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SAND TEXTURED ROOT ZONES IN ATHLETIC FIELDS: TURFGRASS ESTABLISHMENT AND CONSTITUENT SELECTION BASED ON AGRONOMIC AND ENGINEERING PROPERTIES

By

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ABSTRACT

SAND TEXTURED ROOT ZONES IN ATHLETIC FIELDS: TURFGRASS ESTABLISHMENT AND CONSTITUENT SELECTION BASED ON AGRONOMIC AND ENGINEERING PROPERTIES

By

Jason Jeffrey Henderson

Two studies were conducted to address problems associated with sand-based root zones in athletic fields. Sand root zones drain rapidly, but can create problems due to their instability, and their lack of water and nutrient holding capacity can make turfgrass establishment difficult. The objective of the first study was to determine what percentage of silt and clay must be added to a well-graded sand to maximize soil bearing capacity while retaining a hydraulic conductivity value of 7-8 cm hr^{-1}. Mixes containing 10% and 12% silt+clay, compacted at 5% water content, provided over a 100% increase in strength over sand alone, while maintaining hydraulic conductivity values of 19.0 and 8.5 cm hr^{-1} respectively. Study two was conducted in 1998 and 1999. The objectives were to evaluate the effects and interactions of both a plant growth regulator (Primo) and wetting agent (Aqueduct) applied during establishment. First year results showed an increase in density and sod strength due to the application of the plant growth regulator (PGR). However, in 1999 the PGR did not enhance density or sod strength. In 1998, wetting agent applications reduced germination and wear tolerance, and sod strength was reduced in both years.

Dedicated to my mother, Diane Henderson, her parents (Harvey and Fern Reeser), my father, Jeff Henderson, and his parents (Wayne and Joan Henderson). Your love, support, sacrifice, work ethic, and teachings have made me the person I am today. What I am able to accomplish during this lifetime is as much yours as it is mine.

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INTRODUCTION

Athletic fields are subjected to intense traffic under all types of weather and soil moisture conditions. Turfgrass professionals face the challenge of developing the "perfect field" that will endure the rigors of athletic competition during any weather conditions.

An athletic field must provide firm footing, adequate resiliency on impact, and resistance to tearing during play. It must also drain well and resist the compacting effects of severe traffic (Turgeon 1991). The key to constructing the "perfect field" lies in the choice of the root zone material. Traditional fields developed on native soil with high silt and clay content will provide excellent stability but drain poorly, and the quality of the playing surface quickly diminishes in unfavorable weather conditions and with heavy use.

In the early 1960's, the inability to sustain optimal playing conditions and acceptable appearance resulted in the transition to artificial surfaces at many college and professional stadia (Turgeon 1991). Artificial turf was considered advantageous for several reasons: it is immune to turf pests, it does not require cultural practices, and it is adaptable to all types of environmental conditions. However, today it is believed by many that the disadvantages of artificial surfaces exceed their advantages. The disadvantages include high initial cost of construction, substantial heat build-up at and above the surface during hot weather (temperatures at the surface have been known to reach 140° F) (Kanter 1986), and most importantly, the very abrasive, hard surfaces increase player injury (Powell 1987).

After World War II, golf substantially increased in popularity. The native soil (push up) golf greens were unable to withstand the intense traffic and their quality continually deteriorated. Poor putting green quality forced researchers to investigate alternative construction methods. In the 1950's, extensive research was conducted on sands and resulted in the first publication of the United States Golf Association (USGA) specifications for golf green construction in 1960 (Hummel 1993). By the mid 1960's, the knowledge gained on behalf of the golf industry began to transfer to athletic fields when Dr. Roy Goss began recommending high sand content root zones for athletic fields (Goss 1967). In 1970, in a continued effort to return to natural playing surfaces, Bill Daniel, Turfgrass Management Specialist at Purdue University, designed the Prescription Athletic Turf (PAT) system to address drainage problems associated with natural turf fields.

Since the inception of the PAT system, its key component, a sand root zone, has become increasingly popular because it maintains macroporosity once compacted and drains rapidly. The USGA specifications for putting green construction, which is currently being used to construct many athletic fields, recommends a saturated hydraulic conductivity value between 15-30 cm/hr (Hummel 1993); it has never been determined whether such high saturated hydraulic conductivity values are actually necessary, even under extreme conditions. Sand has many advantages, but it can create problems. It is an unnatural growing medium that has little water holding capacity and can store few plant nutrients, making it poorly suited for turfgrass establishment. However, the problem of greatest concern is the instability of sand. Many newly constructed fields have failed because of this instability of the root zone. For example, an athletic field was constructed with a very uniform sand for Hillsdale College, which had a very unstable playing surface (Crum, pers. comm.).

Currently, the predominant specifications used for root zone constituent selection for athletic fields are those recommended by the USGA for putting greens. However, it must be recognized that athletic field requirements differ from those of a golf course green. The activities performed on each surface are drastically different and this difference must be reflected in a separate set of specifications. Specifications currently used in Great Britain already recognize this need by recommending a root zone mix that has less than 20% fines (particles < 0.125 mm), less than 10% silt plus clay (particles < 0.05 mm) and less than 5% clay (particles < 0.002 mm) (Baker 1985). The goal is to adapt the specifications developed for golf green construction to athletic fields.

In spite of the problems that all sand root zones create, they are still being used to construct today's "top" athletic fields. This forces turf managers to deal with specific problems, particularly the establishment of a new turf stand. The challenge for the sports turf manager is to sustain a dense sward throughout the competitive season. However, even with proper management practices, areas of the field or entire fields can be worn very thin or even bare by intense use. Consequently, the perennial focus of athletic field management is the establishment of a new turf stand, often during a competitive season. The quickest method of turf establishment, sodding, provides an instant turf cover, but may not be feasible during season play. In most instances there is insufficient time between games for adequate root development to provide a playable surface. Thick-cut sodding is an option, but is very costly, labor intensive, and time consuming. Sodding can also create other complications such as layering problems, when the soil texture of the sod is not matched properly with the texture of the root zone.

The complications associated with sodding leave seeding as the primary option of establishment during season play. The desired species for athletic fields in cool-season areas is Kentucky bluegrass (*Poa pratensis* L.), which has a slow germination rate of 10-14 days (Parks and Henderlong 1967). Kentucky bluegrass also matures slowly compared to other less desirable cool-season turfgrasses. The slow establishment rate coupled with the challenges presented by the sand growth medium make establishing Kentucky bluegrass particularly difficult.

One way to speed the development of Kentucky bluegrass is through the use of a plant growth regulator, which may promote quicker establishment, increased stand density, and improved recuperative potential (Watschke and DiPaola 1995). The additional use of a wetting agent could increase moisture retention of the sand, thereby enhancing germination. The benefits of using a wetting agent during plant establishment have been shown (Osborn et al. 1964, 1967, 1969).

Over the past 10 to 20 years a tremendous amount of money has been spent to build the "perfect field" at college and professional stadia. Many of these fields have had significant problems or have failed. Sand root zones are believed to have caused many of these failures. Previous attempts at amending sand root zones to improve stability have resulted in limited success, but the strength benefits of amending sands using silt and clay has not been investigated thoroughly. This is worth investigating because as the silt and clay content of a soil mix increase the stability increases. However, as the silt and clay content of the mix increases the hydraulic conductivity of the mix drops quickly (Adams 1976). The majority of the research that has been conducted using silt and clay as an amendment has focused on its effect on hydraulic conductivity rather than the increase in stability. The percent silt and clay that can be added to a sand to maximize stability while retaining adequate hydraulic conductivity has not been determined. Therefore the objectives of these studies were:

OBJECTIVES

1) Determine what percentage of silt and clay must be added to a well-graded sand to maximize soil bearing capacity while retaining a hydraulic conductivity value of 7-8 cm hr^{-1}.
2) Investigate the effects of a plant growth regulator in combination with a wetting agent to aid in the establishment and subsequent development of Kentucky bluegrass in high-sand content root zones.

Chapter 1

EFFECTS OF ADDING SILT AND CLAY ON THE AGRONOMIC AND ENGINEERING PROPERTIES OF A SAND TEXTURED ROOT ZONE MATERIAL

ABSTRACT

An athletic field must provide firm footing, adequate resiliency on impact, and resistance to tearing during intense use under all types of weather conditions. Traditional fields developed on native soil with high silt and clay content provide excellent stability, but drain slowly. In an effort to solve the drainage problems associated with natural playing fields, many newly constructed athletic fields are built with high-sand root zones. Sand root zones maintain macroporosity once compacted and drain rapidly, but can create problems due to their instability. The objective of this study was to determine what percentage of silt and clay must be added to a well-graded sand to maximize soil bearing capacity while retaining a hydraulic conductivity value of 7-8 cm hr^{-1}. Eight different mixtures were subjected to four different analyses: Standard Proctor Compaction Test, bearing capacity, saturated hydraulic conductivity, and pore size distribution. Water content at compaction and percent silt+clay highly influenced soil strength and hydraulic conductivity values. Mixes containing 10% and 12% silt+clay, compacted at 5% water content, provided over a 100% increase in strength over sand alone, while maintaining hydraulic conductivity values of 19.0 and 8.5 cm hr^{-1} respectively.

INTRODUCTION

Athletic fields are subjected to intense traffic under all types of weather and soil moisture conditions. Turfgrass professionals face the challenge of developing the "perfect field" that will endure the rigors of athletic competition during any weather conditions.

An athletic field must provide firm footing, adequate resiliency on impact, and resistance to tearing during play. It must also maintain macroporosity once compacted (Turgeon 1991). Traditional fields developed on native soil with high silt and clay content will provide excellent stability but drain poorly, and the quality of the playing surface quickly diminishes in unfavorable weather conditions and with heavy use.

In an effort to solve drainage problems associated with natural playing fields, Dr. Roy Goss, Turfgrass Specialist at Washington State University, began recommending high sand content root zones for athletic fields by the mid 1960's (Goss 1967). In 1970, Bill Daniel, Turfgrass Management Specialist at Purdue University, designed the Prescription Athletic Turf (PAT) system (Daniel 1973). Since the inception of the PAT system, its key component, a sand root zone, has become increasingly popular because it maintains macroporosity to allow for rapid drainage when compacted. Sand has many advantages, but it can create problems. The problem of greatest concern is the instability of sand. Many newly constructed fields have failed and are unsafe because of this instability of the root zone.

Because drainage and compaction are major drawbacks with native soil fields, agronomic research on sands has focused on water and air movement, not stability (Bingaman and Kohnke 1970, Brown and Duble 1975, Blake 1980). Civil engineers have studied the strength properties of sands for a number of years. Although Chen (1948) concluded the strength of sands increase with increasing uniformity coefficient, early agronomists recommended the use of uniform sands for use in sportsfield root zones because of their high porosity (Bingaman and Kohnke 1970, Adams et al. 1971).

Sandy root zones rely heavily on turfgrass root systems for stability (Adams and Jones 1979, Adams et al. 1985). Once ground cover and root structure is lost, surface stability quickly deteriorates, causing unsafe playing conditions on the highest trafficked areas of the field. This is a serious concern for fields that receive excessive traffic, particularly practice fields. Since the determination that sand relies heavily on root structure for stability, there have been many attempts at adding artificial amendments such as mesh products and many kinds of fibers to sand to increase its stability. (Adams and Gibbs 1989; Beard and Sifer 1993; Canaway 1994; McNitt 1998). These products have been shown to increase the stability of sand root zones, but introduce additional problems. They can be difficult to work with during construction, restrict cultural practices on established turf, and can increase surface hardness (Adams and Gibbs 1989; McNitt 1998).

It is important a field drains well, but it is equally or more important that a field has a stable surface. If artificial amendments can introduce other problems, expanding the particle-size distribution of the root zone by adding silt and clay to the sand may be the only alternative. The problem when considering sand/soil mixes for athletic fields is the relationship between gradation and porosity. As the sand-soil becomes more well-graded its stability increases, but the porosity decreases, reducing hydraulic conductivity and slowing drainage (Crum 1996). Adams (1976) recognized the need for more fine material (particles < 0.05 mm) in a mix to improve surface traction and implied that a small amount of fine material may be necessary to provide surface binding. The primary concern was the silt and clay's effect on hydraulic conductivity. Adams concluded that hydraulic conductivity decreases very rapidly with small additions of fine material (particles < 0.05 mm), which proved percent particles less than 0.05 mm the most appropriate general criterion for predicting the hydraulic conductivity of compacted sand-soil mixes (Adams 1976; Baker 1985).

Currently, the predominant specifications used for root zone constituent selection for athletic fields are those recommended by the USGA for putting greens, which recommends a hydraulic conductivity of 15-30 cm hr^{-1} (Hummel 1993). High hydraulic conductivity values and infiltration rates are desired for athletic fields, but it has not been proven these extreme values are needed for even the worst storms that could be faced during an athletic competition. The lowest possible infiltration rate and hydraulic conductivity value that is recommended for an athletic field varies throughout the literature. Waddington et al. (1974) recommended the infiltration rate for athletic fields should not be below 2.5 cm hr^{-1}. Adams (1976) noted there was a general agreement that hydraulic conductivity values should fall within the range of 1.5 - 7.5 cm hr^{-1} for high-grade facilities.

It must be recognized that athletic field requirements differ from those of a golf course green. The activities performed on each surface are drastically different and this difference must be reflected in a separate set of specifications. Specifications currently used in Great Britain already recognize this need by recommending a root zone mix that has less than 20% fines (particles < 0.125 mm), less than 10% silt plus clay (particles < 0.05 mm) and less than 5% clay (particles < 0.002 mm) (Baker 1985). The goal is to adapt the specifications developed for golf green construction to athletic fields.

It has been well established that the desired hydraulic conductivity will limit how much silt and clay can be added to a sand root zone material. However, the quantity of silt and clay that must be added to sand before a substantial increase in stability is obtained is not known. Adams (1979) concluded that a small portion of fine material, approximately 5%, is mildly beneficial in improving resistance to shear. In 1985, Adams concluded from another study that 12% content of fine soil fractions increases shear resistance by about 50% over that of pure sand. Although these results were encouraging, his methods did not quantify the soils' bearing capacity. Bearing capacity is an important parameter because it quantifies the ability of a soil to carry a load without failure. Vertically loading the soil to determine its strength is the closest laboratory method to simulate the way a root zone is loaded by an athlete performing on the surface.

By combining the knowledge gained by civil engineering and agronomic research, root zone specifications for athletic fields can be determined. The objective of this study is to determine what percentage of silt and clay must be added to a well-graded sand to maximize soil bearing capacity while retaining a hydraulic conductivity value between 7 and 8 cm hr^{-1}.

LITERATURE REVIEW

Since the first sand-based athletic field was built in Puyallup, Washington in 1965 (Goss 1965), there has been a continual increase in the use of sands and amended sands in constructing root zones for athletic fields. This trend has been motivated by the need for efficient drainage to permit athletic field use under adverse weather conditions (Adams 1976). The pore space pattern in native soil is largely the result of aggregation from the cohesive nature of clay. These aggregates can be destroyed by intense foot traffic, which is common on athletic fields. Destruction of aggregates reduces pore space, especially the larger pores causing drainage and aeration problems (Adams and Jones 1979). Sand is desirable for two primary reasons: it maintains macropores and it drains rapidly. It has a coarse, single-grained structure and will maintain its macroporosity once compacted (Bingaman and Kohnke 1970).

Sand-based fields should provide the ultimate playing surface because they are free-draining and resistant to compaction. However, sand root zones can create problems. Sand has little water holding capacity, is chemically inert, and is not conducive to turfgrass establishment. Proper irrigation and fertilization can alleviate some of these problems, however of greater concern is the instability of sand.

Because drainage and compaction are major drawbacks with native soil fields, agronomic research on sands has focused on water and air movement, not stability (Bingaman and Kohnke 1970, Brown and Duble 1975, Blake 1980). Civil engineers have studied the strength properties of sands for a number of years. Although Chen (1948) concluded the strength of sands increase with increasing uniformity coefficient, early agronomists recommended the use of uniform sands for use in sportsfield root zones because of their high porosity (Bingaman and Kohnke 1970, Adams et al. 1971). Uniform sand can lack surface stability (Hummel 1993). There are no smaller particles present to fill the voids between the larger ones making the frictional resistance between particles very low, allowing particles to move very easily when the surface of the root zone is loaded. Hence, some recently constructed fields drain well, but often perform poorly due to the instability of the root zone.

Unfortunately, if water and air movement is a priority, the root zone must have a high porosity. Bingaman and Kohnke (1970) investigated the physical characteristics of sand and how they related to parameters such as porosity and hydraulic conductivity. They determined as sand becomes more well-graded the total pore space decreases. Therefore they concluded that most particles in sand used in root zone construction should be between 0.1 and 0.5 mm with silt, clay and very fine sand essentially absent. Adams et al. (1971) determined that sands which have 10% of their weight outside the range 0.1-0.6 mm were inefficient if not completely unsuitable for use on sportsfields. Following either of these recommendations would produce a uniform particle-size distribution, which could result in an unstable playing surface.

The particle-size distribution of sand is its most important physical property. Particle-size distribution not only influences or controls porosity, bulk density, cation exchange capacity, and plant available water holding capacity, but also soil strength and soil stability (Crum 1996). Hummel (1993) concluded from previous literature regarding sand selection that the most desirable sand size for optimizing growth conditions under high traffic situations falls within the range 0.1-1.0 mm in diameter. These conclusions resulted in the current (1993) United States Golf Association Specifications for Putting Green Construction, which are being used to construct many athletic fields. Although there have been advances in sand selection for stability, such as broadening the particle-size distribution, a well-graded sand is often not stable enough for the rigors of some sports. Research has indicated that particle-size distribution is important in determining the bearing capacity of sand and sand-soil mixes (Crum 1996). Two coefficients commonly calculated to quantify the particle-size distribution of a sand or sand-soil mix are; the coefficient of uniformity (D_{60}/D_{10}) and the gradation index (D_{90}/D_{10}) (Hummel 1993). Given the specifications provided by the USGA regarding the root zone mix, the highest possible coefficient of uniformity (Cu) would be 2.65 and the maximum gradation index (GI) would equal 6.67 (Hummel 1993). Root zone materials that will provide adequate stability will have higher coefficients of uniformity and gradation indices.

Sandy root zones rely heavily on turfgrass root systems for stability (Adams and Jones 1979, Adams et al. 1985). Once ground cover and root structure is lost, surface stability quickly deteriorates, causing unsafe playing conditions on the highest trafficked areas of the field. This is a serious concern for fields that receive excessive traffic, particularly practice fields. Since the determination that sand relies heavily on plant roots for stability, there have been many attempts at adding artificial amendments such as mesh products and many kinds of fibers to sand to increase its stability. (Adams and Gibbs 1989; Beard and Sifer 1993; Canaway 1994; McNitt 1998). These products have been shown to increase the stability of sand root zones, but introduce additional problems. They can be difficult to work with during construction, restrict cultural practices on established turf, and can increase surface hardness (Adams and Gibbs 1989; McNitt 1998).

It is important that a field drains well, but it is equally or more important that a field has a stable surface. If artificial amendments can introduce other problems, increasing the particle-size distribution of the root zone by adding silt and clay to the sand may be the only alternative. The problem when considering sand/soil mixes for athletic fields is the relationship between gradation and porosity. As the sand-soil becomes more well-graded its stability increases, but the porosity decreases reducing hydraulic conductivity and slowing drainage (Crum 1996). Soil has been added to sand with more of an emphasis on increasing water retention and reduce leaching than increasing stability (Brown and Duble 1975). However, Adams (1976) recognized the need for more fine material (particles <

0.05 mm) in a mix to improve surface traction and implied that a small amount of fine material may be necessary to provide surface binding. The primary concern was the silt and clay's effect on hydraulic conductivity. Adams concluded that hydraulic conductivity decreases very rapidly with small additions of fine material, which proved percent particles less than 0.05 mm the most appropriate general criterion for predicting the hydraulic conductivity of compacted sand-soil mixes (Adams 1976; Baker 1985).

Adams and Jones (1979) determined the addition of fine material (particles < 0.05 mm) could improve surface strength characteristics. However, since a high hydraulic conductivity must be maintained for sportsturf facilities, which are often used intensively in wet weather, there was bound to be a strict limitation on the amount of fine material that can be tolerated (Adams 1976). Research indicates pure uniform sands' hydraulic conductivity values can range from 10 cm hr^{-1} for sands 0.1 mm in diameter to 250 cm hr^{-1} for sands 0.5 mm in diameter (Stakman 1969; Adams et al. 1971). Brown and Duble (1975) determined that 2 to 3% clay in the mixture would be optimum. This range will still allow infiltration rates of 17cm hr^{-1}. The USGA specifications recommend a hydraulic conductivity of 15-30 cm hr^{-1} (Hummel 1993). High hydraulic conductivity values and infiltration rates are desired for athletic fields, but it has not been proven that these extreme values are needed for even the worst storms that could be faced during an athletic competition. Brown and Duble (1975) noted that the 100-year expected rainfall for the continental U. S. (Hershfield 1961) indicates a possible precipitation rate of 12 cm hr^{-1} in southern Florida. The lowest possible infiltration rate and hydraulic conductivity value that is recommended for an athletic field varies throughout the literature. Waddington et al. (1974) recommended the infiltration rate for athletic fields should not be below 2.5 cm hr^{-1}, and stated rainfall may exceed infiltration rates but excess water would be removed by surface drainage. Adams (1976) noted there was a general agreement that hydraulic conductivity values should fall within the range of 1.5 - 7.5 cm hr^{-1} for high-grade facilities.

When working with sand-soil mixes, not only does the amount of silt and clay affect hydraulic conductivity and infiltration rates, but the level of compaction and the water content at compaction can significantly decrease these values (Swartz and Kardos 1963; Taylor and Blake 1981). Akron and Kemper (1979) showed the infiltration rate of a loamy sand containing 17% silt plus clay was reduced from 20 to 0.5 cm hr^{-1} when the water content of the soil at the time of compaction was increased from air dry to approximately 14% water content by weight.

The quality of the soil used in sand-soil mixes is another important concern when considering adding silt and clay to sand. Baker (1985) mixed one sand with sixty-seven different soils that covered a wide range of textural qualities to bring the total fines (particles < 0.125 mm) of each mix to 20% by weight. Many of the soils were subsoil or had subsoil contamination. There was substantial variation in the physical properties of each resulting mix. Each mix was subjected to the same compactive effort and hydraulic conductivity values ranged from 0.28 to 12.5 cm hr^{-1}, indicating the need for using high quality soil when producing sand-soil mixes. This will not only improve the physical properties of the resulting mix, but also insure uniform mixing. The higher the silt+clay content of the soil used for mixing, the less soil that can be added to the sand which makes uniform mixing difficult. Soils used for mixing should contain at least 60% sand and contain between 5 and 20% clay (Hummel 1993).

The gradation of the sand being amended has also been reported to have an effect on final mixes. Waddington et al. (1974) reported increased infiltration rates when the coarse sand fraction (0.5-1.0 mm) of the total sand portion exceeded 60%. At 60% by weight, bridging of the coarse particles begins to occur, which increases infiltration. Baker (1988) concluded that sand type had relatively little effect on the performance of sand-soil mixes, describing the coarsest sand in the study as having a mid-particle diameter of 0.55 mm.

