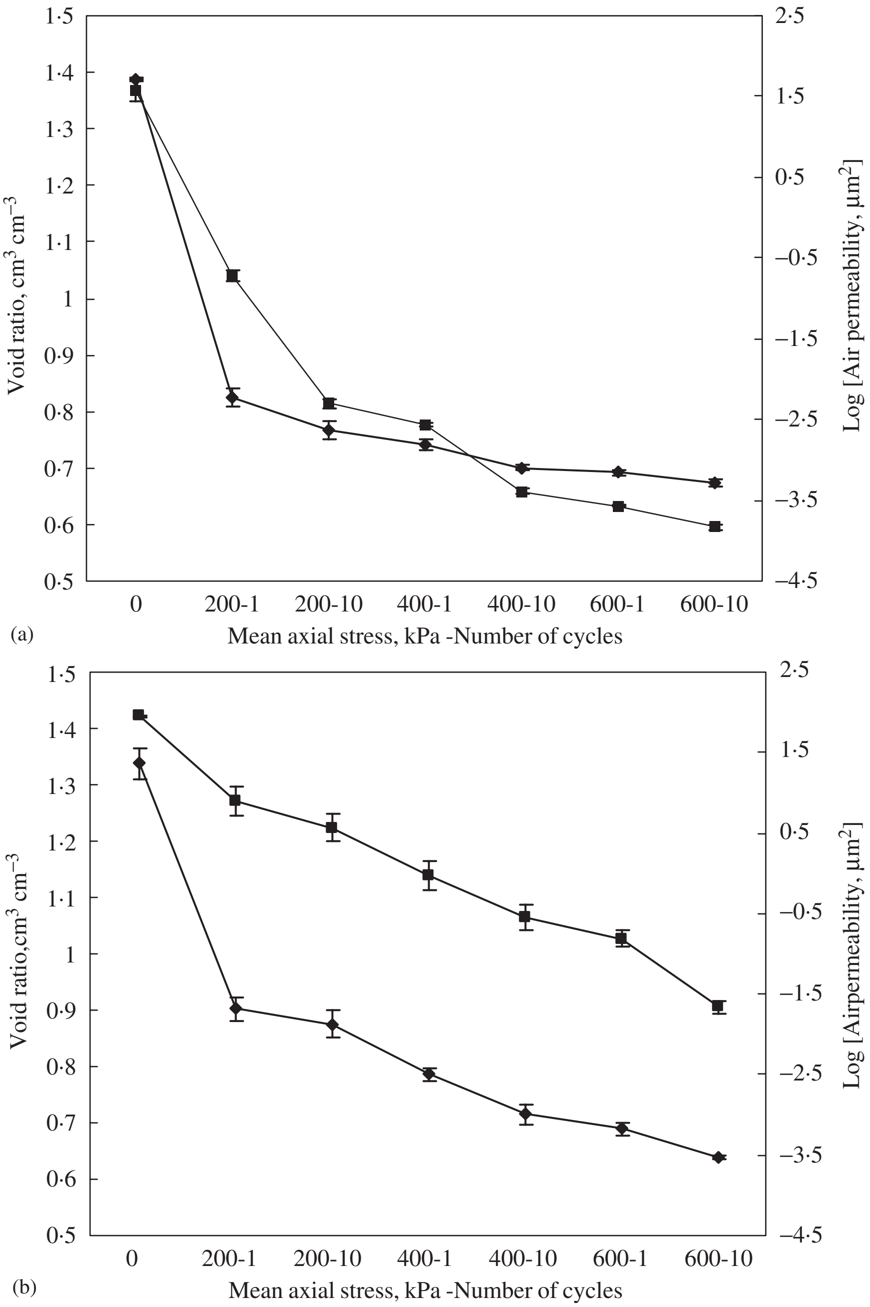


Fig. 2 – Void ratio (–◆–) and air permeability (–■–) of soil no. 1 as affected by the mean axial stress and the number of cycles under cyclic loading of the confined compression test at initial soil matric suctions of 20 (a) and 80 kPa (b); bars indicate the standard deviations of the means.

mean comparisons of the interaction between soil matric suction and loading type showed that at low matric suctions, the effect of kneading compression was more pronounced in decreasing soil physical quality (i.e. K_g) (Table 5). Dawidowski and Koolen (1987) also reported that distortion (deformation at near-constant volume) which happened at high soil water contents, severely diminished pore continuity and conductivities. Alternatively, it seems that kneading created a more open microstructure due to changes in stress directions during loading at the high matric suctions.

Generally for the fine-textured soils, CCT diminished K_g, e and AFP significantly when compared with KCT. The opposite trend was observed for the coarse-textured soils. Change of principal stress directions and the semi-confined condition of the KCT-facilitated rotation of soil particles while loaded, and caused a more packed particle arrangement of sandy and loamy soils as mentioned by Söhne (1958). It is believed that sensitivity to kneading is relatively high in the soils with wide particle size distribution (Koolen, 1987).

