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Stabilization and Enhancement of Sand-modified Root Zones for High Traffic Sport Turfs with Mesh Elements

A Randomly Oriented, Interlocking Mesh Inclusion System

The Texas Agricultural Experiment Station • Edward A. Hiler, Director
The Texas A&M University System • College Station, Texas

Typical mesh element high-sand root zone matrix applications shown on the cover are (clockwise from bottom left):

(a) Santa Anita horse race track in Arcadia, California, installed in 1989.
(b) Ewood Park soccer (football) field in Blackburn, England, rebuilt in 1991.
(c) Golf course tees at Woburn Abbey, Woburn, England, installed in 1988.
(d) Grand Ring in the Stadium Arena at the Royal Show Ground in Stoneleigh, England, installed in 1988. Widely used for animal competitions, including horse show jumping.

Stabilization and Enhancement of Sand-modified Root Zones for High Traffic Sports Turfs with Mesh Elements

A Randomly Oriented, Interlocking Mesh Inclusion System

James B. Beard* and Samuel I. Sifers**

Texas Agricultural Experiment Station and Department of Soil and Crop Sciences
The Texas A&M University Systsem

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* Professor Emeritus of Turfgrass Science, now Director of International Sports Turf Institute
** Turfgrass Research Associate, Turfgrass Physiology

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Abstract

The ever increasing intensity of traffic on golf greens, sports fields and race tracks during the past three decades necessitated the development and use of high-sand root zones, such as the Texas-USGA Method, described in section A. This development minimized serious soil compaction problems, and provided a higher quality turfed playing surface.

The objective of this investigation was to assess the use of randomly oriented, interlocking mesh elements for the stabilization of high-sand root zones, while at the same time retaining or enhancing a favorable environment for turfgrass root growth. The mesh elements consist of discrete 50 by 100 mm (2 x 4 in.) rectangular units, with open ribs extending from the perimeter and a square aperture between the mesh element ribs of 10 by 10 mm (0.4 x 0.4 in.). The open ribs extending from the perimeter facilitate an interlocking structure that provides a unique three-dimensional matrix of a relatively fixed, but microflexible, nature. Five key studies have been conducted since 1985 at College Station, Texas, including two long-term field investigations.

The findings revealed three major beneficial dimensions attributed to the use of a randomly oriented, mesh element matrix. The first dimension was root zone-turf stabilization including (a) enhanced soil stabilization especially in sandy soils and on steep slopes, (b) improved load-bearing capacity, (c) better resistance to surface rutting and deformation, (d) reduced divot size, (e) enhanced divot opening turf recovery, and (f) reduced lateral cleat turf tear. Secondly, in terms of playing surface quality for sport and recreational activities, the research results showed an improved uniformity of ball bounce, less surface hardness for better participant safety, and a sustained level of acceptable turf quality for a greater number of competitions. Finally, an enhanced turfgrass root zone environment was revealed with improvements in the (a) water infiltration rate, (b) soil water percolation rate, (c) soil moisture retention, and (d) overall turfgrass health. There was also less compaction and a reduced potential for black layer problems, especially on relatively fine textured high-sand root zones.

Thus, the randomly oriented, interlocking mesh element matrix offers a diverse array of root zone and turfgrass performance or health benefits with good potential for use on turfed sports fields, race courses, golf courses, animal competition/show grounds, path and road ways, load-bearing areas, and steep sloped banks that are subjected to intense usage.

A. Background of Soil Modification for Green and Sport Turfs

In the pre-1940s, greens and sports fields were constructed with high clay content soils. This was practiced for two primary reasons: (1) better stability of the surface for sports use, and (2) better water holding characteristics that assisted in sustaining an actively growing green turf in the dry summer period when there was no irrigation capability. The compaction proneness of clay was not an issue because traffic was light.

The late 1940s and early 1950s introduced an era of (a) increasingly intense traffic, (b) public demand for higher quality turfed greens and sport surfaces, and (c) the development and widespread use of overhead sprinkler irrigation systems for greens and sports fields. The increasing traffic combined with the traditional construction approach of relatively high clay soils led to soil compaction problems that became the limiting factor in turfgrass culture on recreational surfaces (Beard, 1973).

Because the increasing soil compaction problem was seriously limiting turfgrass growth, both practitioner trial-and-error approaches and detailed soil physics research with high-sand content root zones evolved. The primary objective in using sandy textured soils was to provide adequate drainage of excess water and the resultant aeration needed to support rooting and overall healthy turfgrass growth. This early interest in high-sand root zones for greens and sports fields was pioneered in the United States (Beard, 1973). The first root zone construction system that was soundly based on scientific principles and backed by extensive laboratory and field research was the Texas-United States Golf Association (USGA) Method of root zone construction developed at Texas A&M University under the direction of soil physicists M.E. Bloodworth and J.B. Page (Kunze, 1956; Howard, 1959; USGA Green Section, 1960; Ferguson, 1965; USGA Green Section, 1973; Johns, 1976). M.H. Ferguson, then the USGA Green Section Director, was actively involved in the transfer of this innovative technology to golf course users. For the first time, detailed construction specifications and a soil physical testing procedure were established for green and sport field root zone construction to identify root zone components and their percentage compositions that met those specifications (Ferguson, Howard, and Bloodworth, 1960).

This Texas-USGA Method of root zone construction has proven the test of time with numerous successful turfed root zones having been in place for more than 30 years (Figure 1). Note, just as in proper construction with asphalt or concrete, a key to success is proper construction that follows all the specifications in detail. Also, while this method carries the name of the original research location and the funding agency, the method is uniquely designed for use throughout the world and has successfully functioned in a diverse range of climates.

The Texas-USGA Method

Suggested specifications for the Texas-USGA Method are based on the 1960 specifications, with subsequent evolutionary refinements (USGA Green Section, 1960; USGA Green Section, 1973; Beard, 1982). It consists of a 300 mm (12 in.) settled root zone over a 50 mm (2 in.) intermediate coarse sand zone, over a 100 mm (4 in.) gravel or crushed stone drainage bed which overlays a drain line network (Figure A-2). It is important that the final surface grade insures drainage of excess water across and off the surface, usually in multiple directions. The construction method for sports field and green construction is as follows:

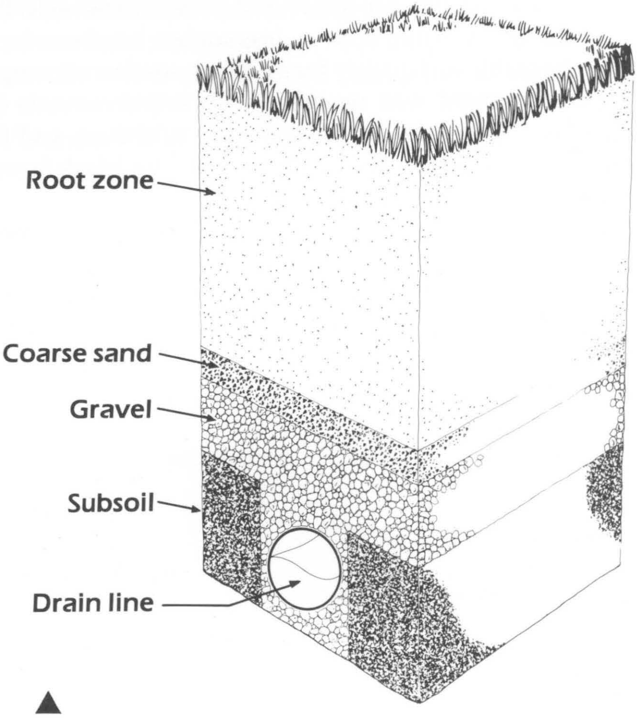

Figure A-2. Profile of a Texas-USGA Method high-sand root zone modification with a water conserving perched hydration zone.

Subgrade

Contour the subgrade so it conforms to the proposed finished grade, with a tolerance of ± 25 mm (± 1 in.). The subgrade should be 450 mm (18 in.) below the planned finish grade and should be firmed to prevent settling. Care should be taken to insure that the final subgrade base contours, within the overall slope, drain of gravitational water to the nearest drain line.

Subsurface Drainage System

A herringbone or gridiron design is utilized, with 100 mm (4 in.) diameter drain lines spaced at 4.6- to 6-meter (15 to 20 ft.) intervals at a minimum grade of 0.5 percent. The drain line trenches should be cut into the subgrade at as shallow a depth as possible. A 38 to 50 mm (1.5 to 2.0 in.) depth of 6 to 10 mm (0.24 to 0.39 in.) diameter crushed stone or gravel is placed in the bottom of the trenches and the drain lines laid. Then additional stone or gravel is placed around and over the drain lines to fill the trenches.

Drainage Layer

Angular, hard, noncalcarious, washed, screened river run gravel or crushed stone of 6 to 10 mm diameter should be selected for covering the subgrade to a minimum settled depth of 100 mm (4 in.). The proper sized crushed stone or gravel must be obtained to prevent migration of the sand into the gravel or stone bed and thereby preserve the integrity of two distinct layers: the upper high-sand mix over gravel or crushed stone. This drainage layer functions in the rapid lateral movement of gravitational water to the drain lines. Also, the porous crushed stone or gravel base prevents the upward capillary rise of salts from the soil base into the root zone. During installation, the crushed stone or gravel is typically dumped from the delivery trucks on the perimeter and then distributed over the construction site by a small, tracked crawler tractor, being careful to avoid driving over and crushing the drain lines.

Coarse Sand Zone

A 50 mm (2 in.) deep layer of washed, screened, hard, angular coarse sand of 1 to 2 mm diameter is carefully spread over the drainage layer. The specific size of the sand particles must be within 5 to 7 diameters of the underlying crushed stone or gravel. Thus, if 6 mm stone or gravel is used, the particle size of the coarse sand zone should be not less than 1 mm in diameter. This coarse sand zone has two key functions: (1) To prevent infiltration of the high-sand root zone mix into the spaces between the drainage layer particles and (2) To create a perched hydration zone of plant available water immediately above the drainage layer in the lower portion of the high-sand root zone mix. The distinct interface between the coarse sand zone and the upper 300 mm (12 in.) of settled high-sand root zone mix disrupts the continuity of surface interfaces among the particles and the downward movement of water. When the perched hydration zone above the interface approaches water saturation, the force of gravity overcomes the interface perched effect and the excess water is released downward.

Installation of the coarse sand zone is best accomplished manually, taking care to not mix the sand with or into the drainage bed. The coarse sand is dumped from the delivery trucks on the outside perimeter, and is typically moved across the crushed stone or gravel by wheelbarrows over a path of plywood boards. This thin coarse sand layer presents some difficulties in installation. However, this intermediate zone is critical to the overall concept and is a modest long term investment compared to turf failure and rebuilding costs if improperly constructed.

Substitution of a nonbiodegradable screenlike material for the coarse sand intermediate zone has been proposed. Problems have been observed with these geofabrics which tend to become clogged to the extent that they are impermeable to water and may cease to drain. However, a more open, non-filter mesh or netting may be used between the intermediate coarse sand zone and the drainage layer when using gravel to provide a stabilizing effect during construction. This netting should not be necessary when using angular crushed stone due to the stability of this material.

Ringing the Perimeter

Polyethylene sheeting should be permanently inserted as a vertical barrier between the outer native soil and the root zone mix. This barrier prevents lateral water transfer into the adjacent dry soil, which would cause perimeter turf water stress. When the sheeting is extended 100 to 150 mm (4 to 6 in.) above the surface during construction, it will also function in preventing erosion of unwanted soil onto the construction area.

Root Zone Mix Installation

Quality control is the key to successful execution of root zone modification. All root zone mixing should be completed off the construction site, termed off-site mixing. Although it sounds good, in practice the procedure of in-place rotary tilling of the organic and/or soil components into the high-sand component has not been successful. Every truck load of each component in the soil mix, as well as the gravel and coarse sand, should be checked at delivery to insure that the specifications are met.

Off-site mixing includes soil shredding, screening to remove any objectionable stones, and addition of the specified proportions of each mix component. Because of the narrow range in acceptable limits of the physical properties, it is very important that the laboratory recommendations be explicitly followed in mixing the components of the root zone mix. Upon confirmation that the root zone mix has met the specifications, it is transported to the construction site and dumped around the perimeter onto the coarse sand zone. A small, crawler tracked tractor with blade then pushes the mix over the area being careful to avoid crushing the drain lines. Be sure the unit is operated with its weight on the root zone mix. This reduces the chance of disturbing the lower construction profile.

Caution

Use of wheeled tractors causes rutting and they are more likely to crush the drain lines than are tracked vehicles. Grade stakes placed in a grid pattern at 3 to 4.5 meter (10 to 15 ft.) intervals will aid in constructing the final contours to the specified root zone depth. Success has been achieved by carefully selecting the components of the root zone mix and by careful adherence to the construction guidelines.

Texas-USGA Root Zone Mix Specifications

The greatest problem encountered in maintaining turfgrasses on sports fields is soil compaction. This pressing together of the soil particles into a more dense mass results in impaired drainage of excess water and a loss of proper aeration needed to provide oxygen for healthy root growth. As a consequence, there is a general decline in turfgrass health, vigor, and recuperative ability following turf injury from wear stresses.

Soil compaction and the resultant negative effects can be minimized by selection of a high-sand root zone of the proper particle size distribution and associated key physical and chemical characteristics. The result is minimum proneness to compaction, adequate drainage of excess gravitational water, and proper aeration to provide needed oxygen for root growth and related soil biological activity.

However, such high-sand root zones are very droughty due to poor water retention capacity unless a perched hydration zone, such as achieved through the Texas-USGA Method, is utilized in the construction specifications. In addition, high-sand root zones tend to have a low cation exchange capacity, thus, the leaching of essential plant nutrients is a greater concern, particularly during the initial years following construction. This potential problem can be minimized through the use of slow release nutrient carriers and/or the timely use of foliar feeding techniques.

Composition of the 300 mm (12 in.) settled depth of root zone mix should be selected based on specific physical tests conducted in a reputable Physical Soil Test Laboratory. The test report specifies the particular materials and the percentages in which they are to be mixed. The desired characteristics for a Texas-USGA Method root zone mix are given in the following paragraphs.

Component Descriptions of Root Zone Mix

It is important that the three components selected for the root zone mix be free of toxic levels of materials such as heavy metals, persistent crop herbicides, and industrial organic chemicals. Minimal amounts of soluble salts, boron (B), and sodium (Na) are preferred.

Sand Component

Angular, hard, washed, screened silica sand is strongly suggested. Avoid high pH calcarious sands. The preferred sand component particle size is: 100 percent below 1.0 mm (18 mesh), 65 percent below 0.5 mm (35 mesh), 25 percent below 0.25 mm (60 mesh), and 5 percent below 0.05 mm (270 mesh). Note: the mesh sieve size refers to the US Standard of the United States Department of Agriculture (USDA).

Organic Matter Component

It is suggested that the organic matter source selected be well decomposed and have no more than 15 percent ash or mineral content, preferably less than 10 percent mineral content. Examples include peat humus and reed-sedge peat. The organic material should be shredded to insure mixing uniformity, but not to the degree that the material is pulverized thereby causing reduced soil water infiltration.

Soil Component

A sand, loamy sand, or sandy loam topsoil is suggested. The soil should be shredded to insure mixing uniformity and should be screened to remove stone and other debris.

Composite Root Zone Mix Particle Size Distribution

It is suggested that the root zone mix contain less than 25 percent particles smaller than 0.25 mm (60-mesh), and contain less than 5 percent silt and 3 percent clay. The suggested specifications for the particle size distribution of the root zone mix are shown in Table A-1. Figure A-3 is a graphic illustration of the same data as a grading analysis distribution envelope.

Composite Rootzone Mix Physical and Chemical Properties Criteria

The physical or chemical properties preferred for the composite root zone mix are summarized in Table A-2.

Mix Water Infiltration Rate

The preferred water infiltration rate for a laboratory compacted root zone mix is in the range of 150 to 300 mm per hour (6 to 12 in./hr.). The rate in the laboratory tests should not exceed 600 mm per hour (24 in./hr.). The upper limit in the water infiltration rate is designed high enough to account for the normal on-site reduction in infiltration rate that occurs during the first 3 to 4 years due to increases in roots and organic material.

Table A-1. Suggested guidelines for particle size distribution of the Texas-USGA root zone mix.

Gravel	Very Coarse	Coarse Sand	Medium Sand	Fine Sand	Very Fine Sand	Silt and Clay
> 2 mm	1 - 2 mm	1.0-0.5 mm	0.50-0.25 mm	0.25-0.10 mm	0.10-0.05 mm	< 0.05 mm
Maximum 3% Ideal 0%	Maximum 7%		Minimum 50%	Maximum 17%		Maximum 3% clay 5% silt
Maximum		Desired range		Maximum		
Not more than 10% of total		65% Minimum 75% Optimum		Not more than 25% of total, preferably 10% of total		

Table A-2. Suggested physical and chemical guidelines for the composite root zone mix.

Physical or chemical property	Units	Acceptable range	Preferred
Infiltration rate of compacted mix	mm per hour (in./hr.)	150-600 (6-24)	150-300 (6-12)
Aeration porosity:	% by volume		
Total pore space		40-55	47
Noncapillary pore space		15-30	25
Capillary pore space		15-25	22
Water retention capacity	% by weight (mm H_2O/10 mm of soil)	12-25 (1-2)	18 (1.5)
Bulk density	gram/cc	1.2-1.6	1.4
Soil reaction 6.0-6.5		pH	5.5-8.0
Soil salinity (electrical conductivity)	EC x 10^{-3} (millimhos/cm)	< 4	0-1
Soil sodium	ESP	< 15	—

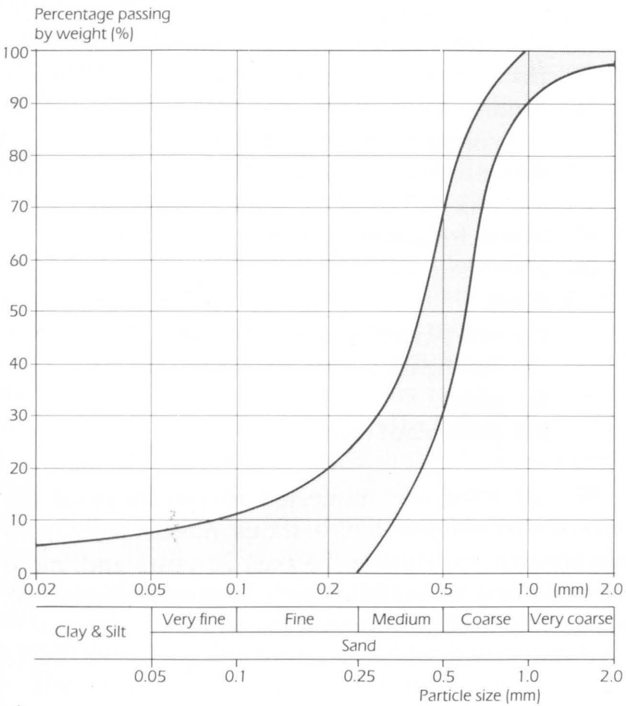

Figure A-3. Grading analysis particle size distribution envelope for the Texas-USGA root zone mix.