The desired hydraulic conductivity will determine how much silt and clay can be added to a sand root zone material. In the laboratory, Adams (1976) determined 1.5 cm hr^{-1} could be achieved with 10% silt+clay content (samples compacted at 25% water content by weight). Adams and Jones (1979) suggested that silt plus clay contents exceeding 12% are not acceptable for high-grade facilities. However, the correlation between laboratory hydraulic conductivity values and field infiltration rates have been poor (Waddington et al. 1974). The performance of sand-soil mixes in the field will ultimately determine their usefulness. A field study conducted by Baker (1988) showed the infiltration rate of a mix (9% silt+clay by weight) drop from 5 cm hr^{-1} to less than 1 cm hr^{-1} in just 3 years. But in a similar study, a mix containing 21.4% silt+clay by weight had an infiltration rate of 4 cm hr^{-1} after 9 years in the field (Waddington et al. 1974). The large differences between these two field studies may be attributed to the intensity and type of cultivation, which are very important when managing sand-soil mixes in situ.

It has been well established that hydraulic conductivity and the amount of silt and clay in a sand root zone material are inversely related. However, the quantity of silt and clay that must be added to sand before a substantial increase in stability is obtained is not known. A small amount of silt and clay added to sand could positively affect surface traction. Adams (1979) concluded that a small portion of fine material, approximately 5%, is mildly beneficial in improving resistance to shear. In 1985, Adams concluded from another study that 12% content of fine soil fractions increases shear resistance by about 50% over that of pure sand. Although these results were encouraging, his methods did not quantify the soils' bearing capacity. Bearing capacity is an important parameter because it quantifies the ability of a soil to carry a load without failure. Vertically loading the soil to determine its strength is the closest laboratory method to simulate the way a root zone is loaded by an athlete performing on the surface.

MATERIALS & METHODS

A well-graded sand and a sandy loam textured soil were selected from Great Lakes Gravel located in Grand Ledge, MI. A particle-size analysis was then completed on both the sand and soil to determine their percent sand, silt and clay. The particle-size analysis of the sand was done by dry sieving (Day

1965). The Michigan State University Soil and Plant Nutrient Lab performed the particle-size analysis of the soil using the hydrometer method (Day 1965). These analyses were necessary in order to calculate the amount of sand and soil that must be combined to yield the mixtures chosen for investigation. The sand and soil were then mixed on a volume basis using a cement mixer to produce eight different soil mixes.

Following mixing, a particle-size distribution was completed on each mixture to determine weight percentage of the five sand fractions, silt and clay (Day 1965). The eight soil mixes were then subjected to four different analyses: Standard Proctor Compaction Test, bearing capacity, saturated hydraulic conductivity, and pore size distribution. These four analyses were important for evaluating the potential performance of these sand-soil mixes in the field.

The Standard Proctor Compaction Test was completed to find the optimum water content, which is the water content at which maximum dry density (bulk density) is produced at a specified compaction effort (592.7 kJ m^{-3}). This was critical because water content is one of the most important factors in soil compaction and largely influences soil behavior (Proctor 1933). The results of the compaction test determined the water contents at which the mixtures would be compacted for subsequent bearing capacity and hydraulic conductivity measurements.

The bearing capacity and saturated hydraulic conductivity of these sand-soil mixes were the primary interest of this study. A modified California Bearing

Ratio (CBR) test was used to evaluate the strength of each sand-soil mix. This test is primarily used in civil engineering to evaluate cohesive materials for pavement subgrade and subbase (ASTM D 1883-94). Hydraulic conductivity is a measure of the soil's ability to transmit water (Klute and Dirksen 1986), which is extremely important to enable athletic fields to withstand traffic during adverse weather conditions. Hydraulic conductivity is highly dependent on the structure of the soil, which is difficult to characterize. An excellent method to evaluate the amount, size, and configuration of the soil pores is by studying the moisture desorption curves created by the soil of interest (Danielson and Sutherland 1986).

Particle-size analysis

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

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

Standard Proctor Compaction Test

The optimum water content of each mix was determined using the Standard Proctor Compaction Test (Proctor 1933). Approximately 6000 g of the sand-soil mix being tested was air-dried. The sample was thoroughly mixed and a subsample was taken to determine its initial percent gravimetric water content (Gardner 1965). The sample was mixed with a measured quantity of water sufficient to produce a water content 4 percentage points below the estimated optimum water content. The lowest water content tested was 5%. The prepared sample was then compacted into a cylindrical mold 10.2 cm I. D. X 11.6 cm deep, using a metal hand rammer having a 5.1 cm diameter circular face and a free falling weight of 2.5 kg. The mold was filled with 3 separately compacted layers. Each layer received 25 uniformly distributed blows from a height of 30 cm. The extension collar from the mold was then removed and the excess compacted sand-soil was carefully removed using a knife, which brought the surface of the soil even with the top of the mold. The mold and the compacted soil were weighed to determine dry density (bulk density). A subsample (100 g) was taken from the compacted soil to determine percent gravimetric water content. The entire sample was removed from the mold and mixed thoroughly with a measured quantity of water sufficient to raise the water content an additional 2%. The water contents tested were 5%, 7%, 9%, 11%, and 13% for each sand-soil mix.

Bearing Capacity

Soil bearing capacity of these sand-soil mixes were measured generally according to the standard test method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils (ASTM-D 1883-94), using a load frame machine (GeoTest Instrument Corporation, model no. 55771, Evanston, IL). Approximately 12 kg of air-dried sand-soil mix was placed in each of five different containers. Each sample was thoroughly mixed and a subsample was taken to determine its initial percent gravimetric water content (Gardner 1965). The sand-soil mix was then mixed thoroughly with a measured quantity of water sufficient to produce the desired water content. The containers were sealed and stored overnight to allow the sand-soil to absorb the moisture. The bearing capacity was measured at three water contents (5, 9, 13% by weight) for mixes containing 2, 5, 7, and 8% silt+clay and at five water contents (5, 7, 9, 11, 13% by weight) for mixes containing 10, 12, 15, and 19% silt+clay.

In order to prepare samples for the CBR test, each prepared sand-soil mix was compacted into a cylindrical compaction mold 15.2 cm I. D. X 11.6 cm deep, with a 5.1 cm extension collar. The mold was filled with 3 equal compacted layers. Each layer received 20 blows with an automatic compactor to obtain a consistent compactive effort for each test (Ploog Engineering Company, Crown Point, Indiana ser.no. M100-21089573). The compactive effort was calculated to match that of the Standard Proctor Compaction Test, 592.7 kJ m^{-3} (Holtz and Kovacs 1981). Once the mixture was compacted, the extension collar was removed and the excess compacted sand-soil was carefully removed using a knife bringing the surface of the compacted mix even with the top of the mold. The mold and the compacted mix were then weighed to determine dry density (bulk density).

The mold containing the compacted mix, was then placed on the CBR load frame machine. The load frame machine was equipped with a movable base that was set to travel at a uniform rate of 0.002 cm s^{-1}, which forced the penetration piston (19.6 cm^2) into the compacted sand-soil mix. The force exerted on the piston was recorded in lbs and divided by the loaded area to get pressure in lb in^{-2}. The penetration piston was forced into the compacted mix until failure occurred or a depth of 1.0 (in.) was reached. Failure occurred at the depth of penetration where the force exerted on the piston began to decrease. Readings were taken every 0.01 in. The sand-soil was then removed from the mold and a subsample was taken to determine the percent gravimetric water content (Gardner 1965).

Saturated Hydraulic Conductivity

After each bearing capacity test was complete, the soil was loosened and compacted again in the same manner as the CBR test. The extension collar was removed and the excess compacted sand-soil was removed using a knife, bringing the level of the compacted mix even with the top of the mold. A 7.62 cm x 7.62 cm core was then extracted from the bearing capacity mold using a double-cylinder, hammer driven core sampler for the determination of hydraulic conductivity (Blake 1965). The core was then trimmed so that the volume of the core was equal to that of the sand-soil mix. A double layer of cheesecloth was placed on the bottom of the core and secured with a rubber band.

Hydraulic conductivity was measured using the constant-head method (Klute 1965). The cores were placed in a tray filled with water to a depth just below the top of the samples for 24 hrs. The cores were then fitted with 2.5 cm extension collars and secured with electrical tape. The cores were then transferred to a rack and a siphon hose was placed on the top of the cores to maintain a constant head of water. Once the water level on top of the sample became stabilized the leachate was collected in a graduated cylinder. The volume of water that passed through the sample in a certain amount of time was measured. The amount of time each sample ran was variable due to the differences in percolation rates. Saturated hydraulic conductivity was calculated using the following equation (Hummel 1993):

$$K_{SAT} = QL/hAt, \text{ where:}$$

K_{SAT} = saturated hydraulic conductivity (cm hr^{-1})
Q = quantity of effluent collected (cm^3) in period of time (t)
L = length of soil column (cm)
h = hydraulic head (cm)
A = cross sectional area of the soil core (cm^2)
t = time required to collect Q (hr)

Pore size distribution

After saturated hydraulic conductivity measurements were taken the cores were saturated again for 24 hrs by placing them in a tray filled with water to a depth just below the top of the samples. The saturated weights of the cores were taken and then placed in pressure chambers to determine pore size distribution according to the Soil Survey Staff (1982). Capillary porosity, air-filled porosity and total porosity determinations were made at the following matric potentials: -0.02, -0.04, -0.06, -0.08, -0.10, -0.20, -0.33, -1.0 bar. Cores were maintained at each matric potential for 48 hrs. The weight of the cores were recorded after each duration under the specified matric potential and the cores were immediately returned to the chambers and the equipment adjusted to measure the next lower matric potential.

RESULTS AND DISCUSSION

Characterizations of the eight sand-soil mixes are listed in Tables 1 and 2. Percent passing curves for each mix are given in Figures 1-8. These curves were used to calculate a coefficient of uniformity (C_u) and a gradation index (GI) for each mix, which are given in Table 2. Researchers have used these

Table 1. Particle-size analysis of sand-soil mixes.

	Percent retained†								
	Size class (mm)								
	FG	VCoS	CS	MS	FS	VFS	Silt	Clay	Silt+Clay
Sand-Soil‡	(12.7-2.0)	(2.0-1.0)	(1.0-0.5)	(0.5-0.25)	(0.25-0.10)	(0.10-0.05)	(0.05-0.002)	(<0.002)	(<0.05)
100-0§	0.4	10.9	25.3	41.6	19.6	0.6	0.9	0.7	2
90-10	0.5	10.9	24.9	39.7	18.2	1.0	1.8	3.0	5
85-15	0.5	10.4	23.6	38.6	18.8	1.3	2.9	3.9	7
80-20	1.1	10.5	22.1	37.2	19.4	1.6	3.8	4.3	8
75-25	1.5	10.0	21.7	35.4	19.2	2.2	7.0	3.0	10
70-30	1.5	8.9	20.0	34.5	20.1	2.7	8.5	3.8	12
60-40	1.6	8.5	18.5	32.5	20.2	3.2	10.7	4.8	15
50-50	1.7	8.0	17.2	30.5	19.8	3.8	13.4	5.6	19
0-100¶	3.0	3.0	7.4	19.0	19.7	6.5	28.7	12.7	41

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

‡ Sand-Soil mixes were mixed on a volume basis.

§ Tri-turf sand #10 (original sand used to make all mixes).

¶ Tri-turf sandy loam soil (original soil used to make all mixes).

Table 3.

Table 2. Percent passing of sand-soil mixes.

	Percent passing†									
	Size class (mm)									
	FG	VCoS	CS	MS	FS	VFS	Silt	Clay	C_u‡	GI§
Sand-Soil¶	(12.7-2.0)	(2.0-1.0)	(1.0-0.5)	(0.5-0.25)	(0.25-0.10)	(0.10-0.05)	(0.05-0.002)	(<0.002)	(D_{60}/D_{10})	(D_{90}/D_{10})
100-0#	99.6	88.7	63.4	21.8	2.2	1.6	0.7	0.0	3.0	6.9
90-10	99.5	88.6	63.7	24.0	5.8	4.8	3.0	0.0	3.1	7.3
85-15	99.5	89.1	65.5	26.9	8.1	6.8	3.9	0.0	3.8	9.2
80-20	98.9	88.4	66.3	29.1	9.7	8.1	4.3	0.0	4.5	12.0
75-25	98.5	88.5	66.8	31.4	12.2	10.0	3.0	0.0	9.0	24.0
70-30	98.5	89.6	69.6	35.1	15.0	12.3	3.8	0.0	17.4	43.5
60-40	98.4	89.9	71.4	38.9	18.7	15.5	4.8	0.0	40.0	100.0
50-50	98.3	90.3	73.1	42.6	22.8	19.0	5.6	0.0	61.6	166.7
0-100††	97.0	94.0	86.6	67.6	47.9	41.4	12.7	0.0	163.6	636.4

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

‡ C_u = Coefficient of uniformity where D_{60}=grain diameter (mm) corresponding to 60% passing, and D_{10}=grain diameter (mm) corresponding to 10% passing by weight.

§ GI = Gradation index where D_{90}=grain diameter (mm) corresponding to 90% passing, and D_{10}=grain diameter (mm) corresponding to 10% passing by weight.

¶ Sand-Soil mixes were mixed on a volume basis.

Tri-turf sand #10 (original sand used to make all mixes).

†† Tri-turf sandy loam soil (original soil used to make all mixes).

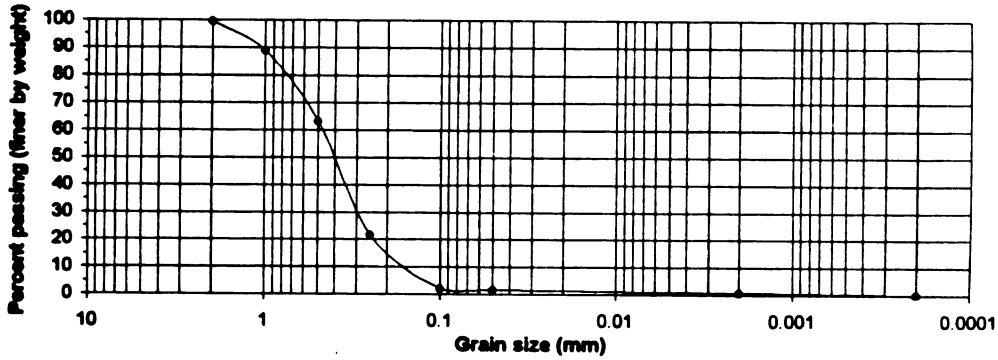

Figure 1. Percent passing curve for sand-soil mix containing 2% silt+clay.

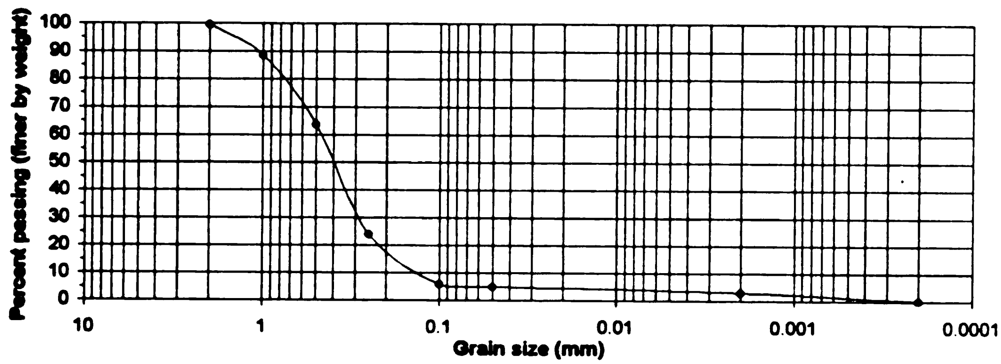

Figure 2. Percent passing curve for sand-soil mix containing 5% silt+clay.

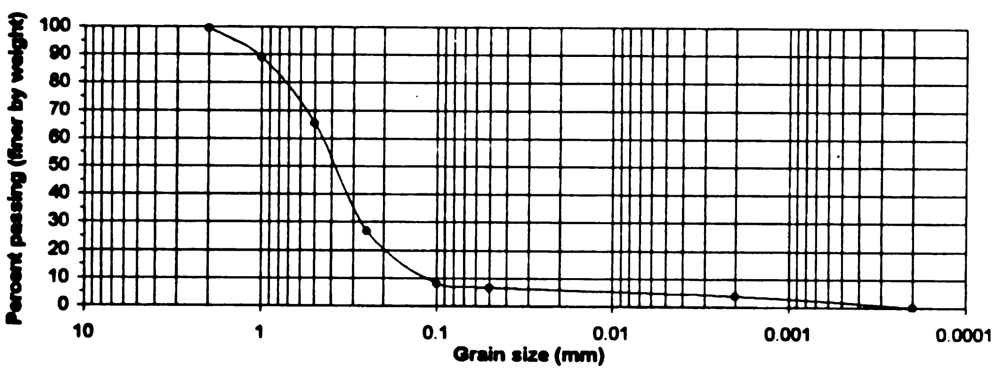

Figure 3. Percent passing curve for sand-soil mix containing 7% silt+clay.

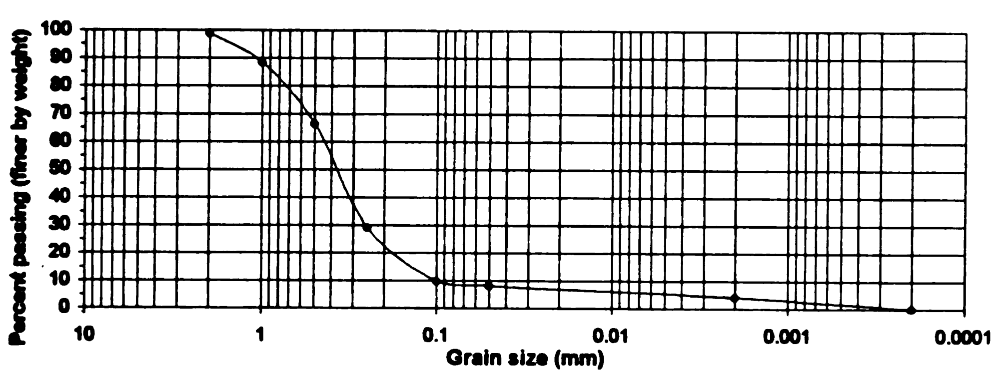

Figure 4. Percent passing curve for sand-soil mix containing 8% silt+clay.

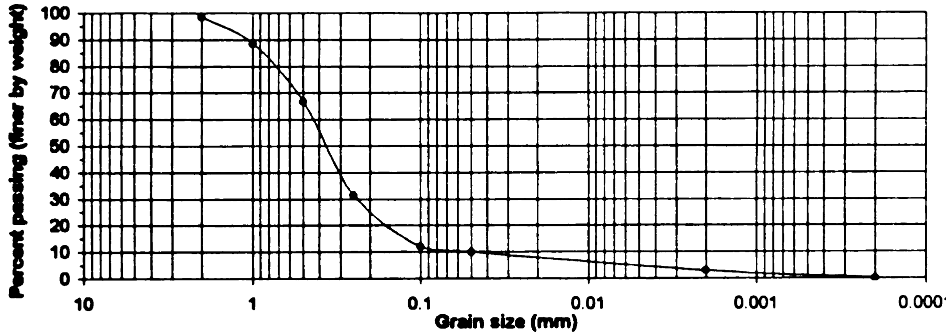

Figure 5. Percent passing curve for sand-soil mix containing 10% silt+clay.

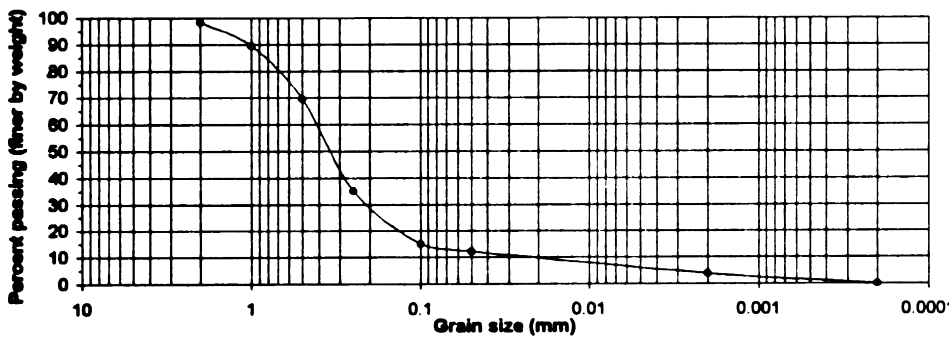

Figure 6. Percent passing curve for sand-soil mix containing 12% silt+clay.

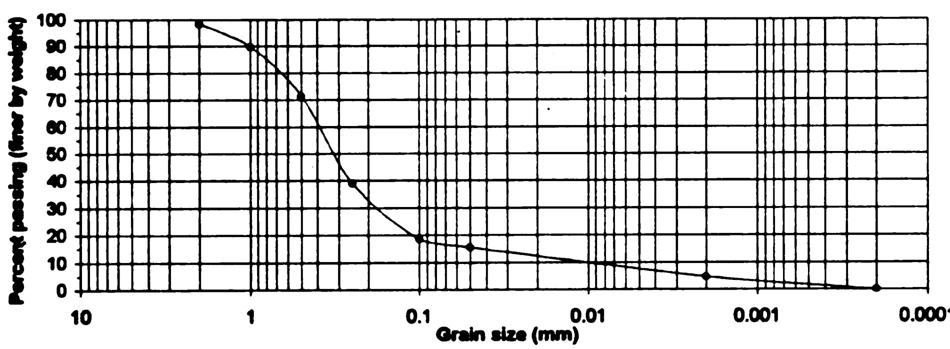

Figure 7. Percent passing curve for sand-soil mix containing 15% silt+clay.

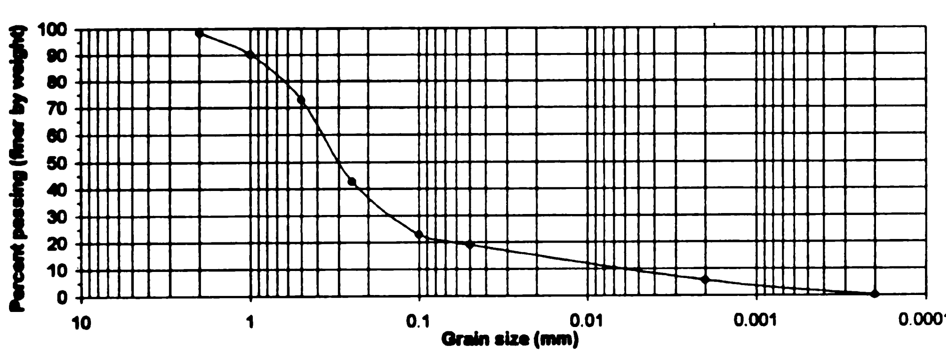

Figure 8. Percent passing curve for sand-soil mix containing 19% silt+clay.

parameters to describe the range of particle diameters in a sample (Janson 1969, Blake 1980). The $C_u=(D_{60}/D_{10})$, D_{60} is the grain diameter where 60% of the particles in a sample are finer by weight and D_{10} is the grain diameter where 10% of the particles are finer by weight (Holtz and Kovacs 1981). The $GI=(D_{90}/D_{10})$, D_{90} is the grain diameter where 90% of the particles in a sample are finer by weight and D_{10} is the grain diameter where 10% of the particles are finer by weight (Hummel 1993). Each parameter value needs to be interpreted with caution. Their value can change drastically with a small change in the composition of the sample. For example, both indices double when the soil portion of the mixture is increased from 20% to 25% of the total volume (Table 2). Therefore, their purpose is to give a general description of how a sample is distributed. The higher the C_u or GI the less uniform the sample. Some recommendations of minimum and maximum values for these indices have been published. To prevent the soil from percolating too slowly due to compaction, Janson (1969) suggested that the C_u should not exceed 10-15 for athletic fields. Blake (1980) recommended a $C_u < 4$ for athletic fields or putting greens. Adams (1982) defined the limits of the GI as being 6-12. For the mixtures produced for this research, after the soil becomes more than 15% of the volume, the C_u and GI values are greater than recommendations from other researchers.

