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Synthetic Turf Surface Temperature Reduction and Performance Characteristics as Affected by Calcined Clay Modified Infill

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To the Graduate Council:

I am submitting herewith a thesis written by Eric Hall Reasor entitled "Synthetic Turf Surface Temperature Reduction and Performance Characteristics as Affected by Calcined Clay Modified Infill." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Plant Sciences.

John C. Sorochan, Major Professor

We have read this thesis and recommend its acceptance:

James T. Brosnan, Thomas J. Samples

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Synthetic Turf Surface Temperature Reduction and Performance Characteristics as Affected by Calcined Clay Modified Infill

A Thesis Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Eric Hall Reasor

May 2014

DEDICATION

I dedicate this thesis to my parents, George and Jennifer. All of your love, support, and life lessons have guided me to where I am today.

To my brother, Luke.

To my uncle, Willie Hall, and my granddad, John Hall. I owe my interest in agriculture to you.

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ABSTRACT

Synthetic turf research plots containing crumb rubber (CR) infill were established in Knoxville, TN in 2012 and 2013. Calcined clay (CC) was amended to CR in several ratios: a 50:50 (vol vol^{-1}) blend; a 50:50 blend with a polymer coating on CC (50 CR:50 CCC); a 15 mm layer of CC under 15 mm of CR (CR over CC); and a 15 mm layer of CC over 15 mm of CR (CC over CR). A 100% CR and a 70:30 blend of CR to sand (70 CR:30 S) were included for comparison. Surface temperature was measured in the summer of 2012 and 2013 at -10, 0, 30, 60, 90, 120, and 150 minutes following 2.8 cm of irrigation. Irrigation reduced surface temperature 60 to 85% regardless of treatment. By 30 minutes after irrigation, surface temperature increased to 74 to 102% of the temperature recorded 10 minutes prior to irrigation. Temperature on the 50 CR:50 CC and CC over CR treatments 150 minutes after irrigation were 10 to 24% and 20 to 21% lower than the hottest surfaces, which ranged from 95 to 137% of the pre-irrigation temperature. Simulated traffic was applied using the Cady Traffic Simulator for a total of 180 traffic events each year. Trends in surface hardness among treatments were inconsistent over years with values ranging from 70 to 160. CC modified infill treatments resulted in a faster increase of surface hardness with traffic compared to 100% CR and 70:30 S. Traffic affected particle size diameter of infill materials. Infill particles ranging in size from 3.35 to 1.0 mm decreased in diameter an average of 1.0 to 12.0%. Particles ranging from 1.0 to <0.002 mm increased in diameter an average of 0.3 to 3.8%. This increase in size was least pronounced for the 100% and 70 CR:30 S treatments and most pronounced for treatment CC over CR. Significant temperature differences were not consistent among treatments and surface hardness with CC tended to measure higher than 100% CR and 70 CR:30 S. The results of this experiment indicate the use of CC in synthetic turf may be limited.

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INTRODUCTION

Athletic fields are difficult to manage due to the high volume of foot traffic surfaces receive and the expectations of end-users (Carrow and Petrovic 1992; Christians 2011). A safe and uniform surface is required by players and coaches that must also be aesthetically pleasing to spectators (Christians 2011). The design and construction of athletic fields has changed throughout the past forty years. In the 1970s and early 1980s, a nylon synthetic turf was widely used for upper-level athletic fields due to its multiuse properties (Serensits et al. 2013). Many of these fields were replaced with natural turfgrass grown over sand-based root zone in the 1990s. In the late 1990s and 2000s, a new generation of synthetic turf surfaces emerged (Christians 2011; McNitt 2005). These new third-generation synthetic turf surfaces consist of upright, polypropylene or polyethylene pile fibers infilled with crumb rubber or a combination of crumb rubber and sand (McNitt 2005; McNitt et al. 2004; Menichini et al. 2011; Serensists et al. 2013).

Excessive surface temperatures associated with third-generation synthetic turf have been measured to be as high as 93°C (Williams and Pulley 2002). The heat transfer from the synthetic turf surface to the inner soles of athlete's shoes has been reported to raise physiological stress to a point where it could result in heat-related illnesses (Buskirk et al. 1971). Consequently, the New York City Department of Health and Mental Hygiene has recognized excessive surface temperature as the number one health concern associated with third-generation synthetic turf athletic fields (Denly et al. 2008). Irrigation has been reported to lower surface temperatures on synthetic turf for 20 to 30 minutes (McNitt et al. 2008; Williams and Pulley 2002). The addition of an inorganic amendment, such as calcined clay, to crumb rubber infill has the potential to increase the water holding capacity of the infill potentially prolonging the evaporative cooling effect of irrigation.

CHAPTER 1

LITERATURE REVIEW

OVERVIEW OF ATHLETIC FIELD DESIGN AND CONSTRUCTION

Athletic fields are difficult to manage due to the high volume of foot traffic playing surfaces receive and the expectations of end-users (Carrow and Petrovic 1992; Christians 2011). A safe and uniform surface is required by players and coaches that must also be aesthetically pleasing to spectators (Christians 2011). Puhalla et al. (2010) described two basic requirements for athletic field design: 1) fields must have the area and shape requirements necessary for a specific sport to be conducted based on rules and regulations, and 2) the surface must allow players to compete safely at a realistic level of competition. Athletic field safety is affected by three surface characteristics: traction, hardness, and evenness (Puhalla et al. 2010).

Traction is defined as a range which allows cleats to be released from the surface during forceful movements while also limiting excessive rotational resistance (Shorten et al. 2003). Traction is essential for player acceleration, the controlling of speed, and changing direction. Poor traction can lead to lower extremity injuries (Puhalla et al. 2010; Shorten et al. 2003). The hardness of an athletic field surface is similar to traction in that it both positively and negatively impacts player safety and performance.

An important characteristic of an athletic field is its ability to absorb shock (Serensits et al. 2013). The harder the surface, the less shock is absorbed. The shock absorbing ability is a strong indication of the safeness associated with an athletic field surface (Morehouse 1992). The less shock that is absorbed by the playing surface, the greater the potential for an injury to occur during impact (Morehouse 1992; Serensits et al. 2013). The third quality of evenness works in combination with surface hardness for ensuring consistent ball response in sports such as soccer, baseball, and field hockey (Puhalla et al. 2010; Serensits et al. 2013).

The design and construction of athletic fields has changed over the past forty years. Throughout the 1970s and early 1980s, a synthetic turf system was widely used for upper-level athletic fields. This traditional synthetic turf system consisted of nylon fibers knitted into a horizontal backing without infill materials (Morehouse 1992; Serensits et al. 2013; Stanitski et al. 1974). These synthetic turf surfaces could withstand high volumes of use which allowed them to be multiuse facilities (Serensits et al. 2013). The traditional synthetic turf systems were receiving criticism for their involvement to athlete injuries (Powell and Schootman 1993; Skovron et al. 1990), therefore in the late 1980s and into the 1990s, a large amount of these fields were replaced with natural turfgrass grown in a sand-based root zone (Christains 2011). In the late 1990s and 2000s, a new generation of synthetic turf surfaces emerged (Christians 2011; McNitt 2005). These new third-generation synthetic turf surfaces consist of upright, polypropylene or polyethylene pile fibers infilled with crumb rubber or a combination of crumb rubber and sand (McNitt 2005; McNitt et al. 2004; Menichini et al. 2011; Serensists et al. 2013).

HISTORY AND DEVELOPMENT OF SYNTHETIC TURF

The evolution of synthetic turf has attempted to create a product that more closely resembles the functional and aesthetic characteristics of natural turfgrass (Menichini et al. 2011; Puhalla et al. 2010; Ruffino et al. 2013; Serensits et al. 2013). The origins of synthetic turf are based on providing a safe playground surface for inner city children to improve their physical fitness. In the early 1960s, the Ford Foundation’s Education Facilities Laboratory and Chemstrand worked to develop a suitable playing surface which would withstand heavy traffic, be easily maintained, and would keep its functional characteristics year round. The first installation of this synthetic turf, known as Chemgrass, was installed in 1964 in the field-house of Moses Brown School of Providence, R.I. Chemgrass consisted of 12.7 mm long nylon fibers without infill materials (Morehouse 1992; Serensits et al. 2013; Stanitski et al. 1974). The first installation of Chemgrass in a major venue took place in 1966 in the Houston Astrodome, resulting in Chemgrass becoming known as AstroTurf (Levy et al. 1990; Morehouse 1992; Puhalla et al. 2010; Serensits et al. 2013). As the popularity of AstroTurf rose, two similar synthetic turf products were introduced in the late 1960s. Tartan Turf was manufactured by the 3M Company and Poly-Turf was a product of the American Biltrite Company (Levy et al. 1990; Morehouse 1992; Stanitski et al. 1974). At the same time, the Adolff Company in Germany developed Poligrass for use primarily for soccer and field hockey (Morehouse 1992). Chemgrass (AstroTurf), Tartan Turf, Poly-Turf, and Poligrass are all considered first-generation synthetic turf systems (Levy et al. 1990; Morehouse 1992; Serensits et al. 2013).

In 1976, second-generation, or sand-filled synthetic turf systems, were invented by Frederick T. Haas, Jr. (McNitt 2005; Serensits et al. 2013). The main differences between first- and second-generation synthetic turf systems are that second-generation systems have longer fibers (pile height) containing silica sand infill. Second-generation synthetic turf systems also included the introduction of polypropylene and polyethylene fibers; however, the majority of fibers remained nylon (McNitt 2005; Morehouse 1992; Serensits et al. 2013). Omniturf was a popular second-generation synthetic turf system in Europe. The first installation of a second-generation system in the United States occurred in 1983; however, these systems were not widely adopted because the sand infill resulted in surface hardness and abrasion potentially becoming hazardous for American football (Levy et al. 1990; McNitt 2005; Morehouse 1992; Serensits et al. 2013).

