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CONFINED AND SEMI-CONFINED COMPRESSION CURVES OF HIGHLY CALCAREOUS SOIL AMENDED WITH ORGANIC MANURES

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ABSTRACT The soil compaction by mechanical and hydraulic stresses is a major factor responsible for physical degradation of cultivated soils with low structural stability in arid and semi-arid regions of the world. Incorporation of organic manures into soil can partially help to prevent soil degradation. Confined and plate sinkage compression tests (CCT and PST, respectively) are usually performed to characterize the compression properties of soil. Two main forms of compression curve have been observed: (i) the bi-linear curve having an elastic rebound curve at low stresses and a linear virgin compression curve at higher stresses and (ii) the S-shaped curve having deviation of the virgin compression curve at high stresses. In the present work, soil samples collected from the topsoil (0-20 cm layer) of experimental plots in which farmyard manure was added to the soil at three rates (25, 50 and 100 Mg ha^{-1}) for 7 years successively under annual wheat (*Triticum aestivum* L.) - corn (*Zea mays* L.) rotation. Large remould specimens were prepared by applying 100 kPa load at two gravimetric water contents (17.1 and 20.9%). The center section of the preloaded soil specimen was firstly submitted to a 50 mm PST; then immediately one cylindrical sample was cored for CCT. The S-shaped compression curves were observed with CCT, whereas bi-linear curves were obtained with PST. The PST and CCT are semi-confined and confined loading tests, respectively. In the PST, because high soil volume was available in the large pre-compressed soil specimen, the elastic deformation of the soil structure and the reduction of the air-pore volume were dominated. For the CCT, the S-shaped form appeared because the flow of water from meso-pores storing free water subjected to high capillary forces became significant at higher stresses. These different processes could explain the observed bi-linear and S-shaped curves under PST and CCT, respectively.

Keywords: Confined compression test, Plate sinkage test, Precompaction stress, Compression index, Compression curve

Introduction Soil compaction by wheeling of agricultural machines is one of the main processes that modifies the structure of cultivated soils and thus affects crop production and the environment (Soane and van Ouwerkerk, 1994). The extent of the soil compaction problem is a function of soil type and water content, vehicle weight, speed, ground contact pressure and number of passes, and their interactions with cropping frequency and farming practices (Larson et al., 1994; Chamen et al., 2003). Compaction impacts the soil pore space and thus may cause a whole series of modified soil physical properties. For example, saturated hydraulic conductivity (Logsdon et al., 1992; Arvidsson, 2001) and air permeability (Blackwell et al., 1990; Kirby, 1991; Ball and Robertson, 1994) can be reduced. This in turn may lead to increased surface runoff and erosion (Fullen, 1985).

Confined uni-axial compression test is usually performed to measure the soil compressibility properties. The stress–strain relationship of soil obtained from this test was characterized by two types of models: i) elasto-plastic and ii) S-shaped models (Tang et al., 2009). In the elasto-plastic model, (bi-linear form), the compression curve can be divided into two parts: an elastic rebound curve at low stress, termed the recompression or swelling line (RCL), and a linear virgin compression curve at higher stress, termed the virgin compression line (VCL). The point of intersection between RCL and VCL is referred to as the pre-compaction stress (σ_{pc}), and the slope of the VCL, termed the compression index (C_c). In S-shaped model, the compression curve is allowed to deviate at high stresses. It was reported that the S-shaped compression curves were observed more frequently when the clay content and/or the initial water content were high. In addition, the S-shaped curves were observed more frequently on remould soils than on undisturbed soils (Tang et al., 2009). They explained the observed S-shaped curves by the difference between the compression of air-filled pores and that of meso-pores storing water subjected to high capillary forces.

In addition to confined uni-axial compression test, constant-rate confined compression tests (CCT) and plate sinkage test (PST) are used to characterize the compression curves of the soils (Hemmat et al., 2009). In the present research, the form of the compression curve obtained from the CCT and PST were analyzed. Remould samples at two water contents (17.1 and 20.9%) were prepared from the soils amended with farmyard manure at three rates (25, 50 and 100 Mg ha^{-1}) for 7 years successively.

