SOIL MIXES FOR PUTTING GREENS*

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The physical properties of most native soils limit their usefulness as putting green soils unless they are physically modified. Poor soil physical conditions, whether natural or due to compaction, may limit grass growth, normal use of a turfgrass area, and performance of essential maintenance operations. Therefore, good soil physical conditions should be established and maintained on turfgrass areas in order to obtain maximum performance of the turfgrass and maximum use of the area.

Putting greens are expensive to construct, and poor initial construction brings additional costs in the form of increased maintenance problems, renovation or reconstruction. Several types of aerating equipment, coarse textured amendments, and wetting agents are used to combat and, hopefully, overcome the effects of compaction on established turf areas. On new greens a soil can be modified by adding physical amendments which will produce a soil mixture that has acceptable physical properties even when compacted.

Various organic and inorganic amendments are available for use in modifying physical properties of soils. The effectiveness of these amendments depends on the properties of the amendment, the amount added, the properties of the soil to which it is added, and the uniformity of mixing of the components.

ORGANIC AMENDMENTS

Peat is the most popular organic amendment. Sawdust, bark, and chemically treated wood products as well as various wastes and by-products, such as digested sewage sludge, tannery waste, manures, cocoa shells, and other seed hulls, can also be used as soil amendments. Organic amendments which decompose rapidly produce soil humus, which is important in aggregate formation and the development of desirable soil structure. Richer et al (1949) reported that cocoa shells decayed more rapidly than peat, but still produced good soil physical conditions because the products of decomposition increased aggregation. However, on heavily used areas, natural aggregation or structure is soon destroyed (Alderfer, 1951). Organic amendments such as peat which resist decomposition give longer lasting effects than readily decomposed materials (Sprague and Marrero, 1932). Fine materials are less effective than coarse or fibrous materials in opening up compacted or fine textured soils. The finer forms may plug pores rather than create larger ones, and would be effective in decreasing permeability of coarse textured soils and sand.

Fibrous peats are preferred over woody and sedimentary peats. Woody peats are granular in nature and are low in moisture holding capacity. Sedimentary peats are very fine and colloidal in nature, and may contain considerable amounts of fine soil (silt and clay). When dry, sedimentary peats become extremely hard and absorb water very slowly.

Common fibrous peats are reed-sedge peat, hypnum moss peat, and sphagnum moss peat. Decomposed peats are referred to as peat humus. Peat humus, having undergone initial decomposition, is more stable in the soil than undecomposed or slightly decomposed peats. It is also finer in texture and less fibrous. Reed-sedge peat is

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more resistant to decomposition than hypnum moss peat, and hypnum is more resistant than sphagnum moss peat (Lucas et al, 1975).

Peats can be used to improve both fine textured and coarse textured soils (Lucas et al, 1965; Sprague and Marrero, 1931). They increase moisture retention and slow down water movement in sandy soils, and they increase the permeability of fine textured soils. Peats increase microbial activity, increase cation exchange capacity, serve as a slow release source of plant nutrients, and usually increase soil acidity.

As a component in modified soils, peat is usually added in the amount of 10 to 20 percent on a volume basis. Peat increases the resiliency of mixtures and during turf establishment it helps to maintain moisture levels favorable for seed germination and rooting of stolons. The need for peat or other organic materials in topdressing may be questioned because established turf usually has adequate organic matter. In fact, one purpose of topdressing is to reduce organic matter (thatch). Possibly the greatest value of organic amendments in topdressing is their conditioning effect on the mixture -- keeping the soil from caking and maintaining a free flowing, easily spread material. This need for conditioning decreases as the soil content in mixtures decreases; however, decreased water and nutrient retention with less soil may give a good argument for the need of organic amendments.

Sawdust has value as a soil amendment (Allison and Anderson, 1951; Anderson, 1957; Bollen and Glennie, 1961; Lunt, 1955, 1961; White et al, 1959). Favorable changes that can be expected from sawdust additions are increases in humus, cation exchange capacity, aggregation, moisture holding capacity, and aeration porosity. On the other hand, the possibility of adverse effects exists. Nitrogen and phosphorus deficiencies often occur as sawdust is decomposed by microorganisms. This condition can be corrected by adding nitrogen and phosphorus fertilizers. About one pound of nitrogen and 0.2 pound of phosphorus are required for each 100 pounds of sawdust. Sawdust from hardwoods decomposes more rapidly than that from softwoods, thus the nitrogen tie-up and the need for supplemental nitrogen is greater with hardwood sawdust. Fresh sawdust from some species has been shown to decrease germination and seedling growth of turfgrasses (Waddington et al, 1967); therefore, it is advisable to use weathered or well-rotted materials.

