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The Characterization, Assessment, and Shear Strength of Turfgrass Soil in North American Thoroughbred Racing

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THE CHARACTERIZATION, ASSESSMENT, AND SHEAR STRENGTH OF TURFGRASS SOIL IN NORTH AMERICAN THOROUGHBRED RACING

DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Agriculture, Food, and Environment and the College of Engineering
at the University of Kentucky

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2024

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ABSTRACT OF DISSERTATION

THE CHARACTERIZATION, ASSESSMENT, AND SHEAR STRENGTH OF TURFGRASS SOIL IN NORTH AMERICAN THOROUGHBRED RACING

Minimizing catastrophic injuries to racehorses, which also protects the riders, is critical for the future of the Thoroughbred racing industry. While the causes of catastrophic injuries are multifactorial, the condition of the racing surface is one of only a few factors that affects all horses in competition. Horse racing surfaces must retain enough shear strength to support the hoof of a Thoroughbred at a gallop. Turfgrass racing surfaces also require healthy turf to reinforce the footing while also achieving a high infiltration rate to allow races to run on the turf soon after or even during rain. This research is an investigation of current and potential future turfgrass soils at North American racing surfaces. The goal is to provide a consistent surface to support the horse and to help protect the horse and rider.

Laser diffraction was used to determine the particle size distribution of soils at 23 turf racing surfaces in North America. Laser diffraction was able to characterize the mean values of a racing surface's particle size distribution and detect differences between racetracks with samples as small as 0.25g. The use of small samples minimizes safety concerns since removal of the sample causes minimal disturbance of the racing surface. This research can help select topdressing and divot mix materials. Potential problem areas in active turf racing surfaces can be investigated with samples as small as aeration cores removed as a part of normal maintenance. Baseline data has already been used to help guide profile selection for construction and renovation projects.

Simple tools suitable for daily use were evaluated against the Orono Biomechanical Surface Tester (OBST). Analysis was performed on test plots which simulate current and potential future fiber reinforced North American racetracks. The study establishes correlations between simple tools and the biomechanically based OBST measurements used for pre-meet inspections. Volumetric moisture content is the most important simple tool and it is well suited for daily measurements at racetracks. The Longchamp Penetrometer, which has an established correlation to horse performance and injuries, can be used to supplement the moisture meter. The inclusion of surface data in epidemiological models has the potential to increase our understanding of the contribution of the racing surface to the risk of injury as well as guide racetrack personnel and regulator decisions on race days.

Soil meeting the recommended profile for golf course greens was tested using triaxial shear. Three different types of fiber reinforcement were considered: no reinforcement, synthetic fiber reinforcement, and natural fiber reinforcement. Fiber reinforcement is the most promising method of modifying soils of this type to produce the shear strength required while maintaining a free draining racing surface. Natural fibers are a promising alternative to the synthetic fibers currently used. These materials avoid the introduction of microplastic into the environment and could reduce the need for aeration of older turf surfaces. Natural fibers are also promising for use in divot mixes in surfaces without fibers since the fibers decompose as the turf root system develops. Both synthetic polypropylene as well as jute and sisal natural fiber reinforcement increase the friction angle and reduce cohesion which makes the free draining soils more suitable for Thoroughbred racing surfaces.

This dissertation provides a better understanding of current and potential future soils used in turfgrass Thoroughbred racing surfaces. Methods which can be used to monitor surfaces both with and without fiber on a daily basis have also been established. The effect of appropriate fiber reinforcement is that even free draining soils may provide sufficient shear strength for Thoroughbred racing which will allow more races to be held on turfgrass racetracks.

KEYWORDS: Equine, Racing, Surfaces, Turfgrass, Rider, Safety

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[04/17/2024]
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THE CHARACTERIZATION, ASSESSMENT, AND SHEAR STRENGTH OF TURFGRASS SOIL IN NORTH AMERICAN THOROUGHBRED RACING

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To Dietrich and Wyatt. Dream big, work hard, and never give up.

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CHAPTER 1. INTRODUCTION

1.1 Background

Thoroughbred racing has been a popular sport in North America since the American Revolution when having the fastest horse meant one received both financial gain and elevated social status [1]. Though its popularity has largely endured into the 21st century, horse racing faces many challenges in modern society. The racing sector of the horse industry is comprised of over 1.2 million horses; over 500,000 of which are Thoroughbreds [2]. It also directly supports over 241,000 jobs and adds $15.6 billion in direct value to the national economy [2]. A further 231,000 jobs and $21.1 billion dollars is then generated from indirect and induced effects [2].

Though few would question the financial success of the horse racing industry, it has encountered significant resistance in recent years as a modern perspective on animal welfare and concern for the safety of the riders has challenged the sport's social license to operate [3]. A particular concern is catastrophic injuries to racehorses, which the Jockey Club defines as the death or euthanasia of the horse within 72 hours of the race [4].

Public outcry over catastrophic injuries has periodically been raised as a concern. For example, a major escalation in awareness occurred after the 2008 Kentucky Derby. At the conclusion of the race, Eight Belles, a filly who finished second to Big Brown, was euthanized on the track in front of over 150,000 fans and a live television audience after a leg injury [5]. More recently over 30 racehorses experienced catastrophic injuries in less than 6 months at Santa Anita Park in 2019 [6, 7]. In an attempt to address the concerns and build public confidence, Congress passed the Horseracing Integrity and Safety Act of 2020

[8] which established the Horseracing Integrity and Safety Authority (HISA). HISA has since established regulations that govern many areas of the sport, including a racetrack safety program [9] which is aimed at ensuring racing surfaces are fit for competition.

Protecting the equine athletes is the primary focus of these discussions. However, the safety of jockeys and exercise riders is also a concern. Racing is a dangerous industry for the human athletes as well as the equine athletes. At least 79 fatalities to riders were reported between 1992 and 2006 [10]. Research indicates that these incidents may be trending downward [11], although the absence of a comprehensive system for tracking injuries to riders has been recognized [12]. In the absence of more comprehensive rider injury data, it is recognized that reducing catastrophic injuries to racehorses also reduces the risk to jockeys and exercise riders [13].

1.2 Catastrophic Injury and the Hoof-Surface Interaction

While the causes of catastrophic injuries are multifactorial, the condition of the racing surface is generally accepted as a primary concern since it is one of very few factors that affects all horses in competition [14]. Preparing a surface for Thoroughbred racing starts with a basic understanding of the gait of the horse including the loads generated by a 450 kg animal traveling at 15 m/s. Prior research [15] has detailed four phases of the movement of the forelimb: impact, stance, breakover, and swing. During the initial impact phase, the hoof contacts the surface at a relatively high velocity and low load. During the secondary impact phase, the downward motion of the center of mass is transferred to the ground and as the fetlock rotates downward the limb experiences its peak vertical loads, which are on the order of 2.5 times its body weight. The stance phase occurs when the weight has been transferred onto the hoof and vertical motion of the horse's body has stopped. During the breakover phase, the horse is applying the horizontal forces required for propulsion with the toe rotating into the surface of the track. The hoof then leaves the ground during the swing phase and returns to a position in front of the horse and the process is repeated.

The actual loads and accelerations experienced by the hoof will vary depending on several factors such as surface type [16] and moisture content [17]. The Orono Biomechanical Surface Tester (OBST) [15], which is the subject of an ASTM standard [18], is the primary device for collecting this data as it replicates the forelimb of the horse at the moment where the peak loads and accelerations are experienced. There are no firm limits established for the OBST parameters which deem a surface "safe" for racing. Though catastrophic injury can certainly be caused by a severe overloading of the limb, it can also be caused by repeated minor overloading of the limb as well [14]. The majority of research on equine surfaces suggests that the minimization of spatial and temporal variation should be the primary focus [14].

The shear strength of the racing surface is one of the most important characteristics for properly supporting the animal. As the hoof transitions from secondary impact into the stance phase and then breakover, large horizontal shear loads are applied [15]. The ideal surface will allow a small amount of slide during the primary impact and then should support the hoof during propulsion. If the surface fails to balance these requirements it can affect both the horse's ability to compete and the risk of injury. In the case of turf surfaces, shear failure is also referred to as "divoting." Divoting is also a safety concern as it leaves a non-uniform surface for the athletes that follow. The tearing of the turfgrass plant from the surface also further reduces the shear strength of the surface by reducing the plant's ability to regenerate its root structure.

1.3 Horse Racing Surfaces in North America

Horse racing in North America has historically been conducted primarily on dirt surfaces [4] and as a result the dirt surfaces have been the primary focus of research. Dirt surfaces have the highest catastrophic injury rate among the three surface types used in North America [4, 19]. There are three different archetypes of dirt surfaces which have been shown to vary by geography and climate, at least in part because of the need to maintain a consistent moisture content in the track [20]. A unique characteristic which sets dirt surfaces apart from synthetic and turf is the way they drain water. While turf and synthetic surfaces move water vertically through the profile, dirt surfaces drain horizontally toward the inside rail.

Synthetic racing surfaces, which are usually a mixture of sand, wax, fiber, and rubber, were more common in the early 2000's in large part due to a mandate by the California Horse Racing Board that all tracks within the state be constructed with synthetic materials [21]. These surfaces have the lowest catastrophic injury rate among the three surface types in North America [4]. Though some synthetic surfaces are still in use today, many were removed from major racetracks due to a lack of acceptance among horsemen [22, 23].

In recent years, the percentage of starts conducted on turf surfaces in North America has been increasing [4]. Turf is also the primary surface used for racing in other parts of the world such as the United Kingdom, Australia, and New Zealand. The primary and most obvious characteristic which distinguishes turf surfaces from dirt and synthetic is the presence of turfgrass. This means that the soil matrix needs to support both the hoof of the animal during propulsion as well as the ability to sustain turfgrass growth. The primary benefit of the addition of turfgrass to a racing surface is the presence of an active network of roots which can significantly increase the shear strength of the racing surface [24].

1.4 Existing Research on Agronomy, Surface Loading, and Terramechanics

While there is not an extensive existing body of research that covers turfgrass Thoroughbred racing surfaces, related research on turfgrass can be applicable. Considerable research has been conducted on the agronomic practices that cultivate a dense, healthy stand of turfgrass. This body of work is directly applicable to Thoroughbred racing as a healthy turfgrass plant will aid in supporting the hoof of a Thoroughbred at a gallop and recover from heavy traffic. Relevant topics include but are not limited to the selection of soils which maximize the ability to cultivate turfgrasses [25], the selection [26] and establishment [27] of proper turfgrass species, fertility practices [28], cultural practices to remove weeds [29] and insects [30], and critical maintenance practices such as aeration [31]. Soil is defined as the in-situ surface mineral and/or organic layer of the earth that has experienced some natural degree of physical, biological, and chemical weathering. For the purpose of this dissertation, the term soil will refer to mineral and organic separates which are combined at specific ratios used in a growing medium for turfgrass in a horse racetrack setting.

There is an abundance of studies that apply turfgrass research to golf [32] though this is often limited to agronomic discussions as there is no need to consider surface response at it relates to the safety of the athlete. Most turfgrass research which does address the safety of the athlete considers the loads applied by humans [33]. The obvious distinction between these studies and the needs of turfgrass Thoroughbred racing surfaces is that the loads and loading rates of a Thoroughbred at a gallop far exceed those experienced by humans [15, 16].

The loading of the surface from a galloping horse is on the order of 950 kPa if 9 kN is distributed over a hoof with a 9,500 mm^2 surface area [15]. Because of the dynamic application of these high loads, heavy-duty military vehicle applications are a better comparison than human sports. For example, the calculated ground pressure of an M1A1 Abrams tank is only 98 kPa [34]. Racetrack loading is closer to the load from landing airplanes which exert ground pressures similar to that of a Thoroughbred at a gallop [35]. Like the airplane or the tank, the loads in Thoroughbred racing are also dynamic which affects the material response. Differences in material response are particularly important in partially saturated soil and at the higher strain rates encountered at high-speed operation or when landing [36]. Fortunately, because of these applications there is well-established literature in the area of terramechanics on which to depend.

Soil particle size distribution and moisture content have been shown to effect the strength of soils in trafficability studies [37]. Root structure has also been shown to have similar effects [38]. The addition of fiber to soils has also been shown to increase shear strength in soils [39, 40]. The preparation of field runways for military aircraft is particularly applicable since the large loads are applied dynamically [41, 42].

1.5 Analysis of Soil Composition at North American Turf Tracks

No standard exists for the composition of a turfgrass racing surface in North America. Turfgrasses grown will obviously vary by climate and it is possible that soils used in turf tracks may vary in a similar fashion. There is a need to document the existing compositions of North American turf tracks as this will have a significant effect on the mechanical properties of the racing surface such as shear strength [43] and infiltration rate [44].

Soil composition is historically determined by sieve and sedimentation methods such as sieve-pipette or sieve-hydrometer. These methods are problematic for the horse racing industry primarily due to the need for large samples of 100g or more [45]. Extracting samples of this size from active turf tracks presents a safety concern as great care is always taken to minimize the disturbance of the racing surface as outlined above.

Laser diffraction is a promising technology for the horse racing application as it has been shown to produce repeatable particle size distribution measurements on soils with much smaller samples [46]. This means samples can be collected when the tracks are aerated which is a part of regular maintenance. Furthermore, laser diffraction has a greatly reduced cycle time compared to sieve and sedimentation methods [46].

1.6 Daily In-Situ Measurements of Racing Surfaces

HISA specifies that daily measurements must be taken at turf racing surfaces including moisture content as well as penetration and shear properties [9]. The OBST is the primary device for evaluating a racing surface and is recognized in ASTM F3400-19 [18]. Though it is uniquely well suited to collect biomechanically based measurements required by HISA for pre-meet inspections it has limitations preventing it from daily use. The OBST is not cost-effective, it requires a trained operator, and it damages the surface which again presents safety concerns. As a result, there is a need to identify simpler tools that do not disturb the surface which can be used for this application.

Many simple and portable tools have been used in turfgrass playing field applications such as the moisture probe [47], the Clegg Impact Hammer [48, 49], the Longchamp Penetrometer [50-52], the Turf Shear Tester [53], and the GoingStick® [54]. Some of these tools have been used in equine applications and some have not. The Longchamp Penetrometer is particularly interesting as research on turf horse racing surfaces in New Zealand has identified relationships between those measurements and horse performance [50, 51] as well as injury [52].

The alternative tools have not been evaluated alongside the OBST for the purposes of investigating potential correlations to biomechanically based measurements. Identifying tool(s) that can objectively quantify the condition of a surface on race days in relation to the speeds and loads generated by a Thoroughbred at a gallop would be of great practical value. For these findings to be applicable to HISA's regulations, the test should be conducted on soil compositions found in North American racetracks.

1.7 Effects of Natural and Synthetic Fiber Reinforcement on Shear Strength of Soils

As previously stated, shear strength is one of the most important characteristics of a racing surface. A failure of the surface due to horizontal shear load results in an inability to support the hoof throughout propulsion [15]. This can adversely affect the performance of the animal as well as potentially increase the risk of injury.

Some bespoke playing field surfaces retain fine content (silt and clay) in order to maintain shear strength but this is at the cost of infiltration rate [55]. To combat this, many soils are constructed of high sand content rootzones which are reinforced with materials designed to improve shear strength without inhibiting drainage. This is frequently done with synthetic fibers, most commonly polypropylene, although many different types of materials have been used for this intended purpose [55-57].

Natural fibers such as jute and sisal have also been shown to increase the shear strength of soils [58, 59]. Though these have not yet been evaluated alongside synthetic fibers for playing field applications they have several potential advantages. These are a more environmentally friendly product that is often made from reclaimed materials as opposed to a petroleum based manufactured product. While the natural fibers will of course biodegrade in the profile, this could make natural fibers a great candidate for divot mixes so that the surface can maintain shear strength as new turfgrass plants take root. Last, synthetic fibers have been shown to increase surface hardness in a soil profile especially after heavy traffic [60]. The common treatment to reduce surface hardness is aeration [61] though not all racetracks can perform this activity as frequently as desired due to extended race meets and agronomic constraints. If natural fibers can combat these surface hardness concerns that would be a tremendous advantage for horse racing.

An ASTM standard exists for the evaluation of the shear strength of equine surfaces [62]. The consolidated, drained triaxial shear test produces a friction angle and cohesion value for the material in question. These parameters are key components in the relationship that governs the shear strength of equine surfaces [63] and are fundamental to modeling of tractive effort over unreinforced surfaces [64]. Performing this analysis on materials commonly used in turfgrass soils can provide insight on their ability to adequately support the hoof of a Thoroughbred at a gallop.

1.8 Research Motivation and Organization of Chapters

Demand for turf racing in North America has been increasing due to many factors that appeal to horsemen. These include a rise in high quality races and a progressively international breeding market which has brought European turf bloodstock into North American racing [65]. As a result of both owner and betting interests, some turf tracks may have as many as 8,000 starts over meets that can last nearly 200 days per year [4]. With this many horses running over a turf surface the potential increases that racing can be impacted by inclement weather or the inability of the surface to recover from rain. If a turf track has a significantly elevated moisture content, divoting of the surface occurs which presents a safety concern. Unlike other countries, turf races in North America can in almost all cases be transferred to an adjacent dirt or synthetic surface if the turf surface does not drain adequately. However, loss of field size and other economic and safety considerations make this decision difficult.

A race which is pulled "off the turf," or transferred to the main dirt or synthetic surfaces can result in a large number of horses that scratch since they are not trained to compete on dirt or synthetic surfaces [66]. Other horses which are amenable to racing on the main track may be entered to fill those slots, but the "handle" or amount bet will be impacted as a result of moving the race off the turf. A pattern of off-the turf races can also impact horsemen who must reconcile the costs associated with bringing their horse to a track that was not able to hold their race of interest.

For turfgrass horse racing surfaces to be successful in North America, two priorities must be addressed. First, infiltration rates must be high to ensure turf races can be conducted on the intended surface regardless of weather conditions either on the day of racing or on previous days. Second, these surfaces must be able to withstand the loads generated by a Thoroughbred at a gallop. The research contained in this dissertation is an evaluation of current and potential soils used for turfgrass horse racing surfaces and their potential ability to fulfill the requirements of the industry.

Chapter One of this dissertation outlines the historical, economic, and safety contexts that surround the problem at hand.

Chapter Two investigates the potential use of laser diffraction to determine the particle size distribution of North American turfgrass horse racing surfaces. Unlike traditional sedimentation methods laser diffraction allows for the use of smaller samples to obtain particle size distribution measurements which is a tremendous advantage for active racing surfaces. This includes a discussion around the number of samples which should be collected from racing surfaces as well as presentation of organic content, climate factors, turfgrasses grown, and mineralogy for each surface. Pretreatment to remove organic content is also discussed as there is not agreement among existing research [67, 68].

Chapter Three evaluates the five simple tools mentioned above along with the OBST at turfgrass plots which simulate compositions that have the potential to be both free draining and have sufficient shear strength for horse racing for North American turfgrass horse racing. The purpose of this study is to identify the simple tools which can be used to collect daily surface measurements that comply with HISA regulations. These tools will allow racetrack personnel to make decisions that impact the safety of the horse and rider based on quantitative data.

Chapter Four considers an alternative approach to creating a high infiltration rate surface with the necessary friction angle and cohesion for horse racing. Soil reinforced with synthetic fiber presents a number of issues including the generation of microplastics [69] and increased surface hardness [60]. Soil reinforced with natural fiber was tested using the ASTM F3415-20 test and compared to the results with synthetic fiber. Results are discussed within the context of turfgrass horse racing surfaces including the potential benefits of each type of reinforcement.

Chapter Five provides conclusions from the research contained in subsequent chapters as well as recommendations for future work.

