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A NEW APPARATUS TO SIMULATE ATHLETIC FIELD
TRAFFIC AND AN EVALUATION AND COMPARISON OF
NATURALLY AND ARTIFICIALLY ENHANCED SAND
TEXTURED ATHLETIC FIELD ROOT ZONES

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of the requirements for the

Doctoral degree in Crop and Soil Sciences

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Date

A NEW APPARATUS TO SIMULATE ATHLETIC FIELD TRAFFIC AND AN EVALUATION AND COMPARISON OF NATURALLY AND ARTIFICIALLY ENHANCED SAND TEXTURED ATHLETIC FIELD ROOT ZONES

By

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ABSTRACT

A NEW APPARATUS TO SIMULATE ATHLETIC FIELD TRAFFIC AND AN EVALUATION AND COMPARISON OF NATURALLY AND ARTIFICIALLY ENHANCED SAND TEXTURED ATHLETIC FIELD ROOT ZONES

By

Jason Jeffrey Henderson

This work was comprised of two studies. The Cady Traffic Simulator (CTS) (a modified walk behind core cultivation unit) was developed to more aggressively simulate athletic field traffic and was utilized to evaluate fifteen athletic field systems. The objective of the first study was to compare the magnitude and direction of the forces produced by two traffic simulators; the Brinkman Traffic Simulator (BTS), the simulator currently most widely used in research, and the CTS. Both simulators were operated over an in-ground force plate which measured the forces in three directions; front to back, side to side, and vertical. The CTS produced higher compressive stress and higher net shear stress when operated in either the forward or reverse direction.

The objective of the second study was to compare artificially enhanced, sand root zones to well-graded sand and to sand-soil mixes under simulated traffic over a three-year period. Sand-soil mixes containing 9% and 15% silt+clay increased soil bearing capacity more consistently than artificial inclusions, but also showed the greatest decrease in infiltration rates over two traffic seasons. The sand-soil mix containing 15% silt+clay had the poorest wear tolerance, while

artificial inclusions had minimal effects on wear tolerance during both traffic seasons.

Dedicated to Wayne W. Henderson and Harvey E. Reeser, my grandfathers, in loving memory.

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Many people contributed to the completion of this dissertation. I would like to thank my guidance committee; Dr. Rogers, Dr. Crum, Dr. Knezek, and Dr. Wolff. Each of you has a wealth of knowledge and is well respected in each of your respective disciplines, but that is not what makes you great professors. Your ability to teach, ability to apply your knowledge in the field, and your genuine interest in mentoring are what set you apart. Thank you for an excellent graduate experience.

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LIST OF ABBREVIATIONS

BTS - Brinkman Traffic Simulator

CTS - Cady Traffic Simulator

CBR - California Bearing Ratio

INTRODUCTION

Subjecting research areas to simulated traffic is imperative when the objective is to contribute to information on the effects of traffic stress on turfgrasses and/or playing surfaces. Turfgrass traffic stresses can be separated into two major components; turfgrass wear and soil surface disruption (Beard 1973). Turfgrass wear can include tissue tearing, tissue bruising and tissue removal (ie. divoting), primarily horizontal forces. Soil surface disruption can include soil compaction (ie. increased soil bulk density) and rutting (ie. soil displacement), primarily vertical forces. Once traffic stresses are imposed on a turfgrass area the factors mentioned above have the ability to combine to yield a deterioration of playing surface quality.

Traffic simulation began in turfgrass research by applying traffic using automobiles and trucks to simulate aircraft traffic on research plots designed to test seed mixture suitability for airfields (Morrish and Harrison 1948). Perry (1958) described the first machine designed specifically to create traffic stress on turfgrass. Many traffic simulators have since been developed and used to create traffic stress on turfgrass areas for research purposes (Shearman et al. 1974, Canaway 1976, Cockerham and Brinkman 1989, Bonos et al. 2001, Carrow et al. 2001, Shearman et al. 2001). Successful simulated traffic should encompass the following; 1) Traffic should be uniform and reproducible. 2) Traffic should be similar to natural wear. 3) The rate of wear must be accelerated greatly over the natural rate of wear in order to keep the relative number of simulated passes to a minimum (Youngner 1961).

Previously developed traffic simulators have proven to induce uniform and reproducible traffic, but the traffic they produce is not similar to the natural wear that takes place on an athletic field (ie rolling drum compaction vs impact compaction) (primarily two dimensional). The Brinkman Traffic Simulator (BTS) is a drawn type traffic simulator that is used widely in the U.S. as an athletic field traffic simulator (Cockerham and Brinkman 1989). This machine utilizes differentially connected studded drums to create traffic stress over large plot areas very quickly, but it must be pulled over the plots.

A new traffic simulator (a modified self-propelled core cultivation unit) has been developed with the goal of producing a realistic pattern of wear typically generated between the hashmarks of a football field (Cockerham 1989). The Cady Traffic Simulator (CTS) has a "foot" attached to each of the four core heads. The feet alternately strike the ground as the machine moves over the turf surface producing dynamic forces in three directions. The CTS has shown to create approximately five times the wear that the BTS produces (Vanini et al. 2003).

Aggressive traffic simulation was necessary to evaluate and compare fifteen athletic field systems currently available on the market. Presently, many athletic fields are constructed with high sand content root zones. Sand root zones maintain macropores once compacted and drain rapidly. Sand has many advantages, but can become unstable under normal playing conditions. The vigorous wear produced on an athletic field often deforms the playing surface making it unsafe.

The stability concern of sand has sparked the development of several products to aid in sand and surface stabilization. These products are in the form of soil amendments, soil inclusions, and reinforced sod materials. Unfortunately, some products have been marketed very aggressively to team owners, universities and high schools without quality research to support their claims. Many newly constructed fields are not performing as promised. After installation, some of these systems have been removed due to rapid deterioration of playing surface quality.

In response to these concerns, a three-year study was initiated at Michigan State University to evaluate and compare fifteen athletic field systems under simulated athletic field traffic. The experiment had a single factor (amendments/Inclusions) with fifteen treatments. Traffic was applied as a strip treatment at two levels: daily, (5 traffic events per week) to simulate a practice field situation and weekly, (1 traffic event per week) to simulate a stadium situation. Treatments were evaluated in two major categories; root zone properties and playing surface characteristics. The root zone properties included: particle-size analysis, bearing capacity, infiltration, saturated hydraulic conductivity, and root mass by depth. Playing surface characteristics included: turfgrass cover, surface hardness, traction, and resistance to divoting. These data will enable team owners, universities, and high schools to make informed decisions when faced with the task of choosing the best field for their situation.

The objectives of this research were 1) to describe the Cady Traffic Simulator, 2) to compare the magnitude and directions of the forces produced by the Brinkman traffic simulator and the Cady traffic simulator, and 3) to use the Cady Traffic Simulator to study the effects of amendments, randomly oriented inclusions, specifically oriented inclusions, and reinforced sods on the playing surface characteristics of Kentucky bluegrass athletic fields.

Chapter 1

CADY TRAFFIC SIMULATOR: A NEW APPARATUS TO SIMULATE ATHLETIC FIELD TRAFFIC

ABSTRACT

Realistic traffic simulation is crucial to the validity of athletic field research. Previously developed athletic field traffic simulators contain studded drums that turn at different speeds creating shear forces at the playing surface. The Cady Traffic Simulator (CTS) (a modified walk behind core cultivation unit) has been recently developed at Michigan State University. The objective of this study was to compare the magnitude and direction of the forces produced by two traffic simulators; the Brinkman Traffic Simulator (BTS), a pull behind unit, and the Cady Traffic Simulator (CTS). Both simulators were operated over an in-ground force plate which measured the forces in three directions; front to back, side to side, and vertical. The CTS produced higher compressive forces and higher net shear forces when operated in either direction. The loading rate of the CTS was higher than the BTS, indicating that the CTS produced dynamic forces similar to that of pushing or running.

INTRODUCTION

The goal in using traffic simulation in athletic field research is to subject turfgrass areas to the conditions experienced by actual playing surfaces. Athletic fields are exposed to forces of varying magnitude and direction. These forces often exceed seven times the body weight of participants because of the actions performed on the playing surface (ie. starting, stopping, running, changing direction, blocking, tackling, etc.) (Canaway 1976) (Gatt et al. 1997). The majority of the wear produced on an athletic field is believed to be caused primarily by these dynamic forces.

Effective athletic field traffic simulators must exert forces necessary to induce soil compaction i.e., vertical and create forces necessary to cause tissue tearing i.e., horizontal. Traffic simulators currently used consist of two cleated or two smooth rollers differentially connected to turn at different speeds to create a shearing action at the playing surface while inducing a rolling type compaction (Canaway 1976, Cockerham and Brinkman 1989, Shearman et al. 2001). The Brinkman Traffic Simulator (BTS) has been described as a very useful research tool because it creates uniform, reproducible wear (Minner 1989). Cockerham and Brinkman 1989 originally estimated that 2 passes with the BTS were necessary to create the same number of cleat marks m^{-2} that one NFL game would produce between the hashmarks at the 40 yard line. However, turfgrass researchers have estimated that up to 15 passes were necessary to simulate the same amount of wear (Kurtz 1987). These rolling types of simulators create both a vertical and horizontal force component, but do not closely simulate the highly variable forces produced at the playing surface during athletic competition. A simulator that produces dynamic forces at the playing surface which are more representative of competing athletes is needed.

A traffic simulator (a modified walk behind core cultivation unit) has been developed with the goal of producing a realistic pattern of wear typically generated between the hashmarks of a football field (Cockerham 1989). The Cady traffic simulator has a "foot" attached to each of the four core heads. The feet alternately strike the ground as the machine moves over the turf surface producing dynamic forces in three directions.

The machine can be operated in two directions; forward and reverse. Operating height can affect the severity of wear, which is adjusted using a metal spacer system on the hydraulic cylinder of the unit. Preliminary tests have indicated an optimal spacer height of 5.1 cm when operating in the forward direction and 8.3 cm when operating in the reverse direction (Henderson et al. 2002).

Both simulators produce a similar number of cleat marks per unit area, but create different levels of wear given the same number of passes. The BTS was designed to create the same number of cleat marks per square meter in two passes (603 cleat marks m^{-2}) that one NFL football game would create between the hashmarks, at the forty yard line (Cockerham and Brinkman 1989). The forward and reverse passes of the CTS combine to create 667 cleat marks m^{-2} and has been shown to create more wear than the BTS (Calhoun et al. 2002).

The objectives of this technical note were 1) to describe the Cady Traffic Simulator, and 2) to quantify the magnitude and direction of forces produced by the Brinkman Traffic Simulator (Figure 1) and the Cady Traffic Simulator (Figure 2).

MATERIALS & METHODS

A greens core cultivation unit (Jacobsen, Charlotte, NC, AERO KING 30, Model 82561) was modified in three ways to create a traffic simulator (Figure 3). *1) Metal spacer system*: the addition of hydraulic cylinder spacers enabled well-graded sand of the operating height (Figure 3A*)*. *2) Crank arm adjustment*: moving the pin from the lower arm crank arm hole to upper crank arm hole creates more lateral motion when the feet hit the ground (Figure 3B). *3) Simulated cleated feet*: tine holders were removed and replaced with "feet" constructed from a section of tire. Each looped tire section has seven cleats fastened to the bottom (Figure 3C). Figure 4 shows a detailed drawing of the foot construction.

The forces exerted on the ground by the BTS and CTS were measured using an in-ground force platform (LG6-4-8000, Advanced Mechanical Technology, Inc., Watertown, MA) located at the McPhail Equine Performance Center, Michigan State University, East Lansing, Michigan. The force plate dimensions were 61 cm by 123 cm. The surface of the plate was protected by a 1.3 cm thick rubber mat which was adhered solidly to the plate. The force plate was capable of measuring applied forces in three dimensions as well as the three corresponding moments of force. The bit resolution of the force was 12 N in the vertical direction and 3 N in both horizontal directions. Images in this dissertation are presented in color.

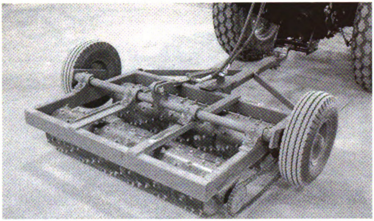


Figure 1. Overall view of the Brinkman traffic simulator.

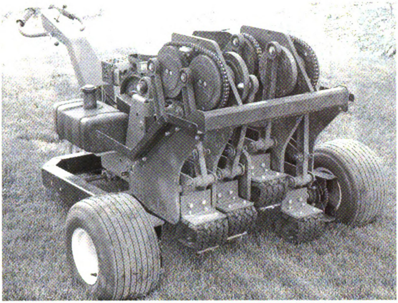


Figure 2. Overall view of the Cady Traffic Simulator.

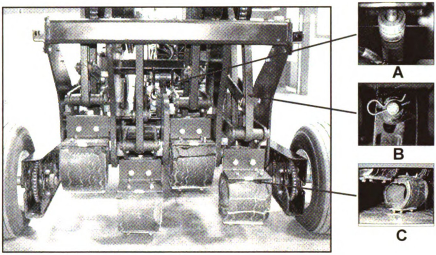


Figure 3. Modifiations made to the self-propelled aerifier A) Metal spacer system. B) Crank arm adjustment. C) Simulated cleated foot.

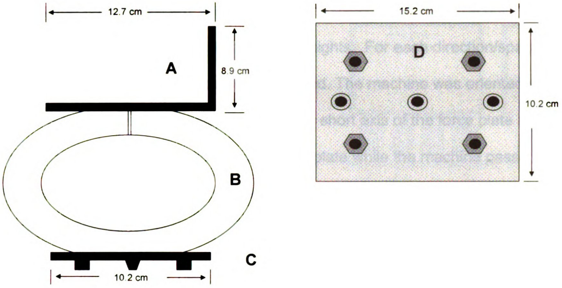


Figure 4. Cady Traffic Simulator "foot" construction. **A**) Angle iron (9.5 mm thick, 15.2 cm wide) fastened to piece of tire using four 8.0 mm carriage bolts and stop nuts **B**) Piece of tire (45.7 cm) looped with tread side out (preferably 8-ply, load range D) **C**) Steel plate fastened to piece of tire using four 8.0 mm carriage bolts and stop nuts. **D**) Bottom view of steel plate, showing four carriage bolts with stop nuts and three screw-in cleats.

To test the CTS (680.0 kg), the machine was passed over the force plate in both operating directions at the optimal spacer heights. For each direction/spacer height combination, five trials were conducted. The machine was oriented such that the direction of travel was parallel to the short axis of the force plate and all four feet struck within the boundaries of the plate while the machine passed over it. To insure that only the feet struck the force plate during the trials, 1.9 cm plywood was placed on both sides of the force plate to support the tires of the machine above the platform.

Before testing the BTS, both drums were completely filled with water to ensure maximum force production. To test the BTS (571.5 kg), the machine was pulled over the force plate using a tractor. The traffic simulator was oriented such that the direction of travel was parallel to the short axis of the force plate so that both rollers struck within the boundaries of the plate. Five trials were collected.