In some cases sawdust or ground bark is fortified with nitrogen and then composted prior to marketing as an amendment. Such is the case with lignified redwood, which has been shown to be better than sphagnum peat for increasing oxygen diffusion (Letey et al, 1966). The contribution of redwood to soil salinity was greater than that of peat (Valoras et al, 1966).

Organic materials other than peat and wood products are not used extensively on turfgrass areas, but they have been included in research studies. Sprague and Marrero (1931) reported benefits from additions of well-rotted manure and spent mushroom compost, and Richer et al (1949) reported soil improvement from mushroom compost and cocoa shells. Davis et al (1970) recently evaluated nine organic amendments including ammoniated rice hulls; an organic compost derived from sewage sludge and other organic residues; peats; and various products from sawdust and bark.

Some properties to look for in an organic amendment are: (1) coarse or fibrous structure, few fines; (2) resistance to decomposition; (3) high organic content, at least 90 percent; (4) good moisture retention, at least 400 percent for peats; (5) freedom from toxic compounds, disease organisms, insects, and weed seeds; and (6) ease of handling and mixing.

INORGANIC AMENDMENTS

Various natural and processed inorganic amendments are available for modifying soil. Most are coarse amendments, although finer forms of some are available.

Inorganic amendments are usually used to increase permeability; however, some may be used to decrease permeability. In research conducted on loamy fine sand in Florida, colloidal phosphate and vermiculite additions decreased aeration porosity and water movement (Smalley et al, 1962).

Examples of coarse amendments are sands of various sizes and origins; calcined clays, such as "Turface', 'Terra-Green', and 'LuSoil'; expanded shale, such as 'Weblite' (used in soil modification research by R. E. Schmidt at VPI and SU); vermiculite, expanded mica minerals such as 'Terra-Lite'; perlite, an expanded obsidian-like volcanic rock available as 'Perl-Gro', 'Perl-Lome', and 'Sponge Rok'; diatomite, a calcined hydrated silica mineral such as 'Dialoam'; and water quenched slag.

Important characteristics of coarse amendments are particle size, uniformity of particle size, and durability. Particles which break down or alter their shape due to weathering or compaction are not satisfactory for intensively used turf areas, although some materials in this category may have exceptional value in greenhouse and potting mixes. For instance, the brittle nature of perlite and the ease of collapse of vermiculite particles could make these materials unsuitable as coarse amendments on intensively used turf areas. Also, some calcined clays may not be hard and stable enough for use as soil amendments.

The objective of coarse amendment additions is to create large pores. The quantity used should be such that amendment particles are in contact with each other in the mixture, so that the bridging formed by the contact can create stable pores. When added in quantities less than needed to obtain bridging, non-porous amendments such as sand may adversely affect physical properties. The amount needed will vary with the soil texture and the particle size of the amendment. Kunze et al (1957) reported that 85 to 90 percent sand was needed to give adequate modification of a clay soil. Swartz and Kardos (1963) concluded that the total sand content of the mixture should approach 70 percent.

The most effective modification (greatest change in physical properties with the least amount of added amendment) has been obtained from sands in the 0.25-2.0 mm size range, with most of the particles falling into two sand separates (very coarse and coarse sands, or coarse and medium sands). Kunze (1956) concluded that sand of a uniform size, 0.5 to 1.0 mm in diameter, appeared to be most desirable for soil modification. Howard (1959) reported that sand with 50 percent of the particles between 0.25 and 0.50 mm was most desirable in sand-soil-peat mixtures ranging from 5-4-1 to 8.5-.5-1 parts by volume. Swartz and Kardos (1963) found the size range of 0.25 to 2.0 mm to be the dominant fraction in controlling percolation rates. In organic matter-sand mixtures, Davis et al, (1970) obtained greatest modification with uniform sands: one having 94 percent of the particles between 0.25 and 1.00 mm and the other having 79 percent between 0.5 and 2.0 mm and 94 percent between 0.25 and 2.0 mm. Unpublished data from Penn State indicate that uniform amendments with particles larger than 2.0 mm will also effectively modify soil; however, large particles in a putting green may clog aerator tines or interfere with the ease of cutting a core of soil for cup placement. Large particles also create problems when working-in topdressing. An exception would be when particles are being worked into holes produced by aerators which remove cores of soil.