CHAPTER 2. LASER DIFFRACTION ANALYSIS OF NORTH AMERICAN HORSE RACING SURFACES

2.1 Abstract

Significant research has focused on North American dirt and synthetic Thoroughbred racing surfaces. Turfgrass racing surfaces have received less consideration. Basic information, including climate and turfgrass species, can be documented relatively easily. However, a key characteristic, the particle size distribution of the growing medium, is not readily available for turf tracks. Particle size distribution and the deviation from nominal values are important to infiltration rate, shear strength, and turf health, as well as being critical for the selection of top-dressing and divot repair sand. The primary difficulty with obtaining the particle size distribution is the relatively large quantity of material required for traditional sedimentation test methods. Sampling an active racing surface could present a risk to the horses and riders. Laser diffraction testing methods present an opportunity to use much smaller samples. The use of smaller samples introduces new questions about the ability of a small sample to represent a large area, such as a racetrack. Tests were carried out with high resolution sampling at one racetrack. By sampling a large number of locations, 96 locations on a single racetrack, the variability of the track could be evaluated, and an eight-sample protocol was developed. Using the eight-location protocol, 22 additional turf racetracks throughout North America were sampled. A total of 23 turf racetracks were tested, representing all three of the designs used for North American turf racetracks. By looking at the three different track designs: engineered profile, engineered profile with fiber, and native soil, appropriate testing parameters and measurements were identified. While the primary objective was to understand turf racetracks, this unique data set also provided a method to investigate the applicability of laser diffraction for the

analysis of soil samples. Mineralogy and organic content had previously been identified as important in the measurement of particle size distribution using laser diffraction. Mineralogy and organic content were determined for samples from each surface using X-ray diffraction (XRD) and loss on ignition. The PSD of the three types of turfgrass horse racing surfaces showed significant differences between native soil (N), engineered surfaces without synthetic fibers (EWOF), and engineered surfaces with synthetic fibers (EWF). These basic design descriptions were also found to be sufficient for making reasonable estimates of the settings used in the machine configuration and sample preparation. A single refractive index was used for the entire range of samples in this group; however, the sample quantity tested was different for the three different types of track designs.

2.2 Introduction

While thoroughbred racing has been part of American life since the colonial era, the risks to human and equine athletes have become an important concern. Of particular concern are catastrophic injuries, which are defined in The Jockey Club's Equine Injury Database as death or euthanasia of the horse within 72 hours of a race [4]. While the causes of catastrophic Thoroughbred injuries are multi-factorial, the consistency of the racing surface is generally accepted as one of the factors that affects every horse on the track [14]. While the literature often focuses on equine athletes, jockeys were also found to be "171 times more likely to be injured when they rode a horse that died in a race" [13]. In particular, the condition or "going" of turf racing surfaces has been shown to directly impact the likelihood of injury to the horse [70-72] and jockey [73]. While a consistent racing surface is one of many factors impacting risk to the horse and rider, it is part of the overall focus on safety.

The current understanding of requirements for consistent racing surfaces includes maintenance, materials, base considerations, and moisture content [14]. The dynamics of the hoof-surface interaction [63] and the magnitude of the loads on the hoof are particularly important to understand for horse racing surfaces [16], since the loads are much higher and applied at a higher loading rate than the surfaces used for human athletes. The majority of racing in the United States and Canada is conducted on dirt and synthetic surfaces. However, the percentage of races conducted on turf surfaces in North America has increased significantly in recent years [4]. At the same time, the understanding of turf racing from countries in which turf is the primary racing surface does not always apply to horse racing in North America. North American races are conducted in a counterclockwise direction on oval tracks. Some turf tracks may have as many as 8,000 starts over meets that can last nearly 200 days per year [4]. At the same time, North American turf racing is rarely conducted on wet turf surfaces since turf tracks have adjacent dirt or synthetic surfaces to transfer the races, which can protect the turf from damage. The amount of time after a rainstorm during which races are moved to other surfaces is both an economic and a safety consideration. The recovery time after a storm is influenced by the design of the track, with native soils typically being the slowest to recover from rain and fiber reinforced sand being the fastest. The most common surface is a bespoke sand surface with some fine material used to increase the shear strength.

The composition and closely related mechanical properties of dirt racetracks have been shown to vary by geography and climate, at least in part because of the need to maintain a consistent moisture content in the track [20]. Geographic and climate trends may also apply to turfgrass racing surfaces. The surface composition will influence the surface’s resistance to compaction, soil water retention, hydraulic conductivity, and the ability to grow healthy turf, which produces a dense network of root fibers that reinforce the footing. The particle size distribution of the growing media, soil mineralogy, amount of organic matter present, and turfgrass species cultivated all combine to produce a unique set of conditions that influence the hoof-surface interaction. Knowledge of a racing surface’s composition is critical for the purpose of ongoing maintenance decisions, including irrigation and topdressing. The selection of topdressing material will prevent layering and enhance drainage. Using topdressing material with a narrow particle size distribution that matches the mean value of the existing particle size distribution will maintain or enhance track drainage. Matching existing sand for divot repair will also help provide a more consistent racing surface.

A primary reason that the particle size distribution has not been reported for existing turf racetracks is the requirement to remove a large specimen for particle size analysis by the common sedimentation methods. Given the potential for spatial variation in the surface, the removal of several large samples is particularly difficult. Areas of concern in the track where damage or contamination has occurred can also be evaluated if small samples can be removed. Compared to sedimentation methods, soil testing performed using laser diffraction requires only a small specimen and also has reduced analysis time and increased repeatability [46]. Specimens tested using laser diffraction are well suited to removal from turf racetracks and sports surfaces since the samples removed can be the same size as cores, which are commonly extracted during aeration. Aeration is a common cultural practice for turf racetracks to reduce compaction of the surface and encourage root growth [31].

Laser diffraction is based on a different set of assumptions compared to sedimentation methods. Sedimentation methods include sieve-pipette and sieve-hydrometer methods [45]. A relatively large sample, 100 g in the case of high sand content mixtures, is typical. These methods have been used extensively in the soil science community over many years, in spite of the labor required [67]. The analysis of sedimentation methods is based on Stokes' law, which assumes that spherical particles are suspended in solution. Clay particles do not fit this assumption well since they may have aspect ratios of 100 or more [74]. Sedimentation results are reported as a percent of the mass of the sample [45]. Laser diffraction, in contrast, is based on the scattering of light and thus the volume of the material rather than the mass [75]. The differences between volume and mass are minimal for sand since the density of most of the minerals is similar. However, this distinction has a significant effect on samples with organic material because of differences between the densities of mineral soil particles and organic matter. Furthermore, laser diffraction has been shown to report higher percentages of silt and lower percentages of clay compared to sedimentation results for equivalent samples [76].

This article explores the use of laser diffraction to measure the particle size distribution of the growing medium used in turfgrass surfaces used for Thoroughbred racing. General characteristics of the racing surfaces, such as turfgrass grown, climate factors, and mineralogy, are documented in order to facilitate future testing by identifying factors that may impact the results. The suitability of this method for this testing application is considered for turf profiles typically used in horse racing.

2.3 Materials & Methods

2.3.1 Turf course descriptions and sampling locations

2.3.1.1 Track Descriptions

Soil samples collected from 23 turfgrass racing surfaces across North America represent the three commonly used track designs. Specifically, these designs are identified as native soil (N), engineered surfaces without synthetic fibers (EWOF), and engineered surfaces with synthetic fibers (EWF). The native soil racetracks have not received any significant modifications to their profile. EWF racing surfaces have either been significantly modified or completely renovated and incorporate the use of synthetic fibers to increase shear strength [55]. EWOF racing surfaces have either been significantly modified or completely renovated and do not incorporate the use of synthetic fibers. The turf racetracks sampled for this study are Aqueduct Racetrack Inner (AQUI), Aqueduct Racetrack Outer (AQUO), Belmont Park Inner (BELI), Belmont Park Outer (BELO), Churchill Downs (CD), Del Mar Thoroughbred Club (DM), Ellis Park (EP), Fair Grounds Race Course (FG), Golden Gate Fields (GG), Gulfstream Park Inner (GPI), Keeneland Race Course (KEE), Laurel Park (LRL), Oklahoma Training Track (OKTT), Pimlico Race Course (PIM), Palm Meadows Training Center (PMTC), Parx Racing (PRX), Remington Park (RP), Santa Anita Park (SA), Saratoga Race Course Inner (SARI), Saratoga Race Course Outer (SARO), Woodbine Racetrack Inner (WOI), Woodbine Racetrack Outer (WOO), and Woodbine Racetrack Training (WOT).

Table 2.1 details the location and climate data for all 23 racetracks. This information can help provide a framework for understanding cultural practices and maintenance schedules. Annual precipitation, average annual temperature, average annual maximum temperature, and average annual minimum temperature information was obtained from the National Centers for Environmental Information for the ten-year period of 2011 through 2020 [77].

Table 2.1: Summary of track locations and climate data

Track	City, State	Annual Precipitation, mm		Annual Mean Temp, ºC		Annual Avg High Temp, ºC		Annual Avg Low Temp, ºC	
		Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
AQUI	Jamaica, NY	1142.7	209.9	13.1	0.57	17.1	0.62	9.1	0.54
AQUO	Jamaica, NY	1142.7	209.9	13.1	0.57	17.1	0.62	9.1	0.54
BELI	Elmont, NY	1173.3	250.2	13.9	0.75	17.7	0.76	10.1	0.77
BELO	Elmont, NY	1173.3	250.2	13.9	0.75	17.7	0.76	10.1	0.77
CD	Louisville, KY	1362.5	249.8	15.2	0.75	20.4	0.83	10.0	0.73
DM	Del Mar, CA	246.7	92.5	16.5	0.76	19.6	0.84	13.5	0.72
EP	Henderson, KY	1339.2	261.9	14.2	0.79	19.8	1.03	8.7	0.60
FG	New Orleans, LA	1662.6	172.5	21.9	0.76	26.5	0.73	17.3	0.85
GG	Berkeley, CA	552.1	260.5	14.8	0.66	19.3	1.50	10.4	1.03
GPI	Hallandale Beach, FL	1700.1	318.4	25.0	0.34	28.7	0.31	21.3	0.43
KEE	Lexington, KY	1402.2	242.3	13.8	0.72	19.2	0.86	8.3	0.65
LRL	Laurel, MD	1177.5	252.6	13.7	0.61	18.9	0.69	8.4	0.61
OKTT	Saratoga Springs, NY	1164.0	146.4	9.3	1.21	15.2	1.06	3.4	1.41
PIM	Baltimore, MD	1236.9	285.8	13.9	0.80	19.3	0.88	8.5	0.76
PMTC	Boynton Beach, FL	1606.8	280.6	24.5	0.59	29.0	0.41	20.1	0.96
PRX	Bensalem, PA	1364.4	251.7	12.2	0.59	18.0	0.66	6.4	0.65
RP	Oklahoma City, OK	980.2	267.9	16.4	0.86	22.7	1.05	10.0	0.72
SA	Arcadia, CA	372.1	150.8	17.2	0.71	21.5	0.72	12.9	0.77
SARI	Saratoga Springs, NY	1164.0	146.4	9.3	1.21	15.2	1.06	3.4	1.41
SARO	Saratoga Springs, NY	1164.0	146.4	9.3	1.21	15.2	1.06	3.4	1.41
WOI	Toronto, Ontario, Canada	885.1	99.1	9.5	0.96	14.0	1.00	4.9	0.96
WOO	Toronto, Ontario, Canada	885.1	99.1	9.5	0.96	14.0	1.00	4.9	0.96
WOT	Toronto, Ontario, Canada	885.1	99.1	9.5	0.96	14.0	1.00	4.9	0.96

The suitability of laser diffraction testing requires the ability to measure the range of soil types used for the turfgrass or turfgrasses cultivated as well as dealing with materials that may include the use of synthetic reinforcing fibers. Table 2.2 details the track design, or archetype, of each surface along with the turfgrasses cultivated, which were documented based on sample observations and verified by consulting with the racetrack superintendents. Two sampling protocols were used: high spatial resolution sampling was used for one track and a lower resolution spatial sampling on the additional 22 turf tracks. Spatial variation in the composition, both radially from the inside rail and circumferentially, from one pole to another, is of interest since it can affect the shear strength and moisture content. To help determine the number of samples required to characterize the surface, a total of 96 samples were collected from Keeneland Racecourse (KEE). Specifically, samples were collected at every 1/16th mile pole at distances of 1 m, 4.8 m, 8.6 m, 12.4 m, 16.2 m, and 20 m from the innermost rail location. However, as the track is only 18m wide at the 3/8 pole, that was the outermost location sampled at that position. The basic set of eight samples, like those collected at the other tracks, were also taken from the most trafficked area of the racetrack to be compared with the full set of 96 samples.

Table 2.2: Summary of turfgrasses grown and archetype of North American racetracks

Track	Turfgrass Species 1	Turfgrass Species 2	Fiber, Y/N/T[a]	Archetype
AQUI	Kentucky Bluegrass	…	N	EWOF
AQUO	Kentucky Bluegrass	…	N	EWOF
BELI	Kentucky Bluegrass	…	N	EWOF
BELO	Kentucky Bluegrass	…	N	EWOF
CD	Tall Fescue[b]	Kentucky Bluegrass[b]	Y	EWF
DM	Bermudagrass	…	Y	EWF
EP	Bermudagrass	…	N	N
FG	Bermudagrass	Perennial Ryegrass[c]	Y	EWF
GG	Kentucky Bluegrass	Perennial Ryegrass	Y	EWF
GPI	Bermudagrass	…	N	EWOF
KEE	Tall Fescue	Kentucky Bluegrass	Y	EWF
LRL	Tall Fescue	Kentucky Bluegrass	N	EWOF
OKTT	Kentucky Bluegrass	Tall Fescue	N	EWOF
PIM	Tall Fescue	Kentucky Bluegrass	N	N
PMTC	Bermudagrass	…	N	EWOF
PRX	Tall Fescue	Kentucky Bluegrass	T	EWOF
RP	Bermudagrass	Perennial Ryegrass[c]	N	EWOF
SA	Bermudagrass	Perennial Ryegrass[c]	Y	EWF
SARI	Kentucky Bluegrass	Tall Fescue	N	EWOF
SARO	Kentucky Bluegrass	Tall Fescue	N	EWOF
WOI	Kentucky Bluegrass	Perennial Ryegrass	Y	EWF
WOO	Kentucky Bluegrass	Perennial Ryegrass	N	EWOF
WOT	Kentucky Bluegrass	Perennial Ryegrass	N	N

[a] The presence or absence of fiber is denoted as Y = Yes, N = No, and T = Trace for minor, trace amounts of fiber present in samples.

[b] CD was renovated in the summer of 2020 to bermudagrass with a perennial ryegrass overseed for winter coverage. References to CD in this paper are based on the track prior to renovations.

[c] Denotes this grass is overseeded for winter coverage and removed in the spring

For the remaining 22 turf tracks, eight samples from the most highly trafficked areas were collected and labeled with the collection date, racetrack, and sampling location. These eight standard sampling locations were the 3/4 pole, 1/2 pole, 1/4 pole, and the wire at distances of 1 m and 8.6 m from the innermost rail position. The innermost rail position is always used as a reference, as the inside rail is moved periodically to manage wear and damage from the hooves on the surface during the race meet. Figure 2.1 depicts the eight standard sampling locations.

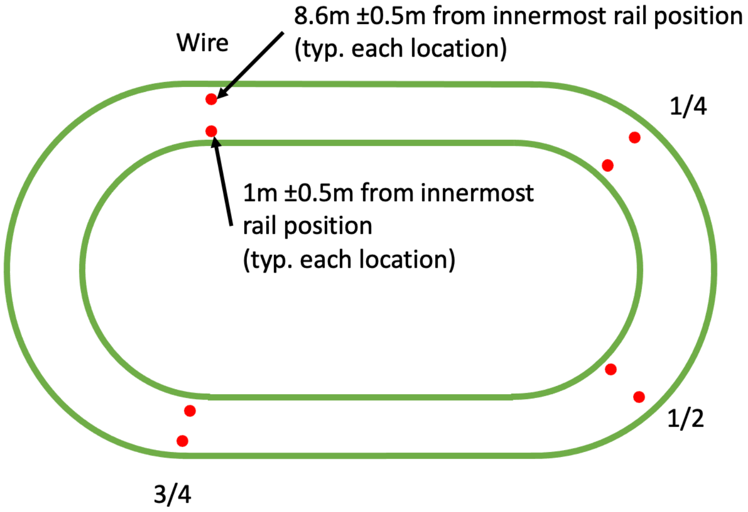

Figure 2.1: Standard soil sampling locations for turfgrass racing surfaces

For all samples collected, a 22 mm diameter sampling probe was inserted multiple times to a depth of 150 to 200 mm within a 0.5 m radius of each nominal sampling location shown in Figure 2.1. The probe was sized to be comparable to the holes produced from hollow tine aeration, which is part of normal maintenance.

2.3.2 Testing Methods

2.3.2.1 Particle Size Distribution of Soil

2.3.2.1.1 Sample Preparation

Samples were weighed on a balance and oven-dried for 16 hours at 60°C to remove moisture. Samples were weighed upon removal from the oven, gently crushed, and sieved to <2 mm. The mass of material greater than 2 mm retained in the sieve was recorded. The laser diffraction particle size analyzer cannot accept particles larger than 2 mm. Macroscopic organic particles such as turf biomass and any synthetic fibers (if present) were also removed with tweezers and documented.

Samples from each racetrack were prepared for testing to determine the appropriate quantity of materials to be used for testing. Sample quantities were determined based on the manufacturer's recommended obscuration value of 10% to 20%. For each surface, different quantities of dried soil were measured into a test tube with a mass tolerance of ±0.01 g. 2 mL of a 50 g/L sodium hexametaphosphate (SHMP) solution and 10 mL of distilled water were then added for each gram of dry soil. Samples were then placed on an end over end shaker for 16 hours. Sample preparation, including the use of chemical dispersants and end-over-end shaking, is consistent with prior soil research [67, 68]. From testing the different samples, the largest specimen size that produced the required obscuration was then chosen as the nominal sample size for samples tested for that racetrack. Three replicate samples of the appropriate size from each sampling location were then prepared using the same methods as the trial runs described in this section.

2.3.2.1.2 LASER DIFFRACTION ANALYSIS

Laser diffraction testing was performed using a Mastersizer 3000 fitted with the Hydro LV attachment (Malvern Panalytical Ltd., Malvern, UK). Samples were sonicated in the laser diffraction instrument at 100% power (40 W) for 60 seconds [67, 68]. Non-spherical particle mode was selected for the particle type, and Mie theory was used for the analysis. The optical settings were 1.544 for the refractive index and 0.01 for the absorption index. The refractive index of 1.544 was based on a weighted average of the refractive index of 80% quartz and 20% feldspar [46]. The mineralogy estimate is supported by the

X-ray diffraction testing results. The absorption index of 0.01 has also been used successfully in the analysis of soils [67]. Both the refractive and absorption indexes were confirmed to generate sufficiently low weighted residual values in all measurements. According to the manufacturer, a weighted residual under 1% implies that the calculated data is reasonably well-fitted to the measurement data, whereas weighted residuals greater than 1% may indicate adjustments to the refractive and absorption indices are necessary. The dispersant used was distilled water, and its refractive index was set to 1.33. Five measurements were recorded for each sample, and the average of those five measurements was reported. The process was then repeated for three replicated samples from each sampling location.

The data output calculated includes statistical parameters of D_{10} (tenth percentile), D_{50} (median grain size), and D_{90} (ninetieth percentile), as well as percent by volume reported in several size classes. The lower boundaries of each of those groups are 0.01µm, 2µm, 4µm, 10µm, 20µm, 32µm, 40µm, 53µm, 74µm, 105µm, 149µm, 250µm, 420µm, 500µm, 1000µm, 1410µm, 2000µm, 2380µm, and 2830µm to allow comparison to historical data or other available sports field data [20].

2.3.2.1.3 ORGANIC MATTER ANALYSIS

Apart from large turf biomass in the samples, organic material was not removed prior to laser diffraction analysis. Previous research has shown a marginal effect of organic matter removal [68]. Specifically, samples varying from 0.32% to 7.18% organic matter were shown to produce a small underestimation of clay content when laser diffraction was performed on samples when organic matter was not removed from the sample. More recently, removing organic carbon has been shown to negatively affect the agreement between laser diffraction results and sedimentation methods [67].