MATERIALS AND METHODS

Soil The soils were collected from a long-term manure experiment conducted at the Isfahan University of Technology Research Station Farm (32º32´N latitude and 51º23´E longitude and 1630 m above sea level) in central Iran (Isfahan). The soil had a silty clay loam texture with calcium carbonate content of 377 g kg^{-1}. The soil received cattle farmyard manure (pH=8.6; EC=17 dS m^{-1}; OM= 430 g kg^{-1}) at three rates (25, 50 and 100 Mg ha^{-1}) and for 7 years successively with a cropping rotation of irrigated wheat (*Triticum aestivum* L.) – silage corn (*Zea mays* L.) every year. The manure was applied and mixed to the 0-20 cm soil layer (topsoil) in fall during land preparation for wheat planting.

Soil specimen preparation The soil was air-dried and passed through a 2 mm sieve. The water contents were chosen such that they were either sides of the soil plastic limit (PL) of the unfertilised treatment. In preliminary tests, soil specimens with low water contents were prepared and tested; however, we had difficulties removing intact soil samples, even at 13.3% (dry basis, d.b.). Finally, two soil water contents of 17.1 and 20.9% d.b. were chosen. To adjust the water content (WC) of the soil specimens to the pre-determined values, a measured amount of water was added to the soil as fine spray while the soil was gently kneaded for 45-60 min until the water was uniformly distributed throughout the specimen. Soil was packed into a cylinder with diameter and height of 255 and 80 mm, respectively, to a wet bulk density of 1.40 Mg m^{-3}.

Loading characteristics Each large cylindrical soil specimen then was preloaded by applying axial load on the soil surface by using a 250 mm diameter perforated-steel plate with a California Bearing Ratio (CBR) apparatus (British Standards, 1975, BS 1377). The perforated plate released the air from the sample during the compression. The tests were performed at a compression speed of 1 mm min^{-1}. When the axial stress reached 100 kPa, the soil specimen was kept under the load for 30 min. The preload stress was chosen such that the bulk densities (BDs) of the soil samples were similar to those of the undisturbed samples obtained from 50-150 mm depth. The centre part of the large pre-compressed soil specimen was subjected to a 50-mm PST, and then separate sample was removed for CCT. The soil sample dimensions for different tests are given in Figure 1. The reloading tests for both PST and CCT were also performed using CBR apparatus. The compression for both PST and CCT was continuous at the same constant displacement rate (1 mm min^{-1}) of the CBR. For CCT, a plate having a diameter of a little less than that of the core sampler was mounted between the loading piston and the soil sample. During testing, force and deformation were recorded manually in deformation increments of 0.5 mm. The PST was continued up to a maximum of 20 mm sinkage, whereas the CCT was terminated when the water started flowing out from the bottom of the samples.

From the output of force and displacement gauges of the CBR in the reloading tests, stress–sinkage and stress–strain curves were obtained for PST and CCT, respectively. Stress (σ) and strain (e) were calculated by dividing the measured force by the loading area and the sinkage (s) by the initial height of the sample, respectively. For both PST and CCT, the ratio of the change of sinkage (s) and strain (e), respectively, and to the change of the logarithm σ was calculated (ds/dlogσ or de/dlogσ, respectively) and plotted versus σ.

RESULTS AND DISCUSSION The results of confined compression test (CCT) on soils amended with different application rates (25, 50, 100 Mg ha^{-1}) of farmyard manure (FYM) and tested at water content (WC) of 17.1 and 20.9% are shown in Figures 2 and 3, respectively. The plot of strain (e) versus log of vertical stress (σ) for 17.1% WC shows that almost all the tests had the S-shaped form. Moreover when analysing the plot of de/dlogσ versus logσ, the slope reached its maximum value under a vertical stress (σ) comprised between 975 and 1750 kPa; this corresponds to the inflection point in the compression curve (e–logσ plot). In the case of soil samples tested at 20.9 WC (Figure 3), the strain–logσ plot shows that all the tests had clear S-shaped compression curve. In addition, the de/dlogσ–logσ plot shows when σ was increasing, de/dlogσ firstly increased and reached its maximum values under a vertical stress (σ) comprised between 350 and 1220 kPa. The compression index C_c was defined as the maximum value of de/dlogσ along the loading path. That corresponds to the slope at the inflection point on the compression curve. The results showed that the C_c occurred at lower vertical stress at higher WC. The end point on each curve in both plots of strain-logσ shows the condition at which the water was squeezed out of the soil sample. Therefore, at both WCs, this condition occurred at high stress/strain level as the organic matter (OM) of the soil sample was higher. This was due to higher initial porosity and lower initial degree of saturation of the soil sample with higher OM (Table 1).

