Effects of Soil Reinforcing Materials on the Surface Hardness, Soil Bulk Density, and Water Content of a Sand Root Zone

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ABSTRACT

This study was conducted to determine the effect of various types and rates of soil reinforcing materials on soil bulk density, soil water content, surface hardness, and turfgrass density of a high-sand root zone exposed to three levels of simulated traffic (wear). Six soil reinforcing materials were mixed at varying rates with a high-sand root zone. These included DuPont Shredded Carpet, Netlon, Nike Lights, Nike Heavies, Turfgrids, and Sportgrass. Three levels of wear were imposed on each treatment. The types and rates of reinforcing materials had varying effects on surface hardness, bulk density, water content, and turf density of the root zone. Surface hardness and soil bulk density were correlated during the 2-yr test period ($r = 0.63$). The reinforcing treatments that lowered soil bulk density and surface hardness were DuPont Shredded Carpet, Nike Lights, and Nike Heavies. Reinforcing material treatments that increased or did not affect soil bulk density generally resulted in increased surface hardness compared with nonamended controls. These treatments included Netlon and Turfgrids. Surface hardness generally became more pronounced as the level of wear increased for Netlon, Turfgrids, and Sportgrass treatments. The Sportgrass treatment consistently measured lower in soil water content than the control and had a turfgrass density lower than the control on all rating dates in 1996 but did not differ from the control in 1997. Athletic field managers considering using reinforcing materials should be aware that the type of material and rate influence athletic field surface hardness.

Soil reinforcing materials have been mixed with high-sand athletic field root zones in an attempt to improve surface stability. Although some of these materials have demonstrated improved playing surface quality through greater surface stability, there is evidence that certain reinforcing materials increase soil bulk density and surface hardness (Baker, 1997). Surfaces that are hard can be dangerous to athletes (Rogers and Waddington, 1990). Reinforcing materials considered for use in athletic field root zones should provide surface stability benefits without increasing surface hardness to unacceptable levels.

Baker (1997) reviewed much of the research on synthetic reinforcing materials for turfgrass soils and proposed two broad categories: (i) randomly oriented fibers, filaments, or mesh elements and (ii) horizontally placed fabrics. Most randomly oriented fiber reinforcing materials studied in turf consist of relatively short polypropylene fibers. Baker and Richards (1995) incorporated both straight and crimped polypropylene fibers (36 mm in length and 113 μm in diameter) into sandy soils at rates up to 7.5 g kg^{-1}. At the 4.0 g kg^{-1} rate they reported increased surface hardness on two of the 11 rating dates. When the rate was increased to 7.5 g kg^{-1}, significant increases in surface hardness were reported on eight of the 11 rating dates. During dry conditions at the end of the study, the fiber reinforcing materials made the surface harder than the range the researchers considered acceptable for player/surface impact.

Mesh elements were first evaluated as a soil reinforcing material by researchers attempting to increase the strength of sand for engineering applications such as support beneath building footings (Mercer et al., 1984; McGown et al., 1985). Mercer et al. (1984) stated that to optimize soil strength, the size and shape of the filaments comprising mesh elements must be related to the size of soil particles in which they are placed. In order not to weaken the soil, the addition of mesh elements must not significantly decrease soil bulk density (Mercer et al., 1984). Mercer et al. (1984) found that at mesh contents up to 5.5 g kg^{-1}, the bulk density of the mixture was the same or greater than the sand alone.

Turfgrass scientists have evaluated mesh elements, similar to those described by Mercer et al. (1984), as reinforcing materials for athletic field root zones. Under simulated soccer-type wear, Baker (1997) reported no significant effect of mesh elements on the retention of grass cover, ball rebound, or surface hardness. In a study without simulated wear treatments, Beard and Sifers (1993) found an increase in soil water content and a small decrease in surface hardness values with increasing concentrations of mesh elements. In another mesh element study using a method different from Beard and Sifers (1993) to assess surface hardness, Canaway (1994) reported a general increase in surface hardness as the rate of mesh elements in sand increased.

Richards (1994) conducted a laboratory study in which mesh elements were mixed with sand and compacted in 100-mm diam. cylinders. The results indicated reduced soil bulk density and increased total porosity of the mixture with increasing rates of mesh elements. These results are not consistent with the civil engineering work of Mercer et al. (1984) where the mesh elements either slightly increased or had no effect on soil bulk density.

Another type of reinforcing material that has been amended into turfgrass soils is shredded carpet. McNitt and Landschoot (2001b) mixed shredded carpet fibers into a sand-based modular turf system and found a reduction in divot size and surface hardness. Shredded carpet is the shredded remains of predominately nylon carpet fragments that include both pile and backing. The yarn-like fibers range in length from 20 to 610 mm.

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Abbreviations: TDR, time-domain reflectometry.

Although shredded carpet has not been widely studied in turf systems, some engineering research has shown that increasing rates of continuous yarn up to 1 m in length increased soil strength significantly more than an equal weight of shorter yarn (Leflaive, 1982). Whereas the strength imparted by shorter fibers is due to friction between individual soil particles and the fibers, Leflaive (1982) explained that continuous yarn increases soil strength by coiling tightly around groups of soil particles. In addition, the random looping and crossover of yarn fibers results in a tightening of slack sections as further soil loading occurs, thus increasing reinforcement.

The conflicting soil bulk density results obtained by civil engineers and turfgrass researchers for mesh element reinforcing materials and the varying results obtained for surface hardness of reinforced sand indicate that additional research is needed on the effects of soil reinforcing materials in high-sand athletic field root zones. Also, shredded carpet should be evaluated as an amendment in high-sand root zones to determine its effect on surface hardness, soil bulk density, and soil water content under different levels of wear.

The objective of this study was to evaluate the effects of varying rates and types of soil reinforcing materials on the surface hardness, soil bulk density, and soil water content of a sand root zone after wear is applied.