Prior work has shown reliable results using laser diffraction without the need to pretreat samples when testing samples with a moderate amount of organic carbon [67]. To verify the range of organic content in the samples, soil from each sampling location was submitted to a loss on ignition procedure to determine organic content [47]. Approximately 100 g of dry soil was measured into a crucible and placed into a 440°C oven for 14.5 hours to burn off organic matter. Samples were weighed to determine the percent loss by mass of organic content.

2.3.2.1.4 X-RAY DIFFRACTION ANALYSIS

For X-ray diffraction analysis, one mixed sample was created from each racetrack. This was done by combining 4.5 g ±0.5 g from each of the eight standard locations described previously. The mixed sample was then sent to an outside lab for X-ray diffraction analysis (K/T GeoServices, Inc., Gunnison, Colorado). The method for the procedure employed is described in Bish and Reynolds [78] and Post and Bish [79] and was also used for dirt racetrack testing [20].

2.3.3 Statistical Methods

The statistical analysis used to test the hypotheses listed in this paper was conducted using a general mixed model estimation (R Development Core Team, 2022). The first hypothesis was tested by comparing the standard eight sampling locations to the full set of 96 samples collected at KEE. Since there were three laser diffraction measurements per sampling location, a repeated measures ANOVA was performed to compare the mean values of the D_{10}, D_{50}, D_{90}, and volume fraction results from each size category detailed. As there was only one measurement each for organic content and the percentage of material in excess of 2 mm, a simple linear model was used to compare those mean values using ANOVA. Significance was set at $p<0.05$. The variation was also investigated by calculating the percentage of the range seen in the 96 samples that was evident in the sample size of eight. To test the second hypothesis, the racetracks were grouped into archetypes based on observations of the soil composition, including the presence or absence of synthetic fiber. Again, since there were three laser diffraction measurements per sampling location, a repeated measures ANOVA was performed to compare the mean values of each archetype for the D_{10}, D_{50}, D_{90}, and volume fraction results from each size category detailed, and a simple linear model was used to compare the organic content and the percentage of material in excess of 2 mm. When significant differences were detected ($p<0.05$), pairwise comparisons were performed using Tukey's honestly significant difference (HSD) test. To investigate the variation between racing surfaces, all numeric response variables were also included in a principal component analysis (PCA) using the prcomp function (R Development Core Team, 2022). The data were centered and scaled as part of the analysis.

2.4 Results

2.4.1 Laser Diffraction Results

A summary of 552 total laser diffraction measurements and 24 samples from 23 different racetracks is shown in the appendix in Table A 1. The mean D_{10}, D_{50}, and D_{90} values for all tracks were 8.41 μm, 93.08 μm, and 420.04 μm respectively, with standard deviations of 4.78 µm, 75.64 µm, and 149.76 µm respectively. Values for KEE in Table A 1 represent the eight standard sampling locations, not the larger 96 sample size.

A total of 816 laser diffraction measurements were made, including the 88 additional samples collected for testing the first hypothesis. 138 of those measurements were outside of the 10%-20% obscuration range. No measurements were flagged by the Malvern software for data quality concerns. A target obscuration range of 10%-20% was used, which resulted in samples sizes ranging from 0.25 g to 2.5 g. The weighted residuals reported had an average of 0.25 with an overall range of 0.10-0.80 for all measurements.

Differences in laser obscuration and the weighted residual were evident between the different track designs, which in turn influenced the size of the sample to be tested. In general, samples with a greater percentage of fine materials necessitated the use of a smaller sample to achieve the required laser obscuration (Figure 2.2).

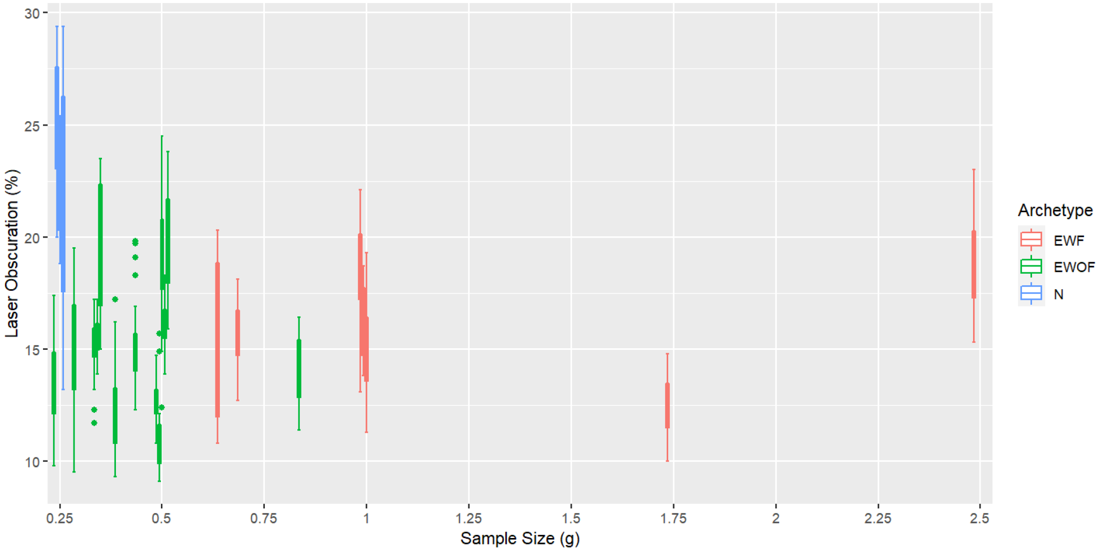

Figure 2.2: Plot of laser obscuration vs. sample size for each racetrack

2.4.2 Organic Matter

A summary of percent organic matter by mass for each racetrack using the eight standard sampling locations is contained in the appendix (Table A 2). The mean organic matter content was 5.47% by mass, with a standard deviation of 3.19%. The range of all measurements recorded was from 1.31% to 17.56%.

2.4.3 Mineralogy

The mineralogy of the surfaces is shown in Table 2.3. The less abundant minerals, including amphibole, hematite, kaolinite, chlorite, R0 ordered mixed-layer illite/smectite with 90% smectite layers, and R3 ordered mixed-layer illite/smectite with 15% smectite layers, were condensed into the column labeled “Other.” This information is included in the appendix (Table A 3).

Table 2.3: Percent by mass mineralogy information for each racing surface

Track	Quartz	K-Feldspar	Plagioclase	Calcite	Dolomite	Illite & Mica	Other
AQUI	85.8	2.6	6.3	0	1.3	3.2	0.8
AQUO	84.4	4.2	4.7	1	1.8	3.2	0.7
BELI	80.8	5.8	8.4	0	0	2.8	2.2
BELO	82.7	3.5	7.4	0	1.2	4.3	0.9
CD	68.2	2.4	6.9	6.7	11	2.2	2.6
DM	48.9	15.7	24.8	1.2	1	6	2.4
EP	69.3	3.9	6.8	0.3	0	11.3	8.4
FG	94.1	2.3	0.8	1.2	0	1.2	0.4
GG	91.5	2.9	2.4	0	0	2.7	0.5
GPI	82.1	0	0	17	0	0.7	0.2
KEE	64.9	6	9.9	5.3	10	2.7	1.2
LRL	95.1	0.8	0.5	0	0	1.9	1.7
OKTT	70.3	10.9	12.3	0	0.8	4.4	1.3
PIM	83.7	3.3	1.8	0.4	0	5.8	5.0
PMTC	82.7	0	0	15.3	0	1.5	0.5
PRX	94	1.4	0.6	0.3	0.7	2.1	0.9
RP	77.6	11.7	7.2	0	0	1.7	1.8
SA	45.6	17.1	27.2	0	0	6.5	3.6
SARI	71.1	10.5	12.5	0	0	3.2	2.7
SARO	72.2	8.4	12.6	0	0	4.2	2.6
WOI	44.8	15.1	32.5	0.4	0	2.9	4.3
WOO	37.5	8.3	23.1	18.4	4.7	3.1	4.9
WOT	44.3	9.9	22.1	3.4	4.9	7.1	8.3

2.4.4 Hypotheses

2.4.4.1 Hypothesis 1 – Number of Samples Per Racing Surface

By determining if the mean values obtained from eight samples were significantly different from the full 96 samples collected, the ability to use fewer samples is evaluated. Table 2.4 shows a summary of laser diffraction results from testing at KEE comparing the eight standard sampling locations to the full set of 96 samples. This data includes the averages and standard deviations for laser obscuration, weighted residual, and the D_{10}, D_{50}, and D_{90} values. Of the 96 samples analyzed, 91 were able to achieve a desirable obscuration with 1.00 g sample size. Three of the remaining specimens were reduced to 0.25 g and two were reduced to 0.50 g to achieve a suitable obscuration value.

Table 2.4: Summary of laser diffraction results for N=8 and N=96 at KEE

Sample Size	Obscuration, %		Weighted Residual		D_{10}, µm		D_{50}, µm		D_{90}, µm	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
N=8	15.2	1.94	0.20	0.02	10.4	1.06	100.8	16.71	534.7	48.83
N=96	16.5	2.54	0.22	0.07	10.2	1.98	93.2	27.4	506.4	80.58

Statistical analysis from the repeated measures ANOVA yielded p-values ranging from 0.25 to 0.97 for the 24 categories observed (Table 2.5 and Table 2.6). None of the p-values were less than 0.05 as a 95% confidence in significantly different mean values, which indicates that eight samples can accurately characterize the mean value for each parameter measured in this study. The results of the percentage of variation captured in eight samples are shown in the appendix (Table A 4). Those values range from 6.5% to 80.0% if non-zero values are ignored due to the very low amount of material observed in the 2000 µm, 2380 µm, and 2830 µm size classes.

2.4.4.2 Hypothesis 2 – Archetypes of turfgrass horse racing surfaces

The three different turf track designs used in North American horse racing were evaluated. For each racetrack design archetype (Table 2.2), a statistically significant difference in mean values for all parameters was found. Table 2.7 provides the D_{10}, D_{50}, and D_{90} values as well as percent sand, silt, clay, organic content, and the percentage of material greater than 2 mm. As the p-values in Table 2.7, Table 2.8, and Table 2.9 indicate, there is a significant difference between the mean values for all of the parameters among the three designs. The only parameter that did not have a clear separation among the three archetypes was the percentage of material greater than 2 mm. The Tukey's HSD values in Table 2.7 for that parameter indicate that while there is a significant difference between the EWF and N archetypes, the EWOF archetype is technically indistinguishable from the other two.

Further breakdowns of the sand and silt sized particle results from laser diffraction analysis are shown in Table 2.8 and Table 2.9. Again, the p values indicate a significant difference between the mean values for each parameter. As the Tukey's HSD values in Table 2.8 and Table 2.9 indicate, though, there is some overlap among the archetypes depending on the exact size category in question. In the silt range, there is a clear distinction between the EWF archetype having significantly lower mean values than the EWOF archetype, which also has a lower mean value than the N archetype (EWF<EWOF<N) for the 2 μm, 4 μm, 10μm, 20 μm, and 32 μm size classes. For the 40 μm class, however, while the EWF archetype is again lower than the other two, EWOF and N are technically indistinguishable from each other (EWF<EWOF=N). There were detectable differences for each class of sand as well. The EWF archetype contains a higher amount of material, while the EWOF and N archetypes contain progressively less (N<EWOF<EWF) for the 250 μm, 420 μm, and 500 μm classes. The separation is not as clear between the EWOF and N archetypes in the 1000 μm and 1410 μm sizes (N=EWOF<EWF) because there is so little material in both archetypes. Across the 53 μm, 73 μm, 105 μm, and 149 μm size classes, the EWOF archetype has the most material, while the N archetype trends downward in comparison and the EWF archetype trends upward as you go up in particle size.

Table 2.5: P-values of D_{10}, D_{50}, and D_{90} values for hypothesis 1

Parameter	D_{10} (µm.)	D_{50} (µm.)	D_{90} (µm.)
p-value	0.97	0.94	0.89

Table 2.6: P-values of laser diffraction size classes for hypothesis 1

Parameter	Percent retained. All values in µm.																				
	0.01	2	4	10	20	32	40	53	74	105	149	250	420	500	1000	1410	2000	2380	2830	%OM	%>2mm
p-value	0.97	0.97	0.97	0.97	0.96	0.90	0.87	0.89	0.92	0.94	0.96	0.92	0.89	0.82	0.77	0.88	0.84	0.83	0.87	0.25	0.82

Table 2.7: Overview of comparisons between EWF, EWOF, and N archetypes

Archetype	D_{10}, µm	D_{50}, µm	D_{90}, µm	Sand[a,b]	Silt[a,b]	Clay[a,b]	%OM[c]	%>2mm[c]
EWF	13.0 (5.5) A	165.3 (92.0) A	578.2 (111.6) A	67.5 (12.7) A	32.1 (12.5) C	0.3 (0.2) C	3.2 (0.01) C	4.1 (0.05) A
EWOF	6.9 (2.5) B	70.5 (33.0) B	392.3 (59.7) B	52.5 (9.6) B	46.5 (9.5) B	1.0 (0.6) B	6.0 (0.03) B	3.0 (0.02) AB
N	4.1 (0.7) C	22.2 (6.9) C	171.0 (60.4) C	27.5 (7.8) C	70.4 (7.0) A	2.1 (0.8) A	8.2 (0.04) A	1.7 (0.02) B
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0352

Note: All data shown is mean value, (standard deviation), and an identifying letter from Tukey's HSD. Within a column, archetypes with the same identifying letter are not significantly different.

[a] These values are percent by volume

[b] Particle size ranges for each category correspond to USDA values of 53µm – 2mm for sand, 2µm – 53µm for silt, and <2µm for clay

[c] These values are percent by mass

Table 2.8: Comparison of archetypes for percent retained in each class size of sand sized particles

Archetype	Sand								
	53 µm	73 µm	105 µm	149µm	250 µm	420 µm	500 µm	1000 µm	1410 µm
EWF	5.1 (1.7) B	5.4 (1.9) B	5.8 (2.0) B	12.3 (3.5) A	18.1 (6.5) A	6.0 (2.2) A	13.6 (5.2) A	1.1 (1.3) A	0.2 (0.4) A
EWOF	6.1 (1.7) A	6.3 (1.8) A	6.8 (1.8) A	11.9 (3.7) A	12.6 (3.8) B	3.4 (1.0) B	5.3 (2.1) B	0.1 (0.3) B	0.0 (0.1) B
N	6.1 (1.3) A	5.4 (1.5) B	4.4 (1.4) C	5.2 (1.9) B	4.4 (1.5) C	1.0 (0.4) C	1.1 (0.9) C	0.0 (0.0) B	0.0 (0.0) B
p-value	0.0011	0.0014	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0001

Note: All data shown is mean value, (standard deviation), and an identifying letter from Tukey's HSD. Within a column, archetypes with the same identifying letter are not significantly different.

Table 2.9: Comparison of archetypes for percent retained in each class size of silt sized particles

Archetype	Silt					
	2 µm	4 µm	10 µm	20 µm	32µm	40 µm
EWF	2.2 (1.0) C	6.9 (3.2) C	8.5 (3.7) C	6.9 (2.7) C	3.4 (1.2) C	4.3 (1.4) B
EWOF	4.2 (1.4) B	11.7 (3.3) B	12.1 (3.1) B	9.0 (2.2) B	4.3 (1.0) B	5.3 (1.3) A
N	7.9 (1.9) A	20.2 (3.5) A	18.7 (2.0) A	12.3 (0.8) A	5.3 (0.5) A	5.9 (0.9) A
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Note: All data shown is mean value, (standard deviation), and an identifying letter from Tukey's HSD. Within a column, archetypes with the same identifying letter are not significantly different.

Four principal components from the PCA analysis, PC1, PC2, PC3, and PC4, explain 48.5%, 17.7%, 15.1%, and 7.5% of the overall variation between racing surfaces, respectively. Figure 2.3 is a biplot of the first two principal components of the PCA. Variables that have a significant contribution (greater than 0.2 or less than -0.2) to PC1 or PC2 are displayed as vectors in Figure 2.3. A full list of contributions from each parameter measured in this study to each PC is shown in Table A 5 in the appendix.

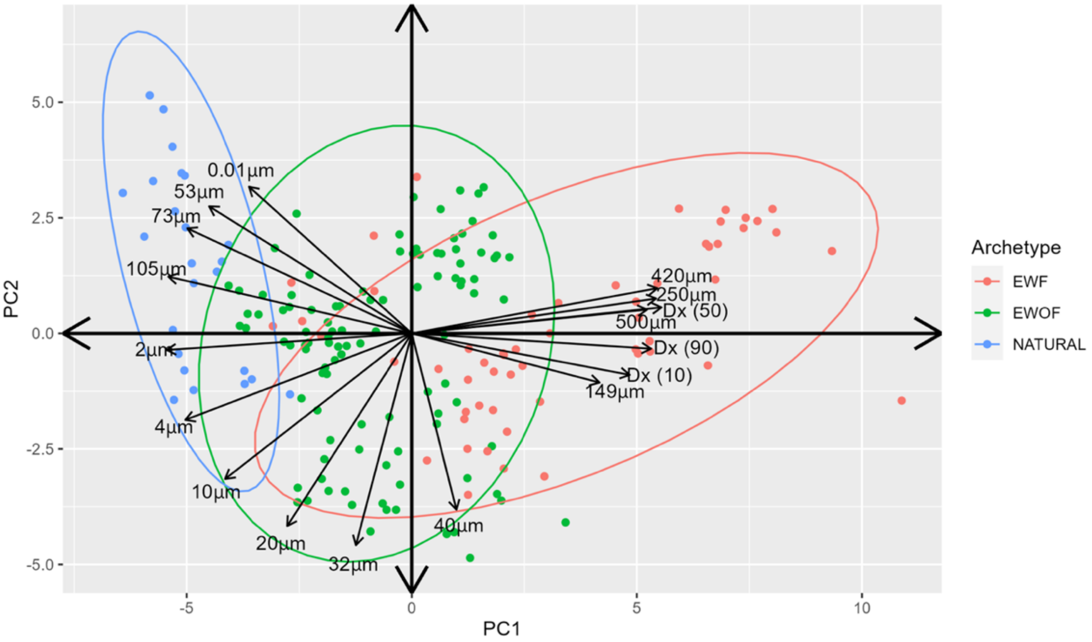

Figure 2.3: PCA of particle size distribution variables along the first two principal components

2.5 Discussion

The goal of this paper was to evaluate the use of laser diffraction to measure the particle size distribution of growing medium used in turfgrass surfaces for Thoroughbred racing. Underlying characteristics such as turfgrasses grown, climate factors, organic content, and mineralogy are documented to identify factors that may impact the results. To support the use of laser diffraction for the application of turfgrass horse racing surfaces, two hypotheses were suggested: that a racing surface could be characterized by using eight sampling locations and that there were three different surface design archetypes. Both of these hypotheses were accepted.

The number of samples required and the effect of various other factors, including mineralogy and organic, will all influence the results from the characterization of the racetrack. Comparison to sedimentation methods has been addressed by other investigators [76], as well as the effects of mineralogy [46] and organic content [67, 68]. However, because of limitations to the sample size that can safely be removed from an operational turf racetrack and the resulting risk to horse and rider, laser diffraction testing provides the baseline data to separate the three types of tracks. Laser diffraction will also allow the mean particle size to be characterized using a small number of samples in order to facilitate the selection of sand for top dressing and repairs.

2.5.1 Laser Diffraction

The first thing to consider for the suitability of this method is to determine if standard test conditions can be met. The weighted residual values shown in Table A 1 are consistent with manufacturer recommendations. This supports the use of a refractive index of 1.544 and an absorption index of 0.01. Table A 1 also displays obscuration values which comply with the manufacturer’s recommendations in most cases. A notable exception to that is the three tracks in the N archetype, that could not achieve below 20% obscuration even when a 0.25 g sample size was used.