For each trial, each machine was started 30 to 40 cm from the edge of the plate, allowed to cross the entire width of the plate, and stopped 30 to 40 cm past the opposite edge of the plate. Force data were collected through the entire trial. Figure 5 provides a schematic of the direction of travel for each machine tested and the relative direction of forces measured.

RESULTS & DISCUSSION

The ground reaction force analysis showed significant force production by each machine in three directions: 1) vertical, 2) front to back, and 3) side to side. For ease of comparison, the front to back forces and the side to side forces

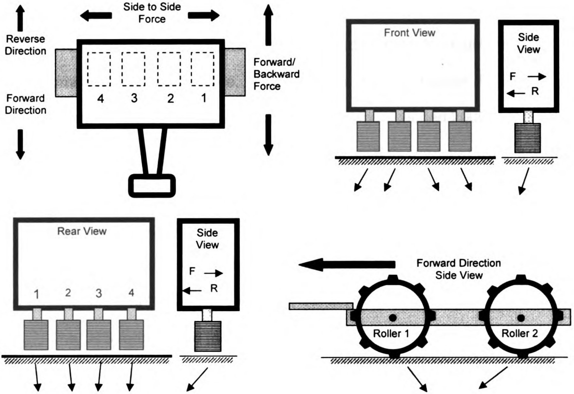


Figure 5. Direction of travel and relative direction of forces measured for the Brinkman Traffic Simulator and the Cady Traffic Simulator. A) Top view of the Cady Traffic simulator. The directions of travel are shown along with the directions of the measured forces. B) Direction of forces for the various feet when operated in the forward direction. C) Direction of the forces of the various feet when operated in the reverse direction. D) Side view of the Brinkman traffic simulator showing the directions of the front/back forces applied by the rollers.

were combined, using Pythagorean Theorem($c^2 = a^2 + b^2$), for each machine and termed Net Shear Force. The vertical force component of each machine has been termed Compressive Force. The Brinkman Traffic Simulator (BTS) produced significant compressive forces. Each drum exceeded 2000 N (Table 1). The direction of the net shear force in the front drum was rearward while it was forward in the rear drum (Figure 5). The rear roller created a substantial net shear force exceeding 1700 N at an angle close to the optimal angle of 45 degrees for pushing (ie. Blocking), this explains why this apparatus has been a useful research tool for several years.

The CTS forces were measured in both the forward and reverse operating directions. The peak values per foot were averaged over the four feet of the CTS. Operated in the forward direction, the four feet produced an average compressive force over 5 times greater than when operated in the reverse direction (Table 1). The forward direction also produced more variable forces than the reverse direction. Operating in the reverse direction, the magnitude of the forces dropped significantly, but created the greatest angle on impact (Table 1). Given the large compressive force created in the forward direction and the high angle of impact induced operating in the reverse direction, it was determined that operating the CTS once in reverse and once forward over an area would combine to produce the desired wear effects of tearing (reverse) and compaction (forward).

Comparing the total load production of each machine describes the overall capability of each machine, but examining multiple load characteristics of each

Table 1. Average peak ground reaction forces and stresses recorded for the Cady Traffic Simulator and the Brinkman Traffic Simulator.

Machine	Force (N)†		Stress (MPa)‡		Angle from vertical§ (deg)	Speed $m\ s^{-1}$
	Compressive	Net Shear¶	Compressive	Net Shear#		
Cady, Forward Direction††	5899 (1283)§§	1613 (873)	43.53 (9.47)	11.91 (6.44)	22.0 (11.3)	0.30 (0.013)
Cady, Reverse Direction‡‡	1041 (44)	454 (50)	7.68 (0.33)	3.35 (0.37)	52.1 (2.9)	0.31 (0.013)
Brinkman, Front Drum	2831 (29)	1004 (78)	0.81 (0.01)	0.29 (0.02)	19.5 (1.4)	1.32 (0.007)
Brinkman, Rear Drum	2297 (47)	1711 (65)	0.66 (0.01)	0.49 (0.02)	36.7 (0.7)	1.32 (0.007)

† Force was measured in Newtons (N).

‡ Stress values were calculated using an individual cleat surface area of 193.5 mm^2 (7 cleats $foot^{-1}$ on the CTS and 18 cleats $drum^{-1}$ on the BTS) and were converted to Megapascals (MPa).

§ The angle of impact was measured from the vertical axis (normal to the force plate surface) in degrees.

¶ Front to back forces and side to side forces were combined using Pythagorean Theorem($c^2 = a^2 + b^2$), for each machine and termed Net Shear Force.

\# Front to back stresses and side to side stresses were combined using Pythagorean Theorem($c^2 = a^2 + b^2$), for each machine and termed Net Shear Stress.

†† Cady Traffic Simulator (CTS) was operated in nuetral at idle engine speed with the power take-off engaged enabling the feet to strike the ground creating forward movement.

‡‡ Cady Traffic Simulator (CTS) was operated in the reverse gear at idle engine speed with the power take-off engaged enabling the feet to strike the ground.

§§ Standard deviation of measurements recorded.

machine enables a more comprehensive means of comparison. Load characteristics such as total load, surface pressure, presence of shear stress and rate of application can highly influence compaction, a major component of wear production (Soane 1970). Each time a "foot" of the CTS hits the ground the total load is spread over a much smaller surface area compared to the BTS. Each foot of the CTS has a cleat surface area of 1354.9 mm^2 compared to the cleat surface area of each roller of the BTS contacting 3483.9 mm^2. The smaller surface area leads to a much larger force production per unit area for the CTS The CTS produced a higher compressive stress and net shear stress when operated in either direction than the BTS (Table 1). The average of the peak compressive stress produced by the feet of the CTS when operated in the forward direction was approximately 30 times higher than the combined compressive stresses of both drums of the BTS. The average of the peak net shear stress produced by the feet of the CTS when operated in the forward direction was approximately 15 times higher than the combined net shear stresses of both drums of the BTS.

The higher force production per unit area of the CTS explains why it has shown to be more destructive than the BTS. The CTS has been used in 2001 and 2002 at the Hancock Turfgrass Research Center, Michigan State University to simulate football traffic on research studies (Calhoun et al. 2002).

Chapter 2

AN EVALUATION AND COMPARISON OF NATURALLY AND ARTIFICIALLY ENHANCED ATHLETIC FIELD SAND TEXTURED ROOT ZONES

ABSTRACT

Many athletic fields are constructed with high sand content root zones. Sand root zones maintain macroporosity once compacted, but can develop problems due to their instability. Many inclusions have been developed to increase the strength, to limit deformation, and to increase the wear resistance of natural playing surfaces. Inclusions were compared to straight sand and sand-soil mixes under simulated traffic in this three year study. The objectives of this study were; 1) to compare the playing surface characteristics of these enhanced root zones under simulated traffic, 2) to monitor the changes in infiltration rates after each season of traffic, and 3) to evaluate the soil physical properties of each root zone and the inclusion effects on root zone strength. Sand-soil mixes containing greater than 9% silt+clay increased soil bearing capacity more consistently than artificial inclusions, but also had the greatest decrease in infiltration rates over the two traffic seasons. The sand-soil mix containing 15% silt+clay had the poorest wear tolerance, while artificial inclusions had minimal effects on wear tolerance during both traffic seasons.

INTRODUCTION

An athletic field should provide a safe, consistent playing surface that will maintain adequate traction, surface hardness, and turfgrass cover regardless of weather conditions. Athletic competitions ensue despite weather conditions, with the exception of lightning. Therefore, athletic fields must have the ability to rid the playing surface of water rapidly through surface drainage or infiltration and percolation.

Surface drainage and constituents of the root zone primarily well-graded sand water movement. The predominant root zone constituent used for athletic field construction is sand because its single-grained structure does not deteriorate with the advent of compactive forces, thus maintaining macroporosity and adequate drainage (Bingaman and Konke 1970). However, sand can cause problems due to its instability.

The greatest disadvantage of using sand to construct athletic field root zones is its poor stability. Stabilizing sand and retaining the macroporosity necessary for rapid water movement has proven to be very challenging. Options to stabilize sand-based athletic fields include: increasing particle-size distribution through sand/soil mixing, adding randomly oriented inclusions, placing specifically oriented inclusions at the playing surface and using reinforced sod to bypass stability concerns.

Sand-soil mixes have been investigated to improve the surface stability of athletic field root zones (Adams 1976, Waddington et al. 1974, Whitmyer and Blake 1989, Henderson 2000). Adding silt and clay to sand increases the stability of sand, but small additions of silt and clay to sand can reduce hydraulic conductivity very quickly (Adams 1976, Henderson 2000). The minimum infiltration rate and hydraulic conductivity value that is considered acceptable for playing surfaces vary throughout the literature. Waddington et al. 1974 recommended a minimum infiltration rate of 2.5 cm hr^{-1} for golf course putting greens, while Adams (1976) indicated a general agreement that athletic field hydraulic conductivity values should be between 1.5 – 7.5 cm hr^{-1}. Research conducted on sand-soil mixes indicates that silt+clay should not exceed 10% of the mix by weight to retain sufficient hydraulic conductivity values (Goss 1967, Adams 1976, Taylor and Blake 1979, Blake et al. 1981 and Henderson 2000). Research also indicates the importance of low water content of sand-soil mixes at compaction to maintain higher hydraulic conductivity values (Swartz and Kardos 1963, Akram and Kemper 1979, Henderson 2000).

Other athletic field stabilization methods include adding synthetic fibers into the sand root zone randomly, placing oriented synthetic fibers directly at the playing surface and using reinforced sod. Randomly oriented inclusions are mixed off-site with sand, specifically oriented inclusions are installed directly at the playing surface after turfgrass establishment, and reinforced sod is produced by establishing turfgrass into a thinly woven artificial turf.

Inclusions strengthen sands by spanning potential failure planes. Effective inclusions will span failure planes, have sufficient friction at the sand-inclusion interface to resist pullout and have a tensile strength greater than the shearing force (Gray and Ohashi 1983). Adding inclusions to sand can increase ultimate shear strength and limit the amount of vertical deformation (Gray and Ohashi 1983, McGown et al. 1978). Inclusions have also shown to improve the load bearing capacity and trafficability of sand (Webster 1979, Beard and Sifer 1993). A few field studies have been conducted to determine the potential benefits artificially enhanced sand root zones offer athletic fields (Adams and Gibbs 1989, Beard and Sifers 1993, Canaway 1994, McNitt and Landschoot 2001, McNitt and Landschoot 2003). Randomly oriented inclusions have shown to increase infiltration rates, reduce divot length and depth (Beard and Sifers 1993, Canaway 1994, McNitt and Landschoot 1998). However, randomly oriented inclusions can be difficult to work with during construction, restrict cultural practices on established turf, and can increase surface hardness (McNitt and Landschoot 1998, McNitt and Landschoot 2003). Specifically oriented inclusions have shown to increase wear tolerance and surface stabilization once turfgrass cover was diminished over the non stabilized well-graded sand (Adams and Gibbs 1989). McNitt and Landschoot (1998) investigated a reinforced sod product, Sportgrass™ , which reduced divot length and improved traction, but increased surface hardness.

Inorganic amendments such as porous ceramic clays and clinoptilolite zeolite products have also shown potential to improve the strength properties of sand indirectly. Sand root zones are highly dependent on roots for stability (Adams and Jones 1979, Adams et al. 1985, Waldron 1977). Inorganic amendments have been shown to increase root development (Ferguson et al. 1986).

Therefore any material added to sand to encourage root development would also help stabilize the playing surface.

Although comparative studies exist on athletic field stabilization systems, they are not fully inclusive of all the latest products currently available on the market. There is limited data on the randomly oriented inclusion, Ventway™, specifically oriented inclusions Grassmaster, and another reinforced sod, Motzgrass™. The artificial inclusions have also not been compared to sand-soil mixes and inorganic amendments in the same study. The objectives of this three-year study were as follows: 1) To compare the playing surface characteristics (traction, surface hardness, divoting resistance, and turfgrass cover) of these enhanced athletic field root zones under simulated traffic. 2) To monitor changes in infiltration rates after each season of simulated traffic. 3) To evaluate the soil physical properties of each field system and the inclusion/amendment effects on the strength of the root zone.

MATERIALS & METHODS

Materials Tested

The following materials were tested during this three-year field study. These root zone enhancements can be divided into 4 main categories; 1) Natural amendments, 2) Randomly-oriented artificial inclusions, 3) Specifically-oriented artificial inclusions, and 4) Reinforced sods. A brief description of each root zone material (Table 2) and artificial/natural enhancement are given below.

Sands and Natural amendments

1. Well-graded sand - Represents the material that is currently recommended to construct high sand content athletic field root zones.

2. Poorly-graded sand - Commonly known as TDS 2150.

3. Sand-Soil 1 - The well-graded sand and a loamy sand were mixed on a volume basis to yield a mix containing 7% silt+clay.

4. Sand-Soil 2 - The well-graded sand and a loamy sand were mixed on a volume basis to yield a mix containing 9% silt+clay.

5. Sand-Soil 3 - The well-graded sand and a loamy sand were mixed on a volume basis to yield a mix containing 15% silt+clay.

6. Bermudagrass - Common bermudagrass *'Cynodon dactylon* [L.] var. *dactylon'* was sprigged into a sand/soil mix containing 9% silt+clay. The Bermudagrass was overseeded with perennial ryegrass (Varieties: SR 4220, SR 4500, and Manhattan III) prior to the second traffic season on 20 August 2002 only.

7. Profile - manufactured from illite clay and amorphous silica to form a stable porous ceramic particle that was mixed with the well-graded sand sand on a volume basis (75% sand, 20% Profile, 5% Canadian sphagnum peat).

8. Zeopro - manufactured from clinoptilolite, a natural form of zeolite, and synthetic apatite to form granules that was mixed with the well-graded sand sand on a volume basis (80% sand, 10% Zeopro, 10% Canadian sphagnum peat).

Randomly-Oriented Inclusions

9. Turfgrids - fibrillated polypropylene fibers were mixed with the well-graded sand sand off-site as an inclusion on a weight basis (4 kg/m^3).

10. Ventway - cylindrically shaped rubber particles were mixed with the well-graded sand sand off-site as an inclusion on a volume basis (80% sand, 20% Ventway).

11. StrathAyr - Reflex mesh elements, 10 cm x 5 cm, polypropylene fibers were mixed off-site with a StrathAyr specified root zone (Table 2) at a rate of 6 kg/m^3. The mesh element/sand mixture was then applied in a 10 cm layer on top of the specified root zone using the PavAyr machine.

Specifically-oriented Inclusion

12. Grassmaster - polypropylene fibers were sewn vertically into an established turfgrass stand, root zone was comprised of the well-graded sand. The fibers are inserted on 2 cm centers and to a depth of 20 cm.

Reinforced Sods

13. Hummer Turftiles - root zone reinforced with shredded nylon carpet fiber to a 5.1 cm depth, which forms a 2.1m x 2.1m turfgrass tile. This product was installed as an established sod on top of the well-graded sand.

14. Motzgrass (TS-II) - polypropylene fibers are sewn into a backing comprised of biodegradable fibers and plastic mesh. The woven artificial fibers are then backfilled with sand and seeded. Product was installed as established sod on a Motz Group specified root zone (Table 2).