The water content of a soil determines the level of friction between soil particles, which is the most important principle of soil compaction (Proctor 1933). The Standard Proctor Compaction Test was done to determine the optimum water content of each mix, which is the water content at which maximum dry density (bulk density) is attained (Holtz and Kovacs 1981) (Figure 9). It was extremely important that this value was known so the strength characteristics of each mixture could be examined when compacted both dry and wet of optimum.

Maximum dry density is achieved through compaction, which occurs when smaller particles move into the pores created by the larger particles, reducing macroporosity and increasing microporosity (Proctor 1933). Compaction will not occur until the compacting force overcomes the frictional resistance between soil particles. The water in a dry soil encapsulates each soil particle through the force of surface tension. This narrow layer of water around each soil particle creates pore water tension pulling the particles tightly together, causing high frictional resistance, which prohibits particle movement and thus compaction. As water is added to the soil, the narrow layer of water molecules around each soil particle thickens to the point where pore water tension (capillary force) is reduced and the water begins to act as a lubricant allowing the smaller particles to move into the voids created by the larger particles. This effect continues until a maximum dry density (bulk density) is reached. If water is steadily added to the point where the soil is wet of optimum water content, the pore water tension (capillary force) is reduced to nearly neutral. The pores in the soil are almost entirely filled with water, not allowing the smaller particles to move into the voids created by the larger particles. Therefore, a lower dry density (bulk density) is achieved.

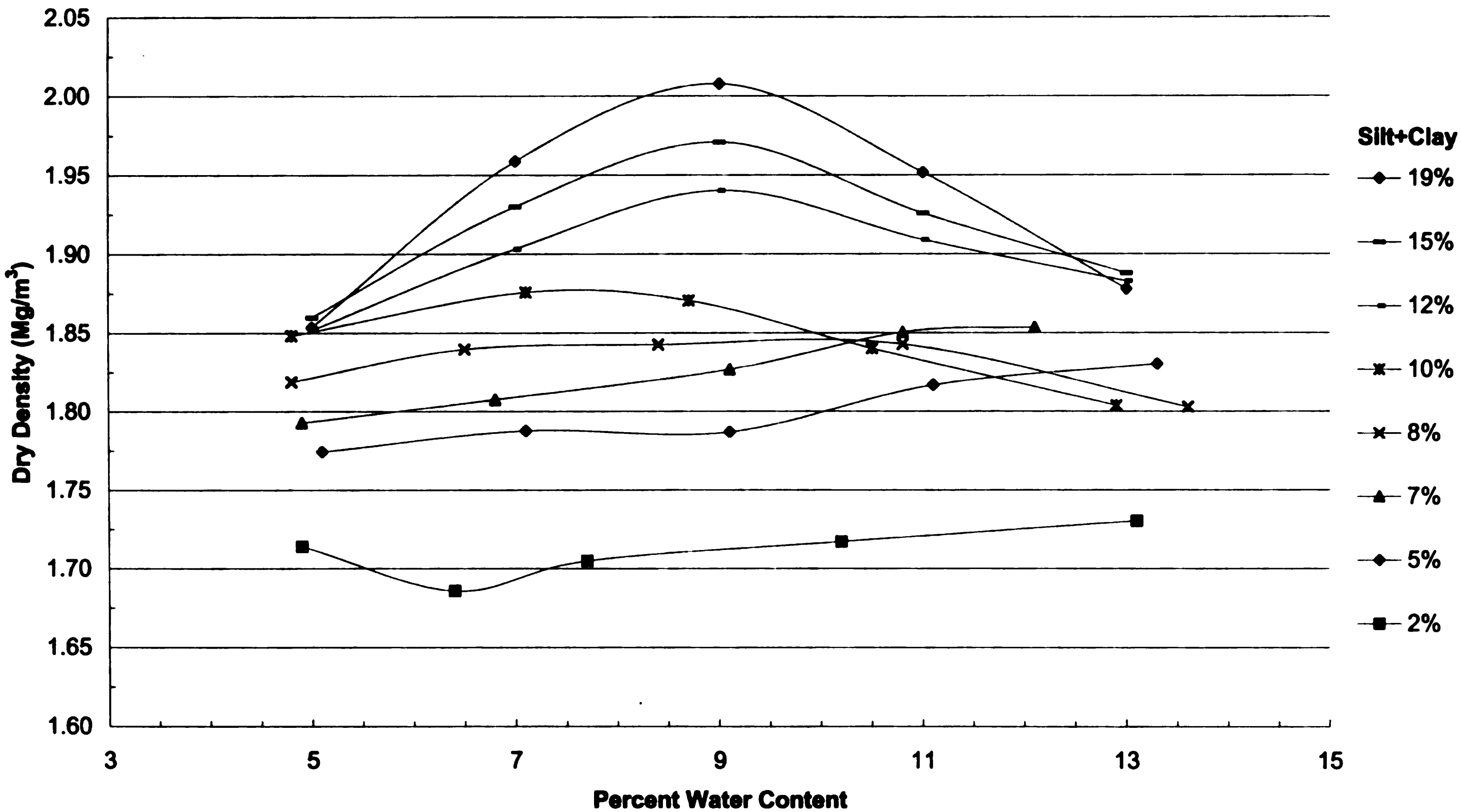

Figure 9. Water content-dry density relationships for the eight sand-soil mixes compacted according to the Standard Proctor Test method.

Mixes containing 10% silt+clay or greater have a clearly observable optimum water content (Figure 9). This indicates the smaller particles, very fine sand (0.10-0.05 mm) and silt+clay (particles < 0.05 mm), are filling voids created by the larger particles, thus increasing dry density (bulk density). As the percent silt+clay increases in each mix, the dry density (bulk density) increases. Mixes containing less than 10% silt+clay are less dependent on water content at compaction for achieving maximum dry density (bulk density) (Figure 9). They have a limited amount of fine particles that can fill the voids created by the larger particles and have less surface area for the forces of water to resist or enhance compaction. Therefore, mixes containing more fines are more dependent on water content for their behavior. Given these differences in behavior attributed to water content, bearing capacity measurements and hydraulic conductivity measurements were completed at multiple water contents. The sand-soil necessary to complete these tests was compacted at three water contents (5, 9, 13% by weight) for mixes containing 2, 5, 7, 8% silt+clay and at five water contents (5, 7, 9, 11, 13% by weight) for mixes containing 10, 12, 15, 19% silt+clay.

This study was conducted to determine the amount of silt and clay that can be added to a well-graded sand in order to increase its strength without severely reducing its hydraulic conductivity. The main physical property that determines the selection of a root zone material is hydraulic conductivity. The root zone material in athletic fields should have a hydraulic conductivity rate of 7-

8 cm hr^{-1} (Crum, pers. comm.) in the laboratory because infiltration rates will decrease by half once turfgrass is established (Brown and Duble 1975).

Water content at compaction in interaction with percent silt+clay was extremely influential in determining hydraulic conductivity (Figure 10). Swartz and Kardos (1963), Adams (1976) and Akram and Kemper (1979) found similar results. The mix containing 5% silt+clay had a hydraulic conductivity value exceeding 27 cm hr^{-1} when compacted dry (5% water content), but hydraulic conductivity was reduced to less than 5 cm hr^{-1} when compacted wet (13% water content). The mixes containing 12% silt+clay or less were the only mixes acceptable, in terms of drainage (7-8 cm hr^{-1}), for an athletic field, but only when compacted at 5% water content or less (Figure 11). Hydraulic conductivity regressions for all mixes compacted at three different water contents are given in Figures 12-14.

This severe reduction in hydraulic conductivity can be attributed to the reduction in macroporosity (air-filled porosity) and increase in microporosity (capillary porosity) with increasing silt+clay and increasing water content at compaction (Figures 15 and 16). Macropores are the pores that are air-filled at -0.04 bars (40 cm), which simulates the hydraulic potential gradient in a 40 cm root zone (Hummel, pers. comm.). Macroporosity mainly controls hydraulic conductivity. Macroporosity designates the pore space where gravitational forces are able to exceed the capillary forces holding water in the pores, allowing water to move through the root zone quickly. The relationship between air-filled porosity (macroporosity) and hydraulic conductivity is shown in Figure 18. The

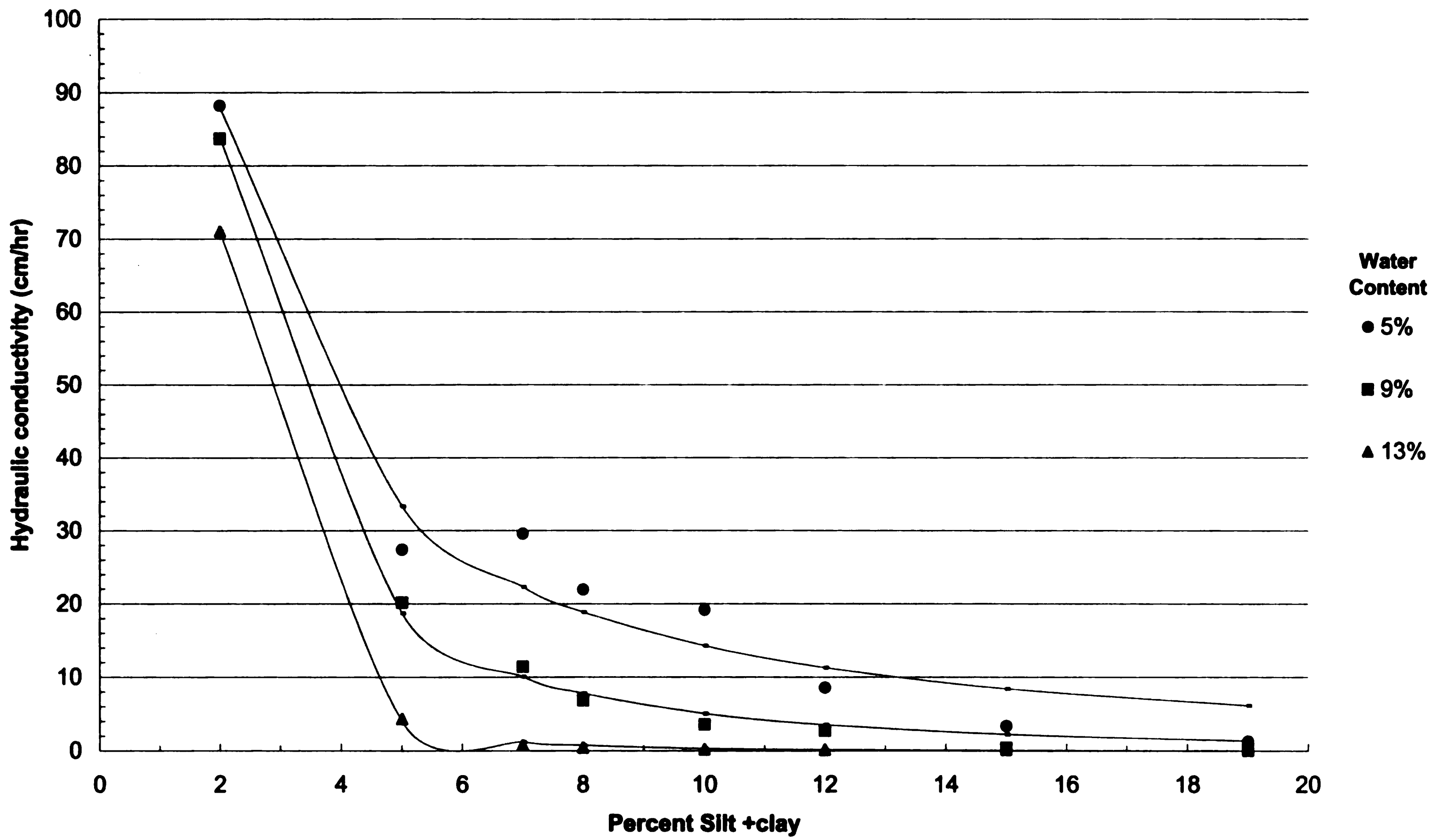

Figure 10. The effect of varying amounts of silt+clay when compacted at different water contents on hydraulic conductivity.

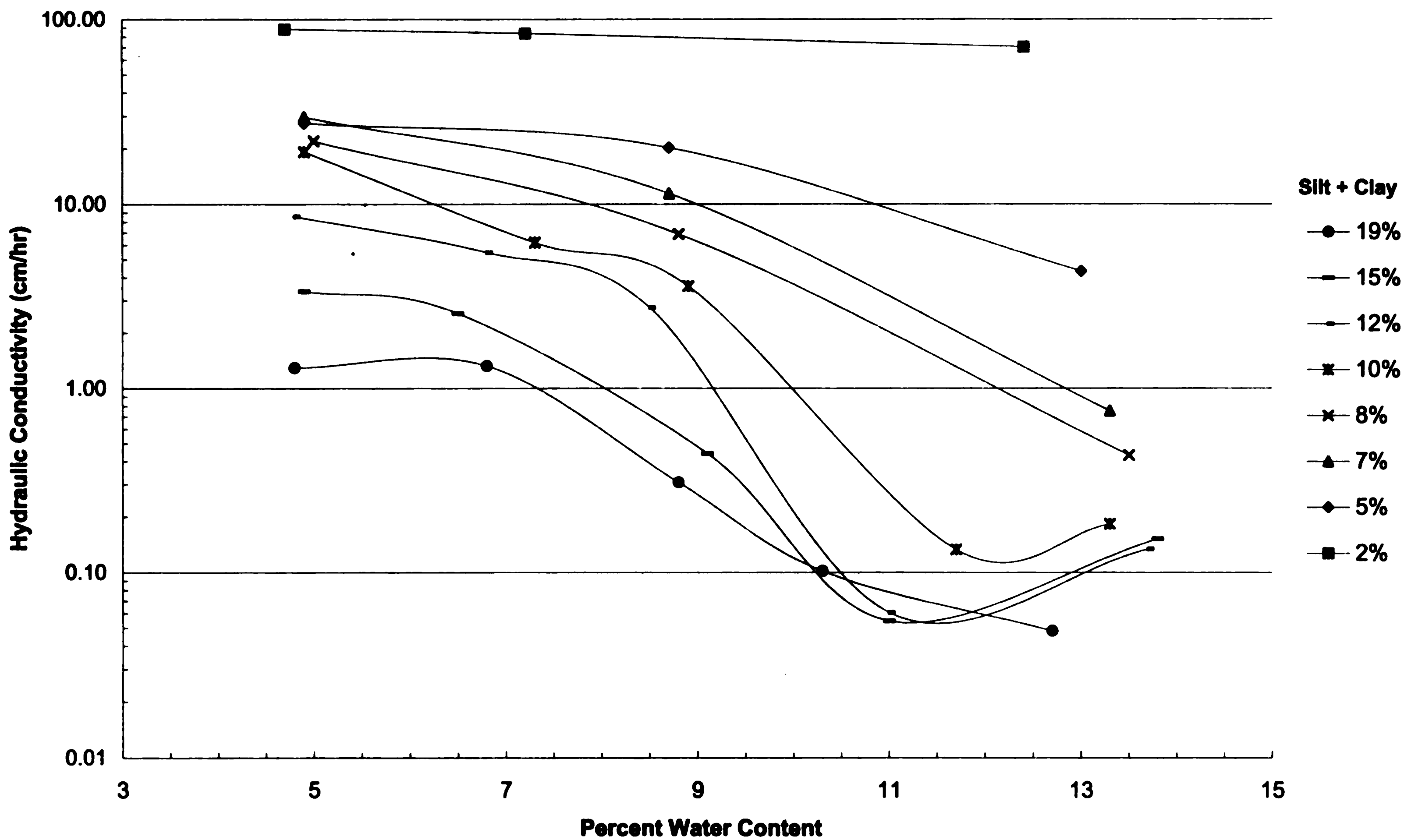

Figure 11. The effect of different water contents at compaction and varying amounts of silt+clay on hydraulic conductivity.

Hydraulic conductivity (cm/hr)

Hydraulic conductivity (cm/hr)

Hydraulic conductivity (cm/hr)

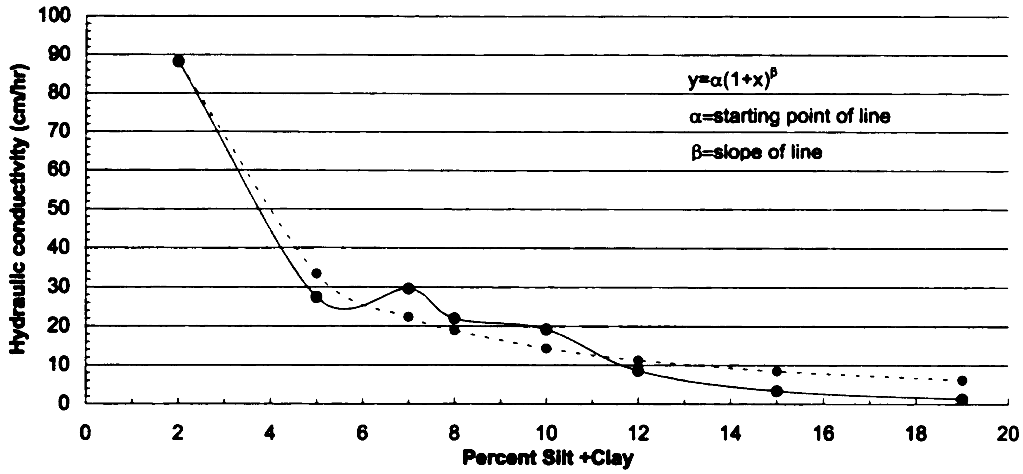

Figure 12. The effect of varying amounts of silt+clay when compacted at 5% water content on hydraulic conductivity.

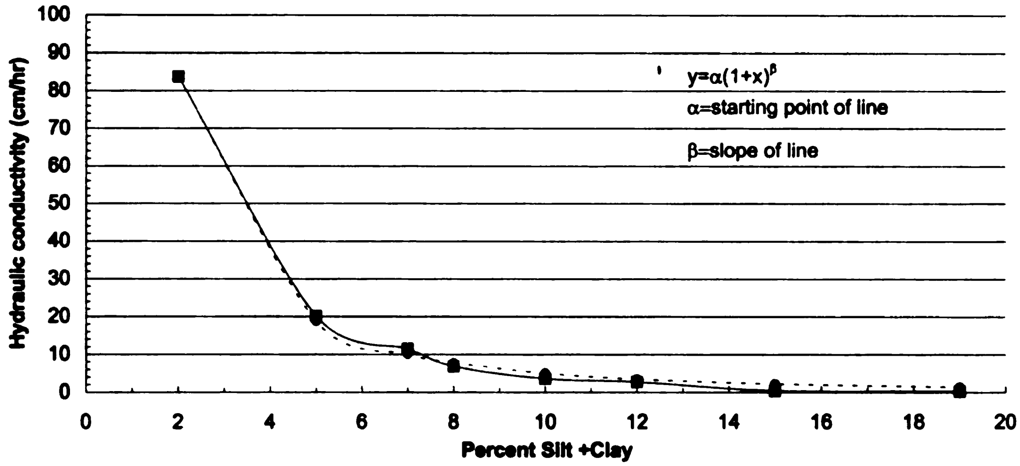

Figure 13. The effect of varying amounts of silt+clay when compacted at 9% water content on hydraulic conductivity.

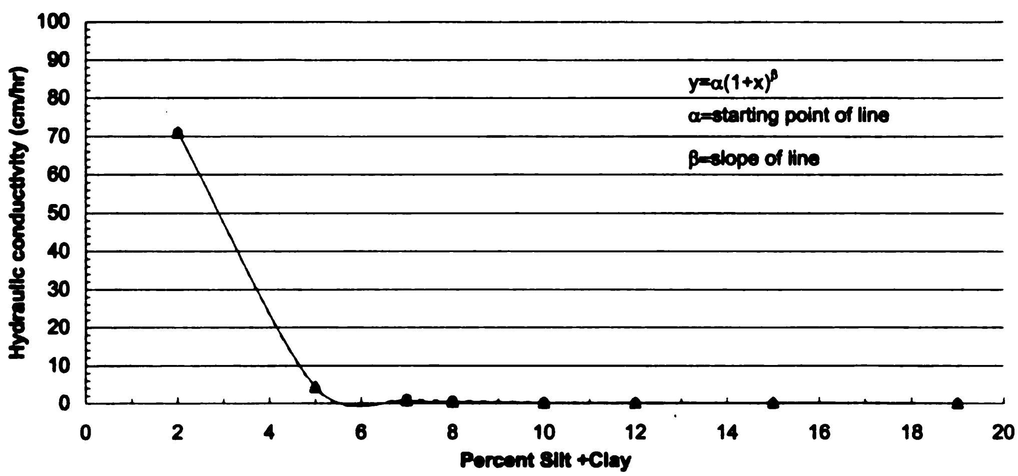

Figure 14. The effect of varying amounts of silt+clay when compacted at 13% water content on hydraulic conductivity.

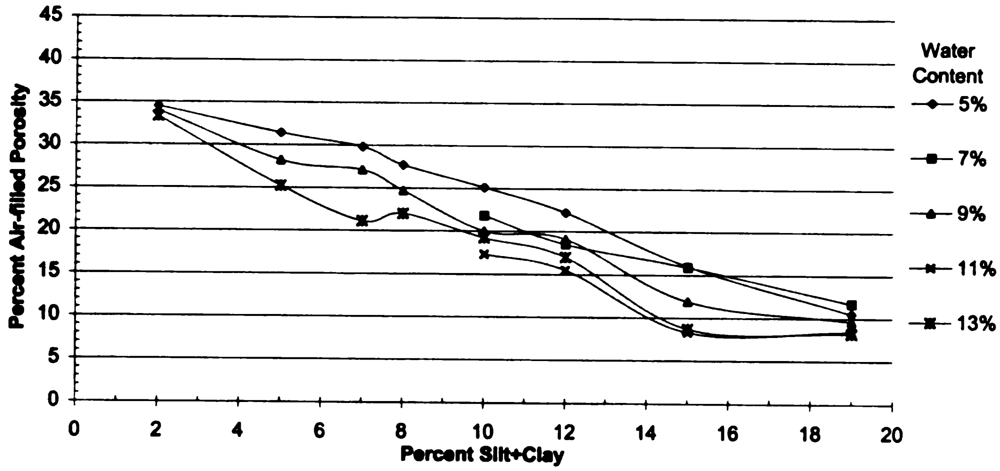

Figure 15. The effect of varying amounts of silt+clay when compacted at different water contents on air-filled porosity at -0.04 bars matric potential.

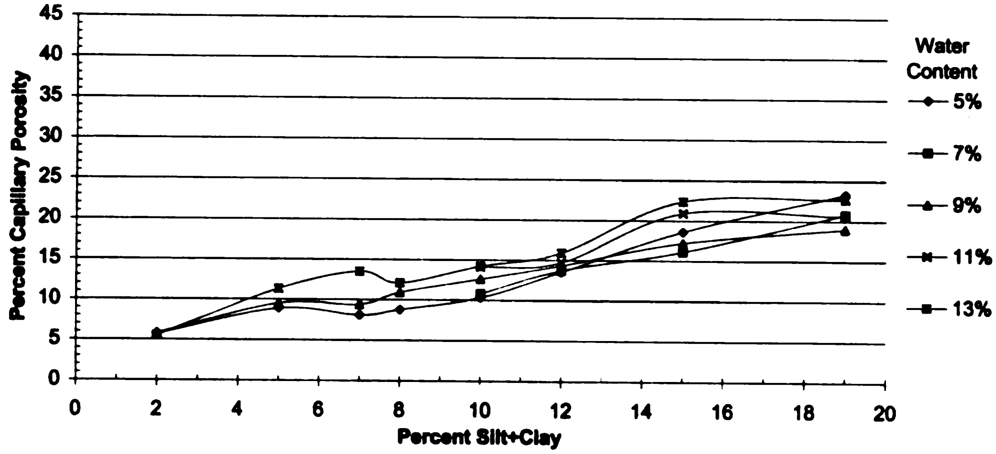

Figure 16. The effect of varying amounts of silt+clay when compacted at different water contents on capillary porosity at -0.04 bars matric potential.