Third-generation synthetic turf replaced the sand infill with crumb (i.e., granulated) rubber or a combination of crumb rubber and silica sand. Additionally, nylon fibers were replaced with polypropylene or polyethylene (Christians 2011; Goatley et al. 2008; McNitt 2005; McNitt et al. 2004; Menichini et al. 2011; Puhalla et al. 2010; Ruffino et al. 2013; Schiliro et al. 2013; Serensits et al. 2013). Replacing the 100 percent sand infill with crumb rubber or crumb rubber/sand mix reduced surface hardness and abrasiveness (Serensits et al. 2013). In 1997, the first third-generation synthetic turf system was installed at Ringgold High School in Monongahela, PA with the brand name FieldTurf, manufactured by FieldTurf, Inc. (Calhoun, GA). This first installation of a third-generation system began the latest period of synthetic turf expansion (McNitt 2005; Serensits et al. 2013). An important advancement in the world-wide acceptance of third-generation synthetic turf occurred when the Federation Internationale de Football Association (FIFA) allowed official matches to be played on these surfaces. The demand for third-generation systems increased, several many new synthetic turf companies introduced new products the marketplace. Although third-generation synthetic turf specifications vary from manufacturer to manufacturer, the basic components are similar (Goatley et al. 2008; Serensits et al. 2013).

MAIN COMPONENTS AND MAINTENANCE OF THIRD-GENERATION SYNTHETIC TURF

Base Construction

The integrity of a synthetic turf system begins with proper base construction meeting two requirements: adequate drainage and firm stability (McNitt and Petrunak 2004; Serensits et al. 2013). Gravel is the typical base material used with synthetic turf because of its hydraulic conductivity and ability to maintain the specified grade or contours (Goatley et al. 2008; McNitt 2005; McNitt and Petrunak 2004; Puhalla et al. 2010; Serensits et al. 2013). The Synthetic Turf Council, formed in 2002, developed a set of minimum specifications to protect consumers from poor-quality field installations (McNitt and Petrunak 2004; Serensits et al. 2013). The council has specified that adequate drainage of a gravel base system must meet a minimum hydraulic conductivity of 50 cm h^{-1} (Serensits et al. 2013). In order to protect the uniformity of the base system, a concrete or asphalt base can be installed instead of gravel where events such as concerts or monster truck races frequently occur (Morehouse 1992; Serensits et al. 2013).

Backing and Pile Fibers

Depending upon the type and manufacturer of the synthetic turf system, the backing and pile fibers will vary. A common characteristic of all backing is the ability to provide adequate drainage by natural or manufactured pores (Puhalla et al. 2010; Serensits et al. 2013). The material of the backing can be either polyester or polypropylene to resist ultraviolet light degradation and prevent rotting. The backing can be woven or nonwoven, single or multilayer, thick or thin, and the pile fibers can either be glued or tufted to the backing. A thin backing will be weak resulting in long-term loss of pile fibers while a thick, strong backing will hold the fibers firmly in place (Christians 2011; Morehouse 1992; Serensits et al. 2013).

The face weight of synthetic turf provides an indication of the density of pile fibers. Face weight is a measure of the amount of pile (yarn) expressed as grams per square meter. Typical face weight values range from 927 to 3708 g m^{-2} (Serensits et al. 2013). Face weight is controlled by the gauge (distance) between rows of fibers, which can vary from 9.5 to 19 mm (Serensits et al. 2013). Pile fibers of first-generation synthetic turf were 12.7 mm long compared to 40 to 70 mm long for third-generation synthetic turf (Serensits et al. 2013). Additionally, third-generation synthetic turf fibers can have either slit-film or monofilament architecture. Slit-film pile fibers are produced in large sheets, cut into thin strips that are sub-divided further and twisted together for ease of tufting into the backing. Once these thin strips are sewn into the backing they are coated with polyurethane and/or latex. Slit-film pile fibers separate over time to reduce the “splash” of infill caused by athletes running on the surface (Serensits et al. 2013). The majority of new synthetic athletic field installations contain monofilament pile fibers due to their more grass-like appearance and resistance to matting. The monofilament systems are single strands of yarn tufted or directly glued to the backing. Direct gluing to the backing created a problem with early monofilament systems. Pile fibers would separate from the backing due to improper gluing; however, this problem has been reduced as the systems continue to be refined (Sandkuehler et al. 2010; Serensits et al. 2013).

Infill Materials

Depending on the manufacturer, infill materials consist of 100 percent crumb rubber or a combination of crumb rubber and silica sand with infill depth ranges from 25 to 45 mm (Christians 2011; Goatley et al. 2008; McNitt 2005; McNitt et al. 2004; Menichini et al. 2011; Puhalla et al. 2010; Ruffino et al. 2013; Schiliro et al. 2013; Serensits et al. 2013). Crumb rubber is styrene-butadiene rubber (SBR) produced from recycled car and/or truck tires with an average granule size of 2 to 3 mm (Menichini et al. 2011; Ruffino et al. 2013; Schiliro et al. 2013; Serensits et al. 2013). SBR has a high elasticity and resistance to weathering, making it an excellent infill material (Serensits et al. 2013). Two types of SBR are currently available for use in synthetic turf. Ambient SBR is produced by grinding tire treads at room temperature while cryogenic SBR is made by freezing and shattering tires. Compared to ambient SBR particles, cryogenic SBR particles are rounder, smoother and do not float in water, which reduces the potential for infill movement (Christians 2011; Gomes et al. 2010; Serensits et al. 2013). Alternatives to SBR have been used in third-generation systems due to potential health and environmental impactions associated with human exposure to crumb rubber (Menichini et al. 2011; Ruffino et al. 2013; Schiliro et al. 2013; Serensits et al. 2013). Alternatives include ethylene propylene diene monomer (EPDM), thermoplastic elastomers (TPE), elastomer-coated sand, polyurethane-coated SBR, coconut fibers, cork, and ground walnut shells (Serensits et al. 2013).

Maintenance Practices

In order to sustain playability and safety of synthetic turf athletic fields, they must receive regular, routine maintenance (Goatley et al. 2008; McLaren et al. 2012; McNitt 2005; Puhalla et al. 2010; Serensits et al. 2013). Surface grooming and cleaning, reduction of static electricity, and weed control must be part of a routine maintenance program. Grooming utilizes a series of brushes to raise matted pile fibers and loosens the top layer of the infill to reduce compaction (McLaren et al. 2012; McNitt 2005; McNitt and Petrunak 2004; Puhalla et al. 2010; Serensits et al. 2013). Contaminants on the pile fibers and infill surface warrant cleaning and disinfecting by spraying antimicrobial and detergent solutions. Surface debris such as leaves, garbage, and metal fragments must be removed by sweepers, blowers, vacuums, and magnets (McLaren et al. 2012; Morehouse 1992; Puhalla et al. 2010; Serensits et al. 2013). Spraying a dilute solution of a fabric softener limits static electricity that causes infill materials to stick to pile fibers and athletes (Goatley et al. 2008; McNitt and Petrunak 2004; Serensits et al. 2013). Weeds, moss, and algae should also be controlled on a regular basis depending on specific locations and environmental conditions within an athletic field (McLaren et al. 2012; Goatley et al. 2008; Puhalla et al. 2010; Serensits et al. 2013).

SURFACE TEMPERATURE ISSUES OF SYNTHETIC TURF

Excessive surface temperatures have been a problem of synthetic turf since its origins with temperatures reported to be as much as 35 to 60°C higher than natural turfgrass (Buskirk et al. 1971). On third-generation systems, surface temperatures as high as 93°C have been recorded (Williams and Pulley 2002). The New York City Department of Health and Mental Hygiene have recognized excessive surface temperatures as the number one health concern associated with third-generation synthetic turf systems (Denly et al. 2008). Buskirk et al. (1971) reported that heat transfer from the synthetic turf surface to the inner soles of athletes' shoes was significant enough to raise physiological stress to a level that could cause heat-related illnesses such as heat stroke and exhaustion. Several researchers have studied why synthetic turf surface temperatures are so extreme and ways to reduce them (Buskirk et al. 1971; Devitt et al. 2007; Koon et al. 1972; McNitt et al. 2008; Williams and Pulley 2002).

Irrigation applied to first-generation synthetic turf lowered surface temperatures similar to those measured on natural turfgrass (Koon et al. 1972). It has been suggested that the evaporation of 1.2 L m^{-2} of water will cool the surface of first-generation synthetic turf to a temperature similar to natural turfgrass (Morehouse 1992; Serensits et al. 2013). Irrigation has also been found to reduce the surface temperatures of third-generation synthetic turf systems. However, the duration of the cooling effect of irrigation is shorter on third-generation systems compared to first generation systems due to the decrease in longevity of surface wetness (McNitt et al. 2008; Williams and Pulley 2002). Williams and Pulley (2002) irrigated third-generation turf for 30 minutes, lowering the surface temperature from 79°C to 29°C, but five minutes after irrigation the temperature increased to 49°, and then rose to 73°C after 20 minutes. Similar results were reported by McNitt et al. (2008) who found that irrigating synthetic turf reduced surface temperatures for approximately 20 minutes, although temperatures three hours after irrigation were only lowered by 10°C compared to a non-irrigated synthetic turf.

The application of a tarp on the surface and the addition of infill amendments have been studied as tools for to maximizing and prolonging the cooling effect of irrigation on synthetic turf (McNitt et al. 2008). Placing a tarp on the surface following a predawn irrigation application had little effect on surface temperature (McNitt et al. 2008). An additional irrigation application in the afternoon just before tarp removal also had only minor effects on surface temperatures (McNitt et al. 2008). McNitt et al. (2008) also attempted to prolong the cooling effect of irrigation by mixing calcined clay with crumb rubber (20% by volume) prior to installation. The calcined clay amended infill was tested on Sprinturf, a third-generation system with an infill depth of 28 mm. The addition of calcined clay (20% by volume) to the infill did not reduce surface temperatures of the synthetic turf (McNitt et al. 2008).

Altering the color of traditional black crumb rubber has also been investigated as a method to reduce surface temperatures on third-generation synthetic turf. Devitt et al. (2007) reported that a loose pile of black crumb rubber painted white measured 9.1°C cooler than a loose pile of black crumb rubber. When installed into a synthetic turf pile, temperatures were only 5.3°C less than the traditional black crumb rubber (Devitt et al. 2007). This response is similar to previous reports on first-generation synthetic turf, (Buskirk et al. 1971; Koon et al. 1972) that all synthetic turf surfaces produce high surface temperatures regardless of the presence of infill.

