International Scholars Journals

African Journal of Soil Science ISSN 2375-088X Vol. 7 (2), pp. 001-009, February, 2019. Available online at www.internationalscholarsjournals.org © International Scholars Journals

Full Length Research Paper

Reducing compaction effort and incorporating air permeability in Proctor testing for design of urban green spaces on cohesive soils

A. M. Ibrahim[1], N. Persaud[2]*, R. W. Zobel[3] and A. Hass[4]

[1]Soils and Water Department, Faculty of Agriculture, El-Fayoum University, Fayoum, Postal Code 63514, Egypt. [2]Crop and Soil Environmental Sciences Department, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061-0404, USA.

[3]USDA/ARS Appalachian Farming Systems Research Center, 1224 Airport Road, Beaver, West Virginia, USA.

[4]West Virginia State University, Gus R. Douglass Institute, P. O. Box 1000, Institute, WV 25112-1000, USA.

Accepted 16 December, 2018

It is well established that compaction negatively affects agronomic productivity, that air permeability is a sensitive measure of the degree of soil compaction and therefore a good indicator of soil productivity impairment from compaction. Cohesive soils in urban settings are often heavily compacted by the common engineering practice to compact sub-grades of urban construction sites to 95% or more of the optimum density obtained in standardized Proctor tests. The objective of this study was to determine to what extent reducing compaction effort would increase the air permeability of Proctor test specimens. Quantifying this relationship would permit more appropriate Proctor test specifications for the design of urban green spaces on cohesive soils. We designed a portable transient flow apparatus for rapidly measuring air permeability and used it to measure air permeability on Proctor test specimens of three cohesive sub-grade soil materials covering a range of USDA textures (loam, silt loam and silty clay) and Proctor compaction characteristics. We compacted test specimens at their Proctor optimum water content using efforts ranging from 100 to 25% (the lowest practicable value) of that used in the standardized Proctor test. Results confirmed that compaction severely reduces air permeability of the test specimens and indicated that the common practice of compaction to 95% or more of the optimum Proctor density is probably not appropriate for construction of urban green spaces. Reducing compaction effort from 100 to 25% of the standardized Proctor test value increased air permeability 30, 89 and 42 times respectively for the loam, silt loam and silty clay test specimens. More extensive studies are needed to correlate measured air permeability of Proctor test specimens to agronomic productivity of urban green spaces.

Key words: Urban soils, air permeameter, modified Proctor test.

INTRODUCTION

Air permeability is the most commonly-used measure to characterize the ability of air to move through unsaturated soils and is the most direct indicator of the soil's ability to breathe and self-aerate. Most terrestrial plant species cannot transport sufficient oxygen from the leaf area to their roots. Overall plant growth and development is a function of proper root respiration and this in turn would depend on the soil self-aeration capacity (Cheng-He et al., 2006). Air permeability has been long-recognized as an important physical indicator of soil productivity and its improvement is the aim and rationale for many agronomic management practices (Glinski and Stepniewski, 1985).

Measurements of soil air permeability have had a long history and excellent reviews are available (Ball et al., 1981; Corey, 1986; Ghildyal and Tripathi, 1987; Hinsinger and Mettauer, 1989; Scanlon et al., 2002; Ball and Schjonning, 2003; Lal and Shukla, 2004; Switzer and Kosson, 2007). In general, air permeability can be measured on laboratory specimens or in-situ by steady or

*Corresponding author. E-mail: npers@vt.edu. Tel: 540 231 3817. Fax: 540 231 3431.

transient-flow methods (Kirkham, 1947; Grover, 1955; Corey, 1957; Li et al., 2004; Tuli et al., 2005). Steady-flow methods require larger volumes of air, take longer and are more prone to measurement error (Lal and Shukla, 2004). Transient-flow measurements are more rapid, use smaller volumes of air, are less prone to measurement error, but require more sophisticated instrumentation and associated physico-mathematical models and tools for their design and data analysis (Smith et al., 1997a, 1997b, 1998).

Studies have shown that air permeability is a sensitive measure of the degree of soil compaction (Blackwell et al., 1990; Kouno et al., 1992; Stepniewski et al., 1994) and it is well-known that compaction negatively affects agronomic productivity (O'Sullivan, 1992; Assouline and Tessier, 1997; Smith et al., 1997a, 1997b; Lipiec and Hatano, 2003) . High compaction levels are especially problematic in urban green spaces where it is common practice to compact sub-grades to 95% or more of optimum Proctor density determined by the standardized ASTM (American Society for Testing and Materials) testing procedures (Baker, 1990; Gilbert, 1991; Harris, 1991; ASTM, 2009). This practice is primarily rooted in customary engineering practices (used to meet grade elevation, strength and load-bearing specifications of soil foundations) that are applied to the construction of urban green spaces without consideration of its intended agronomic uses. For example, it is well-established that high levels of compaction induced during sub-grade construction affects the ability of natural recreational fields to sustain actively-growing turf grass covers (Carrow, 1980; Sills and Carrow, 1983; Kouno et al., 1992); and to provide optimum conditions for player safety and performance (Bramwell et al., 1972; Bonstingl et al., 1975; Baker, 1991; ASTM 1988, 1994, 1995). Indeed, the urban green space maintenance industry has developed costly equipment and practices to mitigate compacted urban green spaces. Clearly, it would be much more cost effective to have in place appropriate ex-ante design and construction practices versus ex-post efforts to mitigate compaction of these soils. Surprisingly, we found no investigations reported in the literature that approached this issue from this ex-ante 'prevention-rather-than-cure' perspective.

Inasmuch as air permeability can serve as an indicator of compaction, it can likewise serve to indicate compaction-induced impairment of the agronomic productivity of soils. Agronomists generally agree that change in porosity and pore size distribution due to compaction has the greatest impact on plant growth and production since these factors control plant root pene-tration and the availability and accessibility of water and nutrients required for optimal biomass production (Ball, 1987; Gupta et al., 1989; Huang and NeSmith, 1999; Stepniewski et al., 1994; Watabe et al., 2000; Richard et al., 2001; Startsev and McNabb, 2001).