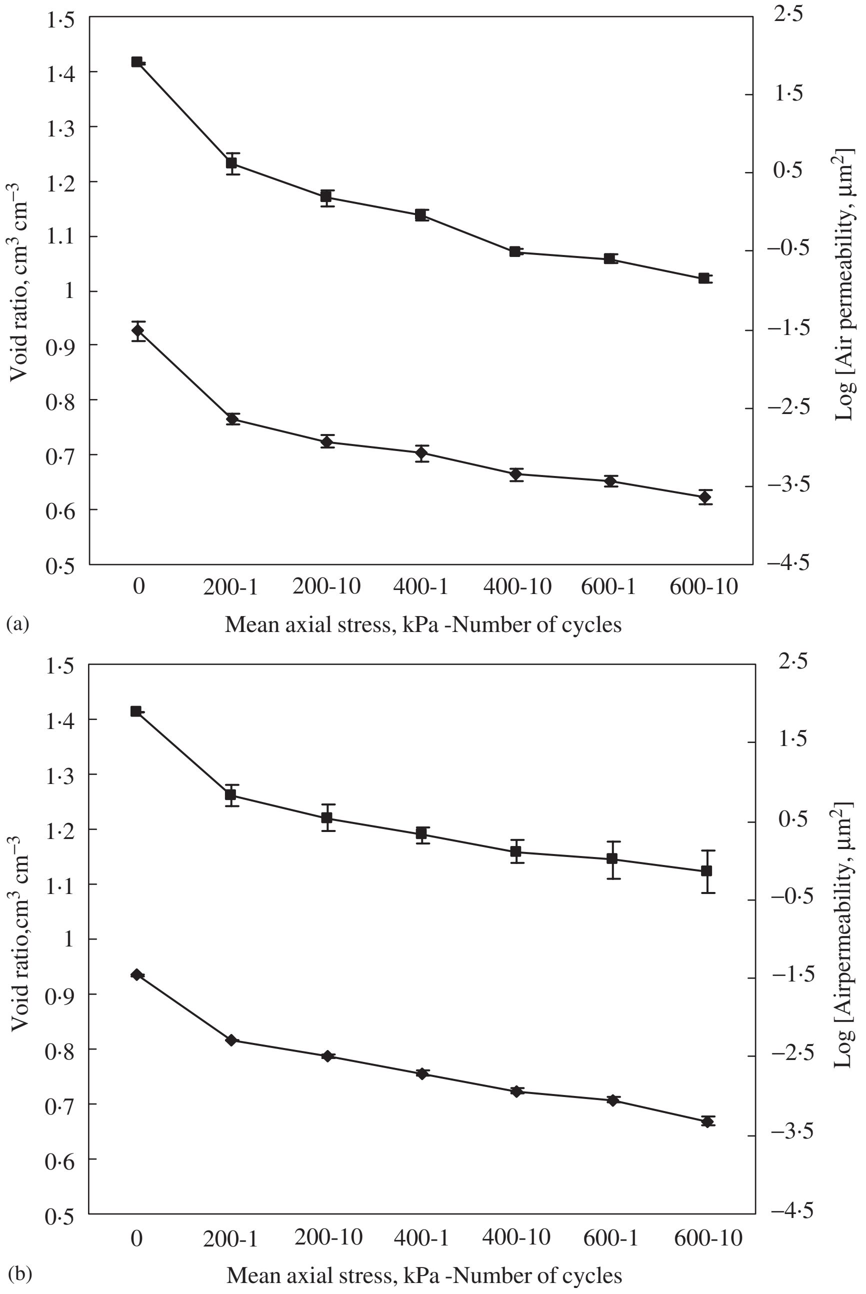


Fig. 3 – Void ratio (–♦–) and air permeability (–■–) of soil no. 4 as affected by the mean axial stress and the number of cycles under cyclic loading of the confined compression test at initial soil matric suctions of 20 (a) and 80 kPa (b); bars indicate the standard deviations of the means.

With increasing maximum applied stress, the soil physical properties decreased dramatically (Table 6). The influence of soil wetness on soil physical properties depended on the maximum applied stress. The rate of decrease in K_g and AFP with increasing stress was larger at low matric suctions. Void ratio was decreased slowly under increased load at low matric suctions due to the incompressibility of soil water. Loading at low matric suctions might distort water menisci around the soil particles and aggregates (Horn *et al.*, 1994). When enough water exists in soil, water can act as a lubricant and push the finer particles in between the coarser particles during repeated loading. These processes are likely to happen under conditions where soil particles do not have permanent and stable bonds, e.g. caused by organic compounds or cementation as in the studied soils. This is especially the case for soil nos. 2, 4 and 5. The processes lead to complete homogenization of pore system and excessive decline of soil quality.