MATERIALS AND METHODS

Descriptions of Reinforcing Materials

Randomly Oriented Fibers, Filaments, or Mesh Elements

DuPont Shredded Carpet. DuPont Shredded Carpet was obtained from DuPont Nylon (Chestnut Run Plaza, Wilmington, DE) and is the shredded remains of carpet fragments that include both pile and backing. The shredded carpet is not commercially available, but is a component of a sand-based modular turfgrass system called GrassTiles (Hummer Sports Turf, Lancaster, PA). DuPont Shredded Carpet is ≈70% nylon, 12.2% calcium carbonate, 10.7% latex, and 7.1% polypropylene on a weight basis (V.J. Kumar, 1998, personal communication). On the basis of 100 randomly selected carpet fibers, the average length was 135 mm, and the range was 20 to 610 mm. Fifteen carpet fibers were randomly selected and measured for width. The width of a carpet fiber averaged 2.4 mm and ranged from 0.5 mm to 4 mm. The compressed and uncompressed density of a mass of shredded carpet was measured using a 1000-mL cylinder. The uncompressed density was determined by measuring the dry weight of shredded carpet required to loosely fill a 1000-mL cylinder. The compressed density was measured using the same mass of carpet compressed in the 1000-mL cylinder using a 1-kg weight. The compressed and uncompressed densities of the shredded carpet were 0.153 and 0.073 g cc^{-1}, respectively.

Netlon. The Netlon discrete mesh elements were supplied by Netlon Ltd. (New Wellington, St. Blackburn, U.K.). The mesh is manufactured from extruded polypropylene and has a mass per unit area of 52 g m^{-2}. The filament thickness is 0.50 mm (vertical medial diameter) and 0.48 mm (horizontal medial diameter). The filaments are arranged in a grid, creating rectangular openings that are 6.7 by 7.1 mm. Each element is 100 by 50 mm.

Nike Reuse-A-Shoe Materials. The Nike Reuse-A-Shoe materials are the shredded remains of used athletic shoes. In the shredding process, the entire shoe is granulated before the components are separated by screening and floating and sinking in water. The Reuse-A-Shoe materials currently do not have a size specification. Their gradation is a result of passing granulated shoes through a 16-mm screen in the primary granulator and a 19-mm shaker screen.

The materials that make up a shoe vary substantially. Most shoes have uppers, midsoles, and outsoles (Malloch, 1996). The most prevalent materials in the upper shoe component are nylon, synthetic leather (polyester with polyurethane coating), leather, cotton, polychloroprene (neoprene sleeves), polyester, polyurethane open cell foam, and cellulose. The midsole contains polyurethane and ethylene vinyl acetate and the outsole contains styrene butadiene rubber, polybutadiene (synthetic rubber), and natural rubber (Malloch, 1996).

Nike supplied two materials from the Reuse-a-Shoe program for this study: Nike Lights and Nike Heavies. Samples of the materials produced at the Wilsonville, WA, processing site were taken on 6 Sep. 1996 by technicians working on the project (Malloch, 1996). The Nike materials were analyzed by the technicians for purity, density, and gradation. The Nike Lights contained 740 g kg^{-1} uppers, 230 g kg^{-1} midsole, and 30 g kg^{-1} outsole. The Nike Heavies contained 150 g kg^{-1} uppers, 510 g kg^{-1} midsole, and 340 g kg^{-1} outsole.

The compressed and uncompressed densities of the Reuse-a-Shoe materials were measured to make a comparison with the Shredded Carpet used in this study. The uncompressed density of each material was determined by weighing loosely placed samples in a 1000-mL cylinder. A compressed density was measured by applying a 1-kg weight to each material in the 1000-mL cylinder. The compressed and uncompressed densities of the Nike Lights were 0.107 and 0.053 g cc^{-1}, respectively. The compressed and uncompressed densities of the Nike Heavies were 0.244 and 0.200 g cc^{-1}, respectively.

Turfgrids. Turfgrids is a commercially available, polypropylene fiber reinforcing material manufactured by Synthetic Industries, Inc. (Chattanooga, TN). It is 99.4% polypropylene and individual fibers are 38-mm long and 5-mm wide. Each individual fiber is fibrillated to form a net-like structure of finer fibers (fibrils). When mixed with soil, each fiber expands and the net-like configuration of fine fibers is randomly-oriented throughout the root zone.

Horizontally Placed Fabrics

Sportgrass. Sportgrass is a commercially available product manufactured by Sportgrass, Inc. (McLean, VA). Sportgrass consists of a polypropylene woven backing with 24 yarn strand ends per 25.4 mm in the lineal direction and 11 yarn strand ends per 25.4 mm in width. Yarn strands are 11 000 denier (1.0 denier is equal to the fineness of a yarn weighing 1.0 g for each 9000 m). The woven backing is tufted with fibrillated polypropylene tufts. In the lineal direction there are 16 tufts per 102 mm. In width, the tufts are 9.5 mm apart. The pile height is 32 mm. The individual tufts form a net-like configuration when expanded. A fibrillated tuft is 6700 denier (W. Cook, 1998, personal communication).

Treatment Rates

Treatment rates of reinforcing materials were based on industry recommendations, previous research, and preliminary lab tests. The preliminary laboratory tests included mixing different rates of reinforcing materials (except Sportgrass) with the sand and peat mixture used in the main field study. The root zone was mixed on a volume basis using nine parts sand to one part sphagnum peat. Two hundred-millimeter-diameter polyvinyl chloride pipe was filled ≈150-mm deep with each mixture and compacted with a Proctor Hammer (American Society for Testing and Materials, 1999). Bulk density, total porosity, aeration porosity, and capillary porosity were determined for each mixture using a tension table and methods similar to those listed in American Society for Testing and Materials (1997). Two rates were chosen for Netlon and Turfgrids; 3 and 5 g kg^{-1}. The 3 g kg^{-1} rate of reinforcements for the Netlon and Turfgrids were based on standard industry recommendations for sports fields (Netlon Advanced Turf, Blackburn, UK; and Synthetic Industries, Chattanooga, TN). The 5 g kg^{-1} rate for both of these products is considered high for sports fields and is primarily recommended for turfgrass horse racing track installations. Rates exceeding 5 g kg^{-1} were not used in this study because of the difficulty in maintaining a homogenous blend of sand root zone and reinforcing material in preliminary studies.