These studies make a case for examining whether or not compaction effort should be reduced and whether air permeability measurements should be incorporated in the standardized Proctor test routinely used for the design and construction of urban green spaces. Research considering the appropriateness of the Proctor test in this context is lacking. The objective of this study was to determine what effect reduction of the compaction effort used in the standard Proctor test would have on the air permeability of the test specimens.

MATERIALS AND METHODS

Test specimens

Available air-dried bulk samples of three natural cohesive soil materials were used to prepare the Proctor-compacted test specimens. These materials were selected because they were known to be physically different. The grain size distribution (Figure 1) and ASTM Proctor test for dry bulk density at optimum water content (Table 1) covered a wide range. These three soil materials were designated according to the USDA classification scheme as loam, silt loam and silty clay (Soil Survey Staff, 2004). The percent of sand, silt and clay were 48.4, 35.8 and 15.8 for the loam; 16.9, 57.0 and 26.1 for the silty loam; and 10.7, 46.8 and 42.5 for the silty clay (Figure 1).

Water was added to air dried samples of these three materials to obtain the optimum water content (Table 1). The samples were mixed and left to equilibrate in sealed plastic bags for at least 24 h. The three compaction efforts (designated as blows per layer) represent the ASTM D698 standard effort using a 2.5 kg rammer with three layers compacted at 25 blows per layer (ASTM, 2009) and close to 50 and 75% reduction of this standard effort obtained using 18 and 12 blows respectively per layer (Table 1). The optimum water content and corresponding dry bulk density values were determined following the ASTM D698 standard test (ASTM, 2009) that details how to prepare the sample, the appropriate apparatus, the test conditions and procedures and data recording and analysis. The compaction effort can also be expressed in terms of energy per unit volume. The rammer mass and drop height were 2.5 kg and 30 cm, respectively and the compaction mold volume (10.2 cm ID and 11.6 cm tall) was 940 cm^3. The energy per unit volume was therefore close to 587, 423 and 282 kN-m m^{-3} for the 25, 18 and 12 blows per layer respectively.

AIR PERMEAMETER

Construction and setup

Figures 2a and 2b illustrate the transient flow permeameter used to measure the air permeability of the compacted specimens. The air reservoir chamber consisted of a length of 10 cm ID schedule 40 PVC pipe (Figure 2a). As shown in Figure 2a, a Schrader valve installed near the bottom of the pipe was used to pressurize the air chamber. A type T thermocouple was made of 30-gauge insulated copper-constantan wire and used to monitor air temperature in the chamber (Figure 2a).

The effective length, L_e, (that is measured from the base of the column to the bottom of the sample) of the PVC pipe was designed to permit at least 300 cm^3 of excess volume in the air chamber available for flow through the sample when the chamber was pressurized to a minimum of 20 cm of water column (1962 Pa) above ambient atmospheric pressure. The ideal gas law and observed local barometric pressure (P_{atm}) were used to determine this appropriate effective length. A fixed mass of air (considered ideal) in volume V_o cm^3 at atmospheric pressure (P_{atm}) compressed isothermally to absolute pressure $P = P_{atm} + P'$ (where P' is the excess pressure) would obey Boyle's Law giving $V_o P_{atm} = (P_{atm} +$

Table 1. Dry bulk density (ρ_b) at the optimum water content (θ_g) obtained from ASTM Proctor tests using varying compaction effort on 3 cohesive soils.

Blows per layer	Loam		Silt loam		Silty clay	
	θ_g(g g^{-1})	ρ_b(g cm^{-3})	θ_g(g g^{-1})	ρ_b(g cm^{-3})	θ_g(g g^{-1})	ρ_b(g cm^{-3})
12	15.9	1.770	19.7	1.620	27.2	1.500
18	15.3	1.812	20.0	1.700	25.9	1.525
75	14.4	1.873	17.0	1.775	22.0	1.595

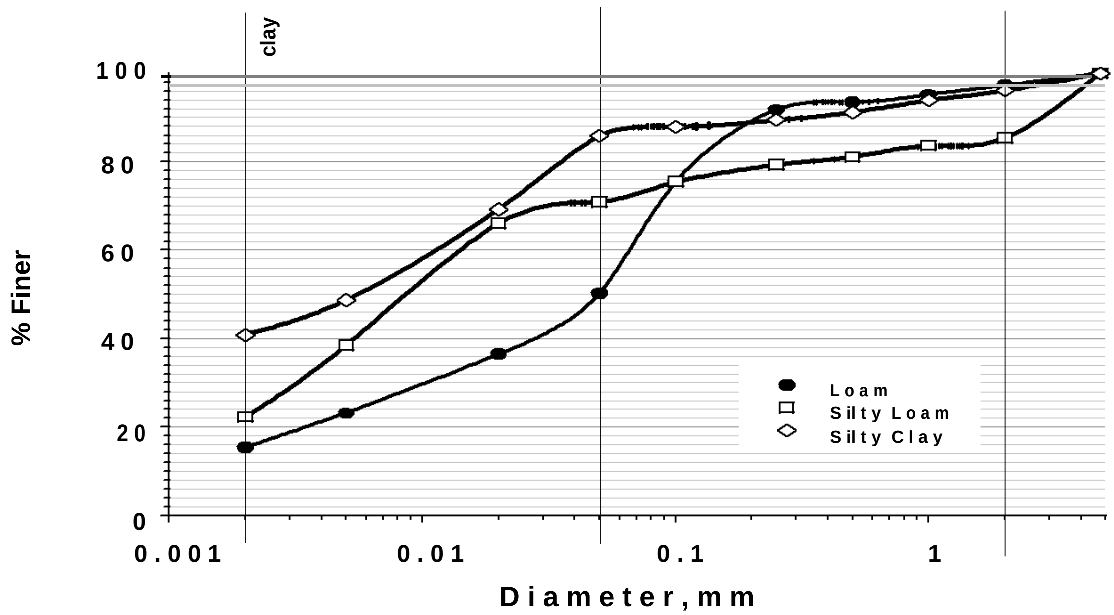

Figure 1. Grain size distribution curves for the three soil materials. Lines represent smooth curves through the data points using natural cubic splines.