CALCINED CLAY

Inorganic amendments, such as calcined clay, have been suggested for use in sandy soils or constructed sand-based root zones to increase moisture retention and cation exchange capacity, while also maintaining excellent drainage and aeration properties (Beard 1973; Li et al. 2000; Wasura and Petrovic 2001).

Calcined clays are naturally occurring clay minerals that are mined and then heated at temperatures of up to 760° C in a rotary kiln where they expand (Evanylo and Goatley 2011). Expansion during the firing process results in calcined clay materials lacking the particle size and plasticity properties to be included in the definition of clay (Waddington 1992). Bigelow et al. (2004) reported that the addition of inorganic amendments, such as calcined clay, to sand-based root zones significantly increased porosity. An increase in capillary porosity was found when calcined clay was amended to sand-based root zones increasing water retention (Bigelow et al. 2004; Githinji et al. 2011). Bigelow et al. (2004) determined the total and capillary porosity of calcined clay was 0.734 cm^3 cm^{-3} and 0.354 cm^3 cm^{-3}, respectively. In this study, the total and capillary porosity of the calcined clay were greater than coarse sand. However, the macroporosity of calcined clay, 0.380 cm^3 cm^{-3}, was similar to that of the coarse sand (Bigelow et al. 2004).

Githinji et al. (2011) measured the saturated volumetric water content (VWC) of calcined clay compared to 100 percent sand. Calcined clay resulted in a saturated VWC of 0.696 cm^3cm^{-3} and the 100 percent sand measured saturated VWC of 0.227 cm^3 cm^{-3}. Saturated VWC for calcined clay was significantly greater than 100 percent sand (Githinji et al. 2011). The water held by calcined clay is available for plant uptake (Miller 2000). Miller (2000) reported a calcined clay amended sand-based root zone provided 56 to 128 grams of more transpirable soil water than a 100 percent sand root zone by subtracting final sample weight from initial sample weight following a two week drying cycle.

Bulk density, saturated hydraulic conductivity, and particle density of calcined clay has also been investigated, along with chemical properties such as pH and cation exchange capacity (Bigelow et al. 2004; Githinji et al. 2011; Li et al. 2000). Bigelow et al. (2004) reported a bulk density of 0.64 g cm^{-3} while Githinji et al. (2011) reported a bulk density of 0.66 g cm^{-3}, both significantly lower than sand. Particle density and saturated hydraulic conductivity of calcined clay were reported to be 2.24 g cm^{-3} and 0.60 m h^{-1}, whereas sand's particle density and hydraulic conductivity were reported to be 2.67 g cm^{-3}and 0.41 m h^{-1} (Githinji et al. 2011). Li et al. (2000) reported that calcined clay had a water pH 6.3 and cation exchange capacity of 30.7 cmol$_c$ kg^{-1}. The physical and chemical properties of calcined clay allow it to be used as a substitute for peat moss as a soil amendment in sand-based turfgrass root zones (Bigelow and Soldat 2013).

Calcined clay has also been studied as a topdressing material due to its coarse-texture (Miller 2008). Miller (2008) reported that topdressing with calcined clay on natural turfgrass resulted in a decrease in surface temperature compared to topdressing with crumb rubber due to its lighter color and its ability to retain moisture in internal pore spaces. Temperatures were reduced for 4 to 8 weeks until the topdressing material worked into the soil or thatch layer. Soil moisture and surface hardness were also affected by the addition of calcined clay. Topdressing calcined clay at 75 kg ha^{-1} yielded greater soil moisture than the crumb rubber topdressing treatments, sand treatments, or the unamended controls (Miller 2008). Two and three sequential applications of calcined clay produced a positive linear rate response with increasing calcined clay rates and increasing surface hardness (Miller 2008).

One advantage of inorganic amendments, such as calcined clay, over organic amendments is that they are not subject to microbial degradation (Bigelow and Soldat 2013). Inorganic substances are subject to physical forces of impact, abrasion, weathering, freezing and thawing. These forces have the potential to fracture inorganic materials into finer particles leading to a decrease in pore space (Li et al. 2001; Wasura and Petrovic 2001; Bigelow and Soldat 2013). When subjected to simulated abrasion and impact using the L.A. Abrasion Test, calcined clay lost 16.5% of the weight of the original sample compared to 8.5% for sand (Wasura and Petrovic 2001). Li et al. (2001) reported a 25% increase in hydraulic conductivity following 20 freeze/thaw cycles on a sand-based root zone amended with 15% calcined clay. The 20 freezing/thawing cycles did not have a significant effect on the amount of the finest particle fraction of calcined clay retained when compared to the sand control (Li et al. 2001).

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CHAPTER 2

SYNTHETIC TURF SURFACE TEMPERATURE REDUCTION AND PERFORMANCE CHARACTERISTICS AS AFFECTED BY CALCINED CLAY MODIFIED INFILL

The intent of this manuscript is to publish an article in the peer-reviewed literature. This work is based on contributions by Eric Reasor, Jim Brosnan, John Sorochan and Tom Samples:

My primary contributions to this paper include (i) designing and conducting the experiments, (ii) processing, analyzing and interpreting data, (iii) review of literature, (iv) writing the manuscript.

ABSTRACT

Synthetic turf research plots containing crumb rubber (CR) infill were established in Knoxville, TN in 2012 and 2013. Calcined clay (CC) was amended to CR in several ratios: a 50:50 (vol vol^{-1}) blend; a 50:50 blend with a polymer coating on CC (50 CR:50 CCC); a 15 mm layer of CC under 15 mm of CR (CR over CC); and a 15 mm layer of CC over 15 mm of CR (CC over CR). A 100% CR and a 70:30 blend of CR to sand (70 CR:30 S) were included for comparison. Surface temperature was measured in the summer of 2012 and 2013 at -10, 0, 30, 60, 90, 120, and 150 minutes following 2.8 cm of irrigation. Irrigation reduced surface temperature 60 to 85% regardless of treatment. By 30 minutes after irrigation, surface temperature increased to 74 to 102% of the temperature recorded 10 minutes prior to irrigation. Temperature on the 50 CR:50 CC and CC over CR treatments 150 minutes after irrigation were 10 to 24% and 20 to 21% lower than the hottest surfaces, which ranged from 95 to 137% of the pre-irrigation temperature. Simulated traffic was applied using the Cady Traffic Simulator for a total of 180 traffic events each year. Trends in surface hardness among treatments were inconsistent over years with values ranging from 70 to 160. CC modified infill treatments resulted in a faster increase of surface hardness with traffic compared to 100% CR and 70:30 S. Traffic affected particle size diameter of infill materials. Infill particles ranging in size from 3.35

to 1.0 mm decreased in diameter an average of 1.0 to 12.0%. Particles ranging from 1.0 to <0.002 mm increased in diameter an average of 0.3 to 3.8%. This increase in size was least pronounced for the 100% and 70 CR:30 S treatments and most pronounced for treatment CC over CR. Significant temperature differences were not consistent among treatments and surface hardness with CC tended to measure higher than 100% CR and 70 CR:30 S. The results of this experiment indicate the use of CC in synthetic turf may be limited.

INTRODUCTION

Surface temperatures on synthetic turf have been reported to be 35 to 60°C higher than natural turfgrass (Buskirk et al. 1971). Temperatures on infilled synthetic turf systems can be as high as 93°C (Williams and Pulley 2002). Buskirk et al. (1971) reported that the heat transfer from the synthetic turf surface to the inner soles of athletes' shoes was significant enough to raise physiological stress to a point where it could result in heat-related illnesses, such as heat stroke and exhaustion. The New York City Department of Health and Mental Hygiene have recognized excessive surface temperatures as the number one health concern associated with infilled synthetic turf systems (Denly et al. 2008).

Irrigation has been found to reduce the surface temperatures of infilled synthetic turf systems (McNitt et al. 2008; Williams and Pulley 2002). Williams and Pulley (2002) irrigated synthetic turf for 30 minutes, lowering the surface temperature from 79°C to 29°C, but five minutes after irrigation the temperature increased to 49°C, and then to 73°C by 20 minutes after irrigation. Similarly, McNitt et al. (2008) observed that 2 cm of irrigation reduced surface temperature 20 to 35°C for approximately 20 minutes; however, temperatures three hours after irrigation were only 10°C less than non-irrigated synthetic turf.

Calcined clay (CC) is a natural occurring material mined and then produced by firing clay minerals at temperatures up to 760° C in a rotary kiln where it expands (Evanylo and Goatley 2011). Expansion during the firing process results in CC materials lacking the particle size and plasticity properties to be included in the definition of clay (Waddington 1992). Githinji et al. (2011) measured CC to have a saturated VWC of 0.696 $cm^3\ cm^{-3}$, whereas 100 percent sand yielded a saturated VWC of 0.227 $cm^3\ cm^{-3}$, respectively. Water retained by the capillary and macroporosity of CC is available for plant uptake (Miller 2000). Miller (2000) found that a CC amended sand-based root zone to provide 56 to 128 grams of more transpirable soil water than a 100 percent sand root zone by subtracting final sample weight from initial sample weight following a two week drying cycle. Use of CC as an infill amendment in synthetic turf has the potential to increase water content in the pile allowing for a prolonged period of evaporative cooling compared to simply irrigating crumb rubber (CR).

A potential reduction in synthetic turf surface temperature from CC modified infill may come at the expense of increased surface hardness or reduced drainage. Miller (2008) reported higher surface hardness values on bermudagrass (*Cynodon dactylon*) topdressed with CC at 50 and 75 kg ha^{-1}. Impact and abrasion forces associated with foot traffic on athletic fields may cause CC particles to fracture into finer diameter inorganic materials reducing hydraulic conductivity (Bigelow and Soldat 2013; Li et al. 2001; Wasura and Petrovic 2001). When subjected to simulated abrasion and impact using the L.A. Abrasion Test, CC lost 16.5% of the weight of the original sample compared to 8.5% for sand (Wasura and Petrovic 2001).