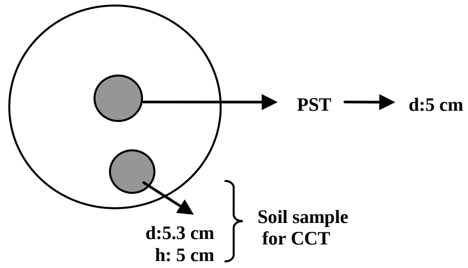

Figure 1. Top view of the large soil specimen and the locations of plate-sinkage test (PST) and soil sampling for confined compression test (CCT). d and h are the soil sample diameter and height, respectively.

Table 1. Initial soil properties

Treatments	WC (%)	PL (%)	BD (Mg m^{-3})	Porosity	S_{ri}
25 Mg FYM ha^{-1}	17.1	22.3	1.24	0.41	0.42
50 Mg FYM ha^{-1}	17.1	24.0	1.20	0.55	0.31
100 Mg FYM ha^{-1}	17.1	26.8	1.11	0.55	0.31
Control	17.1	19.0	1.30	0.35	0.49
25 Mg FYM ha^{-1}	20.9	22.3	1.39	0.36	0.48
50 Mg FYM ha^{-1}	20.9	24.0	1.23	0.52	0.33
100 Mg FYM ha^{-1}	20.9	26.8	1.14	0.52	0.33
Control	20.9	19.0	1.41	0.30	0.57

WC, initial soil water content; PL, water content at the plastic limit; BD, soil bulk density after preloading; Porosity, initial porosity of the soil sample which was assumed to be equivalent to the water content at saturation; S_{ri}, degree of initial water saturation.

The results of plate sinkage test (PST) on soils amended with different application rates (25, 50, 100 Mg ha^{-1}) of FYM and tested at water contents (WCs) of 17.1 and 20.9% are shown in Figures 4 and 5, respectively. The sinkage–logσ plot at both WCs shows that almost all the tests had the bi-linear form. Moreover when analysing the plot ds/dlogσ versus logσ, showed a slight decrease of de/dlogσ followed by an increase. For each test for both WCs, de/dlogσ was not changed significantly when the stresses were higher than 300 kPa; this means that the compression curve (e–logσ plot) was almost linear at high stresses.

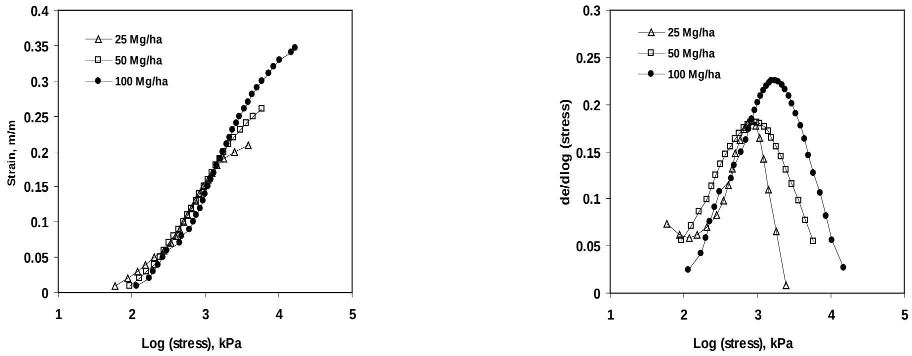

Figure 2. Strain (e) and de/dlogσ versus logarithm of vertical stress for confined compression test (CCT). Results for soils amended with farmyard manure (FYM) with different application rates (25, 50, 100 Mg ha^{-1}) at gravimetric water content of 17.1%

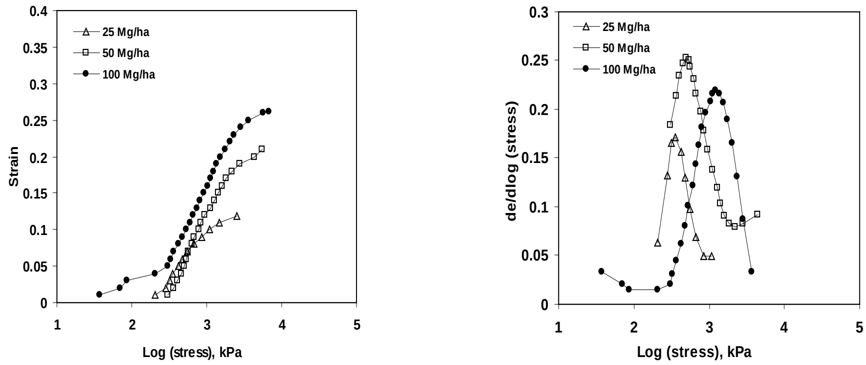

Figure 3. Strain (e) and de/dlogσ versus logarithm of vertical stress (σ) for confined compression test (CCT). Results for soils amended with farmyard manure (FYM) with different application rates (25, 50, 100 Mg ha^{-1}) at gravimetric water content of 20.9%