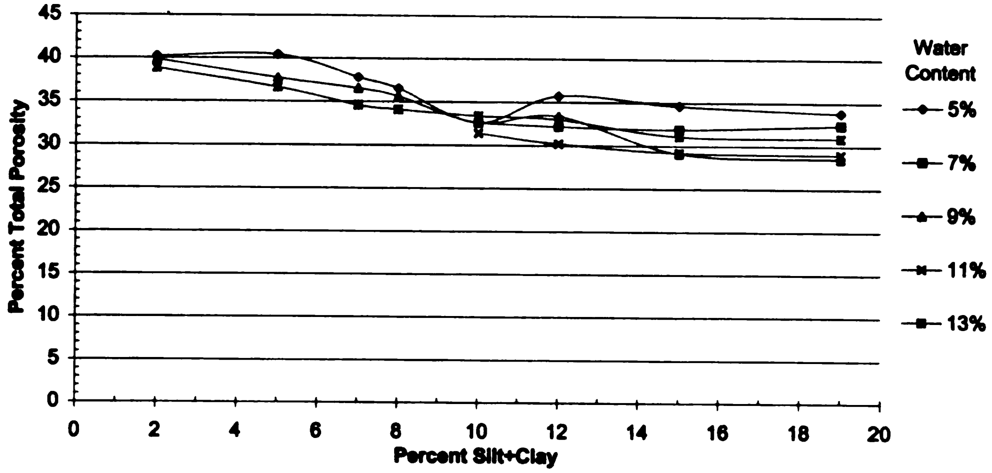

Figure 17. The effect of varying amounts of silt+clay when compacted at different water contents on total porosity at -0.04 bars matric potential.

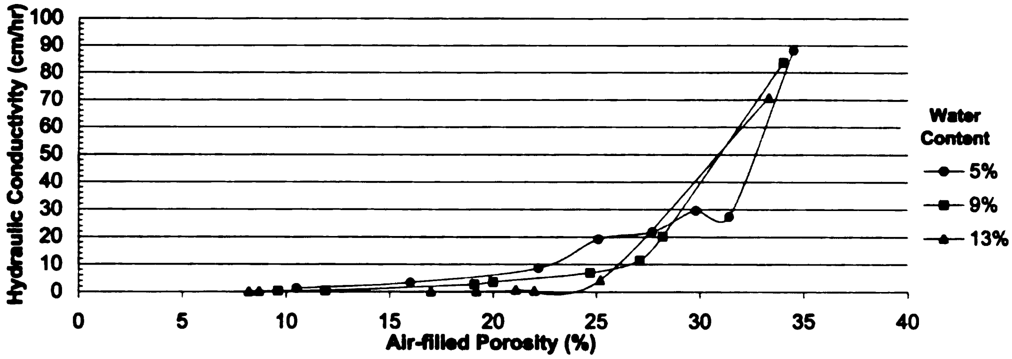

Figure 18. Air-filled porosity vs Hydraulic conductivity at -0.04 bar matric potential when the mixtures were compacted at different water contents.

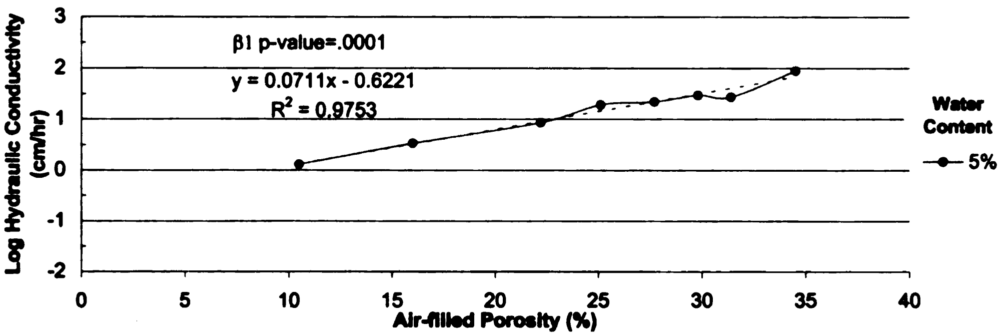

Figure 19. Air-filled porosity vs Log hydraulic conductivity at -0.04 bar matric potential when the mixtures were compacted at 5% water content.

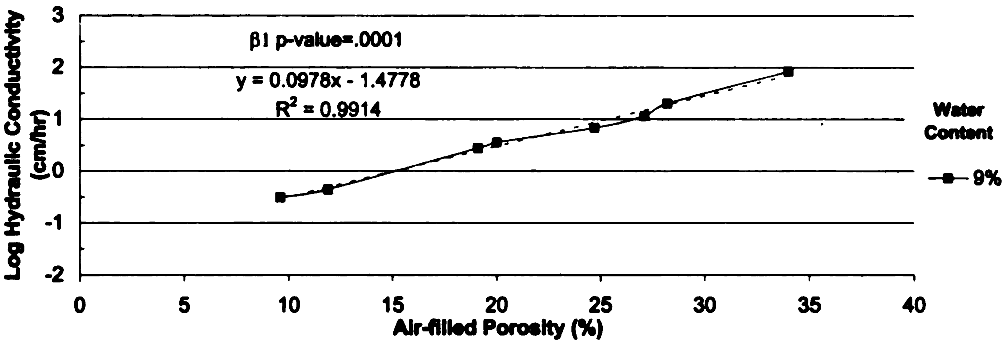

Figure 20. Air-filled porosity vs Log hydraulic conductivity at -0.04 bar matric potential when the mixtures were compacted at 9% water content.

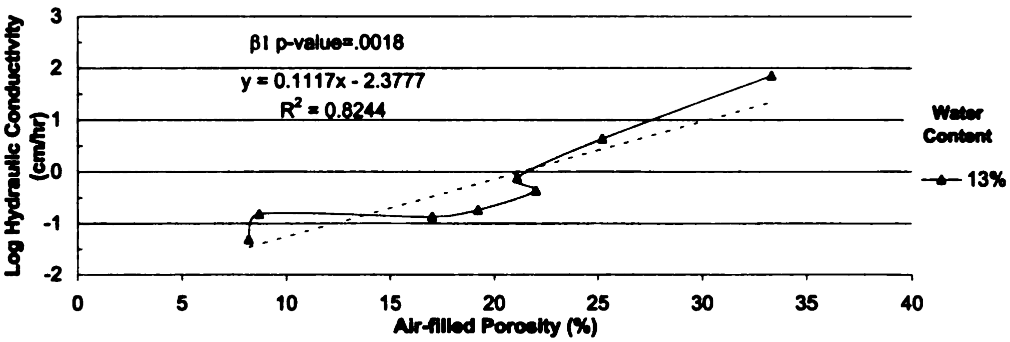

Figure 21. Air-filled porosity vs Log hydraulic conductivity at -0.04 bar matric potential when the mixtures were compacted at 13% water content.

strong log linear relationship between hydraulic conductivity and air-filled porosity is shown in Figures 18-21. Air-filled porosity at -0.04 bars matric potential decreases with increased silt+clay content and increased water content at compaction (Figure 15). Regressions of percent silt+clay versus air-filled porosity compacted at three different water contents are given in Figures 22-24. Some of the mixes meet the USGA specifications for air-filled porosity (Figure 15). However, none of the mixes meet the USGA specifications for all three porosities measured (Figures 15-17). Capilliary porosity increases with increasing silt+clay and increasing water content at compaction (Figure 16). Regressions of percent silt+clay versus capillary porosity compacted at three different water contents are given in Figures 25-27. Volumetric water content increases as silt+clay increases (Figures 28-30). Total porosity decreases with increasing silt+clay and decreases with increasing water content at compaction (Figure 17). Regressions of percent silt+clay versus total porosity compacted at three different water contents are given in Figures 31-33. All of these results indicate the importance of using a dry root zone mix during field construction (5% water content or less), if the root zone material contains more than 2% silt+clay.

The strength characteristics of a soil are also affected by water content at compaction and silt+clay content (Figures 34-36). Root zone mixes containing greater than 12% silt+clay showed large differences in strength with varying water contents regardless of displacement depth (Figures 37-39). These mixes are very strong dry, but very weak wet. The mix containing 19% silt+clay was stronger than the 2% silt+clay mix by over a magnitude of 8 when compacted at

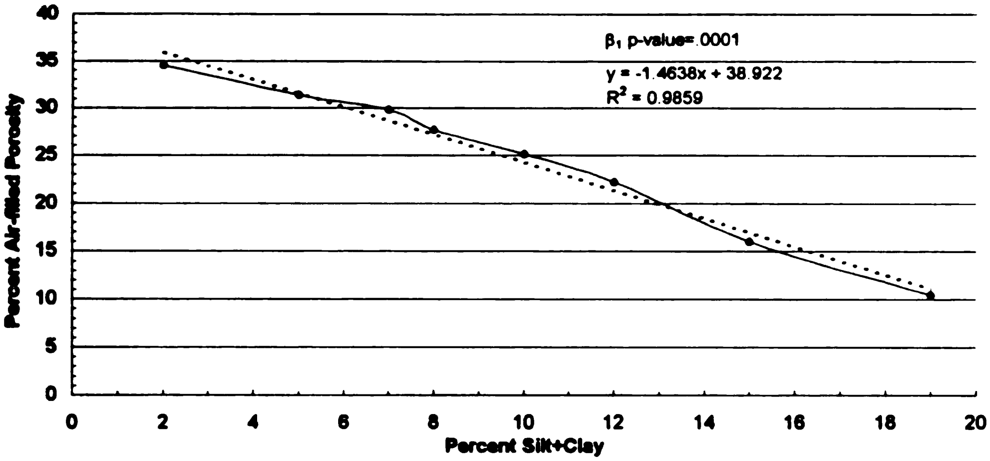

Figure 22. The effect of varying amounts of silt+clay when compacted at 5% water content on air-filled porosity at -0.04 bars matric potential.

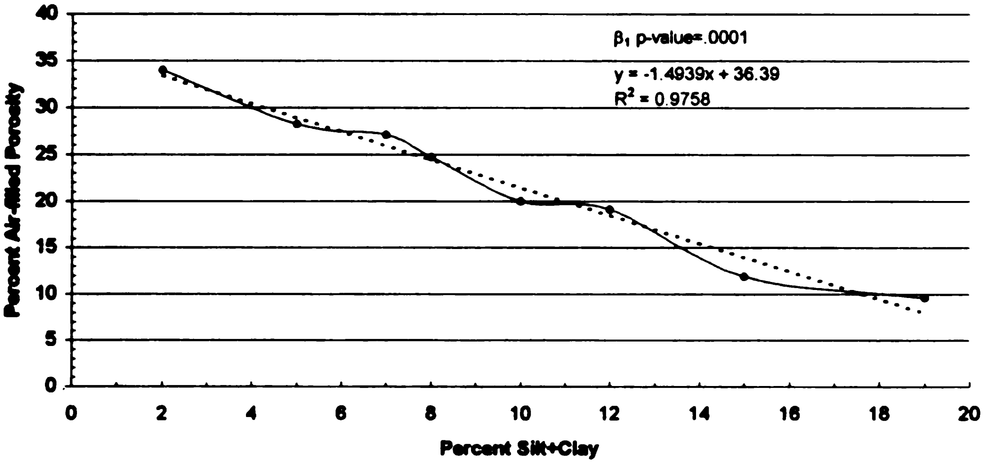

Figure 23. The effect of varying amounts of silt+clay when compacted at 9% water content on air-filled porosity at -0.04 bars matric potential.

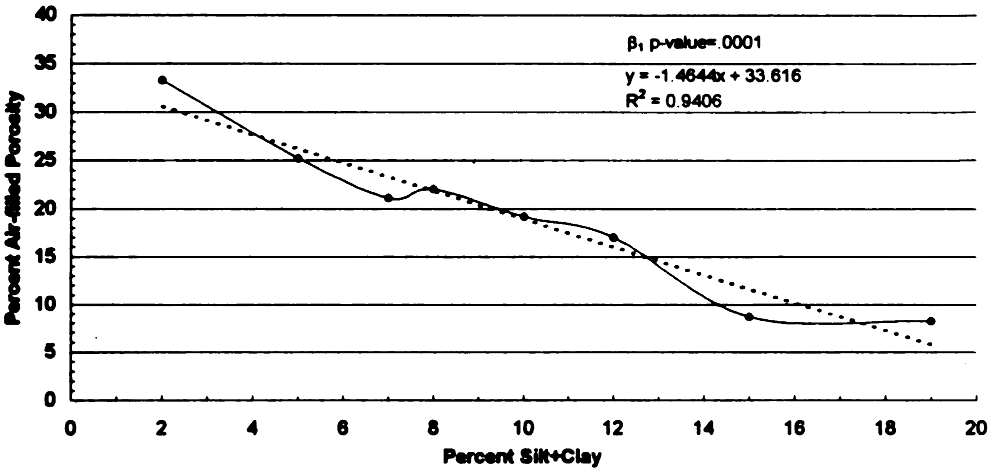

Figure 24. The effect of varying amounts of silt+clay when compacted at 13% water content on air filled porosity at -0.04 bars matric potential.

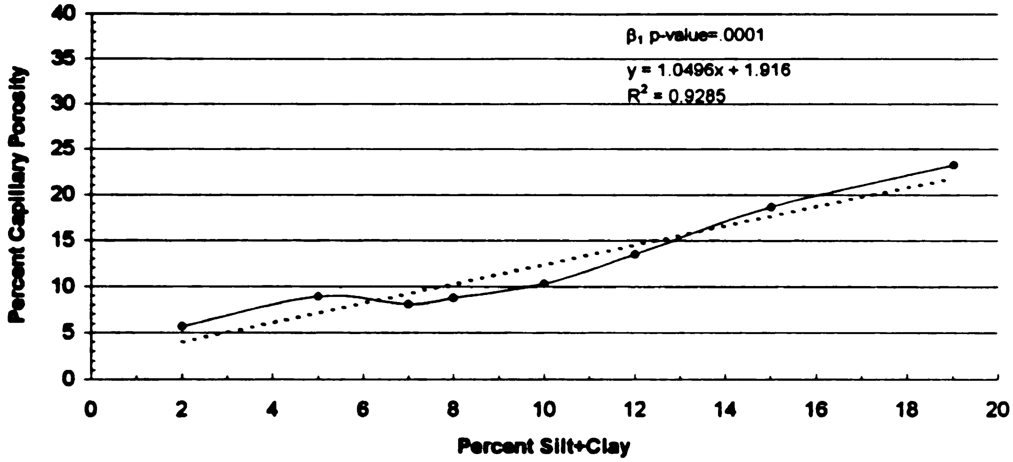

Figure 25. The effect of varying amounts of silt+clay when compacted at 5% water content on capillary porosity at -0.04 bars matric potential.

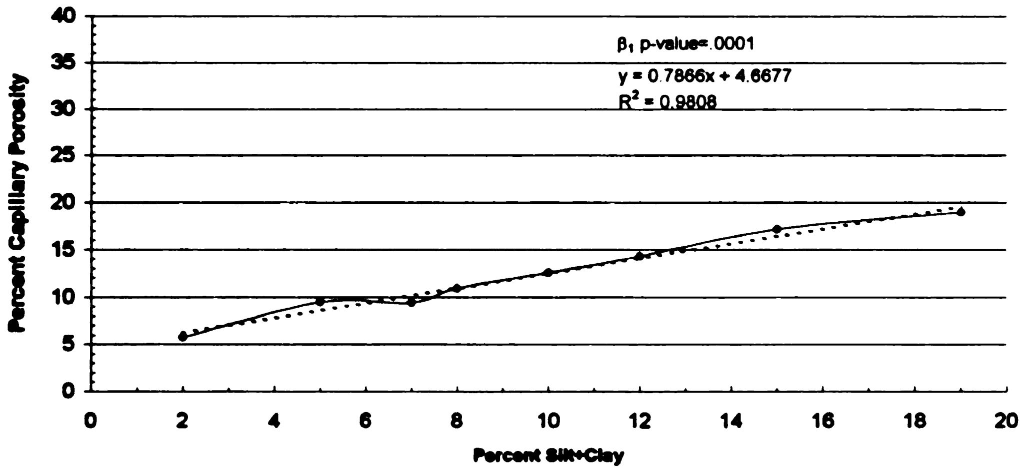

Figure 26. The effect of varying amounts of silt+clay when compacted at 9% water content on capillary porosity at -0.04 bars matric potential.

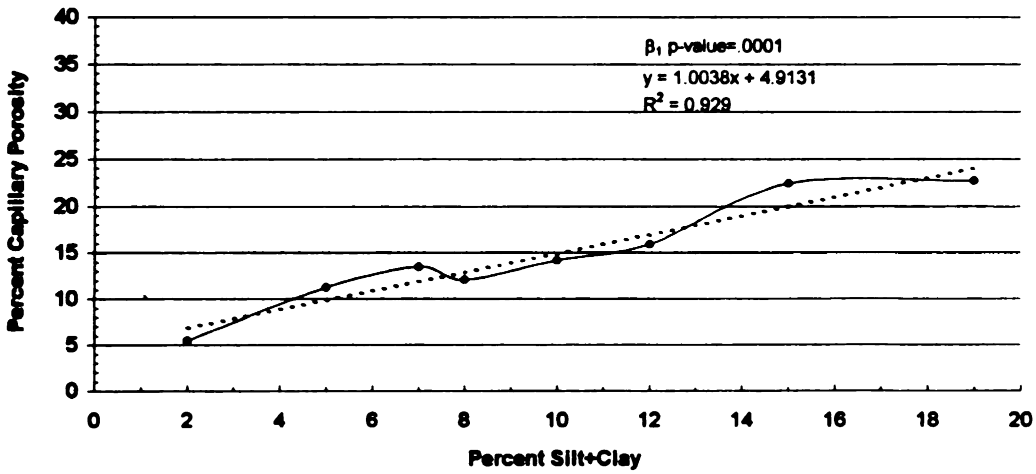

Figure 27. The effect of varying amounts of silt+clay when compacted at 13% water content on capillary porosity at -0.04 bars matric potential.

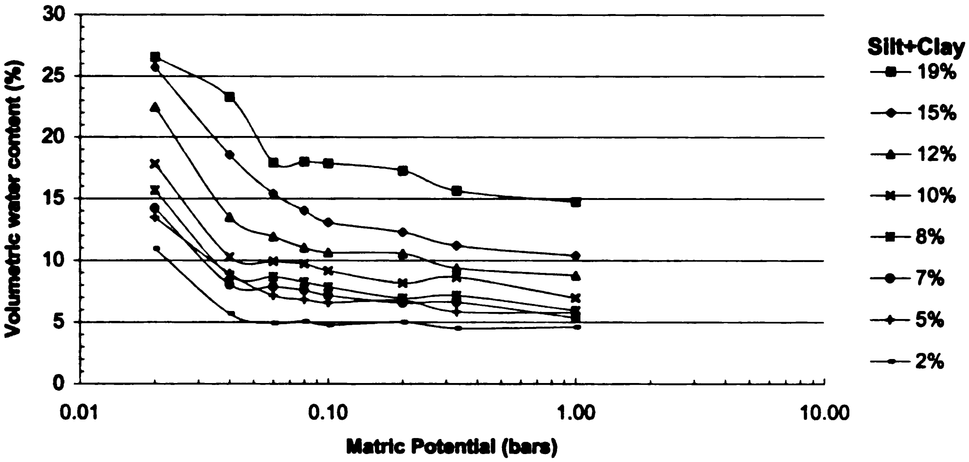

Figure 28. The effect of varying amounts of silt+clay when compacted at 5% water content on volumetric water content when subjected to various matric potentials.

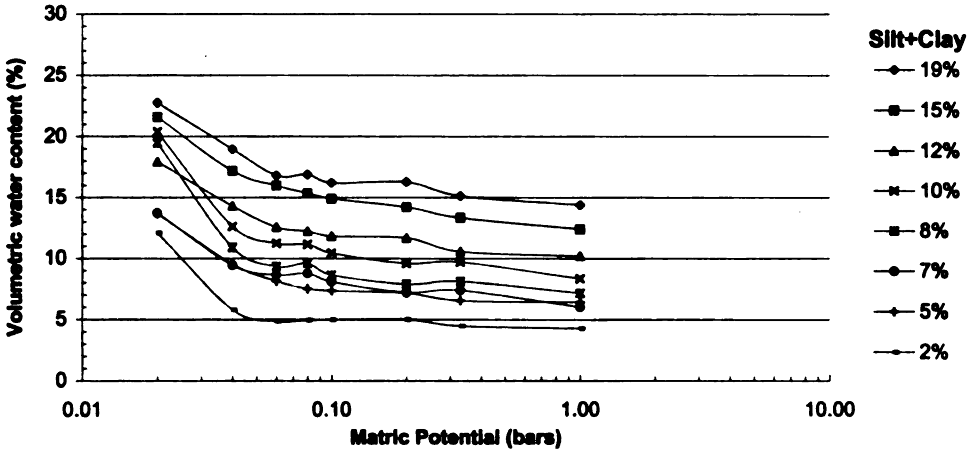

Figure 29. The effect of varying amounts of silt+clay when compacted at 9% water content on volumetric water content when subjected to various matric potentials.

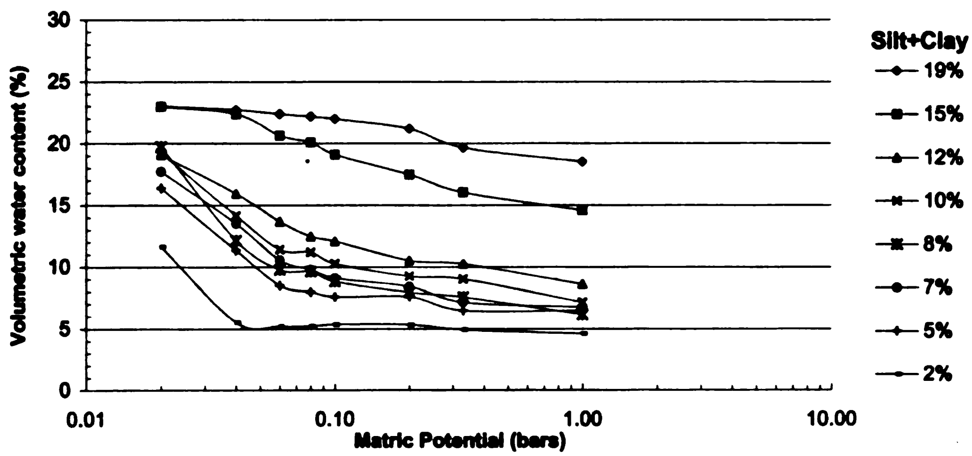

Figure 30. The effect of varying amounts of silt+clay when compacted at 13% water content on volumetric water content when subjected to various matric potentials.