P') V where V is the volume after compression. This gives V = (V_o P_{atm}) / (P_{atm} + P'). The change in volume V' after compression is therefore V' = (V_o – V) = V_o - (V_o P_{atm}) / (P_{atm} + P') = V_o (1 – [P_{atm} / (P_{atm} + P')]. The value of P_{atm} was taken from records of hourly barometric pressure measured at the airport in Blacksburg, Virginia (37° 12' 27.5" N and 80° 24' 28.2"W, elevation 650 m above mean sea level, WBAN ID number 53881, WMO ID number 72318) located about 1 km away from the laboratory where the study was conducted. The effective length (L_e in cm) used in this study was 206.4 cm giving an excess volume at 20 cm water column excess pressure = 347.1 cm^3.

The combination pressure regulator and manometer (Figure 2b) was used to precisely control the excess pressure applied and to prevent overloading of the pressure transducer (Figure 2a). As shown, it was constructed with a 1 m long, 15 cm diameter clear extruded Plexiglas pipe chemically welded using methylene chloride to a 20 cm square base of 12 mm thick Plexiglas sheet. Adhesive-backed metric measuring tape graduated in mm (Sargent-Welch, Buffalo, New York 14217, USA) was attached to the outer wall of the clear Plexiglas pipe to measure the difference between level of water in the pressure regulator and manometer and the level in the plastic tubing (Figure 2b). A stopcock installed in the Plexiglas base of the pressure regulator and manometer permitted drainage and adjusting the water level. In order to minimize any radiant heat exchange the air chamber was completely wrapped in high-strength aluminum foil.

Pressure transducer

A general purpose, full-bridge, mV output, 1 psi full scale, gauge pressure transducer (Model PX480A-001GV, Omega Engineering Inc., Stamford, Connecticut 06907, USA) was used to measure excess pressure over time in the air chamber of the permeameter. A datalogger (Model CR-21X, Campbell Scientific Inc., Logan, Utah 84321, USA) was used to log the mV output of the transducer and the temperature output (in °C) of the thermocouple in the permeameter air chamber. The pressure transducer was calibrated by measuring the mV output to step changes in the excess pressure in the permeameter chamber. For this measurement, the chamber was pressurized to 20 cm of water and step decreases in pressure were applied by releasing short burst of air via the Schrader valve. Ten readings at 2 s intervals of the mV output for each pressure step decrease were then taken on the data logger. This process was repeated for starting values of excess pressure equal to 25, 30, 35 and 40 cm of water. The excess pressure values in cm water versus the corresponding average of the ten mV values were plotted and a least squares linear regression line fitted to the plotted points.

Measurement procedure

Prior to the beginning of any measurement, the air-tightness of the

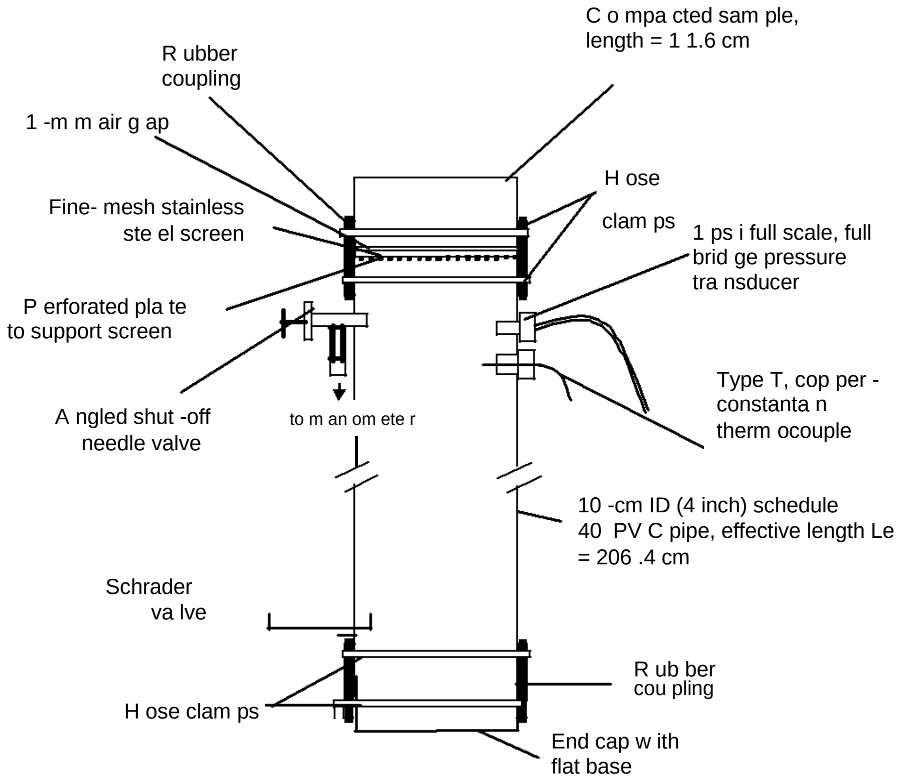

Figure 2a. Air permeameter chamber assembly.