Preliminary studies indicated that the DuPont Shredded Carpet could be mixed effectively at rates up to 30 g kg^{-1}. Nike Lights and Nike Heavies treatments could be mixed at rates higher than 30 g kg^{-1}, but due to a lack of available material and to make a rate comparison with the DuPont Shredded Carpet 30 g kg^{-1}, the 30 g kg^{-1} rates were chosen. Since little data exists for the DuPont Shredded Carpet, four rates were chosen. The rates were 5, 10, 20, and 30 g kg^{-1}.

Plot Construction

Field plots were established at the Joseph Valentine Turfgrass Research Center in University Park, PA, in September of 1995. The plot area consisted of an underdrained gravel layer, ≈150-mm deep, overlaid by a 65-mm intermediate layer. A 100-mm layer of the sand and sphagnum root zone mix that was used during the preliminary testing was installed over the intermediate layer. The mix was donated by the Fertl-Soil Company, Kennett Square, PA (Table 1).

A grid of 3.05- by 3.05-m treatment plots was laid over the level root zone mix. A 300-mm border surrounded each treatment plot. The experimental design was a split block (blocks split by three levels of wear) with 12 treatments and three blocks. All of the treatments (with the exception of Sportgrass) were weighed and mixed with the root zone mix using a front–end loader on an asphalt mixing pad. The sand was saturated with water during mixing. Wooden frames, 3.05 m by 3.05 m by 150 mm high, were placed on each treatment plot and leveled using a transit. After filling the frames with the mixed root zone treatments and allowing the mixture to drain, the surface was leveled by raking and hand tamping.

The Netlon treatments were filled to within 15 mm of the surface and 15 mm of the unamended root zone mix was placed on the surface of the Netlon/root zone mixture as per industry recommendations.

For the Sportgrass treatment, frames were installed and filled with the root zone mix to within 25 mm of the top. The Sportgrass was then cut to fit the frames. Next, small amounts of the root zone mix was applied over the surface and worked into the pile with brooms. The plots were watered and allowed to dry, then more of the mix was broomed into the pile. This process was repeated until ≈3 mm of pile protruded above the settled mix.

After the borders were filled with root zone mix, the frames were removed and plots were seeded with ‘SR 4200’ perennial ryegrass (*Lolium perenne* L.) at the rate of 200 kg ha^{-1}. Nutrients and water were applied as needed to prevent nutritional deficiency and drought stress. The plot area received five N applications equaling 50 kg N ha^{-1} during each growing season (April–October). The turf was mowed twice per week with a reel mower at a height of 38 mm and clippings were not collected in baskets.

Wear level treatments were applied with a Brinkman Traffic Simulator (Cockerham and Brinkman, 1989). The Brinkman Traffic Simulator weighs 410 kg and consists of a frame housing two 1.2-m-long rollers. Each roller has steel dowels or spriggs (12.7-mm diam. by 12.7-mm length) welded to the outside of the rollers, at an average of 150 dowels m^{-2}. These dowels are the approximate length and width of the cleats on the shoe of an American football lineman at the collegiate level. The Brinkman Traffic Simulator produces wear, compaction, and turf/soil lateral shear. The drive thrust yielding lateral shear is produced by different sprocket sizes turning the rollers at unequal speeds. The Brinkman Traffic Simulator was pulled with a model 420 tractor (Steiner Turf Equipment Inc., Dalton, OH) equipped with a dual turf tire package.

Blocks were split with three levels of wear. The wear levels were no-wear, medium-wear (three passes with the Brinkman Traffic Simulator three times per week), and high-wear (five passes three times per week). According to Cockerham and Brinkman (1989), two passes of the Brinkman Traffic Simulator produces the equivalent number of cleat dents created at the 40-yard line during one National Football League game. Thus, 15 passes per week are equivalent to the cleat dents sustained from 7.5 games per week.

In 1996, wear began on 1 June and ended on 17 October. In 1997, wear began on 2 June and ended 17 October. Typically, wear was applied regardless of weather conditions or soil water content. Numerous wear applications occurred when the soil water content was at or near saturation. Occasionally, due to heavy precipitation or schedule conflicts, wear was not applied on the scheduled day. In these cases, wear was applied on the following day.

Data Collection

The criteria used for comparing treatments were surface hardness, soil bulk density, soil water content, and turfgrass density. Surface hardness was measured using a Clegg Impact Tester (Lafayette Instrument Company, Lafayette, IN) equipped with a 2.25-kg missile and a drop height of 440 mm (Rogers and Waddington, 1989). Impact attenuation, as mea-

Table 1. Physical properties of root zone mix.

Size fraction	Percentage by volume	Physical properties†	
	%		
>2.0 mm	1.0	Bulk density	1.68 g cc^{-1}
2.0–1.0 mm	6.8	Total porosity	36.5%
1.0–0.5 mm	33.0	Aeration porosity	29.4% at 40 cm tension
0.5–0.25 mm	34.0	Capillary porosity	7.1% at 40 cm tension
0.25–0.10 mm	17.5	Saturated hydraulic conductivity	730 mm hr^{-1}
0.10–0.05 mm	1.9	Organic matter	0.6%
silt	3.0		
clay	2.8		

† As determined with American Society for Testing and Materials (1997, 1998).

Table 2. Results from regression of water contents taken with time-domain reflectometry and Neutron probe (Troxler unit) across six water contents (ranging from 0.06 to 0.20 $m^3 m^{-3}$).