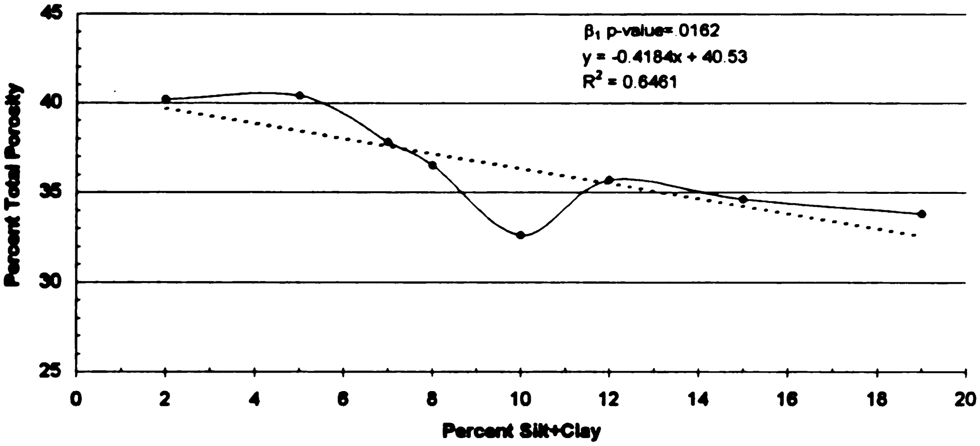

Figure 31. The effect of varying amounts of silt+clay when compacted at 5% water content on total porosity at -0.04 bars matric potential.

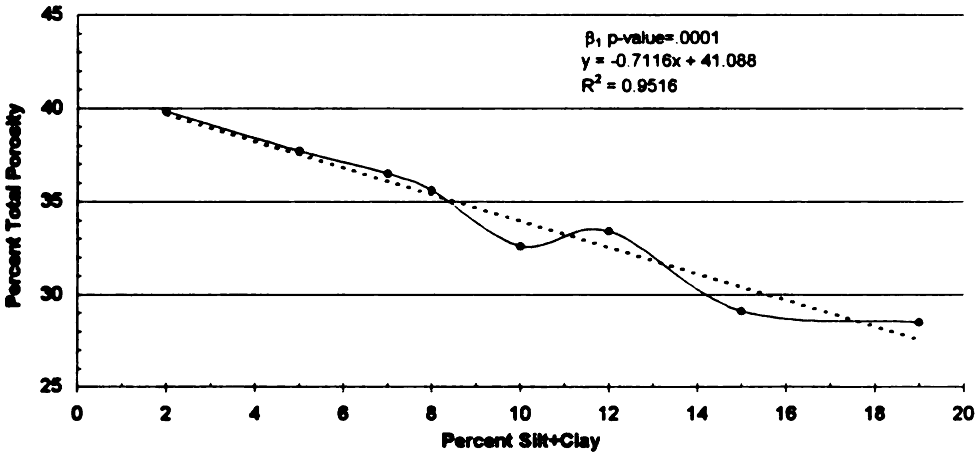

Figure 32. The effect of varying amounts of silt+clay when compacted at 9% water content on total porosity at -0.04 bars matric potential.

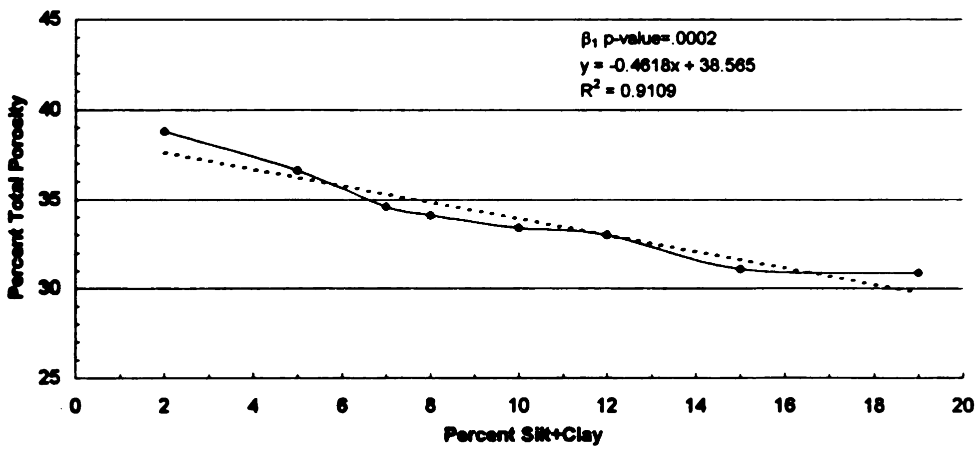

Figure 33. The effect of varying amounts of silt+clay when compacted at 13% water content on total porosity at -0.04 bars matric potential.

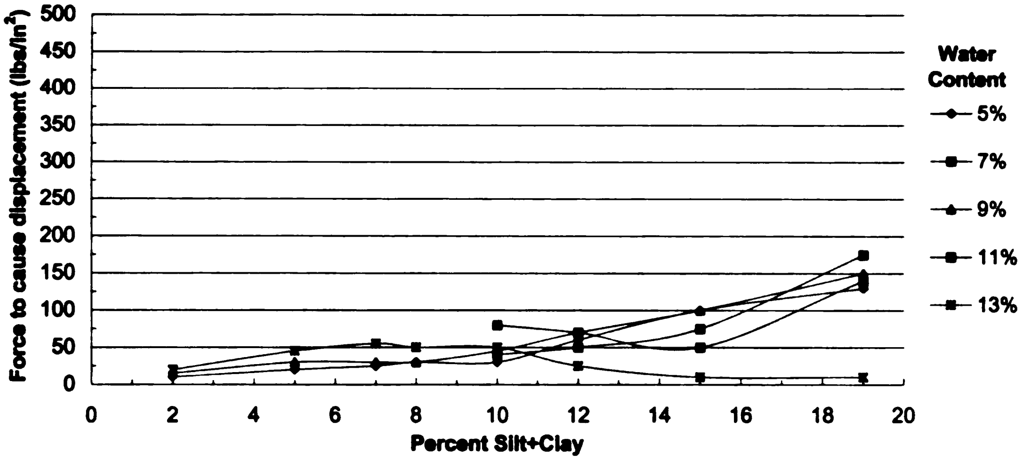

Figure 34. The effect of varying amounts of silt+clay when compacted at different water contents on soil strength at 0.25 inch displacement.

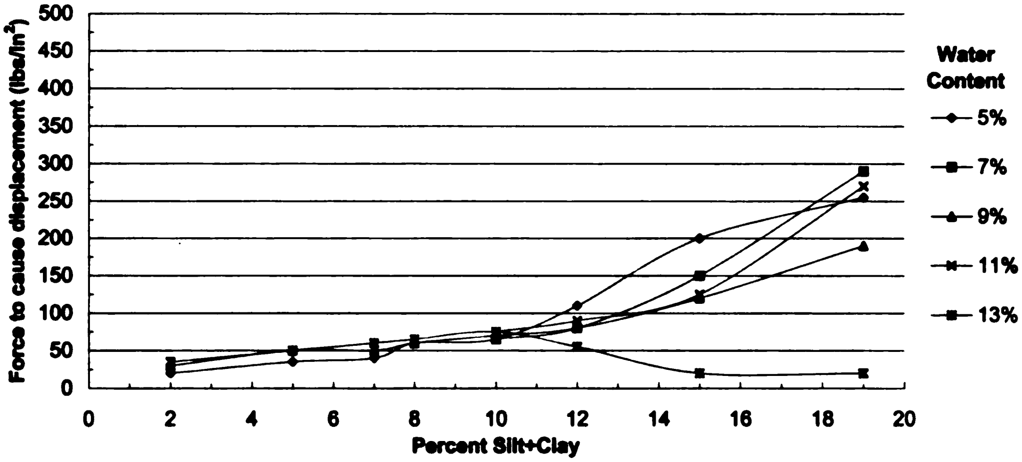

Figure 35. The effect of varying amounts of silt+clay when compacted at different water contents on soil strength at 0.50 inch displacement.

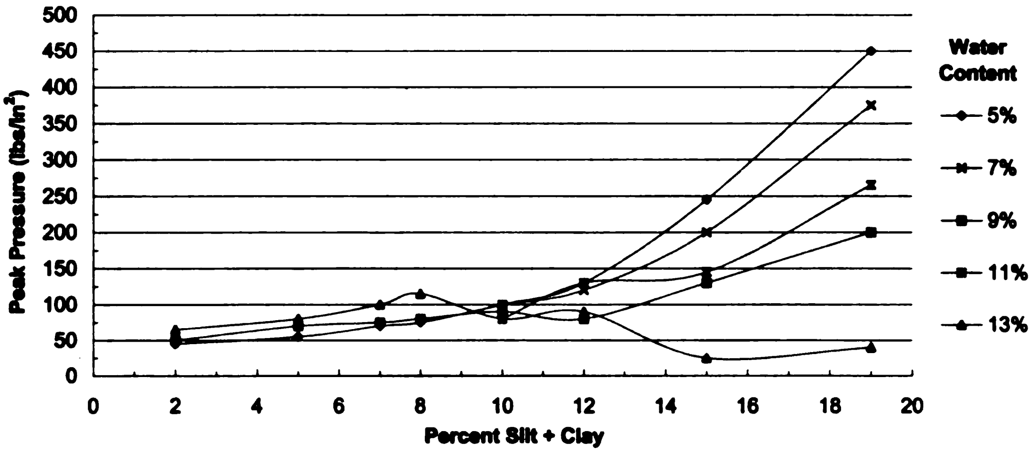

Figure 36. The effect of varying amounts of silt+clay when compacted at different water contents on peak soil strength.

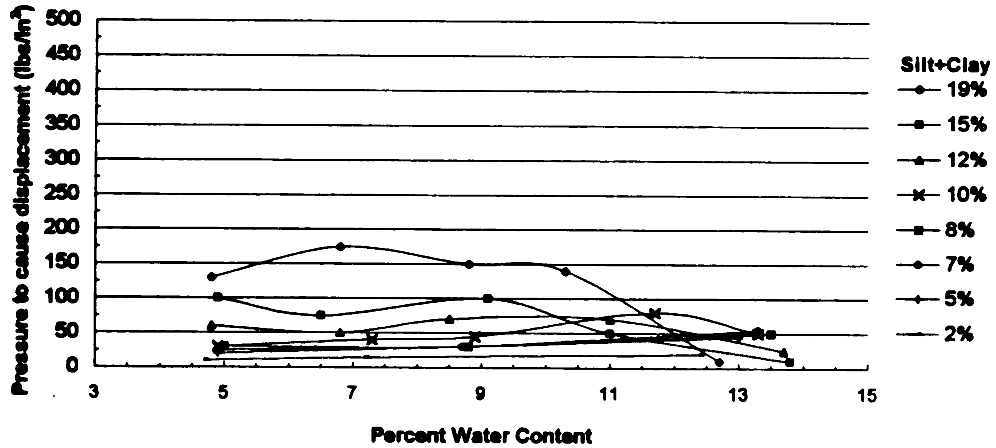

Figure 37. The effects of different water contents at compaction and varying amounts of silt+clay on soil strength at 0.25 inch displacement.

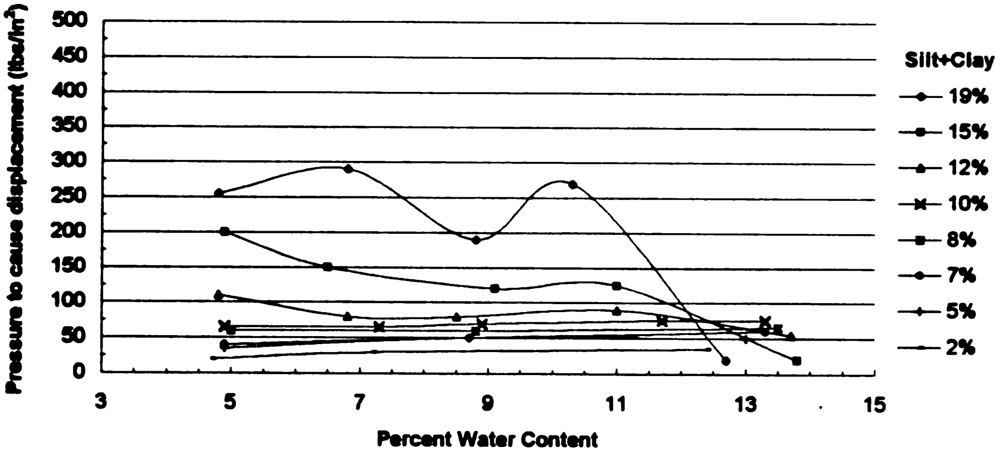

Figure 38. The effects of different water contents at compaction and varying amounts of silt+clay on soil strength at 0.50 displacement.

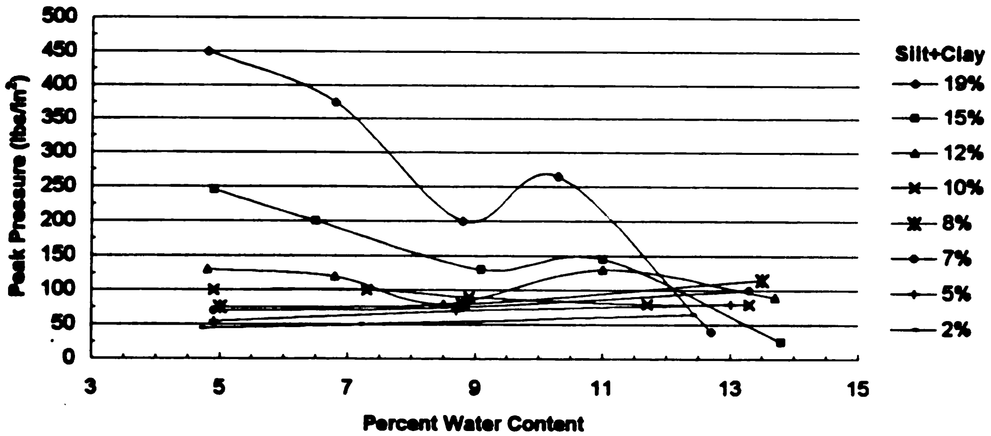

Figure 39. The effect of different water contents at compaction and varying amounts of silt+clay on peak soil strength.

5% water content, but weaker than the 2% silt+clay mix when compacted wet (13% water content) (Figure 36). Proctor (1933) reported similar results. This indicates why native soil fields are destroyed when large amounts of precipitation fall during an athletic event. The native soils high in silt+clay content drain slowly, allowing the water content to rise very quickly. Once the water content reaches a certain level (approximately 11% in this study) the water goes from creating pore water tension to neutral where the effects of the water tension disappear, passing optimal water content, and allowing the soil particles to displace very easily. In this study, when log peak pressure (soil strength) is plotted versus percent silt+clay, the relationship for mixtures compacted at 5% and 9% water content approach linearity (Figures 40 and 41). If a given mixture is compacted at 5% water content, each increase of 2% silt+clay content leads to approximately 30% increase in strength (Figure 40). The strength of a mixture compacted at 9% water content increases approximately 16% for each additional 2% of silt+clay (Figure 41). When the mixtures were compacted at 13% water content, the relationship between log peak pressure and percent silt+clay was no longer linear over the entire range of silt+clay levels tested (Figure 42).

Some current athletic fields with sand root zones are failing regardless of water content because they do not have the surface area for water to act that mixes with higher silt+clay entail (Figure 36). Surface resiliency is poor and severe divoting can occur creating an unsafe playing surface. A compromise must be met between hydraulic conductivity and strength. Mixes containing 10-12% silt+clay do not drain as rapidly as sand, but are over twice as strong

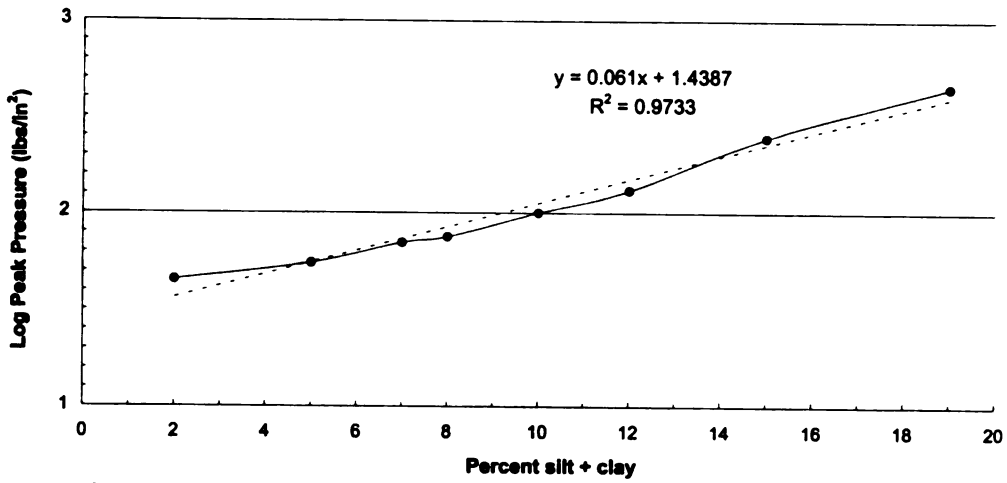

Figure 40. The effect of varying amounts of silt+clay when compacted at 5% water content on peak soil strength.

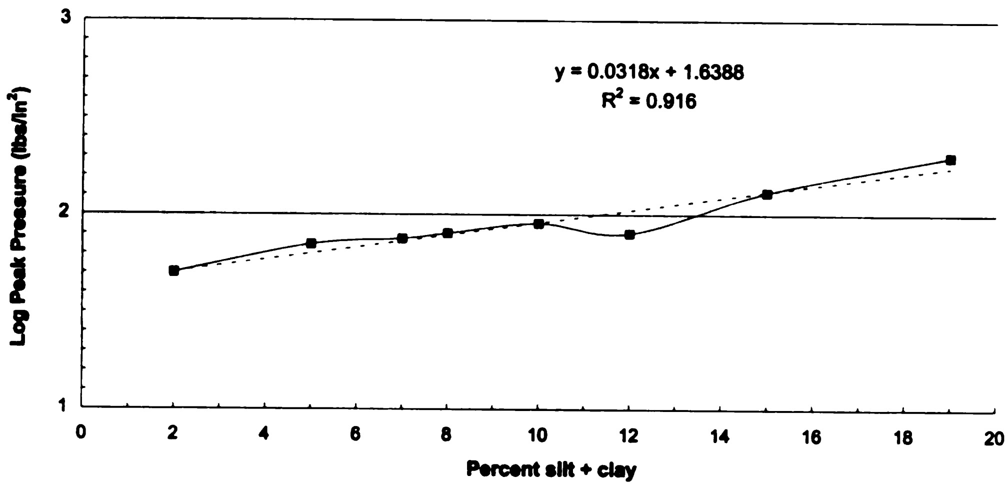

Figure 41. The effect of varying amounts of silt+clay when compacted at 9% water content on peak soil strength.

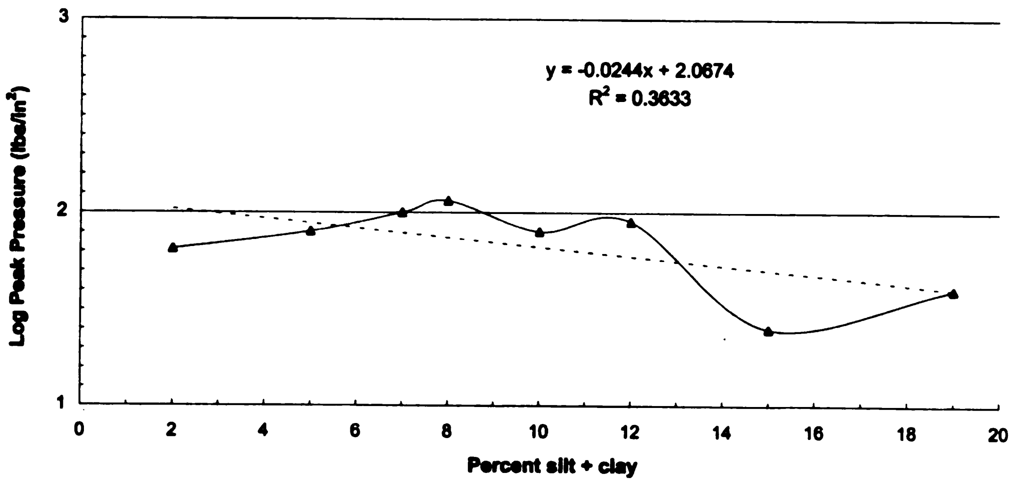

Figure 42. The effect of varying amounts of silt+clay when compacted at 13% water content on peak soil strength.

(Figure 36). Given the sand and soil used to create the mixes in this study, and the limitations of hydraulic conductivity, the highest percentage of silt+clay that can be used for an athletic field is 12%. The mix containing 12% silt+clay had over twice the bearing capacity of 2% silt+clay when compacted at 5% water content or less (Figure 36). Another desirable characteristic of 12% silt+clay is its constant strength regardless of water content (Figures 36 and 39).

Soil elasticity (K) is a parameter used in civil engineering to describe a soil's stiffness. K is the average slope of the bearing capacity curve and is analogous to the stiffness of a spring. Using mixes compacted at 5% water content as an example, increasing silt+clay from 2% to 19% causes over a five fold increase in stiffness (Table 3). When mixes are compacted at 13% water content the stiffness increases up to 10% silt+clay and then decreases rapidly for mixes containing 12% silt+clay and greater (Table 3).

Given the objectives of this study in determining the percentage of silt and clay that can be added to a sand to maximize soil bearing capacity while retaining adequate hydraulic conductivity, mixes containing 10-12% silt+clay have performed most favorably in the laboratory. Compacted at 5% water content, these mixes provided over a 100% increase in strength over sand alone, while maintaining hydraulic conductivity values of 19.0 and 8.5 cm hr^{-1} respectively. However, these measurements were taken in a laboratory setting and their performance in the field will ultimately determine their effectiveness. Field studies conducted on similar mixes have resulted in very different conclusions. Waddington et al. (1974) studied a mix containing 21.4% silt+clay

Table 3. Soil elasticity values.

Sand-Soil‡	Percent Silt+Clay	Soil elasticity (K†) (lb/in^3) Percent water content at compaction 5	7	9	11	13
100-0§	2	50	-	61	-	67
90-10	5	72	-	128	-	189
85-15	7	83	-	111	-	236
80-20	8	139	-	153	-	222
75-25	10	133	144	183	344	194
70-30	12	244	172	267	263	173
60-40	15	407	305	400	297	22
50-50	19	506	667	571	556	33
0-100¶	41	-	-	-	-	-

† Soil elasticity (K) = average slope of the bearing capacity curve.

‡ Sand-Soil mixes were mixed on a volume basis.

§ Tri-turf sand #10 (original sand used to make all mixes).

¶ Tri-turf sandy loam soil (original soil used to make all mixes).

that had an infiltration rate of over 4 cm hr^{-1} after 9 years in the field. However, Baker (1988) completed a field study including a mix with 9% silt+clay, which performed poorly. Infiltration rates dropped from 5 cm hr^{-1} to less than 1 cm hr^{-1} in just 3 years. Water content at construction, gradation of the sand used, and type of cultivation may have contributed to these large differences. Although the results of this study show that mixes containing 10 and 12% silt+clay would be adequate for athletic field root zone construction, 10% silt+clay may be preferred due to its higher hydraulic conductivity. If a field is located in an area where the average rainfall per year is high, the higher permeability may be preferred over the strength gain of the additional silt+clay. Goss (1967), Adams (1976), Taylor and Blake (1979), and Blake et al. (1981) have reached similar conclusions. Precise, uniform mixing, controlling water content at construction and cultivation practices are critical to the success of the athletic field constructed with a mix of these specifications.