Mix Aeration Porosity

An acceptable total pore space volume is between 40 and 55 percent. The preferred distribution would be 22 percent capillary and 25% noncapillary pore space. Noncapillary pore space should be not less than 15%. The measurements are made on a root zone mix that has been allowed to percolate water for 8 hours and then is drained at a tension of 400 mm of water.

Mix Water Retention Capacity

An acceptable laboratory-established 400 millimeter water retention capacity would be between 12 and 25 percent by weight on a 105 to 111°C- oven dry soil basis. The available water in the soil is estimated to be that held at a tension of 400 mm of water, which is the approximate distance from the surface to the drain line. The preferred water retention capacity is 18 percent, or 1.5 mm of water held per 10 mm of soil.

Mix Bulk Density

The preferred root zone mix should have a bulk density of 1.4 grams per cc; with a minimum acceptable bulk density of 1.2 and a maximum of 1.6 grams per cc.

pH

The acceptable pH range is 5.5 to 8.0, and the preferred pH range is 6.0 to 6.5.

Soil Salinity/Electrical Conductivity

The acceptable range is less than 4 millimhos per cm, with the preferred range being between 0 and 1.

Soil Sodium Level

The acceptable range is an exchangeable sodium percentage (ESP) of less than 15, with the preferred being a minimal sodium level.

Root Zone Mix Analysis

The starting point in selection of a root zone mix involves obtaining detailed physical and chemical descriptions of the components being considered for a root zone mix and how they respond when mixed in various combinations. One or more representative samples of each sand, organic matter, and sandy soil component under consideration for use should be submitted to a reputable Physical Soil Test Laboratory. Only a few Physical Soil Testing Laboratories are equipped to conduct the specific Texas-USGA Method tests (Ferguson, Howard, and Bloodworth, 1960).

The primary laboratory physical determinations made are the particle size distribution, bulk density, and mineral composition. The next laboratory step is to combine various proportions of the sand, organic matter, and sandy soil, based on physical determinations. These trial mixes are compacted and then evaluated for water infiltration rate, moisture retention, bulk density, and pore space. Mixes are made and tested until one is found that conforms to the standards. Recommendations as to the relative volume of each component to be used are then given.

The crushed stone or gravel for the drainage layer and the coarse intermediate sand also should be tested for particle size diameter to assure that the root zone mix does not wash down and block the drains.

In addition to recommendations concerning the appropriate sand, organic matter, and soil materials and their mix proportions, a description of the chemical properties of each material is needed. Included are the pH, total salts, and levels of phosphorus (P) and potassium (K). A sodium (Na) analysis is occasionally needed.

Submitting Soil Materials for Testing

A laboratory physical analysis requires a minimum of 8 liters (2 gal.) of sand, and 4 liters (1 gal.) each of organic matter, soil, intermediate coarse sand and crushed stone or gravel. If there is a choice of sands, organic materials, and sandy soil, send samples of each along with a note indicating a preference based on cost, accessibility, and quantity available. The laboratory will attempt to use the preferred, most cost effective materials in the recommended root zone mix.

Representative samples of the materials must be collected. If the materials are stocked, make sure to composite several samples dug from within the side or top of the stockpile. Materials near the edge or on a sloping surface may not be representative. Make sure that a prospective vendor will have sufficient stocks of uniform materials over a long period so that if there is a delay of a few months, the materials available at the time of construction will be the same as the original samples tested. All samples should be packaged separately and securely. Strong plastic bags inside cardboard cartons or metal cans are most satisfactory. Use plastic labels inside the package and also to mark the outside of the package.

Construction Plan

Proper sports field construction usually involves an extensive subsurface drainage system, specialized root zone modification, and subtle surface drainage contours. It is a critical aspect, since improper construction due to cost cutting results in higher long-term maintenance costs, problems in maintaining a quality playing surface, frequent loss of turf, and costly reconstruction (Beard, 1973 and 1982). The steps in construction are:

(1) Survey and stake
(2) Construct subgrade
(3) Install a subsurface drainage system
(4) Modify root zone:
    (a) construct drainage layer
    (b) construct coarse sand zone
    (c) mix and install specified root zone
(5) Install irrigation system
(6) Finish surface contours
(7) Plant
    (a) soil pH adjustment, if needed
    (b) fertilization based on soil tests
    (c) plant
    (d) post-plant care

By following the suggested specifications of the Texas-USGA Method, tens of thousands of greens have been constructed during the past 30 years and, more recently, many sports fields have been constructed and successfully used throughout the world.

B. High-Sand Root Zone Advantages

While there have been a number of high-sand content root zone specifications proposed, many being modifications of the Texas-USGA Method, they tend to be deficient in sound science with inadequate fundamental research to support the concept. Many proposed root zone mixes are only slight modifications of the Texas-USGA Method, but they result in significant changes from a practical soil physical performance standpoint. Among all these proposed root zone mixes, none have proven nearly as successful and reliable under a diverse range of climatic and soil conditions throughout the world as the Texas-USGA Method. The advantages of a high-sand root zone of the proper particle size distribution include:

1. Resistance to compaction problems.
2. Favorable soil water infiltration and percolation rates.
3. Increased effective precipitation due to reduced surface runoff.
4. Enhanced aeration that provides adequate oxygen for root growth.

Scenes of mud-covered players are history for those sports fields properly constructed using the Texas-USGA Method specifications. The primary problem now developing is not the underground limitations of poor drainage and lack of aeration characteristic of the finer textured root zones, but rather the divoting and turfgrass wear of above ground shoots. Under and ever increasing intensity of traffic stress, this latter problem eventually leads to turf thinning and bare areas. The use of improved turfgrass cultivars with (a) more rapid shoot growth rates, (b) a greater green biomass, (c) higher proportion of sclerified tissue in shoots, (d) better recuperative potential, and (e) disease resistance has partially solved this problem. This success has led to even greater use intensity of individual sports fields and race tracks. The next major innovation needed is an effective method of stabilizing the high-sand root zones, while retaining a favorable environment for turfgrass root growth.

C. The Mesh-Element Inclusion Concept

The research reported here assesses the use of randomly oriented, interlocking mesh elements as a means of stabilizing high-sand root zones and improving the playing characteristics of sports turf surfaces. In this system, the stress transfer mechanisms between and among the soil particles and the mesh elements rely upon an interlocking dimension. Mesh inclusion studies have been conducted with a range of soils utilized in roadbed construction (McGown, Andrawes, Hytiris, and Mercer, 1985; Mercer, Andrawes, McGown, and Hytiris, 1984). These studies examined soil stabilization through the use of randomly oriented tensile inclusions or mesh elements in order to alter the stress-strain behavior of granular soils. Soil particles interlock through the apertures in the mesh elements creating stable aggregations within and adjacent to the mesh. Each randomly arranged aggregation in turn interlocks with adjacent mesh-particle aggregations to form isotopically stabilized assemblages. In effect, the randomly arranged mesh elements cause individual soil particles to act in aggregates that join together to form a stable mass (Andrawes, McGown, Hytiris, Mercer and Sweetland, 1986). This aggregate response research emphasized the mesh element influence on silty and sandy soils. The effectiveness of the mesh elements on aggregation on clay soils has not been investigated.

The unique properties of the mesh elements in terms of flexural stiffness, tensile strength, junction strength, and dimensional stability are all critical for the achievement of soil improvement. Since this system has proven very effective in improving the stability of soils for engineering applications, feasibility investigations were initiated concerning the use of randomly oriented, interlocking mesh elements in turfed sports field and race track root zones for the purpose of providing (a) reduced turf divoting and tear through root anchorage, (b) better overall sand root zone-turf stabilization, (c) increased traction, and (d) improved surface uniformity, including ball bounce.

The mesh elements consist of discrete 50 by 100 mm (2 x 4 in.) rectangular elements, with open ribs extending from the perimeter, as manufactured by the Netlon® process from polypropylene. The square aperture between the individual ribs of the mesh element is 10 by 10 mm (0.4 x 0.4 in.) or 100 mm^2 (0.16 in.^{2}). The open ribs extending from the perimeter of each mesh element facilitate an interlocking structure of multiple elements in a randomly oriented matrix (Figure C-1). The result is a unique three dimensional matrix of a relatively fixed, but microflexible nature, which insures that the mesh elements remain in a stable position within the root zone. The turfgrass roots intertwine the mesh element ribs to secure a strong turf anchorage effect. The rectangular shape and specific size of the mesh

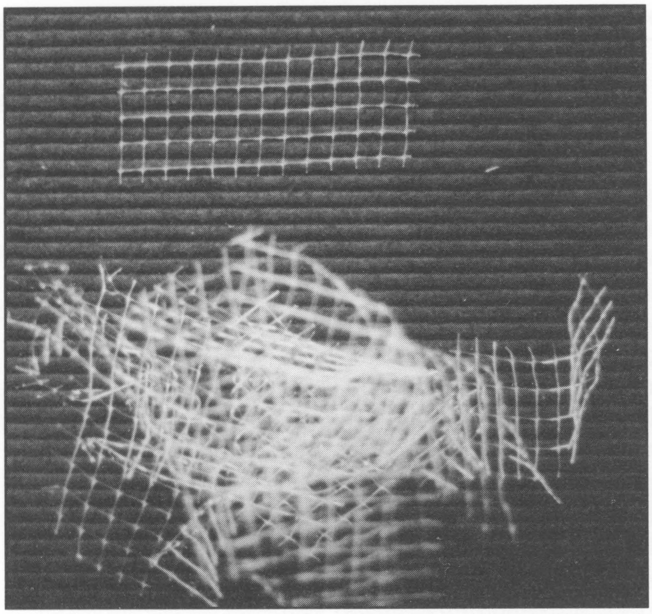

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Figure C-1. Closeup view of the 50 mm by 100 mm rectangular mesh elements with open ribs (above) and in a randomly oriented, interlocking matrix (below).

elements selected for these investigations are based on extensive studies comparing a range of alternative shapes and sizes in terms of the most effective configuration for overall soil stabilization.

In the late 1960's at Michigan State University, J. Beard conducted a number of experiments with two dimensional, horizontal layers of mesh netting in various rib spacings. These horizontally oriented materials rely on simple friction. The two dimensional materials tended to either move downward into the soil relative to the turf surface or, under intensive turfgrass wear, would appear at the surface where they became torn, proved unsightly, and could interfere with ball roll and/or running of participants. The three dimensional interlocking mesh element assemblage provides a far more stable positioning that avoids the problems just described for the two dimensional type nettings.

Efforts also are being made to stabilize sand root zones using textile fibers and synthetic strands, which function primarily in a two dimensional mode and which lack both the flexural stiffness and interlocking capability of the mesh elements produced by the Netlon® process. There is a lack of published, replicated research concerning the effects of these strands and/or fibers on sustained turf performance when under intense traffic stress.

D. Terminology

The terminology for traffic stress used in this paper is as follows (Beard, 1973). Specifically, traffic consists of two primary components. One is turfgrass wear, which involves the above ground injurious effects of concentrated traffic on the turf. The turfgrass wear component is characterized by divot opening, turf tear, and/or bruising dimensions. A divot is a piece of turf severed from the soil by a sports shoe that is usually cleated, a golf club, or a projectile impact such as a golf ball, while a divot opening is the resultant open space left in the turf. Turf tear is damage involving the pulling apart of the turf matrix, especially tillers and secondary lateral stems, typically caused by lateral sliding or twisting of cleats, studs, or spikes on sports footwear. Bruising is injury to the surface of turfgrass plants involving primarily the leaf blades of above ground shoots, caused primarily by the downward and/or lateral pressures of footwear and vehicular tires.

The second traffic component, soil compaction, is a more indirect hidden effect involving the pressing together of soil particles into a more dense soil mass, typically resulting from mechanical pressure applied by human or vehicular traffic.

In terms of playing surface characteristics, assessments such as traction, ball bounce, surface hardness, and compression displacement can be made. Traction encompasses the properties of a turf that enable a player with footwear, usually having cleats, studs, or spikes, to obtain a grip on the turf surface. Ball bounce is the elastic rebound of a ball as a result of collision with a surface, which is quantitatively measured as the percent rebound height when dropped without spin from a fixed height. Surface hardness is the resistance to pressure of a turfed surface or the effect a turfed surface has on absorbing the impact energy of an external object. Compression displacement is the amount of change or lowering of the turfed soil surface caused by an external force pressing the affected area into a smaller space.

The term sports turfs will be used in the broad sense in this paper to include turfed surfaces for team sports fields, horse race tracks, polo fields, horse jumping courses, tennis courts, bowling greens, and golf course tees, fairways, and greens.

E. Research Evaluation Techinques

Divoting

One of the more destructive dimensions on turfs where sports, such as American football or golf, are played is divot removal. A divot simulation apparatus was designed, constructed, and successfully tested in 1985 to assess divot opening size and recovery rate (Beard and Sifers, 1989a; Beard and Sifers, 1989b; Beard and Sifers, 1990) (Figure E-1). It consisted of an adjustable horizontal swinging pivot bar positioned above the soil surface by a metal frame. Attached to the center pivot was a 1400 mm (55 in.) long bar of 25 mm (1 in.) diameter. Attached to the lower end of the free swinging bar was the lower portion of a nine iron golf club, above which was fixed a weight. The bar plus weight totaled 10 kg (22.5 lb.). The free swinging divot apparatus was dropped from a set height of 2000 mm (79 in.) above the soil surface, producing a divot typically ranging from 40 to 300 mm (1.5 to 12 in.) in length and 30 to 90 mm (1.2 to 3.5 in.) in width. To produce this range in divot sizes, the divot simulation device was adjusted so that the bottom of the club was 30 mm (1.2 in.) below the soil surface at the lowest point in the arc of the swing during 1986. It was adjusted to swing 25 mm (1 in.) below the soil surface for 1987 and 20 mm (0.8 in.) below the soil surface for 1988. Three individual divot simulations were imposed within each subplot (Figure E-1). The length, width, and depth of the divot opening was immediately measured at the soil surface. The divot openings were not repaired and were subsequently assessed for recovery rate at weekly intervals using the same measurement techniques.

Compression Displacement-Turf Tear-Traction Apparatus

An apparatus for the assessment of compression displacement, lateral tear, and traction was designed, constructed, and successfully tested in 1985 (Beard and Sifers, 1989a; Beard and Sifers, 1989b; Beard and Sifers, 1990) (Figure E-2). The apparatus consisted of a two-level, four-legged bench of 450 by 250 mm (17.7 x 9.8 in.), with the individual metal benches positioned 900 and 400 mm (35.4 and 15.7 in.) above the soil surface. A 15 mm (0.6 in.) hole was drilled in the center of each bench through which an 8 mm (0.3 in.) diameter by 800 mm (31.5 in.) long metal rod was vertically positioned. A small platform, designed to hold 330 mm (13 in.) diameter metal weights, was attached to the upper end of the vertical rod. Positioned at the lower end of the vertical rod was an attachment to which could be fixed a cleated plate or similar device, depending on the specific assessments desired. The plate used had an oblong shape of 260 by 100 mm (10 x 3.9 in.) with five cleats or studs each of 5 mm (0.2 in.) long and 1.5 mm (0.05 in.) in diameter, with a 40 mm (1.5 in.) spacings between cleats. A 280 mm (11 in.) long bar was attached perpendicular to the center vertical bar at a height of 100 mm (4 in.) from the base. A metal cable was attached to the end of the horizontal bar and extended through a series of pulleys to a scale attached to a winch.

▲

Figure E-1. View of the divot simulation apparatus. A closeup of the resulting divot openings is shown in the color section, page 29.

▲

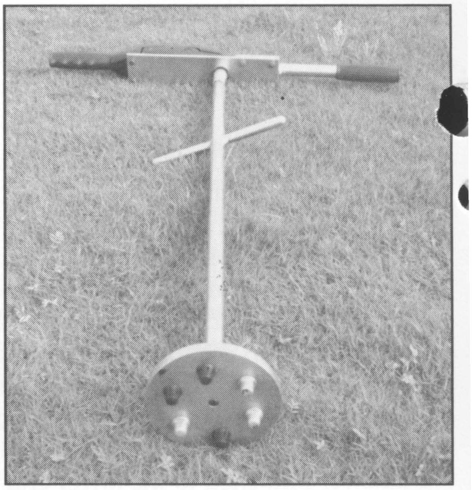
Figure E-2. View of the compression displacement-turf tear-traction simulation apparatus.

Compression Displacement Assessment

The apparatus previously described was used for assessment of compression displacement by dropping the cleated plate from a height of 300 mm (12 in.). The depth of soil displacement was measured from the soil surface downward in a centered position. The apparatus was moved and releveled for three replicate tests within each subplot. Two hammer weights of 4.5 and 11.25 kg (10 and 25 lb.) were utilized in each compression displacement drop test.

Lateral Turf Tear and Traction Assessments

The tearing of sport turfs due to the twisting action of cleated shoes is a very stressful dimension of turfgrass wear. Traction and extent of turf tear were assessed using the simulation apparatus previously described. After dropping the cleated plate from a height of 300 mm (12 in.), a uniform pull was applied with a winch, and the weight required to rotate the cleated plate over 90° was monitored as traction measured in Newton meters (Nm). The length of turf tear produced by the outermost cleat was measured at the soil surface. Two different weights of 4.5 and 11.25 kg (10 and 25 lb.) were utilized in each of the 300 mm (12 in.) drops. Three replicates each of traction and tear length were assessed within each subplot. The apparatus was moved and releveled after each test. This apparatus was used for assessments in 1985 and 1986.