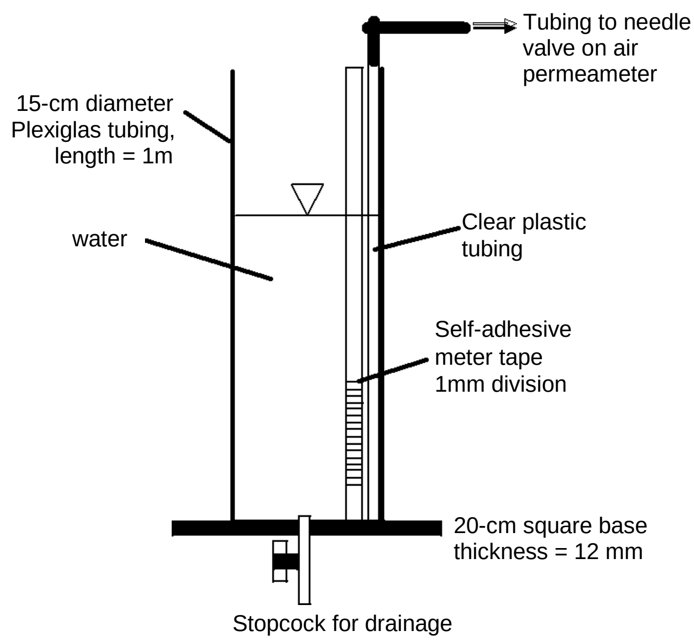

Figure 2b. Pressure regulator and manometer assembly.

permeameter was tested using a soap bubble solution. The Proctor-compacted test specimen was prepared using the soil material at the Proctor optimum moisture content (Table 1) and the standard ASTM D698 apparatus but with a 10 cm ID schedule 40 PVC tube cut to the exact height (11.6 cm) in place of the standard mold. The external and internal diameters of the substitute PVC mold were identical to those of the standard mold.

Compacted test specimens were placed at the sample end of the permeameter and the air chamber over-pressurized to a preset level on the pressure regulator and manometer. Preset excess pressures of 20, 25, 30, 35 and 40 cm of water were used, giving 5 separate tests (numbered as 1 through 5 respectively) on each test specimen for a given compaction effort (an overall total of 45 tests on 9 specimens). The mV output was logged at interval of 3 s and the logged data downloaded manually. The transducer calibration curve equation was used to convert the mV outputs to excess pressure yielding the excess pressure (P') as function of time (t) for each of the 45 tests.

Calculation of air permeability

As proposed by Springer et al. (1995) for transient flow air permeability measurement, the excess pressure (P') in the air chamber decreases with time due to air permeating through the compacted test specimen. The excess volume V' would also decrease as a function of time (t) assuming isothermal conditions in the air chamber. The absolute pressure (P_o) of the air occupying the chamber (volume V_o) is $P_o = P_{atm} + P'_o$ where P'_o is the excess pressure recorded on the datalogger at time t = 0. At some time *t* later, the absolute pressure $P(t) = P_{atm} + P'(t)$. By Boyle's law at any time t, $P(t)V_o = P_o V(t)$ whence $V(t) = P(t)V_o/P_o$ and therefore since $P(t) = P_{atm} + P'(t)$ and $P_o = P_{atm} + P'_o$

$$V'(t) = V_o - V(t) = V_o - \frac{V_o [P_{atm} + P'(t)]}{P_0} \quad (1)$$

Assuming quasi-steady state conditions (meaning uniform pressure gradients are rapidly developed along the length of the specimen) and purely viscous flow, the flux (q = volume per unit time per area) through the specimen is:

$$q = \frac{1}{A}\frac{dV'}{dt} = \frac{1}{A}\frac{d}{dt}\left[V_o - \frac{V_o (P_{atm} + P')}{P_o}\right] = -\frac{1}{A}\frac{V_o}{P_o}\frac{dP'}{dt} \quad (2)$$

Where; A is the cross-sectional area of the specimen. Analogously describing steady water flow using Darcy's law, q =

$$K_a \frac{P - P_{atm}}{L} = K_a . \frac{P'}{L}$$

Here L is the length of the specimen and K_a is a proportionality constant analogous to the saturated hydraulic conductivity in Darcy's law. Therefore,

$$\frac{1}{A}\frac{V_o}{P_o}\frac{dP'}{dt} = -K_a \frac{P'}{L} \quad (3)$$

Separating variables, rearranging algebraically, and integrating between $P' = P_o - P_{atm} = P'_o$ at t = 0 and P' = P(t) at t = t gives ln

$$(P'/P'_o) = . \frac{-K_a A P_o}{V_o L} t$$

The implies that plotting the experimental data as P'/P'_o on the y-axis versus time on the x-axis on a semi-logarithmic graph would yield a decreasing straight line with

$$\text{Slope} = \frac{-K_a A P_o}{V_o L} .$$

From this slope the value of K_a can be obtained.

There are two choices for the form of the exponential decay function to be fitted to the $P'(t)/P'_o$ versus *t* data points. Fitting the one-parameter equation $P'(t)/P'_o = e^{-bt}$ to the data points on a semi-logarithmic plot of $P'(t)/P'_o$ versus time (t), forces the plot through $P'(t)/P'_o = 1$ at t = 0. On the other hand fitting the data to the two-parameter equation $P(t)/P'_o = ae^{-bt}$ would relax this condition. Both equations were fitted to the data for each of the 45 air permeability measurements.

A value of P_{atm} = 966.6 cm water was used to calculate $P_o = P_{atm} + P'_o$ in all calculations. This value represented the mean of the measured hourly barometric pressure at the airport in Blacksburg, Virginia during the hours when the tests were made. The P_o values were converted to Pa using 1 cm of water = 98.1 Pa. The permeability k was calculated as the extracted K_a value ($cm^2\ Pa^{-1}\ s^{-1}$) times the dynamic viscosity of air (μ_a in Pa s). This value of k in cm^2 was converted to $(\mu m)^2$ by multiplying by $10^8\ (\mu m)^2\ cm^{-2}$.

The value of μ_a is very weakly dependent on pressure but increases with absolute temperature. It's value $\mu_a(T)$ at a given temperature T°K can be calculated using Sutherland's equation (Sutherland, 1893) as;

$$\mu_a(T) = \mu_o \frac{T_o + C}{T + C}\left(\frac{T}{T_o}\right)^{\frac{3}{2}}$$

Where; μ_o is the reference value at temperature T_o (°K) and the parameter C (°K) is specific for a given gas. This equation is based on the molecular theory of ideal gases and is valid for a wide range of temperatures. For air, the value $\mu_o = 17.16 \times 10^{-6}$ Pa s at T_o = 273.15°K, and the value of C = 110.4°K. The mean measured air temperature in the chamber during a given permeability test was used to calculate the $\mu_a(T)$ needed to calculate *k* for the given specimen.