Chapter 2

EFFECTS OF TRINEXAPAC-ETHYL AND WETTING AGENT ON ESTABLISHMENT RATE *OF POA PRATENSIS* IN SAND-BASED ROOT ZONES

ABSTRACT

Many athletic fields are constructed with high-sand content root zones. The low water and nutrient holding capacity of sand coupled with the slow establishment rate of Kentucky bluegrass make establishment difficult. The objectives of this study were to evaluate the effects and interactions of both a plant growth regulator (trinexapac-ethyl) and wetting agent (Aqueduct) applied during establishment. Plots were evaluated qualitatively using color and density ratings and quantitatively, measuring sod strength and verdure weights. First year results showed an increase in density and sod strength due to the application of the plant growth regulator (PGR). However, in 1999 the PGR did not enhance density or sod strength. In 1998, wetting agent applications reduced germination and wear tolerance, and sod strength was reduced in both years. PGR and wetting agent used in combination were detrimental to turf establishment. Rust (*Puccinia* spp.) infestations were observed in 1998 and 1999. The plots that received PGR applications in late August or later had the highest disease incidence.

INTRODUCTION

Most athletic fields are subjected to excessive wear, frequently leaving bare soil in areas where traffic is concentrated. This tends to occur in the goal mouths of a soccer field or between the hash marks of a football field. In order to maintain a safe playing surface these areas are in a constant state of re-establishment, which commonly must occur during very short periods of time. This is a particular concern in northern climates, where the growing season is very short. Field use and field renovation oftentimes overlap, which forces field managers to attempt establishment efforts in suboptimal periods of the growing season. This can result in a weak stand of turf that is intolerant to traffic. Any method that can speed establishment is a valuable tool for the athletic field manager.

This narrow window of time for turf establishment makes field renovation difficult. Two additional factors can make re-establishment of athletic turf an even more arduous task. The most desirable species for athletic fields in a cool climate is Kentucky bluegrass. However, it has a slow germination rate of 10-14 days and matures slowly (Parks and Henderlong 1967). Another characteristic common to newer athletic fields is a high-sand content root zone. The low moisture retention of sands combined with the slow germination and subsequent development of the desired species makes the establishment of a dense turf particularly difficult.

Two possible means of enhancing establishment may be through the use of a wetting agent and/or a plant growth regulator. The use of a wetting agent

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could increase moisture retention of the sand, thereby enhancing germination. The benefits of using a wetting agent during plant establishment have been shown (Osborn et al. 1964, 1967, 1969). Plant growth regulators have been shown to increase the density of established turfgrasses (Watschke 1981; Dernoeden 1984). However, their effect on seedling turf has been limited. Ervin and Koski (1998) determined that trinexapac-ethyl can increase the number of tillers per plant when applied to seedling perennial ryegrass in a greenhouse and growth chamber. In a field study, Bingaman et al. (1996) observed no negative effects on the normal growth of the perennial ryegrass seedlings when trinexapac-ethyl was applied. Although there has been some research done on trinexapac-ethyl applied to perennial ryegrass, the effect of class A PGRs on seedling Kentucky bluegrass has not been studied.

The objective of this study is to investigate the effects of a plant growth regulator in combination with a wetting agent to aid in the establishment and subsequent development of Kentucky bluegrass in high-sand content root zones.

LITERATURE REVIEW

Wetting Agents

Wetting agents have been used on turfgrasses for several years (Carrow 1989). They are primarily used to manage localized dry spots (Danneberger 1987, Karnok and Beall 1995). Dry spots tend to occur in coarse sands where the byproducts of fungal hyphae create a non-wettable organic coating over the particles, causing the sand to become hydrophobic (Danneberger 1987). The

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turf in these areas will reach drought stress faster than surrounding turf. The premise behind using wetting agents is to reduce the surface tension of water which allows the water to spread further over a given area and to infiltrate and wet the soil below (York and Baldwin 1992).

Wetting agents can be classified into two categories, ionic and non-ionic (Swope 1985). Ionic wetting agent are used less because they are generally more phytotoxic to turfgrass (Swope 1985; Carrow 1989). Non-ionic wetting agents commonly contain various esters, ethers, and alcohols as their basic ingredients. These groups have different effects on different soil types; esters are more effective in sand, ethers more effective in clays and alcohols more effective in organic matter (Rieke 1981; Swope 1985; York and Baldwin 1992). However, there is no consensus on which wetting agent is most effective on each soil type.

The proper wetting agent applied to a wettable sand may enhance germination. Water contains strong cohesive forces, which cause high surface tension. A water droplet forms because each water molecule at the surface of the droplet experiences an attraction towards the center. The silt, clay and organic matter in native soils provide the counteractive force to disperse the water droplet, thereby retaining moisture. In sand root zones the counteraction is essentially absent, allowing water to leave the root zone quickly (Carrow 1989; Koski 1994). When a non-ionic wetting agent is added to water the normal cohesive attractions are disrupted, causing a 50 to 60 percent decrease in surface tension (Carrow 1989). The disruption of the cohesive attractions in the water molecule allows the water to cover a greater area of the soil surface (Letey et al. 1962) which could enhance germination.

Research using wetting agents to enhance germination was conducted in the late 1960's. Osborn et al. (1967) determined that a non-ionic, alcohol-based wetting agent applied to sand decreased both germination and establishment of annual ryegrass. Endo et al. (1969) studied the effects of two non-ionic surfactants on various monocots. They determined that a non-ionic alcohol at concentrations of 1,000 and 2,000 ppm reduced seed germination. However, a non-ionic surfactant containing 50% ester and 50% ether, applied at a concentration of 4,000 ppm, did not reduce germination in soil.

The goal of this study is to utilize the basic function of the wetting agent, while bypassing its toxic effects. Prior research indicates reduced germination with alcohol-based wetting agents applied to sand, but a wetting agent containing 50% ester and 50% ether did not reduce germination even when applied at very high concentrations to soil. Furthermore, Kaufmann and Jackson (1978) believe that ethers are more effective on sands. Therefore, a non-ionic ether-based wetting agent is worth investigating to enhance germination in sand.

Plant Growth Regulators

Another product that could possibly enhance establishment is the use of a plant growth regulator (PGR). A PGR is an organic compound, produced naturally or applied as a synthetic, which regulates plant growth and development (Watschke and DiPaola 1995; Calhoun 1996). The turfgrass industry uses PGRs primarily to reduce seedhead development or reduce clipping production (Calhoun 1996).

In the 1980's PGRs were classified as Type I or Type II (Watschke and Dipaola 1995). Type I PGRs inhibit cell division, thereby suppressing the initiation of new turfgrass leaves and overall growth and development. The application of these compounds often lead to turf injury, which has limited their use (Calhoun 1996). Type II PGRs inhibit gibberellin biosynthesis, thereby suppressing elongation of cells and internodes (Kaufmann 1994). Because Type II PGRs inhibit the production of gibberellins at different points along the biosynthetic pathway, Watschke and Dipaola (1995) reclassified PGRs into three different groups. Class A PGRs hinder the production of gibberellins late in their biosynthetic pathway. Class B PGRs disrupt the production of gibberellins early in their biosynthetic pathway. Class C PGRs prevent cell division and include all Type I PGRs.

The modes of action unique to each class of PGRs determine their use in turfgrass management. Classes A and B are frequently used for clipping reduction. Class C are primarily used to suppress annual bluegrass by inhibiting seedhead formation (Watschke and Dipaola 1995). Class A PGRs are often used for introducing new and improved cultivars into existing swards and reducing the competitiveness of warm season grasses for winter overseeding. Class B PGRs have been shown to increase density of established stands of Kentucky bluegrass (Watschke 1981; Dernoeden 1984), but their utility has been limited by the turf discoloration that can occur following their use (Watschke and Dipaola 1995).

The objective of this study was to determine if a class A PGR, Trinexapac-ethyl, applied early during the seedling stage of Kentucky bluegrass, will speed the development of a dense turf. Trinexapac-ethyl when applied to other grasses has been shown to increase the number of tillers per plant (Ervin and Koski 1998; Lowe and Whitwell 1999). The mode of action specific to class A PGRs allows normal seedling germination and development (Watschke and Dipaola 1995). The effects of a class A PGR on the establishment and growth of seedling perennial ryegrass has been investigated and no negative effects on the normal growth of the ryegrass seedlings were observed (Bingaman et al. 1996, Ervin and Koski 1998). However, the effect of class A PGRs on seedling Kentucky bluegrass has not been studied.

If the establishment rate of Kentucky bluegrass can be increased through the use of a PGR and/or a wetting agent, wear tolerance could be increased from this perennial activity. Athletic field managers would have another tool to help make fields safer and more playable through the entire season.

MATERIALS & METHODS

This two-year study was initiated in May 1998 on a sand-based root zone research area at the Hancock Turfgrass Research Center located on the Michigan State University campus, East Lansing, MI. The sand root zone is characterized in Table 4. In May 1999 the plots were stripped and tilled and the

Table 4. Particle-size analysis of sand root zone.

Size class	(mm)	(μm)	mesh #	% Ret†	% Passing‡
Fine gravel	12.700-2.000	2000	10	0.4	99.6
Very coarse sand	2.000-1.000	1000	18	7.2	92.4
Coarse sand	1.000-0.500	500	35	31.7	60.7
Medium sand	0.500-0.250	250	60	44.2	16.5
Fine sand	0.250-0.100	106	140	10.4	6.1
Very fine sand	0.100-0.050	53	270	1.0	5.1
Silt	0.050-0.002			1.3	3.8
Clay	< 0.002			3.8	0

† Indicates the percent by weight of soil particles remaining in each size class.

‡ Indicates the percent by weight of soil particles passing through each sieve.

entire experiment was repeated. The experiment was a 5 x 2 (plant growth regulator x wetting agent) factorial in a randomized complete block, strip plot design with three replications. Traffic was applied as a strip treatment. The plots measured 3.0 m (10 ft) by 3.6 m (12 ft). *Poa pratensis* 'Touchdown' was seeded over the entire area at 12.2 g m^{-2} (2.5 lb 1000 ft^{-2}) on 20 May 1998 and 27 May 1999. A non-ionic, ether based wetting agent (Aqueduct™, Aquatrols, Cherry Hill, NJ) was applied on the day of seeding and every 10-14 days throughout the growing season to half the plots in each replication at the rate of 2.0 ml m^{-2} (6.0 fl oz 1000 ft^{-2}). Four plant growth regulator (PGR) treatments (Primo™ (trinexapac-ethyl), Novarits, Greensboro, NC) and a control were used: (1) 0.1 ml m^{-2} (0.3 fl oz 1000 ft^{-2}) 7 days after seedling emergence; (2) 0.2 ml m^{-2} (0.6 fl oz 1000 ft^{-2}) 7 days after seedling emergence; (3) 0.1 ml m^{-2} (0.3 fl oz 1000 ft^{-2}) applied after the first mowing; and (4) 0.2 ml m^{-2} (0.6 fl oz 1000 ft^{-2}) applied after the first mowing. Control plots received no PGR. In 1998, treatments 1 and 2 were applied 28 days after seeding and treatments 3 and 4 were applied 52 days after seeding. In 1999, treatments 1 and 2 were applied 24 days after seeding and treatments 3 and 4 were applied 49 days after seeding. Following turf establishment, all PGR treated plots received two supplemental PGR applications 30 and 60 days after the initial application. In 1998, for treatments 1 and 2 these dates were 20 July and 21 August, for treatments 3 and 4 they were 12 August and 11 September. In 1999, for treatments 1 and 2 these dates were 26 July and 19 August, for treatments 3 and 4 they were 19 August and 18 September. In both 1998 and 1999 the plots received 9.8 g P m^{-2} (2.0 lb P 1000

ft^{-2}) using 13-25-12 (Lebanon Country Club, Lebanon, PA) at seeding and 4.9 g P m^{-2} (1.0 lb P 1000 ft^{-2}) in early June. Beginning the first week in July, the plots received 2.5 g N m^{-2} (0.5 lb N 1000 ft^{-2}) every week throughout the growing season using 26-0-26 (Northern Star Mineral, East Lansing, MI). In 1998 and 1999 broadleaf weeds were controlled in late July using Confront™ applied at 0.2 ml m^{-2} (0.6 fl oz 1000 ft^{-2}). The plots were mowed three times per week at 3.2 cm (1.25 in) using a John Deere 2653A triplex reel mower and were irrigated as needed.

Plots were evaluated weekly or as needed from late June through November using color and density ratings. The color ratings were done visually using a 1-9 scale where 1=brown-yellow, 5=acceptable, and 9=dark green. Density ratings were assessed visually by estimating percent cover. A cup cutter with a diameter of 8.9 cm (3.5 in) was used to take three random cores from each plot to quantify differences in density on 4 September and 20 November in 1998. In 1999 samples were taken on 25 September. The cores were trimmed by hand to remove all green tissue present. Verdure samples were combined to make a composite sample for each plot. Composite samples were then oven dried 48 h at 50°C and weighed. In 1998, from 11 September to 17 November traffic was applied as 2 passes twice per week as a strip application to a portion of each plot using the Brinkman Traffic Simulator (Cockerham and Brinkman 1989). In 1999 traffic was increased to 2 passes three times per week from 21 September to 17 November. The objective was to simulate the traffic between the hashmarks of 2-3 football games per week (Cockerham and Brinkman 1989).

Post-traffic density ratings were taken to determine wear tolerance differences between treatments. In 1998, the sod strength of the untrafficked turf was quantified on 22 October using the Calrochan Sod Puller (Sorochan, et al., 1999), a device developed at Michigan State University. The device measures the peak force necessary to completely tear a piece of sod. The sod strength was tested again on 25 November after the turfgrass had hardened off for the season. In 1999, sod strength measurements were taken on 22 October and 23 November. Data were analyzed by analysis of variance (ANOVA, alpha = 0.1).

RESULTS & DISCUSSION

1998 Results

Trinexapac-ethyl applications increased turfgrass color (Table 5). Significant increases in color occurred soon after each trinexapac-ethyl application. For example, the first PGR treatments were applied 28 days after seeding (DAS) on 18 June, which had the highest color ratings 21 June (Table 5). Wetting agent treatments had no significant effect on turfgrass color except on 24 August where color was significantly reduced.

Wetting agent applications decreased pre-traffic turfgrass cover on every date ratings were recorded (Table 6). Osborn et al. (1967) and Endo et al. (1969) reported similar results where wetting agent applications reduced germination. Trinexapac-ethyl applied at 0.2 ml m^{-2} 28 DAS increased pre-traffic turfgrass

Table 5. Mean squares, main effects and significance of treatment effects on color of establishing Kentucky bluegrass in a sand-based root zone 1998.

		Color†								
Source of variation	df	21-Jun	25-Jun	8-Jul	21-Jul	28-Jul	14-Aug	24-Aug	8-Sep	8-Oct
Block	2	2.70	0.03	2.53	0.87	0.23	0.03	0.53	0.23	4.80
WA	1	1.20	0.03	0.13	0.03	0.30	0.03	1.20 *	0.53	0.03
PGR	4	1.55 **	0.92	0.36	2.53 ***	0.25	0.03	0.95 **	1.88 *	3.00 ***
WAxPGR	4	0.28	0.45	0.13	0.13	0.22	0.03	0.12	1.12 **	0.53
Error	18	0.51	0.92	0.24	0.10	0.31	0.03	0.27	0.27	0.43
Wetting agent (WA)										
No WA		6.80	6.87	6.53	6.20	6.07	6.07	7.33 *	5.87	5.53
WA		6.40	6.80	6.40	6.27	6.27	6.00	6.93	5.60	5.47
Trinexapac-ethyl (PGR)										
0.1 ml m^{-2} 28 DAS‡		6.83 ab	7.17	6.33	6.00 b	6.17	6.00	7.17 abc	5.33 bc	5.83 ab
0.2 ml m^{-2} 28 DAS		7.33 a	7.33	6.83	6.00 b	6.00	6.00	6.67 c	5.00 c	6.00 a
0.1 ml m^{-2} 52 DAS		6.50 bc	6.50	6.17	6.67 a	6.50	6.00	7.67 a	5.83 ab	5.33 b
0.2 ml m^{-2} 52 DAS		6.33 bc	6.67	6.50	6.50 a	6.17	6.17	7.33 ab	6.33 a	4.33 c
No PGR		6.00 c	6.50	6.50	6.00 b	6.00	6.00	6.83 bc	6.17 a	6.00 a

*, **, *** denotes statistical significance at $P < 0.10, 0.05, 0.01$ respectively.

† Color was rated on a 1-9 scale where 1=dead or brown turf, 6=acceptable and 9=dark green turf.

‡ DAS, days after seeding (seeded on 20 May 1998).

Table 6. Mean squares, main effects and significance of treatment effects

Table 6. Mean squares, main effects and significance of treatment effects on pre-traffic turf cover of establishing Kentucky bluegrass in a sand-based root zone 1998.

		Pre-traffic turf cover (%)†								
Source of variation	df	21-Jun	25-Jun	8-Jul	21-Jul	28-Jul	14-Aug	24-Aug	8-Sep	23-Sep
Block	2	122.03	171.30	420.63	2741.70	1939.90	1474.40	2330.86	490.03	426.23
WA	1	108.30 *	580.80 **	770.13 *	1778.70 **	1904.03 **	1360.13 **	760.03 **	580.80 **	288.30 *
PGR	4	13.78	30.71	21.80	138.62	257.53	865.33	1006.46	169.53	147.61
WA*PGR	4	41.22	142.38	212.63	775.45 *	753.86 *	1340.53	921.13	200.13	110.05
Error	18	33.36	93.41	141.37	322.88	276.93	211.31	147.47	104.21	83.86
Wetting agent (WA)										
No WA		17.27 *	21.00 **	33.33 *	57.40 **	73.27 **	93.73 **	93.00 **	95.53 **	95.73 *
WA		13.47	12.20	23.20	42.00	57.33	80.27	82.93	86.73	89.53
Trinexapac-ethyl (PGR)										
0.1 ml m^{-2} 28 DAS‡		15.83	16.83	30.83	55.00	75.00	92.00	94.67	95.17	97.33
0.2 ml m^{-2} 28 DAS		14.50	14.83	28.33	53.83	63.00	80.50	85.00	86.67	89.00
0.1 ml m^{-2} 52 DAS		16.67	17.67	27.17	43.33	58.00	80.50	78.83	84.17	86.17
0.2 ml m^{-2} 52 DAS		16.67	19.67	29.17	47.17	62.17	89.83	87.83	94.17	93.50
No PGR		13.17	14.00	25.83	49.17	68.33	92.17	93.50	95.50	97.17

*, **, *** denotes statistical significance at $P < 0.10, 0.05, 0.01$ respectively.

† Pretraffic turf cover was estimated visually as a percentage (0-100%).

‡ DAS, days after seeding (seeded on 20 May 1998).

cover significantly over the control on 21 July (Figure 43). On 28 July, trinexapac-ethyl applied at 0.1 ml m^{-2} 28 DAS significantly increased pre-traffic turfgrass cover over the control (Figure 44). Watschke (1981) and Dernoeden (1984) observed increased turfgrass density on established turfgrass with applications of a plant growth regulator. However, the effects of a plant growth regulator applied to seedling turf in the field were largely unknown. The findings of this research support Ervin and Koski (1998) conclusions where an increase in tillering of perennial ryegrass was observed in a greenhouse and growth chamber. When the wetting agent and trinexapac-ethyl were used in combination a detrimental effect was observed (Figures 43 and 44). This may be attributed to the wetting agent increasing the phytotoxicity effects of the plant growth regulator. Phytotoxicity can be described as leaf tip yellowing followed by tip die back and has been reported with multiple applications of class B, type II PGRs (Watchke 1981, Dernoeden 1984).

Wetting agent treatments reduced wear tolerance (Table 7). This may be attributed to the initial reduction in pre-traffic turfgrass cover (Table 6). Trinexapac-ethyl used alone had no significant effect on wear tolerance (Table 7). The detrimental effect of the wetting agent continued with sod strength measurements of the untrafficked turf. Sod strength was significantly reduced by wetting agent applications on both dates that measurements were taken (Table 8). Plots that received 0.2 ml m^{-2} of trinexapac-ethyl 28 DAS produced a significantly stronger sod over the control (Figure 45).

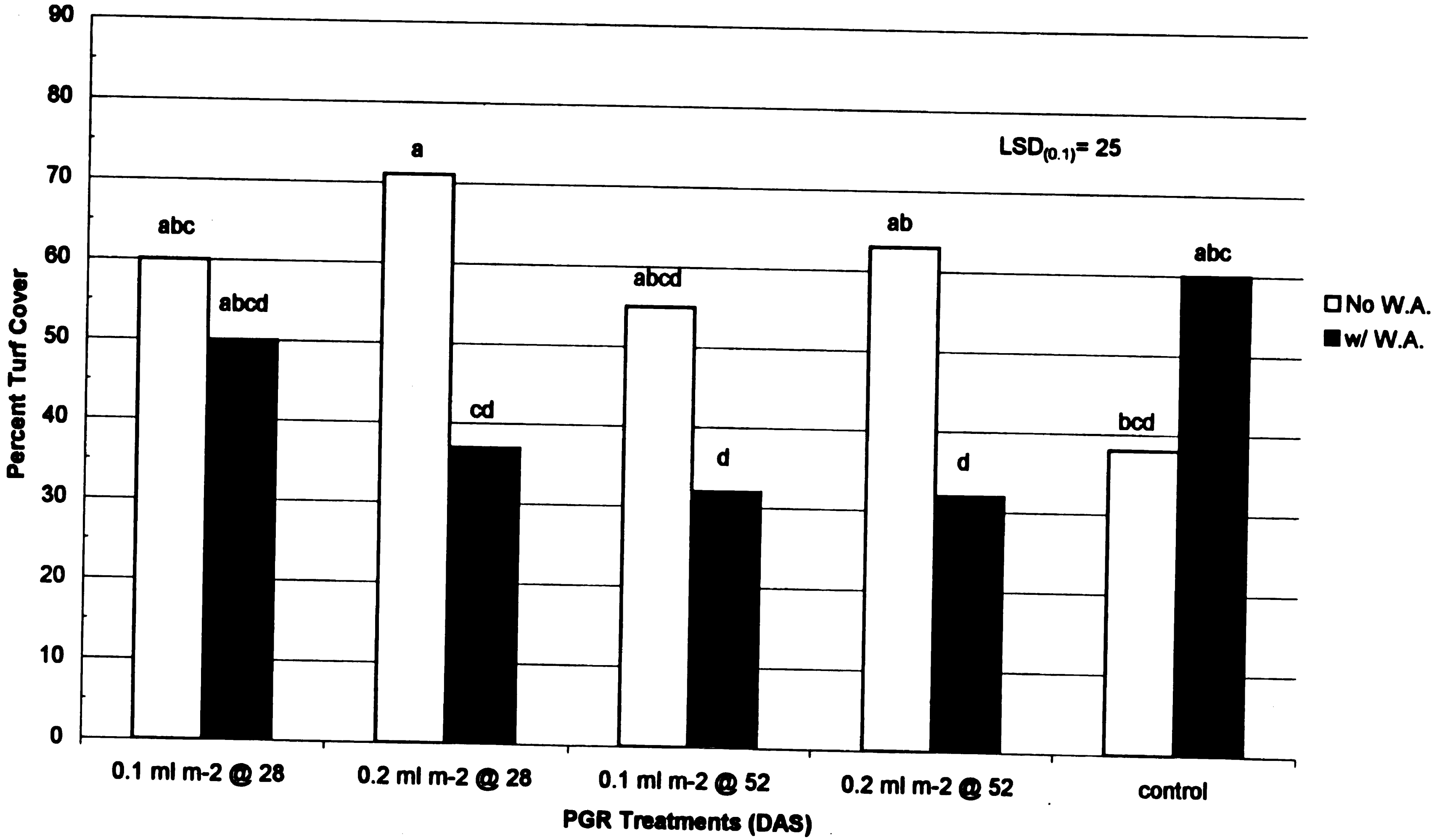

Figure 43. Effects of plant growth regulator and wetting agent on turfgrass cover 21 July 1998 (62 DAS).