Some of the finer sands and non-uniform sands which are available may be acceptable as amendments, but larger quantities are usually required to obtain desirable results. Non-uniform amendments contain many different sizes of particles and the beneficial effect of bridging may be lost as smaller particles fill the voids created by larger particles. Lotspeich (1964) reported that a multi-component sand composed of several size fractions favors compaction, and that maximum compaction occurs when the particle sizes are such as to allow tetrahedral packing with mutual contact of all grains. Uniform sands having a large percentage of particles in the fine sand (0.1-0.25 mm) and medium sand (0.25-0.50 mm) sizes may have limitations as amendments to improve a soil, but they are excellent for "soil-less" greens, which are usually constructed using only sand and an organic matter source. Bingaman and Kohnke (1970) reported that compacted fine to medium sand (0.1 to 0.5 mm) was a satisfactory growth medium for athletic turf. Two sands evaluated by Davis et al (1970) showed characteristics suitable for "soil-less" greens. One contained 39 percent medium sand and 50 percent fine sand, and the other contained 68 percent medium sand and 25 percent fine sand. Coarser materials can be used in "soil-less" greens if they are underlain by a plastic liner to increase water retention (Ralston and Daniel, 1973).

With the wide range of soil amendments available, it is essential for those involved in the construction and maintenance of turfgrass areas to be aware of the properties of amendments as well as knowing of their availability.

PENN STATE SOIL MODIFICATION PROJECT

A soil modification study was started at The Pennsylvania State University in 1960. One of the objectives of this study was to determine the effectiveness of various amendments for modifying soil physical properties. After preliminary laboratory testing, 81 mixtures were selected for field evaluation.

Materials Used in Field Study

Materials used in the field study were:

Soil--Silt loam (22% sand, 59% silt, 19% clay) from the A_p horizon of Hagerstown soil, a deep, well-drained soil developed from limestone. Surface horizons generally have a silt loam texture, whereas B and C horizons are usually clays. Source: experimental site at The Pennsylvania State University.

Peat--Well-decomposed, fine-textured reed-sedge peat, which contained 76 percent organic matter. Source: Boyd Humus Company, New Wilmington, Pa.

Coarse Sand--(5 Q-Rok Sand), Sharp quartz sand derived from quartzite rock. Uniform particle size, with 95 percent of the particles between 0.50 and 2.00 mm in diameter. Source: Pennsylvania Glass Sand Corporation, Mapleton Depot, Pa.

Concrete Sand - Nonuniform washed river sand with particles ranging from gravel to silt, and with 62 percent of the particles between 0.25 and 1.00 mm. Source: Lycoming Sand Company, Williamsport, Pa.

Motar Sand--Washed river sand similar to the concrete sand but with most gravel removed, and with 73 percent of the particles between 0.25 and 1.00 mm. Source: Lycoming Sand Company, Williamsport, Pa.

USS Slag--Water-quenched blast furnace slag. A porous product consisting essentially of silicates and alumino-silicates of calcium and other bases, and with 65 percent of the particles between 0.50 and 2.00 mm. Source: United States Steel Corporation, Pittsburgh, Pa.

Wunderley Slag--Water-quenched blast furnace slag that has been treated with steel pickling liquor. The liquor contains 0.50-2.00 percent free acid and 15-22 percent ferrous sulfate, and gives the slag increased iron and sulfur contents and a lower pH. Product had 75 percent of the particles between 0.5 and 2.0 mm. Source: Wunderley Processing Company, McKeesport, Pa.

Perl-Lome--Horticultural grade of material obtained from a siliceous volcanic rock called perlite, a variety of obsidian. The very porous and fragile particles are formed by the expansion of raw perlite when it is heated to a temperature of approximately 1700°F. Fifty percent of the particles were between 0.50 and 2.00 mm, and 23 percent were greater

Table 1. Particle size distribution of materials used in soil modification field study (Shoop, 1967).

