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CRUMB RUBBER AS A SOIL AMENDMENT
IN A VARIETY OF TURFGRASS SETTINGS

presented by

J. Tim Vanini

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Major professor

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# THE DYNAMICS AND DIVERSITY OF CRUMB RUBBER AS A SOIL AMENDMENT IN A VARIETY OF TURFGRASS SETTINGS

By

J. Tim Vanini

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
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## ABSTRACT

# THE DYNAMICS AND DIVERSITY OF CRUMB RUBBER AS A SOIL AMENDMENT FOR A VARIETY OF TURFGRASS SETTINGS

By

J. Tim Vanini

In 1991, two trial studies were initiated to evaluate the efficiency of chopped tire pieces or crumb rubber as a soil amendment in high traffic areas. Crumb rubber (6mm) was tilled into the soil profile at two depths (7.6 and 15.2 cm) and five volumes (0, 10, 20, 30, and 40% ) in a 2x5 randomized complete block design. In 1993, two additional studies were initiated to evaluate two management strategies to introduce into the turfgrass environment. For the core cultivation study, two particle sizes (6 mm and 2.0/0.84 mm) and six cultivation treatments were evaluated in a 2x6 randomized complete block design, with the crumb rubber treatments using the 20% v/v rate. For the topdressing study, two particle sizes (6 mm and 2.0/0.84 mm) and five topdressing thickness rates (0.0, 3.9, 7.8, 9.6, and 19.2 mm) were evaluated in a 2x5 randomized complete block design. Playing surface characteristics, turf quality, soil physical properties, soil chemical properties, and surface dynamics of crumb rubber particles compared to sand particles were evaluated.

DEDICATION

To My Father

In joyous memory

## ACKNOWLEDGEMENTS

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Special thanks must be extended to Dr. John N. Rogers, III for being my teacher, advisor, graduate committee chair, and friend. Under his guidance, I have truly had an experience that I will never forget, and am thankful that he gave an ex-hockey player a chance.

A special thanks must be extended to my mother for just being my mother and doing what mothers do best....listen.

I want to thank my friends for a great time, and may the force be with you!

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*Introduction*

The demands for quality natural turf sportsfields has steadily increased since the 1980's. Primary reasons for this include an increase in recreational activity (Watson et al., 1992), the gradual shift from artificial turf to natural grass (Berg, 1993), and an increase on concern for the player safety and liability (Duff, 1995). To achieve high standards of quality from an agronomic standpoint, there must be concentrated efforts on two critical components: alleviating soil compaction and improving turfgrasss wear.

Due to the destructive nature of sports turf usage, field renovation and reconstruction is often required on a frequent if not perennial basis. Another practice used to combat these problems is soil modification. Numerous studies have been conducted to evaluate different soil amendments (Morgan et al., 1966; Thurman and Pokorny, 1969; Waddington et al., 1974; Nus, 1984). These studies have been conducted in order to improve soil physical properties which in turn enhance overall turfgrass quality.

Management practices promote turfgrass density and color or the aesthetics of a sportsfield. These essential practices include mowing, fertilization, irrigation, and pest control. Management practices, such as, core cultivation (Rieke and Murphy, 1989; Christians et al., 1993) and topdressing (Madison et al., 1974; Davis, 1983; Rieke, 1991) are the practices most paramount to be employed in high activity areas. These practices can reduce soil compaction, improve soil/plant relationships, and provide a smoother playing surface. However, activity on a football field or a soccer field can be intense, and the turf manager must not only improve the playability and aesthetics of a field, but must reduce the potential of surface-related injuries. The field's surface must be firm and provide adequate traction. Furthermore, any maintenance practices performed to improve playing quality should not promote deleterious effects between soil and plant relationships (van Wijk, 1980).

Numerous studies have been conducted to evaluate playing field quality characteristics (Harper et al., 1984; Baker and Bell, 1986; Rogers et al., 1988; Baker and Canaway, 1993; Canaway and Baker, 1993). There seems to be a general agreement that the most pertinent data to collect with regards to playing quality are surface hardness, traction, and ball bounce. However, there are different ends of the spectrum that are responsible for sportsfield quality. Harper and coworkers (1984) and Rogers and coworkers (1988) have evaluated these factors and have made a number of observations to help quantify playing field quality. More specifically, they were able to quantify differences between practice and game fields at the same school. Harper and coworkers (1984) could pinpoint this due to the lack of management practices (mowing, fertility, core cultivation, and irrigation) performed on a practice field versus a game field. As a result, lower impact values (a softer surface) and higher shear resistance values (increase traction) were associated with game fields and consequently better management practices (Rogers et al., 1988).

The turf manager must realize the important relationships among soil properties, turfgrass species, soil fertility, supplemental irrigation, and other management practices. Integration of agronomic factors and management practices are critical in providing a high quality playing surface at all levels.

Therefore through the aid of a soil amendment, the turf manger has an additional tool which can be used towards improving the playing quality of a sportsfield. The objective of crumb rubber was to improve soil/plant relationships and subsequently increase playing field quality.

*Literature Review*

Turfgrass serves three purposes to man and society: recreational, functional, and ornamental (Beard, 1973). Recreational turf is a diverse term, and it encompasses many different activities, from golf courses and athletic fields to walk paths. Due to the high demand for recreational turf, (e.g. football and soccer fields), areas of research have primarily focused on reducing soil compaction and improving wear tolerance, thus improving overall quality in these high traffic areas (Petersen, 1973). Soil compaction is the change in soil volume, and volume changes due to mechanical sources (machines) or natural sources (drying and wetting) (Harris, 1971). Wear tolerance is due to the morphology and physiology of the plant and its tolerance the tearing, crushing, and abrasion from traffic (Beard, 1973). These two consequences of high traffic force turfgrass professionals to face the constant challenge of finding the tolerance thresholds of the soil and turfgrass plant. In other words, when compaction levels increase, this adversely affects plant and root growth thus affecting the aesthetic value. In regards to sportsfields, to improve the playing surface the soil strength must be increased for smoothness and uniformity, yet not reduce aeration and consequently weaken the plant to reduce the overall turfgrass quality of the playing surface (van Wijk and Beuving, 1978). Subsequently, one method has been to improve fields through the use of sand-based root zones or soil amended soils to reduce compaction which in turn will improve plant properties (Bingaman and Kohnke, 1970, Daniel and Freeborg, 1979, Waddington et al., 1974). In this situation, compaction levels are minimal, but turfgrass wear inevitably results primarily from abrasive forces of the sand on the plant tissue, thus changing the playability and aesthetics of a sportsfield. However, understanding how these two factors are dependent and interdependent on each other will provide clues for improving recreational turf areas at all levels.

*Soil Responses*

Compaction is referred to as the "hidden stress" (Beard, 1973; O'Neil and Carrow, 1982). Watson (1961) refered to compaction as, " Soils in which structure has been destroyed - partially or completely - are said to be dense and compacted". Soil compaction increases soil density, reduces percolation and infiltration, reduces soil aeration and porosity, increases $CO_2$ and toxic gases, and increase water run-off and heat conductivity (Letey et al., 1966; Waddington et al., 1974; Carrow, 1980). Gramckow (1968) reported that soil compaction reduced turfgrass growth on several soil mediums. Carrow (1980) found an increase in bulk density and reduction in porosity strongly correlated to a decrease in visual quality. Beard (1973) stated that coarse-textured soils will compact, but the contact between the sand particles prevents the soil from losing macropores. However, when a fine-texture soil compacts macropores are nearly eliminated thus having an adverse effect on not only soil physical properties but also the turfgrass plant. However, Kunze and coworkers (1957) emphasized the importance of a "graduation and continuity of pore sizes" over that of total porosity. Thus, if the integrity of pore sizes is maintained in the soil, water freely drains. Athletic fields are not regularly subjected to heavy machinery and the player traffic received thereby normally only affects the upper soil surface. O'Neil and

Carrow (1982) observed significant differences in compaction when using a greens roller in the top 3 cm of the soil, but observed very little change in the soil profile from 3-6 cm in recreational turf areas.

*Soil and Plant Responses*

The combination of soil/plant relationships is critical in high traffic areas because one ultimately affects the other. First, the majority of a turf root system is in the upper soil profile. Van Wijk (1980) observed 90% of the root mass in the upper 5 cm of the soil profile. In recreational turf, the top 2-3 cm was considered the most compacted area (Morgan et al., 1966; O' Neil and Carrow, 1982). An adverse affect of rooting from compaction has been shown as Letey and coworkers (1966) observed slower growth of roots in compacted soils as well as fewer young roots generating from the crown tissue. Thurman and Pokorny (1969), while investigating wear and compaction on bermudagrass (Cynodon dactylon v. 'Tifgreen'), reported a more extensive root system was promoted under conditions of less traffic which in turn promoted better recovery of the turf and overall quality. In other words, the more compacted a surface becomes, the lower amount of $O_2$ is in the soil and available to the root system (van Wijk, 1980). Furthermore, O'Neil and Carrow (1982, 1983) concluded that in the upper 3 cm, when evaluating Kentucky bluegrass and perennial ryegrass, respectively, the root weights decreased as compaction levels increased due to low aeration and high soil strength. They also reported oxygen diffusion ratings

(ODR) levels were low enough to limit shoot and root growth. However, van Wijk and coworkers (1977) reported turfgrass density can still be high despite low oxygen levels in the soil profile to adequately supply the root system. Waddington and Baker (1965) measured ODR levels in compacted soil for three different species : Merion Kentucky bluegrass (Poa pratensis, L.), Penncross creeping bentgrass (Agrostis palustris Huds.), and goosegrass (Eleusine indica L. Gaertn.). They concluded the three grasses were tolerant of low levels of oxygen in the soil, but they could not conclude if proper growth would last in all soils.

### *Plant Responses*

Numerous studies have been conducted to measure varying compaction levels along with a decline in turf quality (Valoras et al., 1966; Thurman and Pokorny, 1969; Carrow, 1980; O'Neil and Carrow 1982, 1983; Sills and Carrow, 1983). It was also noted that wear was the significant component to reducing turfgrass quality. Subsequently, when turfgrass wear was induced, it weakened the physiology of the plant and eventually lead to dessication. Furthermore, in assessing sportsfields, van Wijk and Beuving (1978) noticed a strong correlation in the reduction on turfgrass density in high traffic areas versus low traffic areas on a football pitch.

The most sensitive part of the turfgrass plant is the crown tissue area (Beard, 1973). Leaves, roots, stolons and/or rhizomes regenerate from the turfgrass crown, and damage to the crown tissue will adversely affect growth. Thurman and Pokorny

(1969) found that damage to the crown tissue area, in studying bermudagrass (Cynodon dactylon v. 'Tifgreen'), was proportional to the intensity of the traffic applied. Beard (1973) later observed injury was far more severe with damage to the crown tissue versus other parts of the plant. Shearman and Beard (1975) were able to quantify wear tolerance among seven species of cool-season grasses citing verdure as the preferred method to quantitatively assess wear tolerance, thus implying the importance of the crown tissue area in high traffic areas. Later, Shearman and coworkers (1980) emphasized the importance of the crown tissue area in a heavy traffic area by introducing the "paver-system", a system designed to protect the crown tissue thus preserving the turfgrass stand.

A reduction in clipping yields with an increase in compaction treatments has been observed (Thurman and Pokorny, 1969; Carrow, 1980; O'Neil and Carrow, 1982; Sills and Carrow, 1983; Agnew and Carrow, 1985). O' Neil and Carrow (1982) observed this to be the first sign of a decrease in turfgrass wear tolerance. Thurman and Pokorny (1969) reported an increase in fresh weight clippings with milled bark amended soils verus the unamended soils. However, a decline in resiliency was observed with constant compacting implying the ineffectiveness of any amendment to reduce compaction that in of itself is not resistant to compactive forces.

The role of fertility and its relationship with turfgrass wear tolerance has been investigated to suggest that nitrogen fertility will not alleviate or accelerate crown tissue repair in compacted areas, especially during stress periods when conditions for recovery are not ideal (Sills and Carrow, 1983; Krick and Rogers, 1994). Sills and

Carrow (1983) observed a visual quality decrease with increased compaction treatments despite the nitrogen rate or the nitrogen carrier. They also observed increasing nitrogen applications could not alleviate the detrimental effects as a result of improving turfgrass density as compaction levels increased.

van der Horst and Kamp (1974) reported an improvement in wear tolerance with turfgrass mixtures at an optimum annual nitrogen level of 200 kg $ha^{-1}$, but also observed that a good mixture for recreational areas was greatly dependent upon weather conditions. Despite the activity taking place on a sportsfield, Canaway (1985) observed nitrogen to improve traction to its highest values at a yearly rate of 225 kg $ha^{-1}$ on a sand field. Although the measurements varied greatly versus a soil-based field, this does indicate nitrogen having an influence on turfgrass responses on a non-compacted soil profile.

Overall shoot and root density decreases as well as overall quality and turfgrass vigor as traffic and compaction increases (Shearman and Beard, 1975; O'Neil and Carrow, 1982; Sills and Carrow, 1983; Agnew and Carrow, 1985). Watson (1950) noticed the smallest reduction in turfgrass density of a stand (Kentucky bluegrass, a bentgrass mixture, and red fescue) at the "heavy" compaction treatment. However, Harper (1953) observed the greatest reduction, in Kentucky bluegrass, under the "heavy" compaction treatment; a decrease in turfgrass vigor and an increase in weeds. Carrow (1980) noticed that Kentucky bluegrass density decreased, but individual shoot weights increased, as compaction levels increased. Thus, plant size increased with Kentucky bluegrass while perennial ryegrass and tall fescue plant size decreased.