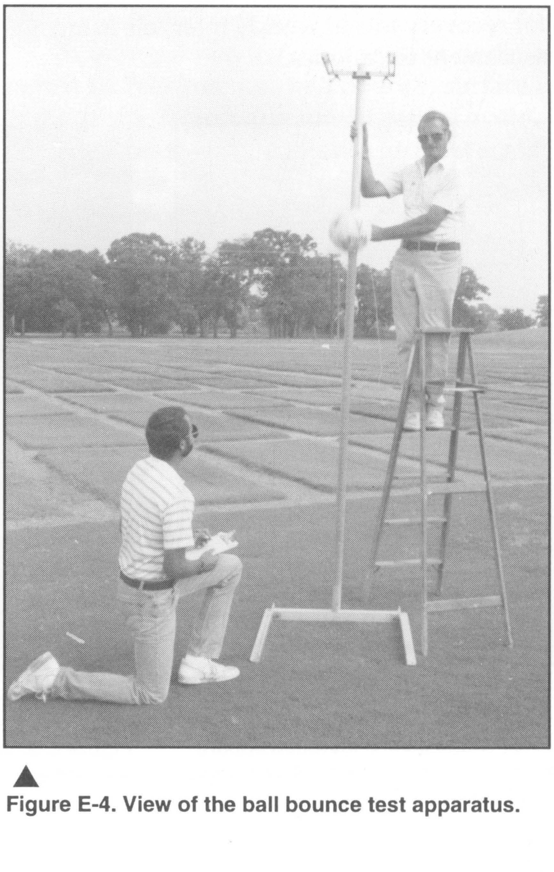
▶ **Figure E-3. Two views of the modified traction simulation device.** ▼

Traction Apparatus

An alternate traction assessment apparatus was employed in 1987 and subsequent years, which is a modification of the traction test device described by Canaway and Bell (1988) (Figure E-3). The apparatus consisted of a 150 mm (6.0 in.) diameter steel disc base. Six football studs, each of 12 mm (0.5 in.) in diameter, were positioned in a circle 46 mm (1.8 in.) from the center of the disc. The disc was attached at the base of a 900 mm (36 in.) long shaft at the top of which were provisions for positioning a two-handled torque wrench. Weights were placed above the steel disc to give a total weight of 4.5, 11.25 or 40 kg (10, 25, or 88 lb.). The entire apparatus was dropped from a controlled height of 60 mm (2.4 in.). Traction was assessed as the torque in Newton meters required to turn the studded plate planted in the turf through 90°. Lateral turf tear and compression displacement were assessed as previously described. Three assessments were made within each subplot.

Ball Bounce

In sports involving the bounce of a ball, the effects of the playing surface characteristics upon the ball are an important dimension. The assessment methodology used involved a vertical support device which released the ball from a height of 3 m (9.8 ft.) (Winterbottom, 1985) (Figure E-4). The ball release mechanism dropped



▲ **Figure E-4. View of the ball bounce test apparatus.**

the ball without impulse or spin. The soccer ball used was approved by the Federation Internationale de Football Association (FIFA), and was inflated to 0.61 bar (9 psi.). The results were based on ball bounce expressed as the ratio of rebound height to height dropped. Five assessments were made within each subplot.

Surface Hardness

The effect a surface has on absorbing the impact energy (hardness) created by ball bounce, player shoe actions, or hooves of a race horse, is an important quality of sports fields and race courses. This characteristic affects players or race horse safety as well as performance. Surfaces that are unduly firm or hard may be dangerous to the point of injury, and those surfaces that are too soft can create fatigue in players or horses. The impact absorption characteristics of a surface can be quantitatively measured using the Clegg Impact Soil Tester (CIT) developed by Dr. Baden Clegg (Figure E-5) for testing road base compaction (Clegg, 1976). The digital read out of the CIT which shows the peak deceleration (g max) of an accelerometer mounted in an impact hammer or missile with a surface area of 202.3 mm^2 (7.9 in^2), dropped from a set height, creates a Clegg Impact Value (CIV).

Standard CIV references of soccer (football) field playing quality for turf have been proposed by Holmes and Bell (1987) using the 0.5 kg (1.1 lb.) hammer weight (Table E-1). Rogers and Waddington (1990) have studied athletic field hardness using the CIT with hammer weights of 0.5, 2.25, and 4.5 kg (1.1, 5 and 10 lb.) for impact absorption measurements in conjunction with other devices.

Three assessments were made within each subplot. Each assessment was the digital reading of the fourth drop from a 300 mm (12 in.) height in the same location. The fourth drop was selected based on extensive statistical analyses of repeatability.

◀ **Figure E-5. View of the Clegg Impact Soil Tester for surface hardness.**

Commencing with the 1989 data collection, surface hardness was assessed using the 0.5 kg and 4.5 kg (1.1 and 10 lb.) Clegg hammers; while in 1990 and subsequent years the 0.5, 2.25, and 4.5 kg (1.1, 5, and 10 lb.) Clegg hammers were used to quantitatively assess the surface hardness of the mesh element treatments at the Texas A&M Turfgrass Laboratory and the turf race course at Santa Anita Park in Arcadia, California. Based on these studies, Sifers and Beard (1992) have determined CIV-performance criteria for turfed horse race tracks (Table E-2).

Soil Moisture

Following the assessments conducted during 1986, it became apparent that some variability among assessment dates was the result of varying soil moisture levels.

Table E-1. Peformance criteria for turfed soccer fields. The following are standards established by the U.K. Sports Turf Research Institute. They are for the Clegg Impact Values (CIV) measured on turfed soccer fields using a 0.5 kg (1.1 lb) hammer. The deceleration peak is expressed as the maximum deceleration of the hammer in gravity (g) units. Each reading was made on the first drop from a 300 mm (12 in.) height.

Turf-soil status	CIV deceleration peak (g)
Too hard	greater than 100
Acceptable	10 to 100
Preferred	20 to 80
Too soft	less than 10

Table E-2. Performance criteria for turfed horse race tracks. The following are standards based on research conducted by Texas A&M Turfgrass Scientists, Sifers and Beard, at the Santa Anita Park turf track in Arcadia, California, using a 0.5 kg (1.1 lb.) hammer. Each reading was made on the fourth drop from a 300 mm (12 in.) height in the same location*.

Turf-soil status	CIV deceleration peak (g)
Excessively firm, more injury potential	greater than 110
Acceptable	90 - 110
Good, most speed, low injury potential	70 - 90
Good, fast, low injury potential	50 - 70
Acceptable	30 - 50
Too soft, slow, more injury potential	less than 30

* The fourth drop reading was selected based on extensive statistical analyses of repeatability.

Thus, starting in 1987, soil moistures were assessed at depths of 50, 100, and 150 mm (2, 4, and 6 in.) at the time the assessment parameters were made. Soil samples were collected, transferred in air-tight containers, weighed, dried in an oven at 105°C (221°F) for 24 h to remove water, and weighed again. The loss of weight on drying is the weight of water originally present, and it is expressed as a percentage of the oven dry weight of the soil. One assessment was made within each subplot for each depth.

F. Mesh Element Inclusion Feasibility Study

Objectives

Feasibility investigations were initiated in 1985 concerning the use of randomly oriented interlocking mesh elements in turfed sports field and race track root zones in terms of the potential effects in providing reduced turf divoting and tear, better overall soil-turf stabilization, increased traction, reduced soil compression displacement, and improved surface uniformity for ball bounce and running.

Materials and Methods

The feasibility assessment study was initiated in 1985 at the Texas A&M Turfgrass Field Research Laboratory in College Station, Texas. There were two basic treatments: (1) no mesh element versus (2) mesh element augmentation of a sand root zone. The mesh treatment consisted of 2.5 kg m^{-3} (4.2 lb./yd^3) density of mesh elements mixed in uncompacted high-sand and installed to a settled depth of 150 mm (6 in.) over a 125 mm (5 in.) settled depth of root zone without mesh and with a 25 mm (1 in.) settled layer of root zone mix without mesh distributed over the top. The 25 mm (1 in.) layer of root zone mix was originally placed on top to facilitate planting of vegetative sprigs or seed. However, an even more important reason for this layer was revealed in this study. The two treatments were arranged in a randomized block design with four replications. The plot size was 2.4 by 4.5 m (8 x 15 ft.), with four 0.6 by 1.1 m (2 x 4 ft.) subplots.

The root zone consisted of a 300 mm (12 in.) deep medium fine sand, with 100 mm (4 in.) diameter subsurface drainage lines in a gridiron arrangement with a 4.5-m (15 ft.) spacing. The root zone-mesh element matrix combination was mixed off-site using a small capacity rotating drum mixer. To achieve maximum uniformity of mixing the drum was closed by a lid and positioned horizontally, as it was found that the mesh element and sand tended to separate if the mixer drum was set in its normal diagonal position. The root zone mix components were premixed off-site prior to addition of the mesh elements. The treatment involving no-mesh consisted of the same sand root zone added to the four replicate plots to a comparable depth as that described for the mesh element-sand root zone matrix treatment.

Turf Establishment

The plot area was planted to Tifway bermudagrass (*Cynodon dactylon* x *C. transvaalensis*) in August of 1985. A preplant fertilization was applied at a rate of 1 kg (2 lb.) each of nitrogen (N), phosphorus (P_2O_5), and potassium(K_2O) per 100 m^2 (1000 ft^2.). The vegetative sprigs were planted by broadcasting across the plot area at a rate of 0.4 m^3 per 100 m^2 (14 bushel/1000 ft^2.), lightly topdressed, and fertilized with 1 kg P_2O_5 per 100 m^2 (2 lb./1000 ft^2.) to encourage rapid establishment. The experiment site was irrigated via pop-up gear-driven sprinkler heads positioned at 3.5 m (11.5 ft.) spacings. Turf establishment was achieved in 6 weeks.

Cultural Practices

The cultural practices imposed on the experimental area were representative of hybrid bermudagrass sports fields. Mowing consisted of a 25 mm (1 in.) cutting height practiced twice weekly using a three-gang reel mower, with clippings returned. The nitrogen fertilization rate was 0.4 kg N 100 m^{-2} (0.8 lb N/1000 f^{t2}.) per growing month, which typically extended from April through September. Phosphorus and potassium levels were maintained in the high range, based on soil tests conducted annually. Irrigation was used as needed to prevent visual wilt. No pesticides were applied to the experimental area during the study, which avoided any potential confounding effects in terms of toxicity to the roots. Also, no turf cultivation or vertical cutting was practiced during the study.

Assessments

The methods used to assess the randomly oriented interlocking mesh element-turfed root zone matrix performance are described earlier in section E. Assessments were accomplished in early summer and in early fall of 1986, early fall of 1987, and at four 6-week intervals during 1988, starting in May.

Results and Discussion

The turfgrass quality was assessed visually, in terms of a uniformity and a high shoot density, at 15-day intervals throughout each growing season. No differences in turf quality were noted between the no-mesh and mesh element-root zone matrix treatments throughout the study. Furthermore, there were no visual symptoms of turfgrass injury caused by disease or insect activity.

Turfgrass Injury

The dimensions of turfgrass injury associated with traffic stress assessed in this study were (a) divot opening length, depth, and width; (b) the associated rate of turf recovery of the divot openings; and (c) the lateral cleat turf tear, as affected by the presence of the mesh element in the root zone matrix. The findings are summarized in the Appendix, Tables F-1 and F-2.

There was a trend in all cases for reductions in both divot length and width as a result of mesh element inclusion. For summer and fall assessments in 1986 through 1988, the divot length and width were significantly reduced by the presence of a mesh element matrix in the root zone, except for the October 1986 and September 1988 assessments when there was a reduction trend but it was not statistically significant. The presence of a mesh element matrix resulted in a significant reduction in divot depth, except at the July 1986 and August 1988 assessments. The reduced divot opening size is probably the result of turfgrass roots being anchored in and around the mesh, as evidenced by physical examinations of the mesh-sand matrix profiles. The typical effect of mesh element inclusions on divot opening is illustrated in Figure F-1 with October 1987 data.

The most striking evidence for the importance of the mesh inclusions is illustrated by the turf recovery rate of the divot openings (Figure F-2). Generally, there was a 25 to 50 percent reduction in the time required for the turf to reestablish in the divot openings where the mesh element-root zone matrix was present, in comparison with the root zone without mesh elements. The smaller divot opening resulted in more rapid turf recovery due to a greater number of new tiller and lateral shoot initiations from the perimeter of the opening relative to the total area to be revegetated. This response translates to the potential for at least doubling the intensity of use on sports fields where a mesh element-root zone matrix system is utilized.

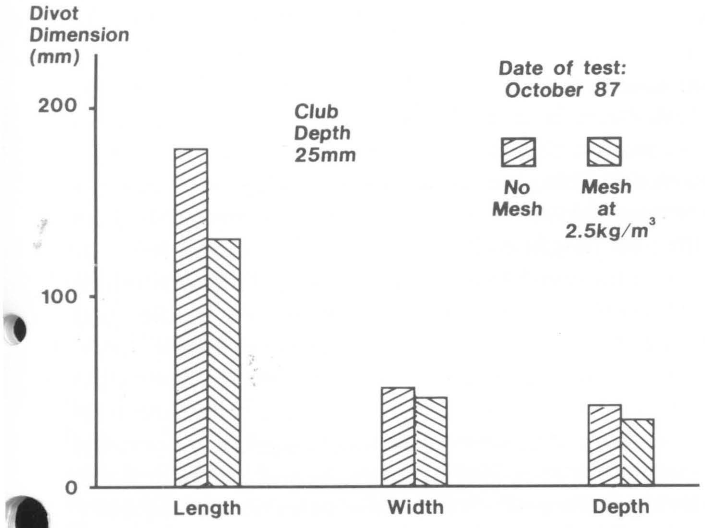
The presence of a mesh element matrix significantly reduced the length of cleat turf tear when under the 4.5 kg (10 lb.) test weight (Figure F-3). The treatment data comparisons for the 11.25 kg (25 lb.) weight were not different, while the 40 kg (88 lb.) weight test data varied.

Playing Surface Characteristics

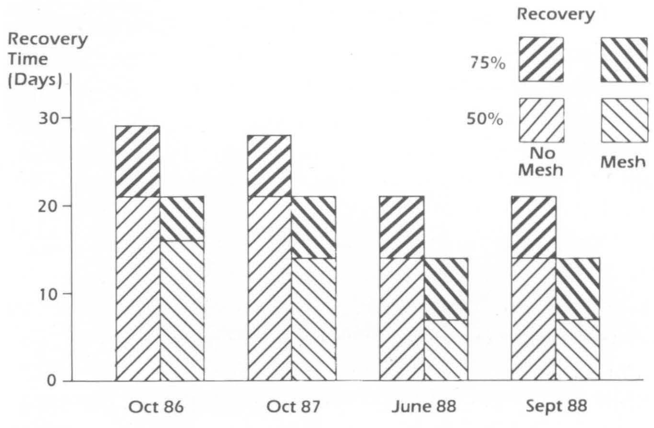
The playing surface characteristics assessed in this investigation included ball bounce, traction, and compression displacement. The findings are summarized in the Appendix Tables F-3 and F-4. No differences in ball bounce, as measured with a soccer ball dropped from a standard height of 3 m (9.8 ft.), were found between no mesh and mesh element inclusion in the turfed root zone, except for October of 1987. These findings were consistent throughout the summer and fall assessments for the years of 1986 through 1988 and also for the four 6-week within year seasonal assessments in 1988.

One other important aspect of ball bounce is the repeatability or uniformity dimensions of the turf surface (Bell, Baker, and Canaway, 1985). The range in percent of drop height from the maximums to the minimums was found to be three to four times greater where there were no mesh elements in the root zone versus the mesh element-root zone matrix. This improved consistency in ball bounce from mesh element augmented turf root zones is a significant component of the surface quality for sports use, including ball bounce and running action.

Results from traction assessments, which simulated the grip achieved by a cleated shoe, were variable in



▲ **Figure F-1. The effects of mesh element inclusions on the length, width, and depth of a divot opening at a depth setting of 25 mm (1 in.).**



▲ **Figure F-2. The effect of mesh element inclusions at the 2.5 kg m^{-3} (4.2 lb./yd^3) rate on divot opening turf recovery.**

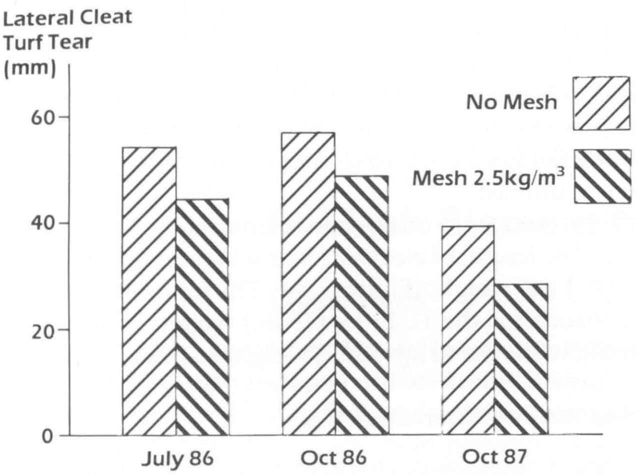


Figure F-3. The effect of mesh element inclusions on lateral cleat turf tear at a 4.5 kg (10 lb.) loading.

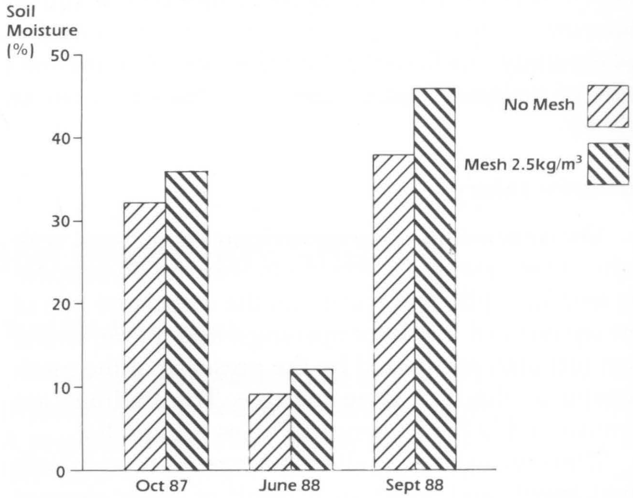


Figure F-4. The effect of mesh element inclusions at the 2.5 kg m^{-3} (4.2 lb./yd^3) rate on the soil moisture percentage at a depth of 50 mm (2 in.).

comparisons between no mesh and mesh element inclusion in the turfed root zone. At the 4.5 kg (10 lb.) test weight, traction was higher for the no mesh treatments on October of 1986 and 1987, whereas there was no difference in July of 1986. At the 11.25 kg (25 lb.) test weight, no differences were noted at any of the three assessment dates. In the case of the assessments using the 40 kg (88 lb.) test weight and the modified traction device, there was higher traction on the root zone without mesh treatment, except in September of 1988. The reasons for this variability in results were not clear.