15. Sportgrass - polypropylene fibers sewn into a woven, synthetic backing. The woven artificial fibers are then backfilled with sand and seeded. Product was installed as established sod on top of the well-graded sand.

Construction and Maintenance

This three-year study began construction in March 2000 at the Hancock Turfgrass Research Center located on the Michigan State University campus, East Lansing, Michigan. Topsoil was excavated from the 45.7 m (150 ft) by 14.6 m (48 ft) plot area and 10.2 cm (4 in.) perforated drain tile was installed on 4.5 m (15 ft) centers. Gravel was spread over the drain tile and subsoil to an average depth of 10.2 cm (4in.) (Table 3). The experiment contained a single factor with 15 levels (treatments) arranged in a randomized complete block design with three replications. A series of walls were constructed from 1.3 cm (0.5 in.)

Table 2. Percent retained of root zone materials in which constituents were mixed on a volume basis. June 2000.

		Percent Retained†								
		Size class (mm)								
	OM‡	FG	VCoS	CS	MS	FS	VFS	Silt	Clay	Silt+Clay
Treatment	%	2.0	1.0	0.5	0.25	0.1	0.05	0.002	<0.002	<0.05
Well-graded sand§	0.21	1.4	13.7	26.0	42.5	14.1	0.4	1.0	0.9	1.9
Poorly graded sand	0.08	0.0	0.0	2.4	64.0	32.9	0.1	0.5	0.0	0.5
Sand-Soil1¶	0.45	1.5	13.0	22.4	38.5	15.9	1.7	3.9	3.1	7.0
Sand-Soil2	0.57	1.5	12.2	21.6	36.6	16.5	2.3	5.7	3.6	9.3
Sand-Soil3	0.91	1.1	10.2	18.9	33.5	17.5	3.7	10.6	4.4	15.0
Profile#	0.62	1.0	11.2	24.8	44.8	14.1	0.8	1.6	1.8	3.4
Zeopro††	0.55	0.5	9.6	25.0	43.4	17.8	0.8	2.0	0.9	2.9
StrathAyr	0.77	0.3	1.8	17.6	53.7	23.3	1.2	1.1	1.0	2.1
Motzgrass	1.09	0.0	0.4	43.8	38.7	13.6	1.5	0.9	1.1	2.0

† Indicates the percent by weight of soil particles in each size class. The size classes according to the United States Department of Agriculture (USDA) are as follows: fine gravel (FG), very coarse sand (VCoS), coarse sand (CS), medium sand (MS), fine sand (FS), very fine sand (VFS), silt and clay.

‡ Percent organic matter was determined by loss on ignition (Hummel 1993) .

§ Used as the base root zone material for all treatments except StrathAyr and Motzgrass.

¶ Well-graded sand was mixed on a volume basis with asandy loam soil to produce desired sand-soil mixes.

Profile is a porous ceramic product mixed with the well-graded sand on a volume basis (75% sand, 20% Profile, 5% Canadian Sphagnum peat)

†† ZeoPro is a manufactured from the naturally occurring mineral, clinoptilolite zeolite, mixed with the well-graded sand on a volume basis (80% sand, 10% Zeopro, 10% Canadian Sphagnum peat)

Table 3. Percent retained of gravel. June 2000.

Gravel	Percent Retained†						
	Size (mm)						
	>9.50	4.75	2.00	1.00	0.05	0.002	<0.002
Birds eye‡	0.0	1.1	36.3	35.6	23.1	2.0	1.8
StrathAyr§	0.0	13.3	74.1	10.9	0.7	1.0	0.0

† Indicates the percent by weight of soil particles in each size class.
‡ Birds eye gravel was placed under all treatments except StrathAyr.
§ Gravel that was installed under all StrathAyr treatments.

oriented strand board to keep root zones separated during installation of treatments. Each plot measured 3.1 m (10 ft) by 4.9 m (16 ft). Treatments were installed from 29 June to 26 July. Root zones were vibratory compacted in two layers and then leveled to a total depth of 25.4 cm (10 in.) (Table 2). Hummer, Motzgrass, and Sportgrass were sodded as their own product with separate Poa pratensis varieties. The remaining treatments were sodded with a blend of washed Poa pratensis (Varieties: Eclipse, Regent, Classic and 1757) obtained from The Manderley Corporation, Nepean, Ontario. The Bermudagrass treatment was sprigged 7 July with *Cynodon dactylon.* This Bermudagrass was originally investigated by Professor W.J Beal in the 1870's and was further studied by Dr. James Beard during his tenure at Michigan State University. This Bermudagrass has adapted to the cold of Michigan and survives the winter months. Plots were mowed three times per week at 3.2 cm (1.25 in.) using a Toro triplex reel mower and were irrigated with 2.5 cm (1 in.) per week or as needed to replace evapotranspiration. All treatments received the same amount of fertilizer (Table 4). On 10 May 2002, after the first traffic season (Fall 2001), all treatments were aerified in two directions using a Toro fairway aerifier, 1.9 cm hollow core tines, 5 cm spacing to a depth of 7.6 cm. On 16 May 2002, prior to the second traffic season, the sod from the daily trafficked portion of treatments was stripped. This portion of treatments was resodded on 22 May with washed Poa pratensis (Varieties: Midnight, Blacksburg, and Unique) purchased from Huggett Sod Farm Inc., Marlette, Michigan. This was done to investigate the effects of the root zone

Table 4. Annual fertilizer schedule for all treatments 2000, 2001, and 2002.

Year	Date	Fertilizer	g N m^{-2} application^{-1}		
			N	P_2O_5	K_2O
2000	17 July	13-25-12†	4.9	9.8	4.7
	31 July	26-0-26‡	4.9	0.0	4.9
	25 August	26-0-26	4.9	0.0	4.9
	5 October	13-25-12	2.4	4.6	2.2
	5 October	46-0-0§	2.4	0.0	0.0
	28 November	13-25-12	2.4	4.6	2.2
	28 November	46-0-0	2.4	0.0	0.0
	Total g N m^{-2}/yr		24.4	19.1	18.9
2001	21 May	46-0-0	2.4	0.0	0.0
	29 May	0-46-0¶	0.0	4.9	0.0
	4 June	46-0-0	2.4	0.0	0.0
	18 June	46-0-0	2.4	0.0	0.0
	18 June	18-3-18#	2.4	0.4	2.4
	4 July	18-3-18	2.4	0.4	2.4
	17 July	18-3-18	2.4	0.4	2.4
	13 August	18-3-18	2.4	0.4	2.4
	6 September	18-3-18	2.4	0.4	2.4
	24 September	46-0-0	2.4	0.0	0.0
	17 October	18-3-18	2.4	0.4	2.4
	26 November	18-3-18	4.9	0.8	4.9
	Total g N m^{-2}/yr		29.3	8.1	19.5
2002	26 April	13-25-12	2.5	4.9	2.3
	15 May	18-3-18	2.4	0.4	2.3
	15 May	0-46-0	0.0	3.7	0.0
	7 June	18-3-18	2.4	0.4	2.4
	7 June	46-0-0	2.4	0.0	0.0
	20 June	18-3-18	2.4	0.4	2.4
	10 July	18-3-18	2.4	0.4	2.4
	10 July	0-46-0	0.0	3.9	0.0
	12 August	18-3-18	2.4	0.4	2.4
	6 September	18-3-18	2.4	0.4	2.4
	6 September	0-46-0	0.0	3.7	0.0
	4 October	18-3-18	2.4	0.4	2.4
	4 October	0-46-0	0.0	4.9	0.0
	1 November	18-3-18	2.4	0.4	2.4
	Total g N m^{-2}/yr		24.5	24.3	21.8

† Lebanon Country Club 13-25-12
‡ Northern Star Mineral 26-0-26
§ Urea 46-0-0
¶ Triple Superphoshate 0-46-0
# Lebanon Country Club 18-3-18

inclusions/amendments on wear tolerance of sod that was established in the spring and trafficked in the fall.

Traffic Applications

Traffic was applied as a strip application at two levels; daily and weekly. A portion of each plot was left untrafficked for the duration of the study. Each traffic level was applied as a strip treatment to separate portions of each plot using the Cady Traffic Simulator (CTS) (Calhoun et al. 2002). No traffic was applied to the plots in fall 2000, due to concerns that the time discrepancy between treatment installations would result in unfair comparisons. Each traffic event application with the CTS included a forward pass and reverse pass. Weekly traffic was applied across 2.3 m of the plot by making 3 consecutive passes side by side in 2001 and 2002. Daily traffic was applied across 0.7 m of each plot by making a single pass with the CTS in 2001 and 1.5 m by making two passes side by side in 2002. In 2001, from 27 August to 1 October daily traffic was applied 5 times per week and was then reduced to 4 times per week until traffic ended on 28 November (60 total traffic events). Weekly traffic was applied once per week, beginning 11 September and continued until 28 November (13 total traffic events). In 2002, daily traffic was applied 5 times per week from 29 August to 21 October and was then reduced to 3 times per week until traffic ended on 22 November (52 total traffic events). Weekly traffic was applied twice per week from 2 September to 21 October and was then reduced to once per week until traffic ended on 22 November (19 total traffic events).

Treatment Evaluations

Treatments were evaluated in two major categories; root zone properties and playing surface characteristics. The root zone properties included: particle-size analysis, bearing capacity, infiltration, saturated hydraulic conductivity, and root mass by depth. Playing surface characteristics included: turfgrass cover, surface hardness, resistance to divoting, and traction.

Root Zone Properties

Particle-Size Analysis

A particle-size analysis was performed on each root zone material to determine the percent sand, silt and clay (Day 1965). Approximately 100 g of air dried (105°C) root zone mix was combined with 100 ml of dispersing agent (5% sodium hexametaphosphate solution) in a 300 ml fleaker. A subsample was taken and oven dried (105°C) to determine gravimetric water content. The mass of solids was then calculated. The fleaker was then placed on a reciprocating shaker for 16 hours. Once the shaking was complete the contents of the fleaker was emptied onto a number 270 sieve placed inside a large funnel. The silt and clay was collected into a 1000 ml Bouyoucos cylinder. The sand fraction was rinsed with distilled water to wash any remaining silt and clay through the sieve and into the cylinder. The washed sand fraction was rinsed into a tared beaker and placed in an oven at 105° C until dry. When dry, the sand was weighed and poured into a nest of sieves and shaken for 2 minutes. The sieves numbers used were 10, 18, 35, 60, 140, and 270. Each sand fraction retained on each sieve was weighed to the nearest 0.1g.

Percent clay content was determined using the hydrometer method (Day 1965). The silt and clay collected in the Bouyoucos cylinder was stirred for 30 seconds using vertical strokes with a plunger. A single hydrometer reading was taken 8 hours after stirring was complete to determine clay content in g L^{-1}, which was then converted to percent by weight.

Bearing Capacity

Soil bearing capacity of these established root zones were measured according to a modified version of the standard test method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils (ASTM-D 1883-94), using a mobile CBR device. The CBR devise was clamped to the bucket of a front end loader. The CBR devise included a low-geared jack (ELE International Soil Test Products Division, Lake Bluff IL, Model No. CN-410AY), load cell that reads force in pounds, a piston (5 cm dia.), and a displacement dial gauge. An apparatus was also constructed to allow downward pressure to be applied to the bucket of the front end loader so the jack would not raise the bucket of the front end loader instead of forcing the piston into the ground. The jack was used to force the piston into the ground at a constant rate to a depth of 2.54 cm. The load cell indicated the amount of force the surface was exerting on the piston. The force measured by the load cell was then divided by the area of the load piston to obtain the pressure exerted on the surface. The pressure exerted on the piston by the surface when the piston reached a depth of 2.54 cm was then recorded.

Infiltration

Infiltration rates were measured using a modified version of the method described by Bertrand (1965). This procedure specifies the use of a double-ring infiltrometer, which includes two concentrically placed rings that are pounded into the soil surface and an apparatus that maintains a constant head throughout the duration of the test. Due to the nature of the materials being tested, two different types of rings and two different methods of placing the rings in to the root zone had to be utilized. Infiltration rings could be placed into non-artificially amended treatments using the traditional method of carefully tamping the rings into the root zone. These rings measured 12.5 cm and 22.7 cm in diameter and 14.0 cm in height and were placed into the ground to a depth of 9.0 cm. However, for artificially amended plots it was necessary to modify rings with a cutting edge so they could be drilled into the root zone. This method was adopted for two reasons; 1) to get the rings into the root zone and 2) to minimize surface disruption. These rings measured 11.4 cm and 21.4 cm in diameter and 14.0 cm in height and were placed into the ground to a depth of 9.0 cm. Once the rings were placed into the root zone, both the inner and outer rings were filled with water and refilled if necessary for 30 minutes prior to initiating infiltration tests. Once infiltration tests were initiated, infiltration rates were recorded for the inner most ring only.

Saturated Hydraulic Conductivity

Three 7.62 cm x 7.62 cm cores were extracted from each plot using a modified double-cylinder, hammer driven core sampler for the determination of hydraulic conductivity (Blake 1965). The core sampler was modified by filing saw teeth into the leading edge and a part was machined to connect the sampler to a drill so the sampler could be used to cut through all artificially and non-artificially amended treatments. The core was then trimmed so that the volume of the core was equal to that of the sample. A double layer of cheesecloth was placed on the bottom of the core and secured with a rubber band.

Hydraulic conductivity was measured using the constant-head method (Klute 1965). The cores were placed in a tray filled with water to a depth just below the top of the samples for 24 hrs. The cores were then fitted with 7.62 cm extension collars and secured with electrical tape. The cores were then transferred to a rack and a siphon hose was placed on the top of the cores to maintain a constant head of water. Once the water level on top of the sample became stabilized the leachate was collected in a graduated cylinder. The volume of water that passed through the sample in a certain amount of time was measured. The amount of time each sample ran was variable due to the differences in percolation rates.

Root Mass by Depth

Root mass by depth was measured in the weekly trafficked portion of plots. A soil probe with an I.D. of 3.2 cm was modified by filing saw teeth into the leading edge. The modified probe was inserted into the root zone to a depth of 22.9 cm using a drill motor. The soil core was then sectioned into three depths: 1) 0-7.6 cm, 2) 7.6-15.2 cm, and 3) 15.2-22.9 cm. Three subsamples were taken from each plot and the common depths of the three subsamples were combined. These root samples were then washed to remove all the root zone material in accordance to a similar method described by (Hummel 1993). Roots and soil were placed into a 300 ml fleaker with 100 ml of dispersing agent (5% sodium hexametaphosphate). The fleakers were then placed onto a reciprocating shaker for 16 hours. The fleakers were then placed onto a 0.05 mm sieve under running water where the roots could be separated from soil particles. Root samples were collected and then dried at 60°C for 72 hours and then weighed.

Playing Surface Characteristics

Turfgrass Cover

Turfgrass cover was quantified using digital image analysis (Richardson et al. 2001). Digital images were taken of plots using a Nikon, cool pix model E995 (Nikon Corporation, Melville, NY). The images were saved in jpeg format with an image size of 1280 by 960 pixels. The camera was set to the following parameters; a shutter speed of 1/400 s, and an aperture of F -3.0.