Figure 2.2 shows the relationship between the amount of material required to meet the target obscuration value and the track design. For future testing of Thoroughbred turf racing surfaces, knowledge of the general type of material and track design may be sufficient to estimate the specimen size required for testing. A more accurate estimate or sample quantity to be used for laser diffraction analysis reduces the number of sample size trials required.

2.5.2 Organic Matter

Samples were tested using loss on ignition to determine their organic content, with the mean organic content of each racetrack ranging from 1.7% to 12.8% (Table A 2). The relatively wide range of organic content suggests that pretreatment may be justified based on the significantly different densities of organic matter and mineral soil particles. While laser diffraction without pretreatment can detect differences in surface composition, a standard method for the racing industry should explicitly define how samples should be pretreated. Several methods have been shown to properly remove organic matter in soil samples, should it be deemed warranted [80].

2.5.3 Mineralogy

Mineralogy results are relevant to the selection of the correct refractive index for the testing as well as being relevant to understanding the wear behavior of the material [81]. With quartz content ranging from 44.3% to 95.1%, the range of mineralogy in the sand is quite large. However, the refractive index of K-Feldspar and Plagioclase is sufficiently close to that of quartz that adjustments may not be required [82]. The higher quartz content sand will generally be more durable in use, although other factors such as shape may be relevant [83].

2.5.4 Hypothesis Testing

2.5.4.1 Hypothesis 1 – Number of Samples Per Racing Surface

Given the size of the specimens being tested from each location, the ability to characterize the entire racing surface is a particular concern. Specifically, is it possible to accurately represent a surface using eight locations? For this testing, the Keeneland racetrack was selected since it included a surface that was designed with a crown on the racetrack surface. The area outside of the crown is not used for racing and contains a higher percentage of native soil. The Keeneland racetrack thus represents one of the more challenging surfaces to characterize, despite its role as one of the premier racetracks for turf and dirt racing. The results show that while small differences in the track are evident, the track surface, in particular the racing surface, is well represented by using eight samples when comparing mean values for every parameter measured in this study. This is particularly important for the selection of appropriate topdressing material. By selecting topdressing material that matches the mean values for a racetrack, potential layering concerns and the resulting drainage issues can be mitigated. The selection of divot repair material as well as top dressing materials that match the mean value of the existing track will reduce variation in the racing surface.

Eight samples were shown to have less variation in every size category observed than the 96 samples collected at Keeneland. A great deal of this can be attributed to the fact that many of these samples were collected in areas of the track not used on race days that are known to remain native soil. Rarely is it feasible for 96 (or more) samples to be collected at regular time intervals for the purpose of making ongoing maintenance decisions. Providing the understanding that eight samples accurately characterize the mean values for a racetrack but not the total variation is a useful finding for this industry, as it helps guide the decision making process.

2.5.4.2 Hypothesis 2 – Archetypes of Turfgrass Horse Racing Surfaces

Using eight samples from standard locations at 23 racetracks, laser diffraction was able to detect differences in the designs of the racetracks. The detection of the differences in design and usage was possible, although a number of these racetracks had been in regular use for several decades with minimal alterations. The PCA is presented as a means for interpreting the sources of variation between racetracks. While the PCA results support the grouping of racetracks into the three archetypes, it also opens the door to retrospective epidemiological studies of Thoroughbred injuries. The four principal components, which represent more than 85% of the total variation, are linear combinations of all the values used in the analysis. To the extent that any of the composition terms may be relevant to the performance or safety of the surface, this suggests that all the values will need to be retained, at least in the initial analysis.

Laser diffraction testing of turf racetracks opens up a range of possibilities for horse racing. The result of this study is not only the development of baseline data for 23 major racetracks in North America but also a method that can now be used as a diagnostic tool for future efforts. Based on the understanding of the different particle size distributions as well as the range of distribution for each surface, the potential influence on infiltration rate would be large. The infiltration rate would in turn influence the amount of water available for the turf growth as well as the recovery of the turf from rainfall. The dynamic response of the surface could, with an open structure and fiber, potentially be consistent over a much wider range of conditions. Recovery from significant rain events would also be facilitated by a free draining surface. The dynamic response is measured by the Orono Biomechanical Surface Tester [15, 18]. Simpler devices have also been used for quality control for new construction as well as having the potential for daily monitoring of surfaces [84]. The protocol for determining the particle size distribution of an active turf racetrack, in combination with daily surface measurements, has the potential to contribute to efforts to enhance the safety of the horse and rider.

2.6 Conclusion

Laser diffraction has previously been shown to be a viable alternative to sedimentation methods for measuring the particle size distribution on turf racetracks. Unlike sedimentation methods, laser diffraction can be performed using small samples, which makes it possible to test turf Thoroughbred racetracks that are used for active racing. No other test method allows this type of testing to be done. This study showed that those samples, sometimes as small as 0.25 g and using eight standard locations, were able to successfully characterize the average particle size of the materials in the track for relatively homogenous surfaces. This method provides baseline data that can be used for the design of new racetracks and for the renovation and maintenance of existing turf racetracks.

The development of methods to ensure the consistency of all types of racing surfaces is potentially important for the safety of the horse and rider. By allowing small samples to be taken at areas of concern with minimal disturbance to the racing surface, variation in the surface, including differences in materials with depth, localized accumulation of fine material and even sand wear can be evaluated. The overall response of the track to rain can then be compared to areas where lower infiltration rates are observed.

Some of the testing parameters may also need to be considered further. Most importantly, there is a need for consensus on the handling of organic content. The data from the present study may help in areas of testing when larger ranges of organic or fine material are encountered. Reporting on the mineralogy and organic content of these samples is intended to provide additional information for future work looking at applications with a wider range of these values compared to the relative consistency of the surfaces used in Thoroughbred horse racing.

Future work with other natural turf surfaces presents opportunities to use laser diffraction in other applications for natural sports fields as well as for infill material used on synthetic playing surfaces. For material with a higher organic or clay content, attention will need to be paid to obscuration and weighted residuals measured during testing.

CHAPTER 3. A COMPARISON OF DEVICES FOR RACE DAY CHARACTERIZATION OF NORTH AMERICAN TURFGRASS HORSE RACING SURFACES

3.1 Simple Summary

The purpose of this study is to investigate the potential of using simple, portable tools to conduct surface condition measurements on race days at turfgrass Thoroughbred racetracks to approximate the biomechanical measurements made prior to the race meet. Test plot measurements were conducted with these tools as well as a more complex biomechanical device which replicates the speeds and loads of a Thoroughbred at a gallop. The turf plots were chosen to simulate a wide range of potential turf profiles that could be used in North American racetracks. The correlations were investigated and linear regression models were constructed to determine the level of approximation the simpler tools might achieve with the range of profiles considered. The volumetric moisture content was found to be the primary simple daily measurement which correlates to biomechanically based measurements. The penetration from the Longchamp Penetrometer and surface hardness from the Clegg Impact Hammer can further improve the approximation to equine biomechanics if desired. As this data are collected on a larger scale, it can then be paired with race times and injuries to investigate potential links between these measurements and horse performance and risk of injury.

3.2 Abstract

Both pre-race meet and daily turf surface condition measurements are required by regulations adopted as part of the Horseracing Integrity and Safety Act (HISA). The Orono Biomechanical Surface Tester (OBST) is the primary device used for characterizing a racing surface and is used for the pre-meet inspections. Tools that are better suited for the daily testing of turf surfaces are also needed to meet the new federal regulations. The purpose of this study was to compare five simple tools commonly used in turf applications to the OBST. Data were collected with each of the six devices at plots chosen to approximate the current and potential compositions of North American turf racetracks. Correlations and linear regression models were then established between the simple tool measurements and the parameters measured by the OBST. The moisture probe was found to be the primary device for race day characterization due to its strong correlation to OBST measurements. The Longchamp Penetrometer is also prioritized for daily measurements due to its established correlation to horse performance and injuries. The Clegg Impact Hammer provides further improvement of the linear regression model. The Turf Shear Tester and GoingStick® were not found to correlate well to the biomechanically based device.

3.3 Introduction

Thoroughbred racing has been a popular sport in North America since the American Revolution [1]. A more modern perspective on animal welfare and the safety of the riders has challenged the sport's social license to operate [3]. Of particular concern are catastrophic injuries, which The Jockey Club defines as the death or euthanasia of the horse within 72 h of a race [4]. While the overall animal welfare is a concern, catastrophic injuries are a particular threat to the sustainability of horseracing due to a direct connection to the racing event. Research has also shown jockeys are at a significantly higher risk of injury when they are on a horse which experiences a catastrophic injury during a race [13].

While catastrophic injuries can result from a number of different sources, the condition of the racing surface is generally accepted as a particular concern since it is one of very few factors that affects all horses in a race [14]. An adequate turfgrass horse racing surface should allow the hoof to penetrate the surface for the purpose of providing stability of the center of mass [85] and reducing secondary impact loads [63] as well as providing adequate traction for the athlete for both straight line movement and turning [86]. These conditions should be met while experiencing the high loads and loading rates applied by a Thoroughbred racehorse at a full gallop [87]. A surface which does not allow for hoof penetration may not provide adequate grip and may increase the risk of high ground reaction forces and the associated risk of musculoskeletal injury [88]. Damage to a surface from divoting will result in an uneven surface for the horses following in a race or in later races. This can introduce loading moments in the mediolateral and craniocaudal axes which may be similar to previously established risk factors for lameness or even musculoskeletal disease [89].

The condition of the turf racing surface has been shown to impact the likelihood of injury to the horse [70, 90] and jockey [73]. This evidence has resulted in regulations from the Horseracing Integrity and Safety Act (HISA) that has established requirements for surface condition measurements prior to the race meet and on race days [9]. Pre-race meet inspections for surfaces include the measurement of the mechanical properties with a surface tester based on the biomechanics of a Thoroughbred horse at a gallop [15]. While the biomechanically based measurements are required for pre-meet inspection [9], smaller and simpler devices are better suited for daily tests. The daily measurements prescribed by the HISA are moisture content as well as penetration and shear properties. This opens the possibility that standard turf testing tools can be used or tools that have been adopted in other countries to characterize turf racing surfaces. The test requirements help ensure the racing surface is as consistent as possible using pre-meet testing protocols as well as simpler tools to detect changes, such as moisture content, that occur over a shorter time period and impact risk [90]. These measurements are reasonably well-established for dirt surfaces, the most common Thoroughbred surface in North America. Turf, however, is the dominant surface in much of the world and has been gaining in popularity in North America [4]. Finding the most appropriate tools for measurements on turf differs by country [52, 54, 91] and only the United States has a biomechanically based system in general use [9].

The Orono Biomechanical Surface Tester (OBST) [15] is the primary method for evaluating an equine surface and is included as an international standard for the in situ testing of the functional properties of equine surfaces [18]. This device mimics the forelimb of a Thoroughbred at a gallop and is ideal for evaluating a racing surface prior to the race meet. The OBST's potential use in daily data collection is limited due to the size and complexity of the test apparatus, but the direction set forth in ASTM F3400-19 should be adopted for daily measurements to the greatest extent possible. The functional parameters of cushioning, impact firmness, grip, and responsiveness are of particular importance.

There are a number of smaller tools which are more cost-effective than the OBST and cause less disruption to the racing surface, which would be beneficial for use on turf surfaces being actively used for racing. This study considers five readily available portable devices: a moisture probe, the Clegg Impact Hammer (CIH), the Longchamp Penetrometer (LP), the Turf Shear Tester (TST), and the GoingStick®. These devices have been used in similar applications (equine sports outside of North America, human sports, and turfgrass research), some of which have even been adopted as ASTM standards [48, 49]. The five simple tools are compared to the OBST in an effort to establish connections to the functional parameters as defined in ASTM F3400-19. Pictures of each device can be found in Figure A 1 through Figure A 6 in the appendix.

The potential suitability of these tools must begin by investigating the correlations to the measurements taken at the speeds and loads of a Thoroughbred at a full gallop since these surfaces are non-linear and strain rate-dependent [92]. The measurements must also be applicable to the wide range of surface compositions used both currently and in future turfgrass racing surfaces [93], as prior research has shown the surface composition to affect characteristics such as surface hardness and divot resistance [55].

The intent of this study is to identify simple tools which are suitable for daily use and can provide quantitative data to describe the condition of Thoroughbred turfgrass racing surfaces on race days. Doing so would allow for racetracks to efficiently use their limited resources to obtain high-quality, repeatable, and objective data to assess the racing surface. The widespread use of standard methods for data collection on race days would complement pre-meet inspections [9] and also allow for future research to examine the potential correlations between measurements to both the performance and risk to the horse and rider.

3.4 Materials and Methods

3.4.1 Materials Tested

The test configurations included Kentucky Bluegrass and Bermudagrass species as well as several types of fiber reinforcements. Data were collected at Michigan State University's Hancock Turfgrass Research Center in East Lansing, MI. The 15 different soil preparations were arranged in a randomized complete block design with three replications per treatment. Each plot measures 3.1 m by 4.9 m and has its rootzone separated from adjacent plots by below-ground walls constructed of oriented strand board. The design of the plots was carried over from prior studies [55, 94], with only seasonal maintenance conducted. These plots were chosen as the subject of this study because they reflect some of the current as well as potential new compositions of North American turf tracks [93]. The treatments are described in Table 3.1, below.

Table 3.1: Description of plots studied

Name	Description
Well-graded sand	Sand profile with a broad distribution
Poorly graded sand	Sand profile with a narrow peak in the medium sand and fine sand size classes
7% silt and clay	Well-graded sand mixed with 7% silt and clay
9% silt and clay	Well-graded sand mixed with 9% silt and clay
15% silt and clay	Well-graded sand mixed with 15% silt and clay
9% silt and clay with Bermudagrass	Well-graded sand mixed with 9% silt and clay
Profile	75% well-graded sand mixed with 5% Canadian sphagnum peat and 20% Profile (ceramic particles made from illite clay and amorphous silica)
Zeopro	80% well-graded sand mixed with 10% Canadian sphagnum peat and 10% Zeopro (granules made from clinoptilolite and synthetic apatites)
Turfgrids	Well-graded sand mixed with randomly oriented fibrillated polypropylene fibers
Ventway	80% well-graded sand mixed with 20% Ventway (randomly oriented cylindrically shaped rubber particles)
StrathAyr	StrathAyr specified root zone mixed with polypropylene fibers
Grassmaster	Well-graded sand with polypropylene fibers sewn vertically into the established turf. Fibers inserted 2 cm on center to a depth of 20 cm
Hummer Turftiles	Reinforced sod with shredded nylon carpet fibers to a 5.1 cm depth established on top of well-graded sand
Motzgrass	Reinforced sod with polypropylene fibers sewn into a backing established over a Motz-specified rootzone
Sportgrass	Reinforced sod with polypropylene fibers sewn into a synthetic backing established on top of well-graded sand

3.4.2 Surface Condition Measurement Tools Used

The OBST replicates the motion from the point when the leading forelimb contacts the surface and the weight of the horse is transferred to the hoof. This is the point where the highest vertical and shear loads are applied. A total of four different parameters are calculated from the OBST [18, 95]. The four parameters include cushioning (peak vertical load [kN]), impact firmness (peak vertical deceleration [g]), grip (fore/aft slide distance of the hoof [mm]), and responsiveness (time between peak spring compression velocity and maximum spring compression divided by the time between maximum spring compression and peak spring recoil velocity [%]). To collect data with the OBST, a 29.9 kg sled equipped with a hoof shaped projectile and a size 2 aluminum racing plate was dropped from a 1.43 m height at an angle of 8° from vertical. Data were collected by a tri-axial load cell, tri-axial accelerometer, a string potentiometer, and a linear potentiometer at a sampling rate of 10 kHz.

A FieldScout TDR 350 (Spectrum Technologies, Inc., Aurora, IL, USA) equipped with two 7.5 cm rods was used to measure volumetric moisture content (VMC [%]). These measurements are also included in ASTM F3400-19 due to VMC having long been shown to have an effect on the animal's response to the condition of the racing surface [17]. Furthermore, VMC measurements can be conducted rapidly and repeatedly with very minimal effort using many different devices found on the open market. This is a distinct advantage for racetrack personnel who would be collecting data.

Surface hardness was measured with a Clegg Impact Hammer (CIH) (Lafayette Instrument Company, Lafayette, IN, USA). This device consists of a 2.25 kg mass with an integrated accelerometer which is dropped through a vertical guide tube from a height of 0.45 m onto the surface. Each time the mass is dropped onto the surface, the device provides a maximum acceleration value in CIT's, which is then multiplied by 10 to obtain units of grams. While the CIH has not been widely adopted for the evaluation of equine surfaces, it has been used in turfgrass research and has a number of associated international standards for athletic field applications and construction [48, 49].

A Longchamp Penetrometer (LP) was also used in this study to measure penetration. This device consists of a 1 kg mass which falls from 1 m onto a rod with a 1 cm^2 surface area that penetrates the surface. Measurements for this study were conducted manually using the scale on the device and recorded in cm. Though there is no international standard for this device, it is commonly used in horse racing as it was developed for France Galop's Longchamp Racecourse and it is used on a daily basis in a number of racing jurisdictions. What makes the Longchamp penetrometer unique among the other tools in this study is published research which correlates these measurements to both race times [50, 51] and injuries [52] on turf racing surfaces. Unlike the track condition ratings used in most other racing jurisdictions, the penetrometer has been used to directly produce track ratings. Track conditions were "firm" for a penetrometer reading of 1.0–2.0, "good" for a penetrometer reading of 3.0–4.0, "soft" for a penetrometer reading of 5.0–7.0 and "heavy" for a penetrometer reading of 8–10 [52].

The Turf Shear Tester (TST) (Dr Baden Clegg Pty Ltd., Jolimont, Australia) was used to measure divot resistance. This device was fitted with a 50 mm wide shearing plate fixed at a depth of 40 mm. The device provides values of kgf on the display which were manually recorded and then multiplied by 9.8 to convert to N and then by a moment arm distance of 0.207 m to obtain units of N-m. While the TST has not yet been used in equine applications, it has been used in turfgrass research for evaluating the shear strength of those surfaces [53, 55].

The GoingStick® (Turftrax, Ltd., Cambridgeshire, UK) is a device that was developed through a collaboration between Turftrax, Ltd. and Cranfield University [54]. This device is used in the horse racing industry to quantify the "going" of turf racing surfaces in some jurisdictions although it is not associated with an industry standard. To collect data with the GoingStick®, the probe of the device is inserted into the ground vertically in a controlled manner (which produces a value for penetration) and the handle was then pulled back to produce a 45-degree angle with the surface (which produces a value for shear). The penetration and shear values are reported on the GoingStick's unitless scale from 1–15, with 1 representing softer ground and 15 representing firmer ground [54]. These values can then be converted to SI units of N for penetration and N-m for shear [84]. The two values are combined into a composite "Going Index," which is the value commonly used in the industry to characterize the racing surface. The Going Index was also calculated using a standard formula [54].

3.4.3 Testing Methods

The turfgrass plots did not receive any irrigation apart from natural rainfall for two weeks prior to testing to achieve a low moisture content. Data from a weather station located at the Hancock Turfgrass Research Center are included in appendix (Table A 6). The experiment began by collecting data with the six different measurement tools. The plots were then irrigated for 1 h and data collection was repeated with the six tools. A total of 4 h of irrigation was then applied overnight. The data collection method was then repeated a third time, resulting in observations with each of the six tools at three different moisture levels.

One OBST drop was conducted at three random locations in each plot during each of the three data collection events. Data were then exported and post-processed in MATLAB to calculate the functional parameters of cushioning, impact firmness, responsiveness, and grip in accordance with the ASTM standard [18].