Results of the compression displacement assessments on the turfed root zone varied between the two treatments. In the 4.5 kg weight test, greater displacement occurred in the no mesh element treatment in July 1986; with no difference noted for the October 1986 and 1987 assessments. In the case of the 11.25 kg test weight, compression displacement was greater in the no-mesh treatment in October 1987, while the reverse occurred in October 1986, with no difference found in July of 1986. For the seasonal assessments within 1988, at the 40 kg test weight, there were no differences between the two treatments for the 1 May and 15 June assessments, while the mesh element treatment exhibited slightly greater compression displacement on 1 August and 15 September.

Soil Moisture

When the authors observed that soil moisture content differentials might exist between the treatments, specific measurements were initiated in 1987. Throughout the subsequent observation period of 1987 through 1988, including the four within year seasonal assessments during 1988, the soil moisture content of the mesh element-root zone matrix was higher than for the no-mesh treatment (Figure F-4). This higher soil moisture could be attributed to the increased aggregation of soil particles between the apertures in the mesh such that the aggregates enhance overall moisture retention of the root zone and/or to the increased void spaces around the mesh where water may be retained. The higher soil moisture retention was found to occur at all three depths of 50, 100, and 150 mm (2, 4, and 6 in.) below the soil surface in 1988. Thus, the use of mesh element inclusions has an additional benefit in terms of reduced irrigation water requirement for turfs grown on sand root zones.

Conclusions

Investigations were conducted to evaluate the effects of using randomly oriented, interlocking mesh-elements on the playing characteristics, turf wear, and soil moisture retention of turfed, high-sand sports fields. Mesh-element inclusion substantially reduced divot opening width and length, and lateral turf tear caused by cleats. This resulted in twice as rapid divot and tear opening recovery. The mesh-element matrix had no effect on height of ball bounce, but substantially enhanced the consistency of ball bounce. The traction and compression displacement results were variable. Soil moisture levels were consistently higher in the mesh-element matrix treatment. This feasibility investigation revealed that augmentation of a sand root zone with mesh element inclusions provided significant benefits in terms of reduced turfgrass injury and a more uniform playing surface which will allow an increased frequency of play or reduced cultural inputs at the same frequency of play.

G. Simulated Assessments of Mesh Density and Placement Depth in Non-Turfed and Turfed Root Zones of Sand and Soil

Objectives

The overall objectives were to determine if there were optima in density and placement depth of mesh element inclusions in a sand root zone and a silty clay soil. The studies were initiated in 1987 at the Texas A&M Turfgrass Field Research Laboratory in College Station. Shrinkage by compaction, infiltration rate before and after compaction, and percolation rates were measured on both non-turfed and turfed sands and soils.

Study G-I. Simulated Non-Turf Test of Mesh Density and Placement Depth

Materials and Methods

This study was conducted by Ken Fujisaki, S. Sifers, and J. Beard in two phases. Common to both phases were (a) mesh elements in 50 by 100 mm (2 x 4 in.) rectangles with apertures of 10 by 10 mm (0.4 x 0.4 in.) as manufactured by Netlon® Ltd., (b) silty clay loam soil and a washed medium fine sand root zone, (c) circular columned containers, 250 mm (10 in.) in diameter and 500 mm (20 in.) deep, that were open at the top with one drain port at the bottom of 6 mm (0.24 in.) in diameter to allow water drainage, and (d) four replications of each treatment.

Infiltration rate determinations were made by saturating the root zone with 3 liters (0.8 gal.) of water (Brown and Duble, 1975). After this water had infiltrated into the root zone, another 1 liter (0.26 gal.) of water was applied and the time to infiltrate into the root zone was measured. The infiltration rate (IR) was calculated by the formula:

$$\text{IR mm min}^{-1} = \frac{1{,}000{,}000 \text{ mm}^3}{49085 \text{ mm}^2 \times \text{T}}$$

where IR = infiltration rate in mm per minute; T = measured time in minutes.

The compaction simulation apparatus consisted of a bottom steel plate with an area of 1,230 mm^2 (19 in.^{2}), a 900 mm (35 in.) long metal rod welded perpendicular to this plate, and a cylindrical metal weight with a hole in the center sized to slide down the rod and impact on the plate (Figure G-1). The cylindrical weight and the rod-plate apparatus weighed 4.0 kg (8.8 lb.).

Moist soil shrinkage from compaction was determined by placing the compaction simulation device in the center of the container on the root zone at a field capacity moisture content, dropping the weight four times from a height of 609 mm (24 in.), and measuring the depth or amount of shrinkage. Dry soil shrinkage from compaction was determined by compacting the entire dry surface with the same apparatus until no further loss of height could be measured. The difference in root zone mix height before and after compaction was then measured.

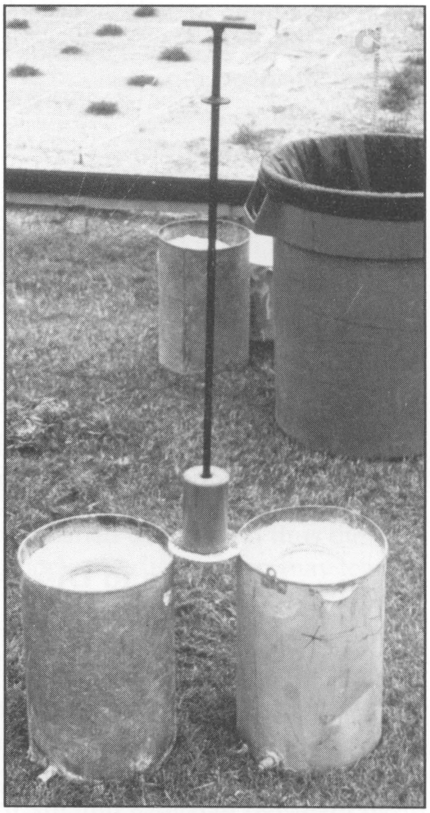


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Figure G-1. View of the root zone compression apparatus (right) and the circular columned containers (below).

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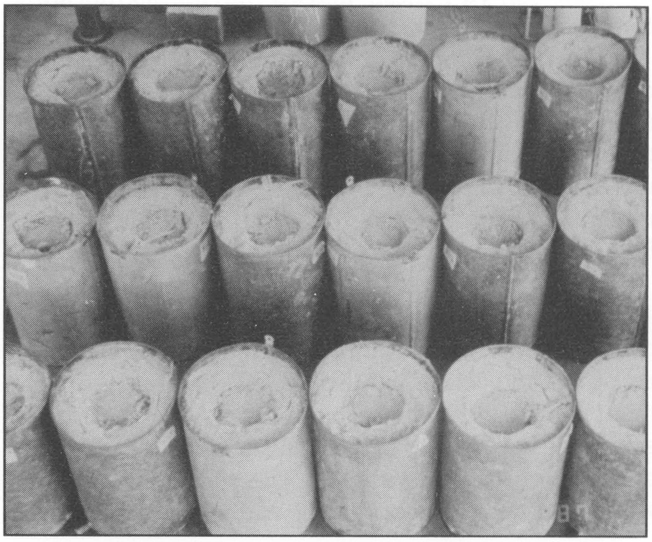

Phase I

The objectives were to determine the infiltration rates before and after compaction, plus the amount of shrinkage due to compaction for seven mesh element density treatments: 0.0, 1.25, 2.50, 3.75, 5.0, 6.25, 7.5 kg m^{-3} (0.0, 2.1, 4.2, 6.3, 8.4, 10.5, 12.6 lb. yd^3) of uncompacted soil mix, which were positioned as a 100 mm (4 in.) depth of mesh-root zone matrix. The containers were filled with either the silty clay soil or medium fine sand up to 150 mm (6 in.) from the container top. Each of the mesh element-root zone mix treatments was added and then 25 mm (1 in.) of the same root zone mix without mesh was placed on top. The physical assessment procedural order followed was: pre-compaction infiltration rate assessment, root zone compaction, soil shrinkage assessment, and infiltration rate assessment after compaction.

Phase II

The objectives were to determine the infiltration rate before and after compaction, plus the amount of shrinkage due to compaction for five mesh depth treatments: 0, 25, 50, 100, and 200 mm (0, 1, 2, 4, and 8 in.). The mesh element density was 3.75 kg m^{-3} (6.3 lb./yd^3) of uncompacted soil mix for all mesh treatments. Each depth treatment terminated at 50 mm (2 in.) from the top of the container and was covered by 25 mm (1 in.) of the same root zone mix without mesh elements. The same physical measurements as those conducted in Phase I were completed in Phase II.

Results and Discussion

Phase I

Infiltration rates on the silty clay before compaction were very similar for treatments with or without mesh elements; while the medium fine sand exhibited no differences in pre-compaction infiltration rates at five mesh inclusion densities ranging from 1.25 to 6.25 kg m^{-3} (2.1 to 10.5 lb./yd^3), with the no mesh and 7.5 kg m^{-3} (12.6 lb./yd^3) mesh density having significantly lower infiltration rates.

The post-compaction infiltration rates of the medium fine sand were significantly higher for the mesh element density treatments than for no mesh. In the case of the silty clay soil, post-compaction infiltration rates were higher than those for the no mesh treatment for mesh inclusion at densities of 2.5, 5.0, and 7.5 kg m^{-3} (4.2, 8.4, and 12.6 lb./yd^3) (Figure G-2).

Significant differences occurred in the amount of shrinkage of the medium fine sand root zone following compaction, with treatments containing mesh elements resisting compaction and shrinkage better than the treatment with no mesh elements. In the case of the silty clay soil, there was a trend of less soil shrinkage as the mesh density increased (Figure G-3). The moist soil shrinkage was significantly lower at a mesh density of 5.0 kg m^{-3} (8.4 lb./yd^3) and above, while dry soil shrinkage was significantly lower at a mesh density of 6.25 kg m^{-3} (10.5 lb/yd^3) and above. These findings are summarized in the Appendix, Table G-1.

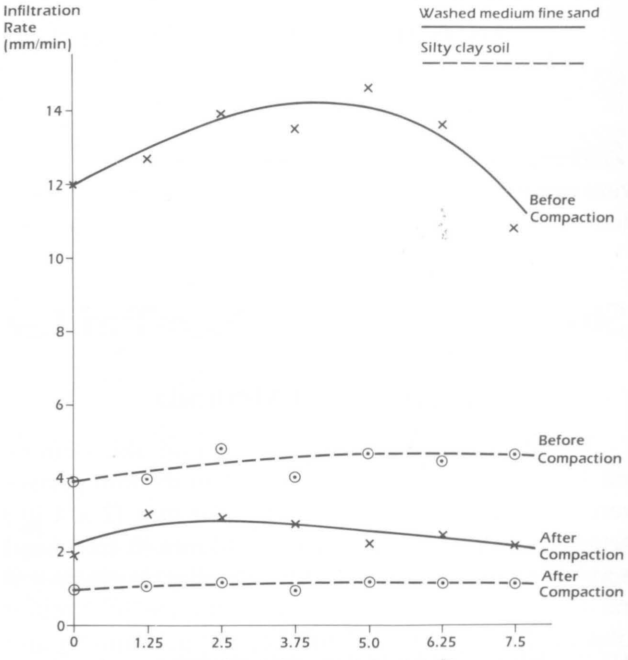

Figure G-2. The influence of seven mesh element inclusion rates on infiltration rate of two soil textures before and after compaction. Depth of mesh-root zone placement was 100 mm (4 in.).

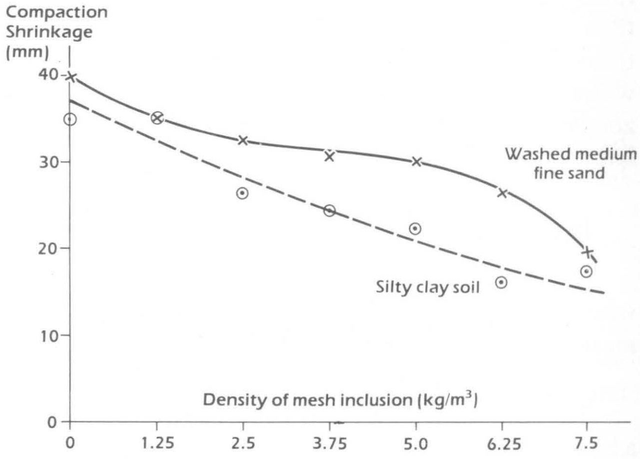

Figure G-3. The influence of seven mesh element inclusion rates on compaction shrinkage of two dry soils of different textures. Depth of mesh-root zone placement was 100 mm (4 in.).

Conclusions

The study involved three replications each of seven mesh element densities and two soil treatments. The data indicate that mesh element inclusions improve water infiltration rates, plus lessen the amount of shrinkage due to compaction, of root zones without a turf cover. This observed inverse relationship between soil physical parameters as influenced by mesh inclusion is as would be expected. Generally, the trend was for an increasing density of mesh elements to produce the better soil physical responses.

Phase II

Pre-compaction infiltration rate comparisons of the washed medium fine sand showed an increased infiltration rate only for the two upper depths of mesh placement, specifically 100 and 200 mm (4 and 8 in.). In the case of the silty clay soil, all four mesh placement depths had higher infiltration rates than the no-mesh treatment. There were no trends specifically related to mesh placement depths.

Post-compaction infiltration rates of the medium fine sand exhibited comparable responses to mesh inclusion, as were observed in the pre-compaction tests. Significant increases in the infiltration rate only occurred at the two higher depths of mesh placement, specifically 100 and 200 mm (4 and 8 in.), with no difference in infiltration rates between these two highest depths. The post-compaction infiltration rates of the silty clay soil responded to mesh element placement depths similar to the pre-compaction infiltration rates, but at lower absolute values.

Moist soil shrinkage from compaction of the medium fine sand was substantially reduced by the inclusion of mesh elements in comparison to no mesh, with no significant differences among the four mesh placement depths. In the case of the silty clay soil, moist soil shrinkage was significantly greater for the no mesh treatment in comparison to the four treatment depths of mesh placement. The 200 mm (8 in.) placement depth resulted in the least moist soil shrinkage.

Dry soil shrinkage from compaction of the medium fine sand was significantly less for the mesh element density treatments than for the no-mesh treatment, with an increasing depth of mesh placement resulting in a trend towards increased soil shrinkage from compaction. In the case of the silty clay soil, the two greater depths of mesh element placement, specifically 100 and 200 mm (4 and 8 in.), were the only mesh inclusion treatments that resulted in significantly reduced soil shrinkage from compaction.

Conclusions

The study encompassed three replications each of four mesh element depths and two soil treatments. These data indicate that the depth of a mesh element root zone matrix should be a minimum of 100 mm (4 in.), based on a non-turf simulation study where a mesh inclusion density of 3.75 kg m^{-3} (6.3 lb./yd^3) was utilized. This threshold depth for best physical parameter performance found in this study was very distinct for the medium fine sand. The effect of mesh element placement depth on a silty clay soil showed very distinct advantages relative to the no mesh treatment, with no striking trends in terms of mesh element depth placement, as were observed in the medium fine sand experiment. It should be noted that the more shallow depths of 25 and 50 mm (1 and 2 in.) were more difficult to accurately install to specified depths and thus the uniformity of mesh interlock and distribution may tend to be more variable, whereas this problem was significantly reduced at depths of 100 mm (4 in.) and deeper. Statistical details are in the Appendix, Table G-2.

Study G-II. Simulated Turfed Test of Mesh Density and Placement Depth

Materials and Methods

This study was conducted by Hideaki Tonogi, S. Sifers, and J. Beard. Following the 1987 study on two non-turfed root zones, soilless Tifway bermudagrass sods were transplanted onto compacted medium fine sand root zone treatments within the circular columned containers (Figure G-4). For two years, the turfs were manually clipped weekly at 25 mm (1 in.) with clippings removed. The nitrogen fertilization rate was 0.4 kg N 100 m^{-2} (0.8 lb N/1,000 $ft.^2$) per growing month. Phosphorus(P) and potassium(K) levels were maintained in the high range based on soil tests. Irrigation was practiced as needed to prevent visual wilt. No turf injury due to diseases or insects was observed during the study and no pesticides were applied.

Using the same procedure as described for Study G-I, the infiltration rates were measured for three mesh element inclusion densities and three depths of mesh placement. Immediately following the infiltration rate test, the percolation rate test was initiated by the application of 4 liter (1.04 gal.) of water. The percolation rate was determined based on the total time required for all gravitational water to percolate through the root zone and out the base of the container (Brady, 1974). The infiltration and percolation rate tests were repeated in four separate months in 1989. Analysis of variance (ANOVA) used a completely randomized design (CRD) for individual days and a split plot extension of CRD for overall days where treatments were main plots split by days.

Results and Discussion

The results are shown in the Appendix, Table G-3, as the means of the four dates. The water infiltration rate varied significantly, with the 5.0 kg m^{-3} (8.4 lb./yd^3) mesh density at 100 mm (4 in.) depth being the fastest, and 1.25 kg m^{-3} (2.1 lb./yd^3) at a 100 mm (4 in.) depth being the slowest. All mesh density treatments had higher infiltration rates than the no mesh control (Figure G-5). All infiltration rates for the turfed sand root zone treatments were much higher than their counterpart rates from the earlier non-turf study. This is a clear indication as to the benefits of turfgrass roots, both dead and alive in improving the root zone environment.

The percolation rates were faster for all mesh inclusion treatments than for the no mesh control. The 5.0 kg m^{-3} (8.4 lb/yd^3) mesh density at a 100 mm (4 in.) depth had the fastest percolation rate. Only the 1.25 kg m^{-3} (2.1 lb./yd^3) mesh density at a 100 mm (4 in.) depth was statistically different from the other mesh inclusion treatments. At the 5.0 kg m^{-3} (8.4 lb./yd^3) mesh density there was improvement in infiltration and percolation rates as the mesh depth increased (Figure G-6). This could be partially attributed to a better distribution of the mesh elements as the treatment installation depth increased.

Conclusions

These data are further evidence that incorporation of mesh elements in root zones increases the soil water infiltration and percolation rates, and that a trend exists in which increasing the mesh inclusion density and the depth of mesh placement provide increased benefits in terms of the soil water infiltration rate. Soil moisture retention was not measured in these studies. However, data from other studies reported herein indicate that more moisture was retained in root zones with mesh elements inclusions. This suggests that mesh element inclusion provides better soil water infiltration and percolation, but not at the detriment of soil moisture.