Digital images were analyzed individually using Sigma Scan Pro (v. 5.0, SPSS, Inc., Chicago, IL). Sigma Scan's measuring tools counted the number of green pixels (hue range from 47 to 107 and a saturation range of 0 to 100) contained in an image and divided that number by the total number of pixels in that image to calculate the percent turfgrass cover in that image.

Surface Hardness

The surface hardness of the daily trafficked, the weekly trafficked, and the untrafficked plots were quantified using the Clegg Impact Tester with a 2.25 kg hammer (Lafayette Instrument Co., Lafayette, IN). The hammer was dropped three times in random locations within each plot area from a height of 0.46 m (Rogers and Waddington 1990). The three peak deceleration (G_{max}) values were recorded for each plot.

Resistance to Divoting

Resistance to devoting was measured using the Turf Shear Tester (TST) (Braden Clegg PTY LTD, Model No. CCB1A). This apparatus was used with the 50 mm wide shearing tip which can be set at multiple depths of 10 mm, 20mm, 30 mm, or 40 mm. Measurements were taken at 20, 30, and 40 mm depths at various points during this study. The apparatus digital display reads in units of kg-force which can then be converted into Newtons or Newton-meters.

Traction

Traction was quantified by measuring the shear resistance of each playing surface. Shear resistance was measured using the Eijkelkamp Shearvane

(Rogers et al. 1988). Three measurements were taken at random locations within each plot area and recorded in N-m.

RESULT & DISCUSSION

Results are grouped and presented by data type. For each data type, data collected from the daily trafficked portion of plots are discussed first, followed by the weekly trafficked data. Years are discussed sequentially.

Turfgrass Cover

2001 Daily Traffic

Turfgrass cover data of the daily trafficked portion of treatments for 2001 are presented in Table 5. Data collection for the daily trafficked portion of the plots began on October 1st. Prior to this date visual differences between treatments could not be ascertained. Both the sand-soil mix containing 15% silt+clay and Bermudagrass consistently performed poorly throughout October and November. The sand-soil mix containing 15% silt+clay had significantly lower turfgrass cover than the well-graded sand 6 out of 8 days data was taken. Grassmaster had significantly higher turfgrass cover than the well-graded sand at the end of November.

2002 Daily Traffic

The daily traffic data for 2002 are shown in Table 6. These data need to be interpreted with caution. Prior to the 2002 traffic season, the daily trafficked

Table 5. Percent turfgrass cover for the daily trafficked portion of treatments in 2001.

	Percent Turfgrass Cover†							
Treatment	1-Oct	15-Oct	22-Oct	29-Oct	7-Nov	14-Nov	21-Nov	28-Nov
Well-graded sand‡	68.3 ab§	70.0 a	59.3 a	26.7 ab	10.0 a-d	13.6 a-d	12.3 bcd	2.7 cde
Poorly graded sand	79.0 a	74.7 a	56.3 ab	38.3 a	11.0 a-d	19.0 abc	17.7 b	5.0 bc
7% Silt+Clay	58.7 a-d	56.7 a-e	47.0 a-d	25.7 ab	10.3 a-d	13.5 a-d	12.0 bcd	3.0 b-e
9% Silt+Clay	58.0 a-d	65.0 abc	46.7 a-d	25.7 ab	12.0 ab	11.0 a-e	11.3 cde	3.7 bcd
15% Silt+Clay	35.3 cd	27.0 fg	27.0 d	7.0 cd	9.7 bcd	4.7 e	6.0 ef	2.0 de
ZeoPro	66.7 abc	70.0 a	38.3 bcd	27.3 ab	10.0 a-d	8.7 b-e	10.7 cde	2.3 cde
Profile	38.3 bcd	38.0 b-f	42.0 a-d	14.7 bc	10.0 a-d	6.8 de	8.7 cde	2.0 de
Ventway	54.3 a-d	28.3 efg	46.3 a-d	20.7 bc	11.3 abc	8.1 cde	11.0 cde	2.3 cde
Turfgrids	59.3 a-d	36.7 c-f	43.3 a-d	19.0 bc	8.7 cd	6.4 de	8.7 cde	2.3 cde
Grassmaster	57.7 a-d	33.7 def	47.7 abc	20.7 bc	11.7 abc	21.2 ab	27.7 a	14.7 a
SportGrass	44.0 bcd	39.3 b-f	34.0 cd	15.3 bc	10.7 a-d	10.3 b-e	11.3 cde	2.7 cde
MotzGrass	57.0 a-d	59.7 a-d	54.7 ab	24.7 ab	13.0 a	19.1 abc	14.0 bc	5.7 b
Hummer Turftiles	37.0 bcd	38.0 b-f	32.7 cd	15.0 bc	11.3 abc	18.2 abc	10.7 cde	4.3 bcd
StrathAyr	34.0 d	65.3 ab	52.3 abc	26.3 ab	8.7 cd	25.1 a	7.7 def	2.3 cde
Bermudagrass	1.0 e	0.0 g	0.7 e	0.3 d	8.0 d	0.6 f	2.3 f	0.3 e
Significance	***	***	***	***	ns	***	***	***

*,**,*** Significant at the 0.10, 0.05, 0.01 level of probability respectively.

† Turfgrass cover was quantified using digital image analysis (Richardson et al. 2001)

‡ Used as the base root zone material for all treatments except StrathAyr and Motzgrass.

§ Means within a column not followed by the same letter are significantly different at the indicated level of significance as determined by Fisher's protected least significant difference. Data collected on separate dates can not be compared due to light intensity discrepancies when digital images were taken.

Table 6. Percent turfgrass cover for the daily trafficked portion of treatments in 2002.

	Percent Turfgrass Cover†								
Treatment	29-Aug	12-Sep	18-Sep	24-Sep	3-Oct	11-Oct	18-Oct	31-Oct	10-Nov
Well-graded sand‡	99.6 ab§	62.3 a-d	46.3 a	56.7 a	45.7 ab	39.3 a	8.7 b	21.7 abc	8.6 b-e
Poorly graded sand	93.8 bc	65.0 a	43.7 a	54.0 abc	49.3 a	39.7 a	7.0 bc	23.0 ab	13.6 abc
7% Silt+Clay	93.3 bc	57.3 b-f	34.7 ab	47.3 b-e	41.0 a-d	33.0 a-d	8.3 bc	16.0 b-f	11.2 a-d
9% Silt+Clay	95.2 abc	57.7 a-f	43.0 a	41.3 efg	40.0 a-d	32.0 bcd	5.2 bcd	16.5 b-e	10.5 a-d
15% Silt+Clay	96.1 abc	60.0 a-e	33.3 ab	34.3 g	30.0 de	19.0 ef	1.6 d	9.7 d-g	4.2 e
ZeoPro	96.3 abc	60.3 a-e	36.0 ab	47.0 cde	38.0 a-d	35.7 ab	3.8 bcd	17.3 a-d	6.2 de
Profile	99.6 ab	64.3 ab	46.0 a	52.7 a-d	49.3 a	33.7 abc	6.9 bc	14.7 c-f	11.6 a-d
Ventway	99.4 ab	55.7 c-f	28.7 b	47.3 b-e	43.7 abc	36.0 ab	7.0 bc	20.7 abc	8.5 b-e
Turfgrids	96.1 abc	65.0 a	47.0 a	56.3 ab	43.7 abc	38.7 ab	21.6 a	24.7 a	10.6 a-d
Grassmaster	99.7 ab	52.3 f	37.3 ab	36.3 fg	33.3 cde	26.0 de	5.2 bcd	22.3 abc	19.6 a
SportGrass	100.0 a	52.0 f	27.0 b	32.7 g	25.0 e	18.3 f	3.4 bcd	9.0 efg	7.3 cde
MotzGrass	100.0 a	55.0 def	36.0 ab	40.3 efg	33.7 cde	18.0 f	4.0 bcd	8.5 fg	14.7 ab
Hummer Turftiles	99.6 ab	53.7 ef	26.7 b	37.0 fg	35.7 b-e	17.3 f	2.8 cd	11.5 d-g	7.3 cde
StrathAyr	100.0 a	63.0 abc	36.7 ab	44.7 def	37.7 a-d	28.0 cd	4.0 bcd	12.0 def	8.3 b-e
Bermudagrass	88.0 c	23.7 g	24.0 b	14.0 h	11.3 f	4.7 g	1.3 d	4.0 g	0.3 f
Significance	ns	***	**	***	***	***	***	***	***

*,**,*** Significant at the 0.10, 0.05, 0.01 level of probability respectively.

† Turfgrass cover was quantified using digital image analysis (Richardson et al. 2001).

‡ Used as the base root zone material for all treatments except StrathAyr and Motzgrass.

§ Means within a column not followed by the same letter are significantly different at the indicated level of significance as determined by Fisher's protected least significant difference. Data collected on separate dates can not be compared due to light intensity discrepancies when digital images were taken.

portion of all the plots except, Grassmaster, Sportgrass, Motzgrass, Bermudagrass and Hummer Turftiles were stripped and resodded with washed Kentucky bluegrass. This was done to investigate the effects of the root zone amendments on wear tolerance of sod that was established in the spring and trafficked in the fall.

The poor performance of the sand-soil mix containing 15% silt+clay and Bermudagrass were seen again in 2002 throughout the traffic period. The sand-soil mix containing 15% silt+clay had significantly lower percent turfgrass cover than the well-graded sand through most of October. The Bermudagrass was overseeded with perennial ryegrass on 20 August, but showed significantly less turfgrass cover than the well-graded sand on all dates data was collected. Sportgrass and Hummer Turftiles had significantly less turfgrass cover than the well-graded sand through September and October. Motzgrass and StrathAyr showed significantly less turfgrass cover than the well-graded sand through October. These data are supported by plant counts of the daily trafficked plots in 2002 (Table 7). The sand-soil mix containing 15% silt+clay had significantly lower plant counts than the well-graded sand throughout October. Hummer Turftiles had significantly lower plant counts in September and Bermudagrass had fewer plant counts through October and November.

2001 Weekly Traffic

Turfgrass cover data for the weekly trafficked portion of treatments in 2001 and 2002 are shown in Table 8. Bermudagrass was the only treatment that had

Table 7. Plant counts of daily trafficked portion of treatments in 2002.

Treatment	plants 100 cm^{-2} †									
	Daily					Weekly				
	28-Aug	25-Sep	7-Oct	28-Oct	18-Nov	23-Sep	25-Sep	9-Oct	30-Oct	20-Nov
Well-graded sand‡	218	99 abc§	78 b-f	34 a-d	35 bcd	168	153	132 a	84 ab	109 a
Poorly graded sand	216	81 b-e	91 a-e	43 abc	42 bc	192	163	115 ab	67 abc	100 ab
7% Silt+Clay	206	103 abc	95 a-d	34 a-d	20 cde	189	163	105 abc	47 a-d	72 ab
9% Silt+Clay	239	132 a	84 a-f	15 c-f	23 b-e	195	167	124 a	76 ab	90 ab
15% Silt+Clay	223	38 e	53 e-h	4 ef	20 cde	204	115	85 bc	47 a-d	67 ab
ZeoPro	214	67 cde	128 a	39 abc	38 bcd	191	168	96 abc	80 ab	103 ab
Profile	232	100 abc	88 a-e	33 a-e	27 b-e	201	168	132 a	61 abc	56 b
Ventway	210	115 ab	109 abc	49 ab	48 ab	210	161	125 a	85 a	94 ab
Turfgrids	214	101 abc	71 c-f	61 a	72 a	211	150	128 a	86 a	67 ab
Grassmaster	208	75 b-e	61 d-g	24 b-f	3 e	194	146	118 ab	62 abc	92 ab
SportGrass	178	58 cde	31 gh	5 def	15 cde	149	119	76 cd	33 cd	71 ab
MotzGrass	224	37 e	63 d-g	10 def	1 e	232	198	101 abc	41 bcd	85 ab
Hummer Turftiles	239	48 de	48 fgh	9 def	13 de	187	133	81 bcd	68 abc	72 ab
StrathAyr	175	91 a-d	118 ab	48 ab	25 b-e	181	146	103 abc	56 abc	72 ab
Bermudagrass	257	61 cde	24 h	0 f	0 e	177	123	46 d	8 d	0 c
Significance	ns	***	***	***	***	ns	ns	***	**	**

*,**,*** Significant at the 0.10, 0.05, and 0.01 level of probability, respectivley.

† Plant counts were had counted taking three subsamples per treatment with a soil probe (diameter=3.2 cm), and converted to plants 100 cm^{-2}.

‡ Used as the base root zone material for all treatments except StrathAyr and Motzgrass.

§ Means within a column not followed by the same letter are significantly different at the indicated level of significance as determined by Fisher's protected least significance.

Table 8. Percent turfgrass cover for the weekly trafficked portion of treatments in 2001 and 2002.

	Percent Turfgrass Cover†												
	2001				2002								
Treatment	7-Nov	14-Nov	21-Nov	28-Nov	29-Aug	12-Sep	18-Sep	24-Sep	3-Oct	11-Oct	18-Oct	31-Oct	10-Nov
Well-graded sand‡	25.3 abc§	68.3 ab	55.0 de	25.0 bcd	99.3 ab	79.3 bcd	99.9 ab	92.3 ab	75.0 abc	55.3 a-d	24.7 ab	44.0 bcd	8.0 cde
Poorly graded sand	26.7 ab	77.0 ab	72.3 abc	42.7 a	90.7 bc	93.3 ab	99.9 ab	95.0 a	79.7 ab	63.7 a	27.7 a	53.3 a	12.0 bcd
7% Silt+Clay	27.7 ab	75.0 ab	58.0 b-e	28.7 a-d	96.7 abc	89.3 abc	94.5 bc	89.3 abc	77.7 abc	51.7 bcd	15.3 bc	43.0 bcd	12.0 bcd
9% Silt+Clay	24.3 abc	80.7 a	63.0 a-e	30.3 a-d	99.6 ab	87.0 abc	99.0 abc	89.0 abc	73.0 a-d	50.7 cd	15.3 bc	43.7 bcd	13.3 b
15% Silt+Clay	28.3 a	72.3 ab	57.3 cde	29.0 a-d	100.0 a	97.7 a	97.1 abc	84.3 cd	64.0 de	41.3 e	5.0 cd	30.0 e	8.0 cde
ZeoPro	23.3 abc	82.0 a	71.3 a-d	37.0 abc	99.6 ab	82.7 abc	100.0 a	95.3 a	81.0 ab	60.0 ab	28.3 a	48.7 ab	10.7 bcd
Profile	27.3 ab	77.7 ab	60.3 b-e	29.3 a-d	99.2 ab	79.3 bcd	99.4 ab	90.7 abc	77.0 abc	54.7 bcd	15.3 bc	41.0 d	11.0 bcd
Ventway	27.3 ab	72.7 ab	56.0 cde	25.3 bcd	83.8 c	81.0 bcd	97.3 abc	88.7 abc	69.3 cde	52.7 bcd	21.0 ab	42.0 cd	7.3 de
Turfgrids	15.3 bc	75.7 ab	59.7 b-e	27.0 a-d	99.9 a	86.7 abc	98.7 abc	91.3 abc	71.3 bcd	52.0 bcd	24.0 ab	40.0 d	5.0 ef
Grassmaster	28.0 a	73.3 ab	59.3 b-e	26.0 a-d	99.9 a	95.0 ab	98.0 abc	88.7 abc	68.7 cde	53.7 bcd	19.0 ab	43.7 bcd	9.3 b-e
SportGrass	21.7 abc	61.7 b	48.0 e	16.7 de	98.7 ab	75.3 cd	90.6 c	81.0 d	60.3 e	48.7 de	7.0 cd	30.0 e	7.3 de
MotzGrass	29.0 a	71.7 ab	74.3 ab	39.3 ab	97.0 abc	87.0 abc	97.7 abc	92.7 ab	82.0 a	60.0 ab	16.0 bc	48.0 abc	21.0 a
Hummer Turftiles	32.3 a	81.3 a	79.0 a	41.0 ab	99.9 a	88.3 abc	98.0 abc	90.3 abc	80.3 ab	57.7 abc	20.0 ab	53.7 a	12.7 bc
StrathAyr	24.3 abc	69.0 ab	51.7 e	20.3 cd	99.6 ab	82.0 abc	97.3 abc	87.0 bcd	73.3 a-d	52.0 bcd	15.7 bc	40.0 d	13.0 bc
Bermudagrass	14.0 c	13.0 c	7.7 f	1.3 e	99.9 a	65.0 d	74.4 d	47.7 e	14.7 f	12.7 f	3.0 d	12.0 f	1.0 f
Significance	ns	***	***	***	ns	**	***	***	***	***	***	***	***

*,**,*** Significant at the 0.10, 0.05, 0.01 level of probability respectively.