Research regarding the use of CC in synthetic turf systems is limited. McNitt et al. (2008) tested the amendment of blending CC (20% by volume) to 80% CR infill with the addition of irrigation on a third-generation synthetic turf system. Researchers utilized the third-generation Sprinturf (Atlanta, GA) with an infill depth of 28 mm. A total of 2 cm of irrigation was applied using hand-held irrigation beginning at 12:40 PM. McNitt et al. (2008) were unsuccessful in prolonging the cooling effect of irrigation by amending CR infill with CC (20% by volume). The researchers only examined one percentage of CC and a single technique for incorporating the amendment (e.g., mixed by volume). More research on the use of CC to lower synthetic turf surface temperature is warranted. Multiple configurations of CR infill amended with CC (e.g., layering by depth and mixing by volume) has the potential to provide a prolonged cooling effect of irrigation on third-generation synthetic turf, not documented by McNitt et al. (2008). Increasing the percentage of CC in the infill to 50% by volume also has the potential to provide a prolonged cooling effect of irrigation. Uniformity of irrigation may have the potential to affect the irrigation's cooling of the synthetic turf surface. McNitt et al. (2008) applied 2 cm of irrigation using hand-held methods, where it would be difficult to measure the precipitation rate across the entire study area. Given the importance of irrigation in synthetic turf temperature studies, automatic irrigation could provide the accuracy required to ensure uniform irrigation coverage. Additionally, a Brinkman traffic simulator was used by McNitt et al. (2008) to apply simulated traffic to the plots; however, no data were reported to quantify the amount of infill material particle breakdown.

Our primary hypothesis is that the addition of CC at a higher rate of 20% by volume would prolong the beneficial cooling effect of irrigation on synthetic turf. A secondary hypothesis is the incorporation of CC into synthetic turf infill will increase surface hardness and CC particles will fracture with simulated traffic. Therefore, the primary objective of this study was to evaluate changes in surface temperature on infilled synthetic turf amended with varying percentages of CC. A secondary objective was to evaluate changes in surface hardness on these surfaces and determine particle stability when subjected to simulated traffic.

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MATERIALS AND METHODS

Plot Construction

Construction of synthetic turf plots began in May 2012 at the East Tennessee Research and Education Center Plant Sciences Unit (Knoxville, TN; 35° 57' N Lat.). Existing vegetation and topsoil were removed and the native soil (Sequatchie loam; fine-loamy, siliceous, semiactive, thermic humic Hapludult) was graded to accommodate installation of drainage, irrigation, and a gravel sub-base beneath synthetic turf. This gravel sub-base consisted of a 15 cm deep layer of washed aggregate (diameter range 2.4 to 25 mm) capped with a 5 cm deep layer of fine aggregate (diameter range 0.3 to 9.5 mm). The aggregate layers were compacted using a vibratory compactor to maximize stability and uniformity. The entire synthetic turf research area was 13.7 x 22.9 m with water uniformly applied using an in ground irrigation system (Hunter Pro-Spray PRS40; Hunter Industries; San Marcos, CA) calibrated to apply 2.8 cm hr^{-1} with an average distribution uniformity of 70%.

A monofilament synthetic turf (LS21; AstroTurf USA; Dalton, GA) was installed over each whole plot. Monofilament fibers in the pile were polyethylene strands, extruded to a diamond shape, and coated with polyurethane before being tufted into a woven backing. The pile height was 50 mm with a specified face weight of 1,390 g m^{-2} (ASTM Test F-1551; Method D-5848). Synthetic turf was installed on 19 June 2012, removed on 14 April 2013. The study was repeated with new synthetic turf installed on 3 June 2013. A small, triangular section of turf from each corner was cut out to allow clearance for irrigation heads.

Infill Treatment Installation

Particle size distribution for all infill materials prior to installation is presented in Table 1. The CC used in the study (Turface Pro League; Profile Products LLC; Buffalo Grove, IL) was non-swelling illite and silica clays with 74% as SiO_2, 11% Al_2O_3, and 5% Fe_2O_3. A coated-calcined clay (CCC) (Experimental; Profile Products LLC; Buffalo Grove, IL) were coated with a proprietary polymer to increase stability and moisture retention. The bulk density of the CC was 0.635 g cm^{-3} compared to 0.613 g cm^{-3} for CCC. CR used in this study (Liberty Tire Recycling; Pittsburgh, PA) is produced by shredding and grinding truck tires and sieving the particles to the desired distribution. The silica sand utilized in this study is typical to that of most synthetic turf installations. The CR has had a bulk density of 0.52 g cm^{-3}, while the bulk density of the silica sand used measured 1.36 g cm^{-3}.

The 13.7 x 22.9 m area were divided into 4.6 x 1.5 m sub-plots to accommodate different infill treatments. Four CC modified infill treatments were evaluated: a 15 mm layer of CR placed over 15 mm of CC (CR over CC); a 15 mm layer of CC placed over 15 mm CR (CC over CR); CR and CC blended in a 50:50 ratio (50 CR:50 CC); and CR and CCC blended similarly (50 CR:50 CCC). A 100% CR infill and a blend of CR and silica sand (70 CR:30 S) were included for comparison. Blended treatments were based on a volume per volume basis and blended in a drum mixer (Model # CM305A; Portable Electric Cement Mixer; Northern Industrial Tool and Equipment; Burnsville, MN) prior to installation.

Infill treatments were incorporated into individual plots on 26 July 2012 and 10 June 2013 to a depth of 30 mm (exposing 20 mm of synthetic turf pile fiber). Infill was applied to plots using a gasoline powered turf cart (Cushman Turf Truckster 4W; Cushman; Augusta, GA) equipped with a 1.5 m wide belt-fed topdresser (Cushman TD 1500; Cushman; Augusta, GA). Treatments were finalized to the correct depth using a manual drop spreader (Scotts AccuGreen 3000; The Scotts Company LLC; Maryville, OH). Infill was incorporated into the synthetic turf pile with a gasoline powered, 60 cm wide rotary brush (STIHL Powerbrush KM110R; STIHL Inc; Virginia Beach, VA) and manual push brooms. The infill depth was measured using a metal ruler graduated in 3 mm increments. A 2.5% solution of fabric softener (Ultra Downy; Procter & Gamble Co.; Cincinnati, OH) and water was applied twice daily (and allowed to dry) during infill installation to reduce static electricity within the pile which prevented proper incorporation of CR. After installation plots were not groomed or brushed to preserve the integrity of the CC treatments within the pile.

Surface Temperature

Surface temperature data were collected on three dates in the summer of 2012 and 2013. Data collection began 10 minutes prior to irrigation until 150 minutes after irrigation. A total of 2.8 cm of irrigation was applied from 12 PM to 1 PM on each date surface temperature data were collected. This method of measuring synthetic turf temperature in response to irrigation is similar to those previously reported by Williams and Pulley (2002) and McNitt et al. (2008). Data loggers (Watchdog B-100 2K; Model No. 3619WD; Spectrum Technologies Inc.; Aurora, IL) placed in the center of each plot measured surface temperature in 2012. These data loggers had a measurement range of -30 to 70°C with an accuracy range of ± 1°C. Data were collected every ten minutes during the measurement window. After each temperature measurement date, data from each logger were retrieved using Specware 6 software (Spectrum Technologies Inc.; Aurora, IL).

In 2013, instrumentation to collect surface temperature data was upgraded to increase the speed and accuracy of measurement. Thermistors (100K; US Sensor Corporation; Orange, CA) were used to collect surface temperature data in 2013 within a range of -80 to 150°C at an accuracy of ±0.1°C. The thermistor used in our study was comprised of an 80.6 KOhm resistor. The resistor measures temperature by the model of the Steinhart-Hart Equation. A data logger (CR1000; Campbell Scientific Inc.; Logan, UT) excited the thermistor with 2500 mV while reading the voltage. A calibration equation was used measure surface temperature by converting voltage output from the thermistors (Wright 2014, personal communication). The sensors were calibrated by comparing the temperature readings of the sensors to a lab grade thermometer measuring ice water heated to boiling point. The entire system was powered by a 115 amp-hr marine battery charged by a 30 watt solar panel and a Morningstar 4.5 amp PWM charge controller. The data collection software (LoggerNet 4.1; Campbell Scientific Inc.; Logan, UT) read the thermistors every 30 seconds, averaged, and reported the readings in ten minute intervals.

In the summer of 2012, surface temperature data were collected on 29 August, 2 September, and 5 September. Average ambient air temperature on these dates from 10 AM to 4 PM measured 31°C, 29 °C, and 30 °C, respectively. In 2013, surface temperature data were collected on 24 June, 18 July, and 25 July. Average ambient air temperature on these dates from 10 AM to 4 PM measured 30°C, 30°C, and 28°C, respectively. Dates of surface temperature collection were chosen based the forecasted absence of rainfall the day prior to and after measurement dates. Surface temperature data collected at 0, 30, 60, 90, 120, and 150 minutes after irrigation were analyzed and reported as a percentage of the surface temperature recorded 10 minutes prior to applying 2.8 cm of irrigation using the following equation:

$$\text{Percent of temperature prior to irrigation}=\left(\frac{\text{Temperature after irrigation}}{\text{Temperature prior to irrigation}}\right)\times 100$$

Application of Simulated Traffic Events

Simulated traffic was applied to all plots using a Cady Traffic Simulator similar to Henderson et al. (2005). The Cady Traffic Simulator used in our study was a modified aerator (Ryan Greensaire GA-24; Jacobsen, A Textron Co.; Charlotte, NC) with artificial rubber feet as described by Henderson et al. (2005). Simulated traffic was applied from 12 September to 3 December 2012 and 16 September to 19 December 2013. A total of 180 simulated traffic events were applied at a rate of 15 traffic events per week to half of the 4.6 x 1.5 m plot, while the other half of the plot remained non-trafficked.

Surface Hardness

Surface hardness of an athletic field describes the surface's ability to absorb impact forces (Rogers III 1992). Surface hardness of an athletic field is measured in G_{max}. G_{max}, as reported by Rogers III (1992), is the ratio of the maximum negative acceleration and the acceleration due to gravity. A playing surface with a low G_{max} has the ability to absorb more energy, while a surface with a high G_{max} has a limited ability to absorb impact forces. High G_{max} values have been associated with an increased risk of head injury while low G_{max} values can increase muscle fatigue (Gadd 1966; Kolitzus 1984). The United States Consumer Products Safety Division (ASTM 2009a) has set a maximum threshold for G_{max} at 200; however there is currently no minimum value.