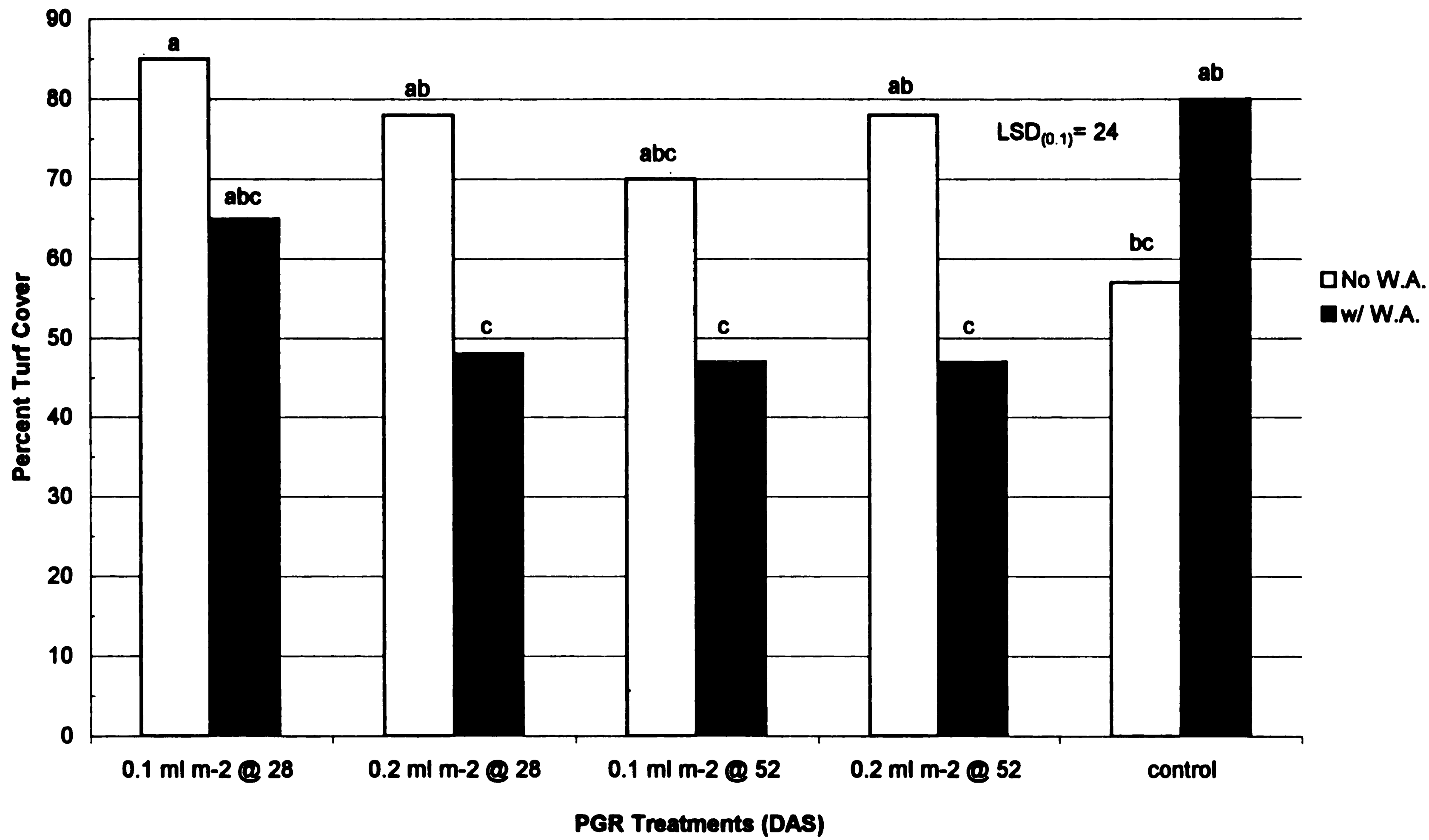

Figure 44. Effects of plant growth regulator and wetting agent on turfgrass cover 28 July 1998 (69 DAS).

Table 7. Mean squares, main effects and significance of treatment effects on post traffic turf cover 1998-99.

		Post traffic turf cover (%)†							
		1998‡				1999§			
Source of variation	df	24-Sep	8-Oct	30-Oct	17-Nov	1-Oct	22-Oct	26-Oct	11-Nov
Block	2	354.90	156.03	418.13	455.83	292.50	253.33	430.00	280.00
WA	1	333.33 *	340.03 **	235.20	213.33 *	13.33	7.50	53.33	83.33
PGR	4	121.55	76.11	193.61	82.08	107.25	344.58 *	363.75 ***	152.91
WAxPGR	4	130.58	97.45	172.45	98.75	405.58 ***	363.75 *	122.08	360.41 **
Error	18	91.97	58.47	87.90	66.01	86.35	148.70	62.40	92.96
Wetting agent (WA)									
No WA		97.73 *	98.33 **	88.67	87.00 *	89.67	68.67	69.33	55.67
WA		91.07	91.60	83.07	81.67	88.33	67.67	66.67	52.33
Trinexapac-ethyl (PGR)									
0.1 ml m^{-2} 28/24 DAS¶		98.67	98.83	92.00	86.67	87.50	72.50 ab	72.50 a	59.17
0.2 ml m^{-2} 28/24 DAS		88.67	91.00	80.83	80.83	89.67	70.00 abc	70.00 ab	53.33
0.1 ml m^{-2} 52/49 DAS#		90.50	91.50	81.17	80.00	84.17	60.83 bc	64.17 bc	52.50
0.2 ml m^{-2} 52/49 DAS		96.67	95.83	83.33	85.83	88.00	60.00 c	56.67 c	46.67
No PGR		97.50	97.67	92.00	88.33	95.67	77.50 a	76.67 a	58.33

*, **, *** denotes statistical significance at $P < 0.10, 0.05, 0.01$ respectively.

† Post traffic turf cover was estimated visually as a percentage (0-100%).

‡ Seeded 20 May.

§ Seeded 27 May.

¶ 1998 = 28 days after seeding (DAS) and 1999 = 24 DAS.

1998 = 52 days after seeding (DAS) and 1999 = 49 DAS.

Table 8. Mean squares, main effects and significance of treatment effects on sod strength 1998-99.

		Sod strength (kg)†			
		1998‡		1999§	
Source of variation	df	22-Oct	25-Nov	22-Oct	23-Nov
Block	2	74.17	41.42	10.93	100.60
WA	1	439.30 **	277.85 ***	305.28 *	156.86 *
PGR	4	36.98	26.26	36.87	43.83
WAxPGR	4	13.76	62.92 **	53.46	6.91
Error	18	55.81	16.32	26.96	24.36
Wetting agent (WA)					
No WA		25.41 **	26.87 ***	30.09 *	27.91 *
WA		17.75	20.78	23.71	23.34
Trinexapac-ethyl (PGR)					
0.1 ml m^{-2} 28/24 DAS¶		21.10	25.50	23.92	27.27
0.2 ml m^{-2} 28/24 DAS		24.45	24.95	25.50	24.47
0.1 ml m^{-2} 52/49 DAS#		21.10	22.89	26.88	24.53
0.2 ml m^{-2} 52/49 DAS		17.97	20.57	27.70	22.48
No PGR		23.28	25.22	30.52	29.38

*, **, *** denotes statistical significance at P < 0.10, 0.05, 0.01 respectively.

† Sod strength was measured using the Calrochan Sod Puller.

‡ Seeded 20 May.

§ Seeded 27 May.

¶ 1998 = 28 days after seeding (DAS) and 1999 = 24 DAS.

1998 = 52 days after seeding (DAS) and 1999 = 49 DAS.

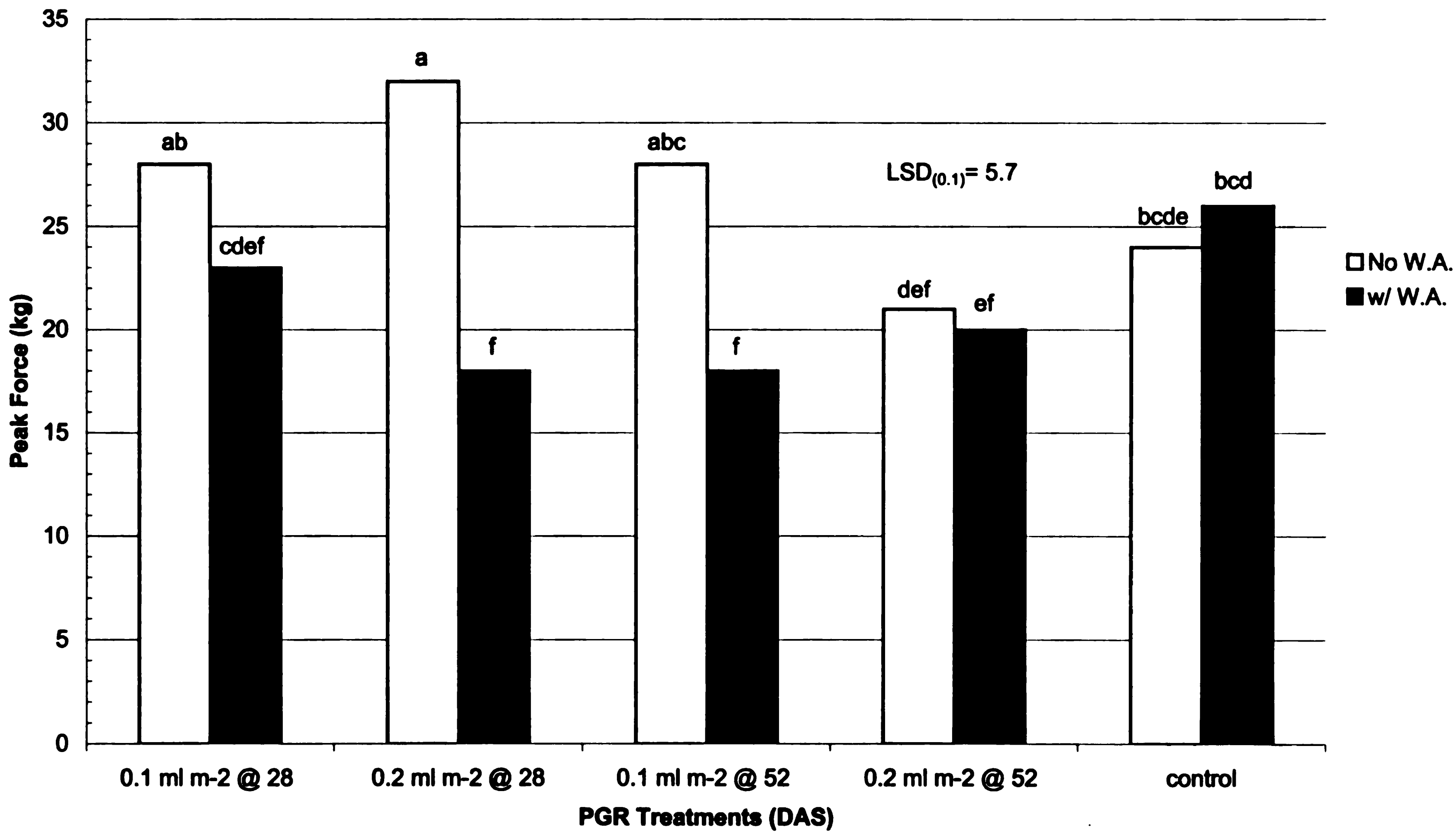

Figure 45. Effects of plant growth regulator and wetting agent on sod strength 25 November 1998 (189 DAS).

Verdure weights were recorded twice in 1998, and on 20 November plots that received trinexapac-ethyl early in the establishment process (28 DAS) had significantly lower verdure weights than the control (Table 9). This indicates a reduction in arial shoots per unit area, or lower density. Although taken at different times of the year, this quantitative data does not match the qualitative pre-traffic turfgrass cover data. Wetting agent effects on verdure weights were insignificant on both dates.

Rust (*Puccinia* spp.) outbreaks were observed in October 1998. The plots that had the high incidence of the disease were those that received trinexapac-ethyl in late August or later (Table 10). The *Puccinia* spp. infestations may have contributed to the reduction in sod strength of the plots that received the late PGR treatments (52 DAS) compared to the plots that were treated (28 DAS) (Figure 45).

1999 Results

Plots treated with trinexapac-ethyl had higher color ratings (Table 11). Wetting agent effects on color were insignificant except on 21 July where color was decreased (Table 11). Plant growth regulator and wetting agent used in combination decreased color ratings (Table 12). These results match those of 1998.

Wetting agent applications did not have a significant effect on pre-traffic turf cover in 1999 (Table 13). Trinexapac-ethyl applied separately, both early and late in the establishment process at 0.2 ml m^{-2} significantly reduced pre-

Table 9. Mean squares, main effects and significance of treatment effects on verdure 1998-99.

		Verdure†		
		1998‡		1999§
Source of variation	df	7-Sep	20-Nov	25-Sep
Block	2	0.44	5.97	0.68
WA	1	1.34	0.16	1.77
PGR	4	0.35	5.63 *	1.74
WAxPGR	4	0.23	1.48	1.49
Error	18	0.67	2.04	1.30
Wetting agent (WA)				
No WA		6.42	5.22	9.71
WA		5.99	5.07	10.19
Trinexapac-ethyl (PGR)				
0.1 ml m^{-2} 28/24 DAS¶		6.35	4.17 b	10.28
0.2 ml m^{-2} 28/24 DAS		5.97	4.16 b	10.70
0.1 ml m^{-2} 52/49 DAS#		6.16	5.30 ab	9.72
0.2 ml m^{-2} 52/49 DAS		6.55	5.70 a	9.72
No PGR		6.01	6.37 a	9.33

*, **, *** denotes statistical significance at P < 0.10, 0.05, 0.01 respectively.

† Verdure weights based on 186.6 cm^2 sample.

‡ Seeded 20 May.

§ Seeded 27 May.

¶ 1998 = 28 days after seeding (DAS) and 1999 = 24 DAS.

1998 = 52 days after seeding (DAS) and 1999 = 49 DAS.

Table 10. Mean squares, main effects and significance of treatment effects on rust incidence 1998-99.

		Rust†	
		1998‡	1999§
Source of variation	df	8-Oct	26-Oct
Block	2	2.53	0.70
WA	1	3.33	2.13
PGR	4	15.83 ***	26.28 ***
WAxPGR	4	0.16	1.38
Error	18	2.45	1.14
Wetting agent (WA)			
No WA		4.67	6.07
WA		4.00	5.53
Trinexapac-ethyl (PGR)			
0.1 ml m^{-2} 28/24 DAS¶		3.83 bc	4.17 d
0.2 ml m^{-2} 28/24 DAS		4.17 b	5.33 c
0.1 ml m^{-2} 52/49 DAS#		4.5 b	7.17 b
0.2 ml m^{-2} 52/49 DAS		6.83 a	8.67 a
No PGR		2.33 c	3.67 d

*, **, *** denotes statistical significance at P < 0.10, 0.05, 0.01 respectively.

† Rust severity was rated visually on a 1-9 scale where 1 = no rust and 9 = desication due to rust.

‡ Seeded 20 May.

§ Seeded 27 May.

¶ 1998 = 28 days after seeding (DAS) and 1999 = 24 DAS.

1998 = 52 days after seeding (DAS) and 1999 = 49 DAS.

Table 11. Mean squares, main effects and significance of treatment effects on color of establishing Kentucky bluegrass in a sand-based root zone 1999.

		Color[†]						
Source of variation	df	24-Jun	5-Jul	21-Jul	11-Aug	2-Sep	1-Oct	11-Nov
Block	2	0.00	0.00	0.03	0.03	0.00	2.80	1.03
WA	1	0.00	0.00	0.53 ***	0.00	0.00	0.00	0.30
PGR	4	0.00	0.00	0.88 ***	0.58 **	4.80 ***	2.25 **	1.20 ***
WAxPGR	4	0.00	0.00	0.28 ***	0.25	0.00	1.42 *	0.96 **
Error	18	0.00	0.00	0.03	0.18	0.00	0.54	0.22
Wetting agent (WA)								
No WA		6.00	6.00	4.40 ***	5.33	7.60	6.00	3.07
WA		6.00	6.00	4.13	5.33	7.60	6.00	2.87
Trinexapac-ethyl (PGR)								
0.1 ml m^{-2} 24 DAS[‡]		6.00	6.00	4.00 c	5.17 b	8.00 a	6.00 b	3.33 a
0.2 ml m^{-2} 24 DAS		6.00	6.00	4.00 c	5.00 b	8.00 a	6.00 b	3.17 a
0.1 ml m^{-2} 49 DAS		6.00	6.00	4.50 b	5.83 a	8.00 a	5.50 b	2.67 b
0.2 ml m^{-2} 49 DAS		6.00	6.00	4.83 a	5.33 b	8.00 a	5.50 b	2.33 b
No PGR		6.00	6.00	4.00 c	5.33 b	6.00 b	7.00 a	3.33 a

*, **, *** denotes statistical significance at $P < 0.10, 0.05, 0.01$ respectively.

† Color was rated on a 1-9 scale where 1=dead or brown turf, 6=acceptable and 9=dark green turf.

‡ DAS, days after seeding (seeded on 27 May 1999).

Table 12. Wetting agent (WA) by plant growth regulator (PGR) means 1998-99.

	Color†			
	1998‡	1999§		
WAxPGR	8-Sep	21-Jul	1-Oct	11-Nov
No WAx0.1 ml m^{-2} 28/24 DAS¶	5.67 bcd	4.00 c	6.67 ab	3.67 ab
No WAx0.2 ml m^{-2} 28/24 DAS	5.00 d	4.00 c	5.33 c	3.00 cd
No WAx0.1 ml m^{-2} 52/49 DAS#	5.33 cd	5.00 a	5.67 bc	2.67 d
No WAx0.2 ml m^{-2} 52/49 DAS	7.00 a	5.00 a	5.33 c	2.00 e
No WAxNo PGR	6.33 ab	4.00 c	7.00 a	4.00 a
WAx0.1 ml m^{-2} 28/24 DAS	5.00 d	4.00 c	5.33 c	3.00 cd
WAx0.2 ml m^{-2} 28/24 DAS	5.00 d	4.00 c	6.67 ab	3.33 bc
WAx0.1 ml m^{-2} 52/49 DAS	6.33 ab	4.00 c	5.33 c	2.67 d
WAx0.2 ml m^{-2} 52/49 DAS	5.67 bcd	4.67 b	5.67 bc	2.67 d
WAxNo PGR	6.00 bc	4.00 c	7.00 a	2.67 d
Significance	**	***	*	**

*, **, *** denotes statistical significance at P < 0.10, 0.05, 0.01 respectively.

† Color was rated on a 1-9 scale where 1=dead or brown turf, 6=acceptable and 9=dark green turf.

‡ Seeded 20 May.

§ Seeded 27 May.

¶ 1998 = 28 days after seeding (DAS) and 1999 = 24 DAS.

1998 = 52 days after seeding (DAS) and 1999 = 49 DAS.

Table 13. Mean squares,main effects and significance of treatment effects on pre-traffic turf cover of establishing Kentucky bluegrass in a sand-based root zone 1999.

		Pre-traffic turf cover (%)†				
Source of variation	df	24-Jun	5-Jul	21-Jul	11-Aug	2-Sep
Block	2	35.10	5.70	730.83	535.83	40.30
WA	1	73.63	154.13	140.83	100.83	64.53
PGR	4	58.05	60.13	555.00	196.66	127.88 **
WAxPGR	4	42.22	96.13	820.00 *	780.00 **	98.78 *
Error	18	27.32	70.58	290.09	233.05	36.30
Wetting agent (WA)						
No WA		8.47	17.67	62.33	75.00	90.87
WA		5.33	13.13	58.00	71.33	87.93
Trinexapac-ethyl (PGR)						
0.1 ml m^{-2} 24 DAS‡		5.00	13.50	57.50	70.00	86.00 b
0.2 ml m^{-2} 24 DAS		4.50	12.50	67.50	70.00	87.17 b
0.1 ml m^{-2} 49 DAS		9.50	18.50	54.17	70.83	88.33 b
0.2 ml m^{-2} 49 DAS		4.50	13.33	49.17	71.67	88.00 b
No PGR		11.00	19.17	72.50	83.33	97.50 a

*, **, *** denotes statistical significance at $P < 0.10, 0.05, 0.01$ respectively.

† Pretraffic turf cover was estimated visually as a percentage (0-100%).

‡ DAS, days after seeding (seeded on 27 May 1999).

traffic turfgrass cover compared to the control (Figure 46). Dernoeden (1982) reported reduced density with some class B, type II PGRs applied to established turfgrasses. When the wetting agent was combined with each of the four trinexapac-ethyl treatments, three of the combinations significantly reduced turf cover compared to the control (Figure 46), which was also observed in 1998. The control had significantly higher turfgrass cover than plots that received the wetting agent and 0.1 ml m^{-2} of trinexapac-ethyl applied early and late in the establishment process, 11 August and 2 September (Figures 47 and 48).

Reduction in wear tolerance due to wetting agent applications was not seen in 1999 (Table 7). However, a significant reduction in sod strength due to wetting agent was recorded again as 1999 (Table 8). Trinexapac-ethyl did not significantly affect sod strength in 1999 (Table 8). Trinexapac-ethyl applied at the full rate both early and late (24 and 49 DAS) had significantly less turfgrass cover after traffic than the control (Figure 49). On 26 October both trinexapac-ethyl treatments applied late in the establishment process (49 DAS) had less wear tolerance than the control (Table 7). This could be contributed to the *puccina* spp. outbreaks that were observed again in 1999 (Table 10). When trinexapac-ethyl and wetting agent were used in combination there was either no significant effect on wear tolerance or wear tolerance was reduced (Figures 49, 50, and 51). No significant differences were recorded with verdure weights in 1999 (Table 9).