	Percent by Weight						
Material	Fine Gravel >2.0 mm	Very Coarse Sand 2.0-1.0 mm	Coarse Sand 1.0-.50 mm	Medium Sand .50-.25 mm	Fine Sand .25-.10 mm	Very Fine Sand .10-.05 mm	Silt .05-.002 mm
Coarse Sand	0.0	14.7	80.7	4.4	0.2	0.0	0.0
Mortar Sand	0.1	4.3	22.5	50.4	19.6	2.8	0.3
Concrete Sand	14.3	6.3	18.4	43.2	14.8	2.1	0.6
USS Slag	5.4	26.1	39.1	19.0	6.3	3.4	0.8
Wunderley Slag	6.0	38.2	36.6	10.0	3.2	2.4	3.6
Perl-Lome	23.0	37.1	13.2	7.1	8.7	7.5	3.3
Turface	5.3	35.4	37.2	20.2	1.7	0.2	0.0
Hagerstown Soil*	0.0	1.2	2.0	1.5	3.6	14.3	58.8

*Also contained 18.6 percent clay

Table 2. Physical properties of materials used in soil modification field study (Shoop, 1967).

Material	Particle Density	Bulk Density	Weight	Moisture Retained at Various Tensions Percent by volume		
	g/cc	g/cc	lbs/cu ft	60 cm	1/3 atm	15 atm
Coarse Sand	2.66	1.47	91.8	4.2	0.8	0.4
Mortar Sand	2.74	1.61	100.5	9.3	5.5	2.6
Concrete Sand	2.77	1.70	106.1	7.7	6.1	2.8
USS Slag	2.79	0.77	48.1	15.6	13.3	12.3
Wunderley Slag	2.78	0.74	46.2	29.5	16.5	14.1
Perl-Lome	2.33	0.13	8.1	27.2	8.8	14.5
Turface	2.55	0.68	42.4	38.4	36.3	32.9
Peat	1.71	0.27	16.9	36.8	28.0	21.0
Hagerstown Soil	2.63	1.16	72.4	43.4	32.6	8.7

than 2.00 mm. Source: Perlite Corporation, Carnegie, Pa.

Turface--Granular calcined clay produced by calcining montmorillonite clay at temperatures above 1300°F. A hard, porous material having 72 percent of the particles between 0.50 and 2.00 mm. Source: Wyandotte Chemical Corporation, Wyandotte, Michigan.

Fert-Soil--Commercially available mixture of composted soil, sand, and organic matter which is heat-treated and contains approximately 16 percent organic matter and 70 percent sand. Source: Fertl-Soil Company, Rahway, New Jersey.

Particle size analysis and physical properties of these materials are shown in Tables 1 and 2, respectively.

Sand content in the mixtures varied between 40 and 80 percent on a volume basis. Slag was used at 30, 40, and 60 percent levels, alone and in combination with coarse sand. Perl-Lome and Turface were used at 10, 20, and 40 percent, alone and in combination with sand. Peat content was either 10 or 20 percent. When peat was increased from 10 to 20 percent, another component was decreased by 10 percent, and thus the ratio of components other than peat also changed.

Establishment of Field Plots

During the summer of 1960 the Hagerstown silt loam topsoil was stripped from the area and stockpiled. The subsoil was graded to a 0.5 percent slope, and a 6 inch layer of 1B (1/2 inch) limestone chips was spread on the area. Beginning in July of 1961, the materials for the various mixtures were mixed off-site and the prepared mixtures were then placed on the stone base in 10 x 18' plots. To insure containment of individual mixtures in each plot, boards were temporarily placed between plots during placement of the mixtures. Depth of mixtures was approximately 12 inches. The mixtures were allowed to settle over the winter, and in the spring of 1962 the settled depth was adjusted to approximately 10 inches by either removal or addition of mixture. The seedbed was prepared and plots were seeded in June and July with 'Penncross' creeping bentgrass (Agrostis palustris Huds.) at a rate of one lb/1000 ft^2. Since establishment, the plots have been maintained as golf green turf.

Compaction and Aerification Treatments

Beginning in 1963, a compaction machine was used to apply traffic to one-half of each plot. The machine was a converted West Point Aerifier with spiked golf shoe soles mounted on a rotating water-filled drum. The total machine weight was 400 lbs and, based on area of the shoe soles, pressures up to 38 psi were obtained. The compaction treatment was applied from 21 to 60 times per season. Compaction was usually applied after irrigation or rainfall, and was concentrated during spring and early summer as well as prior to and during periods when soil physical properties were being measured. The noncompacted area received only the compaction associated with normal maintenance of the area.