† Turfgrass cover was quantified using digital image analysis (Richardson et al. 2001)

‡ Used as the base root zone material for all treatments except StrathAyr and Motzgrass.

§ Means within a column not followed by the same letter are significantly different at the indicated level of significance as determined by Fisher's protected least significant difference. Data collected on separate dates can not be compared due to light intensity discrepancies when digital images were taken.

consistently lower turfgrass cover than the well-graded sand. The poorly graded sand had significantly higher percent turfgrass cover than the well-graded sand in late November. Motzgrass showed higher percent turfgrass cover than the well-graded sand on 21 November, but these treatments were not significantly different on 28 November.

2002 Weekly Traffic

Weekly turfgrass cover data for 2002 are shown in Table 8. The sand-soil mix containing 15% silt+clay, Bermudagrass, and Sportgrass had significantly lower turfgrass cover than the well-graded sand on 18 October and 31 October. Lower plant counts were also recorded for 15% silt+clay, Sportgrass and Bermudagrass when compared to the well-graded sand in October (Table 7). Hummer Turftiles showed significantly higher turfgrass cover than the well-graded sand on 31 October, but was not significantly different from the well-graded sand on 10 November. The sand-soil mix containing 9% silt+clay and Motzgrass had significantly higher turfgrass cover than the well-graded sand on 10 November.

Surface Hardness

2000-2002 Daily Traffic

The results for surface hardness of the daily trafficked portion of the plots for 2000, 2001, 2002 are presented in Table 9. The range of values measured on athletic fields has varied throughout the literature. Surface hardness measured

Table 9. Surface hardness values for the daily trafficked portion of treatments in 2000, 2001and 2002.

	Gmax†							
	2000‡	2001			2002			
Treatment	21-Sep	24-Sep	15-Oct	21-Dec	28-Aug	16-Sep	28-Oct	18-Nov
Well-graded sand§	65 bc¶	61 gh	55 gh	130 gh	70 cd	37 i	72 cde	42 h
Poorly graded sand	57 d	55 i	52 h	150 efg	62 e	39 hi	64 e	52 gh
7% Silt+Clay	66 bc	77 b	77 b	169 def	75 abc	59 cde	93 b	86 bc
9% Silt+Clay	65 bc	77 b	78 b	196 cd	77 ab	66 bc	98 b	93 b
15% Silt+Clay	61 cd	63 fgh	75 bc	247 b	80 ab	71 ab	95 b	113 a
ZeoPro	60 cd	63 fgh	63 f	136 fgh	66 de	54 ef	84 bc	64 efg
Profile	62 cd	70 cde	62 fg	105 h	65 de	51 efg	74 cde	66 d-g
Ventway	61 cd	67 def	62 fg	131 fgh	69 cd	43 ghi	69 de	64 efg
Turfgrids	64 bc	72 cd	68 c-f	124 gh	70 cd	51 ef	78 cde	62 fg
Grassmaster	65 bc	61 h	54 gh	136 fgh	66 de	47 fgh	73 cde	73 c-f
SportGrass	82 a	86 a	90 a	222 bc	80 a	74 ab	123 a	120 a
MotzGrass	60 cd	73 bc	72 b-e	175 de	66 de	57 de	83 bcd	85 bc
Hummer Turftiles	60 cd	66 efg	65 def	148 efg	66 de	55 def	76 cde	80 b-e
StrathAyr	60 cd	70 cde	64 ef	193 cd	61 e	63 cd	85 bc	82 bcd
Bermudagrass	69 b	83 a	73 bcd	309 a	73 bc	75 a	119 a	118 a
Significance	***	***	***	***	***	***	***	***

*,**,*** Significant at the 0.10, 0.05, 0.01 level of probability respectively.

† Surface hardness was measured using the Clegg Impact Soil Tester, peak deceleration (Gmax).

‡ No traffic was applied in 2000.

§ Used as the base root zone material for all treatments except StrathAyr and Motzgrass.

¶ Means within a column not followed by the same letter are significantly different at the indicated level of significance as determined by Fisher's protected least significant difference.

on 24 Pennsylvania athletic fields using a 2.25 kg hammer had a range of 33-167 G_{max} (Rogers et al. 1988), but fields that measure in the 50-90 G_{max} range are typically considered safe. In 2000, the only treatment that had a G_{max} value significantly higher than the well-graded sand was Sportgrass. In 2001, Sportgrass and Bermudagrass were the only treatment that had a significantly higher G_{max} than the well-graded sand. The exception was 21 December when the root zones were frozen when these data were collected. All treatments exceeded 100 G_{max}. In 2002 Sportgrass again showed high clegg readings throughout the traffic season. Sand-soil mixes containing 7%, 9%, 15%, Motzgrass, and StathAyr showed high clegg readings from the end of October and into November.

2000-2002 Weekly Traffic

Results for surface hardness for the weekly trafficked portion of treatments for 2000, 2001, and 2002 are presented in Table 10. Sportgrass and 15% silt+clay were the only treatments with G_{max} values exceeding 80 in 2000 and 2001. The exception was 21 December where the soil was frozen at the time of data collection. In 2002, sand-soil mixes containing 7% and 9% silt+clay measured significantly higher G_{max} values than the well-graded sand in November. Sportgrass and Bermudagrass both exceeded 90 G_{max} in November.

Table 10. Surface hardness values for the weekly trafficked portion of treatments in 2000, 2001and 2002.

	Gmax†							
	2000‡	2001			2002			
Treatment	21-Sep	24-Sep	15-Oct	21-Dec	28-Aug	9-Oct	30-Oct	20-Nov
Well-graded sand§	65.1 bc¶	54.2 gh	46.7 fg	73.0 efg	67.0 ef	58.4 ef	73.1 cde	64.7 gh
Poorly graded sand	57.3 d	52.9 h	44.1 g	60.0 g	63.3 fg	56.6 f	66.8 de	63.5 h
7% Silt+Clay	65.7 bc	62.2 de	64.1 cd	78.6 ef	72.4 bcd	72.4 a-d	79.6 bcd	80.7 cd
9% Silt+Clay	65.0 bc	65.6 cd	68.3 c	84.1 de	77.1 a	74.0 abc	89.0 ab	84.5 bc
15% Silt+Clay	61.2 cd	72.0 b	84.8 a	116.1 c	76.6 ab	70.3 bcd	70.3 cde	75.9 c-f
ZeoPro	59.9 cd	55.8 fgh	53.3 ef	65.9 fg	70.4 cde	68.3 b-f	77.3 b-e	73.8 c-g
Profile	61.7 cd	64.2 cde	58.2 de	76.9 efg	66.0 ef	65.4 b-f	72.0 cde	67.8 e-h
Ventway	61.2 cd	61.6 def	57.3 de	77.4 efg	68.6 de	69.4 b-e	78.8 bcd	72.2 d-h
Turfgrids	64.4 bc	63.1 cde	52.9 ef	82.7 ef	74.2 abc	63.3 c-f	82.3 bc	77.7 cde
Grassmaster	64.8 bc	54.2 gh	44.7 g	79.9 ef	66.3 ef	60.9 def	71.9 cde	69.0 e-h
SportGrass	81.9 a	81.6 a	75.6 b	142.6 b	72.9 a-d	77.2 ab	81.8 bc	93.6 ab
MotzGrass	59.8 cd	62.8 cde	55.9 e	83.3 ef	63.1 fg	65.4 b-f	77.0 b-e	74.5 c-g
Hummer Turftiles	60.4 cd	59.2 efg	56.3 e	84.6 de	63.7 fg	66.4 b-f	65.7 de	76.7 c-f
StrathAyr	60.3 cd	64.0 cde	63.7 cd	101.4 cd	61.4 g	61.2 def	64.2 e	67.4 fgh
Bermudagrass	68.9 b	68.4 bc	69.3 bc	262.3 a	72.0 cd	82.4 a	102.4 a	96.8 a
Significance	***	***	***	***	***	***	***	***

*,**,*** Significant at the 0.10, 0.05, 0.01 level of probability respectively.

† Surface hardness was measured using the Clegg Impact Soil Tester, peak deceleration (Gmax).

‡ No traffic was applied in 2000.

§ Used as the base root zone material for all treatments except StrathAyr and Motzgrass.

¶ Means within a column not followed by the same letter are significantly different at the indicated level of significance as determined by Fisher's protected least significant difference.

Divoting Resistance

2001 and 2002 Daily Traffic

Shear Clegg measurements of the daily trafficked portion of each plot are reported in Table 11. In 2001, Grassmaster, Sportgrass, and Motzgrass provided a significantly higher resistance to divoting than the well-graded sand in November and December. StrathAyr and 9% silt+clay exceeded the well-graded sand significantly in December. In 2002, Grassmaster, Sportgrass, Bermudagrass, and Motzgrass exceeded the well-graded sand significantly in nearly all dates data were collected. The randomly oriented inclusions had a limited effect on divoting resistance, but on 7 October StrathAyr and Ventway exhibited significantly higher divoting resistance than the well-graded sand. Hummer had higher resistance to divoting on 25 September and 7 October.

2001 and 2002 Weekly Traffic

Shear Clegg values for weekly trafficked portions of treatments are shown in Table 12. In 2001, Grassmaster and Sportgrass were the only treatments that exhibited a higher divoting resistance than the well-graded sand. In 2002, Grassmaster, Sportgrass, and Motzgrass had significantly higher resistance to divoting than the well-graded sand throughout the traffic season. Randomly oriented inclusions did not have an effect on divoting resistance in 2001 and 2002.

Table 11. Divoting resistance values for the daily trafficked portion of treatments in 2001 and 2002.

	N-M†									
	2001				2002					
	20 mm‡				20 mm	30 mm	40 mm			
Treatment	1-Sep	24-Sep	9-Nov	21-Dec	28-Aug	16-Sep	25-Sep	7-Oct	28-Oct	18-Nov
Well-graded sand§	49.8 bc¶	58.5 bc	68.2 d	48.9 d	48.0 ab	80.9 c-f	81.3 cd	60.9 e	41.0 d	42.2 cde
Poorly graded sand	39.0 cd	61.8 bc	81.4 c	59.0 d	50.6 ab	93.8 b-e	93.9 c	74.7 de	64.7 cd	58.6 cde
7% Silt+Clay	42.5 bcd	63.6 abc	45.3 ef	32.8 h	49.7 ab	74.4 def	77.9 cd	72.8 de	37.9 d	52.7 cde
9% Silt+Clay	40.5 cd	63.6 abc	52.8 e	51.7 e	46.2 ab	65.5 f	76.5 cd	73.0 de	37.7 d	26.6 e
15% Silt+Clay	42.1 cd	49.7 c	38.1 f	46.5 f	53.5 ab	71.9 ef	93.5 cd	103.7 dc	61.5 cd	61.5 cde
ZeoPro	38.7 cd	62.3 bc	53.9 e	30.1 j	52.4 ab	81.5 c-f	75.9 cd	71.2 de	44.0 d	30.2 de
Profile	42.5 bcd	62.1 bc	40.1 f	31.5 l	45.3 b	70.9 ef	74.2 d	60.9 e	43.2 d	47.3 cde
Ventway	39.6 cd	51.9 c	50.9 e	33.7 g	41.4 b	97.9 bcd	84.6 cd	86.8 dc	48.9 d	76.5 cd
Turfgrids	40.3 cd	63.6 abc	65.2 d	40.5 g	52.6 ab	89.9 b-e	74.9 cd	70.4 de	62.7 cd	36.9 de
Grassmaster	48.0 bc	81.2 abc	98.2 b	84.8 d	62.1 a	102.9 abc	176.9 a	140.0 b	119.1 ab	89.3 bc
SportGrass	34.5 d	18.0 d	150.6 a	115.1 b	47.8 ab	130.2 a	186.8 a	187.2 a	131.3 a	186.4 a
MotzGrass	35.4 d	58.1 bc	130.7 a	148.4 a	42.1 b	115.9 ab	187.0 a	149.3 b	131.0 a	130.6 b
Hummer Turftiles	35.0 d	46.0 c	48.9 e	53.1 d	47.3 ab	86.9 c-f	118.9 b	104.3 c	73.6 cd	74.7 cde
StrathAyr	53.7 b	72.6 abc	50.8 e	85.6 c	46.5 ab	65.1 f	79.1 cd	82.4 d	44.0 d	60.0 cde
Bermudagrass	65.6 a	24.6 d	21.3 g	14.1 k	43.6 b	117.3 ab	128.4 b	128.6 b	88.4 bc	71.0 cde
Significance	***	***	***	***	ns	***	***	***	***	***

*,**,*** Significant at the 0.10, 0.05, 0.01 level of probability respectively.

† Divoting resistance was measured using the Turf Shear Tester (TST) in Newton-Meters (N-M).

‡ Indicates depth of penetration of shearing tip into playing surface.

§ Used as the base root zone material for all treatments except StrathAyr and Motzgrass.

¶ Means within a column not followed by the same letter are significantly different at the indicated level of significance as determined by Fisher's protected least significant difference.

Table 12. Divoting resistance values for the weekly trafficked portion of treatments in 2001 and 2002.