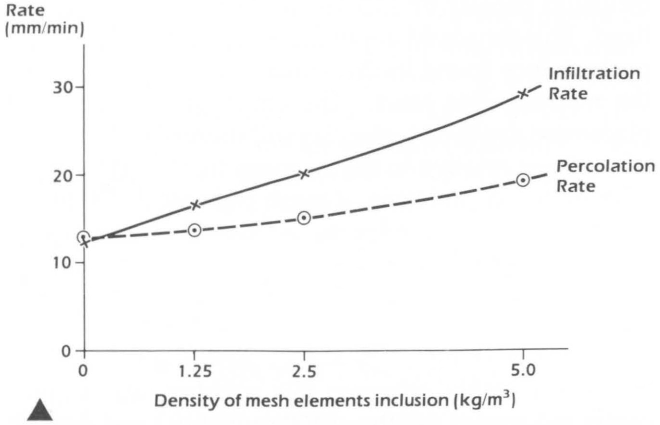

Figure G-5. The improvement in infiltration rate and percolation rate in a medium fine sand root zone as influenced by increasing mesh element inclusion rate, after two years of turf culture. Depth of mesh treatment was 100 mm (4 in.).

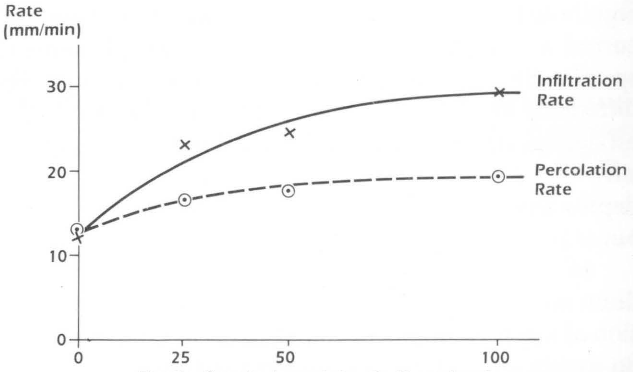

Figure G-6. The improvement in infiltration and percolation rate by increasing depths of mesh element placement in a medium fine sand root zone, after two years of turf culture. Density of mesh element inclusions was 5 kg m^{-3} (8.4 lb./yd^3).

H. Mesh Element Inclusion Rate and Surface Placement Study

Objectives

Based on positive results from the Mesh Element Inclusion Feasibility Study, a more detailed experiment was established in 1986. One objective was to determine the mesh inclusion density that would provide optimum benefits in terms of reduced turf divoting and tear, better overall soil-turf stabilization, uniformity of ball bounce, and increased soil moisture. The assessment parameters were expanded in 1988 to include surface hardness. A second objective was to compare a 150 mm (6 in.) depth of mesh incorporation covered by a 25 mm (1 in.) layer of root zone without mesh, versus the same mesh-root zone matrix that extended to the surface.

Materials and Methods

This study involved comparisons of four densities of mesh incorporation of 0.0, 2.5, 3.75, and 5.0 kg m^{-3} (0.0, 4.2, 6.3, 8.4 lb./yd^3) in uncompacted soil mix. The treatments were installed to a 150 mm (6 in.) settled depth, with a 25 mm (1 in.) settled depth of the same root zone mix without mesh elements applied over the top, plus one treatment where a 3.75 kg m^{-3} (6.3 lb./yd^3) mesh density of 150 mm (6 in.) in depth was extended to the surface. Each treatment was arranged in randomized block design of three replications, with a plot size of 1.8 by 1.8 meters (5 x 5 ft.).

The plot area construction specifications followed the Texas-USGA Method described in the first section. The lower portion of 125 mm (5 in.), high-sand root zone mix was constructed, then the five mesh treatments in three replications were installed in the upper approximately 150 mm (6 in.). The mesh elements were 50 by 100 mm (2 x 4 in.) rectangles with 10 by 10 mm (0.4 x 0.4 in.) square apertures manufactured by Netlon®, Ltd. from polypropylene. Off-site mixing of the mesh element-root zone mix and the no-mesh root zone were followed to maximize mix uniformity.

Turf Establishment

The area was planted to Tifway bermudagrass (*Cynodon dactylon* x *C. transvaalensis*) in September of 1986. Preplant fertilization was at a rate of 1 kg (2 lb.) each of nitrogen(N), phosphorus (P_2O_5), and potassium(K_2O) per 100 m^2 (1000 $ft.^2$). Vegetative sprigs were broadcast at a rate of 0.4 m^3 per 100 m^2 (14 bushels/1000 $ft.^2$), lightly topdressed, and fertilized at a rate of 1 kg phosphorus(P_2O_5) per 100 m^2 (2 lb/1000 ft^2.) to encourage rapid establishment. The area was irrigated with perimeter pop-up, gear driven sprinkler heads positioned at 3.5 m (11.4 ft.) spacings. Turf establishment was achieved in June of 1987 (Figure H-1).

Cultural Practices

The culture practices imposed on the experimental area were representative for hybrid bermudagrass sports fields. Mowing was twice weekly at 25 mm (1 in.) cutting height using a three gang reel mower with clippings returned. The nitrogen fertilization rate was 0.4 kg N/100 m^{-2} (0.8 lb N/1,000 $ft.^2$) per growing month, which extended from April to September. Phosphorus and potassium were maintained in the high range based on annual soil tests. Irrigation was practiced as needed to prevent visual wilt. No pesticides were applied and no turf cultivation or vertical cutting was practiced.

Assessments

The methods used to assess the influence of the randomly oriented interlocking mesh element-turfed root zone matrix treatments were described in an earlier section E. Assessments were accomplished in August 1987, and at 6-week intervals during 1988 starting in May, during 1989 starting in April, and during 1990 starting in June.

Results and Discussion

Turf Quality

Relative turfgrass quality was assessed visually at 15-day intervals in terms of both uniformity and high shoot density. No turf quality differences were noted among treatments throughout the study. There also were no visual symptoms of turfgrass injury caused by disease or insect activity. Initially the treatment with a 3.75 kg m^{-3} (6.3 lb./yd^3) mesh density up to the surface had several of the elements protruding above the soil surface, but they were rapidly covered by turfgrass growth within 6 weeks and caused no mowing problems.

Turfgrass Injury

Turfgrass injury associated with traffic stress was assessed as (a) divot opening length, width, and depth, (b) the associated rate of turf recovery of the divot openings, and (c) the lateral cleat tear of turf as each is affected by the presence, density, and vertical placement of mesh elements in the root zone matrix. The data are shown in the Appendix, Tables H-1 through H-3, as means for each of 3 year's observations.

The size of the divot opening length increased chronologically with each subsequent year following planting. There was a significant difference in divot opening length in all 3 years for the no mesh treatment when compared with the three mesh element inclusion treatments with a 25 mm (1 in.) root zone layer over the top (Figure H-2). For assessments in 1988, the divot opening length for the 3.75 kg m^{-3} (6.3 lb./yd^3) mesh density to the surface treatment was similar to the three other mesh inclusion treatments. However, in 1989 the divot opening length for the 3.75 kg m^{-3} (6.3 lb./yd^3) mesh density to the surface was significantly larger than the three other mesh inclusion treatments of 2.5, 3.75, and 5.0 kg m^{-3} (4.2, 6.3, and 8.4 lb./yd^3), but not as large as the no mesh treatment; while in 1990 the extension of mesh inclusion to the surface caused the divot opening length to exceed that of all other treatments including no mesh inclusion (Figure H-3).

One explanation for this response is that the mesh elements that are close to the surface and that extend laterally outward from the divot simulation head are pulled sufficiently to cause lateral turf tears that radiate out from the divot opening perimeter, thereby causing increased turf damage and an allied slowing of the turf recovery rate. These data indicate the desirability of placing a 25 mm (1 in.) layer of root zone mix over the top of the mesh matrix where divoting will occur.

Divot opening width assessments for 1988 showed no differences between no mesh and any of the four mesh inclusion treatments. In 1989 the no mesh treatment and the 3.75 kg m^{-3} (6.3 lb./yd^3) mesh density to the surface both had significantly larger divot widths than any of the three mesh inclusion density treatments with a 25 mm (1 in.) layer of root zone mix placed on the top of the mesh matrix. The comparative treatment responses for 1990 were similar to those of 1989, except for no significant difference in divot opening width between no mesh and the 2.5 kg m^{-3} (4.2 lb./yd^3) mesh inclusion rate. There was a tendency for the divot width opening size to increase over the 3 years.

There were statistical differences in divot opening depths but, in terms of absolute values, all depth measurements were within a minimal 5 mm (0.2 in.) of each other.

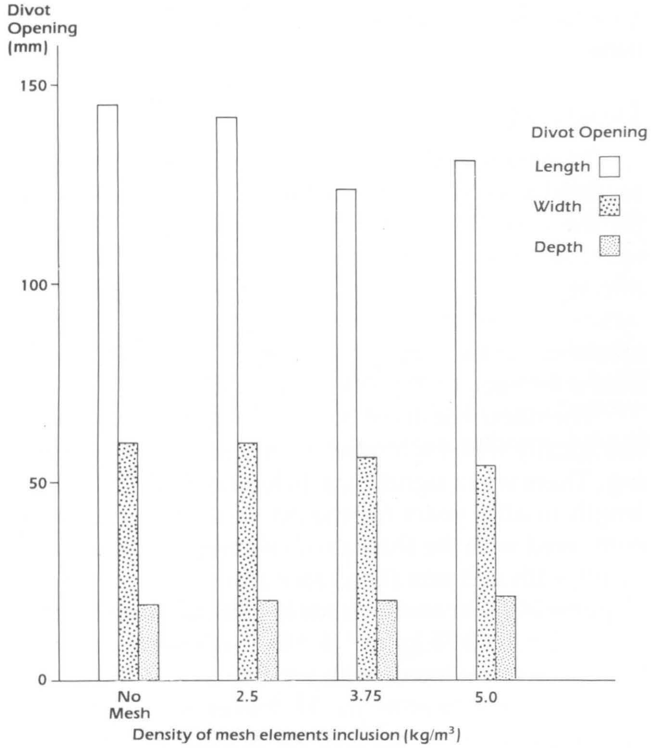

Figure H-2. The effects of mesh element inclusion rate on divot opening length, width, and depth after three years of turf culture, high-sand root zone with 150 mm (6 in.) mesh depth and 25 mm (1 in.) dressing.

In 1988, the most rapid, complete divot opening turf recovery occurred at the three mesh densities of 2.5, 3.75, and 5.0 kg m^{-3} (4.2, 6.3, 8.4 lb./yd^3), with the 3.75 kg m^{-3} (6.3 lb./yd^3) mesh density to the surface being slightly slower on each observation date and the no mesh treatment being 15 to 50 percent slower. Similar comparative responses occurred in 1989 and 1990, except for the 3.75 kg m^{-3} (6.3 lb./yd^3) mesh density to the surface and the no mesh treatments which had recoveries that were more similar to each other.

Overall, the differences in divot opening turf recovery percentages depended on the recovery time frame being assessed. However, divot opening recovery differences among treatments containing mesh elements versus the no mesh treatment or the 3.75 kg m^{-3} (6.3 lb./yd^3) mesh density to the surface treatment ranged from 25 to 40 percent. The example at Figure H-4 compares 5 kg m^{-3} density of mesh elements, versus no mesh, in high-sand root zone, and illustrates the improvement in divot opening recovery due to the presence of mesh elements. The divot openings were not repaired prior to the assessments and topdressing was limited to once yearly after the last simulation test date.

Lateral cleat turf tear data were quite variable from year to year. There were no significant differences among the treatments in 1989. In 1988 there were no significant differences under the 40 kg (88 lb.) drop weight pressure among treatments. At the 11.25 kg (25 lb.) drop weight, the no mesh and the 2.5 and 3.75 kg m^{-3} (4.2 and 6.3 lb./yd^3) mesh inclusion rates had slightly larger lateral cleat turf tear than the other three treatments. In the case of the 4.5 kg (10 lb.) drop weight, the

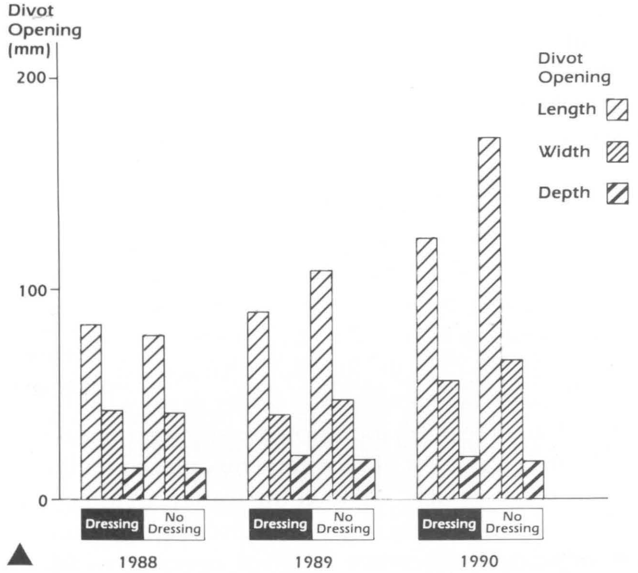

Figure H-3. The positive effects of reduced divot opening length and width resulting from placing 25 mm (1 in.) dressing above a 3.75 kg m^{-3} (6.2 lb./yd^3) mesh element inclusion rate in a 150 mm (6 in.) high-sand root zone.

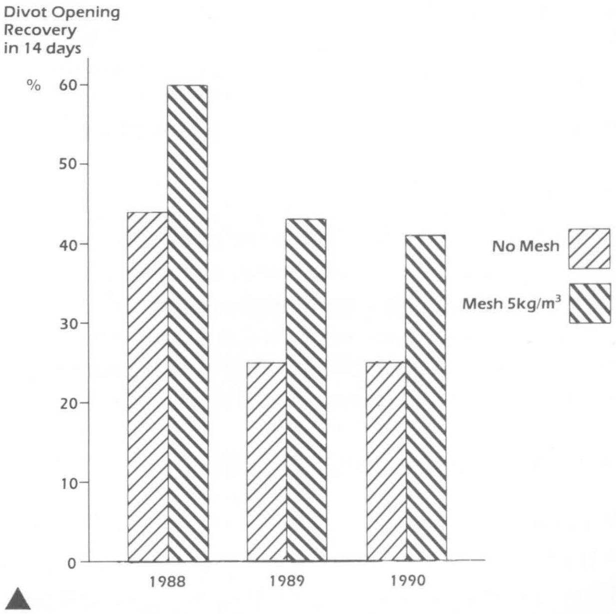

Figure H-4. The improvement in divot opening turf recovery at 14-days regrowth due to presence of mesh element inclusion at a rate of 5 kg m^{-3} (8.4 lb./yd^3) in high-sand root zone after a period of three years turf culture.

no mesh treatment resulted in less lateral cleat turf tear than any of the three mesh inclusion treatments. In the third year, 1990, there were no significant differences in lateral cleat turf tear under the 40 kg (88 lb.) drop weight, whereas, at the 4.5 kg (10 lb.) drop weight, the no mesh treatment resulted in slightly less tear than the four mesh inclusion treatments. The highly variable nature of this lateral cleat turf tear data leads to no distinct conclusions for this experiment. Perhaps other uncontrolled confounding factors are influencing the variability in results.

Playing Surface Characteristics

The playing surface characteristics assessed in this investigation included compression displacement, traction, ball bounce, and surface hardness.

Statistical differences in compression displacement occurred at each of the three test drop weights of 4.5, 11.25, and 40 kg (10, 25, and 88 lb.). The no mesh and the 3.75 kg m^{-3} (6.3 lb./yd^3) mesh density to the surface treatments allowed less surface penetration than the other three mesh density treatments, regardless of the test drop weight used. One interpretation of these data is that greater surface compaction had occurred on the no mesh turf plots and that the 3.75 kg m^{-3} (6.3 lb./yd^3) mesh density to the surface treatment resulted in the surface placed mesh providing greater resistance to penetration of the cleats.

There were no differences in traction measurements attributed to the mesh element treatments, with one sole exception in 1988 with the 40 kg (88 lb.) drop weight on the 2.5 kg m^{-3} (4.2 lb./yd^3) mesh density. However, there were differences in absolute values among assessment dates within each year. These traction differences appeared to be related to soil moisture and the resultant depth of penetration of the cleated base into the turf-soil surface zone.

There were no statistical differences in the treatment means for ball bounce for any of the test dates from 1988 through 1990. The mesh elements stabilized the variance in ball bounce regardless of the density of mesh inclusion.

Surface hardness measurements were initiated in May of 1989 and continued. Two hammer weights of 0.5 and 4.5 kg (1 and 10 lb.) were used at each assessment date in 1989. In 1990, three hammer weights of 0.5, 2.25, and 4.5 kg (1, 5, and 10 lb.), were used.

The 0.5 kg (1 lb.) and 2.25 kg (5 lb.) hammer weight data indicated statistical differences with the no mesh treatment being harder or having a higher CIV than the CIV's of all four mesh inclusion treatments, except for the 3.75 kg m^{-3} (6.3 lb./yd^3) mesh density to the surface treatment in 1990 at the 0.5 kg (1 lb.) hammer weight, which was not different. There was no statistical separation of CIV's for treatment effects using the 4.5 kg (10 lb.) hammer in 1989, but in 1990, the responses were similar to those for the 0.5 kg (1 lb.) hammer weight (Figure H-5).

The data indicate the benefits of mesh element inclusion in sandy root zones in terms of less surface hardness, but no indication of which is the best mesh inclusion density as it affects surface hardness. The variation in CIV results also appears to be a function of the soil moisture content, with higher moisture levels resulting in a lower CIV values.

Soil moisture

There were statistical differences at each soil moisture test depth with more moisture retained in all four treatments with mesh inclusions when compared with the no mesh treatment. These data confirm the findings reported earlier in this bulletin (Figure H-6).

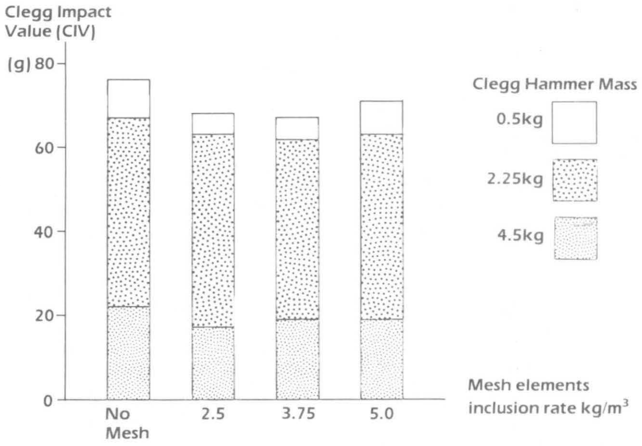

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Figure H-5. The effect of four mesh element inclusion rates on Clegg Impact Values (CIV) after three years of turf culture, high-sand mix with 150 mm (6 in.) mesh placement depth and 25 mm (1 in.) dressing.