In the fall of 1964, the main plots were split perpendicular to the compaction treatment for an aerification treatment. Half of the plot was not aerified and the other half was aerified with a Ryan Greensaire aerator, which was equipped with 3/8 inch hollow tines. Cores were extracted on 2 inch centers to a depth of approximately 3 inches. The plots were aerified once in 1964, 1965, 1966, 1969, 1970, and 1972, and twice in 1967 and 1968. Except when used for topdressing in 1970 and 1972, cores were removed from the area.

Measurements of Soil Physical Properties

Samples taken at the time of establishment were used for laboratory determinations of percolation rate and air porosity on compacted and noncompacted mixtures. Moisture retention at various tensions and the permanent wilting percentage were also determined.

Table 3. The effect of coarse sand and peat contents of soil mixtures on percolation and infiltration rates.

Parts by Volume			Laboratory Percolation Rate* in/hr		1963 Infiltration Rate* in/hr		1972 Infiltration Rate in/hr			
Coarse Sand	Soil	Peat	NC†	C	NC	C	NC	C	NCA	CA
8	0	2	>60.0	53.9	50.4	37.0	8.0	3.0	21.9	13.3
8	1	1	>60.0	23.9	36.5	23.8	6.0	1.1	12.6	9.0
6	2	2	30.1	11.1	20.1	12.4	1.6	0.4	4.2	1.5
6	3	1	23.0	2.3	15.9	5.5	3.3	1.1	2.5	1.4
5	3	2	29.8	1.0	18.5	11.4	1.5	0.5	2.0	0.8
5	4	1	28.5	3.1	12.7	7.8	2.5	0.3	3.7	1.4
4	4	2	29.1	0.9	7.4	3.6	0.7	0.3	2.4	0.9
4	5	1	3.7	0.1	5.0	1.9	0.4	0.2	1.5	0.5
0	8	2	3.7	0.0	3.8	1.2	0.4	0.5	1.4	0.3

*From Shoop (1967)
†NC - noncompacted
C - compacted
NCA - noncompacted, aerified
CA - compacted, aerified

Table 4. The effect of various amendments on percolation and infiltration rates of 4-5-1, 6-3-1, and 8-1-1 mixtures of amendment, soil, and peat.

Amendment	Laboratory Percolation Rate* in/hr		1963 Infiltration Rate* in/hr		1972 Infiltration Rate in/hr			
in 4-5-1 Mixtures	NC†	C	NC	C	NC	C	NCA	CA
Coarse Sand	3.7	0.1	5.0	1.9	0.4	0.2	1.5	0.5
Mortar Sand	7.1	0.3	1.3	0.0	0.6	0.3	0.9	0.6
Concrete Sand	3.6	0.2	2.7	0.1	0.9	0.5	1.9	0.6
USS Slag	30.6	3.4	5.7	1.0	0.8	0.3	2.6	0.6
Perl-Lome	2.8	0.1	0.7	0.4	0.4	0.5	0.6	0.4
Turface	1.2	0.2	5.3	2.7	1.7	0.3	2.0	0.6
in 6-3-1 Mixtures								
Coarse Sand	23.0	2.3	15.9	5.5	3.3	1.1	2.5	1.4
Mortar Sand	19.1	5.6	8.7	4.0	2.5	0.6	2.5	0.6
Concrete Sand	11.4	3.3	8.7	2.2	0.8	0.6	1.5	1.0
USS Slag	>60.0	10.2	15.7	3.4	1.6	0.6	8.7	1.6
in 8-1-1 Mixtures								
8 Coarse Sand	>60.0	23.9	36.5	23.8	6.0	1.1	12.6	9.0
6 USS Slag + 2 Coarse Sand	>60.0	>60.0	37.2	23.0	5.7	1.6	17.8	9.7
4 Perl-Lome + 4 Coarse Sand	47.0	7.0	28.0	11.6	3.7	0.5	6.4	2.1
4 Turface + 4 Coarse Sand	14.6	18.7	35.0	36.5	10.6	4.5	22.5	8.4

*From Shoop (1967)

†NC - noncompacted
C - compacted
NCA - noncompacted, aerified
CA - compacted, aerified

In the field, infiltration rates were measured each year (1963-72) using a double ring infiltrometer, consisting of two concentrically placed cylinders (one 8 inches and the other 14 inches in diameter and 3.5 inches in height) driven into the soil to a depth of about 1 1/2 to 2 inches. Air porosity, bulk density, and water retention were also measured under field conditions.