	N-M†									
	2001			2002						
	20 mm‡			20 mm	30 mm	40 mm				
Treatment	24-Sep	9-Nov	21-Dec	28-Aug	18-Sep	28-Aug	25-Sep	9-Oct	30-Oct	20-Nov
Well-graded sand§	53.5 a-d¶	79.9 bc	94.2 bcd	44.2 b	102.5 bcd	137.7 cd	133.3 def	126.0 cde	110.0 c	113.8 def
Poorly graded sand	42.9 bcd	77.3 bc	76.4 d	52.4 ab	115.3 b	134.5 cd	138.1 def	119.1 de	108.7 c	115.0 cde
7% Silt+Clay	48.0 a-d	84.3 b	110.7 ab	50.9 ab	107.7 bc	133.9 cd	121.7 ef	106.1 de	78.5 de	90.7 efg
9% Silt+Clay	51.5 a-d	83.0 b	90.3 bcd	53.0 ab	93.1 cd	137.5 cd	132.3 def	109.5 de	96.6 cde	100.6 d-g
15% Silt+Clay	64.1 a	67.4 bc	102.6 a-d	51.5 ab	99.2 cd	136.7 cd	126.0 ef	115.4 de	94.9 cde	88.0 fg
ZeoPro	40.5 bcd	89.2 ab	79.0 cd	53.5 ab	95.4 cd	127.6 cd	117.9 ef	102.0 e	93.9 cde	106.7 d-g
Profile	48.7 a-d	81.2 b	103.2 a-d	48.4 ab	93.4 cd	119.3 d	104.3 f	103.3 e	76.9 e	86.4 g
Ventway	53.9 abc	75.5 bc	102.4 a-d	51.3 ab	91.3 d	133.1 cd	120.5 ef	122.9 cde	99.4 cde	103.9 d-g
Turfgrids	48.9 a-d	84.3 b	106.5 abc	49.8 ab	96.3 cd	142.0 cd	140.6 def	129.2 cd	102.9 cde	119.3 cd
Grassmaster	57.0 ab	79.0 bc	126.1 a	50.2 ab	131.7 a	185.8 b	185.4 bc	191.5 b	164.5 ab	201.4 a
SportGrass	37.2 d	110.7 a	126.6 a	48.7 ab	133.8 a	231.3 a	297.8 a	236.1 a	172.8 a	185.0 a
MotzGrass	38.1 cd	70.0 bc	93.8 bcd	47.3 ab	131.5 a	148.1 c	209.6 b	205.5 b	172.8 a	148.5 b
Hummer Turftiles	40.9 bcd	68.2 bc	81.9 cd	50.2 ab	89.6 d	142.4 cd	146.3 cde	130.4 cd	103.5 cd	106.9 d-g
StrathAyr	63.8 a	82.8 b	113.4 ab	50.8 ab	90.7 d	144.4 c	133.3 def	129.6 cd	106.9 c	103.5 d-g
Bermudagrass	60.1 a	57.2 c	25.3 e	55.3 a	102.5 bcd	175.1 b	170.2 bcd	146.3 c	145.7 b	139.8 bc
Significance	**	**	***	ns	***	***	***	***	***	***

*,**,*** Significant at the 0.10, 0.05, 0.01 level of probability respectively.

† Divoting resistance was measured using the Turf Shear Tester (TST) in Newton-Meters (N-M).

‡ Indicates depth of penetration of shearing tip into playing surface.

§ Used as the base root zone material for all treatments except StrathAyr and Motzgrass.

¶ Means within a column not followed by the same letter are significantly different at the indicated level of significance as determined by Fisher's protected least significant difference.

Traction

2000 No Traffic

Initial shear values (traction) are reported in Table 13. High shear values can be associated with higher surface traction. In 2000, Bermudagrass was the only treatment that showed considerably less surface shear resistance than the well-graded sand.

2002 Daily

Shear resistance values for the daily trafficked portion of treatments are reported in Table 13. Motzgrass, Hummer Turftiles, and Bermudagrass were the only treatments that showed significantly less shear resistance than the well-graded sand in August and September. Bermudagrass and 15% silt+clay showed significantly less shear resistance than the well-graded sand in October.

2002 Weekly

Shear resistance values for the weekly trafficked portion of treatments are reported in Table 13. Motzgrass, Hummer Turftiles, and Bermudagrass also showed significantly less shear resistance than the well-graded sand in the weekly trafficked portion of treatments. These treatments and 15% silt+clay had significantly less shear resistance than the well-graded sand throughout the traffic season. The sand-soil mix containing 7% silt+clay and Profile showed significantly less shear resistance than the well-graded sand through October and November.

Table 13. Shearvane values (Traction) for the daily and weekly trafficked portions of treatments for 2000 and 2002.

	N-M†										
	2000‡	2002									
	No Traffic	Daily					Weekly				
Treatment	21-Sep	28-Aug	16-Sep	7-Oct	28-Oct	18-Nov	28-Aug	18-Sep	9-Oct	30-Oct	20-Nov
Well-graded sand§	28.2 b¶	33.3 a	22.3 abc	21.1 a-d	14.2 a	14.0 abc	30.2 ab	29.2 ab	27.2 ab	26.7 a	26.1 a
Poorly graded sand	30.4 a	32.4 ab	28.3 a	20.7 a-d	16.9 a	14.4 abc	30.7 a	28.0 abc	25.8 bc	26.0 ab	26.3 a
7% Silt+Clay	29.1 ab	29.8 abc	22.7 abc	23.1 a	16.0 a	14.7 abc	31.3 a	27.6 abc	21.1 def	21.1 b-e	17.7 fg
9% Silt+Clay	30.4 a	30.9 ab	21.7 a-d	21.8 a-d	13.3 a	12.3 abc	28.7 abc	28.7 ab	24.0 cd	21.6 a-e	24.8 ab
15% Silt+Clay	30.0 a	28.9 a-d	19.7 b-e	13.3 e	12.0 a	10.2 c	25.3 de	24.3 cde	19.0 fg	18.9 de	20.5 c-g
ZeoPro	30.2 a	32.2 ab	26.1 ab	22.9 ab	15.8 a	12.9 abc	29.1 abc	28.8 ab	26.1 bc	22.9 a-d	25.8 a
Profile	29.8 ab	30.4 ab	21.2 bcd	22.9 ab	12.9 a	11.3 bc	29.8 ab	26.0 bcd	22.2 de	21.1 b-e	19.0 d-g
Ventway	30.7 a	30.7 ab	22.9 abc	22.2 abc	17.8 a	16.4 ab	27.6 bcd	29.3 ab	25.7 bc	24.1 abc	21.2 b-f
Turfgrids	29.8 ab	32.0 ab	21.2 bcd	17.1 b-e	12.2 a	13.6 abc	30.7 a	28.7 ab	25.8 bc	24.7 abc	24.4 abc
Grassmaster	30.2 a	30.9 ab	22.6 abc	22.0 abc	16.2 a	16.0 ab	31.1 a	31.3 a	29.3 a	24.0 a-d	24.1 abc
SportGrass	30.4 a	28.2 bcd	17.6 cde	18.9 a-e	15.3 a	17.3 a	26.9 cd	26.0 bcd	22.0 def	21.9 a-e	22.4 a-d
MotzGrass	29.8 ab	24.4 d	15.5 e	16.7 cde	15.3 a	14.2 abc	23.6 ef	23.1 de	19.8 ef	19.6 cde	18.2 fg
Hummer Turftiles	29.3 ab	25.3 cd	16.7 de	15.9 de	12.4 a	11.3 bc	25.3 de	23.3 de	19.6 ef	19.6 cde	18.6 efg
StrathAyr	30.7 a	32.2 ab	24.6 ab	21.0 a-d	17.1 a	14.7 abc	30.2 ab	26.1 bcd	24.0 cd	20.0 cde	22.1 a-e
Bermudagrass	15.1 c	16.9 e	14.9 e	13.1 e	12.0 a	12.9 abc	21.6 f	22.0 e	16.0 g	17.1 e	17.2 g
Significance	***	***	***	***	ns	ns	***	***	***	ns	***

*,**,*** Significant at the 0.10, 0.05, 0.01 level of probability respectively.

† Shear resistance (traction) was measured using the Eijelkamp Shear vane in Newton-Meters (N-M).

‡ No traffic was applied in 2000.

§ Used as the base root zone material for all treatments except StrathAyr and Motzgrass.

¶ Means within a column not followed by the same letter are significantly different at the indicated level of significance as determined by Fisher's protected least significant difference.

Bearing Capacity

2001 Weekly

The bearing capacity values at 2.54 cm of displacement for 2001 are reported in Table 14. The reinforced sods (Sportgrass, Motzgrass and Hummer Turftiles) showed the highest bearing capacity values. The sand-soil mix containing 9% silt+clay and Ventway each showed significantly higher bearing capacity than the well-graded sand.

2002 Weekly

The bearing capacity values at 2.54 cm of displacement for 2002 are reported in Table 14. The reinforced sod materials (Sportgrass, Motzgrass and Hummer Turftiles) again showed significantly higher bearing capacity than the well-graded sand. Silt+clay showed a positive correlation to soil bearing capacity. As silt+clay content of the sand-soil mix increased, bearing capacity increased. However, only 15% silt+clay was significantly higher than the well-graded sand. The Bermudagrass treatment also had significantly higher bearing capacity than the well-graded sand. None of the randomly-oriented or specifically-oriented inclusions were significantly different from the well-graded sand.

2002 Daily

The bearing capacity of the daily trafficked portion of treatments were only measured in September 2002 to assess the playing surface strength as turfgrass cover began to diminish (Figure 6) (Turfgrass cover, daily 2002 are presented in

Table 14. The effect of natural and artificial root zone enhancements on bearing capacity at 2.54 cm of displacement in weekly trafficked portion of treatments for 2001 and 2002.

	kPa†	
	2001	2002
Treatment	1-Sep	7-Sep
Well-graded sand‡	1227 ef§	1256 fg
Poorly graded sand	1151 f	1111 g
7% Silt+Clay	1361 def	1376 d-g
9% Silt+Clay	1590 bcd	1429 c-g
15% Silt+Clay	1387 def	1762 bc
ZeoPro	1289 ef	1297 fg
Profile	1497 b-e	1367 efg
Ventway	1618 bcd	1451 c-g
Turfgrids	1478 b-e	1485 c-f
Grassmaster	1420 c-f	1557 b-f
SportGrass	1934 a	2299 a
MotzGrass	1701 ab	1726 bcd
Hummer Turftiles	1690 abc	1717 b-e
StrathAyr	1461 b-e	1605 b-f
Bermudagrass	1231 ef	1859 b
Significance	***	***

*,**,*** Significant at the 0.10, 0.05, 0.01 level of probability respectively.

† Bearing capacity was measured using a modified California Bearing Ratio apparatus. Indicates pressure in kilopascals to displace the turf/soil to a depth of 2.54 cm.

‡ Used as the base root zone material for all treatments except StrathAyr and Motzgrass.

§ Means within a column not followed by the same letter are significantly different at the indicated level of significance as determined by Fisher's protected least significant difference.

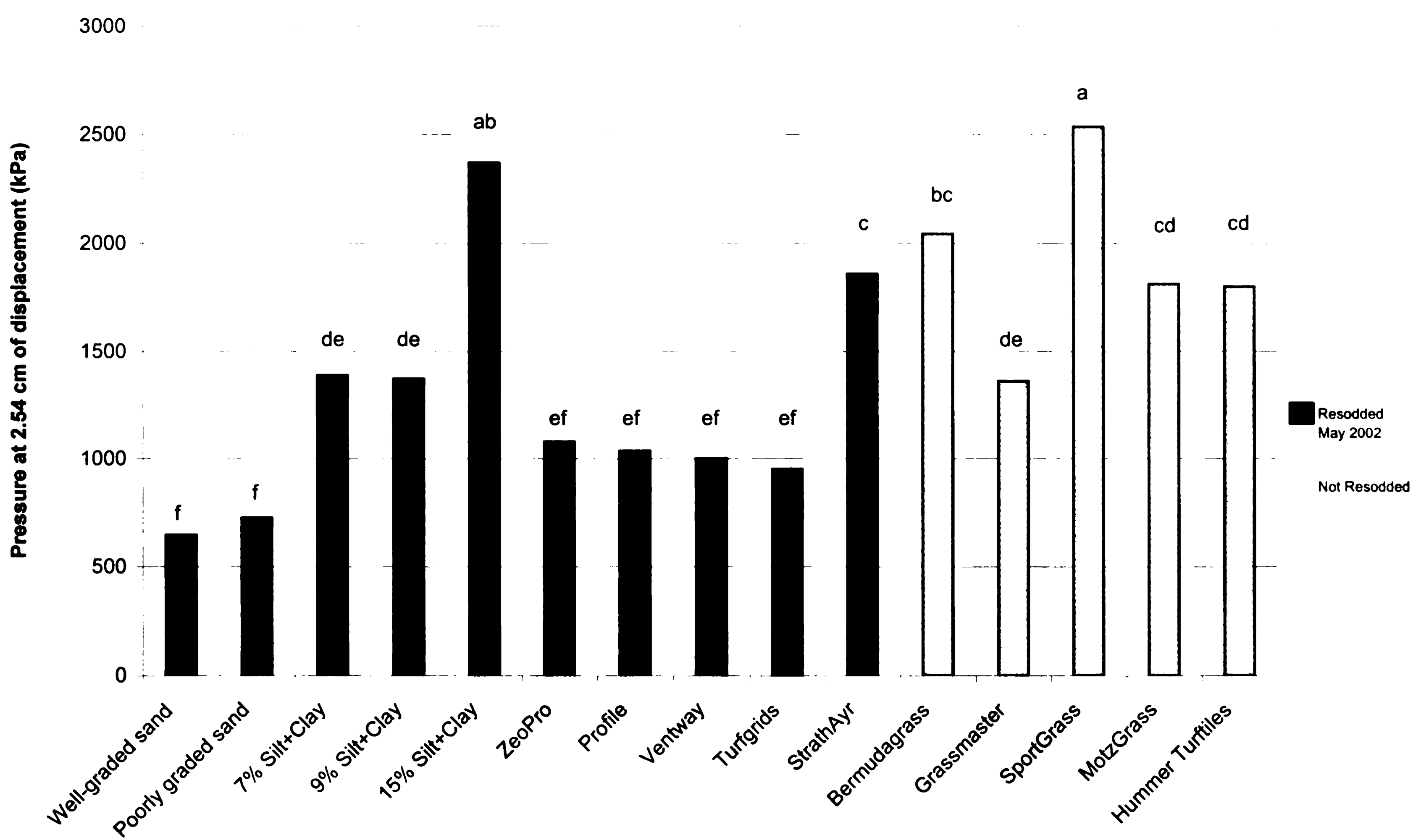


Figure 6. The effect of natural and articifial enhancements on the bearing capacity of the daily trafficked portion of treatments 26 Sept 2002.

Table 6). These data need to be interpreted with caution because the following treatments were not resodded in Spring 2002: Grassmaster, Sportgrass, Motzgrass, Hummer Turftiles, and Bermudagrass. Therefore these treatments can not be compared fairly to other treatments.

All three sand-soil mixes exhibited significantly higher bearing capacity than the well-graded sand. StrathAyr was the only randomly oriented inclusion that showed significantly higher bearing capacity than the well-graded sand.