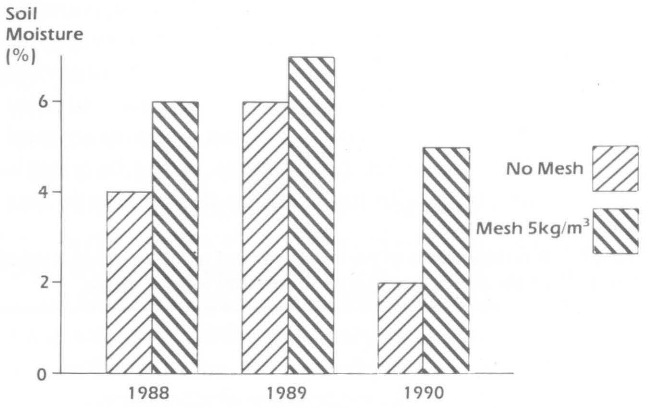

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Figure H-6. Typical increase in soil moisture percentage at a depth of 50 mm (2 in.) due to mesh element inclusion at a rate of 5.0 kg m^{-3} (8.4 lb./yd^3) in a high-sand root zone over a period of three years of turf culture.

Conclusions

These results indicate clear benefits to the turfgrass user accruing through the use of mesh elements including (1) a decreased size of divot openings, (2) much faster turf recovery of divot openings, (3) a more consistent and predictable ball bounce, (4) a lessening of surface hardness, (5) no decrease in traction, or lateral cleat turf tear, and (6) improved soil moisture. These benefits occurred consistently when mesh elements were placed below the surface with a 25 mm (1 in.) deep root zone mix topdressing, without mesh elements, placed above. Over the mesh density range of 2.5 to 5.0 kg m^{-3} (4.2 to 8.4 lb./yd^3), all densities performed similarly.

I. Mesh Element Inclusion Influence on the Turfgrass Root Zone Environment

The primary objectives when this series of studies initiated in 1985 was to assess the role of mesh elements in stabilization of high sand root zones, and the reduction in turf divoting and tear as a result of root entwinement that stabilizes the turf. However, as the field study assessments progressed, it became apparent that the presence of the mesh element matrix was influencing the growth of the turfgrass plant itself. The difference first observed related to the moisture content of root zones where mesh element inclusion treatments were involved. It has since been shown in both studies reported herein that the mesh element matrix increases the moisture content of the high sand root zones utilized in the order 2 to 8 percent of the soil dry weight, depending upon the season and environmental conditions. Note that an increase in moisture content of 2 percent from 6 to 8 percent represents a 33 percent increase in water content. In addition, the simulation studies, as reported earlier in this bulletin, showed the presence of the mesh element matrix caused a general enhancement of both soil water infiltration and percolation rates.

In early November of 1989, profile assessments were made of the turf treatments in Study I. The extent of biomass accumulation and rooting was evaluated to determine the potential impact of the mesh element inclusion on bermudagrass shoot and root growth after the root zone biological ecosystem had been allowed to stabilize for 4 years. Three 100 mm (4 in.) diameter by 218 mm (8.5 in.) long core samples were examined within each of the three replications of the two treatments. The composite turf canopy-thatch depth was measured as well as the depth of root extension and viability as evidenced by thick white versus black spindly roots. The findings are summarized in Table I-1.

Turf-root zone profile comparisons between the no mesh and the 2.5 kg m^{-3} (4.2 lb./yd^3) mesh density treatments were very striking and certainly did not require sophisticated measuring techniques to illustrate the effects.

In terms of the depth of the turf canopy and thatch, there was obviously a greater amount of live and dead vegetative accumulation where mesh elements were present in comparison with where there was no mesh. A portion of this biomass was thatch. Thatch accumulates when the rate of vegetative production exceeds the rate of decomposition. There should have been a minimal differential adverse effect from the two treatments that would decrease decomposition. In fact, the better aeration and drainage in the mesh inclusion root zone should have stimulated decomposition. Thus, one concludes that there was a greater quantity of dry matter production occurring on the mesh inclusion turfs than on the no mesh treatment turfs.

Rooting differences were particularly striking, with the mesh inclusion treatment producing significantly deeper roots than the no-mesh turf treatment. Even more striking was the root viability. The roots were distinctly white, full, and healthy in the case of the mesh inclusion treatment, whereas most of the roots were black and spindly in the no-mesh turf treatment, especially below 75 mm (3 in.).

Table I-1. A comparison of no mesh versus a 2.5 kg m^{-3} (4.2 lb/yd^3) mesh density on Tifway bermudagrass (a) depth of turf canopy plus thatch, (b) root depth, and (c) root viability after 4 years.

	Root Zone Treatment	
Plant Response	No mesh	Mesh inclusion of 2.5 kg m^{-3} (4.2 lb./yd^3)
Depth of turf canopy and thatch in mm (in.)	40 (1.6) a*	62.5 (2.5) b
Root depth in mm (in.)	150 (5.9) a	+216 (8.5 in.) b**
Root viability (%)	14	100

* Values followed by the same letter in the same line are not significantly different, LSD T Test, alpha = 0.05.

** 216 mm was depth of the plug. There were visible roots below this depth.

Soil Black Layer Problem

Before the November 1989 turf-soil profile characterizations, an extended, wet rainy period occurred. A distinct black layer problem was discovered during this turf-soil profile examination of Study I. A black layer was present in all turf plots without mesh elements, but it was not observed in any of the adjacent plots where there was a mesh element inclusion treatment. The black layer occurred from 90 to 120 mm (3.5 to 4.7 in.) below the soil surface and had an average depth of 30 mm (1.2 in.) (Figure I-1). A distinct hydrogen sulfide type odor was noted in the region of the visual black layer.

Examination of the bermudagrass roots growing in the non-mesh treatment plots revealed that they extended into the black layer where the roots turned black, spindly, and apparently became nonfunctional. In contrast, roots in the adjacent mesh inclusion plots appeared thick, white, and healthy, and they extended to a normal depth for that time in the growing season.

The soil black layer problem was first noted a little over 4 years after the initial plots were installed. It persisted over the winter period until June of 1990, or approximately 8 months. The same black layer symptoms and associated rooting problems have reoccurred three more times through 1992. In each instance, black layer development has been associated with a wet rainy period. Furthermore, the black layer problem has been limited to the four replicates of non-mesh turf plots, with not one of the four randomly placed adjacent replicates of the mesh inclusion turf plots exhibiting any symptoms of black layer.

The reduced rooting in the no mesh treatments was attributed primarily to the development of the black layer. This poor rooting is a result of a sand root zone with too high a sand particle fraction in the 0.1 to 0.25 mm range combined with the lack of mesh element inclusion matrix that could counteract the adverse effects caused by a sand particle size distribution that is too fine. This leads to the conclusion that a randomly oriented interlocking mesh element inclusion system might be beneficial for high-sand root zones with a broader range in particle size than specified for the Texas-USGA Method, especially when the range extends into the finer particle size between 0.1 and 0.25. The current maximum limit for fine and very fine sand is 17 percent, with 10 percent being preferred. Should these findings be confirmed under practical field conditions, it would allow a broader percentage of fine sands to be utilized, when a mesh element inclusion system is added. The result could be a significant reduction in cost for sand, if the fine sand is locally available and where the proper Texas-USGA Method specification medium sands are not available or are very costly to obtain due to expense of hauling long distances.

Mesh Element-Root Zone Matrix Micromorphology Studies

These studies were conducted in 1990 by Michael DePew, L. Wilding, and J. Beard. Distinct favorable responses in terms of turfgrass growth and rooting when bermudagrass was grown in the presence of a mesh element high-sand matrix suggested the need for detailed soil micromorphology studies. This experiment evaluated the physical and structural properties of paired root zones with and without mesh inclusion, using various soil physical and micromorphological techniques, including soil thin-section analyses to determine the degree of translocated particulate and chemical constituents.

Soil cores were collected in pairs from the no mesh and mesh inclusion turf plots and frozen in liquid nitrogen. They were then cut to size in a cold room followed by freeze drying. The thin-section cores were then impregnated with epoxy, mounted, cut, ground, and polished for the development of micrographs. Micrographs also were prepared by a modified procedure for scanning electron microscope (SEM) assessments.

The cross-polarized light microscope micrograph revealed the presence of voids around the mesh element strands (Figure I-2). The presence of these voids around certain of the mesh strands may be a contributing factor to the increased infiltration and percolation rates. It is also hypothesized that when under traffic pressures, the randomly oriented interlocking mesh element matrix may actually be flexing slightly in a microcultivation type soil action.

The benefits of mesh element inclusion in preventing concentrations of finer textured clay and iron oxide accumulations in specific zones that result in the formation of black layer are illustrated in Figure I-3 as seen through a scanning electron microscope. Where the mesh is present, there are clay coatings but they do not extend or bridge between the sand grains. In contrast, the same high sand root zone without mesh element inclusions has clay coatings that extend continuously over and across the sand grains in a bridging action. The bridged sand contributes to reduced soil water infiltration and percolation, followed by the development of a micro-waterlogged zone perched above the underlying clay-bridged sand zone. This results in anaerobic chemical conditions that favor formation of reduced iron compounds such as Fe S. This may result in the soil black layer problem and the eventual loss of roots. This is not to say that this is the only means by which a black layer problem occurs, but it is certainly one of the potential causes. The data confirm the utility of microfabric analyses to directly observe soil-root interface and redox micro environment. It also illustrates the value of randomly oriented, interlocking mesh element inclusions in preventing black layer in fine sand root zones.

Conclusions

An unanticipated discovery in this investigation was that the randomly oriented, interlocking mesh element matrix contributes substantial benefits to the soil environment that in turn produces more favorable conditions for root growth. These studies show the benefits to include (a) increased moisture retention, (b) improved soil water infiltration and percolation, (c) improved aeration porosity, (d) improved root growth and (e) a possible way to prevent black layer formation in fine sands of 0.1 to 0.25 mm in diameter that would normally not be acceptable for use in the Texas-USGA Method.

J. Mesh Element Mixing, Installation, and Turf Cultural Procedures

The interlocking nature of mesh elements within a root zone matrix requires special physical handling and movement procedures. In some cases normal movement and grading procedures will not be successful, such as the forward pushing of the mesh-root zone matrix with a bulldozer blade with the objective of final leveling.

Construction Procedure

All of the successful applications to date have used a high-sand content root- zone mesh element mix placed over a properly prepared base, such as the Texas - USGA Method described earlier and illustrated in Figure J-1. Some difficulty in leveling the mesh element sand mix was initially encountered in large scale operations. This was overcome by using a traxcavator or front end loader bucket in a back-blade position, followed by final leveling using a motor grader with the diagonal blade set in shallow increments. These operations are most effectively accomplished when the high-sand root zone mix is moist.

Mixing Procedures

It is important that proper mixing procedures be followed to obtain a uniform interlocking distribution of mesh elements within the root zone mix. The same principle also is important in the mixing of soil components utilized in the root zone mix prior to additions of the mesh elements.

Off-Site Mixing

The only approach that ensures uniform mixing of components such as sand, organic matter, and a sandy soil is off-site mixing. Similarly, off-site mixing is the best approach for the uniform, random interlocking orientation of mesh elements within the root zone. It is important that all off-site mixing operations be accomplished on a hard, clean surface such as concrete or asphalt, in order to avoid contamination from unwanted sources such as a high clay or silt soil.

A number of techniques have been successfully employed for off-site mixing of mesh elements with a premixed root zone. The method selected depends on the site requirements and the amount of mix required. The off-site mixing methods include:

(1) ***Conventional front end loaders or traxcavators.*** This involves adding the appropriate quantities of mesh elements and root zone mix to a cone shaped pile, followed by continual lifting and dumping of increments until a uniform mix is achieved (Figure J-2). Do not attempt to push mix into mounds. Be sure to calibrate the capacity of each bucket being used.

(2) ***Continuous paddle blender or pug mill.*** This system is commonly used in asphalt mixing plants and will produce a very consistent mix at a very fast rate. The key is the tossing action of this mixing system.

(3) ***Truck mounted concrete mixers.*** The paddle arrangement and orientation of the drum must be properly positioned to ensure uniform mixing. This is a somewhat slower and more costly procedure that has been used for smaller installations.

(4) ***Batch rotating drums/manual shovel mixing.*** Conventional low capacity cement mixers can be used if the drum is positioned horizontally and a cover placed over the opening. The mesh-soil root zone components will not mix if the drum is placed in the normal diagonal position. Manual mixing involves placing materials in a cone shaped pile on a hard surface and using shovels to lift and drop the material repeatedly until fully mixed. These two procedures are limited to very small installations, such as repair installations where a portion of a larger existing facility has been damaged and/or has been dug up for other facility construction purposes.

On-Site Mixing

A second far less desirable option for mixing is on-site by a rotary tillage unit. The soil incorporation of mesh elements has been accomplished with a Bomag MPH 100, which is capable of mixing up to 40 m^3 (52 yd^3) per hour in a single pass to a depth of 150 mm (6 in.). However, the relative uniformity of incorporation and extent of random interlocking are unknown; but it is most probably less effective than off-site mixing, as has been shown when conducting high sand-organic matter root zone mixing operations. An additional key point is the importance of using a low speed rotary tillering device. High speed units result in separation of soil particle sizes into concentrations with the finer particles being near the surface, resulting in impaired water movement through the soil profile.

Installation Procedures

A bucket front-end loader or mechanical shovel is typically utilized to load the mesh-root zone mix into trucks for transport to the construction site. The mesh-root zone mix is typically dumped in small piles on the perimeter. A tracked dozer with blade or mechanical shovel is used to push the mix out over the construction site to the desired depth, which is typically 150 mm (6 in.) of settled mesh-root zone mix. It is important that all construction vehicles and related root zone mix hauling equipment be operated on top of the final mesh-root zone mix surface. This avoids disturbing the subbase construction layers of coarse sand and pea gravel, as well as the underlining drainlines that are quiet prone to crushing from truck tires. A diagonally oriented, front mounted dozer blade or a back-action bucket unit can be used to achieve rough leveling to the desired surface grade (Figure J-3). Small installations may involve shovelling. In this case the mesh high-sand mix should be lifted and placed, rather than thrown in order to minimize mesh separation.

Special procedures are required to achieve the final leveling of the mix composed of mesh and high-sand root zone components. First, the sand should be kept moist to promote cohesion during movement and prevent separation of the mix components. The root zone mix is firmed with two or three passes of a powered roller. Grading of a moist mesh-high sand root zone mix is best achieved by making blade cuts, as with a grader, of no more than 25 mm (1 in.) per pass to minimize the undesirable "lumpy movement" tendency of the interlocking mesh element matrix. Excess mix can be removed with an elevating scraper (Figure J-4).

Following another rolling, the final grade is established with a diagonal blade, as with a road grader (Figure J-5). Once the desired level and smoothness of settled mesh matrix is achieved, a 20 to 25 mm (0.7 to 1 in.) depth of the same root zone mix without mesh is dressed uniformly over the top. Truck mounted rear positioned centrifugal distribution systems can be used to accomplish this high volume topdressing (Figure J-6). The key point to emphasize here is to avoid applying more than a 25 mm (1 in.) depth to ensure that the mesh system will perform with minimal divoting tendency.

A machine for the in situ fully automated, continuous laying of the pre-mixed mesh element high-sand root zone matrix to a firm uniform depth has been developed by Netlon Limited. The basic structural frame is similar to an asphalt road laying machine, with significant modifications in the vertical feed device and the laying apparatus to ensure a uniform dense, strip installation to a specified depth with a level surface (Figure J-7). This technique would be very useful for large scale installations.

Turf Cultural Maintenance Procedures

The mesh elements are composed of polypropylene, which is non-biodegradable, non-toxic, and will not react with chemicals normally present in the soil or likely to be applied to turfgrass. Mesh elements that are exposed at the surface will break down under ultraviolet (UV) light from the sun. A number of turfgrass cultural procedures involve physical manipulation of the root zone. Thus, the presence of mesh elements within the root zone raises concerns relative to any changes in cultural practices that may be required. These aspects are addressed in this section.

Mowing

A wide range of mowing equipment has been operated for 5 years on extensive mesh element installations around the world without problems.

Turf Cultivation

One of the turfgrass cultural practices that is of concern relative to the presence of mesh elements in the root zone is turf cultivation. Turf cultivation operations, such as greens coring, deep coring, slicing and spiking, have been conducted over mesh high-sand root zone installations at the TAMU Turfgrass Field Research Laboratory and also over more extensive installations without problems, including no clogging of coring tines. Turf cultivation procedures such as water or air injection are yet to be assessed. However, a key point is that root zones properly constructed with the Texas-USGA Method of root zone construction in combination with mesh inclusion will reduce the need for turf cultivation.

A more likely issue might involve a surface compaction zone related to soil which has been blown in and deposited from off-site and/or accumulation of thatch-like organic layers that need to be broken up. In this case, such procedures as coring or slicing would be helpful and could be done to a shallow depth of 25 mm (1 in.), especially if originally constructed with a 25 mm (1 in.) layer of the same root zone mix without mesh elements on top of the mesh installation.

Slit Seeding

A mechanical slit seeding operation may be required for replanting of thinned areas and/or winter overseeding of cool-season turfgrasses into warm-season turfgrasses. This type of overseeding procedure involves a shallow slit penetrating to a depth of no more than 20 mm (0.8 in.). Thus, this penetration depth would not be of concern in relation to the underlying interlocking mesh element matrices. Winter overseeding of perennial ryegrass (Lolium perenne) using a mechanical slit seeder has been utilized for 3 years at the 5.67 ha (14 acre) Santa Anita Park mesh high-sand turf race track without problems.

Vertical Cutting

A turfgrass cultural procedure utilized for (a) the removal of an excessive thatch accumulation, (b) the removal of excess shoot growth prior to winter overseeding to allow better seed-soil contact, or (c) an extensive renovation procedure prior to interseeding is termed vertical cutting. It involves vertical knives operated at a high velocity by a power unit. Vertical cutting is designed to operate at or above the soil surface and into any thatch layer that has accumulated. Since it is not designed to penetrate into the soil, as is the case for soil cultivation machines, vertical cutting presents no problems in terms of the mesh element matrix.