RESULTS AND DISCUSSION

The calibration for the general purpose differential (gauge) pressure transducer showed almost perfect linearity. The calibration equation was P' = 1.503 × (mV) - 1.8591 with an r^2 = 0.999. This equation shows the general purpose transducer resolution was quite good, giving 1 mV output for a change of 1.5 cm water column. During the tests, the transducer mV output was read on the data-logger over a firmware-selectable full-scale range of 0 to 50 mV. In this range, the data logger's voltmeter could detect changes of 3.33 μV for a differential voltage measurement. Therefore the pressure measuring system could resolve a change of 0.05 mm of water (approximately = 0.5 Pa) pressure change in the air chamber of the permeameter. The regression line equation showed that a reading of 1.24 mV input into the calibration equation would indicate zero excess pressure in the permeameter air chamber.

The air temperature in the chamber recorded for all tests never exceeded the mean value by more that 0.35°C. Wrapping the permeameter with aluminium foil was effective in maintaining close to isothermal conditions in the permeameter air chamber during tests although the climate in the laboratory was uncontrolled. Nevertheless, it is recommended that the air chamber should be very well insulated with better materials. With proper insulation the permeameter could be used outdoors at construction sites.

Despite its age, Sutherland's equation was reliable for calculating the air dynamic viscosity at room temperatures. The values of dynamic viscosity (μ_a) calculated by Sutherland's equation at 300°K were very close to the measured value of 1.82 x 10^{-5} Pa s at this temperature reported in the CRC Handbook of Chemistry and Physics (Lide, 1995). Calculated values at 10, 20, 30 and 40°C were respectively (1.763, 1.811, 1.859, 1.906) × 10^{-5} Pa s and practically the same as the corresponding values of (1.77, 1.81, 1.85, 1.89) × 10^{-5} Pa s reported by Scanlon et al. (2002).

The experimental data on $P'(t) / P'_o$ versus time were plotted on semi-logarithmic graphs for all 45 tests. In all cases these plots were linear until an inflexion point that occurred at some point after $P'(t) / P'_o < 0.2$. This could only mean that after this point the assumptions made in developing the foregoing physico-mathematical model discussed above were no longer applicable. These assumptions would imply linearity as long as the air flow through the voids in the test specimen was purely viscous. Gaseous viscous advective flux generally predominates over viscous slip and diffusive fluxes even under low pressure gradients when pore radii are much greater than the mean free path of the air molecules. But if the pore radii are small (as would be expected for the partially saturated compacted test specimens), viscous slip (when mean free path ≈ pore radii), Knudsen diffusive (mean free path > pore radii), or molecular diffusive flow (mean free path >> pore radii) would be expected to predominate over viscous advective fluxes as the pressure decreases (Alzayadi, 1975; Alzayadi and Moore, 1978; Thorstenson and Pollock, 1989). Also, the mean free path is inversely proportional to pressure at a given temperature implying it is greater at lower pressure. Therefore, depending on the pore-sizes and their distribution, the predominance of advective viscous flow would decrease relative to viscous slip, Knudsen diffusive, or molecular diffusive flows at some value of the excess pressure in the chamber. In this case, the quasi- steady state conditions for purely viscous flow would no longer be valid. This changeover value would depend on the permeability of the test specimen. For the test specimens in this study this value occurred at some point after $P'(t) /P'_o < 0.2$.

Since the primary interest and the assumptions made in this study were to quantify the air permeability under predominantly viscous flow, the ($P'(t) /P'_o$) versus time data points for all 45 test cases were truncated and the portion for $P'(t) /P'_o > 0.2$ used to estimate *k*. The two-parameter fitting equation $P(t) /P'_o = ae^{-bt}$ tended to give better and more consistent fits to the data for all 45 tests compared to the one-parameter equation $P'(t) /P'_o = e^{-bt}$. The coefficient of determination (r^2) for all fits with the two-parameter equation was never < 0.98 and never < 0.94 for the one-parameter equation. Two- tailed t-tests (assuming equal variances) showed that the mean of the k-values over the 5 tests for the one-parameter and two-parameter fitting equations were not statistically different at the 5% level of significance. Nevertheless, the k-values obtained using the two-parameter equations were considered more valid.

A typical case (for the silty loam specimen at 18 blows per layer) for the two-parameter fits is illustrated in Figure 3. The tests numbered as 1 through 5 are for targeted excess pressures of 20, 25, 30, 35 and 40 cm of water, respectively. The mean and standard deviation of the k-values obtained using the two-parameter fitting equation for the 5 tests for each of the 9 treatment combinations were calculated and showed that the 5 k-values for a given treatment combination fell within the mean ± < 2 standard deviations.

Since there was negligible differences in the slope of the fitted lines for different values of P'_o, the 5 k-values obtained using the two-parameter fitting equation were treated as repeated measurements for a given test specimen. A two-way analysis of variance was conducted using the soil material and compaction effort as factors. The results showed highly significant effects for soil material, compaction effort and their interaction. Interestingly, the results (Table 2) showed in order of decreasing overall mean permeability silt loam > loam > silty clay. Figure 1 shows the order of decreasing (clay + silt) % was silty clay > silt loam > loam, the order of decreasing sand was loam > silt loam > silty clay and the order of decreasing gravel (> 2mm) was silt loam > loam = silty clay. It would appear that the higher % of gravel in the silt loam had a disproportional effect on the air permeability.

In general, decreasing the compaction effort increased the permeability (Table 2). In most cases the means were significantly different (or very close to being significant) at the 5% level using the Fisher's LSD values in Table 2. However the pattern of these increases were different for the different soil materials (Figure 4) and explained the significant interaction obtained in the analysis of variance. Overall, the mean permeability estimates (Table 2) were very low as would be expected for Proctor-compacted specimens at the optimum water content. More surprising was the rather insignificant (from an agronomic perspective) increase in permeability with decreasing compaction effort (Table 2 and Figure 4). For natural un-compacted soil, low air permeability is taken as k < 10 $(\mu m)^2$ and high permeability as k > 250 $(\mu m)^2$ (Ball and Schjonning, 2003).