Percolation and Infiltration Rates

The effects of the amount and kind of amendment on percolation and infiltration rates are shown in Tables 3 and 4. Laboratory percolation rates were significantly affected by mixtures and were decreased by compaction. Low levels of modification were ineffective in bringing about an increase in permeability under compacted conditions. In general, compacted mixtures needed 60 percent or more coarse amendments to have percolation rates greater than 1 inch/hour. Similarly, little change in value of infiltration rate and air porosity occurred until the coarse amendment level reached 50 to 60 percent. Thus, a general statement that additions of coarse amendments increase permeability cannot be made; however, once a threshold level is reached, where bridging of coarse particles begins to occur, increases in coarse amendment did increase permeability.

On compacted coarse sand mixtures, increasing peat from 10 to 20 percent at the expense of soil (8-1-1 vs 8-0-2; 6-3-1 vs 6-2-2; etc.) increased percolation except at the 50 percent sand level. Increasing peat at the expense of sand (6-3-1 vs 5-3-2 and 5-4-1 vs 4-4-2) decreased percolation.

Infiltration rate is one of the best measures of soil physical condition, and in most instances it should be the primary criterion in evaluating the various treatments. Significant differences in infiltration rates were caused by mixtures, compaction, aerification, and time. The coarser textured mixtures had the higher rates. In general, compaction decreased and aerification increased infiltration rates; however the effects of these treatments were influenced by the mixtures. Infiltration rates of some mixtures decreased rapidly with time and leveled off, while others still show a decreasing trend after 10 years. Rates of fine-textured mixtures tended to level off earlier than those of coarse-textured mixtures; although the magnitude of decreases with time has been greater with the coarse mixtures, which initially had very high rates. Decreases with time were favored by compaction, whereas aerification tended to slow the decrease.

Differences in infiltration rates due to compaction treatments decreased over the years. It had taken longer for the noncompacted plots to approach or reach an ultimate soil compaction level which is characteristic of the mixture. Aerification tended to increase infiltration rates, and may improve the acceptability of an insufficiently modified putting green mixture. The beneficial effect of aerification may be dependent on whether the poor permeability is caused by a poor physical condition which exists throughout the depth of the mixture, or by a compacted surface layer which can be penetrated by aerator tines or spoons. In contrast to a beneficial effect, there was a tendency with several mixtures toward lower infiltration rates with the aerified, noncompacted treatment than with the nonaerified, noncompacted treatment.

When added in adequate amounts, either alone or with other amendments, coarse amendments increased infiltration. When various coarse amendments were used at a 40 percent rate, the 1972 infiltration rates were quite low; whereas at a 60 percent rate USS Slag and coarse sand gave greater increases than mortar and concrete sands (Table 4). In general, coarse sand and Turface were the most effective materials for increasing infiltration, followed by the slags and concrete and mortar sands. Perl-Lome was relatively ineffective. Results for coarse sand mixtures show that increasing peat at the expense of sand decreased infiltration in 1972, while no consistent trend existed for increasing peat at the expense of soil (Table 3).

Infiltration rates should be high enough to allow irrigation water to infiltrate without runoff. In other words, the infiltration rate should be equal to or greater than the application rate to obtain efficient water use. High intensity rain storms may exceed infiltration rates, but if the area is properly designed, excess water will be removed by surface drainage.

Infiltration rates on a green will vary, with lower rates occurring in the high traffic areas such as cupping areas and areas used to enter and leave a green. Higher rates will occur at the rear of the green and in non-cupping areas. Ideally, the lowest infiltration rate will be high enough to accommodate the irrigation rate, which usually falls within the range of 0.5 to 1.0 inch per hour.

Variations in infiltration rate also occurred on the small, relatively uniform subplots in this study; thus, some values were above and others below the reported average value. Therefore, there is some risk in designating an average of 0.5 inch per hour as an acceptable rate, and a value of 1.0 inch per hour is recommended as the minimum acceptable value. Rates for compacted, or compacted and aerified plots would be typical of high traffic areas such as putting greens. Some unacceptable compacted mixtures become acceptable when aerified.