Topdressing

The main objectives of topdressing are typically to smooth the surface of greens and to stimulate thatch decomposition. However, a sports field constructed with a mesh element high-sand root zone mix, plus a moderate nitrogen fertilization which minimizes thatch accumulation, should substantially reduce the need for topdressing. One concern with topdressing is that if it is used at a high rate and frequency it could eventually elevate the turf surface to a level that is so high above the mesh element matrix, root entwinement with the mesh elements is reduced. The cultural system should be adjusted such that minimal topdressing is used. This would retain the benefits of mesh element installations in terms of root entwinement, soil-turf stabilization, and soil environmental enhancement.

Rolling

Rolling is an effective practice on sports turfs where extensive divoting occurs, such as on horse race courses, polo fields, and football fields. The mesh element inclusion high-sand root zone system greatly reduces the size and depth of divots such that releveling divoted areas with rolling is done much easier. At the Santa Anita Park turf course, manual divot filling and tamping repair were reduced ten-fold after the mesh high-sand matrix was installed. In addition, rolling is helpful during the first year after installation in firming the surface zone. Do not use so heavy a roller that it causes lateral movement of sand particles and root breakage. Note that rolling is inadvisable on loam, silt, and clay soils that are prone to soil compaction problems, but high-sand root zones constructed with the correct particle size distribution are more resistant to compaction and can be rolled as part of the normal cultural program.

K. Turfgrass Mesh Element-Soil Matrix Applications: Present and Future

The multiple dimensional roles of mesh elements in (a) soil-turf stabilization, (b) extended surface quality enhancement, and (c) improved environmental quality for rooting of turfed root zones have been documented in this publication. Specific contributions of mesh element inclusions to a turfed root zone constructed with adequate surface and internal drainage that have been demonstrated by the research reported herein include:

A. **Soil-Turf Stabilization:**
  - Enhanced soil stabilization, especially in sandy soils and on steep slopes.
  - Improved load bearing capacity.
  - Resistance to rutting and deformation.
  - Reduced divot size.
  - Enhanced divot opening turf recovery.
  - Reduced lateral cleat turf tear.

B. **Surface Quality for Sports and Recreation:**
  - Improved uniformity for ball bounce and running.
  - Surface turf quality is sustained for a greater number of competitions.
  - Better participant safety due to less surface hardness.

C. **Soil Root Zone Environment:**
  - Less compaction.
  - Improved water infiltration rate.
  - Improved soil water percolation rate.
  - Improved soil moisture retention.
  - Improved turfgrass rooting.
  - Improved turfgrass health.
  - Reduced potential for soil black layer problems.

Figure A-1. View of a 32 year old creeping bentgrass putting green on hole number 2 at Orchard Lake Country Club, Orchard Lake, Michigan, which was constructed to exact Texas-USGA Method specifications in 1960.

Figure E-1A. A Closeup view of divots created by the divot simulation apparatus discussed in Section E.

Figure G-4. View of Tifway bermudagrass turf grown in 250 mm (10 in.) diameter circular columned containers.

Figure H-1. View of experimental Tifway bermuda-grass plot area.

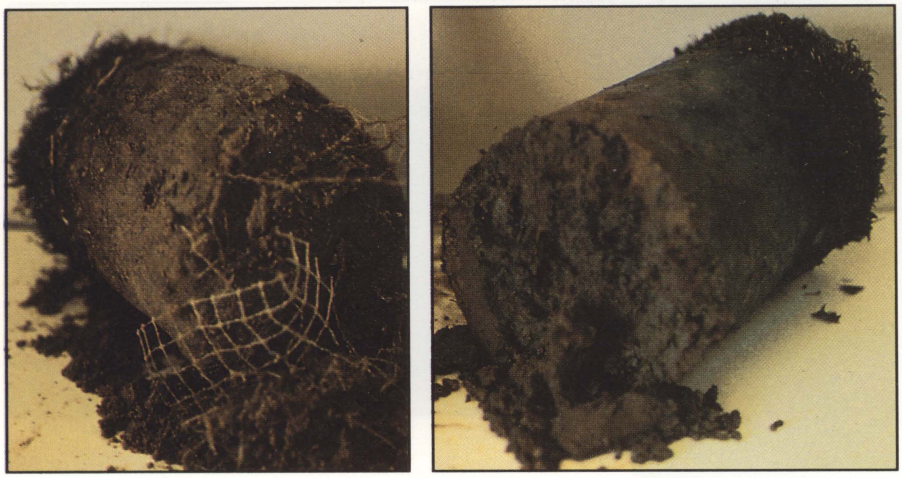

Figure I-1. View of turf-root zone profiles from a no-mesh treatment with soil black layer problems and loss of roots (right) and a mesh element inclusion treatment free of black layer (left).

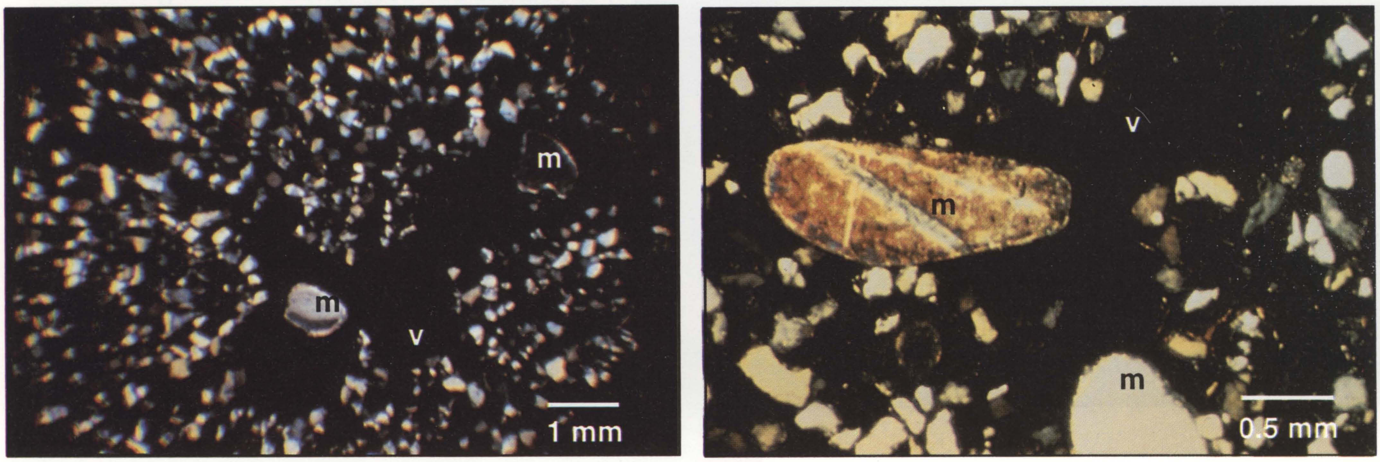

Figure I-2. Mesh element strands (m) associated with a void (v) located approximately 125 mm (4.9 in.) deep in the root zone (left). Then on the right is shown a closer view of a mesh element (m) associated with a void (v) located approximately 50 mm (2 in.) deep in the root zone. Shown by cross-polarized light.

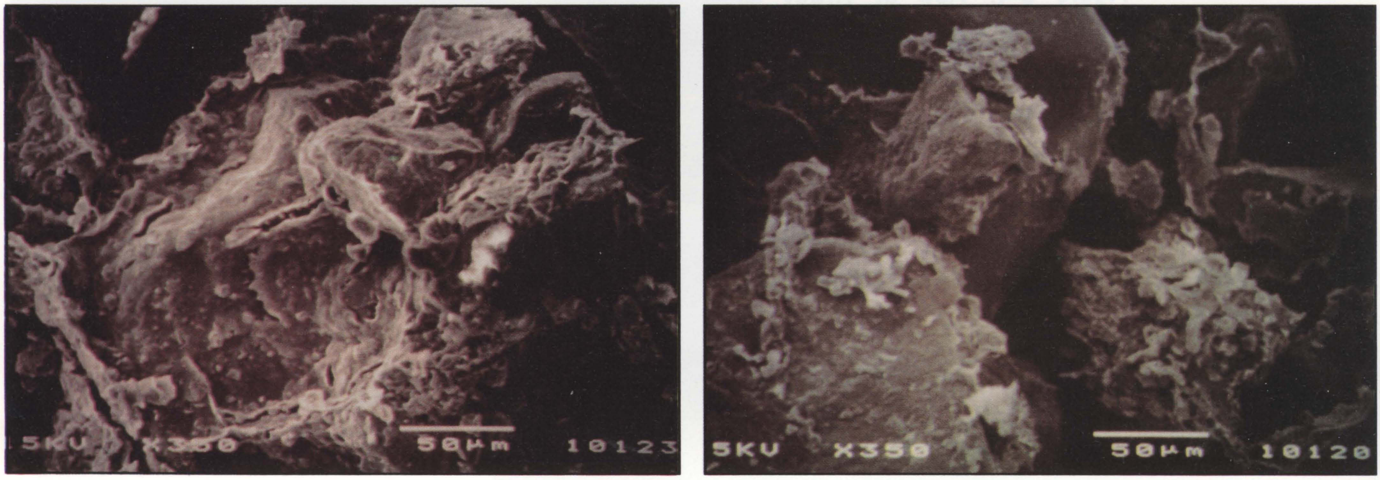

Figure I-3. On the left is a scanning electron micrograph of a non-mesh root zone, illustrating sand particles coated with clay. Note the continuous clay coating and bridging among the sand particles. To the right is a scanning electron micrograph of a mesh root zone. Clay coatings are present, but are discontinuous with no apparent bridging among sand particles.

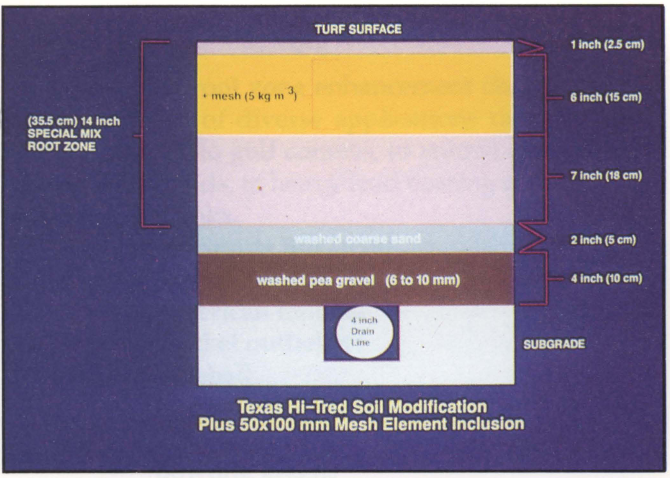

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Figure J-1. Profile of a Texas-USGA Method of high-sand root zone construction with mesh element matrix inclusions.

▲

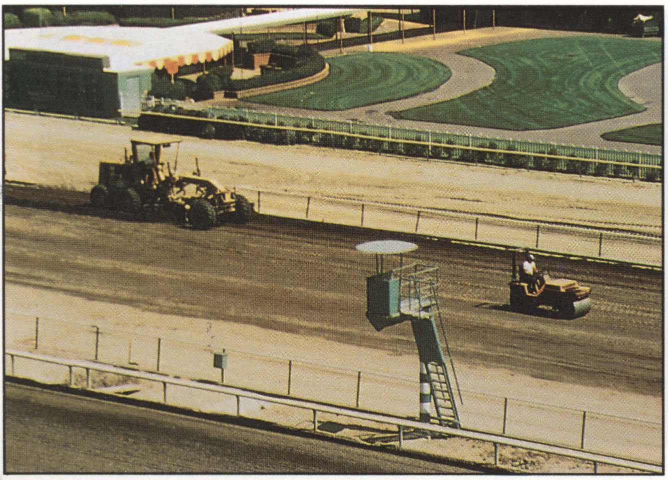
Figure J-2. A conventional front end loader being utilized in a mesh-root zone mixing operation on a hard surface.

▲

Figure J-3. A back action bucket unit being utilized in rough grading the high-sand mesh matrix mix after dumping of the mix in piles on-site.

▲

Figure J-4. A road grader and elevating scraper grading and removing excess windrowed mix.



▲

Figure J-5. A power roller and road grader executing the final leveling operations on a moist mesh element high-sand root zone matrix.

▲

Figure J-6. A centrifugal distributor unit mounted on the back of a truck that is being utilized for application of the 25 mm (1 in.) topdressing.

Figure K-2. One of four golf course tees installed at Texas A&M University golf course in 1989.

Figure K-1. Sha Tin horse race track in Hong Kong, installed in 1989.

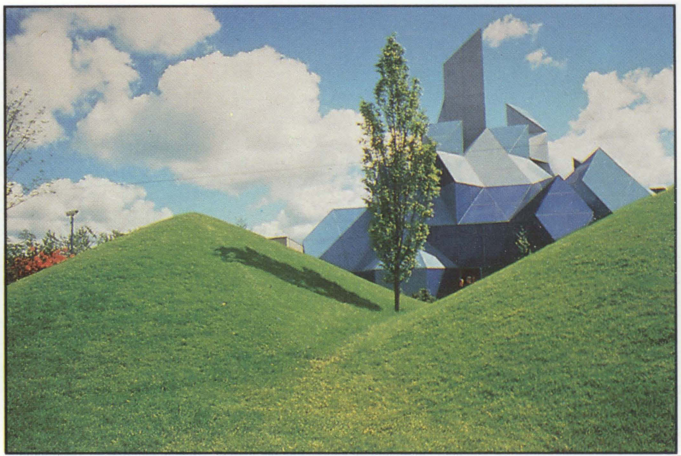


Figure K-3. Steeply sloped, geometric design, turfed ornamental bank, installed in 1987.

Figure J-7. A machine for continuous installation of the mesh element-high sand matrix to a firm, controlled depth of 150 mm (6 in.).

Figure K-4. Turfed overflow automobile parking site in Great Britain.

Turf Applications

The turfed-root zone enhancement characteristics offer a number of diverse applications ranging from sports surfaces, to golf courses, to animal competition and show grounds, to heavy load bearing areas, and to steep sloped banks.

A. **Turfed Sports Surfaces:**
  - Soccer
  - American football
  - Cricket outfields
  - Baseball
  - Rugby
  - Tennis courts
  - Bowling greens
  - Track field events - shot put, discus, and javelin
  - School playgrounds
  - Recreational areas

B. **Golf Courses:**
  - Tees
  - Cart paths
  - Bunker and grassy mound banks
  - Putting greens

C. **Animal Competition and Show Grounds:**
  - Horse race courses
  - Horse show/jumping arenas
  - Animal show/competition areas
  - Polo fields

D. **Load Bearing Areas:**
  - Turfed roadways
  - Turfed parking areas
  - Turfed perimeters of airfield runways
  - Turfed perimeters of tall building to support emergency/fire ladder trucks
  - Turfed crossovers of fairways and race tracks
  - Turfed bicycle lanes
  - Turfed walking paths

E. **Steep shaped banks:**
  - Roadside slopes
  - Ski slopes
  - Ornamental turfed landscape forms
  - Terrace slopes
  - Grassed theater seats and walkways

Specifications for the high-sand root zone typically used have been developed as part of the Texas-USGA Method. The mesh element density used in large installations at the Hong Kong and Santa Anita Park turfed horse race courses was 6 kg of mesh per cubic meter of high-sand mix (10 lb./yd^3). Non-equestrian sports turf applications have effectively used 5 kg of mesh per cubic meter of high-sand mix (8.3 lb./yd^3). Research using high clay and silty clay loam soils combined with mesh elements was initiated at College Station in 1990. The results are promising, but it is too early in this investigation to make conclusive statements.

Some examples of typical mesh element high-sand root zone matrix applications are shown on the front cover.

A Perspective

The main thrust in this research since 1985 has been the development of a stabilized turf-root zone system that will allow substantial increases in the frequency of use for competitive games, recreational activities, horse/animal show events, and roadway/parking lot/cart path traffic and to provide the increased traffic tolerant surfaces while still retaining an acceptable level of turf quality. It is designed to be as close to an all weather surface as possible, including freezing conditions if a soil heating system is installed.

In order to achieve this type of multi-functional surface that will function under a range of diversities, it obviously is going to be somewhat more expensive to install, but it will function satisfactorily for a longer time than other less science-based alternatives. By the same token, it will have a carrying capacity to handle a much larger number of competitive events, recreational activities, or traffic pressures. However, an upper limit always exists as to how much traffic even the best of turf systems can accommodate without eventually starting to thin.

One additional key in this overall system is the turf specialist. Although ultimately turfs grown on high-sand root zones are technically easier and less costly to maintain than finer textured, clayey soils, there is a critical learning curve of several years for turf managers who have no previous experience with high-sand modified root zones. Also, the first 3 years following construction are a dynamic transition period from a man-made root zone mix to a biologically active, living soil ecosystem. The mesh element high-sand system has superior capabilities in terms of traffic tolerance, but to maximize these capabilities for enhanced turf performance requires a turfgrass manager knowledgeable in the maintenance of turfs on high-sand root zones especially when grown under very intense traffic conditions.

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M. Appendix

Table F-1. The effects of a randomly oriented, interlocking mesh element-root zone matrix on turf injury and soil moisture during the years 1986 through 1988.

Assessment parameter	July 1986 Mesh	July 1986 No mesh	Oct. 1986 Mesh	Oct. 1986 No mesh	Oct. 1987 Mesh	Oct. 1987 No mesh	June 1988 Mesh	June 1988 No mesh	Sept. 1988 Mesh	Sept. 1988 No mesh
Divot opening size:										
Length (mm)	287.3 a*	327.0 b	208.8 a	248.4 a	119.8 a	173.3 b	38.6 a	67.3 b	57.5 a	63.0 a
Width (mm)	64.6 a	90.9 b	71.1 a	76.7 a	40.9 a	46.5 b	30.3 a	36.4 b	34.8 a	37.6 a
Depth (mm)	33.7 a	37.0 a	18.3 a	23.2 b	30.0 a	39.6 b	9.3 a	12.8 b	12.9 a	17.4 b
Divot opening recovery Days to:										
50%	—	—	16.0 a	21.0 b	14.0 a	21.0 a	7.0 a	14.0 b	7.0 a	14.0 b
75%	—	—	21.0 a	29.0 b	21.0 a	28.0 a	14.0 a	21.0 b	14.0 a	21.0 b
Lateral cleat turf tear (mm):										
4.5 kg weight (10 lb)	44.5 a	53.8 b	48.5 a	56.3 b	28.3 a	39.3 b	—	—	—	—
11.25 kg weight (25 lb)	60.8 a	67.0 a	71.3 a	75.7 a	58.3 a	64.5 a	—	—	—	
40.00 kg weight (88 lb)	—	—	—	—	—	—	35.0 a	35.5 a	40.0 a	38.1 b
Soil moisture % at 50 mm (2 in.)	—	—	—	—	36	32	12	9	46	38

* Means followed by the same letter in the same row within an assessment date are not significantly different, LSD T Test, alpha = 0.05.