Cuddeback and Petrovic (1985) reported an improvement in visual quality and a decrease in weather injury and thatch on Agrostis palustris Huds. on a sandy loam soil at the highest traffic frequency (20 passes per week versus 12, 8, and 0).

Most research to determine wear tolerance has used the aid of a traffic simulator (Gramckow, 1968; Shearman and Beard, 1975; Gore et al., 1979; Carrow, 1980; Canaway, 1982; Cuddeback and Petrovic, 1985; Cockerham and Brinkman, 1989) before making recommendations to assess plant and soil relationships, and to make evaluations under controlled environments. A wear machine can serve in two capacities: first, a specific number of passes can be made and then treaments can be evaluated; or second, treatments can be worn until necrosis and then the differences among the number of passes can be evaluated as well (Youngner, 1961; Shearman and Beard, 1975). The apparatuses have included a greens roller, a modified golf shoe spiker, an automobile tire travelling around a pole and a studded roller. The purpose of these devices was to simply repeat wear treatments at a constant level, and then vary frequency to establish differences among treatments. Gramckow (1968) and Shearman and Beard (1975) used a modified turfgrass wear tester which was staked into the ground and rotated around in a circle. Gore and coworkers (1979) and Canaway (1982), in assessing a variety of turfgrass mixtures, used a studded roller.

In sportsfield research, the importance of wear simulation cannot be overemphasized due to time and space constraints, and the variety of treatments to be evaluated. Cockerham (1989) was able to quantify that 78% of American football is played on 7% of the field. Therefore, Cockerham and Brinkman (1989) were able to build a wear machine specifically geared towards American football. They further quantified wear simulation by counting, on average, 56 "dent" marks per square foot between the hashmarks between the forty yardlines, and noted this was the highest number in a designated area on a football field.

*Playing Surface Quality and Characteristics*

In recreational turf, the combination of vegetation and the soil profile acting together introduces the concept of surface hardness (Lush, 1985). Recreational turfgrass activities, on all scales, has increased due to the increase in the standard of living and income (Petersen, 1973). According to Watson and coworkers (1992; a personal communication through Kurtz, 1986), it is estimated approximately 3.2 million youngsters are involoved in Little League or other baseball and softball leagues while several other million are participating in soccer (America's fastest growing sport). Also, Kurtz approximated more than 22 million adults participating in just under 175,000 softball leagues.

Stanaway (1981) concluded grass surfaces were inconsistent in regards to ball bounce and roll. He claimed playing conditions were too inconsistent when the playing surface was too dry or too wet. Furthermore, Harper and coworkers (1984) and Rogers and coworkers (1988) were able to quantify unpredictable factors even within the site from practice field and game field. As the number of games increases, aesthetics, and playability was reduced as well as increasing the potential of surface-related injuries (although thresholds have not been quantified as to determine what agronomic factors will cause a surface-related injury) (Harper et al., 1984; Rogers and Waddington, 1992). Bramwell (1972) observed an increase in surface-related injuries, regardless of either artificial or grass fields, when the surface was dry versus wet. After conducting a study throughout Pennsylvania at various high schools, Harper (1984) estimated 20.9% of all injuries occuring during the football season were definitely or possibly field related injuries. Ekstrand and Nigg (1989) in evaluating soccer fields, observed that 24% of the injuries were surface-related. However, it is believed that most of the injuries were a combination of the playing surface and other factors involved such as human elements and/or improper footwear. Furthermore, they were able to generalize that more injuries occurred on a "hard" surface versus a "soft and well-cushioned" surface. Agronomic factors were not evaluated as to specifically define these two generalities.

Numerous studies have been conducted on playing surface quality (Bell et al., 1985; Baker and Bell, 1986; Baker and Canaway, 1993; Canaway and Baker, 1993). Evaluating playing quality relies on the interaction of player and surface as well as the ball and surface (Baker and Canaway; 1993). Agronomic factors important to evaluating playing quality include soil (soil moisture and drainage) and plant (species and cultivar, density, height of cut, and root biomass) interaction (Canaway and Baker, 1993). Assessment of playing quality include test methods such as surface hardness, traction, ball bounce, ball roll, and sliding traction, with the first three being the most important components of the playing quality (Bell et al., 1985).

Arguably the most pertinent data to evaluate surface characteristics is the measurement of surface hardness or impact absorption. The first reported work in this area was by Gramckow (1968). He evaluated the surface hardness of different soil mixtures and species. To evaluate surface hardness, a 3.64 kg weight was dropped at a height of 1.83 m. He reported that surface hardness increased as soil moisture decreased as well as citing differences in surface hardness among bermudagrass (Cynodon dactylon v. Tifway), bluegrass (Poa spp.), and fescue (Festuca spp.). Clegg (1976) measured surface hardness on dirt-based road surfaces in Western Australia using a portable device called the Clegg Impact Soil Tester (CIT). The CIT measures surface hardness by dropping a hammer (0.5, 2.25 or 4.5kg) at a given height (0.30 or 0.46m). At the end of the hammer is an accelerometer which transmits an impulse or a negative acceleration value (opposite of gravity) through a cable to a hand-held readout box thus displaying a peak deceleration value ($G_{max}$). The lower the number, the softer the surface. Thomas and Guerin (1981) developed the "Sports Simulator" which measured the $G_{max}$ value of a 25kg weight, and the time for the surface to return to its original state. Lush (1985) introduced the concept of the CIT (using a 0.5kg hammer) for testing turfgrass surface hardness on cricket pitches. Following this, numerous studies were initiated on a variety of playing surfaces such as tennis courts (Holmes and Bell, 1986b), bowling greens (Holmes and Bell, 1986c), and soccer fields (Holmes and Bell, 1986a; Baker, 1987; Rogers and Waddington, 1989).

Rogers and Waddington (1990) evaluated surface hardness on turfgrass surfaces at different mowing heights and cool season species by replacing the hand-held box and using a Brüel and Kjaer 2515 Vibration Analyzer with an oscilloscope. Rogers and Waddington (1992) further defined surface hardness parameters by introducing the time element, and the area underneath the impact curve. Two primary parameters reported, along with $G_{max}$, included time to peak deceleration ($T_p$), and total duration of impact ($T_t$) (both measured in milliseconds). These numbers, in particular, represented the time factor, and indicated a softer, more resilient surface as the time increased. They have shown instances where there were not differences in $G_{max}$ but significant differences in both $T_p$ and $T_t$ between treatments thus demonstrating their importance (Rogers and Waddington, 1992). They also noted that the most important tests to include the time element were those involving different surfaces (turf vs. bare soil, artificial vs. grass surfaces). Furthermore, they were able to correlate differences between the 0.5kg and 2.25kg hammers; the 0.5kg hammer was significantly correlated to ball bounce, and the 2.25kg hammer was significantly correlated to an athlete falling down to the playing surface (Holmes and Bell, 1986a; Rogers and Waddington, 1990).

Recently, Beard (1993), and Dunn and coworkers (1994) have used the CIT to evaluate surface hardness after either altering the soil profile with a mesh system or by evaluating a variety of turfgrass mixtures of warm and/or cool season species. Both investigators reported $G_{max}$ values, but did not evaluate the time differences among treatments.

Adrian and Xu (1990) emphasized the importance of surface hardness in relation to surface quality as the ability of the player's effectiveness relied on the energy returned to the athlete in order to enhance performance. However, it should be noted, Zebarth and Sheard (1985) and Rogers and coworkers (1988) were able to report that mowing height had no effect on surface hardness, and that soil moisture and surface type did influence surface hardness. Therefore, the lower the soil water content and the turfgrass density, the harder the surface thus increasing the susceptibility of compaction, and potential player injury (Harper et al., 1984; Rogers et al., 1988).

Other surface measurements include traction and ball bounce. Traction measurements can also be referred to as shear resistance, and, the higher the number, the higher the resistance to shear. Traction measurements have been reported by Gramckow (1968), Canaway (1975), van Wijk (1980), Zebarth and Sheard (1985), Henderson (1986), Rogers and Waddington (1989), Middour (1992), and McNitt (1994). These measurements have been reported on a variety of situations as well as measuring devices, from a healthy turf stand to bare soil. Zebarth and Sheard (1985) reported a significant correlation between an increase in shearing and bulk density when evaluating turf cover for thoroughbred race tracks. Zebarth and Sheard (1985) and Rogers and Waddington (1989), using a hoof simulator device and Eijkelkamp shearvane, respectively, reported an increase in traction on a turfgrass stand and tall fescue, (Festuca arundinacea), respectively, when compared to bare soil citing the prescence of roots as the reason. Thus, being able to maintain turfgrass throughout a playing season only improves traction and does not deteriorate the playing field. Rogers and Waddington (1989) also reported the highest traction measurements on tall fescue when soil moisture was lowest. Adams (1981) did report that fine material (organic matter; peat moss) can increase shearing, but this depends on soil water content and bulk density.

There has been poor correlations among the devices reported in the literature due to the variety of appartuses being used. Middour (1992) showed a poor correlation between the PENNFOOT and the shear apparatus used by Canaway (1975) and the Eijkelkamp shearvane (Henderson, 1986). Unlike previous devices, the PENNFOOT has been able to measure not only rotational, but also linear traction. Thus, McNitt (1994), reported that tall fescue and Kentucky bluegrass had the highest measurements followed by perennial ryegrass, and creeping red fescue having the lowest. Also, it should be noted the heaviest loading weight (102 kg.) provided the highest traction measurements as well.

Ball bounce was defined by Bell and coworkers (1985) to indicate surface hardness as well as surface quality. Holmes and Bell (1986b) were even able to utilize Clegg measurements (0.5 kg) to evaluate tennis ball bounce by utilizing the equation (%)=20.71 + Clegg value (0.17) with asymptotic limit of 58%. In another study, in evaluating soccer pitches, Holmes and Bell (1986a) were able to highly correlate (r=0.84) between ball bounce and the CIT (0.5 kg hammer). Factors affecting ball bounce include soil moisture, bulk density and turfgrass cover (Canaway, 1985). Utilization of these different measurements can further characterize playing surfaces, and potentially correlate to agronomic factors as well as thresholds in relation to the biomechanics of the human body.

*Soil Modification and Amendments*

With areas subjected to high traffic, soil modification has been a focus to not only improve soil characteristics but to also improve turfgrass wear tolerance. Soil amendments can increase macropore space which could reduce soil moisture content and be able to improve turfgrass vigor and quality when traffic increases, thus improving infiltration (Thurman and Pokorny, 1969). However, in order for a soil amendment to be effective, various factors must be considered in order to determine its feasibility such as, the proper amounts, the properties of the amendment, soil physical characteristics, and the mixing procedure (Waddington et al., 1974).

Proper volumetric mixtures of sand:peat:soil has been evaluated for reducing compaction and increasing turfgrass vigor in high traffic areas (Kunze et al., 1957, Swartz and Kardos, 1963). Kunze and coworkers (1957) observed that soil mixtures should be able to resist compaction while still providing a soil medium which would promote turfgrass growth. Furthermore, Swartz and Kardos (1963) reported inadequate soil percolation rates with sand contents below 50%. Furthermore, they confirmed a threshold of 70% sand was required for proper soil modification in a traffic area. This would allow for an increase in macropores and a reduction in compaction, thus percolation rates would increase allowing for proper drainage and healthy turf stand. Baker and Issac (1987) observed a higher turfgrass stand on a well-drained soil versus a poorly-drained soil.

Organic amendments evaluated for improving soil/plant relationships have included peat, lignified wood, sawdust, rice hulls, and pine bark, (Morgan et al., 1966, Thurman and Pokorny, 1969, Paul et al., 1970, Waddington et al., 1974, Nus, 1984). Waddington (1992) summarized organic amendment uses ranging from improving nutrient holding capacity and water holding capacity as well as an increase in air porosity. However, regardless of breakdown, percolation rates decrease due to the presence of finer textured particles filling in the pores (Adams, 1976; Swartz and Kardos, 1963; van Wijk, 1978).

Various inorganic amendments have been evaluated for improving soil physical properties. These have included calcined clays, diatomite, perlite (Morgan et al., 1966; Waddington et al., 1974; Nus, 1984), coke bottles, bottle caps, bricks (Wood, 1973), vermiculite (Paul et al., 1970), and zeolite (Nus, 1984; Ferguson et al., 1986). Advantages of these amendments include increased water retention, air porosity, and increased nutrient retention, but due to intense traffic conditions these qualities subside quickly. Rieke and coworkers (1992) recently evaluated a ceramic, isolite, to improve soil physical properties and to withstand traffic. Although no significant differences were found with soil water content and surface hardness (CIT), the study was not conducted on a long-term basis. Polyacrylamide gels (Nus, 1984; Baker, 1990) is an amendment that can improve water holding capacity in the soil profile while also reducing surface hardness. However, incorporation rates are still being evaluated for proper volumes because an excess amount can make the surface too soft when soil water content is high.