It was reported that when the structure of the soil was destroyed as for the remould samples, the S-shape could be expected (Tang et al., 2009); however, our results showed that the shape of the compression curves also depends on the degree of soil confinement during compression test. The CCT is a confined test, whereas the PST is a semi-confined test. Soils are three-phase systems which undergo changes as soon as the external stresses exceed the internal soil strength (pre-compaction stress). The decrease of soil volume upon stress increase involves firstly the air-filled pores. The pore-water pressure and the pore-air pressure are then increased and reduced with time due to the dissipation process. This process depends strongly on the permeability of the soil sample which also decreases during the compaction (Horn et al., 1995; Tang et al., 2009). In CCT, the compression speed (1 mm min^{-1}) was probably much higher than the drainage capability of the soil. Therefore, the degree of saturation was increased upon compaction which was resulted in an increase in pore water pressure. These results are similar to those reported by Hemmat et al. (2009). In the PST, because high soil volume was available in the large pre-compressed soil specimen, the pore water was released from the soil below the loading piston, and the degree of saturation did not increase with loading as fast as in the CCT. These different processes could explain the observed bi-linear and S-shaped curves under PST and CCT, respectively.

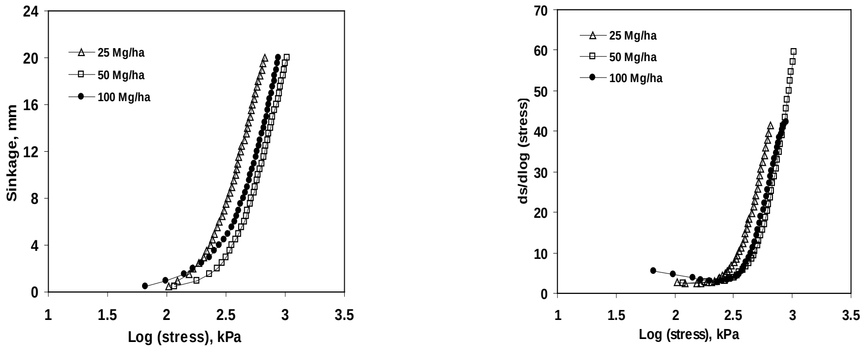

Figure 4. Sinkage (s) and de/dlogσ versus logarithm of vertical stress for plate sinkage test (PST). Results for soils amended with FYM with different application rates (25, 50, 100 Mg ha^{-1}) at gravimetric water content of 17.1%

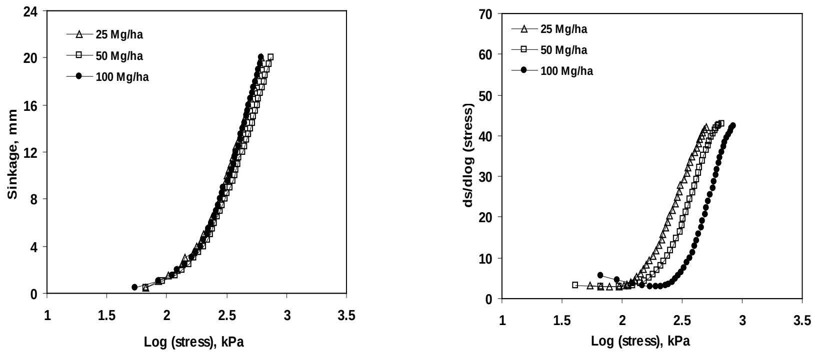

Figure 5. Sinkage (s) and de/dlogσ versus logarithm of vertical stress for plate sinkage test (PST). Results for soils amended with FYM with different application rates (25, 50, 100 Mg ha^{-1}) at gravimetric water content of 20.9%

CONCLUSION In this research, the S-shaped curves were observed with confined compression test (CCT) on remould soil samples amended with three application rates (25, 50, 100 Mg ha^{-1}) of farmyard manure (FYM), whereas the bi-linear form was obtained with the same soil types using plate sinkage test (PST). In CCT, the S-shaped form was more obvious at higher water content (WC).

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