VMC was measured with the TDR 350 in accordance with ASTM D6780 [96]. Three measurements were taken per plot in random locations for each of the three data collection events. Three consecutive drops of the CIH were made without moving the guide tube and the deceleration value of each drop was recorded manually. This allows results to be reported in accordance with ASTM F1702-10 (which reports the first drop only) as well as based on ASTM F1936-07 (which reports the average of the second and third drops). These values are labeled CIH_1 and CIH_{23}, respectively, in this study. Though ASTM F1936-07 specifies the use of a 9.1 kg CIH, the 2.25 kg CIH is used in this study, which is consistent with ASTM F1702-10. Three measurement locations, with three drops each, were taken per plot in random locations in each of the three data collection events.

For each data collection event with the LP, a scale is read prior to and after releasing the 1 kg mass, with both values recorded manually. The reason for taking a penetrometer reading prior to dropping the mass is to account for potential surface irregularities such as minor elevation changes and the thatch layer of the turfgrass. Doing so allows for potential correlations to the OBST parameters to be investigated for the maximum penetration value as well as the difference between the maximum penetration and the penetrometer reading prior to dropping the mass. These values are labeled LP_{max} and LP_{delta}, respectively, in this study. This process was repeated at three locations in each plot for each data collection event.

Divot resistance was measured by the TST. The device was zeroed out on the display before inserting the device into the ground for each data collection. After pulling the handle to shear off a piece of turf, the value of kgf on the display was recorded. Three such measurements were taken per plot in random locations in each of the three data collection events.

The GoingStick® was used to obtain three measurements per plot in random locations in each of the three data collection events. This is distinct from the method used in most prior testing, where the only reported data are single values representing the average of three measures [97]. Penetration and shear from the GoingStick® are labeled GS_P and GS_S in this study. Going Index was then calculated and is labeled GS_I in this study. The GoingStick® was equipped with software version 2.29 with the “+33%” mode engaged. This software contains three modes: “jump” which was developed for jump racing, “flat” which was developed for flat racing in the UK, and “+33%” which was developed for flat racing in North America. The +33% mode is named as such because 33% firmer ground would be required to obtain the same reading as the flat mode in the GoingStick’s 1 to 15 scale.

To accurately determine gravimetric water content, one mixed sample was collected at each of the three data collection events from each plot with a 22 mm diameter sampling probe. The samples were mixed and then the composite sample was weighed on a balance and placed in a 60 ˚C oven for 16 h to remove moisture. Samples were weighed again upon removal from the oven. Gravimetric water content was calculated as the mass of water removed from the sample divided by the mass of dry soil.

3.4.4 Statistical Analysis

All statistical analysis was conducted using SAS system software, version 9.4 (SAS Institute, Inc., Cary, NC, USA). The proc corr function was used to generate Pearson’s correlation coefficients for each of the five simpler tools as compared to the four parameters measured by the OBST. The resulting correlation coefficients and associated *p*-values provide an indication of the strength and direction of a potential linear relationship between each set of measurements. The proc glm function was then used to generate linear models for each of the four measured OBST parameters. This was conducted for many different combinations of the five simpler tools as explained below. The simple tool variables listed in Table 3.3 through Table 3.7 below were included in each of the respective linear regression models. There were no covariates added to any of the models.

3.5 Results

There were 404 unique observations with each device described above. One OBST measurement was deemed erroneous and subsequently discarded along with the corresponding observations from the other tools. The mean and standard deviations for each parameter measured are presented in the appendix (Table A 7). The Pearson correlation coefficients (PCCs) between each of the simple tool measurements and the OBST parameters as well as the associated *p*-values are shown in Table 3.2 below.

Table 3.2: Pearson correlation coefficients (PCC) for comparing each simple tool to the four OBST parameters.

Simple Tool	Cushioning		Impact Firmness		Grip		Responsiveness	
	PCC	p	PCC	p	PCC	p	PCC	p
Volumetric Moisture Content	-0.63	<.0001	0.57	<.0001	0.21	<.0001	0.14	0.006
Clegg Hammer (Average of Drops 2 & 3)	0.62	<.0001	-0.51	<.0001	-0.14	0.005	-0.19	0.0002
Clegg Hammer (Drop 1)	0.53	<.0001	-0.44	<.0001	-0.12	0.012	-0.14	0.004
Longchamp Penetrometer Delta	-0.56	<.0001	0.45	<.0001	0.17	0.003	0.13	0.013
Longchamp Penetrometer Max	-0.53	<.0001	0.43	<.0001	0.15	0.0005	0.12	0.008
Turf Shear Tester	0.37	<.0001	-0.32	<.0001	-0.09	0.080	-0.22	<.0001
GoingStick Penetration	0.41	<.0001	-0.28	<.0001	0.03	0.496	-0.11	0.027
GoingStick Shear	-0.04	0.383	0.05	0.278	0.12	0.013	0.002	0.959
Going Stick Index	0.28	<.0001	0.18	0.0004	0.08	0.091	-0.08	0.120

A linear regression model was then generated for each OBST parameter that includes all the measurements from the simpler tools. The results are in Table 3.3 below.

Table 3.3: Linear regression model for each of the four OBST parameters considering all measurements from simpler tools.

Simple Tool	Cushioning (R^2=0.57)		Impact Firmness (R^2=0.40)		Grip (R^2=0.07)		Responsiveness (R^2=0.07)	
	Estimate	p	Estimate	p	Estimate	p	Estimate	p
Volumetric Moisture Content	-0.056	<.0001	0.517	<.0001	0.079	0.039	-0.0001	0.647
Clegg Hammer (Average of Drops 2 & 3)	0.039	0.004	-0.181	0.131	0.021	0.702	-0.0009	0.027
Clegg Hammer (Drop 1)	-0.015	0.386	0.024	0.874	-0.031	0.654	0.0009	0.081
Longchamp Penetrometer Delta	-0.717	0.045	2.413	0.444	1.980	0.172	0.002	0.865
Longchamp Penetrometer Max	0.227	0.473	-0.541	0.846	-1.213	0.344	-0.0007	0.941
Turf Shear Tester	0.009	<.0001	-0.067	0.001	-0.012	0.225	-0.0002	0.0006
GoingStick Penetration	0.004	<.0001	-0.016	0.011	0.003	0.260	-0.0001	0.441
GoingStick Shear	-0.024	0.013	0.115	0.181	0.062	0.113	0.0003	0.323
Going Stick Index	0.00	-	0.00	-	0.00	-	0.00	-
Intercept	11.24	<.0001	-77.51	<.0001	0.13	0.970	0.64	<.0001

To reduce the time demands on the maintenance personnel and enhance compliance, the objective is to identify the minimum data required to obtain an accurate representation of the surface conditions. The linear regression model was repeated to identify three simple tools which achieve the closest approximation of the OBST parameters (Table 3.4).

Table 3.4: Linear regression model for each of the four OBST parameters considering three simpler tools which provide the most attractive R^2 values.

Simple Tool	Cushioning (R^2=0.51)		Impact Firmness (R^2=0.39)		Grip (R^2=0.07)		Responsiveness (R^2=0.07)	
	Estimate	p	Estimate	p	Estimate	p	Estimate	p
Volumetric Moisture Content	-0.076	<.0001	0.594	<.0001	0.104	0.002	0.00007	0.794
Clegg Hammer (Average of Drops 2 & 3)	0.043	<.0001	-0.219	<.0001	-0.005	0.815	-0.0003	0.048
Turf Shear Tester	0.011	<.0001	-0.069	0.0006	-0.006	0.503	-0.0002	0.001
Intercept	11.00	<.0001	-75.49	<.0001	4.45	0.110	0.64	0.0005

3.6 Discussion

While the simpler tools in this study have previously been used in other turfgrass applications, many have not been evaluated for equine surfaces. Previous studies have shown that tools developed for human athletes are insensitive to the higher loads in deep layers and the greater strain rates produced by a Thoroughbred at a gallop [98]. Comparing the simpler tools to the OBST on the plots used in this study provides a close approximation of the measurements on North American turfgrass racing surfaces. In particular, the use of synthetic reinforcing fibers has becoming increasingly common in order to handle heavier traffic due to the increasing popularity of turf racing. The plots at the Hancock Turfgrass Research Center used in this study represent a range of compositions. Some of these profiles are representative of current profiles with others have potential utility for future Thoroughbred tracks. With the increasing number of races run on turf these reinforced profiles may help maintain consistency.

The OBST measurements of the cushioning and impact firmness produced stronger PCC values and higher R^2 values in the linear regression models than the grip and responsiveness. This finding was true for all the measurements from the simpler tools. Much of this can be attributed to the considerable noise in the grip and responsiveness measurements from the OBST. The noise is associated with the dynamic loading of the shoe and may be attributable to the complex physics of interface conditions. The frictional interfaces between a solid interface and granular materials exhibit stick–slip at the interface, which is sensitive both to small scale variation such as particle shape [99] as well as the dynamics of the interface such as the vibration of the load [100]. In an attempt to simplify the data analysis, bidirectional Butterworth filters were applied to the signals, as specified in ASTM F3400-19, which did not have a significant effect. The additional consideration of the dynamics of the interface would be beneficial but would need to consider both the dynamics of the machine and the properties and behavior of the surface. While the noise presents challenges associated with the data from the OBST, testing devices such as the TST or GS are less likely to represent the behavior of the racing surface because of the lower loading rate [63].

The VMC measurements displayed the strongest PCC values to cushioning, impact firmness, and grip, which indicates a strong linear correlation. The VMC also was the most significant contributor to the linear regression models for those variables as well. Racetrack maintenance personnel are also familiar with the VMC and many tracks already collect this data daily, as required by the HISA regulations. The importance of moisture measurements is evident. Relationships between the moisture content and hoof loads have previously been identified [17]. The strength of this correlation is such that moisture is the primary characteristic used for the characterization of Japanese racetrack conditions [91]. This observation is not limited to animal surface interactions but is also well-established in off-road vehicle mobility [37] where the loading and loading rates are similar to those in racetrack design.

The parameters measured by the OBST are biomechanically representative of the forelimb of a Thoroughbred at a gallop and so are also strongly influenced by the VMC. The cushioning of the surface is a shear failure in the top harrowed layer of the racetrack and is strongly dependent on the VMC [101]. Firmness is primarily determined by the layer under the harrowed surface, a partially saturated porous structure. The VMC determines if the pores are filled with air, water, or incompressible flow, which influences the response of the material, especially under dynamic loading [102]. Grip is also a shear-related phenomenon, not only in the granular material but also the frictional interface with the horse shoe. Frictional interfaces are sensitive to the effect of lubricants, with the well-established effect of water on the sliding between the grains of sand [103]. Thus, the VMC is the primary measurement to be taken on race days to characterize the surface and would be expected to impact the measurements made with the OBST.

The CIH value is calculated two different ways. The average of the second and third drops produced stronger PCC values as well as more significant contributions to the linear regression model than using the first drop alone. For this reason, collecting data in a similar fashion to ASTM F1936-07 is preferred (CIH_{23}). Those data showed the second strongest PCC values for cushioning, impact firmness, and grip as well as the highest PCC value for responsiveness. The lightweight projectile and low drop height of the CIH results in a low impact velocity and low load. Since the strain rate sensitivity of partially saturated sand varies with the VMC, the ability to generalize results across a range of moisture content may be limited. The strain rate effects will differ in porous materials based on both the type of sand [104] and degree of saturation [105]. The averaging of the second and third drop does reduce the effect of the top layer of the material which, with the small mass of the projectile, can be heavily influenced by factors such as the grass cutting height and the presence of grass clippings, which would not be important to the performance of the surface when dynamically loaded by a 450 kg animal traveling at 15 m/s.

The LP data can also be calculated in two different ways. Reporting the difference between the maximum penetration value and the value prior to dropping the 1 kg mass (LP_{delta}) resulted in a stronger correlation to the OBST parameters than the LP_{max}. The LP uses a foot with a relatively large area to position the device which can result in a gap between the foot and the top of the soil. Unless the difference between the initial and final measurement is calculated, relatively unimportant factors like the grass cutting height would alter the initial measurement, which would be adjusted by using a differential measurement.

LP_{delta} and CIH_{23} displayed comparable correlations to the four OBST measurements, in particular, the cushioning and impact firmness. A key differentiator is that while the CIH has been used extensively in human sport applications, the LP has already been shown to be well-suited for race day measurements at turfgrass horse racing surfaces in New Zealand [50-52]. Furthermore, as these datasets were collected over a period of many years, they have shown the LP to be capable of assessing day-to-day variations in the racing surface, which is consistent with prior research [50-52]. Minimizing the spatial and temporal variation in a racing surface has already been shown to be key in the prevention of injury [14]. Thus, while the CIH and LP provide comparable results in the test boxes, the LP has already been accepted and has been shown to correlate to the performance and risk on active turfgrass horse racing surfaces. Unlike other measures of track conditions used in other jurisdictions, the New Zealand data are notable for being directly based on objective measurements [52], rather than using a subjective measure, which may include the interpretation of objective measures.

The TST had the highest PCC value for responsiveness among the five simple tools and was included in the three-device linear regression model, above, because of this relationship. However, as the R^2 value for the linear model of responsiveness is never greater than 0.07, greater emphasis is placed on linear regression models which show stronger relationships such as cushioning and impact firmness. The TST is also heavier and more destructive, which also limits its potential usefulness for this application.

The GS, like the LP, was developed for the purpose of evaluating turfgrass horse racing surfaces. However, the device was less effective at approximating the parameters measured by the OBST based on the correlation and linear regression models. Of the 404 measurements collected with the GS, 53 were recorded at the upper limit of the shear value. This was the case even though the testing was primarily on cool weather grasses and the GS was set to the +33% mode, which was developed for the evaluation of North American surfaces. The range undoubtedly influenced the results and may indicate that while the GS may be useful in unreinforced soil, it may not be well-suited for the assessment of North American turfgrass horse racing surfaces, particularly if fiber or other reinforcement is present. These reinforcements are used to increase the shear strength of the surface without inhibiting drainage and are commonly found in North American turf tracks [93].

The GS is also more difficult to use than the LP and CIH since it is difficult to control the rate of loading and turf is strain rate-dependent [92]. While the LP and CIH measure the surface with a consistent energy input (falling mass dropped from a fixed height), the GS relies on the user to insert the tool to the full depth of the blade and pull back on the tool in the same manner every time. Different users, as expected, can then obtain different results with the GS on the same surface because of seemingly imperceptible differences in their rate of loading. As a result, it is difficult to compare data between racetracks to arrive at informed decisions about potential safety and performance implications. However, even when a single trained user took all the GS measurements in this study, the tools with a fixed energy input produced a closer approximation of the OBST parameters.

In addition to the distinctions from the fixed energy loading condition, the length scale over which the measurement is made differs between the LP, the CIH, and the GS. A turf track which is not damaged significantly but provides sufficient traction would have hoof prints which penetrate the surface but do not result in a divot. The penetration into the surface for the ideal surface would be the width of the shoe rather than the area of the hoof. The width of a racing plate is on the order of one centimeter. The depth of penetration would also be of the same order length scale. In this type of surface, the shoe would penetrate the surface to the depth of the frog but would not separate the turf in the area of the hoof during propulsion. The depth of the penetration and the probe on the LP has length scales on the order of a centimeter using a single drop. In contrast, the CIH projectile has a diameter of 50 mm with penetration dependent on the number of drops. The GS has a blade with dimensions of 100 mm long x 21 mm wide and is always pushed into a depth where the top plate is in contact with the surface. While the flat plate on the top of the GS is the approximate size and shape of a horseshoe, it is flat and the measurements are primarily influenced by the blade. In general, with a granular material, which has the characteristic lengths of grains that are on the order of 5 μm to less than 1 mm, the difference between the CIH and LP primarily becomes a concern when fibers with longer lengths are included. The depth of the CIH is, however, measuring a very different parameter since it is a repeated drop, so the length of measurement is dependent on the change in compaction, not the resistance to penetration, like the GS or LP. The penetration depth of the blade of the GS is greater than the other devices so the resulting measurement occurs at a different length scale.

Significant constraints related to time and labor availability limit racetracks' ability to collect quality data on race days. The key aim of this paper is to ensure North American racetracks can collect sufficient data in a practical manner that can be used for evidence-based decision making. Surface condition measurements must be objective, repeatable, and efficient so as to be easily compared between surfaces [106]. As the data will be collected on active turf racing surfaces, minimizing the disruptions of the surface will also help to leave turf roots and thatch intact to support athletes during racing.

With moisture being identified as the primary simple measurement for the assessment of a racing surface, it would be useful to show comparisons to the OBST measurements. Moisture data can be collected quickly with virtually no disruption of the racing surface and produces a reasonable approximation of the cushioning and impact firmness. A linear regression model for the VMC is shown in Table 3.5 below.

Table 3.5: Linear regression model for each of the four OBST parameters considering VMC only.

Simple Tool	Cushioning (R^2=0.39)		Impact Firmness (R^2=0.33)		Grip (R^2=0.04)		Responsiveness (R^2=0.02)	
	Estimate	p	Estimate	p	Estimate	p	Estimate	p
Volumetric Moisture Content	-0.126	<.0001	0.859	<.0001	0.114	<.0001	0.0005	0.006
Intercept	17.61	<.0001	-112.13	<.0001	2.78	0.003	0.56	<.0001

The LP measurements have already been shown to predict horse performance and injuries over an extended period [50-52]. The LP also has a minimal impact on the surface and, as a point measurement, it is well-suited to assess the temporal variations in the racing surface. A linear regression model for the VMC and LP_{delta} is shown in Table 3.6.

Table 3.6: Linear regression model for each of the four OBST parameters considering VMC and LP_{delta}.

Simple Tool	Cushioning (R^2=0.45)		Impact Firmness (R^2=0.34)		Grip (R^2=0.05)		Responsiveness (R^2=0.02)	
	Estimate	p	Estimate	p	Estimate	p	Estimate	p
Volumetric Moisture Content	-0.091	<.0001	0.707	<.0001	0.088	0.009	0.0004	0.148
Longchamp Penetrometer Delta	0.832	<.0001	3.70	0.0009	0.626	0.200	0.005	0.208
Intercept	18.72	<.0001	-117.09	<.0001	1.95	0.085	0.55	<.0001

To further improve the quality of the data, the CIH would be the next device to add to daily surface monitoring. A linear regression model for the VMC, LP_{delta}, and CIH_{23} is shown in Table 3.7, below. The R^2 values for these linear models indicate that the variation in the cushioning and impact firmness can be reasonably accounted for with these simpler tools. The grip and responsiveness, however, are not easily characterized by the simple tools used in this study. The OBST remains the primary device for assessing an active racing surface, and especially, the grip and responsiveness.

Table 3.7: Linear regression model for each of the four OBST parameters considering VMC, LP_{delta}, and CH_{23}.

Simple Tool	Cushioning (R^2=0.51)		Impact Firmness (R^2=0.38)		Grip (R^2=0.05)		Responsiveness (R^2=0.04)	
	Estimate	p	Estimate	p	Estimate	p	Estimate	p
Volumetric Moisture Content	-0.063	<.0001	0.552	<.0001	0.088	0.018	0.00009	0.754
Longchamp Penetrometer Delta	-0.568	<.0001	2.242	0.046	0.624	0.221	0.002	0.600
Clegg Hammer (Average of Drops 2 & 3)	0.041	<.0001	-0.224	<.0001	-0.0003	0.989	-0.0004	0.015
Intercept	13.89	<.0001	-90.39	<.0001	1.98	0.490	0.60	<.0001

3.7 Conclusions

The volumetric moisture content is the one simple measurement which has the strongest correlation to the parameters measured by the OBST and is the priority for data collection on race days. The resulting model can be improved using either the Longchamp Penetrometer or the Clegg Impact Hammer. However, the Longchamp Penetrometer is preferred due to the previously established correlations to horse performance and injuries [50-52]. While further marginal refinements of the model are possible using CIH_{23} measurements, the use of additional tools increases the complexity and may be a practical barrier to adoption. The TST and GS do not appear to be well-suited to the representation of the OBST data.