In this study, surface hardness data were collected using devices similar to Brosnan et al. (2009). Surface hardness was measured using the F355 Apparatus-A (F355) (Triax 2000; Playground Clearing House, USA; Malvern, PA) that consisted of a 9.1 kg missile with a flat face of 120 cm^3. The missile was dropped in a tube from a height of 61 cm (ASTM 2009b). The G_{max} value reported was the average of three sub-samples taken from each plot. Each sub-sample was the average of two missile drops with the F355 at the same location with a one minute (± 30 seconds) interval between drops. Values from the first drop of the F355 were discarded as they are only used for conditioning.

A Clegg Impact Soil Tester (CIST) was also used to measure surface hardness in this study (Clegg 1976). This device is commonly used on natural turfgrass surfaces, but can also be used on synthetic turf (ASTM 2009c). The CIST (Lafayette Instrument Company; Lafayette, Indiana) is equipped with a 2.25 kg missile dropped from a height of 45.5 cm. The G_{max} value reported with this device was the average of three sub-samples taken from each plot. Data for each sub-sample were collected by dropping the missile in three separate locations within each plot. Surface hardness data with both instruments were collected before simulated traffic was applied and after every 45 simulated traffic events were applied each year.

Particle Size Analysis

Particle size analysis was conducted after 180 simulated traffic events were applied to plots to characterize changes in CC (or CR) particle size due to traffic stress. Three samples were removed from both the trafficked and non-trafficked portions of each sub-plot. A 176 (± 20) cm^2 area of synthetic turf was removed using a circular template. These samples consisted of synthetic turf and infill materials. All samples were dried for 24 hours at 25°C prior to particle size analysis.

Infill materials were separated from the synthetic turf fibers and backing, ran through a 3.35 mm sieve to catch any remaining fibers or large particles, and then weighed to measure the initial mass of the sample. The sample was then transferred to a portable sieve shaker (Model RX-24; W.S. Tyler Inc.; Mentor, OH) where the different particle sizes were separated through sieves (USA Standard Test Sieve; ASTM E-11; Fisher Scientific Company; Hampton, NH) ranging in size from 2.0 to 0.05 mm. Samples weighing less than 125 grams remained on the shaker for 5 minutes, compared to 10 minutes for those weighing more than 125 grams (Gee and Or 2002). The mass retained in each sieve was then divided by the initial mass of the sample to determine the percentage of the sample retained on each sieve. The United States Golf Association specifications for sand-based root zones (USGA 1993) were used to determine the particle size distribution of the infill treatments.

Experimental Design and Statistical Analysis

The experiment was arranged as a randomized complete block design with three replications and repeated in time. The surface temperature and hardness measurements were analyzed using a single factor analysis of variance (ANOVA) to determine changes in temperature and hardness due to infill treatment. To assess changes in particle size following traffic stress, a split-plot ANOVA was used with infill treatments serving as the whole plot and simulated traffic (0 or 180 events) serving as the subplot treatment. Data were analyzed in SAS (SAS version 9.3; SAS Institute; Cary, NC). Significant year-by-treatment interactions resulted in data from 2012 and 2013 being analyzed separately. Similarly, significant treatment-by-date interactions resulted in surface temperature data collected on each date to be analyzed separately as well.

Surface temperature and particle size analysis means were separated using Fisher's Protected Least Significant Difference with a 5% probability level. Surface hardness means were separated by determining best-fit parameter estimates using a sums-of-squares reduction F-test for linear equations in Prism software (Prism 6.0 for Windows; GraphPad Software; La Jolla, CA).

RESULTS AND DISCUSSION

Surface Temperature

Temperatures recorded for each infill treatment 10 minutes prior to applying irrigation are presented in Table 2. Surface temperature data at 0, 30, 60, 90, 120, and 150 minutes after irrigation are presented as percentage of the surface temperature 10 minutes prior to applying 2.8 cm of irrigation (pre-irrigation temperature) in Tables 4 and 5. Table 3 displays the analysis of variance results for infill treatment significance at each time after irrigation.

No differences in surface temperature were detected 0 minutes after irrigation in either year (Table 4 and 5). However, irrigation resulted in a 15 to 40% reduction of surface temperature. These percentages are similar to previous reports of irrigation cooling synthetic turf by Williams and Pulley (2002) and McNitt et al. (2008). These two previous studies have reported surface temperatures immediately after irrigation to be approximately 30 to 60% of the surface temperature prior to applying irrigation (McNitt et al. 2008; Williams and Pulley 2002).

Thirty minutes after irrigation, date 1 and date 2 of 2012, and date 3 of 2013 had significant treatment differences; however, sixty minutes after irrigation, the percentages of the pre-irrigation surface temperatures did not produce any significant results (Tables 4 and 5). Date 1 2012 and date 2 2013, had significantly different percentages at 90 minutes after irrigation, then at 120 minutes after irrigation, treatments on date 1 2012 and dates 1 and 3 in 2013 were significantly different (Tables 4 and 5). The temperature measurement time of 150 minutes after irrigation produced two significant dates for infill treatments (Tables 4 and 5). On date 1 2012, treatments 100% CR and 70 CR:30 S, with 132 and 137%, were greater than CC over CR at 116%. In 2013, date 2 had significant treatment differences, where 50 CR:50 CCC (122%) was greater than the other treatments (98 to 104%).

Surface temperature on nearly all of the treatments evaluated did not reach 100% of the pre-irrigation temperature until 60 to 120 minutes after irrigation (Tables 4 and 5). This suggests that the cooling effect of irrigation will not last the entire length of an athletic competition. Our findings also support previous reports by Williams and Pulley (2002) who reported that surfaces temperatures on irrigated synthetic turf surface temperature increased to 92% of pre-irrigation levels 20 minutes after irrigation.

Few consistently significant differences in surface temperature were detected among infill treatments over the course of the two-year study (Tables 4 and 5). Treatments CC over CR and 50 CR:50 CC resulted in a lower range of percentages of 91 to 116% and 81 to 126% at 150 minutes after irrigation compared to 100% CR at 91 to 137% and 70 CR:30 S at 91 to 132% (Tables 4 and 5). McNitt et al. (2008) did not report a cooling effect of CR infill amended with 20% by volume CC with irrigation; however, increasing this percentage to at least 50% by volume may provide a cooling effect on synthetic turf surface temperatures. Miller (2008) did report a decrease in surface temperature when CC was topdressed on natural turfgrass compared to topdressing with CR due to a higher moisture content associated with the CC. Applying a layer of CC over CR or blending CC without a polymer coating with CR will lower surface temperatures longer than using a 100% CR or a 70 CR:30 S blend.

Surface Hardness

Linear regression equations fit surface hardness (G_{max}) data collected with the F-355 Apparatus. A sums-of-squares reduction F-test determined that best-fit parameter estimates for the linear equations were significantly different among treatments in 2012 ($P < 0.0001$) and 2013 ($P = 0.0004$) (Figure 1). Best-fit lines for all treatments had positive slopes indicating that surface hardness increase following the application of simulated traffic, regardless of treatment (Table 6).

In 2012, slope (β_1) indicated that surface hardness increased at faster rate on plots infilled with CC over CR and 50 CR:50 CC than the other infill treatments (Table 6). Surface hardness increased more than 1.5 times faster on plots infilled with CC over CR and 50 CR:50 CC than 70 CR: 30 S. In 2013, surface hardness increased fastest on plots infilled with CR over CC and 50 CR:50 CCC (Table 6). The difference between 2012 and 2013 could be contributed to the mixing of CR over CC treatment layers at a faster rate than the CC over CR treatment when exposed to simulated traffic.

Linear regression equations also fit surface hardness (G_{max}) data collected with the CIST. A sums-of-squares reduction F-test determined that best-fit parameter estimates for the linear equations were significantly different among treatments in 2012 ($P < 0.0001$) and 2013 ($P < 0.0001$) (Figure 2).

Best-fit lines for all treatments had positive slopes indicating that surface hardness increase following the application of simulated traffic, regardless of treatment (Table 6). In 2012, slope (β_1) indicated that surface hardness increased at faster rate on plots infilled with 50 CR:50 CCC and 50 CR:50 CC than the other infill treatments (Table 6). Surface hardness increased more than 2.8 times faster on plots infilled with either CC blended treatments than CR over CC. In 2013, surface hardness increased fastest on plots infilled with CR over CC (Table 6). The difference between 2012 and 2013 could be contributed to the mixing of CR over CC treatment layers at a faster rate in 2012 than 2013 when exposed to simulated traffic.

The use of CC as a synthetic turf infill amendment produced an increase in surface hardness compared to using CR alone or a blend of 70 CR:30 S. These results are similar to Miller (2008) who reported the use of CC as a topdressing material on natural turfgrass increased the surface hardness compared to using CR. Increases in surface hardness on layered plots could be attributed to the fact that layers combine when exposed to simulated traffic. It is also important to note the differences in y-intercept values (β_0) from 2012 to 2013 for linear regression equations used to model changes in surface hardness (Table 6). Y-intercept values increased more than 10 G_{max} units from 2012 to 2013 with both instruments. The increase may have been caused by the synthetic turf in 2013 being re-installed over the same sub-base system which sustained compaction from traffic application the previous year.

Particle Size Analysis

Year by-treatment and treatment-by-traffic level interactions were detected in particle size analysis data (Tables 7, 8, and 9). In both years of the study, percent change of particle sizes diameter decreased from non-trafficked to trafficked plots for the 3.35 to 1.0 mm particle sizes and increased for the 1.0 to <0.002 mm particle sizes (Tables 8 and 9). Treatments 100% CR and 70 CR:30 S resulted in only five significant changes in percent change in diameter with application of simulated traffic (Tables 8 and 9). Average percent change in diameter for these treatments across all particle sizes in 2012 was 0.6% and 1.0% in 2013. Treatments with any incorporation of CC produced significant changes for most particle sizes from non-trafficked to trafficked plots (Tables 8 and 9). The particle size 2.0 to 1.0 mm resulted in the greatest percent change at 8.4 and 14.8% in 2012 and 2013 across all CC amended infill treatments. The 100% CR and 70 CR:30 S treatments only produced a 2.5% change in diameter for the 2.0 to 1.0 mm particle size in 2012 and 1.1% in 2013. Treatments CC over CR and 50 CR:50 CC produced the highest percent changes in diameter across both years and all particle sizes. CC over CR and 50 CR:50 CC resulted in a percent change of 5.3 and 4.6% in 2012, and 6.3 and 5% in 2013. The treatments of CR over CC and 50 CR:50 CCC resulted in lower percent changes than the other two CC infill treatments at 3.1 and 2.8% in 2012, and 3.2 and 3.6% in 2013 across all particle sizes. The addition of a polymer coating on the CC particles when blended with CR and applying a layer of CR over a layer of CC increases the particle stability of the CC infill amendments when subjected to simulated athletic field traffic.