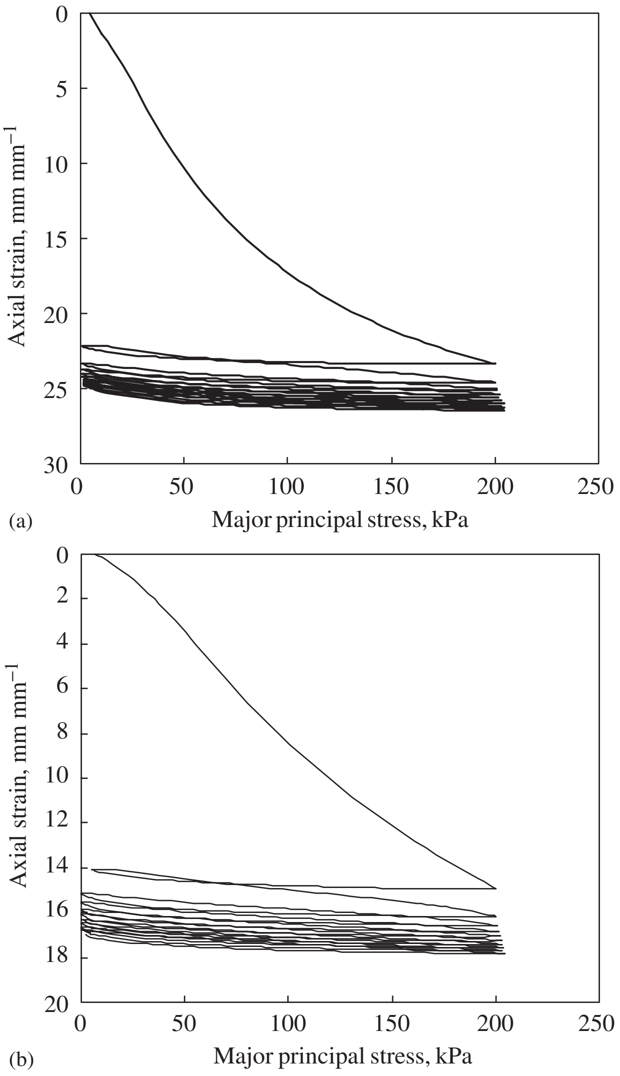


Fig. 4 – Stress–strain curves of soil no. 2 under cyclic loading of the confined compression test at initial soil matric suctions of 20 (a) and 80 kPa (b).

The number of loading cycles affected the soil physical quality significantly (Table 7). This implies that though σ_{pc} of the soil was not exceeded, the soil physical properties were changed significantly. Cyclic loading was not always accompanied by significant irreversible strain e but could result in up to 10 times decrease in K_g at the low matric suctions. Horn and Fleige (2003) proposed for some soils found in Germany that the soil structure is unchanged if the ratio of σ_{pc} to the imposed stress is in the range 1.2–1.5. If the ratio is 0.8–1.2, the soil will deform irreversibly. So they proposed some higher safety constants appear for the structurally unstable soils of central Iran.

The effect of maximum stress and number of loading cycles on e and K_g of soil nos. 1 and 4 at two matric suctions are shown in Figs. 2 and 3, respectively. It is obvious that the higher the maximum stress, the lower are the values of e and K_g although the trends were not linear. Void ratio did not change highly, but K_g decreased extremely during cyclic loading (i.e. constant σ_{pc}). It is more pronounced at matric suction of 20 kPa; at maximum stress of 200 kPa, K_g decreased significantly after 10 cycles while e was almost constant (Fig. 2). However, according to the σ_{pc} concept, nothing should happen to soil structure during repeated loading. Arvidsson and Keller (2004) reported that even with high values of σ_{pc}, a significant risk of subsoil compaction was experienced on Swedish soils. Keller (2004) and Keller *et al.* (2004) also concluded that σ_{pc} concept did not work as a threshold between reversible and irreversible deformation when σ_{pc} values were compared with stress and displacement measured in situ in the field.

Comparing Fig. 2 with 3 showed that the compressibility of soil no. 4 (sandy loam) is lower than that of soil no. 1 (clay). Variation range of K_g and e was smaller for soil no. 4. Despite the lower e of soil no. 4, its K_g values were higher than soil no. 1 due to more continuity of the pores and lower water content at similar matric suctions.

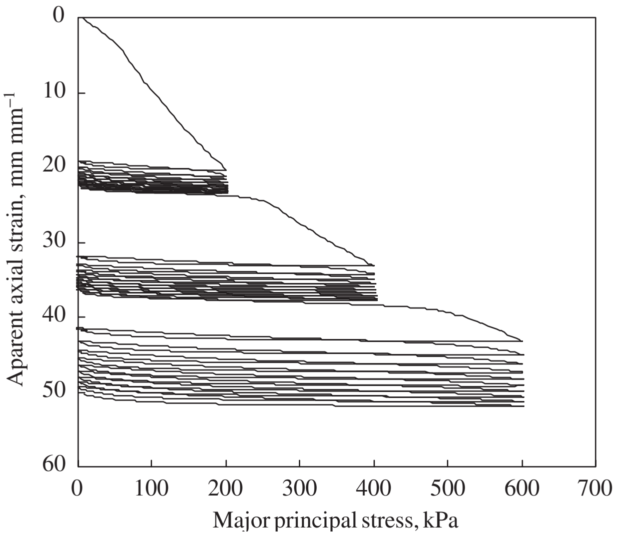


Fig. 5 – Stress–strain curve of soil no. 2 under cyclic loading of the semi-confined compression test at initial soil matric suctions of 50 kPa.