Due to low water holding capabilities, mixtures with high levels of modification may create establishment and maintenance problems. Based on 1963 infiltration data, drying during establishment and drought susceptibility of established turf were not problems on mixtures that had infiltration rates less than 12 inches per hour following compaction.

Bulk Density and Porosity

In the field it was found that bulk density, total porosity, and air porosity varied with depth and that the magnitude of variation depended on the mixture. Air porosity was lowest in the 0-1 inch depth and increased with depth, indicating that the greatest effect of compaction was near the surface. There was a trend toward highest bulk density and lowest total porosity in the 1 to 2 inch depth, rather than the 0-1 inch layer. Closeness to the zone of maximum compaction combined with a greater mineral content may have contributed to this trend. Greater root content and higher organic matter content would result in a lower bulk density even though air porosity was lowest in the 0-1 layer. Clogging of pores by roots is another factor to consider when interpreting porosity results. No data were collected on this effect.

Some effects of the amount and kind of amendment on bulk density, total porosity, and air porosity are shown in Tables 5 and 6. Both total porosity and air porosity were decreased by compaction. Air porosity usually decreased to a greater extent, indicating a greater effect on large pores than small pores.

For a given soil, bulk density is a satisfactory indicator of compaction; however, in this study it was a poor indicator because mixtures had different inherent bulk densities due to differences in the densities of amendments and in the ratio of components. Addition of peat at the expense of soil or sand decreased bulk density, and the use of low density amendments such as slag, Perl-Lome, and Turface decreased bulk density. The internal pore space (within a particle) of these low density materials also resulted in a higher total porosity than when sand was the sole coarse amendment in a mixture.

Air porosity, a measure of the larger pores, was a good indicator of physical condition, and results compared favorably with those found with infiltration rate. Increasing sand, slag, or Turface content increased air porosity. Only a slight effect was obtained with Perl-Lome. In the laboratory tests, increasing peat at the expense of soil or sand decreased air porosity. The effect of peat on air porosity was not as apparent in the field data. Air porosity tended to increase with Turface substitution for sand and decrease with Perl-Lome substitution for sand. The effect of USS Slag substitution for sand was variable.

Table 5. The effect of coarse sand and peat contents of soil mixtures on bulk density, total porosity, air porosity, available water, and permanent wilting percentage.

Parts by Volume			Field; 0-1 inch depth (Zimmerman, 1973)						Laboratory (Shoop, 1967)			
			Bulk Density g/cc		Total Porosity, %		Air Porosity, %		Air Porosity, % at 60 cm Tension		Available Water at 60 cm Tension, NC	Permanent Wilting Percentage, NC
Coarse Sand	Soil	Peat	NC*	C	NC	C	NC	C	NC	C	Inches H_2O/ft of soil	
8	0	2	1.24	1.27	50.7	49.4	29.2	24.4	29.9	17.6	1.0	0.4
8	1	1	1.25	1.37	50.6	46.0	22.1	15.2	31.9	21.9	1.2	0.4
6	2	2	1.26	1.30	50.1	48.6	16.1	14.6	27.9	13.6	1.8	0.6
6	3	1	1.23	1.34	50.4	46.2	21.5	17.5	30.3	17.6	1.7	0.5
5	3	2	1.20	1.27	53.2	50.4	20.2	15.5	18.9	1.3	2.5	1.0
5	4	1	1.32	1.33	48.0	48.0	18.8	17.1	25.5	13.5	2.0	0.4
4	4	2	1.17	1.29	54.0	49.4	16.2	13.0	25.6	0.0	2.4	0.7
4	5	1	1.26	1.39	50.8	46.3	16.1	11.7	13.9	0.9	3.3	0.9
0	8	2	1.20	1.25	53.7	52.0	11.9	10.9	6.5	0.0	4.3	1.4

* NC - noncompacted

C - compacted

Table 6. The effect of various amendments on bulk density, total porosity, air porosity, available water, and permanent wilting percentage of 4-5-1, 6-3-1, and 8-1-1 mixtures of amendment, soil, and peat.