While the OBST is currently used for the evaluation of equine surfaces on a seasonal basis, it appears that measurements from as few as two devices are a reasonable basis for daily decisions by racetracks and regulators on race days. These simple tools can be deployed on a large scale, based on the new federal regulations enabled by the HISA regulations [9]. Once the large-scale data collection has reached maturity, it can then be combined with additional data about the racetrack so as to continue additional information collection for large-scale epidemiological studies. Consistent objective data of a high quality has the potential to have a significant impact on our understanding of the racing surface's contribution to the risk of injury and how racetrack personnel can make informed decisions on race days.

CHAPTER 4. EFFECTS OF NATURAL AND SYNTHETIC FIBERS IN TURFGRASS HORSE RACING SURFACES AS CHARACTERIZED BY TRIAXIAL SHEAR TESTS

4.1 Abstract

Soils used in putting green applications are designed to move water quickly through the profile yet are still able to support turfgrass growth. North American turfgrass horse racing surfaces often use similar soils which are reinforced with synthetic fibers in order to achieve both high infiltration rates and high shear strength. Natural fibers, in particular jute and sisal, are a promising and more environmentally benign method of increasing shear strength of soils. No previous work has evaluated these fibers for equine applications. The purpose of this study was to submit unreinforced and reinforced golf course soil with synthetic and natural fibers to triaxial shear testing. Laser diffraction particle size analysis and bulk density testing were used to determine the moisture content at which peak bulk density occurs. Triaxial shear analysis was then conducted on the soil with the three different types of reinforcement at a moisture content above and below the peak bulk density value. Synthetic fiber reinforcement produced a 10% increase in friction angle and nearly a 50% reduction in cohesion. Both are beneficial improvements for the turfgrass Thoroughbred racing application. Natural fibers produced a comparable change in both properties which potentially makes them well suited for both divot mixes and newly established turf courses. Future research is needed to understand the life span of natural fibers in the soil profile as well as their impact on surface hardness.

4.2 Introduction

In North America, Thoroughbred racing has traditionally been conducted primarily on dirt surfaces. In recent years, however, a greater percentage of starts has been conducted on turf [4]. Turf surfaces present a unique challenge in that water must move vertically through the soil profile whereas dirt surfaces drain horizontally toward the inside rail [14]. The differences in drainage methods means that free draining turf surfaces can be used sooner after a rainstorm, which avoids the safety and economic impact of switching the races to the adjacent dirt or synthetic surface. However, inadequate shear strength of the turf track can result in divoting which produces an uneven surface that is a potential risk to the horse and rider. A free draining soil with the shear strength required to support a Thoroughbred at a gallop can be accomplished by using a bespoke high sand content soil composition with the addition of synthetic fibers [93]. Fibers have been shown to increase shear strength without inhibiting drainage [55].

Perhaps no other turf application in North America has received as much research focus as golf. Decades of research led to the USGA's Recommendation for a Method of Putting Green Construction which specifies a high sand content rootzone without fiber reinforcement [32]. While these soils were not originally designed to withstand the loads and loading rates of a Thoroughbred at a gallop they share the requirements of being able to drain water quickly through the profile yet still be able to support turfgrass growth. As a result there is an interest to learn from these soils and evaluate how they may or may not apply to Thoroughbred racing.

Soil reinforcement for athletic field applications is typically done through the addition of synthetic fibers. Polypropylene is a common material for synthetic fibers and has been studied extensively in turfgrass playing field research [55, 57, 60]. While these fibers have the advantage of being a consistent, manufactured product that performs well and remains in the soil matrix for an extended period, they do eventually add to landfill waste. Recent health and environmental concerns have also been raised which are associated with the generation of microplastics from playing fields [69]. Natural fibers such as jute and sisal provide an alternative method to increase the shear strength of soils [58, 59]. These types of reinforcement are promising but have not yet been evaluated against their synthetic counterparts such as those used in Thoroughbred racing surfaces.

Previous studies have shown that fiber reinforced profiles are common in North American turf racing [93]. Due to the recent passage of the Horseracing Integrity and Safety Act (HISA) additional consideration of these materials is important [107]. This study considers an unreinforced golf course soil as well as the same soil with synthetic and natural fiber reinforcement through the use of a standard test method used for the evaluation of the shear strength of equine sports surfaces and other granular materials [62].

4.3 Methods

4.3.1 Soil Composition

Soil was weighed on a balance and oven-dried for 16 hours at 60°C to remove moisture. The sample was weighed upon removal from the oven, gently crushed, and sieved to <2 mm. The mass of material greater than 2 mm retained in the sieve was recorded. The laser diffraction particle size analyzer cannot accept particles larger than 2 mm.

Samples were prepared for testing to determine the appropriate quantity of material to be used for laser diffraction analysis. Sample quantities were determined based on the manufacturer’s recommended obscuration value of 10% to 20%. Different quantities of dried soil were measured into a test tube with a mass tolerance of ±0.01 g. 2 mL of a 50 g/L sodium hexametaphosphate (SHMP) solution and 10 mL of distilled water were then added for each gram of dry soil. Samples were then placed on an end over end shaker for 16 hours. From testing the different samples, the largest specimen size that produced the required obscuration was then chosen as the nominal sample size for laser diffraction analysis. Three replicate samples of the appropriate size were then prepared using the same methods as the trial runs described in this section.

Laser diffraction testing was performed using a Mastersizer 3000 fitted with the Hydro LV attachment (Malvern Panalytical Ltd., Malvern, UK). Samples were sonicated in the laser diffraction instrument at 100% power (40 W) for 60 seconds [67, 68]. Non-spherical particle mode was selected for the particle type, and Mie theory was used for the analysis. The optical settings were 1.544 for the refractive index and 0.01 for the absorption index. The dispersant used was distilled water, and its refractive index was set to 1.33. Five measurements were recorded for each sample, and the average of those five measurements was reported. The process was then conducted for three replicated samples of the soil used in this study.

The data output includes statistical parameters of D_{10} (tenth percentile), D_{50} (median grain size), and D_{90} (ninetieth percentile), as well as percent by volume reported in several size classes. The lower boundaries of each of those groups are 0.01μm, 2μm, 4μm, 10μm, 20μm, 32μm, 40μm, 53μm, 74μm, 105μm, 149μm, 250μm, 420μm, 500μm, 1000μm, 1410μm, 2000μm, 2380μm, and 2830μm. This is consistent with prior testing of turfgrass racetrack materials [93].

To determine the amount of organic content in the soil, a sample was submitted to a loss on ignition procedure to determine organic content [47]. Approximately 100 g of dry soil was measured into a crucible and placed into a 440°C oven for 14.5 hours to burn off organic matter. Samples were weighed to determine the percent loss by mass of organic content. This method of determining soil composition is also consistent with prior research [93].

4.3.2 Laboratory Compaction of Non-reinforced soil

A laboratory compaction procedure was conducted similar to ASTM D698 [108] but with the use of a smaller 68.7 cm^3 mold, which has been shown to produce similar results for fine grained soils while using less material [109]. Field wet soil was placed in a 60^{o}C oven for 16 hours to remove moisture. Dry soil was then measured into a container and water added to reach a desired moisture content. For all tests in this study, moisture content is calculated on a dry basis, which is calculated as the mass of water in the sample divided by the mass of dry soil. The empty mold was then weighed on a balance. The collar was then secured to the mold which was then filled with soil. Samples were compacted with five blows of a 2.5 kg hammer dropped from a height of 0.3 m. The collar was then removed and the samples were trimmed flush with the top edge of the mold. The mold was then weighed again on a balance. Bulk density was calculated by dividing the mass of sample compacted in the mold by the volume of the mold.

The sample was then removed from the mold, placed into a container, weighed again, and placed in a 60^{o}C oven for 16 hours to remove moisture. The mass of the sample was recorded to obtain the actual moisture content observed in each test. This test was conducted at 14%, 16%, 17%, 18%, and 20% nominal moisture content. A plot of bulk density vs. moisture content was then constructed and a curve was fit to the data to allow determination of the moisture content which produces the peak bulk density for the given material. This procedure was conducted on non-reinforced soil.

4.3.3 Triaxial Shear Analysis

4.3.3.1 Nonreinforced Soil

Soil without fiber was dried in a 60°C oven for 16 hours to remove moisture. Water was added to reach the moisture content found above which was shown to produce the peak bulk density for the material. This batch of material was submitted to triaxial shear analysis in accordance with ASTM F3415-20 [62] as specified below.

A rubber membrane was secured to a cylindrical shaped aluminum mold with a 70 mm inner diameter. After being fixed to the testing apparatus, filter paper was placed in the bottom and soil was compacted in six 25 mm lifts, each with 25 blows from a hand tamper, to a total height of 150 mm. Another piece of filter paper was added to the top of the soil column and the top cap was secured. The aluminum shell mold was then removed and a plexiglass shell was secured to the testing apparatus. After the cap of the testing apparatus was secured to the plexiglass shell the cell was filled with water and pressurized with shop air to the desired confining pressure. A small container was placed near the drain valve for the sample which was left open as this is considered a Consolidated Drained (CD) test.

An Instron 4465 load cell was used to apply load to the soil column. The machine's strain rate was set to 0.853 mm/min and the test was initiated. Labview software was used to collect position data from the LVDT and load from the Instron. The load cell was allowed to run until the soil column had visibly failed.

Upon completion of the test, the confining pressure was reduced to zero. The test cell was broken down in reverse order of assembly and the soil was reclaimed from the rubber membrane. Water from the container placed at the drain valve was reintroduced into the soil. After mixing, the process was repeated for the next confining pressure. Triaxial shear analysis was performed at 5 psi, 10 psi, 15 psi, and 20 psi confining pressures for each soil type and moisture content mentioned in this study. All tests were conducted at ambient temperature. Data was then processed in Microsoft Excel. The maximum shear stress at each confining pressure was then calculated as well as the friction angle and cohesion values.

4.3.3.2 Soil Reinforced with Synthetic Fiber

Soil without fiber was dried in a 60°C oven for 16 hours to remove moisture. Polypropylene fibers 19 mm in length were then added to the soil at a rate of 4g of fiber per liter of soil in accordance with the manufacturer's recommendations (Stabilizer Solutions, Phoenix, AZ). The soil/fiber mixture was then tumbled in a Gilson MD-2000 Micro-Deval apparatus at 100 rpm for 5,000 revolutions to simulate mixing that would be conducted in the field at the time of construction. Water was added to reach the desired moisture content. This batch of material was submitted to triaxial shear analysis in accordance with ASTM F3415-20 [62] as specified above. Upon completion of the triaxial shear test for each of the four confining pressures, the sample was placed in a 60°C oven for 16 hours again to remove moisture and the process was repeated for a different moisture content. The moisture contents used for this analysis were 16%, 17%, and 18%.

4.3.3.3 Soil Reinforced with Natural Fiber

Soil without fiber was dried in a 60ºC oven for 16 hours to remove moisture. A mixture of jute and sisal fibers 25 to 38 mm in length was sourced from reclaimed coffee bags (Miller Waste Mills, Winona, MN). Fiber was added to the soil at a rate of 4g of fiber per liter of soil consistent with the rate of synthetic fiber addition. Water was then added to reach the desired moisture content. Samples were then mixed by hand as concerns over shredding the natural fiber prevented the use of mechanical mixing. This batch of material was submitted to triaxial shear analysis in accordance with ASTM F3415-20 [62] as specified above. Due to concerns over potential degradation of natural fibers, the material was not dried in the oven and reused. A fresh batch of soil, fiber, and water was prepared for each moisture content. The moisture contents used for this analysis were 16%, 17%, and 18%.

4.4 Results

4.4.1 Soil Composition

A 1.25 g sample size was used for the laser diffraction analysis to obtain an average of 14.6% obscuration for the three replicate measurements. The D_{10}, D_{50}, and D_{90} values were 12.7 μm, 362.7 μm, and 720.7 μm respectively. Organic content was determined to be 3.5% by mass. Full details are located in Table A 8 in the appendix.

4.4.2 Laboratory Compaction of Non-reinforced Soil

The bulk densities observed were 97.80 lb/ft^3 at 14.06% moisture content, 99.47 lb/ft^3 at 16.20% moisture content, 101.01 lb/ft^3 at 16.96% moisture content, 101.01 lb/ft^3 at 17.78% moisture content, and 98.08 lb/ft^3 at 18.61% moisture content. The moisture content of non-reinforced soil which produced the peak bulk density measurement was calculated as 17.4% as shown in Figure 4.1 below.

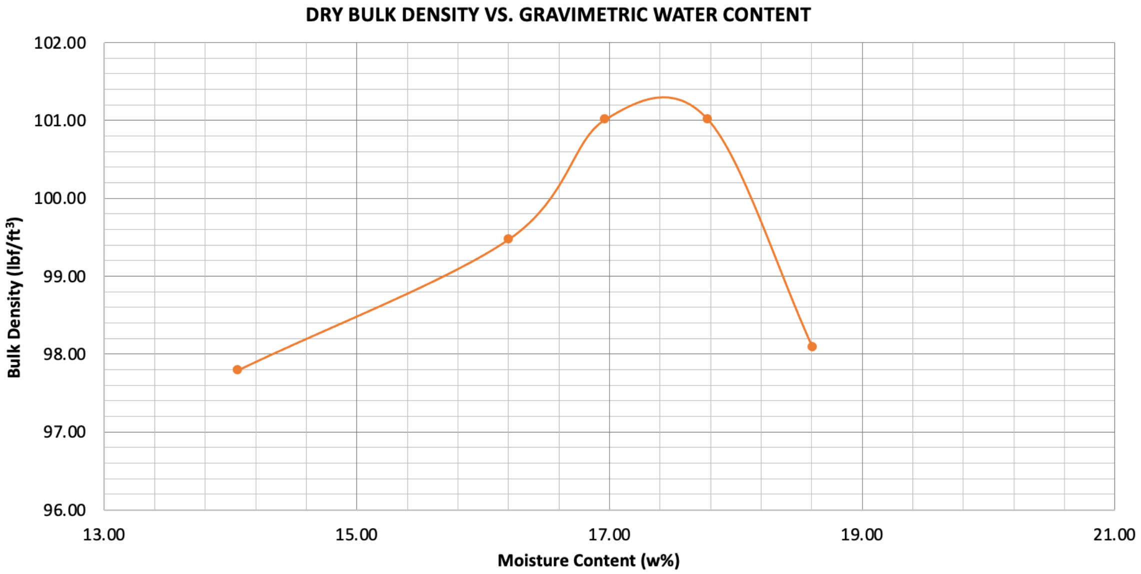

Figure 4.1: Plot of bulk density vs gravimetric water content

4.4.3 Triaxial Shear Analysis

A summary of results from triaxial shear analysis of all materials is shown in Table 4.1 below. Plots of confining pressure vs shear stress with curve fits can be found in Figure A 7 through Figure A 13 in the appendix. The fitted lines to these curves indicate quality data was obtained in triaxial shear tests as R^2 values ranged from 0.9983 to 1.

Table 4.1: Summary of triaxial shear analysis results

Soil Reinforcement	Nonreinforced	Synthetic Fiber	Synthetic Fiber	Synthetic Fiber	Natural Fiber	Natural Fiber	Natural Fiber
Moisture Content (% by mass)	17.4	16.0	17.0	18.0	16.0	17.0	18.0
Friction Angle (deg)	28.94	31.15	33.27	31.50	32.61	32.07	33.57
Cohesion (psi)	3.52	1.55	1.60	1.79	1.44	2.58	1.44
Max Shear Stress at 5 psi (psi)	12.89	11.56	13.73	12.91	12.86	14.48	15.64
Max Shear Stress at 10 psi (psi)	22.00	19.17	24.06	19.46	21.38	24.68	22.72
Max Shear Stress at 15 psi (psi)	26.99	26.83	34.24	29.44	31.50	32.73	32.47
Max Shear Stress at 20 psi (psi)	31.48	34.49	42.07	35.84	39.04	39.62	44.94

4.5 Discussion

4.5.1 Soil Composition

Laser diffraction results indicate the soil used for this study would have firmly been placed in the Engineered With Fiber (EWF) archetype of North American racetracks [93]. It is particularly useful to evaluate a soil of this archetype so that the increase in shear strength due to fiber reinforcement can be evaluated quantitatively and compared to typical Thoroughbred racing surfaces.

4.5.2 Laboratory Compaction of Non-reinforced Soil

The moisture content which produced the greatest bulk density of compacted nonreinforced soil is used for triaxial shear analysis as specified in the ASTM standard [62]. This produces the most efficient packing of material and allows it to obtain its highest possible shear strength. Triaxial shear analysis of the fiber reinforced soils was then conducted at 16%, 17%, and 18% moisture content to evaluate a range of similar moisture contents. The optimal moisture content is likely to shift marginally due to the addition of fiber reinforcement and the type of fiber [110]. Compaction of material is further complicated by the hydrophobic synthetic fibers which behave differently from the natural fibers. The triaxial shear testing demonstrates different behavior at the range of moisture contents tested.

4.5.3 Triaxial Shear Analysis

Triaxial shear on unreinforced soil establishes a baseline for comparison to the fiber reinforced soils. Racetracks with fiber reinforced soil should also be using a divot mix that matches the mean particle size distribution of their racing surface, but fiber reinforcement is not always added to the divot mix. The lower shear strength of unreinforced soil may raise concerns related to the use of unreinforced sand for this purpose.

Soil reinforced with synthetic fibers produced a 10% increase in friction angle as compared to nonreinforced soil. The friction angle and cohesion relate the shear strength and normal stress in the Mohr-Coulomb relation [63],

$$\tau = \sigma \, tan\phi + C$$

where τ is the shear strength of the soil, σ is the stress applied, ϕ is the friction angle of the soil, and C is the cohesion of the soil. An increase in the friction angle of the materials will increase the shear strength of the soil to support the hoof as it applies the forces required for propulsion to the ground [15]. A plot of friction angle vs. moisture content for all triaxial shear analyses is shown in Figure 4.2 below.

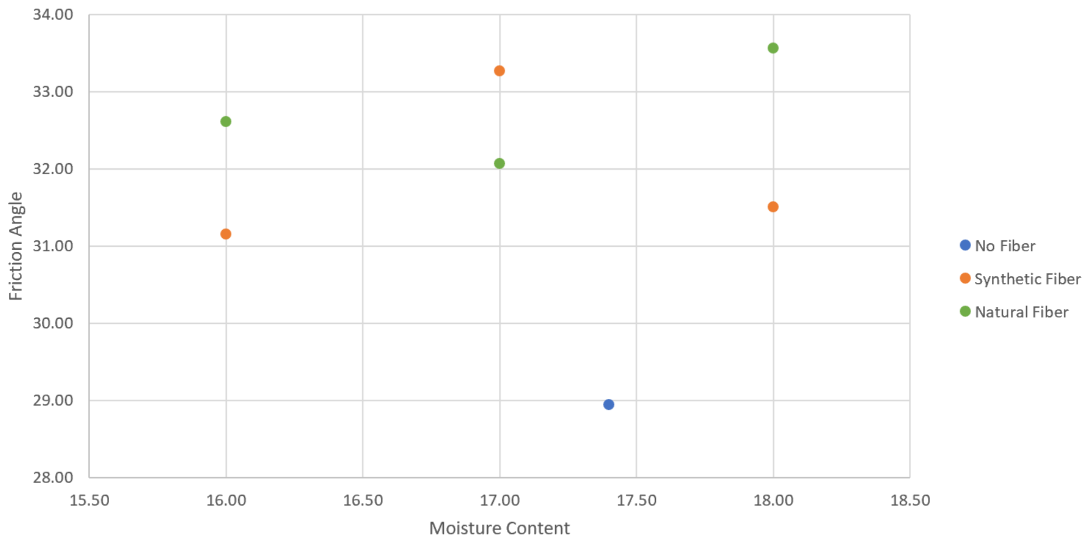

Figure 4.2: Plot of friction angle vs. moisture content for each of the seven triaxial shear analyses

While the friction angle was increased, soil reinforced with synthetic fibers had cohesion reduced by nearly half. The reduction in cohesion would be advantageous for the Thoroughbred racing application since smaller agglomerates of soil (informally referred to as "kickback") will be flung towards the horses and jockeys at the rear of a race should the surface fail in shear. A plot of cohesion vs. moisture content for all triaxial shear analyses is shown in Figure 4.3 below.