A concern with using CC as an infill amendment for synthetic turf is the potential for the particles to fracture to a smaller diameter; consequently reducing macroporosity and restricting hydraulic conductivity (Bigelow and Soldat 2013; Li et al. 2001; Wasura and Petrovic 2001). The United States Golf Association specifications for sand-based root zones suggests that less than 33% of root zone should be comprised of particles 0.25 to < 0.002 mm in diameter to maintain a hydraulic conductivity of 15 to 30 cm h^{-1} (USGA 1993). After applying 180 simulated traffic events in the current study, a total of 0 to 8.4% of particles ranged from 0.25 to <0.002 mm in diameter suggesting that plots have hydraulic conductivity > 15 cm h^{-1}.

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APPENDIX

TABLES AND FIGURES

Table 1. Particle size distribution analysis of infill materials prior to installation into synthetic turf plots located in Knoxville, TN in 2012 and 2013. Materials were installed alone, in homogenous blends, or in layering configurations.

		Crumb Rubber	Silica Sand	Calcined Clay[b]	Coated Calcined Clay[c]
Sieve No.[a]	**Particle Size**	---------------------**Percent Retained[d]**			--------------------
10	> 2.0 mm	8.18	0.00	34.44	30.27
18	2.0 - 1.0 mm	78.52	4.97	64.98	68.17
35	1.0 mm - 0.5 mm	12.63	93.03	0.44	1.30
60	0.5 - 0.25 mm	0.23	1.99	0.02	0.04
100	0.25 - 0.15 mm	0.21	0.00	0.02	0.04
140	0.15 - 0.1 mm	0.14	0.00	0.00	0.00
270	0.1 - 0.05 mm	0.02	0.00	0.00	0.00
Pan[e]	0.05 - < 0.002 mm	0.00	0.00	0.00	0.00

[a] Sieve number based on number of holes per linear inch associated with the sieve screen

[b] Calcined clay material is Turface Pro League from Profile Products LLC

[c] Coated calcined clay material is Turface Pro League with a polymer coating surrounding the clay particles

[d] Percent retained calculated by dividing the mass retained in each sieve by the initial total mass of the sample

[e] Pan retains all remaining particles which include silt and clay particle factions

Table 2. Surface temperatures (°C) at 10 minutes prior to application of 2.8 cm of irrigation for individual infill treatments on three dates during 2012 and 2013 located in Knoxville, TN. The temperatures were used to calculate the percentage of surface temperature for respective infill treatments at 0, 30, 60, 90, 120, and 150 minutes after irrigation reported in Tables 4 and 5.

		Temperature (°C) 10 Minutes Prior to Irrigation	
		2012	**2013**
Date 1[a]	100% CR[d]	40	55
	70 CR:30 S[e]	40	56
	50 CR:50 CC[f]	39	57
	50 CR:50 CCC[g]	40	53
	CR over CC[h]	40	56
	CC over CR[i]	40	54
Date 2[b]	100% CR	36	53
	70 CR:30 S	36	52
	50 CR:50 CC	37	51
	50 CR:50 CCC	31	49
	CR over CC	37	53
	CC over CR	31	49
Date 3[c]	100% CR	31	51
	70 CR:30 S	32	49
	50 CR:50 CC	32	46
	50 CR:50 CCC	33	47
	CR over CC	31	48
	CC over CR	31	47

[a] Date 1, 29 August 2012 and 24 June 2013, average air temperature 10 AM to 4 PM was 30.8 and 29.7°C

[b] Date 2, 2 September 2012 and 18 July 2013, average air temperature 10 AM to 4 PM was 29.3 and 29.7°C

[c] Date 3, 5 September 2012 and 25 July 2013, average air temperature 10 AM to 4 PM was 29.9 and 28.3°C

[d] 100% crumb rubber infill treatment at 30 mm depth

[e] 70% crumb rubber: 30% silica sand by volume homogenous blend infill treatment at 30 mm depth

[f] 50% crumb rubber: 50% calcined clay by volume homogenous blend infill treatment at 30 mm depth

[g] 50% crumb rubber: 50% coated-calcined clay by volume homogenous blend infill treatment at 30 mm depth

[h] 15 mm crumb rubber over 15 mm calcined clay infill treatment

[i] 15 mm calcined clay over 15 mm crumb rubber infill treatment

Table 3. Analysis of variance for infill treatment surface temperature data on 6 dates during 2012 and 2013 located at Knoxville, TN. Statistical analysis was performed on data at 0, 30, 60, 90, 120, and 150 minutes after irrigation expressed as a percentage of the surface temperature 10 minutes prior to applying 2.8 cm of irrigation.

		Minutes after Irrigation					
Year	**Dates**	**0**	**30**	**60**	**90**	**120**	**150**
2012	Date 1[a]	NS	*	NS	***	***	***
	Date 2[b]	NS	**	NS	NS	NS	NS
	Date 3[c]	NS	NS	NS	NS	NS	NS
2013	Date 1[d]	NS	NS	NS	NS	*	NS
	Date 2[e]	NS	NS	NS	*	*	*
	Date 3[f]	NS[g]	*	NS	NS	NS	NS

[a] Date 1, 29 August 2012, average air temperature from 10 AM to 4 PM was 30.8°C

[b] Date 2, 2 September 2012, average air temperature from 10 AM to 4 PM was 29.3°C

[c] Date 3, 5 September 2012, average air temperature from 10 AM to 4 PM was 29.9°C

[d] Date 1, 24 June 2013, average air temperature from 10 AM to 4 PM was 29.7°C

[e] Date 2, 18 July 2013, average air temperature from 10 AM to 4 PM was 29.7°C

[f] Date 3, 25 July 2013, average air temperature from 10 AM to 4 PM was 28.3°C

[g] NS, non-significant

*, **, *** indicates significance at $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$ level

Table 4. Infill treatment surface temperature results at 0, 30, 60, 90, 120, and 150 minutes after application of 2.8 cm of irrigation during 2012 at Knoxville, TN. Data are presented at a percentage of the surface temperature 10 minutes prior to irrigation. Dates and times were analyzed separately.

		Minutes after Irrigation					
		0	30	60	90	120	150
Infill Treatments		Percentage of the Pre-Irrigation Temperature[a]					
Date 1[j]	100% CR[b]	85	99	110	128	133	137
	70 CR:30 S	84	100	115	128	131	132
	50 CR:50 CC[d]	82	102	113	121	125	126
	50 CR:50 CCC[e]	81	90	105	122	127	129
	CR over CC[f]	80	101	117	126	128	128
	CC over CR[g]	81	101	109	113	115	116
	$\mathrm{LSD}_{0.05}$[h]	NS[i]	6.9	NS	5.1	4.6	5.0
Date 2[k]	100% CR	63	83	79	82	87	94
	70 CR:30 S	63	79	85	81	87	91
	50 CR:50 CC	63	86	81	75	79	87
	50 CR:50 CCC	63	89	86	83	88	95
	CR over CC	60	74	80	80	86	91
	CC over CR	64	93	86	82	84	91
	$\mathrm{LSD}_{0.05}$	NS	8.8	NS	NS	NS	NS
Date 3[l]	100% CR	70	81	91	128	125	105
	70 CR:30 S	70	80	91	132	126	104
	50 CR:50CC	70	80	92	131	124	103
	50 CR:50CCC	71	80	91	128	123	102
	CR over CC	71	83	92	131	126	106
	CC over CR	73	79	89	125	124	105
	$\mathrm{LSD}_{0.05}$	NS	NS	NS	NS	NS	NS

[a] Temperature 10 minutes prior to irrigation. See Table 2 for specific values

[b] 100% crumb rubber infill treatment at 30 mm depth

[c] 70% crumb rubber: 30% silica sand by volume homogenous blend infill treatment at 30 mm depth

[d] 50% crumb rubber: 50% calcined clay by volume homogenous blend infill treatment at 30 mm depth

[e] 50% crumb rubber: 50% coated-calcined clay by volume homogenous blend infill treatment at 30 mm depth

[f] 15 mm crumb rubber over 15 mm calcined clay infill treatment

[g] 15 mm calcined clay over 15 mm crumb rubber infill treatment

[h] Fisher's Protected Least Significant Difference at 5% significance level

[i] NS, non-significant

[j] Date 1, 29 August 2012, average air temperature from 10 AM to 4 PM was 30.8°C

[k] Date 2, 2 September 2012, average air temperature from 10 AM to 4 PM was 29.3°C

[l] Date 3, 5 September 2012, average air temperature from 10 AM to 4 PM was 29.9°C

Table 5. Infill treatment surface temperature results at 0, 30, 60, 90, 120, and 150 minutes after application of 2.8 cm of irrigation during 2013 at Knoxville, TN. Data are presented at a percentage of the surface temperature 10 minutes prior to irrigation. Dates and times were analyzed separately.