Shearman and coworkers (1980) investigated and analyzed the turfgrass-paver complex system for intensely trafficked areas. By protecting the crown tissue areas, the system was an attempt to reduce soil compaction. Surface hardness was not the objective as was the importance of keeping vegetation present in a high traffic area. Recently, an inter-locking mesh system was evaluated for high traffic turf (Beard and Sifers, 1993; Canaway, 1994; Richards, 1994). Although, it was not specifically protecting the crown tissue, the inventors have observed, and termed, a "self-cultivation" process taking place with constant traffic being applied thus improving turfgrass vigor and soil aeration. The mesh system was able to increase stability and traction, and decrease surface hardness.

The need for a product that will aid in soil physical properties and resistant to breakdown is in need. Furthermore, the soil amendment must in turn improve playing field qualities ranging from a decrease in surface hardness and an increase in traction to improving overall quality.

### *Crumb Rubber as a Soil Amendment*

In 1991, 234 million tires were discarded in the United States, many of them in landfills. However, in 1994, 25 out of 47 states had banned tires from landfills. Furthermore, 46 out of 47 states had legislated funding for marketing and recycling the use of tires so they are not disposed of improperly. It is predicted by 1998, the estimated 250 million tires discarded annually will be used due to the variety of demand for this recycled product (Riggle, 1994).

To recycle the tire, this usually means the tire must be broken down into very small pieces and subsequent uses for these parts sought out. While the metal/steel in the tire are easily sold, finding a market for crumb rubber particles (6.0mm or less) has been more challenging.

One idea for crumb rubber, in a recycled use in a turfgrass scenario was conducted by golf course superintendent Ted Woehrle at Beverly Country Club in Chicago, Illinois in 1959 (personal communication, 1995). Crumb rubber was used on a cement walkway, on an declining slope, with an adhesive to keep the crumb rubber in place, to pad the area from slippage, improve traction, and reduce the golf spikes from wearing down quickly.

However, due to its elastic properties (Treloar, 1975), crumb rubber particles introduced to highly compacted turf areas could be beneficial to both the soil profile and the turfgrass community. In the soil profile, fluctuations in soil moisture or soil heat could provide air pockets which in turn improve soil structure and turfgrass physiology. Theoretically, crumb rubber would be able to reduce soil compaction, and increase turfgrass wear tolerance. Furthermore, crumb rubber would be able to stabilize fluctuations in soil moisture, thus providing a more stable playing surface. As a result, this would subsequently reduce turf system inputs and the potential for surface-related injuries. Therefore it was hypothesized, as compaction levels and soil moisture increased, the crumb rubber would contract. However, once soil moisture decreased this would allow crumb rubber to expand thus creating air pockets to improve the soil aeration and subsequently increase root density. Furthermore, turfgrass quality and vigor would improve. These positive relationships would enable the turfgrass stand to recuperate quicker especially in a high traffic and compacted area.

The use of crumb rubber for turfgrass was first reported by Ward (1970) as a soil amendment with sand, soil or peat, and rice hulls. It was noted that crumb rubber treatments had the highest hydraulic conductivity but also had the lowest root mass. However,the addition of soil or peat, to sand with crumb rubber was able to reduce the phytotoxicity versus crumb rubber and sand alone. Greenhouse studies (Ventola et al., 1992) found that the addition of crumb rubber, on a Lolium perenne turf stand and a variety of soil types, introduced to the soil/turfgrass community tilled into the soil increased clipping yields at 10% and 20% crumb rubber (v/v) in the soil. Furthermore, they concluded an increase in the macropore to micropore ratio when water was withheld from the treatments. This research was conducted on three different soils (sand, loam, and a fine sand).

In a short communication from Powlson and Jenkinson (1971), they reported carbon sulphide, at low concentrations, inhibited nitrification. They attributed this to the "extreme sensitivity" of *Nitrosomonas* sp. to carbon sulphide from the rubber bungs. Furthermore, Bowman and coworkers (1994) evaluated crumb rubber coarse and fine particles, as an amendment at different ratios with sand and sawdust, in potting soils for chrysanthemums [Dendranthema x grandiflorum (Ramat.) Kitamura]. They observed a decrease in total porosity , but both particle sizes increased air filled porosity relative to the sawdust controls. Furthermore, crumb rubber amended soils reduced shoot tissue concentrations of N, P, K, Ca, Mg, and Cu, but zinc increased to as high of levels as 74x that of the controls. There were no accumulation of heavy metals (Cd, Cr, Ni, and Pb) in the tissue as a result from crumb rubber amended soils. Thus crumb rubber reveals the potential of being a dynamic soil amendment in regards to soil physical properties and biochemistry.

However, the physical dynamics of crumb rubber to improve playing surface characteristics, maintain aesthetics and reduce the potential of surface-related injuries are most important parameters. Due to its elastomeric properties and resiliency (Treloar, 1975), the effect is two-fold; first, the potential of improving soil/plant relationships and/or protection of the turfgrass plant, and second providing a more resilient, softer surface which in turn improves the repeatable performanance of a playing surface (in other words, the potential for maintaining first-day game conditions throughout the season even when wear tolerance is steady and the growing environment dissipates).

The objective of the research was to determine the feasibility and efficiency of incorporating crumb rubber from used tires to modify athletic fields and other high traffic soils. Furthermore, to determine the specific crumb rubber volumes and incorporation depths which would provide a greater wear tolerant turf stand and resilient soil profile. Additionally, research was conducted to find the most efficient incorporation method of crumb rubber that would reduce soil compaction and improve wear tolerance.

Chapter 1

# Effects of crumb rubber on soil incorporation rates and depths on Kentucky bluegrass and perennial ryegrass turf

## ABSTRACT

In 1991, 234 million tires were discarded in the United States, many of them in landfills. While more and more of these landfills are refusing these tires for health and spatial reasons, the used tire has proven itself a difficult, if not impossible, product to recycle and therefore has to be reused. In 1991, two trial studies were initiated to evaluate the efficiency of chopped up tires pieces or crumb rubber as a soil amendment in high traffic areas. Crumb rubber (6mm) was tilled into the soil profile at two depths (7.6 and 15.2 cm) and five volumes (0, 10, 20, 30, and 40%) in a 2x5 randomized complete block design with three replicates. One trial study was sodded with Poa pratensis L., and the other was seeded with Lolium perenne var. 'Dandy'. Wear treatments were applied with the Brinkman Traffic Simulator (BTS) with an average of 7 passes per week during the fall season (Sept.-Nov.) over the four year study. Playing feild characteristics evaluated included surface hardness, shear resistance, soil moisture, and surface and soil temperatures as well as turfgrass density and quality ratings. Nutrient concentrations were evaluated for both studies confirming no leaching or phytotoxicity being reported on crumb rubber when it was tilled into the soil profile.

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*Introduction*

With an increase in recreational sports and intensive use of sportsfields, the need to improve playing field conditions has risen (Watson et., 1992). Subsequently, the turfgrass manager faces the challenge of providing a high quality playing surface that enhances the performance of the athlete or the ball, and still reduce the potential for field related injuries without compromising the aesthetics of the playing area (higher turfgrass density, improved color). With an increase in the use of these recreational and athletic areas, two factors under constant focus are soil compaction and turfgrass wear. Since these areas are not typically subjected to heavy machinery, the concern is the upper three centimeters of the soil profile and the overall performance of the turf stand. However, Carrow and Petrovic (1992) summarized that depending on your soil profile (sand-based vs. non sand-based profile), turfgrass wear is eminent but soil compaction does not necessarily take place.

Soil modification is an important management strategy to consider when managing high traffic sportsturfs. Depending on the severity of the area, reconstruction or re-establishment by core or deep-tine cultivation are also viable options. Through either method, soil amendments are excellent tools to be considered due to the potential of a longer lasting improvement in soil physical properties. When using soil amendments, the turf manager must consider proper amounts, the properties of the amendment, soil physical properties, and the mixing procedure (Waddington et al., 1974).

Several amendments have been researched and recommended because due to their abilities to increase air porosity, infiltration rates, and improve nutrient holding capa

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capacities (Waddington, 1992). Organic amendments have included peat, lignified wood, sawdust, rice hulls, and pine bark while inorgranic amendments have included sand, calcined clays, diatomite, perlite, coke bottles, bottle caps, bricks, vermiculite, zeolite, isolite, and polyacrylamide gels (refer to literature review). All of the amendments mentioned have been able to improve soil physical properties to varying degrees. However, in compacted areas, these improvements can quickly dissipate due to the soil amendments breaking down under the constant force being applied. Furthermore, "agronomic systems", such as using concrete blocks or wired mesh, have been evaluated to be more consistent in improving soil physical properties (Shearman et al., 1980; Beard, 1993).

A more recent approach to reducing compaction has been the idea of using crumb rubber (recycled from used car tires). Due to its elastomeric properties as a compound (Treloar, 1975), crumb rubber should be able to expand and contract due to soil heating and/or fluctuations in soil water content or mechanical relief of compaction via core cultivation (Rieke and Murphy, 1989). By improving these properties and primarily reducing compaction, the turfgrass will produce a better root system which inturn can provide a stronger plant and improve the overall quality. This can produce a higher quality playing field by decreasing surface hardness, increasing traction, and improving the aesthetics and playability of the sportsfield.

The objective of this research was to evaluate the efficiency of crumb rubber as a soil amendment for high traffic and compacted soils. This would subsequently promote turfgrass vigor, in an athletic field situation or activity area, especially during the spring and fall seasons when the growth rates are declining. Incorporation depths and cr

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and crumb rubber volume rates were evaluated to determine the optimum rate in these activity areas.

*Materials & Methods*

Two trial plots were established at the Hancock Turfgrass Research Center at Michigan State University, East Lansing, Michigan on 20 May 1991. The soil was a Capac loam containing 61% sand, 23% silt and 16% clay (Fine-loamy, mixed mesic Aeric Ochraqualfs). Appropriate volumes of crumb rubber were laid out onto each respective treatment area (6.1 m x 1.5 m). Crumb rubber (6 mm diameter) was rototilled, on-site, in a 2x5 randomized complete block design replicated three times with two incorporation depths (7.6 cm and 15.2 cm), and five crumb rubber volume concentrations [( 0, 10, 20, 30 and 40%)(v/v). The first plot (Experiment I) was sodded with Poa pratensis L. (received from Halmich's Sod Farm, East Lansing, Michigan), with a visual estimation of 15% Poa annua L. contamination, and the second plot (Experiment II) was seeded with a Gandy drop spreader (1.5 meter width) with Lolium perenne L. var. 'Dandy' (244.5 kg $ha^{-1}$).

During establishment of the turf, 36.75 kg N $ha^{-1}$ of 13-25-12 was applied. Later, 24.5 kg N $ha^{-1}$ of 25-0-25 was applied every 14 days in June and July 1991. In the fall, 49.0 kg N $ha^{-1}$ sulfur-coated urea was applied. A nutsedge (Cyperus esculentus) problem was rectified with three applications of 2.26 kg $ha^{-1}$ of Basagran [(3-(1-methylethyl)-1H-2,1,3-benzothiadiazin-4 (3H)-one 2,2-dioxide)] plus 6.5 ml Lesco Sticker spreader added to each application. Irrigation was applied daily during establishment and as necessary throughout the experiment. The turf was mowed three times per week, at a cutting height of 38 mm, with a Ransom 180 triplex reel mower (Lincoln, NE) 1991 - 1993, and in 1994 mowed with a Toro (Bloomington, MN) 105 cm walking rotary deck mower. Clippings were returned at all times. Pest control was adminstered on a curative basis.

Traffic treatments were simulated with the Brinkman Traffic Simulator (BTS) (Cockerham, 1989). The BTS weighed 409 kg. When filled with water, the BTS weighed 474 kg with a force of 99 $kg/cm^2$ being applied. Two passes represent the traffic received between the 40 yardlines between the hashmarks for one football game (Cockerham et al., 1989). The BTS was pulled by a Cushman truck (Lincoln, NE) in 1991, and in 1992-94 pulled by a John Deere 5100 (Moline, IL). Traffic treatments were made from 25 August to 20 November in 1991, 1 September to 31 October in 1992, and 26 August to 14 November in 1993. In 1994, a new traffic lane was established within each plot and traffic applied from 6 September until 15 November. The average number of passes made per week from 1991-1994 were 6, 6, 7 and 9, respectively. The total number of games simulated per year were 39, 30, 48, and 48 games, respectively.

Data were collected on traffic surfaces for both experiments on 5 September, 17 September, 12 October and 9 November 1991; 26 September, 2 October, and 20 November 1992; 22 September, 11 October, and 14 November 1993, and 19 September, 21 October and 19 November 1994.

The Clegg Impact Soil Tester (CIT) with a 2.25 kg impact hammer (Lafayette Instrument Co., Lafayette, IN), was used to measure surface hardness. The hammer was dropped three times from a height of 0.46 m, randomly throughout the treatment area (Rogers and Waddington, 1990). The average of three peak deceleration ($G_{max}$) were transmitted to a hand-held Clegg Impact readout box recorded in 1991-93. In 1994, a Brüel and Kjaer 2515 Vibration Analyzer (Brüel and Kjaer Instruments, Marlborough, MA) replaced the Clegg readout box and was used to measure surface hardness (Rogers and Waddington, 1992). In 1994, an average of four peak deceleration values from each plot were recorded.