Infiltration

2000, 2001, 2002 Weekly

Infiltration data was only collected on the weekly trafficked portion of treatments. The nature of the artificial materials in the randomly oriented, the specifically oriented, and the reinforced sod treatments required that modified rings be driven into the soil surface using a different method than the non-artificially amended treatments. Due to the different methods of inserting the infiltration rings into the ground (Driven vs. Pounded) the data can not be directly compared. Driving the modified infiltration rings into the artificially amended plots produced higher variances than pounding the standard rings into the non-artificially amended plots. The higher variances could have been associated with creating preferential voids using the driven method, thereby producing unusually high infiltration rates.

Infiltration rates for the non-artificially amended treatments (pounded rings) are presented in Table 15. In 2000, silt+clay had the largest effect on

Table 15. Infiltration rates for treatments measured using pounded rings† for 2000, 2001, and 2002.

Treatment	cm/hr‡ 1-Oct-00		1-Nov-01		Dec-02
Well-graded sand§	157.6 a¶	A#	107.6 a	B	17.0 C
Poorly graded sand	137.7 b	A	92.9 ab	B	14.9 C
7% Silt+Clay	111.7 c	A	27.4 d	B	8.1 C
9% Silt+Clay	69.6 d	A	16.9 de	B	1.9 B
15% Silt+Clay	3.5 f	A	0.8 f	A	0.4 A
ZeoPro	153.9 a	A	85.3 bc	B	13.9 C
Profile	152.1 ab	A	84.7 c	B	7.0 C
Bermudagrass	44.9 e	A	12.6 e	B	2.6 C
Significance	***		***		ns

*,**,*** Significant at the 0.10, 0.05, 0.01 level of probability respectively.

† Rings were pounded into the ground using a hand tamp.

‡ Infiltration rates were measured using a double-ring infiltrometer.

§ Used as the base root zone material for all treatments except StrathAyr and Motzgrass.

¶ Means within a column not followed by the same letter are significantly different at the indicated level of significance as determined by Fisher's protected least significant difference.

Means accross columns not followed by the same letter are significantly different at the 0.05 probability level as determined by Fisher's protected least significant difference..

infiltration rates. Percent silt+clay was negatively correlated with infiltration rates. As percent silt+clay increased, infiltration decreased. Sand-soil mixes containing 7%, 9%, 15%, and Bermudagrass had significantly lower infiltration than the well-graded sand. In 2001, after the first traffic season, the infiltration rates significantly reduced for all treatments compared to the first year (No traffic) except 15% silt+clay. Percent silt+clay again had the largest effect on infiltration, deceasing as silt+clay increased. In 2002, after the second season of traffic, infiltration again reduced significantly over all treatments except for sand-soil mixes containing 9% silt+clay and 15% silt+clay. However, there was no amendment affect after the second traffic season.

Infiltration rates for the artificially amended treatments (driven rings) are presented in Table 16. Infiltration rates using the driven method showed some treatments with extremely high infiltration rates. The nature of the material of each respective inclusion may have created preferential voids while the rings were driven into the playing surface. In 2000, Sportgrass and StrathAyr were the only treatments that were significantly lower than all other artificially amended treatments. In 2001, no significant differences were measured between treatments. In 2002, data for the artificially amended plots could not be collected after the second traffic season due to weather interference.

However, in spring 2003, three undisturbed soil cores were extracted from the weekly trafficked portion of all treatments in an effort to assess differences in hydraulic conductivity. All cores were extracted using the same method, but variances for the artificially amended plots were higher. Hydraulic conductivity

Table 16. Infiltration rates for treatments measured using driven rings† for 2000 and 2001.

Treatment	cm/hr‡ 1-Oct-00			28-Nov-01	
Ventway	210.7	a§	A¶	120.8	B
Turfgrids	277.4	a	A	150.4	B
StrathAyr	139.1	b	A	55.0	B
Grassmaster	211.3	a	A	129.7	B
SportGrass	103.8	b	A	87.6	A
MotzGrass	217.2	a	A	111.6	B
Hummer Turftiles	241.7	a	A	81.3	B
Significance	***			ns	

*,**,*** Significant at the 0.10, 0.05, 0.01 level of probability respectively.

† Rings were driven into the ground using an apparatus powered by a drill motor.

‡ Infiltration rates were measured using a double-ring infiltrometer.

§ Means within a column not followed by the same letter are significantly different at the indicated level of significance as determined by Fisher's protected least significant difference.

¶ Means accross columns not followed by the same letter are significantly different at the 0.05 probability level as determined by Fisher's protected least significant difference..

values for all treatments are shown in Figure 7. Percent silt+clay had the largest effect on hydraulic conductivity. All three sand-soil mixes had significantly lower hydraulic conductivity than the well-graded sand. TDS 2150, Zeopro, Profile, and Bermudagrass had significantly lower hydraulic conductivity than the well-graded sand. Artificially amended plots, Sportgrass and StrathAyr exhibited significantly less hydraulic conductivity than the well-graded sand.

Root Mass by Depth

Root mass by depth data was only collected in November 2001 during the first traffic season (Table 17). Data could not be recorded for all treatments because artificial materials could not be separated from roots sufficiently to obtain accurate data. No significant differences were shown by amendments at depth 1 (0-7.6 cm) or depth 2 (7.6-15.2 cm). However, there was a significant amendment effect at depth 3 (15.2-22.9 cm). TDS 2150, and Grassmaster had significantly less root mass at depth 3 (15.2-22.9 cm) than the well-graded sand. TDS 2150, Zeopro, Profile, Sportgrass, and Bermudagrass were the only treatments to show no significant difference in root mass between depths.

Summary

This study evaluated and compared 15 athletic field systems under two traffic regimes; daily and weekly. Considering all the parameters measured, the well-graded sand performed well compared to all other treatments, and even maintained one of the highest infiltration rates over all three years. However,

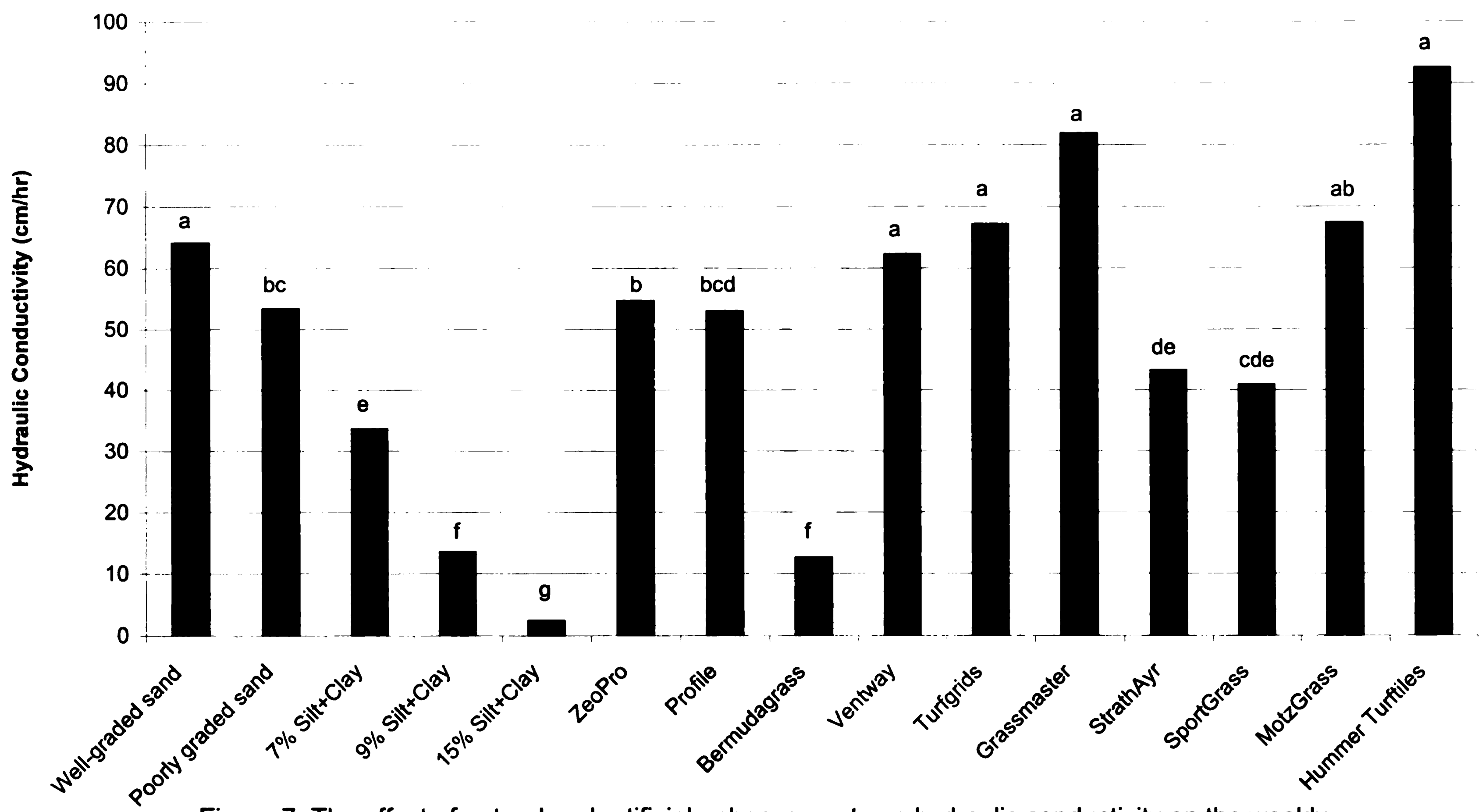


Figure 7. The effect of natural and artificial enhancements on hydraulic conductivity on the weekly trafficked portion of treatments April 2003.

Table 17. Root mass for the weekly trafficked portion of treatments in November 2001.

Treatment	Root mass (g)† 0 - 7.6 cm		7.6 - 15.2 cm		15.2 - 22.9 cm		
Well-graded sand‡	0.428	A	0.175	B	0.076	bc§	B¶
Poorly graded sand	0.265	A	0.170	A	0.204	a	A
7% Silt+Clay	0.654	A	0.363	B	0.063	bc	C
9% Silt+Clay	0.565	A	0.106	B	0.058	bc	B
15% Silt+Clay	0.421	A	0.117	B	0.052	bc	B
ZeoPro	0.317	A	0.088	A	0.112	bc	A
Profile	0.302	A	0.125	A	0.072	bc	A
Ventway#	-		-		-		
Turfgrids#	-		-		-		
Grassmaster	0.357	A	0.085	B	0.026	c	B
SportGrass	0.261	A	0.100	A	0.101	bc	A
MotzGrass	0.444	A	0.132	B	0.053	bc	B
Hummer Turftiles#	-		-		-		
StrathAyr#	-		-		-		
Bermudagrass	0.210	A	0.105	A	0.122	ab	A
Significance	ns		ns		***		

*,**,*** Significant at the 0.10, 0.05, 0.01 level of probability respectively.

† Root mass samples were extracted using a modified soil probe (diameter=3.2 cm). The cutting edge of the soil probe was filed to cut the artificial amendments. Soil probe was inserted into the soil using a drill motor. Three samples were collected from each treament and common depths were combined for analysis.

‡ Used as the base root zone material for all treatments except StrathAyr and Motzgrass.

§ Means within a column not followed by the same letter are significantly different at the indicated level of significance as determined by Fisher's protected least significant difference.

¶ Means accross columns not followed by the same letter are significantly different at the 0.05 probability level as determined by Fisher's protected least significant difference.

Root samples could not be separated from artifical amendments, without significant loss of root material.

some naturally and artificially amended treatments proved advantageous in a few parameters measured, but in some instances had unfavorable consequences such as increasing surface hardness or decreasing traction.

Silt+Clay had the largest detrimental effect on infiltration. In terms of infiltration, the sand-soil mix containing 15% silt+clay proved to be the only unacceptable root zone for a high quality athletic field. This mix was well below the suggested minimum of 1.5-2.5 cm hr^{-1} (Waddington et al 1974, Adams 1976) after the first season of traffic. The sand-soil mix containing 9% silt+clay was near the suggested minimums, but maintained an infiltration rate of 1.9 cm hr^{-1} after two seasons of traffic with minimal root zone management over a three year period. Adding any enhancement materials to a sand with the purpose of increasing infiltration rates should be done with minimal expectation of positive results. The high variance associated with the artificially amended treatments indicates that the nature of the artificial amendments were possibly creating preferential voids when samples were taken from the field thus showing unusually high infiltration rates (Figure 7).

The reinforce sod products (Sport grass, Motzgrass, and Hummer Turftiles) had the highest bearing capacity over both years on the weekly trafficked portion of treatments. This strength is primarily due to their reinforcements materials located directly at the playing surface. The sand-soil mix containing 9% silt+clay and Ventway had significantly higher bearing capacity in 2001. However, the strength increase of these materials was not significantly different in 2002. The strength increase provided by each amendment may not be apparent in 2002 due to a further increase in root development (Waldron 1977). The most important bearing capacity data was recorded from the daily trafficked portion of treatments after turfgrass cover had reduced. The bearing capacity of a treatment after turfgrass cover has been reduced is very important in predicting how a particular athletic field system will perform. This parameter is essential in a practice field situation where a significant reduction in turfgrass cover is imminent. All three sand-soil mixes and StrathAyr showed significantly higher bearing capacity over the well-graded sand on the daily trafficked portion of treatments.

The reinforced sod products had excellent bearing capacity in both the weekly and daily trafficked portions of treatments. However, the location of the reinforcement materials could have caused these products to show the most consistent reduction in shear resistance (Traction) in both daily and weekly trafficked plots. Reinforced sod products seem to develop problems as they mature. Generally, unamended root zones struggle the first year they are installed because the time from establishment to traffic is typically short, but as they mature they become more wear resistant. Reinforced sod materials seem to provide a benefit early (1st year) because they are installed as established sod that is very strong. However, they seem to cause problems as they continue to mature. This was exhibited during the second season of daily traffic, where most of the treatments were resodded. Many of the reinforced sod materials retained less turfgrass cover than the newly sodded treatments in September and October (Table 6). The artificial materials in these products seem to act as a barrier to the sand/soil surface and the developing thatch layer. The thatch layer develops from an imbalance between accumulation and decomposition of organic surface debris (Hurto and Turgeon 1978). Once a thin layer of thatch develops and does not decompose, new crowns can develop from emerging rhizomes within the thatch layer. Over time, the thatch layer becomes the primary growing medium. This results in a week union between the thatch layer and the underlying root zone material, allowing turf to displace easily.

Grassmaster, Sportgrass, and Motzgrass exhibited the highest, most consistent divoting resistance over both daily and weekly trafficked plots in 2001 and 2002. Bermudagrass also exhibited higher resistance to divoting in the daily trafficked plots during the second traffic season.

The only treatment that showed a consistent increase in surface hardness was Sportgrass. This increase in surface hardness has been well documented by other researchers (McNitt and Landschoot 2001, McNitt and Landschoot 2003). The sand-soil mixes exhibited higher surface hardness values towards the end of the second traffic season on daily trafficked portions of treatments in late October and into November. Motzgrass and StrathAyr also showed higher G_{max} values under the same traffic regime.