		Minutes after Irrigation					
		0	30	60	90	120	150
Infill Treatments		Percentage of the Pre-Irrigation Temperature[a]					
Date 1[j]	100% CR[b]	74	79	83	83	90	91
	70 CR:30 S	73	79	86	86	93	92
	50 CR:50 CC[d]	72	76	79	79	81	81
	50 CR:50 CCC[e]	74	80	89	89	106	103
	CR over CC[f]	67	82	89	89	95	95
	CC over CR[g]	77	82	84	84	91	93
	$LSD_{0.05}$[h]	NS	NS	NS	NS	13.6	NS
Date 2[k]	100% CR	70	84	90	93	94	98
	70 CR:30 S	69	87	94	98	101	104
	50 CR:50 CC	71	86	91	95	96	98
	50 CR:50 CCC	75	92	101	111	118	122
	CR over CC	69	90	95	98	98	101
	CC over CR	74	90	94	95	98	102
	$LSD_{0.05}$	NS	NS	NS	11.5	11.9	12.6
Date 3[l]	100% CR	71	88	96	98	108	118
	70 CR:30 S	71	91	98	95	98	105
	50 CR:50 CC	75	92	95	94	98	106
	50 CR:50 CCC	75	95	101	97	102	108
	CR over CC	70	90	97	97	102	108
	CC over CR	77	93	97	93	97	103
	$LSD_{0.05}$	NS	3.6	NS	NS	NS	NS

[a] Temperature 10 minutes prior to irrigation

[b] 100% crumb rubber infill treatment at 30 mm depth

[c] 70% crumb rubber: 30% silica sand by volume homogenous blend infill treatment at 30 mm depth

[d] 50% crumb rubber: 50% calcined clay by volume homogenous blend infill treatment at 30 mm depth

[e] 50% crumb rubber: 50% coated-calcined clay by volume homogenous blend infill treatment at 30 mm depth

[f] 15 mm crumb rubber over 15 mm calcined clay infill treatment

[g] 15 mm calcined clay over 15 mm crumb rubber infill treatment

[h] Fisher's Protected Least Significant Difference at 5% significance level

[i] NS, non-significant

[j] Date 1, 24 June 2013, average air temperature from 10 AM to 4 PM was 29.7°C

[k] Date 2, 18 July 2013, average air temperature from 10 AM to 4 PM was 29.7°C

[l] Date 3, 25 July 2013, average air temperature from 10 AM to 4 PM was 28.3°C

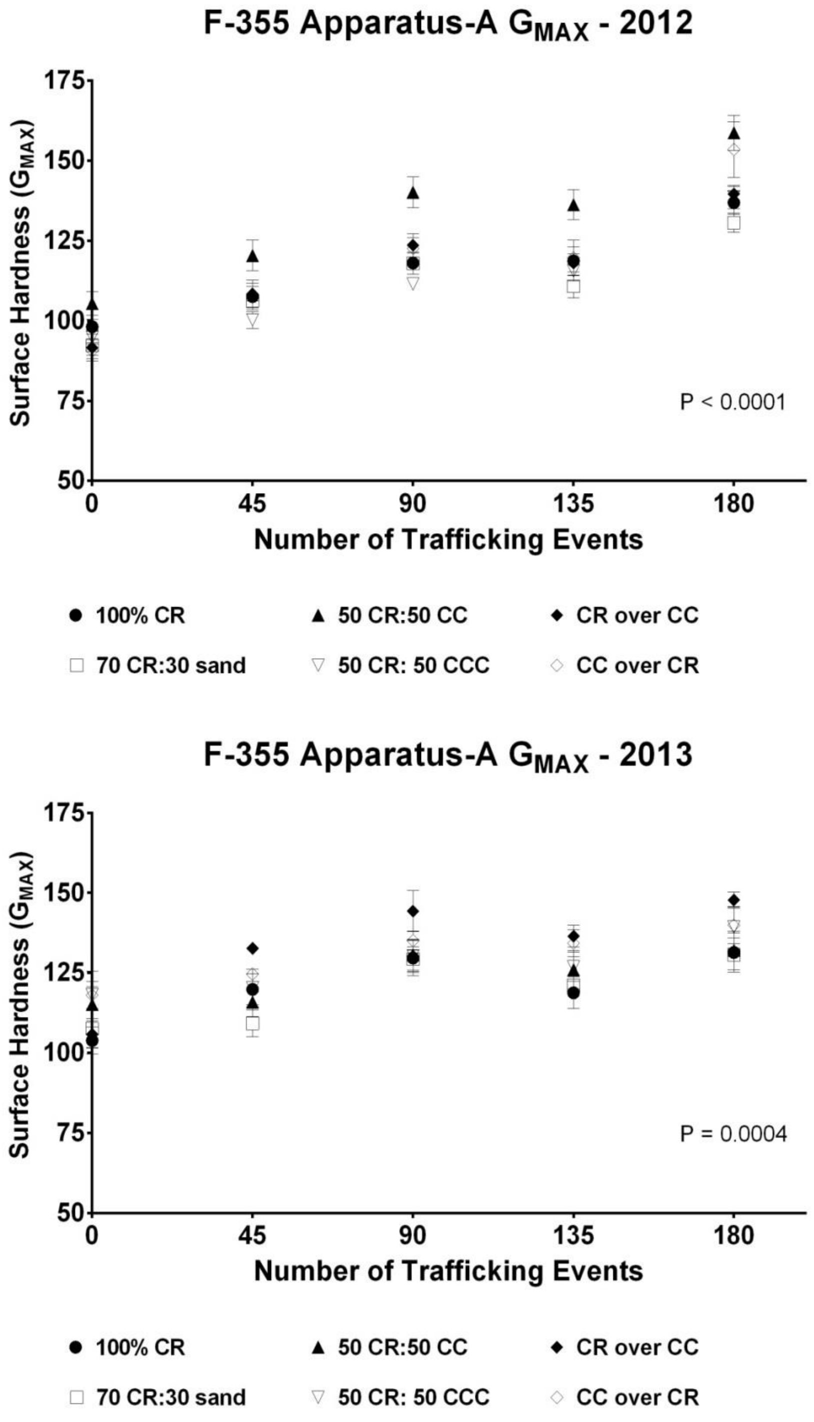

Figure 1. Changes in infill treatment surface hardness (G_{max}) as measured by the F355 Apparatus-A following 180 simulated traffic events during 2012 and 2013 in Knoxville, TN. Data for each year was analyzed separately. Standard errors of the mean values are presented for statistical comparison. Best-fit parameter estimates for linear regression equations are presented in Table 6.

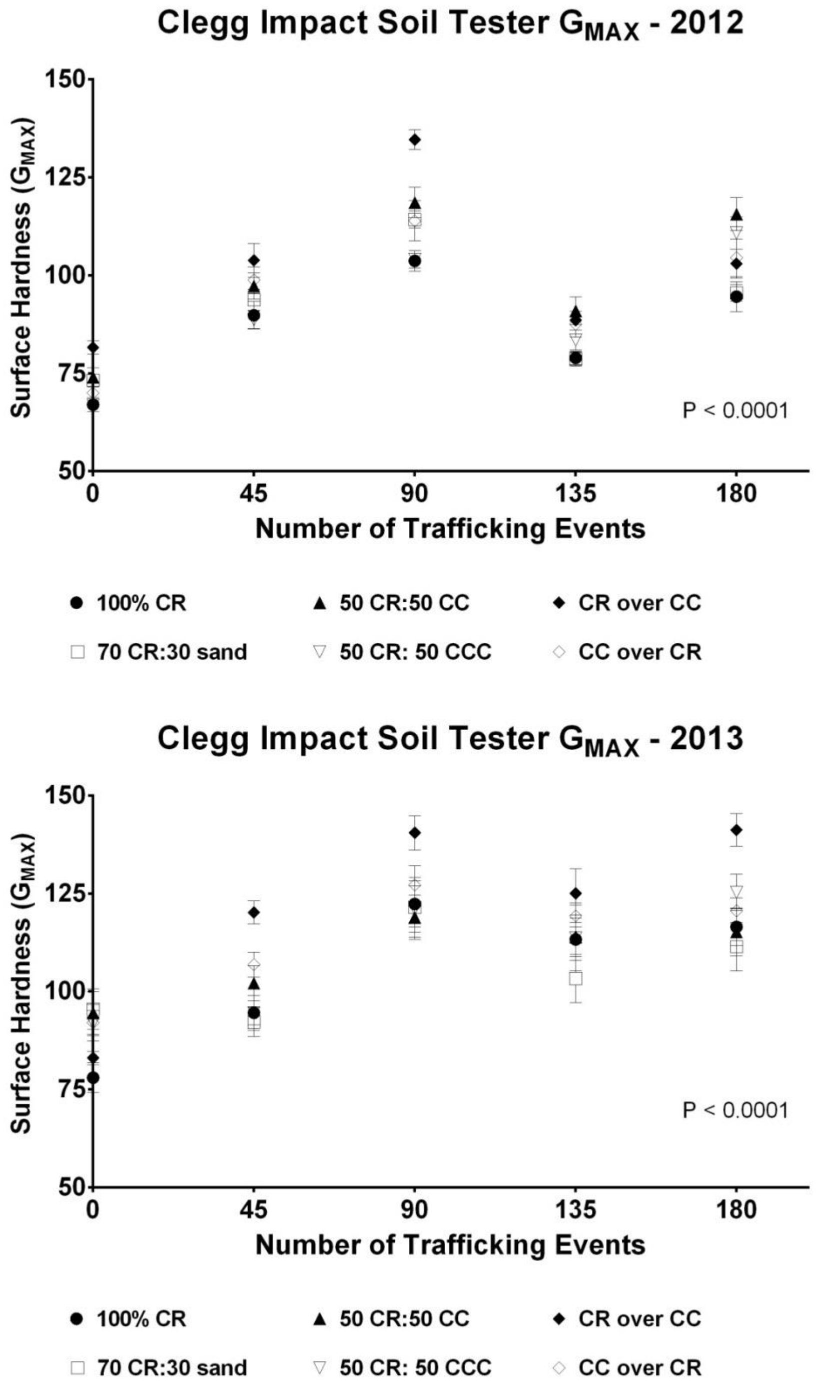

Figure 2. Changes in infill treatment surface hardness (G_{max}) as measured by the Clegg Impact Soil Tester following 180 simulated traffic events during 2012 and 2013 in Knoxville, TN. Data for each year was analyzed separately. Standard errors of the mean values are presented for statistical comparison. Best-fit parameter estimates for linear regression equations are presented in Table 6.

Table 6. Best-fit parameter estimates for linear regression equations characterizing changes in infill treatment surface hardness (G_{max}) following 180 simulated traffic events during 2012 and 2013 in Knoxville, TN. Both F355 Apparatus-A and Clegg Impact Soil Tester measuring devices are included. Standard errors for each parameter are listed in parentheses.