Shear resistance was measured by the Eijkelkamp Shearvane Type 1B (Henderson, 1986). The value recorded (N m) was an average of three measurements. Soil temperature (°C) was recorded at the turf/soil interface and at 7.6 cm depth via a Barnant 115 Thermocoupler Thermometer. Soil moisture (kg $kg^{-1}$) was measured gravimetrically (Gardner, 1965). Three soil samples (7.6 cm) were taken randomly for each treatment in the traffic area.

Turfgrass root samples were taken in 1993 and 1994. In 1993, five samples were taken on 22 November from each traffic treatment area. Sampling depth was 15 cm deep by 7.5 $cm^2$. Additionally, for Exp II in 1994, four samples were taken on 13 September and 15 November at a sampling depth of 15 cm deep by 5.1 $cm^2$. Each sample was subdivided into three 5 cm intervals. Roots were seperated from the soil by the hydropneumatic elutriation system (Smucker et al., 1982). Roots were weighed, ashed at 500°C for 5 hours, and then reweighed.

Turfgrass density and quality ratings were recorded in 1993, and 1994 for Exp I, and additionally in 1991 for Exp II. Density was visually rated on a scale from 0 - 100%. Overall quality and color were rated on a scale from 1-9; 1 = poor, 9 = excellent, and 6 = acceptable.

Bulk density (Blake and Hartage, 1992) and air-filled porosity (Danielson and Sutherland, 1986) were measured from two undisturbed cores from the traffic area in November 1993 as well as crumb rubber particle density from its respective treatments in October 1994. Core samples were 7.6 cm by 45.8 $cm^2$. Samples were taken below thatch/mat layer. Soil and crumb rubber was crushed to smaller aggregates and then later separated by the hydropneumatic elutriation system (Smucker et al, 1982). Particle density of the rubber, from the amended soil, was determined by the "submersion method" (Blake and Hartage, 1992), and then rubber was weighed and a corrected bulk density was calculated [fresh crumb rubber particle density is 1.2 g/cc (Epps, 1994) versus a soil particle density being 2.65 g/cc, Hillel, 1980]. Air porosity was measured as the soil water lost from saturation to matric potentials of -0.0040, -0.010, -0.033, -0.10 MPa, and oven dry (105°C). Saturated hydraulic conductivity was measured using a constant head in the laboratory (Klute and Dirksen, 1992).

Soil cores were collected for nutrient concentration analysis in October 1993 for Exp I and August 1994 for Exp II. Twelve cores were taken from each treatment with a sampling depth of 15.2 cm by 5.1 $cm^2$ for Exp I and 22.8 cm by 5.1 $cm^2$ for Exp II. Each sample was sudivided into 7.6 cm intervals, and then mixed for a composite sample from each depth of the treatment. Soil cores were air-dried at 105 °C for analysis in 1993 and 35 °C for analysis in 1994. Soil samples were extracted with 0.1 N HCl, and extracts were analyzed for zinc, manganese, boron, iron, lead, cadmium, copper, molybdnum (only in Exp I), chromium, sodium, and nickel by the ARC D.C. Plasma Emission Spectrophotometer V-B (Elverson, PA).

Results from both experiments were analyzed using the MSTAT analysis of variance and the least significant difference (LSD) test at the 0.05 level. Soil extractions were analyzed by a three factor analysis (incorporation depth, crumb rubber volume, and sampling depth, respectively) using the MSTAT analysis of variance at the least significant difference (LSD) test at the 0.05 level.

***Results and Discussion***

Experiment I - Kentucky bluegrass

Peak deceleration values for the Kentucky bluegrass stand (Exp I) are listed in Table 1. From four years of data collection, peak deceleration values were not significant between incorporation depths nor among crumb rubber volume rates except for dates in 1992. Also in 1992, soil water content was higher than any other recorded values except for 17 November 1993. From 12 October 1991 to 11 October 1993, peak deceleration values ranged from 48 to 97 $G_{max}$. However, after 11 October 1993, impact values ranged from 59 to 79 $G_{max}$. This could be attributed to soil settling and thatch accumulation.

Shear resistance values (Table 2) were not significant throughout the duration of the experiment for either incorporation depths or crumb rubber volume rates. Although shear values were high (only one mean value below 20 N m, on 19 Nov 1994), there were no significant differences among treatments. Rogers (1988) and Krick and coworkers (1994) have reported shearing values on a Kentucky bluegrass sod well above 20 N m. High shear values can be attributed to the thatch layer of the Kentucky bluegrass sod, the growth habit of the bluegrass, and the limitation of the appartus.

Table 1. Effects of crumb rubber volume rates and incorporation depths on peak deceleration ($G_{max}$) on a trafficked Kentucky bluegrass stand (Exp I) at the Hancock Turfgrass Research Center.

| | 1991 | 1992 | | 1993 | | | 1994 | | |
|---|---|---|---|---|---|---|---|---|---|
| | 12 Oct | 2 Oct | 20 Nov | 22 Sept | 11 Oct | 17 Nov | 19 Sept | 21 Oct | 19 Nov |
| | | | ---------- $G_{max}$ ---------- | | | | | | |
| Incorporation Depths | | | | | | | | | |
| 7.6 cm | 88 | 90 | 71 | 52 | 74 | 62 | 76 | 73 | 69 |
| 15.2 cm | 89 | 90 | 70 | 51 | 75 | 60 | 75 | 75 | 70 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Volume (v/v) | | | | | | | | | |
| 0% | 91 | 97 | 73 | 54 | 76 | 62 | 74 | 75 | 71 |
| 10% | 92 | 97 | 75 | 56 | 76 | 62 | 79 | 75 | 68 |
| 20% | 87 | 84 | 69 | 49 | 75 | 62 | 77 | 72 | 71 |
| 30% | 89 | 87 | 70 | 48 | 74 | 59 | 76 | 74 | 68 |
| 40% | 85 | 86 | 65 | 50 | 72 | 60 | 74 | 75 | 71 |
| LSD (0.05) | -NS- | 9 | 7 | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Soil Water, kg $kg^{-1}$ | 0.150 | $0.261^{\dagger}$ | 0.317 | 0.182 | 0.257 | 0.279 | 0.179 | 0.173 | 0.181 |

NS = not significant
† indicates an interaction at the 0.05 level.

The Eijkelkamp shearvane, once it was "dug" into the turf only penetrated 16-20 mm from the surface. The thatch heavily influenced shearing regardless of the soil water content. However the limitation of the shearvane appartus was twofold; first the inability to resemble the linear traction motion that is most paramount in assessing traction for practice or game conditions, and second, the sharp fins which penetrated the thatch layer for measurements was not representative of the bottom of an athlete's shoe coming in contact with the playing surface. There was no significant differences in root mass between the incorporation depths nor among treatments at each sampling depth (Table 3). Rogers and Waddington (1989) have reported low soil soil moisture can improve traction. However, in Exp I, regardless of soil moisture, the thatch layer played a major role in shear resistance measurements as well as the lack of adaptability of the shearing appartus could resemble an athlete's shoe shearing the turf stand.

Turfgrass density and quality rating values are listed in Tables 4 and 5, respectively. Density and quality ratings were not collected in 1991 and 1992. Density values were not significantly different among treatments except for 25 Oct 1993. There were no significant differences in quality ratings between incorporation depths nor among crumb rubber treatments.

Bulk density, air porosity and saturated hydraulic conductivity values recorded in 1993 are listed in Table 6. The crumb rubber volumes analyzed were 0%, 20%, and 40% v/v. For bulk density values, although there was not a significant difference between crumb rubber incorporation depths, there was a significant difference among crumb rubber volume treatments. Air porosity and saturated hydraulic conductivity values revealed significant differences among treatments, but only saturated hydraulic

Table 2. Effects of crumb rubber volume rates and incorporation depths on shear resistance (N m) on a trafficked Kentucky bluegrass stand (Exp I) at the Hancock Turfgrass Research Center.

| | 1991 | 1992 | | 1993 | | 1994 | | |
|---|---|---|---|---|---|---|---|---|
| | 12 Oct | 2 Oct | 20 Nov | 22 Sept | 11 Oct | 19 Sept | 21 Oct | 19 Nov |
| | N m | | | | | | | |
| Incorporation Depths | | | | | | | | |
| 7.6 cm | 25.5 | 27.4 | 24.8 | 33.2 | 26.3 | 24.2 | 28.2 | 21.2 |
| 15.2 cm | 25.5 | 27.5 | 24.0 | 31.4 | 25.3 | 23.9 | 27.0 | 22.1 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Volume (v/v) | | | | | | | | |
| 0% | 24.5 | 26.8 | 23.3 | 32.6 | 23.8 | 24.5 | 29.4 | 23.6 |
| 10% | 25.9 | 29.0 | 24.3 | 31.9 | 25.7 | 24.9 | 28.4 | 23.3 |
| 20% | 26.2 | 27.4 | 24.3 | 29.9 | 25.3 | 23.6 | 26.0 | 19.1 |
| 30% | 25.8 | 27.4 | 25.3 | 30.1 | 24.6 | 24.3 | 25.7 | 21.6 |
| 40% | 25.1 | 26.7 | 25.0 | 36.8 | 27.1 | 23.1 | 28.5 | 20.7 |
| LSD(0.05) | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Soil Water, kg $kg^{-1}$ | 0.150 | 0.261 | 0.317 | 0.182 | 0.257 | 0.179 | 0.173 | 0.181 |

NS = not significant

Table 3. Effects of crumb rubber volume rates and incorporation depths on root mass (g * $cm^{-3}$) on a trafficked Kentucky bluegrass stand (Exp I) on 12 November 1993 after 46 simulated football games at the Hancock Turfgrass Research Center.

| | Kentucky bluegrass | | | |
|---|---|---|---|---|
| | 0-5 cm | 5-10 cm | 10-15 cm | Total 0-15 cm |
| | ---------- g * $cm^{-3}$ ---------- | | | |
| Incorporation Depths | | | | |
| 7.6 cm | 0.41 | 0.12 | 0.09 | 0.62 |
| 15.2 cm | 0.41 | 0.10 | 0.10 | 0.61 |
| Significance | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Volume (v/v) | | | | |
| 0% | 0.41 | 0.12 | 0.06 | 0.59 |
| 10% | 0.40 | 0.08 | 0.07 | 0.55 |
| 20% | 0.41 | 0.10 | 0.12 | 0.63 |
| 30% | 0.41 | 0.16 | 0.10 | 0.67 |
| 40% | 0.43 | 0.08 | 0.14 | 0.65 |
| LSD (0.05) | -NS- | -NS- | -NS- | -NS- |

Table 4. Effects of crumb rubber volume rates and incorporation depths on turfgrass density ratings on a trafficked Kentucky bluegrass stand (Exp I) at the Hancock Turfgrass Research Center.

| | 1993 | | | 1994 | | |
|---|---|---|---|---|---|---|
| | 7 Oct | 25 Oct | 15 Nov | 23 Aug | 6 Oct | 4 Dec |
| | ---- Density (%) ---- | | | | | |
| Incorporation Depths | | | | | | |
| 7.6 cm | 78 | 62 | 59 | 100 | 86 | 60 |
| 15.2 cm | 74 | 57 | 56 | 99 | 81 | 59 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Volume (v/v) | | | | | | |
| 0% | 76 | 53 | 53 | 98 | 79 | 59 |
| 10% | 78 | 65 | 57 | 100 | 87 | 58 |
| 20% | 76 | 62 | 57 | 100 | 82 | 60 |
| 30% | 76 | 62 | 61 | 100 | 84 | 62 |
| 40% | 74 | 57 | 58 | 99 | 84 | 63 |
| LSD (0.05) | -NS- | 8 | -NS- | -NS- | -NS- | -NS- |
| Games Simulated | 24 | 37 | 48 | 0 | 28 | 44 |

Density scale - 0-100%
Density ratings were not available in 1991 and 1992.
NS = not significant

Table 5. Effects of crumb rubber volume rates and incorporation depths on turfgrass quality ratings on a trafficked Kentucky bluegrass stand (Exp. I) at the Hancock Turfgrass Research Center.

| | Kentucky bluegrass | | | |
|---|---|---|---|---|
| | 1993 | 1994 | | |
| | 15 Nov | 23 Aug | 6 Oct | 4 Dec |
| Incorporation Depths | | | | |
| 7.6 cm | 6.4 | 8.4 | 7.2 | 5.0 |
| 15.2 cm | 6.1 | 8.1 | 6.8 | 5.0 |
| Significance | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Volume (v/v) | | | | |
| 0% | 5.9 | 8.0 | 6.7 | 4.7 |
| 10% | 6.3 | 8.4 | 7.2 | 4.9 |
| 20% | 6.2 | 8.3 | 7.0 | 5.0 |
| 30% | 6.4 | 8.3 | 7.0 | 5.1 |
| 40% | 6.2 | 8.2 | 7.1 | 5.2 |
| LSD (0.05) | -NS- | -NS- | -NS- | -NS- |
| Games Simulated | 48 | 0 | 28 | 44 |

Turfgrass Quality Ratings 1-9: 1=Poor (dead; brown), 9=Excellent (dark green), and 6=Acceptable
NS = not significant

conductivity was significant between tilling depths. As crumb rubber levels increased, there was an increase in air-filled porosity as well as saturated hydraulic conductivity. Figure 1 represents an interaction at the -0.0040 MPa between incorporation depth and crumb rubber volume.