** Except for means for early summer of 1987.

Table F-2. The effects of a randomly oriented, interlocking mesh element-root zone matrix on turf injury and soil moisture during the 1988 growing season.

Assessment parameter	May 1 Mesh	May 1 No mesh	June 1 Mesh	June 1 No mesh	August 1 Mesh	August 1 No mesh	September 15 Mesh	September 15 No mesh
Divot opening size:								
Length (mm)	48.6 a*	82.9 b	38.6 a	67.3 b	58.1 a	71.5 b	57.5 a	63.0 a
Width (mm)	37.1 a	50.9 b	30.3 a	36.4 b	36.7 a	44.9 b	34.8 a	37.6 a
Depth (mm)	10.1 a	15.0 b	9.3 a	12.8 b	14.8 a	13.6 a	12.9 a	17.4 b
Divot opening recovery Days to:								
50%	7.0 a	16.0 b	7.0 a	14.0 b	7.0 a	21.0 b	7.0 a	14.0 b
75%	10.0 a	28.0 b	14.0 a	21.0 b	14.0 a	28.0 b	14.0 a	21.0 b
Lateral cleat turf tear (mm)								
4.5 kg (10 lb.)	—	—	—	—	—	—	—	—
11.25 kg (25 lb.)	—	—	—	—	—	—	—	—
40.0 kg (88 lb.)	37.0 a	37.2 a	35.0 a	35.5 a	35.5 a	40.0 a	40.0 a	38.1 b
Soil moisture (%)								
50 mm (2 in.) depth	35	31	12	9	29	21	46	38
100 mm (4 in.) depth	25	19	14	13	22	21	44	38
150 mm (6 in.) depth	26	21	13	13	24	22	41	37

*Means followed by the same letter in the same row within a date are not significantly different, LSD T Test, alpha = 0.05.

Table F-3. The effects of a randomly oriented, interlocking mesh element-root zone matrix on turf playing surface characteristics during the years 1986 through 1988.

Assessment parameter		July 1986		Oct. 1986		Oct. 1987		June 1988		Sept. 1988	
		Mesh	No mesh	Mesh	No mesh	Mesh	No mesh	Mesh	No mesh	Mesh	No mesh
Ball Bounce (% of drop height)	Mean	—	—	—	—	17.6 a*	22.2 b	20.1 a	20.8 a	15.0 a	14.6 a
	Maximum	—	—	—	—	19	27	23	29	17	23
	Minimum	—	—	—	—	16	14	17	13	13	7
Traction (Nm for 90° turn)	4.5 kg (10 lb)	56.4 a	58.0 a	40.5 a	49.5 b	50.5 a	56.9 b	—	—	—	—
	11.25 kg (25 lb)	68.1 a	67.7 a	66.5 a	63.7 a	66.5 a	66.5 a	—	—	—	—
	40.00 kg (88 lb)	—	—	—	—	53.3 a	57.1 b	49.0 a	54.9 b	42.2 a	41.5 a
Compression displacement (mm)	4.5 kg (10 lb)	25.1 b	29.6 a	24.9 a	24.2 a	28.7 a	30.7 a	—	—	—	—
	11.25 kg (25 lb)	36.7 a	35.7 a	34.8 a	28.0 b	35.3 a	44.8 b	—	—	—	—
	40.00 kg (88 lb)	—	—	—	—	—	—	11.3 a	11.4 a	17.1 a	13.3 b

* Means followed by the same letter in the same row within an assessment date are not significantly different, LSD T Test, alpha =0.05.

Table F-4. The effects of a randomly oriented, interlocking mesh element-root zone matrix on turfed playing surface characteristics during the 1988 growing season.

Assessment parameter		May 1		June 15		August 1		September 15	
		Mesh	No mesh	Mesh	No mesh	Mesh	No mesh	Mesh	No mesh
Ball bounce (% of drop height)	Mean	26.8 a*	28.6 a	20.1 a	20.8 a	17.3 a	18.9 a	15.0 a	14.6 a
	Maximum	36	37	23	29	19	27	17	23
	Minimum	20	19	17	13	15	10	13	7
Traction (Nm for 90 ° turn):	4.5 kg (10 lb)	—	—	—	—	—	—	—	—
	11.25 kg (25 lb)	—	—	—	—	—	—	—	—
	40.0 kg (88 lb)	73.4 a	81.6 b	49.0 a	54.9 b	43.3 a	48.1 b	42.2 a	41.5 a
Compression displacement (mm):	4. 5 kg (10 lb)	—	—	—	—	—	—	—	—
	11.25 kg (25 lb)	—	—	—	—	—	—	—	—
	40.0 kg (88 lb)	12.3 a	12.5 a	11.3 a	11.4 a	15.3 a	11.4 b	17.1 a	13.3 b

*Means followed by the same letter in the same row within a date are not significantly different, LSD T Test, alpha = 0.05.

Table G-1. Influence of seven mesh element densities on the soil shrinkage from compaction and infiltration rates when placed as a 100-mm (4 in.) thick layer in (a) washed medium fine sand and (b) a silty clay soil.

a. Washed medium fine sand:

Density of mesh element inclusion in kg m^{-3} (lb/yd^{3})	Moist soil shrinkage from compaction (mm)	Dry soil shrinkage from compaction (mm)	Infiltration rate before compaction (mm min.$^{-1}$)	Infiltration rate after compaction (mm min.$^{-1}$)
0.0	62.7 a*	40.0 a	12.0 c	1.97 d
1.25 (2.1)	35.0 b	35.0 b	12.7 ab	3.06 a
2.50 (4.2)	39.7 b	32.7 b	13.9 ab	2.95 ab
3.75 (6.3)	36.7 b	30.7 b	13.5 ab	2.76 ab
5.0 (8.4)	38.7 b	30.3 b	14.6 a	2.21 bc
6.25 (10.5)	34.3 b	26.3 b	13.6 ab	2.47 abc
7.5 (12.6)	34.0 b	19.7 b	10.8 d	2.19 bc

b. Silty clay soil:

Density of mesh element inclusion in kg m^{-3} (lb/yd^{3})	Moist soil Shrinkage from compaction (mm)	Dry soil shrinkage from compaction (mm)	Infiltration rate before compaction (mm min.$^{-1}$)	Infiltration rate after compaction (mm min.$^{-1}$)
0.0	40.5 a*	35.0 a	3.90 a	0.97 b
1.25 (2.1)	35.5 abc	34.8 a	4.00 a	1.00 ab
2.50 (4.2)	26.8 abcd	26.5 ab	4.81 a	1.20 a
3.75 (6.3)	3.8 ab	24.5 ab	4.02 a	1.00 ab
5.0 (8.4)	19.0 cd	22.5 ab	4.68 a	1.17 a
6.25 (10.5)	20.0 bcd	16.3 b	4.49 a	1.12 ab
7.50 (12.6)	17.8 d	17.5 b	4.65 a	1.16 a

*Means followed by the same letter in the same column are not significantly different, LSD T Test, alpha = 0.05.

Table G-2. The influence of five depths of mesh element placement at 3.75 kg m^{-3} (6.3 lb/yd^{3}) density on soil shrinkage from compaction and infiltration rates in (a) washed medium fine sand and (b) a silty clay soil.

a. Washed medium fine sand:

Depth of mesh element placement in mm (in.)	Moist soil shrinkage from compaction (mm)	Dry soil shrinkage from compaction (mm)	Infiltration rate before compaction (mm min.$^{-1}$)	Infiltration rate after compaction (mm min.$^{-1}$)
0	45.0 b*	28.0 d	9.63 b	2.29 b
25 (1)	28.0 a	20.0 a	9.80 b	2.69 ab
50 (2)	29.0 a	22.3 ab	9.98 b	3.66 ab
100 (4)	29.0 a	22.7 ab	16.73 a	4.26 a
200 (8)	27.0 a	25.7 c	16.73 a	4.26 a

b. Silty clay soil:

Depth of mesh element placement in mm (in.)	Moist soil shrinkage from compaction (mm)	Dry soil shrinkage from compaction (mm)	Infiltration rate before compaction (mm min.$^{-1}$)	Infiltration rate after compaction (mm min.$^{-1}$)
0	22.3 d*	21.0 b	1.74 c	0.43 c
25 (1)	16.3 b	19.0 ab	4.29 a	1.08 a
50 (2)	17.0 c	22.0 b	3.65 ab	0.91 b
100 (4)	14.0 ab	17.0 a	4.01 ab	1.00 a
200 (8)	9.0 a	17.3 a	4.31 a	1.07 a

* Means followed by the same letter in the same column are not significantly different, LSD T Test, alpha = 0.05.

Table G-3. Influence of three mesh inclusion densities and three depths of mesh element placement on the infiltration and percolation rates in a simulated turf-medium fine sand root zone with turfs that had been grown in situ for 2 years.

Mesh treatment		Mean infiltration rate	Mean percolation rate
Density kg m^{-3} (lb/yd^{3})	Depth mm (in.)	mm min^{-1}	mm min^{-1}
1.25 (2.1)	25 (1)	22.7 abcd*	17.0 ab
1.25 (2.1)	50 (2)	23.2 abcd	16.9 ab
1.25 (2.1)	100 (4)	16.6 cd	13.8 b
2.5 (4.2)	25 (1)	23.3 abcd	17.4 ab
2.5 (4.2)	50 (2)	26.9 ab	17.7 ab
2.5 (4.2)	100 (4)	19.9 bcd	15.4 ab
5.0 (8.4)	25 (1)	23.3 abcd	17.3 ab
5.0 (8.4)	50 (2)	24.6 abc	17.7 ab
5.0 (8.4)	100 (4)	29.4 a	19.4 a
Untreated non-mesh control		12.5 e	13.0 c

*Means followed by the same letter in the same column are not significantly different, LSD T Test, alpha = 0.05.

Table H-1. Summary assessments concerning the effects of four densities of randomly oriented interlocking mesh element-root zone matrices on turf injury, playing surface characteristics, and soil moisture in 1988.

		Quantity of mesh m^{3} (yd^{3})				
Assessment parameter	Weight (kg)	0.0	2.5 kg (4.2 lb)	3.75 kg (6.3 lb)	3.75 kg (6.3 lb) to surface	5.0 kg (8.4 lb)
Lateral cleat turf tear (mm)	4.5	15.0 b*	24.0 a	24.0a	21.0 a	24.0 a
	11.25	23.0 c	29.0 a	28.0 ab	25.3 bc	26.0 abc
	40	40.0 a**	40.0 a	40.0 a	40.0 a	40.0 a
Compression displacement (mm)	4.5	7.0 b	17.0 a	18.0 a	13.0 b	19.0 a
	11.25	9.0 d	21.0 a	17.0 bc	15.0 c	20.0 ab
	40	14.0 c	22.0 a	20.0 ab	13.0 c	18.0 b
Traction (Nm for 90 ° turn)	4.5	6.0 a	6.0 a	7.0 a	6.0 a	7.0 a
	11.25	12.0 a	12.0 a	12.0 a	11.0 a	11.0 a
	40	43.0 a	40.0 b	42.0 ab	43.0 a	44.0 a
Divoting						
	Length (mm)	103.0 a	75.0 bc	83.0 b	78.0 bc	68.0 c
	Width (mm)	46.0 a	40.0 ab	42.0 ab	41.0 ab	41.0 ab
	Depth (mm)	12.0 b	16.0 a	15.0 a	15.0 a	15.0 a
	Recovery (%)					
	7 days	18.0 c	43.0 a	35.0 ab	30.0 bc	31.0 abc
	14 days	44.0 c	70.0 a	67.0 a	55.0 bc	60.0 ab
	21 days	66.0 c	90.0 a	87.0 a	76.0 ab	78.0 ab
	28 days	76.0 c	96.0 a	90.0 ab	88.0 b	91.0 ab
Ball bounce (% of drop height)		18.0 a	17.0 a	17.0 a	17.0 a	17.0 a
Soil moisture						
	50 mm	4.0 c	6.0 a	6.0 a	5.0 b	6.0 a
	100 mm	4.0 b	5.0 a	6.0 a	5.0 a	5.0 a
	150 mm	6.0 b	7.0 a	5.0 c	4.0 d	5.0 c
Clegg impact values in gravities (g)	Hammer wt.					
	0.5	—	—	—	—	—
	2.25	—	—	—	—	—
	4.5	—	—	—	—	—

* Means within the same line followed by the same letter are not significantly different. T Test (LSD), alpha = 0.05.

** Cleat spacing on STRI traction device was 40 mm. Tear measurements of 40.0 mm indicate tearing from cleat to cleat.

Table H-2. Summary assessments concerning the effects of four densities of randomly oriented interlocking mesh element-root zone matrices on turf injury, playing surface characteristics, and soil moisture in 1989.

		Quantity of mesh m ^{3} (yd^{3})				
Assessment parameter	Weight (kg)	0.0	2.5 kg (4.2 lb)	3.75 kg (6.3 lb)	3.75 kg (6.3 lb) to surface	5.0 kg (8.4 lb)
Lateral cleat turf tear (mm)	4.5	19.0 a	18.0 a	18.0 a	18.0 a	19.0 a
	11.25	25.0 a	24.0 a	26.0 a	24.0 a	25.0 a
	40	36.0 a*	37.0 a	37.0 a	36.0 a	36.0 a
Compression displacement (mm)	4.5	15.0 a	18.0 b	18.0 b	15.0 a	18.0 b
	11.25	16.0 a	18.0 b	19.0 b	15.0 a	19.0 b
	40	20.0 a	24.0 b	24.0 b	20.0 a	24.0 b
Traction (Nm for 90 ° turn)	4.5	15.0 a	14.0 a	15.0 a	14.0 a	15.0 a
	11.25	14.0 a	14.0 a	15.0 a	14.0 a	15.0 a
	40	35.0 a	35.0 a	34.0 a	34.0 a	35.0 a
Divoting						
	Length (mm)	121.0 a	89.0 c	81.0 cd	109.0 b	75.0 d
	Width (mm)	48.0 a	42.0 b	40.0 b	47.0 a	42.0 b
	Depth (mm)	18.0 c	21.0 ab	21.0 ab	19.0 bc	22.0 a
	Recovery (%)					
	7 days	14.0 b	22.0 ab	19.0 ab	16.0 b	26.0 a
	14 days	25.0 b	45.0 a	41.0 a	32.0 b	43.0 a
	21 days	46.0 b	67.0 a	64.0 a	52.0 b	65.0 a
	28 days	68.0 b	82.0 a	81.0 a	71.0 b	79.0 a
Ball bounce (% of drop height)		19.0 a	19.0 a	24.0 a	20.0 a	21.0 a
Soil moisture (%)						
	50 mm	6.0 c	7.0 b	7.0 b	8.0 a	7.0 b
	100 mm	6.0 b	7.0 a	7.0 a	9.0 a	8.0 a
	150 mm	6.0 c	8.0 b	9.0 b	10.0 a	8.0 b
Clegg impact values in gravities (g)	Hammer wt.					
	0.5	78.0 a	76.0 b	74.0 b	72.0 c	75.0 b
	2.25	—	—	—	—	—
	4.5	26.0 a	26.0 a	27.0 a	26.0 a	27.0 a

* Means within the same line followed by the same letter are not significantly different. T Test (LSD), alpha = 0.05.

Table H-3. Summary assessments concerning the effects of four densities of randomly oriented interlocking mesh element-root zone matrices on turf injury, playing surface characteristics, and soil moisture in 1990.

		Quantity of mesh m^3 (yd^3)				
Assessment parameter	Weight (kg)	0.0	2.5 kg (4.2 lb)	3.75 kg (6.3 lb)	3.75 kg (6.3 lb) to surface	5.0 kg (8.4 lb)
Lateral Cleat turf tear (mm)	4.5	31.0 c*	34.0 a	32.0 b	35.0 a	34.0 a
	11.25	—	—	—	—	—
	40	40.0 a**	40.0 a	40.0 a	40.0 a	40.0 a
Compression displacement (mm)	4.5	17.0 c	23.0 a	22.0 b	18.0 c	23.0 a
	11.25	—	—	—	—	—
	40	21.0 b	25.0 a	24.0 b	19.0 c	25.0 a
Traction (Nm for 90 ° turn)	4.5	23.0 a	23.0 a	23.0 a	22.0 a	23.0 a
	11.25	—	—	—	—	—
	40	40.0 a	41.0 a	40.0 a	41.0 a	40.0 a
Divoting						
	Length (mm) 145.0 b	142.0 c	124.0 c	172.0 a	131.0 c	
	Width (mm)	60.0 b	60.0 b	56.0 c	66.0 a	54.0 c
	Depth (mm)	19.0 a	20.0 a	20.0 a	18.0 b	21.0 a
	Recovery (%)					
	7 days	14.0 b	20.0 a	19.0 a	14.0 b	20.0 a
	14 days	25.0 b	39.0 a	38.0 a	24.0 b	41.0 a
	21 days	63.0 b	62.0 a	63.0 a	43.0 b	65.0 a
	28 days	65.0 b	83.0 a	83.0 a	64.0 b	85.0 a
Ball bounce (% of drop height)		20.0 a	20.0 a	19.0 a	18.0 a	20.0 a
Soil moisture						
	50 mm	2.0 c	5.0 a	4.0 b	4.0 b	5.0 a
	100 mm	5.0 a	5.0 a	5.0 a	5.0 a	5.0 a
	150 mm	4.0 b	5.0 a	5.0 a	5.0 a	5.0 a
Clegg impact values in gravities (g)	Hammer wt.					
	0.5	76.0 a	68.0 b	67.0 b	75.0 a	71.0 b
	2.25	67.0 a	63.0 b	61.0 c	64.0 b	63.0 b
	4.5	22.0 a	17.0 b	19.0 b	21.0 a	19.0 b

* Means within the same line followed by the same letter are not significantly different. T Test (LSD), alpha = 0.05.

** Cleat spacing on STRI traction device was 40 mm. Tear measurements of 40 mm indicate tearing from cleat to cleat.

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