Treatment	Rate	Slope	*y*-intercept	R^2
	g kg^{-1}			
Control	—	0.912	0.763	0.99
DuPont Shredded Carpet	5	0.663	1.644	0.95
DuPont Shredded Carpet	10	0.763	1.033	0.97
DuPont Shredded Carpet	20	0.794	1.394	0.98
DuPont Shredded Carpet	30	0.852	1.491	0.99
Netlon	3	0.822	1.705	0.95
Netlon	5	0.851	1.998	0.98
Nike Heavies	30	0.881	−0.604	0.99
Nike Lights	30	0.761	0.684	0.91
Sportgrass	—	0.822	0.394	0.97
Turfgrids	3	0.856	1.514	0.99
Turfgrids	5	0.677	2.868	0.97

sured by an accelerometer mounted on the missile, was used to indicate surface hardness and is reported as Gmax, which is the ratio of maximum negative acceleration on impact in units of gravities to the acceleration due to gravity. The average of six hardness measurements taken in different locations on each subplot was used to represent the hardness value of the subplot.

Soil bulk density data were derived from measurements of soil total density and volumetric water content taken with a Troxler 3400-B Series surface moisture-density gauge (Troxler Electronic Laboratories, Inc., Research Triangle Park, NC). The Troxler Gauge uses neutron scattering simultaneously with γ ray attenuation to measure the volumetric water content and total density of the soil (Gardner, 1986). A 150-mm deep guide hole was created in the soil using a template and guide rod. A ^{137}Cs source was then inserted into the hole to a depth of 150 mm. The amount of photons emitted from the source and reaching the receiver on the surface is a measure of total soil density. Soil bulk density is derived by subtracting the density due to water from the total soil density.

Because some reinforcing materials could influence water content measurements, the Troxler Gauge was calibrated using a Tektronix 1502B time-domain reflectometry (TDR) unit (Tektronix, Inc., Beaverton, OR). To calibrate the Troxler Gauge, water contents were determined from each treatment plot, using both the TDR and the Troxler Gauge, on six different occasions to provide a range of soil water contents. Linear relationships between the two methods for each reinforcement treatment were evident, with regression coefficients greater than 0.90 (Table 2).

All water content values reported in this experiment were collected using the Troxler gauge and then adjusted using the appropriate regression equation. The values represent the water content in the surface 150 mm of root zone mix. The adjusted soil water contents were used to calculate the density due to water which was subtracted from total density to provide soil bulk density.

Turfgrass density was rated visually and served as an estimate of number of tillers per unit area. Density was rated using a scale of 0 to 5 with half units. A plot with no turfgrass present is rated as 0, and 5 indicates maximum possible tiller density.

The turfgrass density ratings and the means of the three soil bulk densities, three soil water contents, and six surface hardness measurements were analyzed using analysis of variance and Fisher's least significant difference test at the 0.05 level. A LSD was not calculated when the *F* ratio was not significant at the 0.05 level.

RESULTS

Surface Hardness

Significant treatment differences for surface hardness were found on each rating date (Table 3). Surface hardness of plots generally increased with increasing wear levels in both years of the study (Table 4). Although surface hardness for medium and high-wear treatments was significantly greater than for no-wear treatments on all evaluation dates, actual Gmax values did not differ by >10 units on any date. Surface hardness also increased as each season progressed for wear and no-wear treatments.

When surface hardness data were averaged across all wear levels, differences were detected among reinforcing materials (Table 3 and 5). Generally, surface hardness differences among reinforcing material treatments were greater than differences among wear treatments. The range of Gmax values for reinforcing material treatments exceeded 20 Gmax units on all rating dates.

Sportgrass had higher surface hardness values than all other treatments on four of six rating dates and ranged between 28 and 37% higher in surface hardness than the control on each rating dates (Table 5). Both rates of Turfgrids and Netlon produced higher surface hardness values than the control on all rating dates. When averaged across all rating dates, the low rates of Netlon and Turfgrids increased surface hardness by 13 and 14%, respectively, when compared with the control, while the high rates increased surface hardness by an average of 22 and 24%, respectively.

DuPont Shredded Carpet and both Nike treatments usually produced lower surface hardness values than Sportgrass, Netlon, and Turfgrids (Table 5). Surface hardness generally decreased as rates of DuPont Shredded Carpet increased from 5 to 30 g kg^{-1}. When averaged across all rating dates, the 30 g kg^{-1} rates of DuPont Shredded Carpet and Nike Lights produced surface hardness values that were 10.5 and 12.5% lower than the control, respectively.

Reinforcing material treatment $\times$ wear interactions occurred on 18 Oct. 1996 and on all rating dates in 1997 (Tables 3 and 6). The interactions indicate that the surface hardness values of some treatments were more strongly influenced by wear than others. In the case of Sportgrass, surface hardness values for the high-wear level ranged between 16.5 and 25.4% higher than the no-wear level on each rating date. Sportgrass consistently measured higher in surface hardness than all other treatments after wear was applied. Whereas under no-wear, Sportgrass had surface hardness values similar to the 5 g kg^{-1} rates of Netlon and Turfgrids. DuPont Shredded Carpet 30 g kg^{-1} and both Nike treatments responded differently to increasing wear than Sportgrass. For these treatments, the surface hardness values for the high-wear level were only 5% higher than the no-wear level when averaged across all rating dates.

Soil Bulk Density

No significant wear $\times$ reinforcing material interactions were detected for bulk density on any of the rating

Table 3. Treatment and wear level main effects and interactions for surface hardness, soil bulk density, soil water content, and turfgrass density.