Air-filled porosity can be further evaluated from Figures 2-6. The $r^2$ values were 0.69, 0.83, 0.68, 0.43, and 0.18, respectively. A positive slope indicated the usefulness crumb rubber provides in reducing bulk density and maintaining a higher air-filled porosity as crumb rubber volumes increase. Furthermore, when the soil profile was most vulnerable to compaction at matric potentials of -0.004 and -0.010 MPa, the integrity of the pores were maintained. Although total porosity is relatively unaffected by the crumb rubber as soil water content decreased, air-filled porosity increased as well. Thus crumb rubber can reduce compaction and subsequently improve soil/plant relationships when the soil profile is most susceptible.

Intended crumb rubber incorporated volumes did not match actual incorporated volumes. When crumb rubber amounts were extracted from the cores intended for a 20% volume, the average was 11.7%; with 11.3% at the 7.6 cm depth and 12.0% at the 15.2 cm depth. At the 40% volume, the average was 21.8%; with 18.7% at the 7.6 cm depth and 24.9% at the 15.2 cm depth. Although crumb rubber amounts were lower than intended, the tilling process might have not been thorough enough to allow for a representative sample. This again shows the difficulty of tilling amendments uniformly in the soil profile (Hummel, 1993). Nevertheless, crumb rubber demonstrated the ability to reduce compaction when the soil profile is most vulnerable as the volume increased.

Table 6. Effects of crumb rubber volume rates and incorporation depths on bulk density (g * $cm^{-3}$), air porosity (%), and saturated hydraulic conductivity (cm * $hr^{-1}$) on a trafficked Kentucky bluegrass turf (Exp I) on 3 November 1993 at the Hancock Turfgrass Research Center.

| | Bulk Density | Adjusted Bulk Density | Change in Bulk Density | -0.0040 | -0.010 | -0.033 | -0.10 | O.D. | Saturated Hydraulic Conductivity |
|---|---|---|---|---|---|---|---|---|---|
| | ----- g * $cm^{-3}$ ----- | | | --------- MPa --------- / ----- Air Porosity (%) ----- | | | | | cm * $hr^{-1}$ |
| **Incorporation Depths** | | | | | | | | | |
| 7.6 cm | 1.63 | 1.64 | 0.01 | 6.1 | 11.4 | 14.1 | 14.7 | 36.9 | 13 |
| 15.2 cm | 1.60 | 1.61 | 0.01 | 6.8 | 12.3 | 15.1 | 15.6 | 37.0 | 23 |
| Significance† | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | * |
| **Crumb Rubber Volumes (v/v)** | | | | | | | | | |
| 0% | 1.77 | 1.77 | 0.00 | 3.3 | 6.9 | 10.1 | 11.8 | 35.5 | 1 |
| 20% | 1.59 | 1.60 | 0.01 | 6.4 | 12.3 | 15.7 | 16.4 | 38.2 | 11 |
| 40% | 1.48 | 1.50 | 0.02 | 9.7 | 16.5 | 18.0 | 17.4 | 37.1 | 28 |
| LSD (0.05) | 0.06 | 0.06 | 0.01 | 3.9 | 3.9 | 3.3 | 4.2 | 1.4 | 15 |

† * indicates a significant difference at a 0.05 level
NS = not significant
O.D. = Oven dry

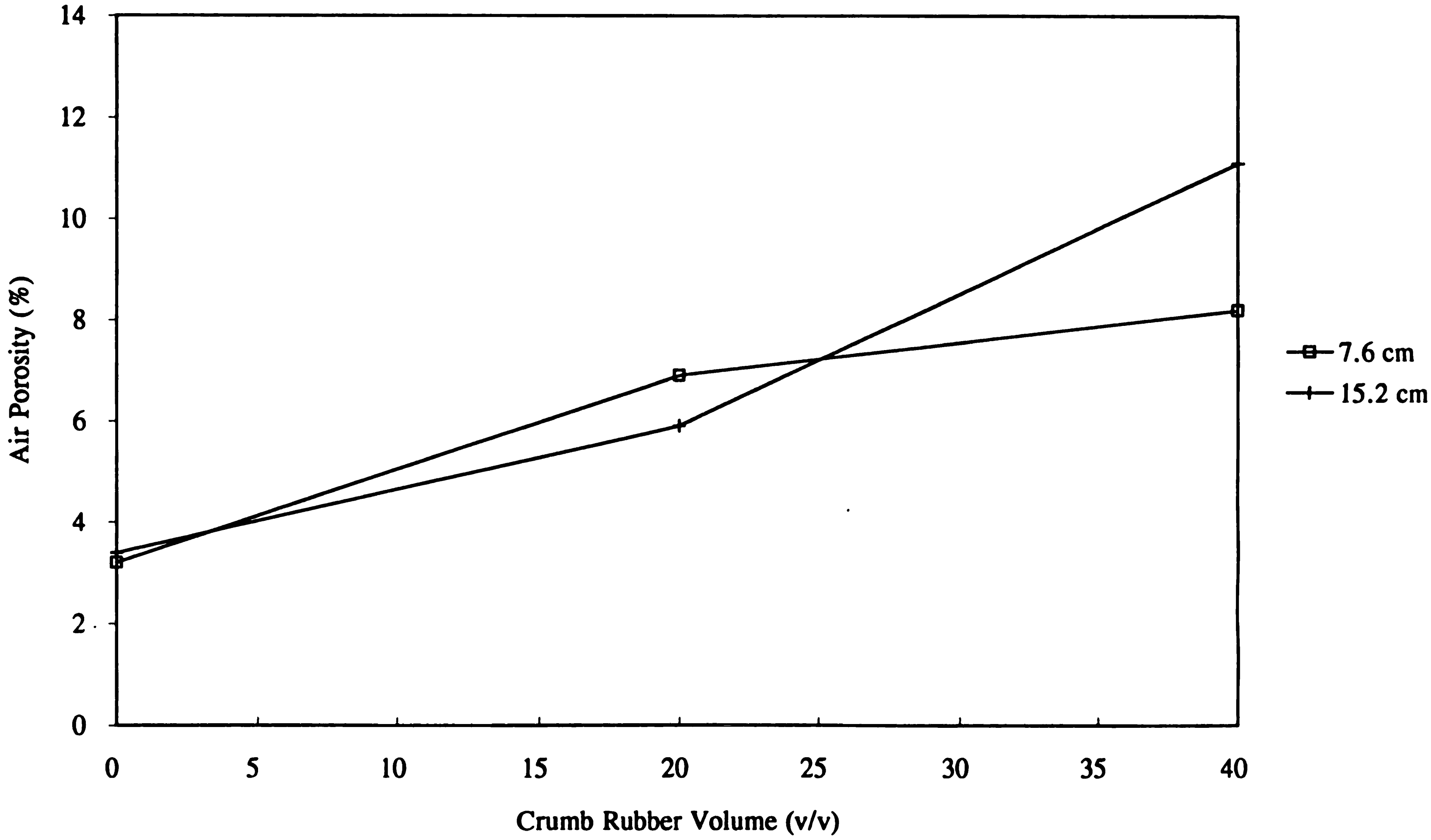


Fig. 1. The effect of -0.0040 MPa matric potential on tilling depth x crumb rubber volume interaction on a trafficked Kentucky bluegrass stand at the HTRC, 1993.

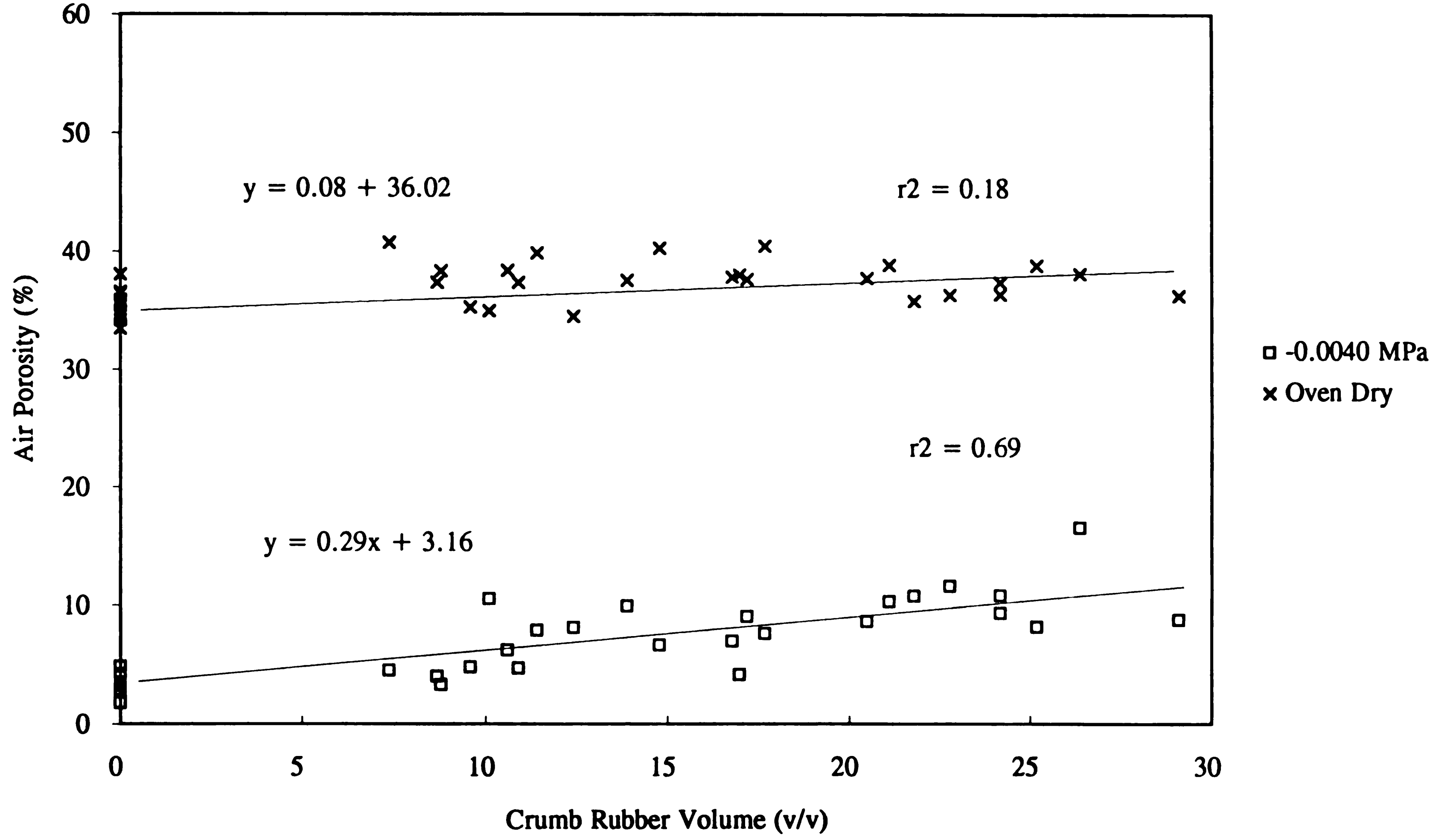


**Fig. 2. Air-filled porosity as a function of volumetric proportion on incorporated crumb rubber at -0.0040 MPa matric potential and oven dry on a trafficked Kentucky bluegrass stand at the HTRC, 1993.**