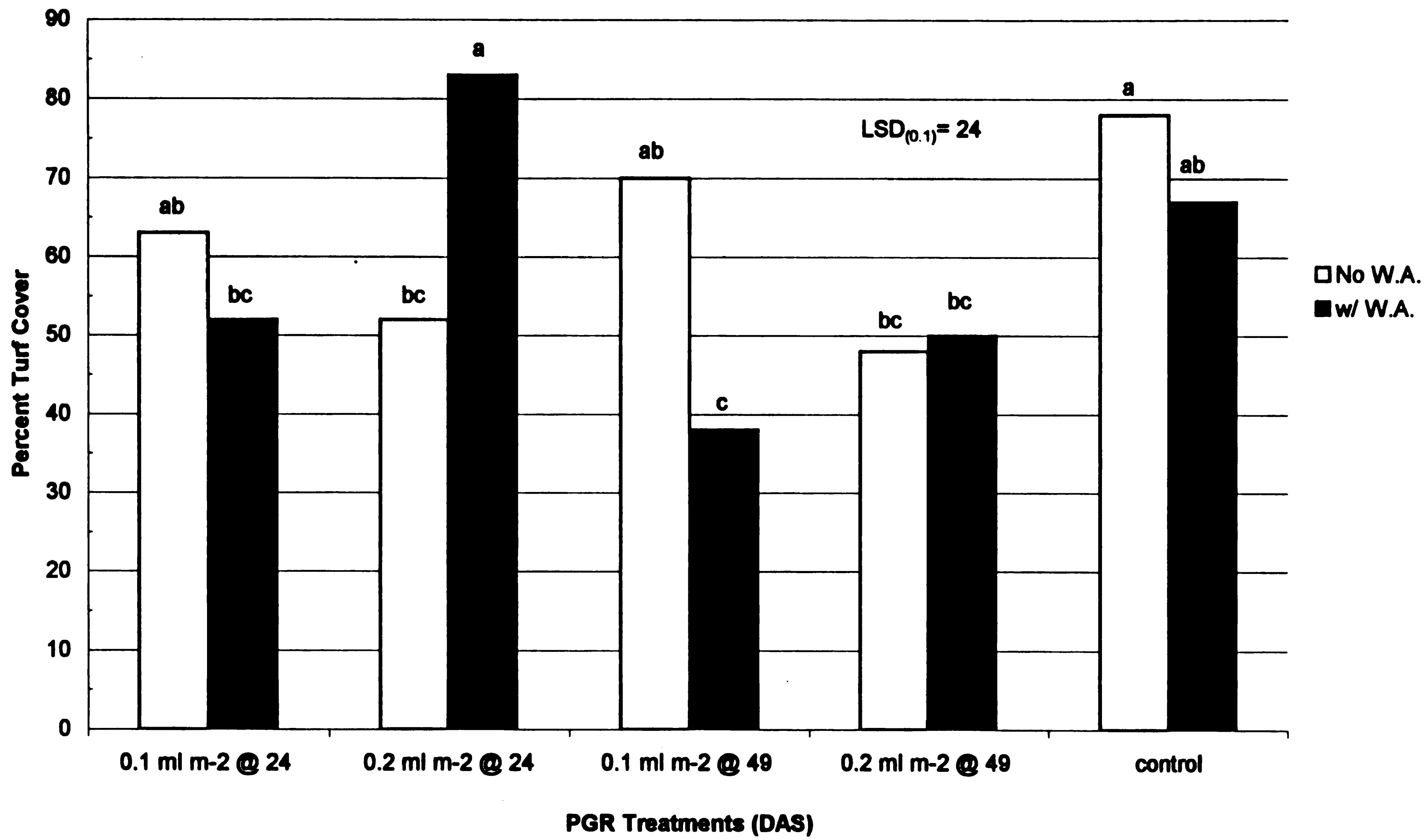

Figure 46. Effects of plant growth regulator and wetting agent on turfgrass cover 21 July 1999 (55 DAS).

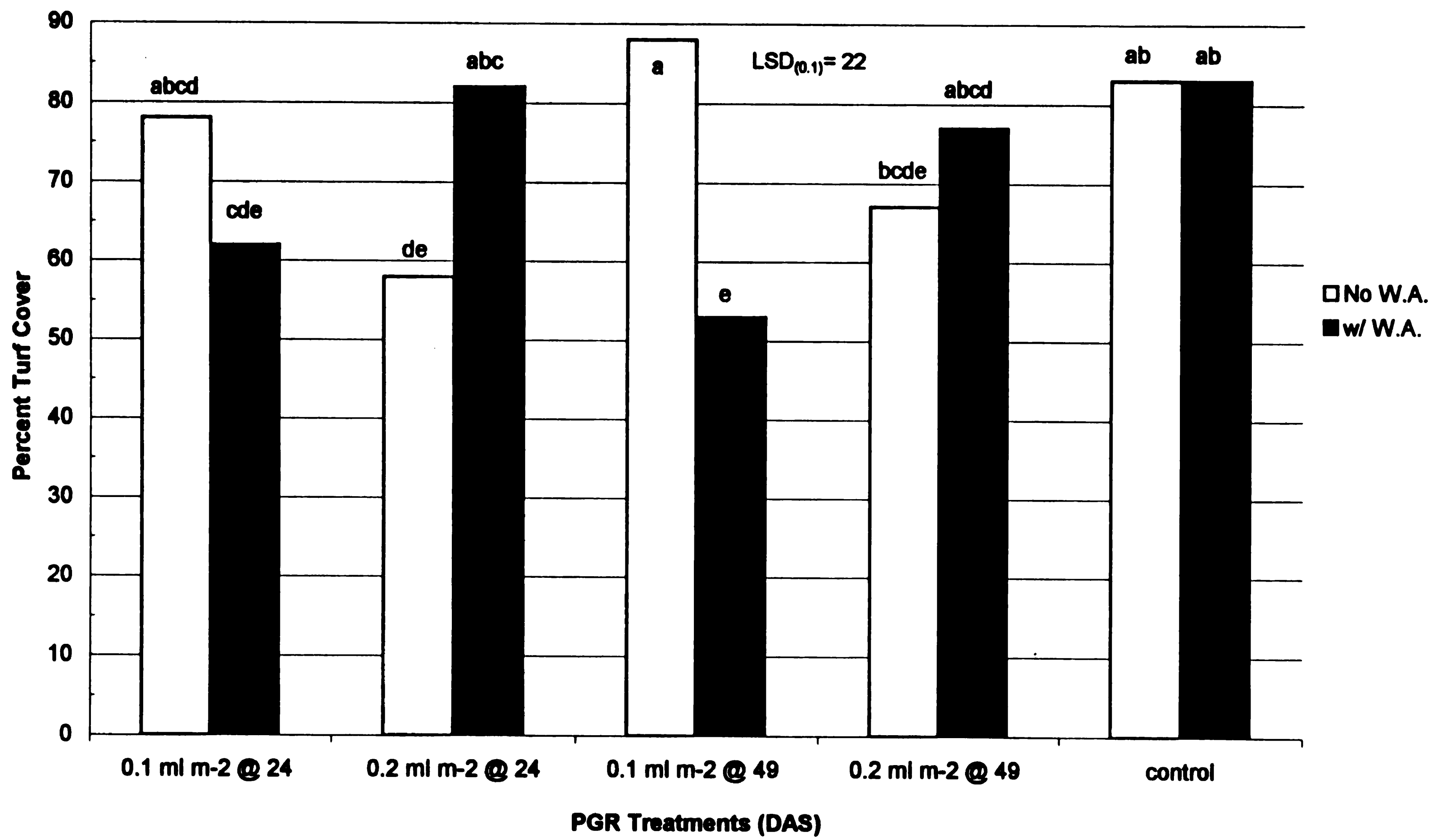

Figure 47. Effects of plant growth regulator and wetting agent on turfgrass cover 11 August 1999 (76 DAS).

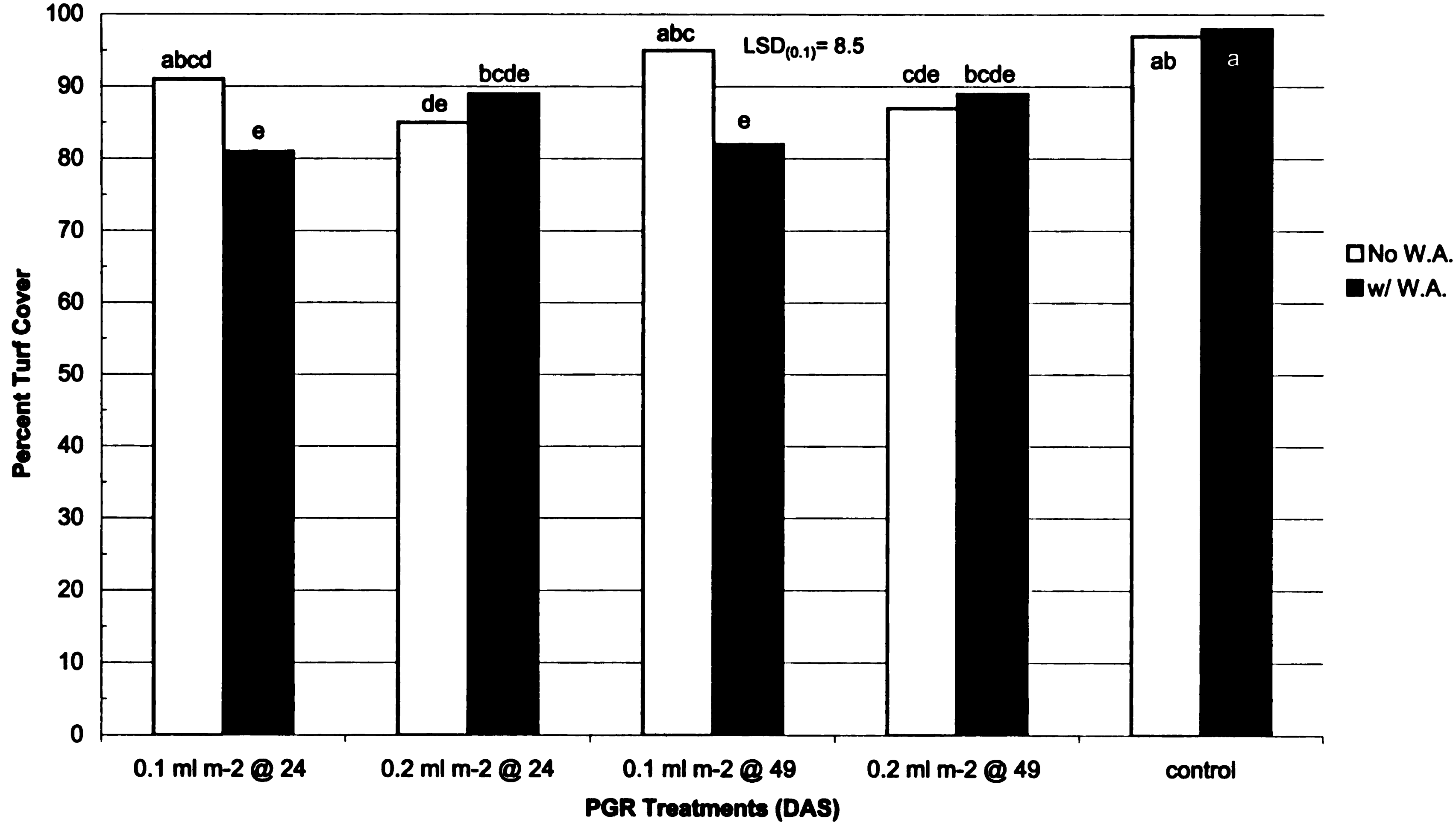

Figure 48. Effects of plant growth regulator and wetting agent on turfgrass cover 2 September 1999 (98 DAS).

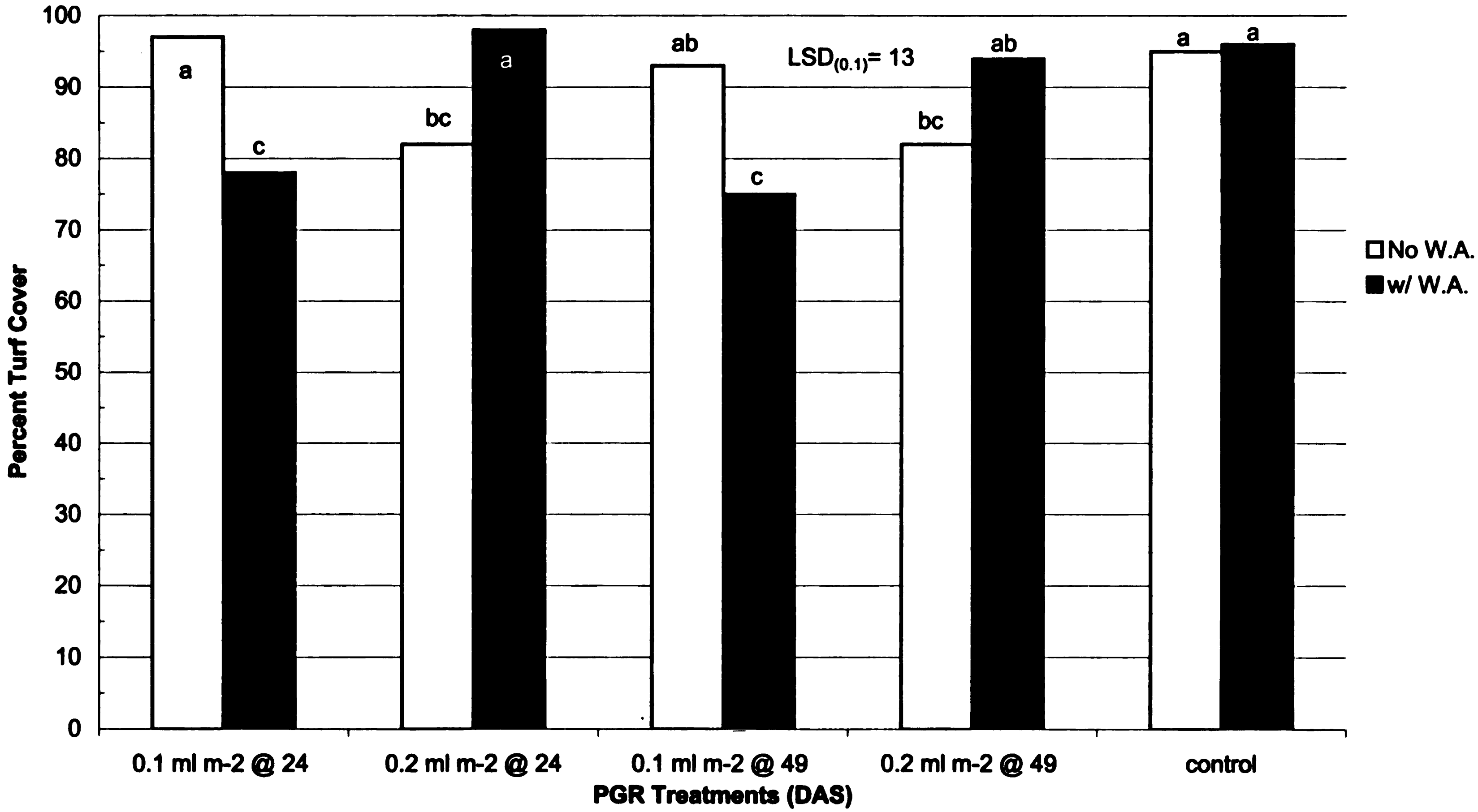

Figure 49. Effects of plant growth regulator and wetting agent on turfgrass cover after traffic 1 October 1999.

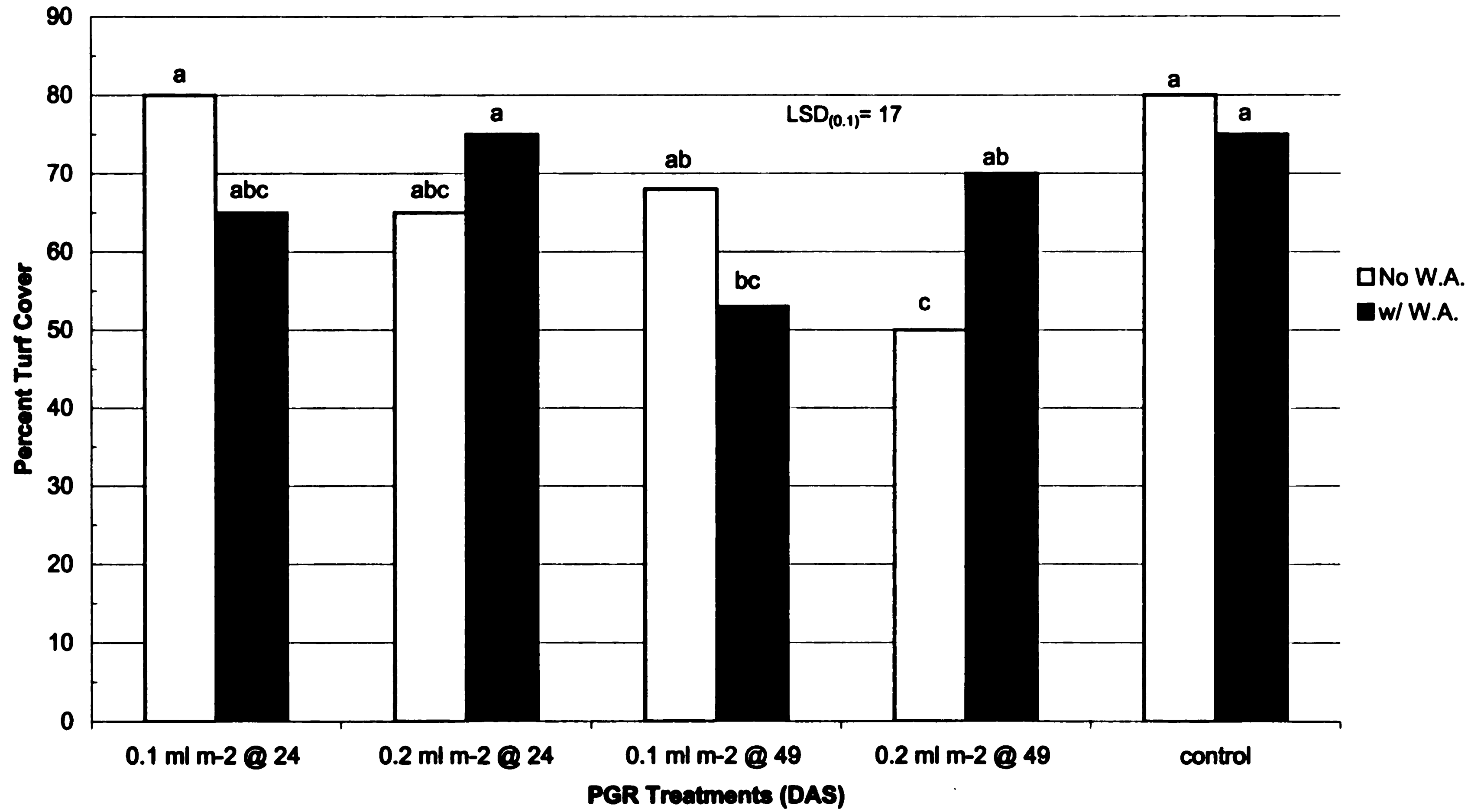

Figure 50. Effects of plant growth regulator and wetting agent on turgrass cover after traffic 22 October 1999.

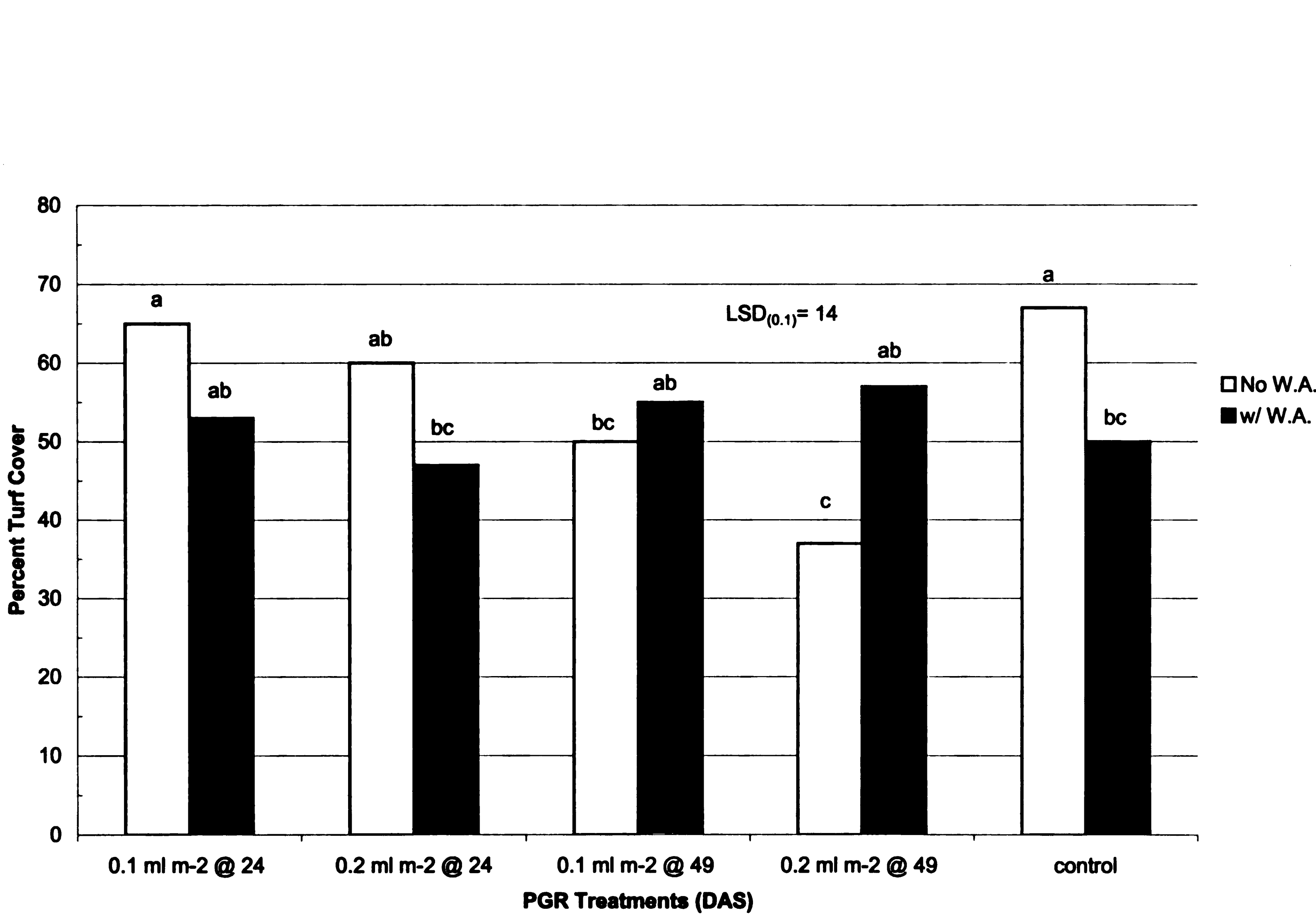

Figure 51. Effects of plant growth regulator and wetting agent on turfgrass cover after traffic 11 November 1999.

Discussion

In 1998, it appeared that trinexapac-ethyl had the potential to accelerate Kentucky bluegrass establishment, but in 1999 the results did not match those of 1998. Temperature and precipitation were monitored daily throughout the study and can not explain the differences between the years. However, given previous literature and some consistencies between years, partial conclusions can be drawn. Turfgrass color was increased due to trinexapac-ethyl treatments in both years. In 1999, trinexapac-ethyl did not enhance density or sod strength. Bingaman et al. (1996) also reported no beneficial effects of trinexapac-ethyl when applied to establishing perennial ryegrass in the field. It is worth noting that the control performed equally well in both years.

Results on plant growth regulator effects to date are contradictory. It has been shown that plant growth regulators can increase density of established stands of various grasses (Watschke 1981, Dernoeden 1984). They have also been shown to increase tillering of seedling perennial ryegrass in a growth chamber and greenhouse (Ervin and Koski 1998). However, plant growth regulators used to increase the establishment rate in the field may not be worth the time and money. Trinexapac-ethyl can be applied to seedling Kentucky bluegrass at 0.1 ml m^{-2} to attempt to delay mowing without significant reductions in stand density. However, Bingaman et al. (1996) recorded no significant reductions in the growth of seedling perennial ryegrass.

The effect of wetting agent on establishment was consistent over both years. In 1998, wetting agent applications significantly reduced germination and wear tolerance, and sod strength was reduced in both years. Rust (*Puccinia* spp.) infestations were observed in 1998 and 1999. The plots that received trinexapac-ethyl applications in late August or later had the highest disease incidence. Therefore, late fall applications of plant growth regulators should be avoided.

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