Decrease in air permeability from compaction is due

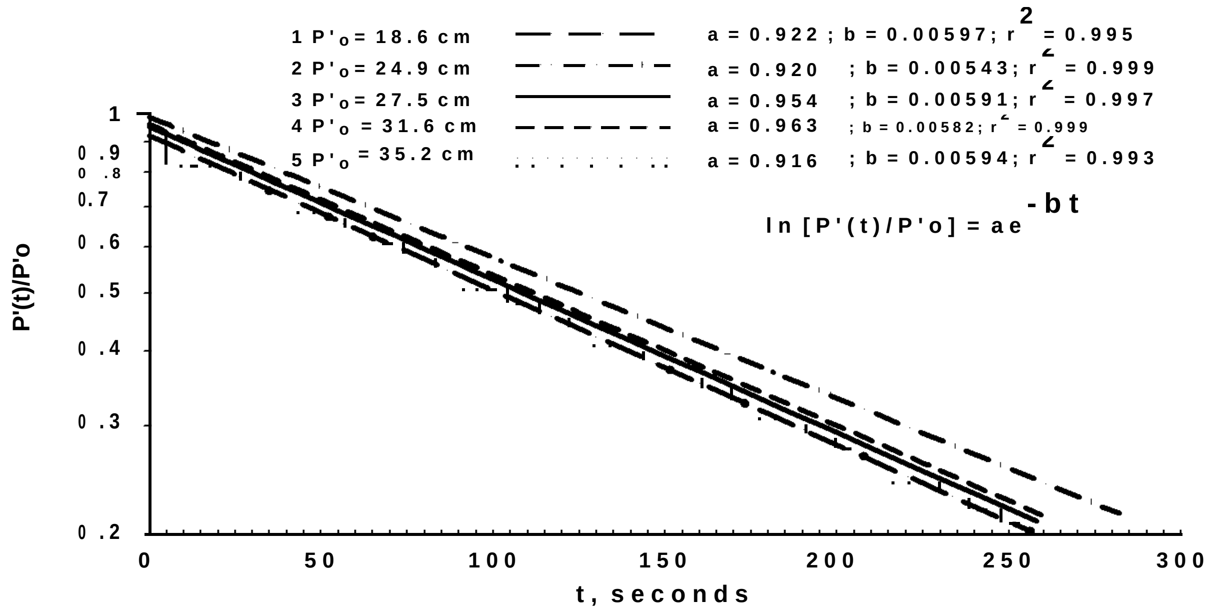

Figure 3. Semi-logarithmic plots for fitting the two-parameter equation P(t) /P'o = ae^{-bt} to a truncated set of data points for P'(t) /P'o versus time (t) measured for the 5 values of P'o.

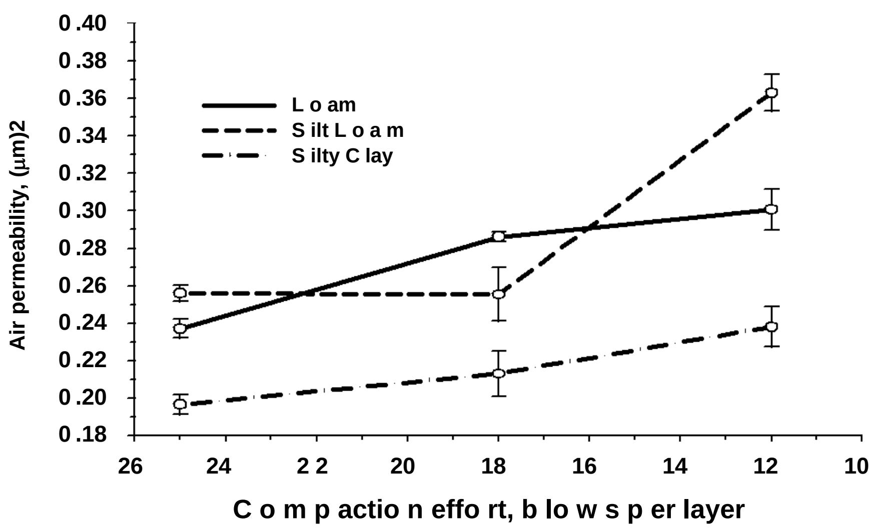

Figure 4. Air permeability (estimated using the two- parameter fitting equation P(t) /P'o = ae^{-bt}) with decreasing compaction effort. Error bars represent the standard error of the mean of 5 repetitions on a given test specimen.

primarily to its effect on total porosity and pore size distribution as a result of re-arrangement of the soil particles (Sridharan et al., 1971; O'Sullivan, 1992; Assouline and Tessier, 1997; Smith et al., 1997; Lipiec and Hatano, 2003).

If θ_a is the volume fraction of air and $V \sim L^3$ is the total bulk volume of the specimen then, assuming a specific gravity of water = 1, $V(1 - \theta_a) = V_s(1 + \theta_g \rho_p)$ where V_s is the volume of dry solids, θ_g is the gravimetric water content and ρ_p is the mean particle density. Therefore, $V_s/V = (1 - \theta_a) / (1 + \theta_g \theta_p)$ and since by definition $\rho_b = W_s/V$ and $W_s = V_s\rho_p$, then

$$\rho_b = \frac{W}{V} = \frac{V_s \rho_p}{V} = \frac{(1-\theta_a)\rho_p}{1+\theta_g \rho_p} \quad (4)$$

Using a reasonable value for ρ_p = 2.65 g cm^{-3} with the values of θ_g and ρ_b in Table 1 shows that the volumetric air content of the test specimens was 5% of the sample

Table 2. Air permeability measured using the two-parameter fitting equation for three sub-grade soil materials under varying compaction effort. Values represent the mean of 5 repetitions on a given test specimen.

Soil material	Compaction effort, blows per layer			Overall mean
	25	18	12	
Loam	0.237	0.286	0.301	0.275
Silt Loam	0.256	0.253	0.363	0.291
Silty Clay	0.197	0.213	0.238	0.216
Overall mean	0.230	0.252	0.301	0.261

LSD = 0.026 $(\mu m)^2$ and 0.035 $(\mu m)^2$ for comparison of means at the 5 and 1% significance levels, respectively

volume.