Source	df	1996 18 June	1996 23 Aug.	1996 18 Oct.	1997 11 June	1997 19 Aug.	1997 15 Oct.
		Surface hardness					
		Gmax†					
Blocks (R)	2	*	NS‡	**	**	**	NS
Wear (W)	2	**	**	**	**	**	**
Error (a) (RW)	4						
Treatment (T)	11	**	**	**	**	**	**
Error (b) (RT)	22						
WT	22	NS	NS	**	*	**	**
Error (c) (RWT)	44						
		Soil bulk density					
		g cc^{-1}					
Blocks (R)	2	NS	*	NS	NS	**	NS
Wear (W)	2	**	**	**	**	**	**
Error (a) (RW)	4						
Treatment (T)	11	**	**	**	**	**	**
Error (b) (RT)	22						
WT	22	NS	NS	NS	NS	NS	NS
Error (c) (RWT)	44						
		Soil water content					
		m^3 m^{-3}					
Blocks (R)	2	**	**	NS	*	NS	**
Wear (W)	2	NS	NS	**	**	**	**
Error (a) (RW)	4						
Treatment (T)	11	**	**	**	**	**	**
Error (b) (RT)	22						
WT	22	NS	NS	NS	NS	NS	NS
Error (c) (RWT)	44						
		Turfgrass density§					
Blocks (R)	2	NS	NS	NS	NS	NS	NS
Wear (W)	2	**	**	**	**	**	**
Error (a) (RW)	4						
Treatment (T)	11	**	**	**	**	**	**
Error (b) (RT)	22						
WT	22	*	**	**	**	NS	NS
Error (c) (RWT)	44						

* Significant at the 0.05 level.
** Significant at the 0.01 level.
† Gmax, the ratio of maximum negative acceleration on impact in units of gravities to the acceleration due to gravity.
‡ NS = not significant.
§ Visual estimate of number of tillers per unit area on a 0 to 5 scale. Zero represents bare ground and five represents maximum turfgrass density considering species and mowing height.

Table 4. Mean surface hardness, soil bulk density, soil water content, and turfgrass density values for wear levels.

Wear level	1996 18 June	1996 23 Aug.	1996 18 Oct.	1997 11 June	1997 19 Aug.	1997 15 Oct.
	Surface hardness					
	Gmax†					
No wear	57.5	59.2	63.9	53.9	57.6	61.7
Medium wear	60.0	63.3	68.6	57.5	62.4	67.3
High wear	61.3	62.6	67.2	58.8	64.2	70.5
LSD0.05	1.3	1.7	1.5	1.2	1.3	1.8
	Soil bulk density					
	g cc^{-1}					
No wear	1.39	1.39	1.40	1.35	1.38	1.37
Medium wear	1.41	1.42	1.44	1.37	1.40	1.41
High wear	1.42	1.44	1.47	1.41	1.46	1.47
LSD0.05	0.01	0.01	0.01	0.01	0.01	0.01
	Soil water content					
	m^3 m^{-3}					
No wear	0.133	0.130	0.122	0.140	0.120	0.129
Medium wear	0.133	0.130	0.115	0.157	0.143	0.142
High wear	0.135	0.126	0.107	0.133	0.120	0.113
LSD0.05	NS	NS	0.006	0.006	0.008	0.008
	Turfgrass Density‡					
No wear	4.9	4.9	5.0	5.0	5.0	5.0
Medium wear	4.2	3.5	3.2	4.9	3.4	3.4
High wear	3.8	2.5	2.2	4.7	2.5	2.4
LSD0.05	0.1	0.1	0.1	0.1	0.1	0.1

† Gmax, the ratio of maximum negative acceleration on impact in units of gravities to the acceleration due to gravity.
‡ Visual estimate of number of tillers per unit area on a 0 to 5 scale. Zero represents bare ground and five represents maximum turfgrass density considering species and mowing height.

Table 5. Mean surface hardness, soil bulk density, and soil water content values for treatments across all wear levels.

Treatment		1996			1997		
Reinforcing material	Rate	18 June	23 Aug.	18 Oct.	11 June	19 Aug.	15 Oct.
	$g\ kg^{-1}$	Surface hardness					
		Gmax†					
Control	—	54.8	58.2	62.1	54.2	58.1	65.0
DuPont Shredded Carpet	5	58.1	58.1	63.4	54.1	57.7	62.4
DuPont Shredded Carpet	10	54.7	56.0	59.9	51.4	55.2	59.9
DuPont Shredded Carpet	20	53.0	54.5	57.9	50.0	54.4	58.1
DuPont Shredded Carpet	30	50.0	50.7	56.2	48.9	53.3	56.6
Netlon	3	65.2	68.8	70.0	60.5	65.0	70.2
Netlon	5	72.6	71.9	77.4	65.4	66.4	74.5
Nike Lights	30	46.6	48.3	56.3	48.0	51.8	56.7
Nike Heavies	30	52.1	55.8	61.4	51.7	57.0	62.9
Sportgrass	—	70.3	75.4	83.6	70.1	79.6	85.9
Turfgrids	3	65.6	67.9	71.3	61.3	66.6	70.7
Turfgrids	5	72.1	75.0	79.3	65.2	71.9	75.0
LSD0.05		2.6	3.3	3.1	2.4	2.6	3.6
		Soil bulk density					
		$g\ cc^{-1}$					
Control	—	1.42	1.41	1.45	1.39	1.43	1.45
DuPont Shredded Carpet	5	1.43	1.46	1.46	1.39	1.42	1.43
DuPont Shredded Carpet	10	1.40	1.41	1.43	1.37	1.39	1.40
DuPont Shredded Carpet	20	1.39	1.41	1.42	1.35	1.39	1.38
DuPont Shredded Carpet	30	1.36	1.37	1.40	1.35	1.37	1.37
Netlon	3	1.43	1.42	1.46	1.39	1.43	1.44
Netlon	5	1.45	1.47	1.47	1.42	1.46	1.46
Nike Lights	30	1.37	1.40	1.42	1.34	1.40	1.39
Nike Heavies	30	1.40	1.39	1.42	1.35	1.39	1.41
Sportgrass	—	1.42	1.42	1.45	1.38	1.44	1.44
Turfgrids	3	1.42	1.42	1.44	1.39	1.42	1.40
Turfgrids	5	1.43	1.45	1.45	1.39	1.43	1.42
LSD0.05		0.02	0.03	0.02	0.02	0.03	0.02
		Soil water content					
		$m\ m^{-3}$					
Control	—	0.140	0.139	0.113	0.147	0.135	0.118
DuPont Shredded Carpet	5	0.144	0.126	0.114	0.143	0.135	0.138
DuPont Shredded Carpet	10	0.136	0.135	0.128	0.156	0.143	0.140
DuPont Shredded Carpet	20	0.129	0.130	0.118	0.145	0.129	0.143
DuPont Shredded Carpet	30	0.131	0.123	0.117	0.136	0.129	0.131
Netlon	3	0.143	0.144	0.123	0.153	0.131	0.126
Netlon	5	0.138	0.124	0.110	0.131	0.125	0.121
Nike Lights	30	0.130	0.106	0.097	0.132	0.109	0.118
Nike Heavies	30	0.130	0.130	0.114	0.151	0.126	0.114
Sportgrass	—	0.118	0.117	0.098	0.135	0.104	0.100
Turfgrids	3	0.146	0.146	0.131	0.151	0.139	0.153
Turfgrids	5	0.129	0.124	0.112	0.139	0.123	0.134
LSD0.05		0.006	0.013	0.013	0.014	0.016	0.017
		Turfgrass density‡					
Control	—	4.3	3.6	3.5	4.8	3.4	3.3
DuPont Shredded Carpet	5	4.4	3.8	3.6	5.0	3.5	3.7
DuPont Shredded Carpet	10	4.4	3.6	3.4	4.9	3.7	3.6
DuPont Shredded Carpet	20	4.3	3.7	3.6	5.0	3.8	3.7
DuPont Shredded Carpet	30	4.4	3.7	3.6	4.9	3.7	3.6
Netlon	3	4.2	3.6	3.3	4.7	3.6	3.5
Netlon	5	4.3	3.6	3.4	4.9	3.5	3.6
Nike Lights	30	4.7	4.0	3.7	5.0	3.7	3.8
Nike Heavies	30	4.8	3.9	3.6	5.0	3.9	3.9
Sportgrass	—	3.8	3.3	3.2	4.7	3.4	3.3
Turfgrids	3	4.1	3.5	3.3	4.8	3.6	3.6
Turfgrids	5	4.2	3.4	3.4	4.7	3.5	3.6
LSD0.05		0.3	0.2	0.2	0.2	0.3	0.3