3.2. Stress–strain curves of the soils

The stress–strain curves of the soils were affected by the treatments. The effect of initial matric suction on the shape of the compression curve of soil no. 2 is illustrated in Fig. 4. The relative effect of repeated loading on incremental irreversible strains increased with increasing soil matric suction. The retarding effect of positive pore pressure decreased the incremental irreversible strains for the matric suctions of 10 and 20 kPa. Hence the incremental irreversible strains were the highest at the intermediate water contents where the soil strength is low and the effect of positive pore

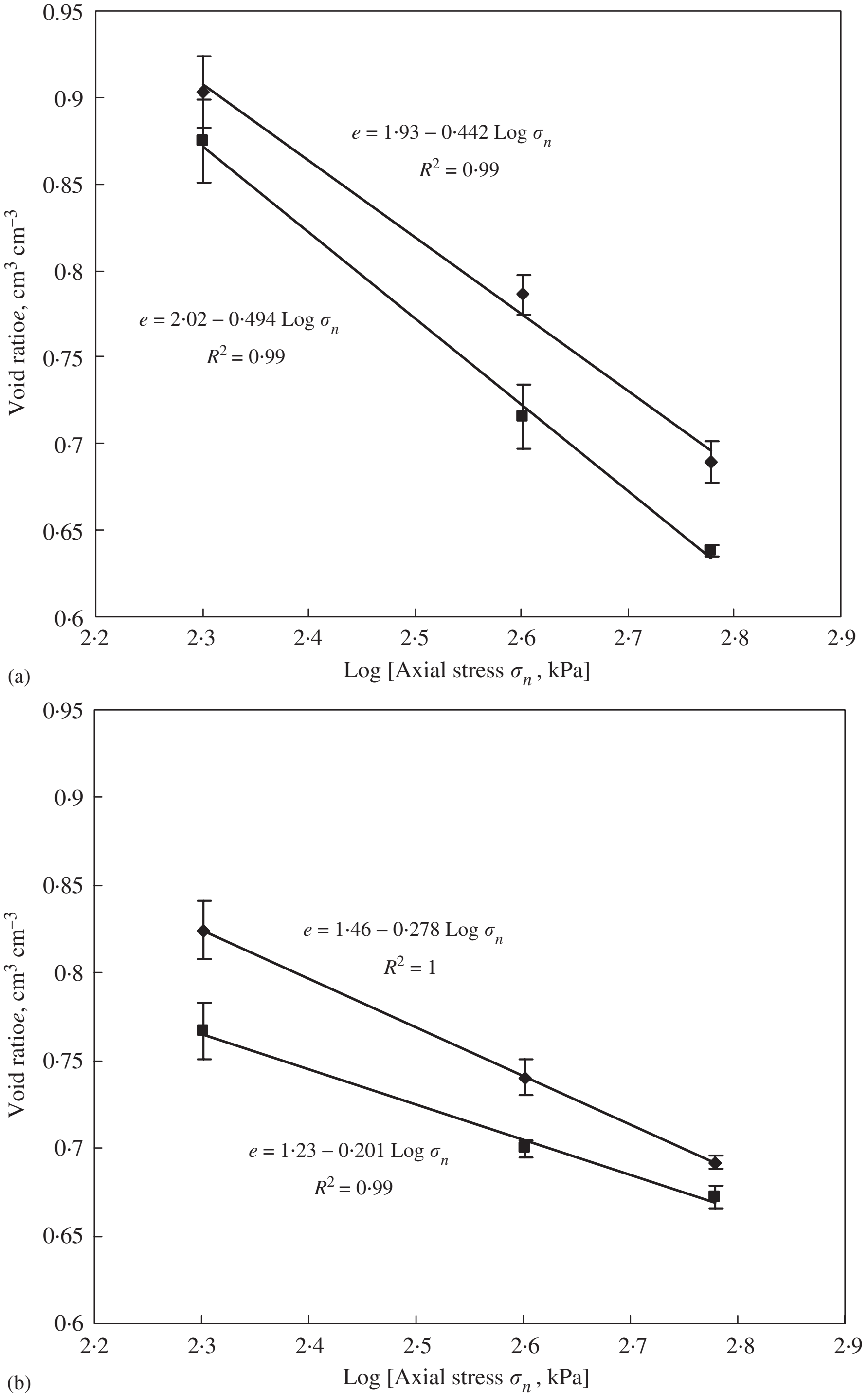


Fig. 6 – Virgin compression lines of void ratio for soil no. 1 as affected by cyclic loading in the confined compression test at initial soil matric suctions of 20 (a) and 80 kPa (b); bars indicate the standard deviations of the means; ◆, first cycle; ■, tenth cycle.

water pressure on soil compression was not considerable. Under cyclic loading, soil strain increased more for SCCT and KCT in comparison with CCT.