Yet this question remained short of no compaction: what level of reduction in compaction of the specimens would produce substantial increase in the permeability? Although reducing from 25 to 12 blows per layer produced statistically significant differences (Table 2) the actual differences appeared insignificant from the agronomic perspective. Reducing the compaction effort to 6 blows per layer would be equivalent to 141 kN-m m^{-3} and would be the lowest possible reduction practicable to still achieve uniform compaction in the Proctor test. The Proctor density (g cm^{-3}) at optimum water content (%) were determined as 1.681 at 18.3; 1.607 at 19; and 1.365 at 26.6 for the loam, silt loam and silty clay, respectively.

Using Equation (4) with these values showed that the volumetric air content would be appreciably higher at 6 blows per layer and therefore an increase in permeability was to be expected. When the air permeability measurements were initiated on test specimens compacted using 6 blows per layer, it was immediately apparent that an appreciable change had indeed occurred since 40 cm water excess pressure (P'_o) was dissipated in less than 10 to 20 s. It was not possible to make reliable $P'(t)/P'_o$ versus time measurements at $P'_o < 40$ cm water.

The k-values using P'_o = 40 cm water estimated using the one-parameter fitting equation was 7.21, 22.46 and 8.53 $(\mu m)^2$ for the loam, silt loam and silty clay, respectively. Corresponding values using the two-parameter fitting equation was 7.12, 22.78 and 8.34 $(\mu m)^2$. These latter air permeability values, albeit still considered low, were 30, 89 and 42 times the values obtained using the standardized Proctor compaction effort (25 blows per layer) for the loam, silt loam and silty clay test specimens, respectively (Table 2).

CONCLUSION

We compacted test specimens at their Proctor optimum water content using efforts ranging from 100 to 25% (the lowest practicable value) of that used in the standardized Proctor test. Results confirmed that compaction severely reduces air permeability of the test specimens and indicated that the common practice of compaction to 95% or more of the optimum Proctor density is probably not appropriate for construction of urban green spaces. Reducing compaction effort from 100 to 25% of the standardized Proctor test value increased air permeability 30, 89 and 42 times, respectively for the loam, silt loam and silty clay test specimens. More extensive studies are needed to correlate measured air permeability of Proctor test specimens to agronomic productivity of urban green spaces.

The transient-flow permeameter we designed to measure air permeability of Proctor test specimens is rapid, was quite reliable and had good resolution. The most important parameter in the design is the volume (V_o) of the air chamber. Solving the equation ln $(P'/P'_o) = (-K_a A P_o t) / V_o L$ for V_o, gives V_o in $cm^3 = -(K_a A P_o t)/[L \ln (P'/P_o')]$ with $K_a = [k \text{ in } (\mu m)^2 \times 10^{-8}] / \mu_a$. This permits specifying V_o based on expected values of the air permeability and the time (*t*) for the excess pressure in the air chamber to dissipate.

ACKNOWLEDGEMENTS

Funding for this study was provided by the United States Department of Agriculture, Agricultural Research Service (USDA/ARS) under Specific Collaborative Agreement 58-1932-6-636 between the USDA/ARS Appalachian Farming Systems Research Laboratory, Beaver, West Virginia and Virginia Polytechnic Institute and State University, Blacksburg, Virginia; and Cooperative Agreement #58-1932-5-539 between the USDA/ARS Appalachian Farming Systems Research Laboratory, Beaver, West Virginia and West Virginia State University, Institute, WV.

REFERENCES

Alzayadi AA (1975). Flow of gases in porous media. Ohio State Univ. Press, Columbus, Ohio, USA. 172 p.

Alzayadi AA, Moore CA (1978). Combined pressure and diffusional transition region flow of gases in porous media. Amer. Institute of Chem. Engineers J. 24:35–43,

Assouline S, Tessier D (1997). Effect of compaction on soil physical and hydraulic properties: experimental results and modeling. Soil Sci.