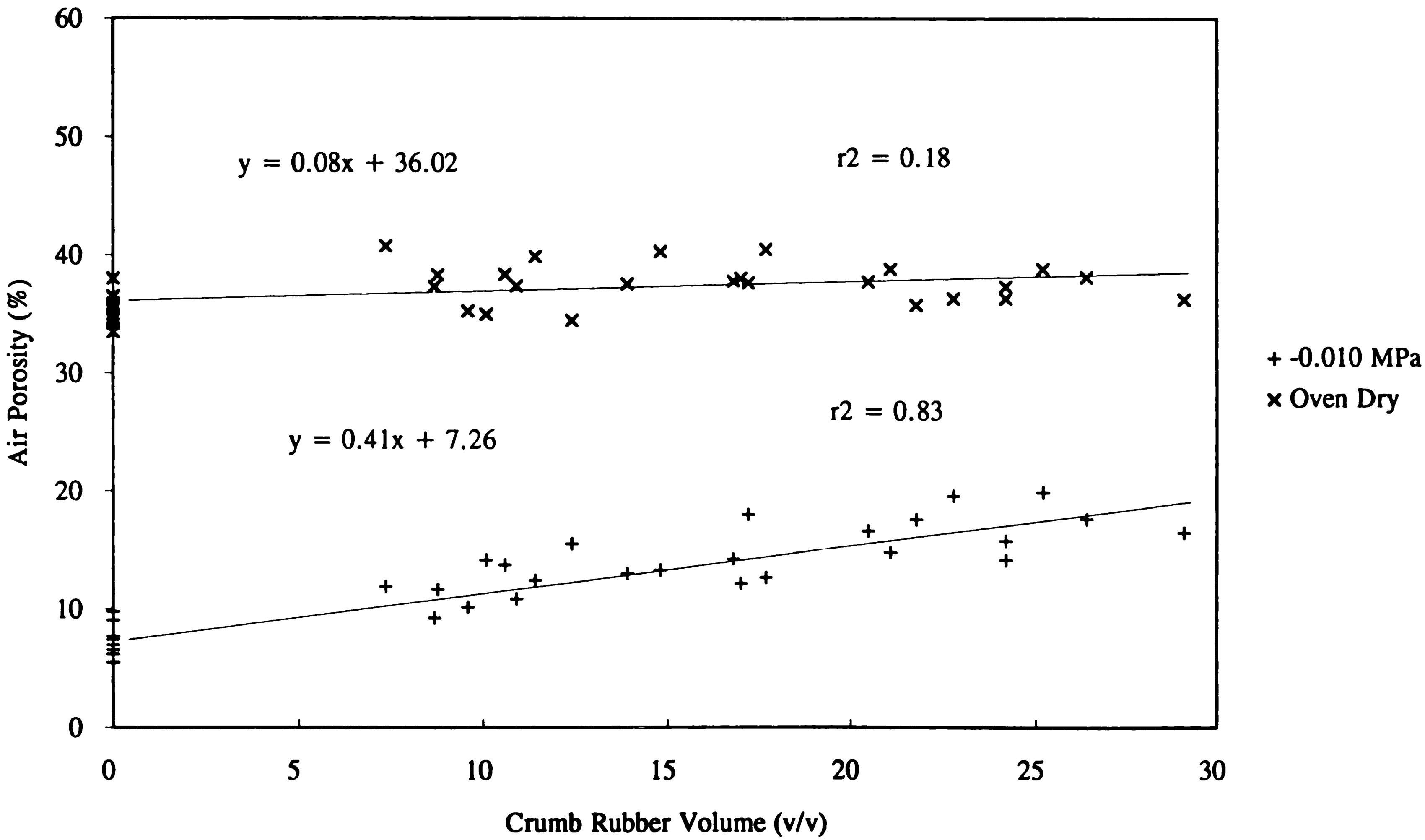


Fig. 3. Air-filled porosity as a function of volumetric proportion on incorporated crumb rubber at -0.010 MPa matric potential and oven dry on a trafficked Kentucky bluegrass stand at the HTRC, 1993.

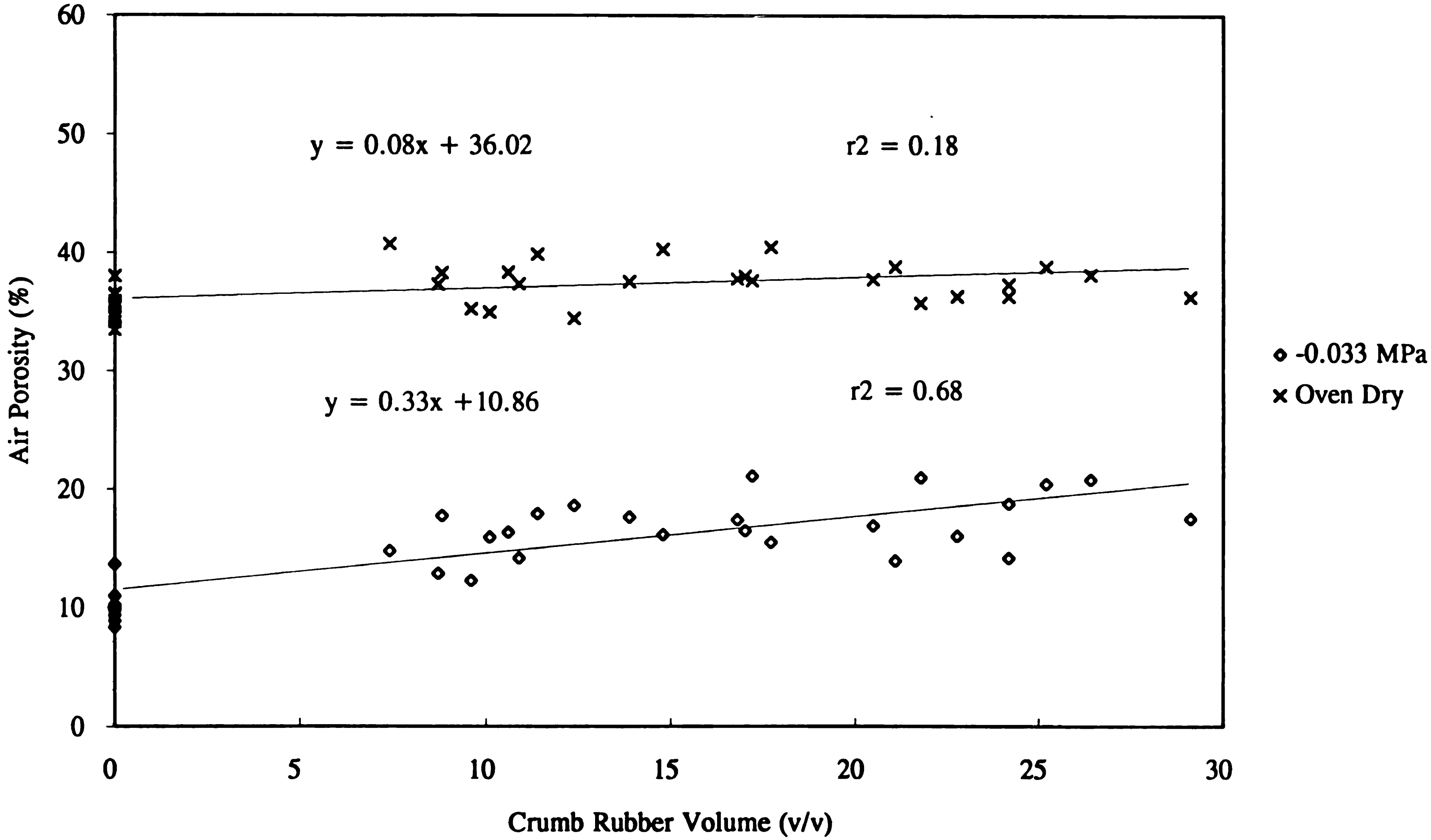


**Fig. 4. Air-filled porosity as a function of volumetric proportion on incorporated crumb rubber at -0.033 MPa matric potential and oven dry on a trafficked Kentucky bluegrass stand at the HTRC, 1993.**

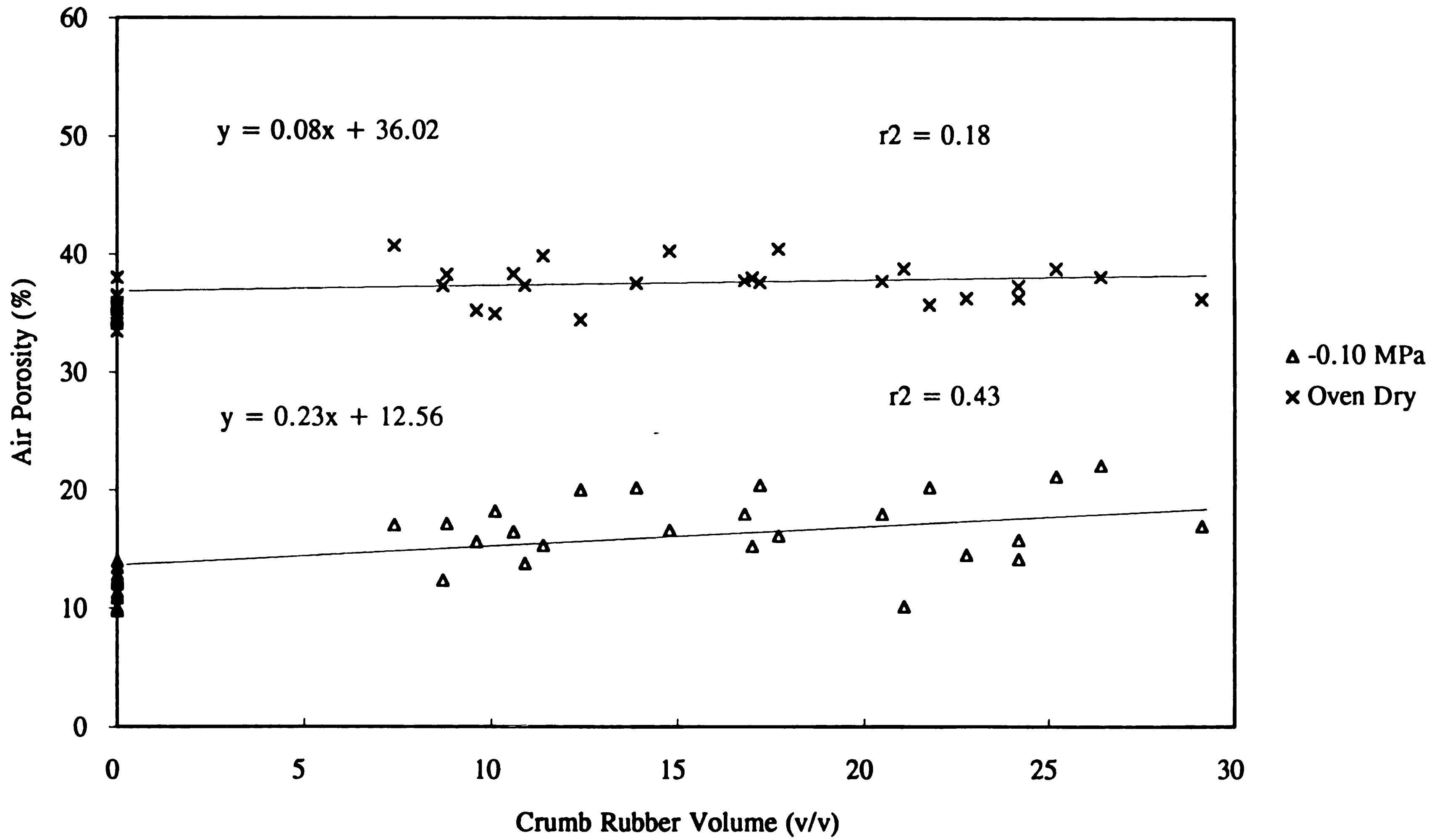


**Fig. 5. Air-filled porosity as a function of volumetric proportion on incorporated crumb rubber at a -0.10 MPa matric potential and oven dry on a trafficked Kentucky bluegrass stand at the HTRC, 1993.**

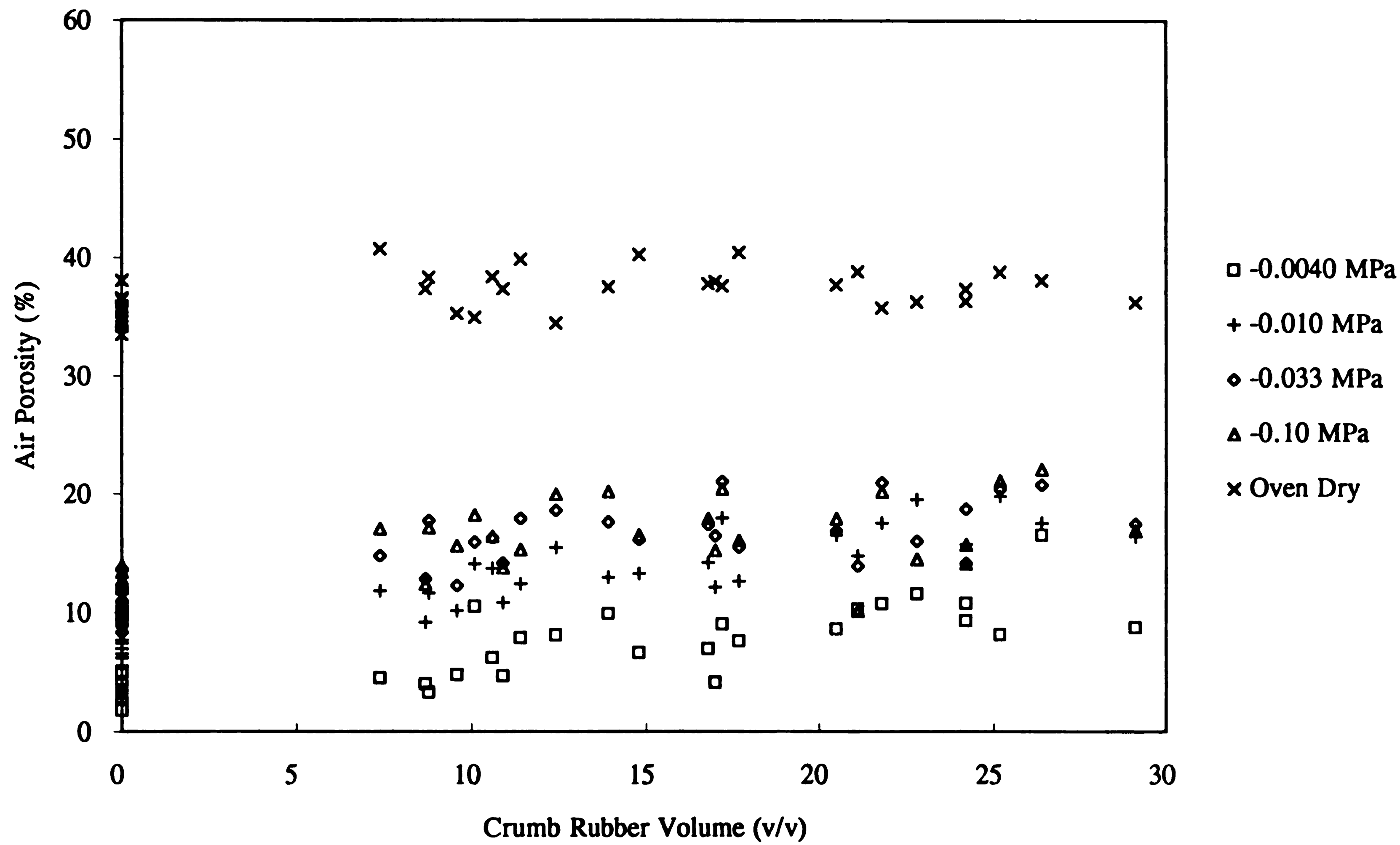


**Fig. 6. Air-filled porosity as a function of volumetric proportions on incorporated crumb rubber at -0.0040, -0.010, -0.033, -0.10 MPa versus oven dry on a trafficked Kentucky bluegrass stand at the HTRC, 1993.**

Soil nutrient concentration values (Table 7) revealed no significant differences between incorporation depths except for manganese. There were no significant differences among treatments and sampling depths except for zinc, manganese, and lead. Lindsay (1978) reported on common ranges of elements for soils. Boron, zinc, cadmium, manganese, copper, molybdnum, lead, nickel, and iron all had values below or well within the acceptable ranges. Zinc, manganese, and lead had ranges between 10-300, 20-3000, and 2-200 ppm, respectively. Deal and Engel (1965) observed that applications of manganese, iron, boron, and zinc were unsuccessful in promoting growth on a Poa pratensis L. var. 'Merion' turf. However, except for zinc, the addition of boron, manganese, and iron revealed some improvement in turfgrass quality when the major nutrients were limiting.