The additional compaction due to reloading varied with soil type, structure and loading condition. The incremental strains under the cyclic loading were higher for the coarse-textured than the fine-textured soils (data not shown). Koolen and Kuipers (1989) found that any reloading might cause additional compaction, even when reloading stress was much lower than σ_{pc}. Keller (2004) measured soil stress and displacement under a running wheel and observed irreversible vertical strain of the soil even though the measured vertical stress was smaller than σ_{pc}. Koolen and Kuipers (1989) presumed that additional compaction during reloading is negligible for well-structured, dry and compacted soil. However, they found that the reloading stress–strain curve of a sandy soil low in organic matter might lack any relation with σ_{pc} and show significant porosity decreases, even for very low reloading stresses. A sandy soil low in organic matter appeared to compact further during removal of the stress in triaxial test (van den Akker, 1988).

The critical region in the SCCT was almost sharp independent of the soil water content and maximum axial stress (Fig. 5). This may have been because of the semi-confined condition, which allowed lateral movement and freedom of the soil particles to rearrange during loading. Furthermore, it would not cause a build-up in the pore water pressure. The stress–strain curves obtained using the CCT showed a gradual transition from elastic to plastic deformation. The soils behaviour under *staircase* loading was investigated in another study. In general, the curvature of the stress–strain curve at σ_{pc} reduced when soil water content was higher and soil texture was coarser. The curvature at σ_{pc} was low for the CCT at high water contents and maximum axial stresses and very low values of σ_{pc} could be determined because of the extremely gradual change of plastic strain during reloading.

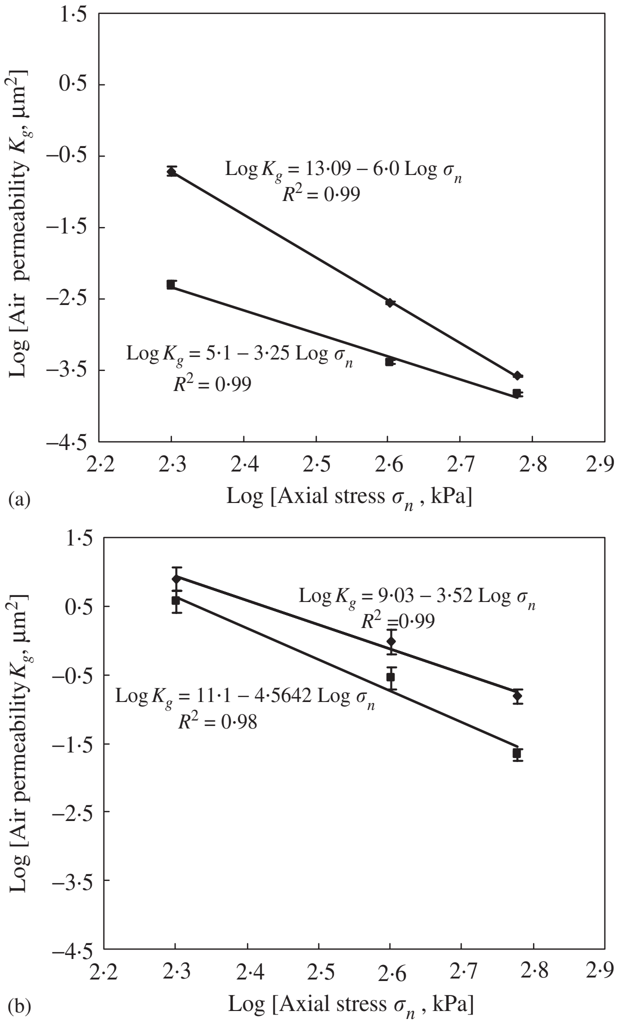


Fig. 7 – Virgin compression lines of air permeability for soil no. 1 as affected by cyclic loading in the confined compression test at initial soil matric suctions of 20 (a) and 80 kPa (b); bars indicate the standard deviations of the means; ♦, first cycle; ■, tenth cycle.