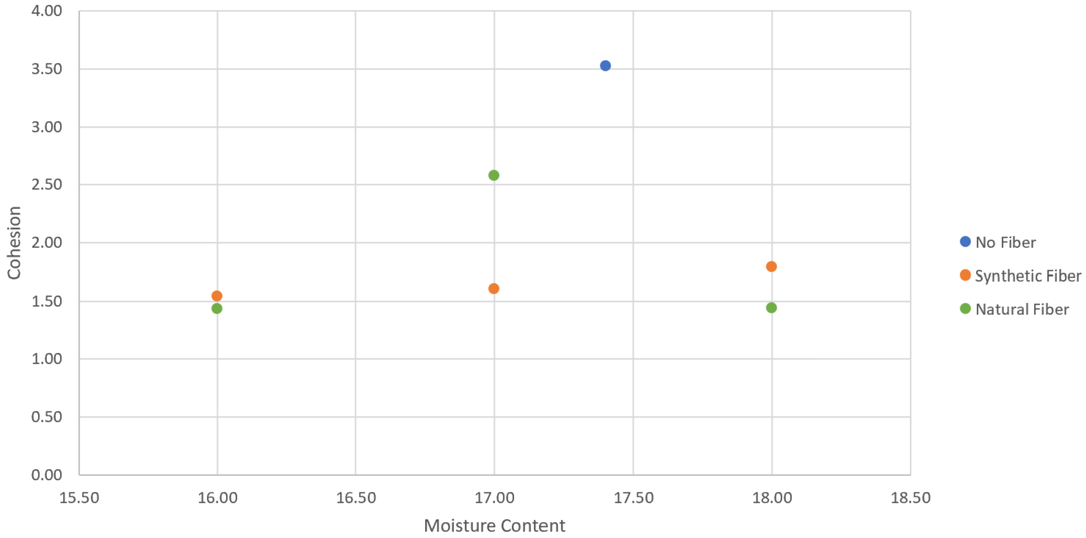

Figure 4.3: Plot of cohesion vs. moisture content for each of the seven triaxial shear analyses

Natural fibers were shown to produce comparable increases in frictional angle and decreases in cohesion to those seen with synthetic fiber as shown in Figure 4.2 and Figure 4.3. A unique relationship with moisture content appears to exist but the testing may also be influenced by the preparation of separate material for the tests at each moisture content. Differences in the sampling of the natural fibers is also possible since a mixture of jute and sisal is used. Jute and sisal are both used in coffee bags and the ratio of fibers is not controlled in the processing. However, the mechanical properties of the two fibers are sufficiently similar that they should perform in a reasonably similar manner [111]. Both jute and sisal have been shown to increase the shear strength of soil in similar tests [58, 59].

Natural fibers show promise in the turfgrass horse racing application. Natural fibers would be beneficial as a divot mix to repair the surface from racing traffic or for newly established materials. Since the natural fibers would biodegrade over time they could potentially avoid the issue with mature synthetic fiber surfaces increasing in surface hardness after traffic [60]. The lifespan of natural fibers in situ is currently unknown and would depend on climate, moisture content, and maintenance practices such as aeration. As the natural fibers degrade turfgrass will have presumably developed an active root system, which has already been shown to significantly increase the shear strength of turfgrass horse racing surfaces [24] as well as off-road vehicle applications which have similar loads and loading rates [38]. Further studies should also be conducted on the infiltration rates associated with jute and sisal fiber addition, though other organic materials have performed well in this regard [112].

4.6 Conclusions

The addition of synthetic fiber reinforcement increases the friction angle and reduces cohesion in turfgrass Thoroughbred racing application. Natural fiber reinforcement produces comparable effects on friction angle and cohesion to those observed with synthetic with an added benefit of environmentally conscious, biodegradable fibers. Natural fibers are particularly promising for use in divot mixes where the fibers would disappear as the turf root system develops. Further studies should be conducted on the degradation of natural fibers in the profile as well as their effects on surface hardness and infiltration rate.

4.7 Acknowledgements

Soil for this study was supplied by Lexington Country Club in Lexington, KY. Natural fibers were supplied by Miller Waste Mills of Winona, MN. Synthetic fibers were supplied by Stabilizer Solutions of Phoenix, AZ.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

5.1 Conclusions

This research focused on furthering our understanding of current and potential future soils used in North American turfgrass Thoroughbred racing. While there are many subtleties to consider, the two major requirements of these surfaces are that they be freely draining and that they be able to support the hoof of a Thoroughbred at a gallop. In addition, the profile must encourage the cultivation of a dense, healthy stand of turfgrass which can further reinforce footing.

Laser diffraction has demonstrated its ability to measure the particle size distribution of turf racetracks using small samples taken from racetracks during active racing. Samples as small as 0.25g when collected from eight standard locations have been shown to successfully characterize the average particle size distribution of a racing surface. This makes it possible to test turf Thoroughbred racetracks that are used for active racing with minimal surface disturbance. The baseline data from this testing has already been used to guide the design of new turf racetracks. The data will also provide information to support the renovation of existing surfaces and ensure the consistency of active turf racing surfaces. The improved consistency of the surfaces can potentially contribute to improved safety for horses and riders.

Laser diffraction is particularly useful for several different maintenance aspects of existing turf racetracks. The average particle size distribution of a racetrack facilitates proper selection of topdressing material and divot mix. Using divot mix and topdressing material which matches the mean values of the existing surface minimizes spatial variation and helps prevent layering which can inhibit drainage. Problem areas in existing racetracks such as layering and/or drainage issues, localized fine material accumulation, or sand wear can all be diagnosed using the baseline data when compared to samples as small as aeration cores.

Simple tools have also been evaluated against the OBST for the purpose of establishing correlations to biomechanically based measurements. Volumetric moisture content was shown to be the most important simple surface measurement for race days on a wide range of fiber reinforced and other amended turf surfaces. Results can be improved using either the Longchamp Penetrometer or the Clegg Impact Hammer. The Longchamp Penetrometer is preferred because of the established correlations to horse performance and injuries [50-52]. While further marginal refinements of the model are possible using CIH_{23} measurements from the Clegg Impact Hammer, the use of additional tools increases the complexity and may be a practical barrier to adoption. Collecting complete and reliable data from the fewest types of measurements will require fewer resources from the racetracks. The TST and GS do not appear to be well-suited to the representation of the OBST data.

While the OBST is currently used for the evaluation of equine surfaces on a seasonal basis for pre-meet inspections, the potential to use measurements from as few as two simple devices for daily data collection is very important. This allows racetracks to collect consistent objective data that satisfies the HISA regulations and which can be used for epidemiological models. The inclusion of surface data in epidemiological models has the potential to increase our understanding of the racing surface's contribution to the risk of injury as well as guide racetrack personnel and regulator decisions on race days for both traditional and fiber reinforced surfaces.

Fiber reinforcement is the most promising method of creating a racing surface with high shear strength that is also free draining. As synthetic fiber reinforced surfaces age their surface harness increases. This is typically mitigated by increased aeration which is not always feasible depending on the race meet schedule and agronomic needs of the turf. At the same time synthetic fibers have the potential to introduce microplastics into the environment, especially when aggressively aerated to mitigate hardening of the surface with age. One promising alternative is the use of natural fibers in turf surfaces since they will degrade over time. Natural fibers could reduce the need for aeration on older turf surfaces since they degrade with time and they will not introduce microplastic into the environment. Unreinforced soil was compared to synthetic and natural fiber reinforcement using triaxial shear testing consistent with ASTM F3415-20 [62]. The addition of synthetic polypropylene fiber reinforcement increases the friction angle and reduces cohesion; both of which are advantageous for the turfgrass Thoroughbred racing application. Natural fiber reinforcement in the form of jute and sisal produces comparable effects on friction angle and cohesion to those observed with synthetic. Natural fibers are also promising for use in divot mixes where the fibers would disappear as the turf root system develops.

The findings summarized above serve as an investigation of current and potential future soils used in North American turfgrass horse racing surfaces. The primary benefit of this research is that it allows for decisions regarding the construction of new turf tracks as well as the maintenance of existing turf tracks to be made based on quantitative data. The data from this work will be added to existing epidemiological models to understand how the construction and maintenance of turfgrass racing surfaces can impact horse performance and potential risk of injury as well as their ability to hold as many races as possible on the turf regardless of weather conditions.

5.2 Recommendations for Future Work

While this research furthers our understanding of current and potential future soils used for North American turfgrass horse racing, numerous opportunities for future research and development remain. Both the development of test methods and the design of turf racing surfaces present significant research challenges.

Laser diffraction is uniquely suited to the testing of Thoroughbred turf racing surfaces. However, there is a need for consensus on the pretreatment to remove organic content prior to laser diffraction analysis. The larger data set in the present study may help guide testing when larger ranges of organic or fine material are encountered. New methods of removing organic material may provide more consistent results and address inconsistencies in silt measurements. Reporting on the mineralogy and organic content of the samples tested for this research will provide a basis for future work looking at applications with a wider range of organic content when compared to the relative consistency of the surfaces used in Thoroughbred horse racing.

Future work with other natural turf surfaces presents opportunities to use laser diffraction in other applications for natural sports fields as well as for infill material used on synthetic playing surfaces. For material with a higher organic or clay content, attention will need to be paid to obscuration and weighted residuals measured during testing to ensure quality data is obtained.

It is expected that the simple tools identified in this work will be deployed on a large scale for the daily measurements required by HISA [9]. Once a larger data set is available it can be combined with additional data from each racetrack such as particle size distribution, winning race times, and injury events. Doing so would allow for large-scale epidemiological studies to provide potential insight into how surface condition may impact horse performance and potential risk of injury.

Finally, while jute and sisal fibers have produced favorable results in the shear properties of soils, further work is recommended to fully investigate their feasibility in turfgrass horse racing surfaces. In particular the degradation of natural fibers in the profile under different climatic conditions as well as their effects on surface hardness and infiltration rate should be investigated as these are key characteristics for the for these surfaces.

APPENDICES

[APPENDIX 1. LASER DIFFRACTION SUPPLEMENTARY TABLES]

Table A 1: Summary of laser diffraction analysis results for each racetrack

Track	Sample Size, g	Obscuration, %		Weighted Residual		D_{10}, µm		D_{50}, µm		D_{90}, µm	
		Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
AQUI	0.50	12.7	0.97	0.3	0.10	5.7	0.25	66.2	11.76	481.8	29.53
AQUO	0.50	11.2	1.84	0.3	0.10	6.5	0.55	100.2	25.53	470.0	31.65
BELI	0.30	14.7	2.65	0.3	0.04	5.5	0.18	34.9	7.74	363.9	60.37
BELO	0.25	13.4	1.97	0.3	0.04	5.2	0.39	29.8	4.46	343.5	57.44
CD	0.65	15.5	3.54	0.3	0.05	6.1	0.64	38.0	8.10	491.2	83.67
DM	1.00	18.5	2.53	0.2	0.04	11.4	1.40	110.7	14.48	542.7	70.69
EP	0.25	25.2	3.03	0.4	0.04	3.6	0.36	17.2	3.78	117.0	33.91
FG	2.50	18.8	2.09	0.2	0.07	21.3	3.77	256.9	31.28	568.8	32.61
GG	1.00	16.4	1.65	0.3	0.13	11.5	2.06	202.0	39.87	738.7	115.04
GPI	0.50	19.3	2.98	0.3	0.07	5.6	0.88	120.9	15.66	412.7	29.75
KEE	1.00	15.2	1.94	0.2	0.02	10.4	1.06	100.8	16.71	534.7	48.83
LRL	0.50	16.1	1.19	0.2	0.02	8.6	0.57	89.4	14.84	370.7	25.11
OKTT	0.35	15.1	1.32	0.2	0.05	5.8	0.52	48.8	6.47	353.4	36.02
PIM	0.25	22.1	1.96	0.5	0.07	3.8	0.34	19.3	2.57	171.2	32.47
PMTC	0.45	15.3	2.11	0.3	0.05	5.1	0.66	108.7	21.68	417.0	19.47
PRX	0.50	19.7	2.22	0.2	0.00	8.3	0.68	59.2	6.31	351.9	23.36
RP	0.85	14.0	1.50	0.2	0.05	13.4	1.31	108.5	9.18	439.2	44.23
SA	0.70	15.6	1.50	0.2	0.05	10.6	0.73	139.8	35.28	489.6	45.25
SARI	0.35	15.5	0.94	0.3	0.05	5.7	0.38	46.8	6.19	357.9	24.84
SARO	0.35	19.4	2.96	0.3	0.07	5.0	0.75	34.7	6.51	324.0	23.27
WOI	1.75	12.4	1.33	0.3	0.09	19.7	3.72	308.7	21.88	681.8	46.79
WOO	0.40	12.2	2.30	0.2	0.02	9.7	1.04	69.0	9.81	414.3	29.63
WOT	0.25	21.6	5.07	0.3	0.06	5.0	0.55	30.3	4.78	224.9	54.51

Table A 2: Mean and standard deviation of percent organic matter by mass for each racetrack

Track	Organic Matter, % by mass	
	Mean	Standard Deviation
AQUI	2.9	0.004
AQUO	2.3	0.004
BELI	7.6	0.027
BELO	7.7	0.008
CD	3.7	0.008
DM	3.4	0.006
EP	4.2	0.008
FG	1.7	0.003
GG	5.0	0.012
GPI	4.1	0.003
KEE	3.3	0.004
LRL	4.6	0.007
OKTT	6.8	0.015
PIM	7.5	0.012
PMTC	3.9	0.006
PRX	12.8	0.025
RP	4.7	0.010
SA	3.7	0.003
SARI	6.2	0.007
SARO	7.1	0.005
WOI	1.8	0.003
WOO	7.9	0.023
WOT	12.8	0.032

Table A 3: Supplementary percent by mass mineralogy information

Track	Amphibole	Hematite	R0 M-L I/S (90%S) [a]	R3 M-L I/S (15%S) [b]	Kaolinite	Chlorite
AQUI	0	0	0	0	0.3	0.5
AQUO	0	0	0	0	0.4	0.3
BELI	1.3	0	0	0	0.4	0.5
BELO	0	0	0	0	0.3	0.6
CD	1.8	0	0	0	0.3	0.5
DM	1.2	0	0.6	0	0.3	0.3
EP	0	0	0	4.5	2.9	1
FG	0	0	0	0	0.2	0.2
GG	0	0	0	0	0.2	0.3
GPI	0	0.2	0	0	0	0
KEE	0	0	0	0	0.5	0.7
LRL	0	0	0	0	1.2	0.5
OKTT	0	0	0	0	0.5	0.8
PIM	0	1.6	0	0	2.5	0.9
PMTC	0	0	0	0	0.5	0
PRX	0	0	0	0	0.6	0.3
RP	0	0	1.3	0	0.2	0.3
SA	1.7	0	1.2	0	0.3	0.4
SARI	1.2	0	0	0	0.5	1
SARO	1.4	0	0	0	0.4	0.8
WOI	3.2	0	0	0	0.4	0.7
WOO	3.4	0	0	0.7	0.4	0.4
WOT	4.3	0	0	2.9	0.4	0.7

[a] R0 M-L I/S (90%S) - R0 Ordered Mixed-Layer Illite/Smectite with 90% Smectite Layers

[b] R3 M-L I/S (15%S) - R3 Ordered Mixed-Layer Illite/Smectite with 15% Smectite Layers

Table A 4: Percentage of range shown in 96 samples that is covered by eight samples for KEE

Parameter	Percentage of Total Range Shown With Eight Samples
D_{10}	21.0
D_{50}	24.7
D_{90}	22.6
2830 µm	0.0
2380µm	0.0
2000 µm	0.0
1410 µm	20.0
1000 µm	80.0
500 µm	35.1
420 µm	23.7
250 µm	18.1
149 µm	31.4
105 µm	34.4
74 µm	35.7
53 µm	29.9
40 µm	30.3
32 µm	29.3
20 µm	21.7
10 µm	14.9
4 µm	10.1
2 µm	8.4
0.01 µm	6.5
%OM	19.9
%>2mm	58.5

Table A 5: Contributions of each variable to the four principal components. Values greater than 0.2 or less than -0.2 are shown in bold.

Variable	PC1	PC2	PC3	PC4
D_{10}	**0.2420**	-0.0899	-0.0531	0.1104
D_{50}	**0.2775**	0.0562	-0.0165	-0.0074
D_{90}	**0.2658**	-0.0332	0.0593	**0.2075**
2830µm	0.0927	-0.0183	**0.4157**	-0.1097
2380µm	0.1089	-0.0591	**0.4389**	-0.1094
2000µm	0.1172	-0.0728	**0.4425**	-0.1225
1410µm	0.1260	-0.0742	**0.4224**	-0.0844
1000µm	0.1685	-0.0568	**0.3184**	0.0956
500µm	**0.2613**	0.0513	0.0559	**0.2782**
420µm	**0.2726**	0.0977	-0.0768	0.1514
250µm	**0.2713**	0.0753	-0.1519	-0.0387
149µm	**0.2085**	-0.1065	**-0.2096**	-0.3443
105µm	0.0496	**-0.3814**	-0.1382	-0.3409
73µm	-0.0621	**-0.4582**	-0.0537	-0.1054
53µm	-0.1384	**-0.4169**	-0.0024	0.0740
40µm	**-0.2073**	**-0.3151**	0.0377	0.1633
32µm	**-0.2515**	-0.1873	0.0730	0.1964
20µm	**-0.2723**	-0.0360	0.1033	0.1846
10µm	**-0.2705**	0.1228	0.1145	0.0888
4µm	**-0.2493**	**0.2271**	0.1003	-0.0669
2µm	**-0.2251**	**0.2748**	0.0786	-0.1563
0.01µm	-0.1808	**0.3174**	0.0421	-0.2406
% OM	-0.1751	-0.1809	0.0769	-0.0816
% >2mm	-0.0207	-0.0129	-0.0042	**0.5793**

[APPENDIX 2. RACE DAY DATA COLLECTION SUPPLEMENTARY TABLES & FIGURES]

Figure A 1: Orono Biomechanical Surface Tester on a dirt racetrack

Figure A 2: TDR 350 moisture probe in use at turfgrass test plots

Figure A 3: Clegg Impact Hammer in use at turfgrass test plots

Figure A 4: Longchamp Penetrometer in use at turfgrass test plots


Figure A 5: Turf Shear Tester in use at turfgrass test plots

Figure A 6: GoingStick® in use at turfgrass test plots

Table A 6: Daily average weather data from Hancock Turfgrass Research Center (Data for this research was collected on June 16 and 17, 2021)

Date	Ambient Temperature (^{0}C)[a]		Soil Temperature (^{0}C)[b]		Total Precipitation (mm)	Estimated Potential Evapotranspiration (mm/day)[c]
	Max	Min	Max	Min		
6/2/2021	23.2	8.2	18.2	15.2	0.8	3.1
6/3/2021	27.2	15.1	21.7	16.4	0.0	5.2
6/4/2021	30.1	16.9	20.1	17.9	0.0	6.0
6/5/2021	30.4	19.8	20.7	17.3	0.0	7.0
6/6/2021	31.2	20.8	21.4	18.0	0.0	6.7
6/7/2021	27.0	20.1	20.9	18.9	1.0	2.6
6/8/2021	28.7	17.6	22.3	19.0	0.3	3.3
6/9/2021	31.2	18.3	23.2	19.6	0.0	4.6
6/10/2021	31.1	17.3	23.6	20.1	0.0	4.8
6/11/2021	32.7	16.2	24.8	19.9	2.5	4.8
6/12/2021	31.8	15.4	25.4	20.5	1.5	4.3
6/13/2021	28.4	17.9	24.2	21.1	0.0	5.8
6/14/2021	24.7	14.6	21.8	19.6	0.8	4.3
6/15/2021	24.1	14.4	21.8	18.3	0.0	5.3
6/16/2021	24.9	7.7	22.3	17.2	0.0	5.2
6/17/2021	28.7	8.8	23.1	17.2	0.0	5.7

[a]Air temperatures taken at a height of 1.5 m (5 ft).