An athletic field manager considering installing a new athletic field has many factors to contemplate in evaluating different athletic field systems such as; geographic location of the field, intensity of intended traffic, and cost. The main concern should be how the new system could potentially affect the long term management of the field such as; mowing, cultivation, irrigation, pest control, and fertility. Any artificial material added to a root zone has the potential to make cultivation more challenging. (ie limited tine penetration, bringing artificial material to the surface and damaging the material that was initially installed to enhance the root zone). Selection of an athletic field system should also be driven by the ability of the system to maintain playing surface quality once turfgrass cover is reduced. Sand-soil mixes containing 7%, 9% silt+clay and StrathAyr showed the greatest potential for enhancing playing surface characteristics once turfgrass cover has diminished. Under the daily traffic regime, Grassmaster was the only enhanced root zone that showed promise in retaining more turfgrass cover into November over well-graded sand. Under weekly traffic Motzgrass, TDS 2150, and 9% silt+clay were the only treatments that showed significantly higher turfgrass cover than the well-graded sand in November.

DISSERTATION SUMMARY

The data and experience gained from completing the previous two chapters has provided a new tool for athletic field researchers and provided the data necessary to help athletic field managers, team owners and school administrators choose an athletic field system that best fits their situation. Conclusions and closing thoughts on each chapter follow.

Chapter one - **Cady Traffic Simulator: A New Apparatus to Simulate Athletic Field Traffic.**

The CTS has shown excellent promise of becoming a tool for athletic field researchers. The aggressiveness of the CTS increases the rate of wear beyond that of traditional traffic simulators, which is its primary advantage. The design of the self-propelled unit also makes it maneuverable, enabling its use in confined areas. However, there is still room for improvement. The CTS has a slow operating speed and narrow effective swath making traffic applications to large areas (greater than 740 m^2) impractical. The CTS also has more moving parts than traditional simulators making potential down time (breakdowns) a greater possibility. The 'feet' of the CTS also wear fairly quickly. If the machine is used daily, the feet should be replaced every month. The creation of this machine has brought us closer to consistently applying realistic athletic field traffic to research areas, but this machine can be improved given the financial resources and time.

The most immediate improvement can be made on the design and construction of a more durable and shock absorbing foot.

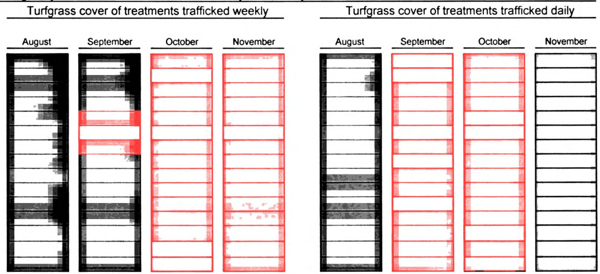
Chapter two – An Evaluation and Comparison of Naturally and Artificially Enhanced Athletic Field Sand Textured Root Zones.

The primary objective of enhancing sand textured root zones is to maintain as much turfgrass cover as possible as the optimal growing temperatures decline late into each football season. This must be accomplished without affecting playing surface safety. Every system that was evaluated in this test, averaged across the month of November, had 49% turfgrass cover or less in either the weekly or daily trafficked portion of treatments (Table 18). Neither naturally or artificially amended sand retained more turfgrass cover than the sand alone into the late months of the simulated season of traffic. Table 19 includes a general summary of how these systems performed in terms of playing surface characteristics and root zone properties.

Today the greatest challenge of constructing a quality athletic field is time (proper planning). Too often, fields are sodded in late spring, early summer and then have the first game in late August. This scenario often results in poor field quality because typically, two of the three establishment months offer terrible growing conditions for cool season grasses. Due to time discrepancies between the installations of treatments, all parties involved agreed that no traffic was to be applied in fall 2000. Therefore, the first season of traffic began in fall 2001 and every treatment had nearly two full growing seasons of establishment before any

Table 18. General summary of turfgrass cover averaged by month for treatments trafficked daily and weekly for 2001 and 2002.

	System Type	Estimated* cost ft^{-2}
Well-graded sand	-	-
Poorly graded sand	-	-
7% Silt+Clay	NAT	$0.37
9% Silt+Clay	NAT	0.37
15% Silt+Clay	NAT	0.37
Bermudagrass	NAT	0.37
ZeoPro	NAT	1.10
Profile	NAT	1.30
Ventway	ROI	1.57
StrathAyr	ROI	†
Turfgrids	ROI	0.21
Grassmaster	SOI	3.50
SportGrass	RS	4.50‡
MotzGrass	RS	4.50‡
Hummer Turftiles	RS	†



* Estimate is approximate cost above and beyond the cost of a standard straight sand root zone to include amendment/inclusion. Cost of materials were calculated as the materials were tested (inclusions mixed to the full depth of the root zone). Costs were estimated assuming an athletic field construction in Michigan.

† Data not volunteered

‡ Price is based on product as tested, installed as an established sod. Product can be installed on a sand root zone and seeded on site at $2.50 ft^{-2}$

System Type

NAT - Naturally amended
ROI - Randomly Oriented Inclusions
SOI - Specifically Oriented Inclusions
RS - Reinforced Sod

Percent Turfgrass Cover (Athletic Field Traffic Survey and Quality Assessment, D.D. Minner)

Excellent	90-100	
Good	70-89	
Fair	50-69	
Poor	30-49	
Very Poor	0-29	

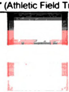


Table 19. General summary of playing surface characteristics and root zones properties of treatments trafficked daily and weekly for 2001 and 2002.

			Playing Surface Characteristics						Root Zone Properties				
	System Type	Potential to* limit cultural practices	Shearvane (daily)	Shearvane (weekly)	Divot Resistance (daily)	Divot Resistance (weekly)	Surface Hardness (daily)	Surface Hardness (weekly)	Bearing Capacity (weekly)	Bearing Capacity (daily)	Infiltration (weekly) 2000	Infiltration (weekly) 2001	Infiltration (weekly) 2002
Well-graded sand	-	Low	Green	Green	Red	Green	Green	Green	Red	Red	Green	Green	Green
Poorly graded sand	-	Low	Green	Green	Blue	Green	Green	Green	Red	Red	Green	Green	Green
7% Silt+Clay	NAT	Low	Green	Green	Red	Blue	Green	Green	Blue	Blue	Green	Green	Green
9% Silt+Clay	NAT	Low	Blue	Green	Red	Green	Green	Green	Blue	Blue	Green	Green	Red
15% Silt+Clay	NAT	Low	Blue	Blue	Blue	Green	Blue	Green	Blue	Green	Blue	Red	Red
Bermudagrass	NAT	Low	Red	Blue	Blue	Green	Blue	Red	Blue	Green ‡	Green	Green	Blue
ZeoPro	NAT	Low	Green	Green	Red	Blue	Green	Green	Red	Red	Green	Green	Green
Profile	NAT	Low	Blue	Green	Red	Blue	Green	Green	Blue	Red	Green	Green	Green
Ventway	ROI	Medium	Green	Green	Blue	Green	Green	Green	Blue	Red	Green	Green	Green
StrathAyr	ROI	High	Green	Green	Red	Green	Green	Green	Blue	Green	Green	Green	Green
Turfgrids	ROI	Medium	Blue	Green	Red	Green	Green	Green	Blue	Red	Green	Green	Green
Grassmaster	SOI	Medium	Green	Green	Green	Green	Green	Green	Blue	Blue ‡	Green	Green	Green
SportGrass	RS	High	Blue	Green	Green	Green	Red	Blue	Green	Green ‡	Green	Green	Green
MotzGrass	RS	High	Blue	Blue	Green	Green	Green	Green	Green	Green ‡	Green	Green	Green
Hummer Turftiles	RS	High	Blue	Blue	Blue	Green	Green	Green	Green	Green ‡	Green	Green	Green

* Potential to challenge cultural practices such as hollow core cultivation (limit penetration) and verticutting (inclusion removal).

†All parameters were averaged across all dates data were collected except infiltration.

‡ These treatments were not resodded prior to the 2002 traffic season

System Type
NAT - Naturally amended
ROI - Randomly Oriented Inclusions
SOI - Specifically Oriented Inclusions
RS - Reinforced Sod

			Performance Range		
Parameter	Units	Range Measured		Med	Low
Bearing Capacity	kPa	1934 - 1151	> 1600	1600 - 1300	< 1300
Infiltration	cm hr^{-1}	277.4 - 0.4	> 30	30 - 2.5	< 2.5
Shearvane	N-M	33 - 10	> 22	22 - 18	< 18
Divot Resistance	N-M	298 - 27	> 110	110-70	< 70
Surface Hardness	Gmax	123 - 44	50 - 80	80-90	> 90 or < 50

traffic was applied. This long establishment period made it difficult to evaluate the amendment affects on traditional short establishment periods.

However, after the first season of traffic we were able to re-establish the daily trafficked portions of most of the treatments with washed sod to investigate the effectiveness of the different amendments on this short establishment period. Only the sand-soil mixes and StrathAyr showed adequate soil strength once turfgrass cover had diminished into the 2002 traffic season. The retention of soil strength once turfgrass cover diminishes is extremely important for athletic field quality, particularly for practice fields because inevitably turfgrass cover will be reduced. Sands are highly dependent on plant material for stability. Therefore, athletic fields that expect any significant reduction in turfgrass cover should have a root zone containing 7-10% silt+clay or relex mesh elements.

Designing and constructing a quality athletic field is a challenge, but assessing the performance of a field quantitatively for record keeping or research purposes is equally challenging. A new type of method was used to collect turfgrass cover for this study. Traditionally, collecting turfgrass cover data quantitatively is time consuming and of questionable accuracy, but researchers recently developed a method to measure turfgrass cover using digital image analysis. This method has many advantages such as accuracy and speed of data collection, but does have its disadvantages. The imaging software that is used to count the number of green pixels identifies the desired color of turfgrass over a particular hue range. Any color out of this hue range is not counted as turfgrass cover. The problem is that as the turfgrass is trafficked and progresses later into the growing season the color of the turfgrass falls out of the turfgrass hue range and may not be counted as turfgrass cover, but the surface is very uniform. Other plots may have divots that have been removed creating a very non uniform surface. The divoted plot may come out in the analysis as having the same turfgrass cover as the plot that was very uniform, making comparisons between treatments very difficult. Another challenge with digital image analysis is the inconsistency of light on different days of data collection, which prohibits the comparison of data from treatments collected on different days. Plant counts per unit area and a measure of uniformity are still more reliable in accessing what plant material is actually present. If traffic tolerance is the question, I think it would be of interest to collect random samples with a cup cutter to determine the amount of biomass present.

A general observation while maintaining these treatments over a three year period has been that the artificially enhanced systems offer significant maintenance challenges. Systems such as StrathAyr, Hummer Turftiles, Motzgrass, and Sportgrass generally require more expertise to manage than a traditionally constructed field. The location and nature of each reinforced system creates challenges when conducting routine cultural practices. The primary concern is the limitation placed on traditional means of managing the accumulation of organic matter at the playing surface. The option of hollow tine core cultivation is severely limited due to the strength and location of the reinforment fibers restricting the penetration of the tines into the root zone.

Verticutting must be very precise due to the possibility of destroying or removing the reinforcement material. Topdressing applications have to be few and far between because you can actually bury the reinforcement fibers causing the turfgrass plants to separate from the reinforcement fibers.

What's next?

Better traffic simulation – I feel we need to develop a research project jointly with a specialist from biomechanics aimed at determining the typical forces produced at the shoe to playing surface interface of football players at the line of scrimmage (offensive and defensive lineman). This could be done using force plates and/or force sensors on actual players. Once the relative magnitude and direction of these forces are determined we can more accurately develop a traffic simulator to reproduce these forces on research plots. Robotic specialists can work with us to develop this machine.

Better data collection methods – The types of data we currently collect is very time consuming and difficult to interpret what the data actually means in terms of predicting, based on a measured value, whether a particular field is safe for play or not appropriate for play. At this point the majority of the data we collect can only be used to state that treatment X had a higher value than treatment Y. The question we have difficulty answering is 'is treatment X still adequate for a safe, quality playing surface or is treatment Y an absolute must'. For these data we are currently collecting, I feel we need to go to fields that we regard as top quality field or hold up well through the entire season and take several measurements using the current instruments that we have. Then we need to go to fields that are considered poor in quality or play poorly and do the same thing. This way we know relatively where a particular treatment or field we are measuring falls in regards to predicting its performance.

At some point, I feel we need to do a collaborative study with a biomechanics specialist/athletic trainer/ physical therapist to determine at what point does the amount of energy being returned to the athlete result in a higher potential for injury. The key in doing this lies in the capability in measuring and or predicting the amount of energy being returned to the athlete on a particular surface.

APPENDIX A

Percent organic matter for the untrafficked portion of non-artificially amended treatments in April 2003.

Treatment	Percent Organic Matter by Depth†			
	0 - 1.3 cm	1.3 - 2.5 cm	2.5 - 5.0 cm	5.0 - 7.6 cm
Well-graded sand‡	0.75 c§ A¶	0.41 A	0.28 A	0.20 a A
Poorly graded sand	0.56 c A	0.27 A	0.16 A	0.12 abcd A
7% Silt+Clay	1.43 abc A	0.54 B	0.29 C	0.14 abc D
9% Silt+Clay	1.10 bc A	0.47 B	0.27 C	0.10 cd D
15% Silt+Clay	2.40 a A	0.51 B	0.26 C	0.15 abc D
ZeoPro	1.10 bc A	0.38 B	0.26 B	0.19 ab B
Profile	1.19 bc A	0.42 B	0.15 C	0.05 d D
Bermudagrass	2.13 ab A	0.74 B	0.26 C	0.11 bcd D
Significance	**	ns	ns	**

*,**,*** Significant at the 0.01, 0.05, 0.01 level of probability respectively.

† Soil samples were extracted using a soil probe (diameter=3.2 cm). Three samples were collected from each treament, thatch layer was removed and common depths were combined for analysis. Percent organic matter was determined by loss on ignition (Hummel 1993).

‡ Used as the base root zone material for all treatments except StrathAyr, Motzgrass, and Poorly graded sand.

§ Means within a column not followed by the same letter are significantly different at the indicated level of significance as determined by LSD.

¶ Means accross columns not followed by the same letter are significantly different at the 0.05 probability level as determined by LSD.

APPENDIX B

Thatch depth for the untrafficked portion of selected naturally and artificially amended treatments in May 2003.

	cm†
Well-graded sand‡	3.04 a§
Poorly graded sand	2.61 ab
7% Silt+Clay	2.77 ab
9% Silt+Clay	2.96 a
15% Silt+Clay	2.22 bc
ZeoPro	2.89 a
Profile	2.53 ab
SportGrass	2.51 ab
MotzGrass	2.46 abc
Bermudagrass	1.88 c
Significance	**

*,**,*** Significant at the 0.01, 0.05, 0.01 level of probability respectively.

† Samples were extracted using a soil probe (diameter=3.2 cm) and thatch was measured uncompressed.

‡ Used as the base root zone material for all treatments except StrathAyr, Motzgrass, and Poorly graded sand.

§ Means within a column not followed by the same letter are significantly different at the indicated level of significance as determined by LSD.

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