*Experiment II - Perennial ryegrass*

There were no significant differences between incorporation depths for peak deceleration values except for 20 November 1992 (Table 8). Crumb rubber volumes were not significant among percent crumb rubber treatments except for 2 October, and 20 November 1992, and 22 September and 11 October 1993. The differences among treatments on these dates as well as the trend throughout the experiment indicated that as crumb rubber levels increased, peak deceleration values decreased.

Shear resistance values (Table 9) had no significant differences between incorporation depths except on 5 September 1991. There were no significant differences among crumb rubber treatments except on 5 September 1991, 2 October

Table 7. Effects of crumb rubber volume rates and incorporation depths on soil nutrient concentrations at depths of 0-7.6 cm, and 7.6-15.2 cm on a Kentucky bluegrass stand (Exp I) on 4 October 1993 at the Hancock Turfgrass Research Center.

| | ppm | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | B | Zn | Cd | Mn | Cu | Mo | Pb | Ni | Fe | Cr | Na |
| Incorporation Depths | | | | | | | | | | | |
| 7.6 cm | 0.8 | 15.5 | 0.3 | 88.9 | 2.0 | 0.6 | 2.0 | 1.1 | 71.0 | 186.4 | 79.3 |
| 15.2 cm | 0.0 | 25.8 | 0.1 | 104.5 | 2.5 | 0.0 | 1.7 | 0.9 | 75.3 | 192.6 | 71.1 |
| Significance† | -NS- | -NS- | -NS- | * | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Volume (v/v) | | | | | | | | | | | |
| 0% | 1.6 | 7.6 | 0.4 | 81.1 | 2.0 | 0.9 | 2.0 | 1.2 | 69.1 | 192.7 | 76.4 |
| 20% | 0.0 | 19.6 | 0.0 | 92.7 | 1.8 | 0.0 | 0.8 | 0.5 | 70.5 | 187.9 | 69.7 |
| 40% | 0.4 | 34.9 | 0.3 | 116.3 | 2.4 | 0.4 | 2.7 | 1.2 | 79.9 | 118.0 | 79.5 |
| LSD (0.05) | -NS- | 15.9 | -NS- | 13.7 | -NS- | -NS- | 1.0 | -NS- | -NS- | -NS- | -NS- |
| Sampling Depth | | | | | | | | | | | |
| 0-7.6 cm | 0.5 | 34.3 | 0.2 | 111.0 | 2.3 | 0.4 | 2.4 | 1.2 | 72.5 | 210.8 | 86.8 |
| 7.6-15.2 cm | 0.1 | 7.1 | 0.2 | 82.4 | 2.3 | 0.1 | 1.3 | 0.8 | 73.7 | 168.3 | 63.6 |
| Significance† | -NS- | * | -NS- | * | -NS- | -NS- | * | -NS- | -NS- | 28.0 | -NS- |
| Treatment, Sampling Depth | | | | | | | | | | | |
| 0%, 0-7.6 cm | | 10.1 | | | | | | | | | |
| 0%, 7.6-15.2 cm | | 5.0 | | | | | | | | | |
| 20%, 0-7.6 cm | | 35.3 | | | | | | | | | |
| 20%, 7.6-15.2 cm | | 3.8 | | | | | | | | | |
| 40%, 0-7.6 cm | | 57.3 | | | | | | | | | |
| 40%, 7.6-15.2 cm | | 12.4 | | | | | | | | | |
| LSD (0.05) | -NS- | 22.5 | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |

† * indicates a significant difference at a 0.05 level, NS = not significant

Table 8. Effects of crumb rubber volume rates and incorporation depths on peak deceleration ($G_{max}$) on a trafficked perennial ryegrass stand (Exp. II) at the Hancock Turfgrass Research Center.

| | 1991[1] | | 1992 | | 1993 | | | 1994 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 17 Sept | 12 Oct | 2 Oct | 20 Nov | 22 Sept | 11 Oct | 17 Nov | 19 Sept | 21 Oct | 19 Nov |
| | $G_{max}$ | | | | | | | | | |
| Incorporation Depths | | | | | | | | | | |
| 7.6 cm | 103 | 83 | 108 | 68 | 61 | 80 | 59 | 74 | 78 | 72 |
| 15.2 cm | 117 | 81 | 110 | 65 | 63 | 81 | 59 | 76 | 79 | 72 |
| Significance† | -NS- | -NS- | -NS- | * | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Volume (v/v) | | | | | | | | | | |
| 0% | 116 | 82 | 116 | 70 | 65 | 85 | 61 | 75 | 78 | 73 |
| 10% | 119 | 85 | 112 | 70 | 65 | 82 | 62 | 75 | 81 | 73 |
| 20% | 116 | 80 | 109 | 67 | 63 | 82 | 58 | 75 | 77 | 73 |
| 30% | 115 | 81 | 106 | 63 | 59 | 77 | 58 | 75 | 80 | 71 |
| 40% | 106 | 80 | 100 | 62 | 59 | 78 | 54 | 76 | 78 | 71 |
| LSD (0.05) | -NS- | -NS- | 10 | 4 | 4 | 5 | -NS- | -NS- | -NS- | -NS- |
| Soil Water, kg $kg^{-1}$ | 0.158 | 0.181 | 0.195 | 0.251 | 0.190 | 0.216 | 0.256 | 0.190 | 0.183 | 0.190 |
| Interaction | | | | | | | | | | |
| 7.6 cm, 0% | | | | | | 86 | | | | |
| 7.6 cm, 10% | | | | | | 76 | | | | |
| 7.6 cm, 20% | | | | | | 82 | | | | |
| 7.6 cm, 30% | | | | | | 78 | | | | |
| 7.6 cm, 40% | | | | | | 79 | | | | |
| 15.2 cm, 0% | | | | | | 84 | | | | |
| 15.2 cm, 10% | | | | | | 88 | | | | |
| 15.2 cm, 20% | | | | | | 82 | | | | |
| 15.2 cm, 30% | | | | | | 75 | | | | |
| 15.2 cm, 40% | | | | | | 76 | | | | |
| LSD (0.05) | -NS- | -NS- | -NS- | -NS- | -NS- | 8 | -NS- | -NS- | -NS- | -NS- |

[1] In 1991, soil moisture was measured volumetrically by time domain reflectrometry (TDR). Therefore values were converted by dividing by the bulk density (1.3 g/cc ).
† indicates a significant difference at a 0.05 level, NS = not significant

and 20 November 1992, and 19 September 1994. At the beginning of Exp. II (in 1991 and 1992), as crumb rubber levels increased, shear resistance decreased. However, in 1993 shear values stabilized among crumb rubber treatments. Krick and coworkers (1994) reported similar shearing values for a seeded perennial ryegrass turf stand. In 1994, a new traffic lane was initiated and shear resistance values were quite low on 19 September and 21 October and then increased on 19 November. Regardless of three years of soil settling, the weight of the BTS over the fall season, compacted the soil profile enough to allow for shearing to increase as the season progressed. This was evident with shear resistance values for the first three years of the experiment over recurring traffic lane.

There were no significant differences between incorporation depths or treatment levels for root mass values in 1993 (Table 10). However, when comparing root mass values in 1994 (Table 10) between September and November, a significant difference existed in the 10-15 cm depth in September and all depths in November among crumb rubber volume treatments. For both years, there was more root mass with the check treatments versus crumb rubber volumes 20 and 40%. This could be attributed to with increase in crumb rubber in the soil thus the crumb rubber taking up of space and the impeding root growth. Due to the inefficiency of rototiliing (Hummel, 1993), if crumb rubber particles were concentrated in a particular area, it was observed the roots grew through the crumb rubber. Thus the shearing or stability in the soil profile was improved in 1994 throughout the season after some compaction from the BTS was applied. Thus shear resistance increased as the season progressed.

Table 9. Effects of crumb rubber volume rates and incorporation depths on shear resistance (N m) on a trafficked perennial ryegrass stand (Exp II) at the Hancock Turfgrass Research Center.

| | 1991 | 1992 | | 1993 | | 1994 | | |
|---|---|---|---|---|---|---|---|---|
| | 5 Sept | 2 Oct | 20 Nov | 22 Sept | 11 Oct | 19 Sept | 21 Oct | 19 Nov |
| | | ---------- N m ---------- | | | | | | |
| Incorporation Depths | | | | | | | | |
| 7.6 cm | 11.5 | 18.4 | 19.3 | 21.4 | 20.3 | 12.3 | 12.4 | 18.0 |
| 15.2 cm | 9.8 | 19.3 | 19.1 | 21.4 | 19.6 | 12.8 | 13.2 | 18.9 |
| Significance† | * | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Volume (v/v) | | | | | | | | |
| 0% | 13.5 | 20.7 | 20.7 | 20.9 | 21.2 | 13.7 | 13.1 | 19.8 |
| 10% | 12.2 | 19.3 | 19.6 | 21.2 | 19.9 | 12.1 | 12.6 | 17.7 |
| 20% | 11.3 | 18.4 | 19.5 | 21.9 | 20.4 | 12.4 | 12.2 | 16.9 |
| 30% | 8.4 | 17.2 | 18.7 | 21.2 | 19.1 | 12.4 | 13.5 | 18.6 |
| 40% | 8.0 | 15.2 | 17.2 | 21.7 | 19.2 | 11.9 | 12.6 | 19.3 |
| LSD (0.05) | 3.5 | 2.3 | 1.2 | -NS- | -NS- | 1.1 | -NS- | -NS- |
| Soil Water, kg $kg^{-1}$ | 0.162[1] | 0.195 | 0.251 | 0.190 | 0.216 | 0.190 | 0.183 | 0.190 |

† indicates a significant difference at a 0.05 level
NS = not significant
[1] In 1991, soil moisture was measured volumetrically by time domain reflectometry (TDR). Therefore values were converted by dividing by the bulk density (1.3 g/cc).

Table 10. Effects of crumb rubber volume rates and incorporation depths on root mass ($g * cm^{-3}$) on a trafficked perennial ryegrass stand (Exp II) at the Hancock Turfgrass Research Center.

| | 1993 | | | | 1994 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 12 November | | | | 13 Sept | | | 15 Nov | | |
| | 0-5cm | 5-10cm | 10-15cm | Total 0-15 cm | 0-5 cm | 5-10 cm | 10-15 cm | 0-5 cm | 5-10 cm | 10-15 cm |
| | | | | ---------- $g * cm^{-3}$ ---------- | | | | | | |
| Incorporation Depths | | | | | | | | | | |
| 7.6 cm | 0.96 | 0.31 | 0.18 | 1.45 | 0.34 | 0.14 | 0.06 | 0.17 | 0.06 | 0.06 |
| 15.2 cm | 0.99 | 0.27 | 0.17 | 1.43 | 0.53 | 0.12 | 0.04 | 0.17 | 0.06 | 0.05 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Volumes (v/v) | | | | | | | | | | |
| 0% | 1.00 | 0.28 | 0.21 | 1.49 | 0.45 | 0.21 | 0.07 | 0.20 | 0.08 | 0.08 |
| 20% | 0.98 | 0.32 | 0.17 | 1.47 | 0.56 | 0.07 | 0.04 | 0.15 | 0.06 | 0.04 |
| 40% | 1.08 | 0.28 | 0.14 | 1.50 | 0.29 | 0.10 | 0.05 | 0.16 | 0.05 | 0.04 |
| LSD (0.05) | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | 0.02 | 0.04 | 0.02 | 0.01 |

NS = not significant

Turfgrass density and quality values are listed on Tables 11 and 12, respectively. Density values and quality ratings were not recorded for 1992. There were no significant differences for turfgrass density and quality ratings between incorporation depths. Over a three - year period, turfgrass density ratings were significant among crumb rubber volume treatment for five out of 9 dates. In 1991, the effects of the 40% crumb rubber rate revealed a decrease in density ratings. In 1993-94, turfgrass density ratings increased as crumb rubber volume rates increased. In 1993, there was a significant difference in turfgrass densities among crumb rubber volumes for all dates versus only 4 December in 1994. This can be attributed to a cooler fall season in 1993 versus 1994. In 1994, the effects of crumb rubber improving overall quality were less apparent. The temperature in September, October, and November 1993 had an average daily low of 6.4, 0.3, and -0.5 °C to the average daily high being 19.2, 14.8, and 7.4 °C, respectively with the total rainfall equalling 20.75 cm. In 1994, the average temperature from September to November had an average daily low of 11.5, 4.4, and 0.6 °C to the average daily high being 24.7, 16.7, and 11.0 °C, respectively with the total rainfall equalling 25.60 cm. Quality ratings were not significant among crumb rubber volume treatments except on 4 December 1994. This difference was again partially attributed to the higher fall temperatures.