Amendment	Field; 0-1 inch depth (Zimmerman, 1973)						Laboratory (Shoop, 1967)			
	Bulk Density g/cc		Total Porosity, %		Air Porosity, %		Porosity, % at 60 cm Tension		Available Water at 60 cm Tension, NC	Permanent Wilting Percentage NC
in 4-5-1 Mixtures	NC*	C	NC	C	NC	C	NC	C	Inches H_2O/ft of soil	
Coarse Sand	1.26	1.39	50.8	46.3	16.1	11.7	13.9	0.9	3.3	0.9
Mortar Sand	1.35	1.43	48.3	45.3	11.9	7.6	21.3	2.5	2.5	0.9
Concrete Sand	1.28	1.35	51.1	48.5	14.6	11.6	18.3	1.7	2.6	1.0
USS Slag	1.10	1.17	57.7	54.2	14.4	10.0	33.8	9.8	2.1	1.1
Perl-Lome	0.95	1.06	60.9	57.7	7.9	9.5	16.5	1.9	4.3	1.2
Turface	1.01	1.09	62.1	59.4	16.5	13.1	15.8	3.1	3.1	2.3
in 6-3-1 Mixtures										
Coarse Sand	1.24	1.34	50.4	46.2	21.5	17.5	30.3	17.6	1.7	0.5
Mortar Sand	1.29	1.33	50.6	49.3	17.3	14.8	25.0	13.9	1.4	1.3
Concrete Sand	1.29	1.40	50.9	46.4	16.7	12.3	23.3	11.0	1.9	0.7
USS Slag	1.08	1.12	59.0	57.0	14.8	13.7	38.8	16.5	1.8	1.1
in 8-1-1 Mixtures										
8 Coarse Sand	1.25	1.37	50.6	46.0	22.1	15.2	31.9	21.9	1.2	0.4
6 USS Slag + 2 Coarse Sand	1.08	1.11	57.7	56.2	22.9	18.1	38.7	25.6	1.2	1.3
4 Perl-Lome + 4 Coarse Sand	1.03	1.15	59.1	54.2	20.8	11.9	25.4	11.1	2.6	0.8
4 Turface + 4 Coarse Sand	0.96	1.03	64.0	62.0	36.1	29.9	26.6	17.8	1.7	1.8

* NC - noncompacted
C - compacted

Available and Unavailable Water

Amendments differed in their influence on unavailable water (permanent wilting percentage) and available water (Tables 5 and 6). Sand additions decreased both available and unavailable water, with coarse sand having the greatest effect. The slags decreased available water but did not affect unavailable water. When substituted for coarse sand in the 8-1-1 mixtures Turface greatly increased unavailable water and slightly increased available water, while Perl-Lome substitution doubled both the unavailable and available water. Of the 4-5-1 mixtures, those containing Perl-Lome had more available water than those containing sands, slag, or Turface; and those containing Turface had the most unavailable water but more available water than those containing mortar sand, concrete sand, or slag.

Turface additions at the expense of soil increased unavailable water and decreased available water, and Perl-Lome additions had little or no effect on both unavailable and available water. These trends are not the same as when these amendments were substituted for sand. Thus, when statements are made concerning the effects of one amendment, it is important to consider which of the other components are also changed.

Conclusions

This study has shown that soil modification can be used to obtain mixtures of soil and amendments which retain good soil physical conditions even when severely compacted. Results were dependent on the kind and amount of soil amendments used. Coarse sand and Turface ranked highest, Wunderley and USS slags, and concrete and mortar sands were intermediate, and Perl-Lome was least effective for increasing soil permeability of compacted mixtures. At least 50 to 60 percent of coarse amendment was required to modify the Hagerstown silt loam soil effectively. Decreases in water retention were associated with increased levels of modification.

Compaction decreased soil permeability; however, the coarser textured mixtures exhibited greater resistance to compaction than did the finer textured mixtures. Compaction effects were greatest in the surface inch or two of soil. Aerification increased infiltration rates of most mixtures, and appears to be an essential practice with some mixtures to make them acceptable for intensively used turf areas.

This study illustrated the importance of long-term experimentation in the evaluation of soil amendments. Permeability decreased over the years and the magnitude of change was affected by the mixture, as well as by compaction and aerification. Decreases in permeability were accelerated by compaction and delayed by aerification. With time, physical properties of soils receiving compaction from maintenance operations approached those of the soils more severely compacted with a compaction machine. This result was more apparent in mixtures with low levels of modification. The low level of compaction resulting from maintenance operations was more severe on the finer textured mixtures. The resistance of the coarser mixtures to compaction was seen in wider differences in soil permeability and air porosity between the compaction treatments.

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