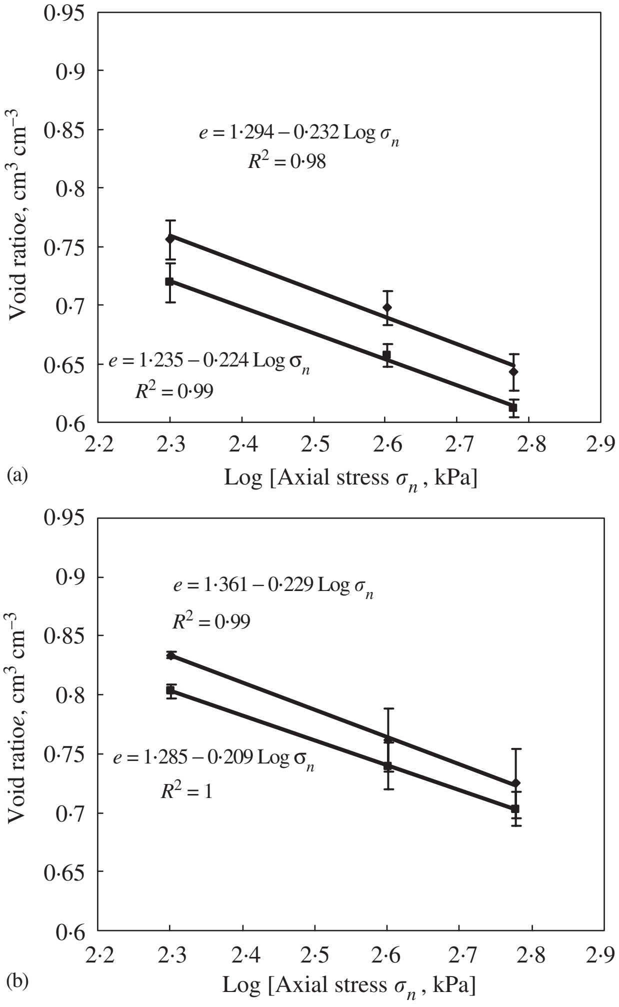


Fig. 8 – Virgin compression lines of void ratio for soil no. 4 as affected by cyclic loading in the kneading compression test at initial soil matric suctions of 20 (a) and 80 kPa (b); bars indicate the standard deviations of the means; ♦, first cycle; ■, tenth cycle.

Berli (2001) mentioned that σ_{pc} is not usually clear as a sharp boundary on the stress–strain curve but rather an operationally defined point in an often rather gradual transition between RCL and VCL.

The cyclic loading increased the curvature of the critical region and the value of σ_{pc} (Fig. 5). While the maximum applied stress did not apparently change during the cyclic loading, the rearrangement and translocation of the particles as well as changes in the effective stress would increase σ_{pc}. Thus, the soil behaviour in the over-compacted region might not be completely elastic and the effect of the plastic deformation under cyclic loading appeared in the increased value of σ_{pc}.

3.3. *Virgin compression lines of void ratio and air permeability*

The virgin compression lines (VCLs) of e and K_g for soil Nos. 1 and 4 are illustrated in Figs. 6–9, respectively. The intercept and the slope of VCL, compression index C_c, was affected by initial values of soil matric suction as well as by repeated loading. Since the maximum stresses were constant in the cyclic loading, VCLs were not expected to be changed. The lower the initial matric suction, the higher was the C_c. Comparisons of the graphs showed that the effect of repeated loading on K_g is more obvious at low matric suctions. Thus, e is less suitable for assessing soil quality under loading especially at high water contents. However, K_g could be used as an index of soil physical quality because it is depending on the soil structure and connectivity of air-filled pores.

Stress directional rotation in the KCT created further homogenization of pore system and resulted in further decrease in e and K_g when compared with the CCT at matric suctions of 10 and 20 kPa [Figs. 8(a) and 9(a)8,9 vs. 6(a) and 7(a)]. On the other hand, for drier conditions (i.e. matric suctions of 50 and 80 kPa), the KCT formed a more open microstructure, i.e. anisotropic arrangement of soil particles, which resulted in higher values of K_g in comparison with the CCT though the strains were almost the same ([Figs. 8(b) and 9(b) vs. 6(b) and 7(b)]). The C_c and the compressibility were greater for fine-textured than coarse-textured soils (Fig. 6, 8 and Fig. 7 vs. 9).