† Gmax, the ratio of maximum negative acceleration on impact in units of gravities to the acceleration due to gravity.

‡ Visual estimate of number of tillers per unit area on a 0 to 5 scale. Zero represents bare ground and five represents maximum turfgrass density considering species and mowing height.

dates in this study (Table 3). Bulk density increased with increasing wear levels in 1996 and 1997 (Table 4). Also, soil bulk density generally increased for all wear levels as each growing season progressed. Soil bulk density values ranged from a low of 1.35 $g\ cc^{-1}$ for the no-wear treatment on 11 June 1997 to 1.47 $g\ cc^{-1}$ for the high-wear treatment on 15 Oct. 1997.

Increases in bulk density on no-wear plots were presumably due to routine maintenance and foot traffic during data collection. The drop in bulk densities for all treatments between 18 Oct. 1996 to 11 June 1997 was likely due to freeze-thaw cycles during the winter months.

Soil bulk density values averaged across wear levels revealed differences among the reinforcing material treatments (Table 5). The range of bulk density values among reinforcing material treatments was similar to the range for wear treatments (1.34 $g\ cc^{-1}$ for Nike Lights 30 $g\ kg^{-1}$ on 11 June 1997 to 1.47 $g\ cc^{-1}$ for Netlon 5 $g\ kg^{-1}$ on 18 Oct. 1996).

Table 6. Turfgrass soil surface hardness values for the treatment × wear interaction in Exp. 1.

Treatment				
Reinforcing material	Rate	No wear	Medium wear	High wear
	g kg^{-1}	Gmax		
		18 Oct. 1996		
Control	—	59.3	65.8	61.3
DuPont Shredded Carpet	5	64.0	64.1	62.1
DuPont Shredded Carpet	10	59.6	59.4	60.7
DuPont Shredded Carpet	20	56.9	58.3	58.4
DuPont Shredded Carpet	30	54.6	59.1	54.9
Netlon	3	69.6	71.6	68.9
Netlon	5	69.9	80.7	81.5
Nike Lights	30	54.8	58.9	55.1
Nike Heavies	30	59.9	62.1	62.3
Sportgrass	—	74.4	87.5	89.1
Turfgrids	3	67.5	73.2	73.1
Turfgrids	5	75.9	82.1	80.0
LSD0.05		5.4	5.4	5.4
		11 June 1997		
Control	—	51.9	56.1	54.7
DuPont Shredded Carpet	5	53.1	54.6	54.7
DuPont Shredded Carpet	10	49.6	52.3	52.3
DuPont Shredded Carpet	20	47.9	50.7	51.4
DuPont Shredded Carpet	30	48.3	49.6	48.7
Netlon	3	57.9	60.9	62.7
Netlon	5	62.0	64.6	69.5
Nike Lights	30	46.2	49.5	48.3
Nike Heavies	30	48.6	51.6	54.8
Sportgrass	—	61.9	72.2	76.2
Turfgrids	3	57.6	62.0	64.3
Turfgrids	5	61.4	65.9	68.2
LSD0.05		4.2	4.2	4.2
		19 Aug. 1997		
Control	—	54.2	58.5	61.5
DuPont Shredded Carpet	5	55.4	58.7	59.1
DuPont Shredded Carpet	10	52.9	56.3	56.3
DuPont Shredded Carpet	20	52.0	55.4	55.8
DuPont Shredded Carpet	30	51.4	56.3	52.1
Netlon	3	60.5	66.7	67.8
Netlon	5	65.2	65.9	68.1
Nike Lights	30	50.3	52.4	52.8
Nike Heavies	30	53.7	57.1	60.3
Sportgrass	—	66.5	83.3	89.2
Turfgrids	3	61.6	67.1	71.0
Turfgrids	5	67.3	71.4	76.9
LSD0.05		4.6	4.6	4.6
		15 Oct. 1997		
Control	—	62.8	65.2	67.1
DuPont Shredded Carpet	5	58.7	63.1	65.5
DuPont Shredded Carpet	10	55.9	61.3	62.4
DuPont Shredded Carpet	20	55.3	58.6	60.4
DuPont Shredded Carpet	30	54.6	57.3	58.1
Netlon	3	63.6	71.5	75.6
Netlon	5	68.0	76.6	79.1
Nike Lights	30	55.4	56.8	57.9
Nike Heavies	30	60.0	62.2	66.3
Sportgrass	—	70.9	89.2	97.7
Turfgrids	3	65.2	71.5	75.4
Turfgrids	5	69.6	74.9	80.7
LSD0.05		4.6	4.6	4.6