Soc. Am. J. 61: 390 –398.
ASTM (1988). Natural and artificial playing fields: characteristics and safety features. ASTM Special Technical Publications 1073. ASTM, Philadelphia.
ASTM (1994). Safety in American football. ASTM Special Technical Publications 1305. ASTM, Philadelphia.
ASTM (1995). Safety in baseball/softball. ASTM Special Technical Publications 1313. ASTM, Philadelphia.
ASTM (2009). Standard test methods for laboratory compaction characteristics of soil using standard effort 12 400 ft-lbf/ft^3 (600 kN-m/m^3) ASTM D698. In: ASTM Annual Book of Standards Volume 4.08, ASTM, Philadelphia.
Baker SW (1990). Sands for sports turf construction and maintenance. Sports Turf Research Institute, Bingley, West Yorkshire, United Kingdom. 58p.
Baker SW (1991). Temporal variation of selected mechanical properties of natural turf football pitches. J. Sports Turf Res. Inst. 67: 53 – 65.
Ball BC, Harris W, Burford JR (1981). A laboratory method to measure gas diffusion and flow in soil and other porous materials. J. Soil Sci. 32: 323–333.
Ball BC (1987). Air permeability and gas diffusion measurements to quantify soil compaction. In Monnier, G. and M. J. Goss (ed), Soil Compaction and Regeneration: pp.15–23.
Ball BC, Schjonning P (2003). Air permeability. In Methods of Soil Analysis, Part 4, Physical Methods. Soil Sci. Soc. Amer. Inc., Madison, Wisconsin, USA: pp.1141 – 1158.
Blackwell PS, Ringrose-voase AJ, Jayawardane NS, Olsson KA, Mckenzie DC, Mason WK (1990). The use of air-filled porosity and intrinsic permeability to air to characterize structure of macropore space and saturated hydraulic conductivity of clay soils. Eur. J. Soil Sci. 41: 15 – 228.
Bonstingl R, Morehouse C, Niebe IB (1975). Torques developed by different types of shoes on various playing surfaces. Med. Sci. Sports Exerc. 7: 127 –131.
Bramwell S, Requa R, Garrick J (1972). High school football injuries: a pilot comparison of playing surfaces. Med. Sci. Sports Exerc. 4: 166 – 169.
Carrow RN (1980). Influence of soil compaction on three turfgrass species. Agron. J. 72: 1038 - 1042
Cheng-He H, Ouyang Y, Zhang JE (2006). Effects of a compact layer on soil O_2 diffusion. Geoderma 135: 224 –232.
Corey AT (1957). Measurement of water and air permeability in unsaturated soil. Soil Sci. Soc. Am. Proc. 21: 7 – 10.
Corey AT (1986). Air permeability. In Methods of Soil Analysis Part1 Physical and Mineralogical Methods (2nd edition). Am. Soc. Agron. Madison, Wisconsin, USA: pp.1121–1136.
Ghildyal BP, Tripathi RP (1987). Soil physics. New York, Wiley, 656p.
Gilbert OL (1991). The ecology of urban habitats. Chapman and Hall, New York.
Glinski J, Stepniewski W (1985). Soil aeration and its role for plants. CRC Press, Boca Raton, Florida, USA. 229 p.
Grover BL (1955). Simplified air permeameters for soil in place. Soil Sci. Soc. Am. Proc. 19: 414 – 418.
Gupta SC, Sharma PP, De Franchi SA (1989). Compaction effects on soil structure. Adv. Agron. 42: 311 – 338.
Harris JA (1991). The biology of soils in urban areas: In: Bullock P, Gregory PJ (ed.) Soils in the urban environment. Blackwell Scientific Publications, Oxford, UK. pp139–152.
Hinsinger P, Mettauer H (1989). Soil air permeability and its application. 1. Air permeability: theory and methodology. Agronomie 9: 3 –12.
Huang B, NeSmith SD (1999). Soil aeration effects on root growth and activity. Acta Hortic. 504: 41–52
Kirkham D (1947). Field method for determination of air permeabilty of the soil in its undisturbed state. Soil Sci. Soc. Am. Proc.11: 93 –99.
Kouno K, Ogata S, Takiyama S (1992). Soil compaction effects on root development of grasses and some soil physical properties. Jpn. J. Soil Sci. Plant Nutr. 63:154–160.
Lal R, Shukla M (2004). Principles of soil physics. New York, Marcel Dekker. 716p.
Li H, Jiu J, Luk M (2004). A falling-pressure method for measuring air permeability of asphalt in laboratory. J. Hydrol. (Amsterdam) 286: 69 – 77.
Lide DR (Editor-in-Chief). (1995). CRC handbook of chemistry and physics: a ready-reference book of chemical and physical data, 76th edition. CRC Press, Boca Raton, Florida, USA.
Lipiec J, Hatano R (2003). Quantification of compaction effects on soil physical properties and crop growth. Geoderma 116: 107 – 136.
O'Sullivan MF (1992). Uniaxial compaction effects on soil physical properties in relation to soil type and cultivation. Soil Tillage Res. 24: 257 – 269.
Richard G, Cousin I, Sillon JF, Bruand A, Guérif J (2001). Effect of compaction on the porosity of a silty soil: influence on unsaturated hydraulic properties. Eur. J. Soil Sci. 52: 49 – 58.
Scanlon BR, Nicot JP, Wassman JW (2002). Soil gas movement in unsaturated systems. In. Soil physics companion, Warrick AW (ed.) CRC Press, Boca Raton, Florida, USA. pp.297 –341.
Sills MJ, Carrow RN (1983). Turfgrass growth, N use, and water use under soil compaction and N fertilization. Agron. J. 75: 488 – 492.
Smith CW, Johnston MA, Lorentz S (1997a). The effect of soil compaction and soil physical properties on the mechanical resistance of South African forestry soils. Geoderma 78: 93 –11.
Smith JE, Robin MJL, Elrick DE (1997b). A source of systematic error in transient-flow air permeameter measurements. Soil Sci. Soc. Am. J. 61: 1563–1568.
Smith JE, Robin MJL, Elrick DE (1998). Improved transient-flow air permeameter design: dampening the temperature effects. Soil Sci. Soc. Am. J. 62: 1220–1227.
Soil Survey Staff. (2004). Soil survey laboratory methods manual. Version No. 2.0. USDA-NRCS
Soil Survey Investigations Report No. 42. Washington, D.C.: U.S. Government Printing Office.
Springer DS, Cullen SJ, Everett LG (1995). Laboratory studies on air permeability. p. 217-248. In LG Everett, SJ Cullen (ed.) handbook of vadose zone characterization and monitoring, Lewis Publishers, Boca Raton, Florida.
Sridharan A, Altschaeffl AG, Diamond S (1971). Pore-size distribution studies. J. Soil Mech. Found. Div. ASCE, 97: 771 – 787.
Startsev AD, McNabb DH (2001). Skidder traffic effects on water retention, pore-size distribution, and van Genuchten parameters of boreal forest soils. Soil Sci. Soc. Am. J. 65: 224 – 231.
Stepniewski W, Glinski J, Ball BC (1994). Effects of compaction on soil aeration properties. In Soane BD, van Ouwerkerk C (ed) Developments in Agricultural Engineering 11, Soil compaction in crop production. pp.167–189.
Sutherland W (1893). The viscosity of gases and molecular force. Philos. Mag. Series 36(5): 507 – 531.
Switzer C, Kosson DS (2007). Evaluation of air permeability in layered unsaturated materials. J. Contam. Hydrol. 90: 125–145.
Thorstenson DC, Pollock DW (1989). Gas transport in unsaturated porous media, the adequacy of Fick's Law. Rev. Geophys. 27: 61–78.
Tuli A, Hopmans JW, Rolston DE, Moldrup P (2005). Comparison of air and water permeability between disturbed and undisturbed soils. Soil Sci. Soc. Am. J. 69: 1361 – 1371.
Watabe Y, Leroueil S, Le Bihan JP (2000). Influence of compaction conditions on pore-size distribution and saturated hydraulic conductivity of a glacial till. Can. Geotech. J. 37: 1184 – 11