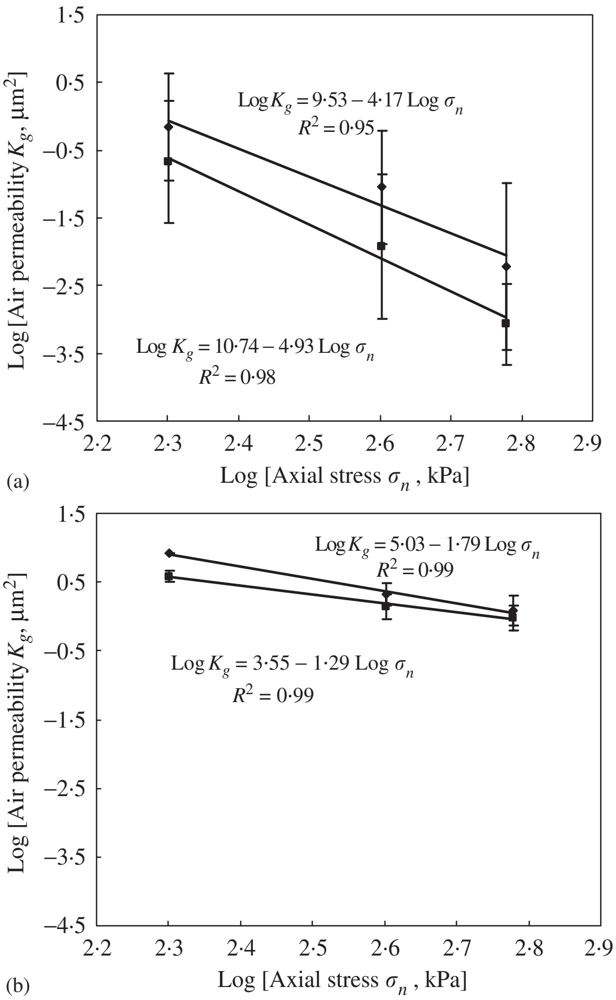


Fig. 9 – Virgin compression lines of air permeability for soil no. 4 as affected by cyclic loading in the kneading compression test at initial soil matric suctions of 20 (a) and 80 kPa (b); bars indicate the standard deviations of the means; ◆, first cycle; ■, tenth cycle.

4. Conclusions

Soil type, soil matric suction, loading type, maximum applied stress and number of loading cycles as well as their interactions significantly affected air permeability K_g, void ratio e and air-filled porosity (AFP) of the studied soils. The significant effect of number of loading cycles implies that though the pre-compression stress σ_{pc} was not exceeded, the soil physical quality was declined significantly. Thus, e is less suitable for assessing soil quality under loading especially at high water contents. However, K_g could be used as an index of soil physical quality because it is depending on the soil structure and connectivity of air-filled pores.

The results showed a gradual transition from elastic to plastic deformation on the stress–strain curves obtained using confined compression test. Results indicated that the σ_{pc} might not be a real critical stress from a view of soil physical quality indices, e.g. K_g, especially at low matric suctions for the studied soils. Particles of the unstable soils do not have permanent and stable bonds, e.g. by organic compounds or cementation to resist the loading, so that stresses lower than σ_{pc} might affect the structure of unstable soils.

In agriculture, characterization of soil compaction may not be completely accounted by a single bulk property such as strain or e, but additional information on pore characteristics are needed to describe the soil physical quality. Study of soil microstructure after loading by thin section preparation and microscopy techniques is very useful to test our hypothesis concerning the σ_{pc} and soil physical quality.

Acknowledgements

This study was accomplished while the first author was on sabbatical leave in Soil Technology Group of the Wageningen University, The Netherlands. The authors would like to thank the Soil Technology Group for providing the facilities and the lab equipments. We are thankful to Ministry of Science, Research and Technology (MSRT) of Iran for the financial support to the first author.

REFERENCES

Alexandrou A; Earl R (1995). In situ determination of the pre-compaction stress of a soil. Journal of Agricultural Engineering Research, **61,** 67–72

Arvidsson J; Keller T (2004). Soil precompression stress, I: a survey of Swedish arable soils. Soil & Tillage Research, **77,** 85–95

Berli, M (2001). Compaction of agricultural subsoils by tracked heavy construction machinery. PhD Thesis. 105pp, ETH Diss. No. 14132, Swiss Federal Institute of Technolgy, ETH Zurich, Switzerland

Canarache A; Horn R; Colibas I (2000). Compressibility of soils in a long term field experiment with intensive deep ripping in Romania. Soil & Tillage Research, **56,** 185–196

Casagrande A (1936). The determination of preconsolidation load and its practical significance. International Conference on Soil Mechanics and Foundation Engineering, 22–26 June, Vol. 3, pp 60–64, Cambridge, MA

Dawidowski J B; Koolen A J (1987). Changes of soil water suction, conductivity and dry strength during deformation of wet undisturbed samples. Soil & Tillage Research, **9,** 169–180

Dawidowski J B; Koolen A J (1994). Computerized determination of the preconsolidation stress in compaction testing of field core samples. Soil & Tillage Research, **31,** 277–282

Helwig J T; Council K A (1982). SAS User's Guide. Statistical Analysis System Institute, Raleigh, NC

Horn R (2000). Subsoil compaction processes — state of knowledge. Proceedings of Fourth International Conferences of Soil Dynamics (ICSD-IV), 26–30 March, Adelaide, Australia

Horn R (2002). Stress–strain effects in structurally unsaturated soils on coupled mechanical and hydraulic processes. Proceedings of 17th World Congress of Soil Science (WCSS), 14–21 August, Bangkok, Vol. 387, pp. 1–10, Thailand. 387, 1—10

Horn R; Baumgartl T (2001). Dynamic properties of soil. In: Soil Physics Companion (Warrick A W, ed), pp 17–48. CRC Press, Boca Raton, FL

Horn R; Fleige H (2003). A method for assessing the impact of load on mechanical stability and on physical properties of soils. Soil & Tillage Research, **73,** 89–99