The 5 g kg^{-1} Netlon treatment produced higher bulk density values than the control plots on five of six rating dates. This treatment generally produced higher bulk density values than Sportgrass; the 10, 20, and 30 g kg^{-1} rates of DuPont Shredded Carpet; Nike Lights and Heavies; and the 3 g kg^{-1} rate of Turfgrids. The 3 g kg^{-1} Netlon treatment and 3 g kg^{-1} Turfgrids treatment typically did not influence bulk density relative to the control.

The 10, 20, and 30 g kg^{-1} rates of DuPont Shredded Carpet lowered soil bulk density relative to the control on five of six rating dates. The 5 g kg^{-1} rate of shredded carpet had no affect on soil bulk density on four of six rating dates. This treatment resulted in a soil bulk density that was higher than the control on 23 Aug. 1996 and lower than the control on 15 Oct. 1997. As with surface hardness, bulk density generally decreased with increasing rates of DuPont Shredded Carpet. Nike Lights and Nike Heavies treatments also lowered bulk densities relative to the control on five of six rating dates.

Soil Water Content

No reinforcing material treatment × wear interactions occurred in this study with respect to soil water

Table 7. Correlation coefficients ($n = 216$) between surface hardness, soil bulk density, and turfgrass density during two growing seasons.

	Soil bulk density	Soil water	Turfgrass density
Surface hardness	**0.63****	**−0.34****	**−0.44****
Soil bulk density	—	**−0.60****	**−0.67****
Soil water		—	**0.33****

** Significant at the 0.01 level.

content (Table 3). Differences in soil water content were found among wear levels on four of six rating dates (Table 4). When differences occurred, water contents were higher in no-wear and medium-wear treatments than in high-wear treatments. However, the differences were slight, with an overall variation of only 0.05 m m^{-3} across the duration of the study.

Soil water contents differed among reinforcing material treatments during both years of the study (Table 5). Nike Lights 30 g kg^{-1} and Sportgrass had lower soil water contents than the control on five of six rating dates. No other reinforcing material treatment had a soil water content lower than the control on more than two of the six rating dates. The only treatments which measured higher in soil water content than the control were Turfgrids 3 g kg^{-1} on three rating dates and all four rates of DuPont Shredded Carpet on one or two rating dates. The range in water contents during both years of the study was <0.06 g kg^{-1}.

Turfgrass Density

Significant treatment differences for turfgrass density were found on each rating date (Table 3). Means of turfgrass density ratings show that high-wear treatments resulted in the lowest turfgrass density, no-wear treatments had the highest density, and medium-wear treatments produced density intermediate between no-wear and high-wear treatments (Table 4). The data also show that turfgrass density generally decreased as each season progressed for medium- and high-wear treatments, but that no-wear treatment showed little change in turfgrass density during the seasons. Turf in medium- and high-wear treatments showed nearly complete recovery with respect to density between the end of the 1996 season and the first rating date in 1997.

Turfgrass density ratings differed among reinforcing material treatments during both years of this study (Table 5). Differences were slight on most rating dates and never exceeded one whole unit on any date during the test. The Sportgrass treatment showed lower turfgrass density than the control on all three rating dates in 1996, but did not differ from the control plots in 1997. Turfgrids 3 and 5 g kg^{-1} were the only other treatments that had turfgrass density ratings lower than the control, and this occurred on two rating dates for each treatment.

Nike Lights and Heavies provided higher turfgrass density than the control on six and five rating dates, respectively. Most of the other treatments were not different or were slightly higher in density than controls on one to three rating dates.

Reinforcing material treatment × wear interactions were significant for turfgrass density on four rating dates (Table 3). While these interactions were statistically significant, the differences among treatments and wear levels with respect to turfgrass density were small and of little practical significance.

Correlations

Correlation coefficients were significant ($P = 0.01$) between all variables examined in this study (Table 7). The strongest correlations were between soil bulk density and surface hardness ($r = 0.63$) and between soil bulk density and turfgrass density ($r = -0.67$). Another strong correlation was between soil bulk density and soil water content ($r = -0.60$).

DISCUSSION

Reinforcing materials used in this study had varying effects on surface hardness, bulk density, and water content of a sand root zone. They also influenced turfgrass density, but to a minor degree. Effects were dependent on the type and rate of reinforcing material, as well as the amount of wear imposed on the treatment. Reinforcing material treatments that lowered soil bulk density generally lowered surface hardness and treatments that increased or did not affect bulk density generally resulted in increased surface hardness compared with nonamended controls. As wear levels increased, the treatments that lowered soil bulk density usually showed smaller increases in surface hardness than the other treatments.

Surface hardness was affected to a much greater degree by bulk density than by water content. These findings agree with those of Baker (1991), where soil water content had little effect on surface hardness of sand-dominated root zones. For mixes where soil was the dominant mix component, soil water content was the major factor controlling surface hardness (Baker, 1991).