[b]Soil temperatures taken at a depth of 50 mm (2 in.) under bare soil

[c]Potential evapotranspiration is calculated via the FAO Penman-Montieth equation[113]

Table A 7: Mean and standard deviation of parameters measured for all data collection events

Parameter [Units]	Mean	Standard Deviation
Cushioning [kN]	13.5	1.99
Impact Firmness [g]	-84.1	14.93
Grip [mm]	6.5	5.47
Responsiveness [Unitless]	0.58	0.042
Volumetric Moisture Content [%]	32.6	9.92
Clegg Hammer (Average of Drops 2 & 3) [g]	79.2	15.78
Clegg Hammer (Drop 1) [g]	58.2	11.11
Longchamp Penetrometer Delta [cm]	2.7	0.68
Longchamp Penetrometer Max [cm]	3.5	0.75
Turf Shear Tester [Nm]	154.9	31.03
GoingStick Penetration [N]	448.6	81.11
GoingStick Shear [Nm]	34.28	6.21
Going Stick Index [Unitless]	8.61	1.34

Table A 8: Laser diffraction analysis of non-reinforced soil

Parameter	Average Volume %
Laser Obscuration	14.6
Weighted Residual	0.3
D_{10}	12.7
D_{50}	362.7
D_{90}	720.7
2830 µm	0.0
2380µm	0.0
2000 µm	0.0
1410 µm	0.0
1000 µm	1.2
500 µm	28.4
420 µm	11.2
250 µm	27.2
149 µm	9.6
105 µm	1.3
74 µm	1.0
53 µm	1.4
40 µm	1.4
32 µm	1.2
20 µm	2.9
10 µm	4.7
4 µm	5.2
2 µm	2.3
0.01 µm	0.9
%OM[a]	3.5
%>2mm[a]	2.9

[a]These values are percent by mass

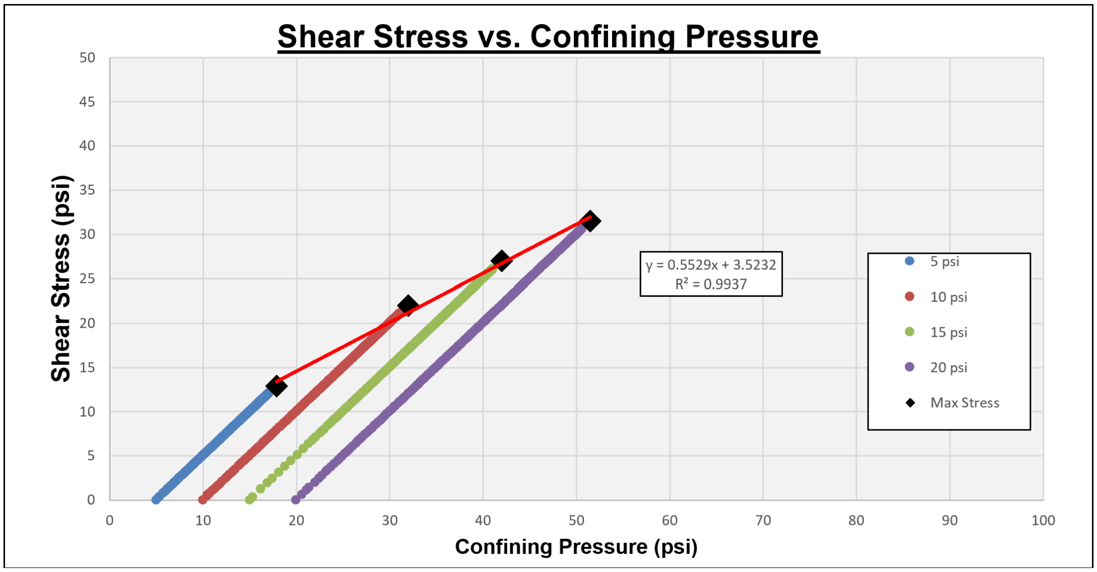

Figure A 7: Shear stress vs. confining pressure plot for nonreinforced soil at 17.4% moisture content

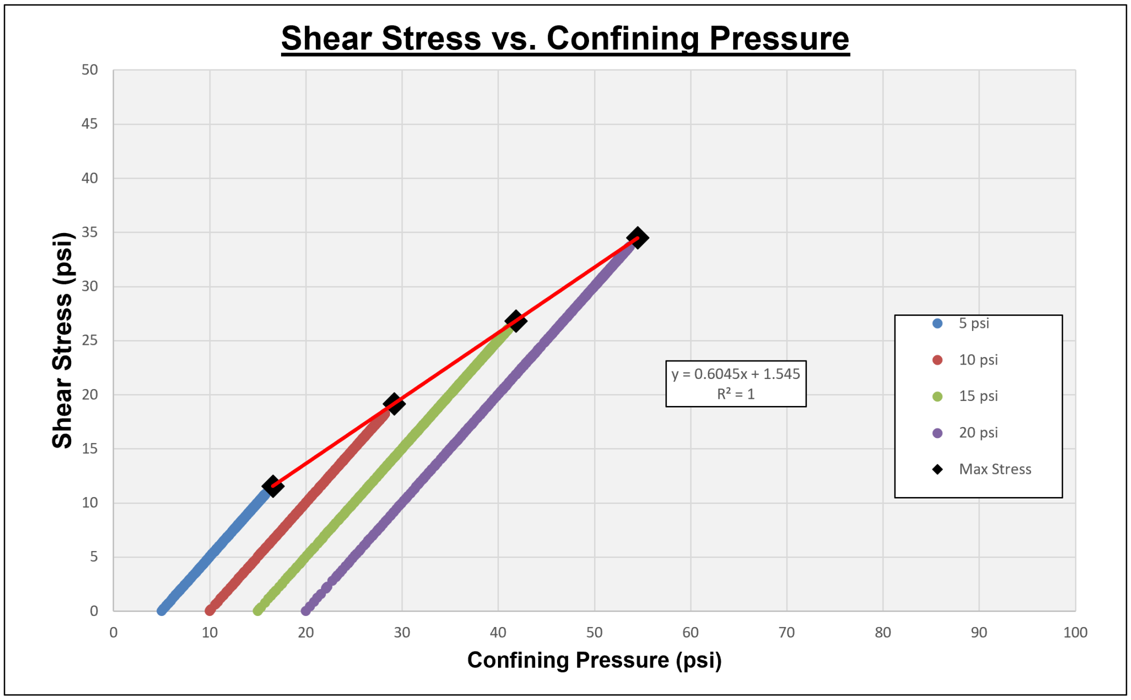

Figure A 8: Shear stress vs. confining pressure plot for soil with synthetic fiber at 16% moisture content

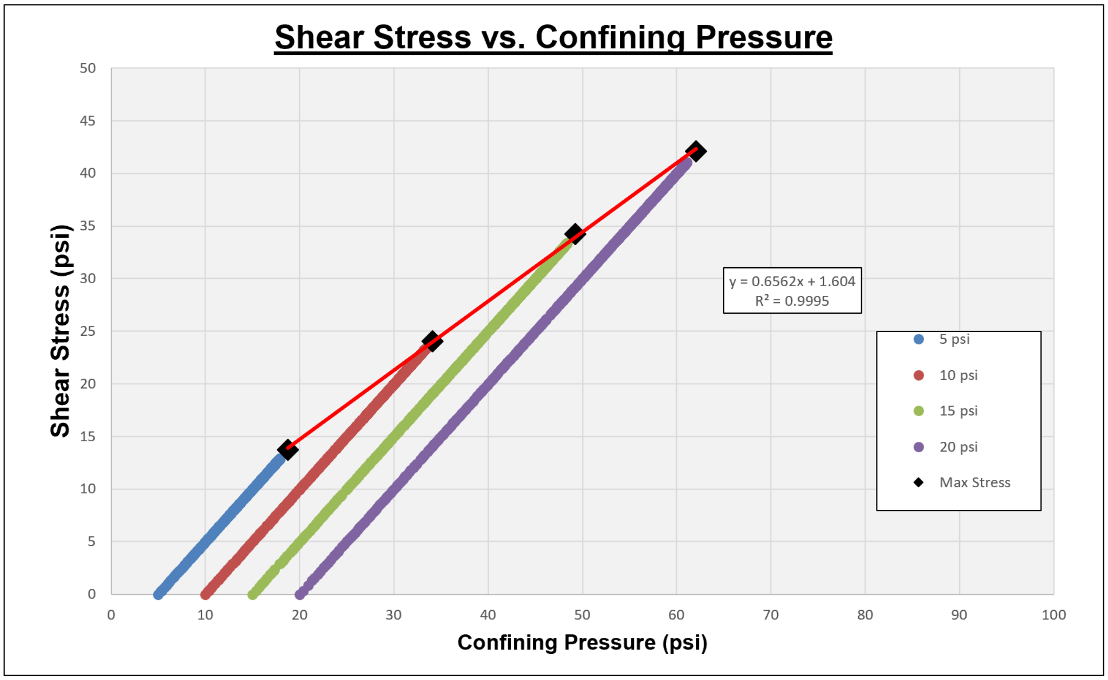

Figure A 9: Shear stress vs. confining pressure plot for soil with synthetic fiber at 17% moisture content

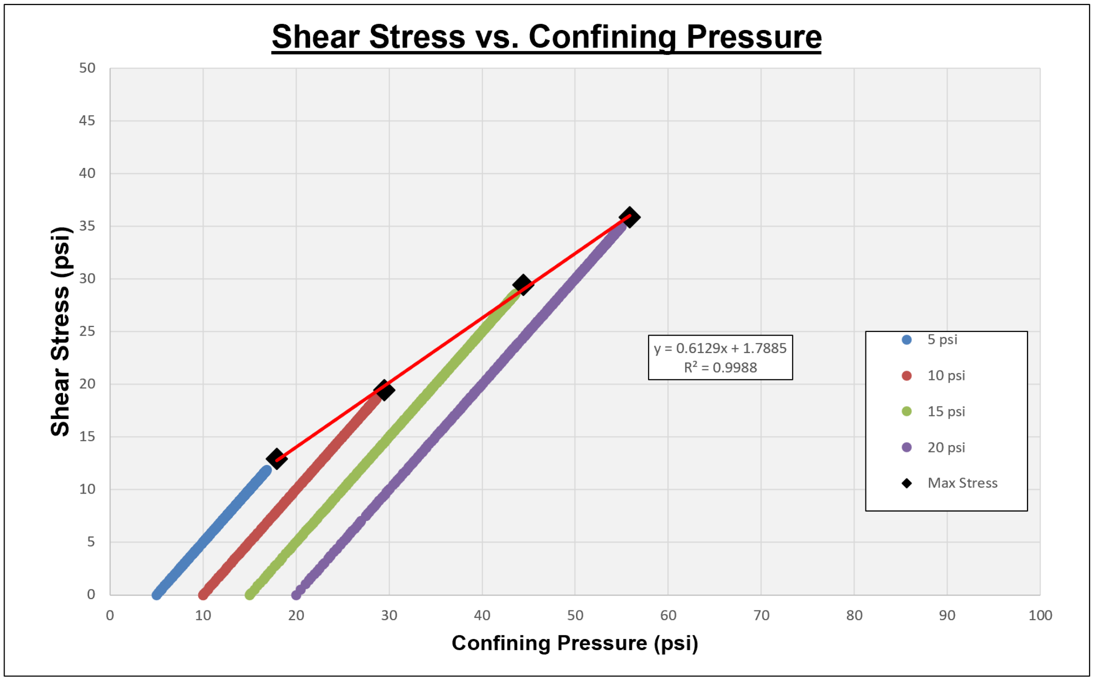

Figure A 10: Shear stress vs. confining pressure plot for soil with synthetic fiber at 18% moisture content

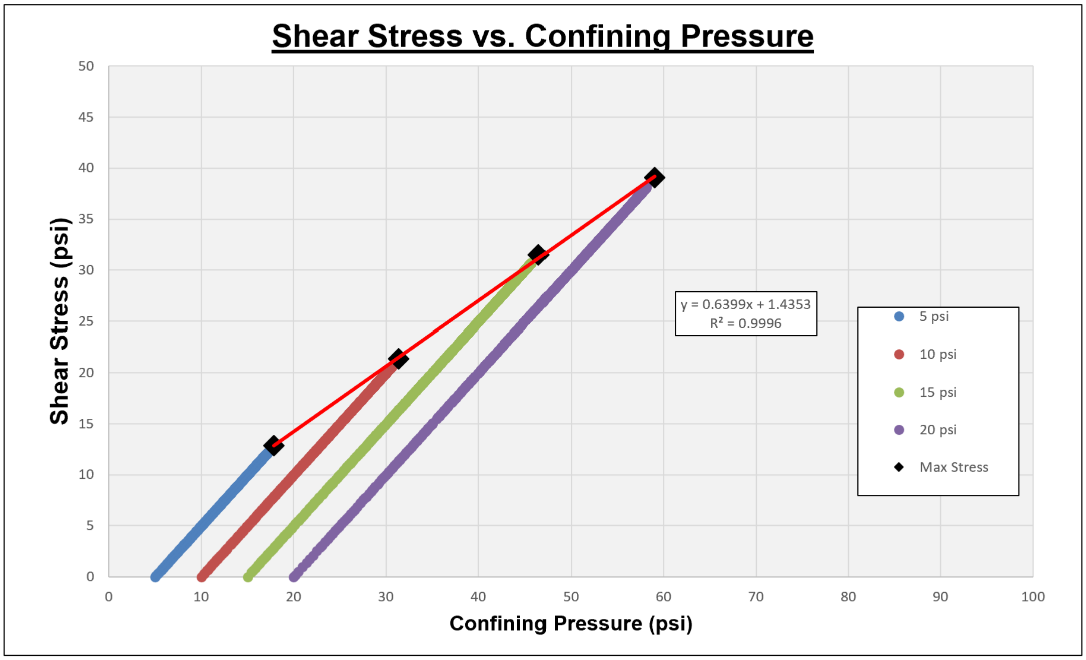

Figure A 11: Shear stress vs. confining pressure plot for soil with natural fiber at 16% moisture content

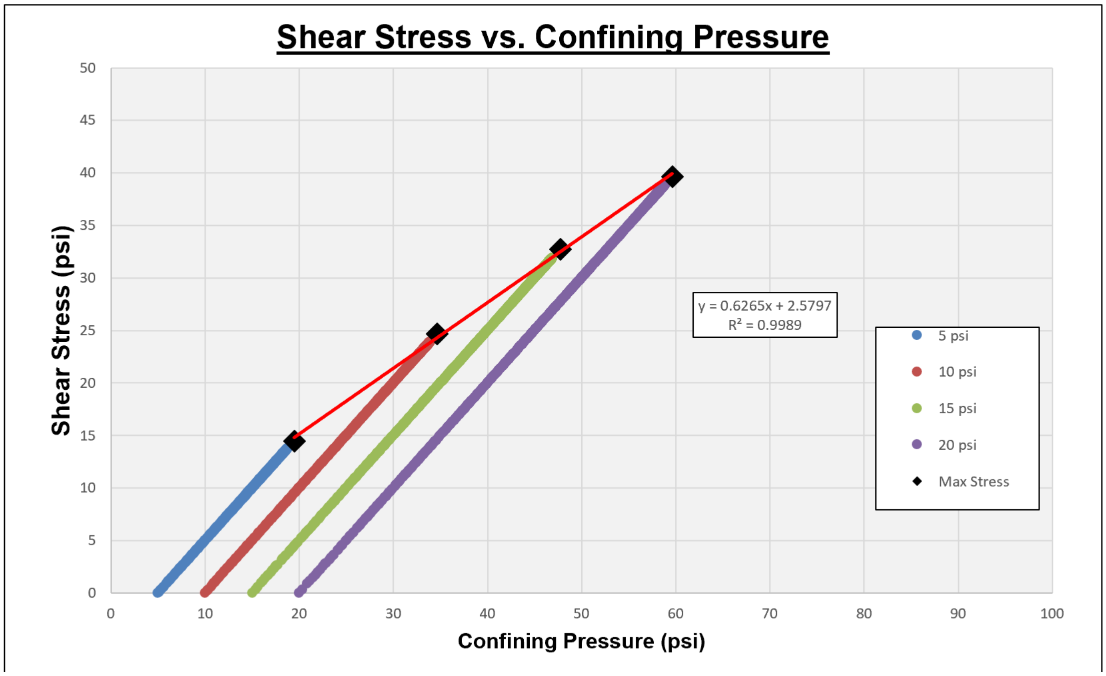

Figure A 12: Shear stress vs. confining pressure plot for soil with natural fiber at 17% moisture content

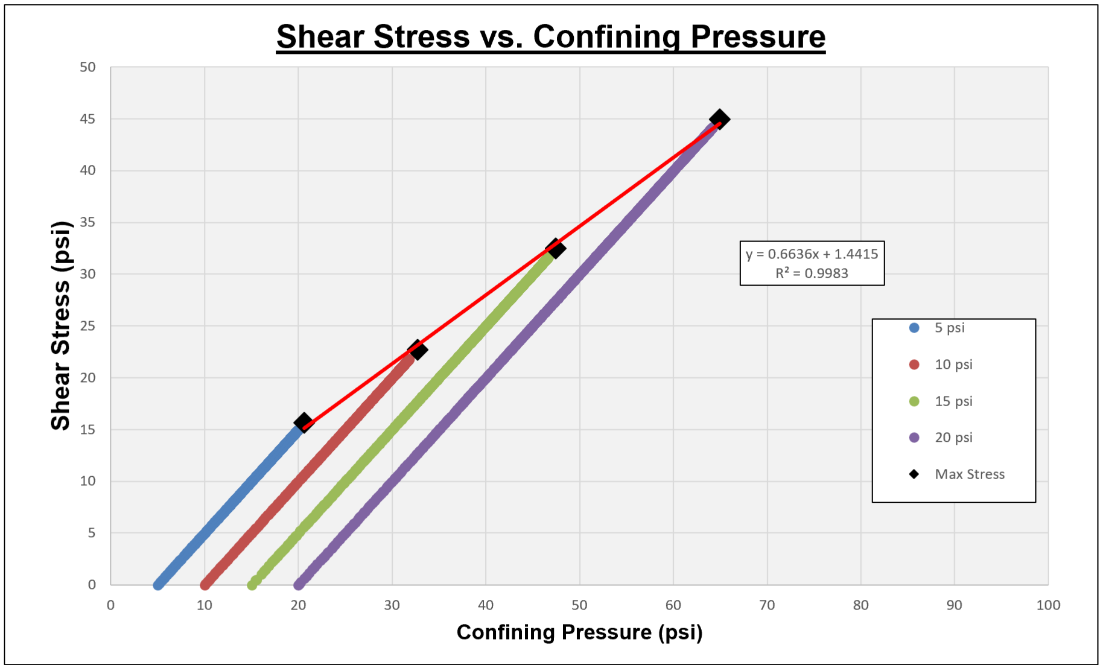

Figure A 13: Shear stress vs. confining pressure plot for soil with natural fiber at 18% moisture content

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2. Schmitt, P; Stanton, V; Peterson, M. Laser Diffraction Particle Size Distribution of North American Turfgrass Horse Racing Surfaces. *Journal of the ASABE* 2023, 66(3), 735-746. https://doi.org/10.13031/ja.15396
3. Blanco, MA; Hourquebie, R; Dempsey, K; Schmitt, P; Peterson, M. An Experimental Comparison of Simple Measurements Used for the Characterization of Sand Equestrian Surfaces. *Animals* 2021, 11, 2896. https://doi.org/10.3390/ani11102896

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Engineer Intern, State of Indiana, Apr. 2008

AWARDS

NIOSH Trainee, Agricultural Safety and Health training program, Central Appalachian Regional Education and Research Center, Jul. 2020 – Jun. 2022