Horn R; Lebert M (1994). Soil compactibility and compressibility. In: Soil Compaction in Crop Production (Soane B D; van Ouwerkerk C, eds), pp 45–69. Elsevier, Amsterdam

Horn R; Taubner H; Wuttke M; Baumgartl T (1994). Soil physical properties related to soil structure. Soil & Tillage Research, **30,** 187–216

Keller T (2004). Soil compaction and soil tillage – studies in agricultural soil mechanics. PhD Thesis, 75pp, Swedish University of Agricultural Sciences, Uppsala, Sweden

Keller T; Arvidsson J; Dawidowski J B; Koolen A J (2004). Soil precompression stress II. A comparison of different compaction tests and stress–displacement behaviour of the soil during wheeling. Soil & Tillage Research, **77,** 97–108

Kmoch H G; Hanus H (1965). Vereinfachte Methodik und Auswertung der Permeabilitätsmessung des Bodens für Luft. Zeitschrift für Pflanzenernährung, Düngung, 111. Band, Heft 1, Bodenkunde

Kooistra M J; Tovey N K (1994). Effects of compaction on soil microstructure. In: Soil Compaction in Crop Production (Soane B D; van Ouwerkerk C, eds), pp 91–111. Elsevier, Amsterdam

Koolen A J (1987). Deformation and compaction of elemental soil volumes and effects on mechanical soil properties. Soil & Tillage Research, **10,** 5–19

Koolen A J (1994). Mechanics of soil compaction. In: Soil Compaction in Crop Production (Soane B D; van Ouwerkerk C, eds), pp 23–44. Elsevier, Amsterdam

Koolen A J; Kuipers H (1983). Agricultural Soil Mechanics. Advanced Series in Agricultural Sciences, Vol. 13, 235pp. Springer-Verlag, Berlin

Koolen A J; Kuipers H (1989). Soil deformation under compressive forces. In: Mechanics and Related Processes in Structured Agricultural Soils. Proceedings of Second Workshop. NATO ASI Series, (Larson W E; Blake G R; Allmaras R R; Voorhees W B; Gupta S C, eds), pp 37–52. Kluwer, Dordrecht, The Netherlands

Koolen A J; van den Akker J J H (2000). On the use of agricultural soil data required in soil deformation models. In: Subsoil Compaction: Distribution, Processes and Consequences. Advances in GeoEcology (Horn R; van den Akker J J H; Arvidsson J, eds), Vol. 32, pp 118–125. Catena Verlag

Lerink P (1990). The kneading distortion apparatus. Soil & Tillage Research, **17,** 173–179

Lerink P (1994). Prediction of the immediate effect of traffic on field soil qualities. PhD Thesis, 221 pp, Wageningen University, The Netherlands

Mosaddeghi M R; Hemmat A; Hajabbasi M A; Vafaeian M; Alexandrou A (2006). Plate sinkage versus confined compression tests for in situ soil compressibility studies. Biosystems Engineering, **93**(3), 325–334, doi:10.1016/j.biosystemseng.2005.12.005

Mosaddeghi M R; Koolen A J; Hemmat A; Hajabbasi M A; Lerink P (2007). Comparisons of different procedures of pre-compaction stress determination on weakly structured soils. Journal of Terramechanics, **44,** 53–63

O'Sullivan M F (1992). Uniaxial compaction effects on soil physical properties in relation to soil type and cultivations. Soil & Tillage Research, **24,** 257–269

Pagliai M (1987). Micromorphometric and micromorphological investigations on the effect of compaction by pressures and deformation resulting from tillage and wheel traffic. In: Soil Compaction and Regeneration. Proceedings of the Workshop on Soil Compaction, Consequences and Structural Regeneration Processes (Monnier G; Goss M J, eds), pp 31–38. A.A. Balkema, Rotterdam

Römkens M J M; Miller R D (1971). Predicting root size and frequency from one-dimensional consolidation data — a mathematical model. Plant and Soil, **35,** 237–248

Sanchez-Giron V; Andreu E; Hernanz J L (1998). Response of five types of soil to simulated compaction in the form of confined uniaxial compression tests. Soil & Tillage Research, **48,** 37–50

Söhne W (1958). Fundamentals of pressure distribution and soil compaction under tractor tires. Agricultural Engineering, **39,** 276–281 290

Trautner A (2003). On soil behaviour during field traffic. PhD Thesis, 89pp, Swedish University of Agricultural Sciences, Uppsala, Sweden

van den Akker J J H (1988). Model computation of subsoil stress distribution and compaction due to field traffic. Proceedings of 11th ISTRO Conference, 11–15 July, Vol. 1, pp 403–408, Edinburgh

Watts C W; Hallett P D; Dexter A R (1999). Effects of mechanical stresses and strains on soil respiration. In: Effects of Mineral-Organic-Microorganism Interactions on Soil and Freshwater Environments (Berthelin J; Huang P M; Bollag J M; Andreaux F, eds), pp 305–316. Plenum Publishers, New York