The DuPont Shredded Carpet treatments either lowered or had no effect on soil bulk density and surface hardness when compared with the control and some other reinforcing material treatments. Increasing the rate of DuPont Shredded Carpet from 5 to 30 g kg^{-1} played a strong role in lowering bulk density and surface hardness of the sand root zone. The highest rate (30 g kg^{-1}) of this fibrous, low-density product presumably diluted the density of heavier soil particles, thereby decreasing the overall bulk density of the soil/shredded carpet mix. Despite lowering the bulk density of the sand root zone, the 30 g kg^{-1} rate of DuPont Shredded Carpet did not greatly reduce soil water content. The benefits of shredded carpet may be limited to sandy soils, since McNitt and Landschoot (2001a) found that the 30 g kg^{-1} rate of DuPont Shredded Carpet had no pronounced effect on soil bulk density or surface hardness in a silt loam soil.

The Nike Lights (30 g kg^{-1}) treatment consistently lowered surface hardness and bulk density compared with the control and some other reinforcing material treatments. Nike Lights consist primarily of nylon, polyester, cotton, and polychloroprene remnants from the upper portions of athletic shoes. The fibrous, low-density properties of this amendment apparently reduced the density of the sand root zone in a manner similar to the 30 g kg^{-1} rate of DuPont Shredded Carpet. Nike Lights lowered soil water content relative to the control on more dates than the DuPont Shredded Carpet, but the actual differences between treatments were of little practical significance.

The Nike Heavies treatment decreased surface hardness and bulk density compared with the control on some occasions, but it was not as consistent in these respects as Nike Lights. The varying effects on surface hardness and bulk density between the two Nike products may be due to density differences between the products. The compressed densities of Nike Lights and Nike Heavies were 0.107 g cc^{-1} and 0.244 g cc^{-1}, respectively. The higher density of Nike Heavies was probably due to the predominance of polyurethane and rubber constituents in the product.

Both rates of Netlon and Turfgrids consistently increased surface hardness of the sand root zone mix when compared with the unamended control and some other treatments. Surface hardness increased to a greater extent under high-wear treatments with the Turfgrids and Netlon treatments compared with the control, DuPont Shredded Carpet treatments, and Nike Lights and Heavies treatments. The results for the Netlon treatments agree with those of Canaway (1994), who reported increased surface hardness with mesh elements after wear was applied. Other than the 5 g kg^{-1} rate of Netlon, the Netlon and Turfgrids treatments had little influence on soil bulk density and in most cases, both rates of Netlon and Turfgrids had little effect on soil water content.

The increase in surface hardness resulting from the 3 g kg^{-1} rate of Netlon and both rates of Turfgrids does not appear to be related to an increase in soil bulk density. Instead, the surface hardness increase may be due to an increase in soil strength caused by these reinforcement treatments. Waddington (1992) stated that soil strength reflects the soil's ability to resist or endure an applied force and that low soil strength allows deformation, whereas high soil strength may be too hard and thus affect the safety of the playing surface. Fibrous soil reinforcing materials have been shown to increase soil strength and reduce soil deformation under loads (Gray and Ohashi, 1983; McGown et al., 1985). Mercer et al. (1984) reported increased soil strength without a corresponding increase in soil bulk density for a mesh reinforcing material treatment very similar to Netlon.

The Sportgrass treatment produced the highest surface hardness of any treatment in this test. Surface hardness for this treatment increased substantially as wear level increased and as each season progressed. Surface hardness did not appear to be related to soil bulk density, as there were no differences in bulk density between the Sportgrass treatment and the control.

The increased surface hardness of the Sportgrass treatment may have been the result of an increase in soil strength near the root zone surface. Horizontally-oriented fabrics at or near the soil surface have dramatically increased soil strength and load carrying capacity (Gray and Al-Refeai, 1986). Increased soil surface strength typically results in a higher surface hardness (Waddington, 1992).

The Sportgrass treatment showed a consistent reduction in soil water content compared with the control throughout the study. Dryer soil conditions produced by Sportgrass may have resulted in slightly higher surface hardness. However, the moisture differences between the Sportgrass treatment and the control were only 0.02 to 0.03 m m^{-3}, and probably not enough to account for the large differences in surface hardness.

CONCLUSIONS

Overall, the greatest impact of reinforcing materials subjected to different wear levels in a sand root zone was on surface hardness. This is potentially significant because increased surface hardness of an athletic field results in a greater risk of athlete injury in the event of a fall (Baker and Canaway, 1993). Conclusions and recommendations based on surface hardness data from the present study are difficult to formulate because no recognized standards currently exist for acceptable surface hardness values of athletic fields as measured by the Clegg Impact Tester. In an attempt to relate surface hardness to athlete performance and safety, Canaway et al. (1990) correlated athletic field surface hardness measurements with athlete's perceptions of surface hardness. On the basis of hardness values obtained with the Clegg Impact Tester and a 0.5-kg missle, Canaway et al. (1990) suggested a preferred upper limit of 80 Gmax. A 2.25-kg missile was used in the present study and has been shown to produce lower Gmax values compared with the 0.5-kg missile (Rogers and Waddington, 1990). Rogers and Waddington (1990) reported that the 0.5-kg missile will typically record Gmax values that are 24 to 50 units higher than values produced by the 2.25-kg missile. Using this comparison, Sportgrass, Netlon 5 g kg^{-1}, and Turfgrids 5 g kg^{-1} reinforcing material treatments resulted in hardness values that were probably greater than the preferred upper limit suggested by Canaway et al. (1990).

Athletic field managers considering the use of soil reinforcing materials should be aware that if a field is exposed to high wear, Netlon and Turfgrids at the 5 g kg^{-1} rate and Sportgrass have the potential to exceed the preferred upper surface hardness limit suggested by Canaway et al. (1990). The high rates of DuPont Shredded Carpet and Nike Lights consistently resulted in surface hardness values lower than the control, even under high wear, and may be less likely to result in athlete injury during player/surface impacts.

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