F355 Apparatus-A

	2012			2013		
Infill Treatment	β_0	β_1	R^2	β_0	β_1	R^2
100% CR[a]	98.18 (±2.87)	0.20 (±0.03)	0.57	109.9 (±4.19)	0.12 (±0.04)	0.19
70 CR:30 S[b]	95.37 (±2.79)	0.18 (±0.03)	0.54	108 (±3.72)	0.13 (±0.03)	0.25
50 CR:50 CC[c]	107.80 (±3.82)	0.27 (±0.03)	0.59	115.2 (±4.15)	0.10 (±0.04)	0.14
50 CR:50 CCC[d]	91.58 (±2.34)	0.23 (±0.02)	0.73	117.2 (±4.52)	0.19 (±0.04)	0.14
CR over CC[e]	95.18 (±2.36)	0.23 (±0.02)	0.74	115.8 (±3.69)	0.20 (±0.03)	0.44
CC over CR[f]	91.58 (±4.53)	0.30 (±0.04)	0.56	119.7 (±3.06)	0.12 (±0.03)	0.30

Clegg Impact Soil Tester

	2012			2013		
Infill Treatment	β_0	β_1	R^2	β_0	β_1	R^2
100% CR	77.94 (±3.62)	0.10 (±0.03)	0.17	85.79 (±4.12)	0.21 (±0.04)	0.43
70 CR:30 S	85.22 (±3.94)	0.07 (±0.04)	0.07	96.15 (±4.98)	0.10 (±0.05)	0.09
50 CR:50 CC	83.88 (±4.20)	0.17 (±0.04)	0.32	98.27 (±4.86)	0.12 (±0.04)	0.14
50 CR:50 CCC	74.22 (±3.35)	0.18 (±0.03)	0.46	92.13 (±4.01)	0.19 (±0.04)	0.39
CR over CC	96.83 (±5.20)	0.06 (±0.05)	0.04	97.72 (±4.54)	0.27 (±0.04)	0.50
CC over CR	83.40 (±4.4)	0.13 (±0.04)	0.19	99.28 (±3.53)	0.15 (±0.03)	0.35

[a] 100% crumb rubber infill treatment at 30 mm depth

[b] 70% crumb rubber: 30% silica sand by volume homogenous blend infill treatment at 30 mm depth

[c] 50% crumb rubber: 50% calcined clay by volume homogenous blend infill treatment at 30 mm depth

[d] 50% crumb rubber: 50% coated-calcined clay by volume homogenous blend infill treatment at 30 mm depth

[e] 15 mm crumb rubber over 15 mm calcined clay infill treatment

[f] 15 mm calcined clay over 15 mm crumb rubber infill treatment

Table 7. Analysis of variance for particle size distribution analysis performed on infill treatments receiving 0 or 180 simulated traffic events using the Cady Traffic Simulator in 2012 and 2013 located in Knoxville, TN.

		Sieve Number[a]							
		#10	#18	#35	#60	#100	#140	#270	Pan[b]
		Particle Size (mm)							
Year	Source	3.35-2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.15	0.15-0.1	0.1-0.05	0.05 - <0.002
2012	Infill x Traffic	***	***	**	***	***	***	***	***
2013	Infill x Traffic	*	***	***	***	***	***	***	**

[a] Sieve number based on number of holes per linear inch associated with the sieve screen

[b] Pan retains all remaining particles which include silt and clay particle factions

*, **, *** indicates significance at $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$ level

Table 8. Particle size distribution analysis performed on individual infill treatments receiving 0 or 180 simulated traffic events using the Cady Traffic Simulator during 2012 located in Knoxville, TN.

		Particle Size (mm)							
		3.35-2.0	**2.00-1.0**	**1.0-0.5**	**0.5-0.25**	**0.25-0.15**	**0.15-0.1**	**0.1-0.05**	**0.05 - <0.002**
Infill Treatments		----------Percent Retained[a]----------							
Non-Trafficked	100% CR[b]	4.1	81.7	13.3	0.2	0.1	0.1	0.1	0.0
	70 CR:30 S[c]	1.9	37.5	57.8	2.2	0.1	0.0	0.0	0.0
	50 CR:50 CC[d]	18.0	72.9	8.0	0.4	0.1	0.1	0.1	0.0
	50 CR:50 CCC[e]	18.2	71.8	8.3	0.4	0.1	0.7	0.0	0.0
	CR over CC[f]	16.6	74.9	7.5	0.3	0.1	0.1	0.1	0.0
	CC over CR[g]	15.6	76.6	6.7	0.3	0.1	0.1	0.1	0.0
Trafficked[h]	100% CR	4.1	77.9	16.2	0.6	0.1	0.2	0.2	0.0
	70 CR:30 S	2.0	36.4	58.2	3.0	0.1	0.1	0.1	0.0
	50 CR:50 CC	6.5	66.0	15.7	4.9	2.1	2.3	1.4	1.0
	50 CR:50 CCC	12.4	66.9	13.3	3.4	1.3	1.3	0.8	1.0
	CR over CC	11.5	67.7	12.8	3.5	1.3	1.5	0.8	0.6
	CC over CR	8.5	62.2	13.9	6.0	2.6	3.4	1.4	1.0
	LSD$_{0.05}$[i]	2.9	3.2	2.9	0.7	0.3	0.7	0.2	0.4

[a] Percent retained calculated by dividing the mass retained in each particle size by the initial total mass of the sample

[b] 100% crumb rubber infill treatment at 30 mm depth

[c] 70% crumb rubber: 30% silica sand by volume homogenous blend infill treatment at 30 mm depth

[d] 50% crumb rubber: 50% calcined clay by volume homogenous blend infill treatment at 30 mm depth

[e] 50% crumb rubber: 50% coated-calcined clay by volume homogenous blend infill treatment at 30 mm depth

[f] 15 mm crumb rubber over 15 mm calcined clay infill treatment

[g] 15 mm calcined clay over 15 mm crumb rubber infill treatment

[h] Trafficked sub plot received a total of 180 simulated trafficking events using the Cady Traffic Simulator from 12 September to 3 December 2012

[i] Fisher's Protected Least Significant Difference at 5% significance level

Table 9. Particle size distribution analysis performed on individual infill treatments receiving 0 or 180 simulated traffic events using the Cady Traffic Simulator during 2013 located in Knoxville, TN.

		Particle Size (mm)							
		3.35-2.0	**2.00-1.0**	**1.0-0.5**	**0.5-0.25**	**0.25-0.15**	**0.15-0.1**	**0.1-0.05**	**0.05 - <0.002**
Infill Treatments		**Percent Retained[a]**							
Non-Trafficked	100% CR[b]	12.1	73.1	12.4	1.3	0.1	0.1	0.0	0.0
	70 CR:30 S[c]	8.4	36.4	52.4	2.3	0.1	0.0	0.0	0.0
	50 CR:50 CC[d]	19.9	74.1	4.9	0.4	0.1	0.1	0.1	0.0
	50 CR:50 CCC[e]	17.4	76.4	5.3	0.3	0.0	0.0	0.0	0.0
	CR over CC[f]	21.6	73.0	4.6	0.2	0.0	0.0	0.0	0.0
	CC over CR[g]	19.8	74.5	4.6	0.2	0.1	0.1	0.1	0.0
Trafficked[h]	100% CR	12.2	72.8	12.1	1.6	0.3	0.2	0.2	0.0
	70 CR:30 S	6.2	34.6	55.4	2.9	0.2	0.1	0.1	0.0
	50 CR:50 CC	16.7	56.6	11.3	7.1	3.4	2.5	0.6	0.2
	50 CR:50 CCC	15.1	63.9	11.0	4.6	2.2	1.5	0.4	0.2
	CR over CC	15.4	66.3	9.3	4.1	1.9	1.4	0.3	0.1
	CC over CR	15.8	52.2	13.8	8.3	4.4	2.1	0.4	0.1
	$LSD_{0.05}$[i]	3.8	5.6	4.6	1.4	0.4	0.3	0.1	0.1

[a] Percent retained calculated by dividing the mass retained in each particle size by the initial total mass of the sample

[b] 100% crumb rubber infill treatment at 30 mm depth

[c] 70% crumb rubber: 30% silica sand by volume homogenous blend infill treatment at 30 mm depth

[d] 50% crumb rubber: 50% calcined clay by volume homogenous blend infill treatment at 30 mm depth

[e] 50% crumb rubber: 50% coated-calcined clay by volume homogenous blend infill treatment at 30 mm depth

[f] 15 mm crumb rubber over 15 mm calcined clay infill treatment

[g] 15 mm calcined clay over 15 mm crumb rubber infill treatment

[h] Trafficked sub plot received a total of 180 simulated trafficking events using the Cady Traffic Simulator from16 September to 19 December 2013

[i] Fisher's Protected Least Significant Difference at 5% significance level

CONCLUSIONS

Irrigation of synthetic turf reduced surface temperatures to 60 to 85% of the surface temperatures 10 minutes prior to irrigation. However, by thirty minutes after irrigation, surface temperatures increased to 74 to 102% of the pre-irrigation temperature. By 150 minutes after irrigation, plots infilled with 50 CR:50 CC and CC over CR were 10 to 24% and 20 to 21% lower than the surfaces with the highest percentage of pre-irrigation temperature, which ranged from 95 to 137%. While CC modification had a transient effect on surface temperature, inclusion within crumb rubber infill increased surface hardness. In 2012, plots infilled with CC increased at a faster rate of surface hardness compared to 100% CR and 70 CR:30 S with application of 180 simulated traffic events. In 2013, surface hardness increased plots receiving CR over CC infill increase faster than the remaining five treatments. Infill material particles, specifically the CC treatments, fractured with simulated traffic. Applying a 15 mm layer of CR over a 15 mm layer of CC or having a polymer coating on the CC particles reduces the breakdown. While CC particles did fracture to a smaller size following simulated traffic, 82 to 99% of the infill was > 0.5 mm in diameter and 0 to 8.4% of the infill was 0.25 to <0.002 mm in diameter. This suggests that plots have hydraulic conductivity > 15 cm h^{-1}. Significant temperature differences were not consistent among treatments and surface hardness with CC tended to measure higher than 100% CR and 70 CR:30 S. The results of this experiment indicate the use of CC in synthetic turf may be limited.

VITA

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