Fewer playing surface measurements were significant among crumb rubber treatments in 1994 versus 1993, a factor attributed to significantly warmer air temperatures during fall 1994. With temperatures in the optimum range for cool-season grasses between 15.5 to 23.9 °C (Beard, 1973), and adequate moisture being provided throughout the fall season in 1994, wear was less dramatic on both

Table 11. Effects of crumb rubber volume rates and incorporation depths on turfgrass density ratings on a trafficked perennial ryegrass stand (Exp II) at the Hancock Turfgrass Research Center.

| | 1991 | | | 1993 | | | 1994 | | |
|---|---|---|---|---|---|---|---|---|---|
| | 5 Sept | 12 Oct | 9 Nov | 7 Oct | 25 Oct | 15 Nov | 23 Aug | 6 Oct | 4 Dec |
| | Density (%) | | | | | | | | |
| **Incorporation Depths** | | | | | | | | | |
| 7.6 cm | 89 | 70 | 68 | 61 | 31 | 23 | 98 | 55 | 28 |
| 15.2 cm | 86 | 72 | 67 | 60 | 28 | 25 | 99 | 58 | 28 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| **Crumb Rubber Volume (v/v)** | | | | | | | | | |
| 0% | 91 | 69 | 63 | 53 | 23 | 20 | 98 | 52 | 21 |
| 10% | 88 | 68 | 69 | 60 | 28 | 20 | 98 | 53 | 20 |
| 20% | 91 | 71 | 69 | 57 | 27 | 20 | 98 | 57 | 29 |
| 30% | 91 | 71 | 71 | 65 | 32 | 30 | 99 | 62 | 35 |
| 40% | 78 | 68 | 65 | 68 | 37 | 32 | 98 | 59 | 35 |
| LSD (0.05) | 11 | -NS- | -NS- | 10 | 7 | 8 | -NS- | -NS- | 8 |

Density scale - 0-100%
NS = not significant
Density ratings were not recorded in 1992

Table 12. Effects of crumb rubber volume rates and incorporation depths on turfgrass quality ratings on a trafficked perennial ryegrass stand (Exp II) at the Hancock Turfgrass Research Center.

| | 1993 | 1994 | | |
|---|---|---|---|---|
| | 15 Nov | 23 Aug | 6 Oct | 4 Dec |
| Incorporation Depths | | | | |
| 7.6 cm | 4.2 | 7.5 | 5.9 | 3.4 |
| 15.2 cm | 4.2 | 7.6 | 6.1 | 3.4 |
| Significance | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Volume (v/v) | | | | |
| 0 | 3.7 | 7.5 | 5.7 | 3.1 |
| 10 | 3.8 | 7.5 | 5.7 | 3.0 |
| 20 | 4.0 | 7.6 | 6.1 | 3.5 |
| 30 | 4.5 | 7.7 | 6.3 | 3.8 |
| 40 | 5.0 | 7.5 | 6.1 | 3.8 |
| LSD (0.05) | -NS- | -NS- | -NS- | 0.4 |
| Games Simulated | 48 | 0 | 28 | 44 |

Turfgrass Quality Ratings 1-9: 1 = Poor (dead; brown), 9 = excellent (dark green), and 6 = Acceptable.
NS = not significant

experiments because of optimum conditions for regrowth or sustaining growth. Although overall quality ratings were lower in 1994 at the end of the fall season versus 1993, this can be attributed to the last 20 days of the experiment having 12 days below 0°C. However, density ratings were higher in 1994 versus 1993, due to the temperatures remaining in the optimum range consistently throughout the season.

Bulk density values are listed on Table 13. There was a significant difference between tilling depths and crumb rubber volume treatments for bulk density and adjusted bulk density. Bulk density decreased as crumb rubber levels increased. Air-filled porosity and total porosity had a significant difference between incorporation depths. Significant differences among crumb rubber volumes treatments were revealed at all matric potentials except at -0.10 MPa . Figure 7 represents an interaction at the -0.004 MPa between incorporation depth and crumb rubber volume. This can be attributed to the actual amounts of 20% only representing an average of 9.2%. Thus, an actual crumb rubber volume of 10 % does very little in reducing compaction. However, 40% crumb rubber volumes had actual average amount of 21.8%, but due to the tilling depth, crumb rubber was more uniformly mixed into the soil profile at 15.2 cm versus 7.5 cm as crumb rubber volume increased.

Air-filled porosity can be further evaluated from Figures 8-12. Regression lines reported $r^2$ values equal to 0.78, 0.72, 0.66, 0.44, and 0.32 for matric potentials of -0.0040, -0.010, -0.033 and -0.10 MPa, and total porosity (oven dry), respectively. Crumb rubber volumes increased as did air-filled porosity at -0.0040 MPa and -0.010 MPa matric potentials. The $r^2$ value decreased as matric potential decreased, but a positive relationship was consistent for all matric potentials. Total porosity had a experiments because of optimum conditions for regrowth or sustaining growth. Although overall quality ratings were lower in 1994 at the end of the fall season versus 1993, this can be attributed to the last 20 days of the experiment having 12 days below 0°C. However, density ratings were higher in 1994 versus 1993, due to the temperatures remaining in the optimum range consistently throughout the season.

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Table 13. Effects of crumb rubber volume rates and incorporation depths on bulk density (g * $cm^{-3}$), and air porosity (%) on a trafficked perennial ryegrass stand (Exp II) on 19 November 1993 at the Hancock Turfgrass Research Center.

| | Bulk Density | Adjusted bulk density | Change in bulk density | -0.0040 | -0.010 | -0.033 | -0.10 | O.D. |
|---|---|---|---|---|---|---|---|---|
| | | ----- g * $cm^{-3}$ ----- | | | ----- Air Porosity % ----- (MPa) | | | |
| **Incorporation Depths** | | | | | | | | |
| 7.6 cm | 1.61 | 1.62 | 0.007 | 4.9 | 9.2 | 11.5 | 12.9 | 39.4 |
| 15.2 cm | 1.56 | 1.57 | 0.010 | 6.7 | 10.8 | 13.1 | 13.8 | 37.7 |
| Significance† | * | * | -NS- | * | -NS- | -NS- | -NS- | * |
| **Crumb Rubber Volumes (v/v)** | | | | | | | | |
| 0% | 1.63 | 1.63 | 0.000 | 3.5 | 8.0 | 10.7 | 11.8 | 40.0 |
| 20% | 1.60 | 1.62 | 0.014 | 4.5 | 9.7 | 12.0 | 13.4 | 38.5 |
| 40% | 1.53 | 1.54 | 0.011 | 9.5 | 12.3 | 14.2 | 14.8 | 37.1 |
| LSD (0.05) | 0.05 | 0.05 | -NS- | 2.0 | 2.0 | 2.2 | -NS- | 1.1 |

† * indicates a significant difference at the 0.05 level
NS = not significant
O.D. = Oven Dry

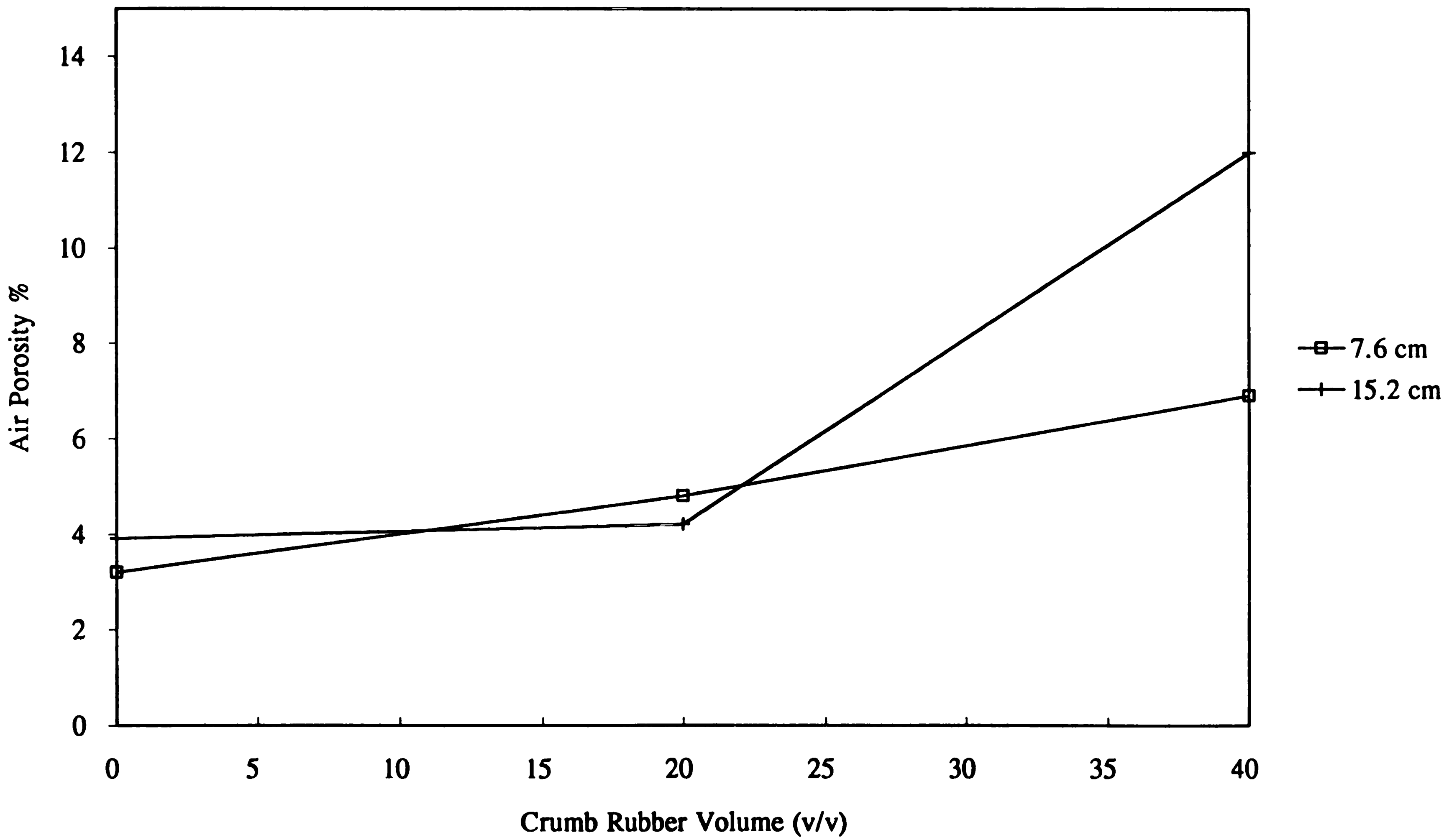



Fig. 7. The effect of -0.0040 MPa matric potential on tilling depth x crumb rubber volume interaction on a trafficked perennial ryegrass stand at the HTRC, 1993.

negative relationship; as the soil water decreased total porosity decreased as well. However, as the same in Experiment I, air-filled porosity was highest when the soil profile was most susceptibile to compaction. Thus, the more crumb rubber incorporated to the soil profile, the more macropore space was available for drainage while not increasing micropores (due to compaction and the lack of macropores). Baker and Issac (1987) reported a higher turfgrass stand on a well-drained soil versus a poorly-drained soil. Furthermore, Hillel (1980) reported a limitation of plant growth when aeration porosity was below 10% of the soil volume. On a silt loam, Carrow (1980) determined that -0.010 MPa was an optimum matric potential for compaction. Soil physical measurements revealed a statistical difference at this matric potential; as crumb rubber volumes increased, air porosity increased as well.

For Exp II, when crumb rubber volumes were extracted, actual crumb rubber in the cores at 20% averaged to be 9.2%; with 6.8% in the 7.6 cm depth and 13.6% in the 15.2 cm depth. At 40 % the average was 21.8%; with 11.7% in the 7.6 cm depth and 30.0% in the 15.2 cm depth. Although, crumb rubber was below expected amounts, incorporating crumb rubber on site could not allow for a uniform mixing process (Hummel, 1993).

Soil nutrient concentration values are listed on Table 14. There were no significant differences between incorporation depths except for zinc and manganese. There were no significant differences among crumb rubber volumes except for boron, zinc, manganese and nickel. There were significant differences among sampling depths except for boron, cadmium, and iron, but all were in normal soil ranges (Lindsay, 1978).

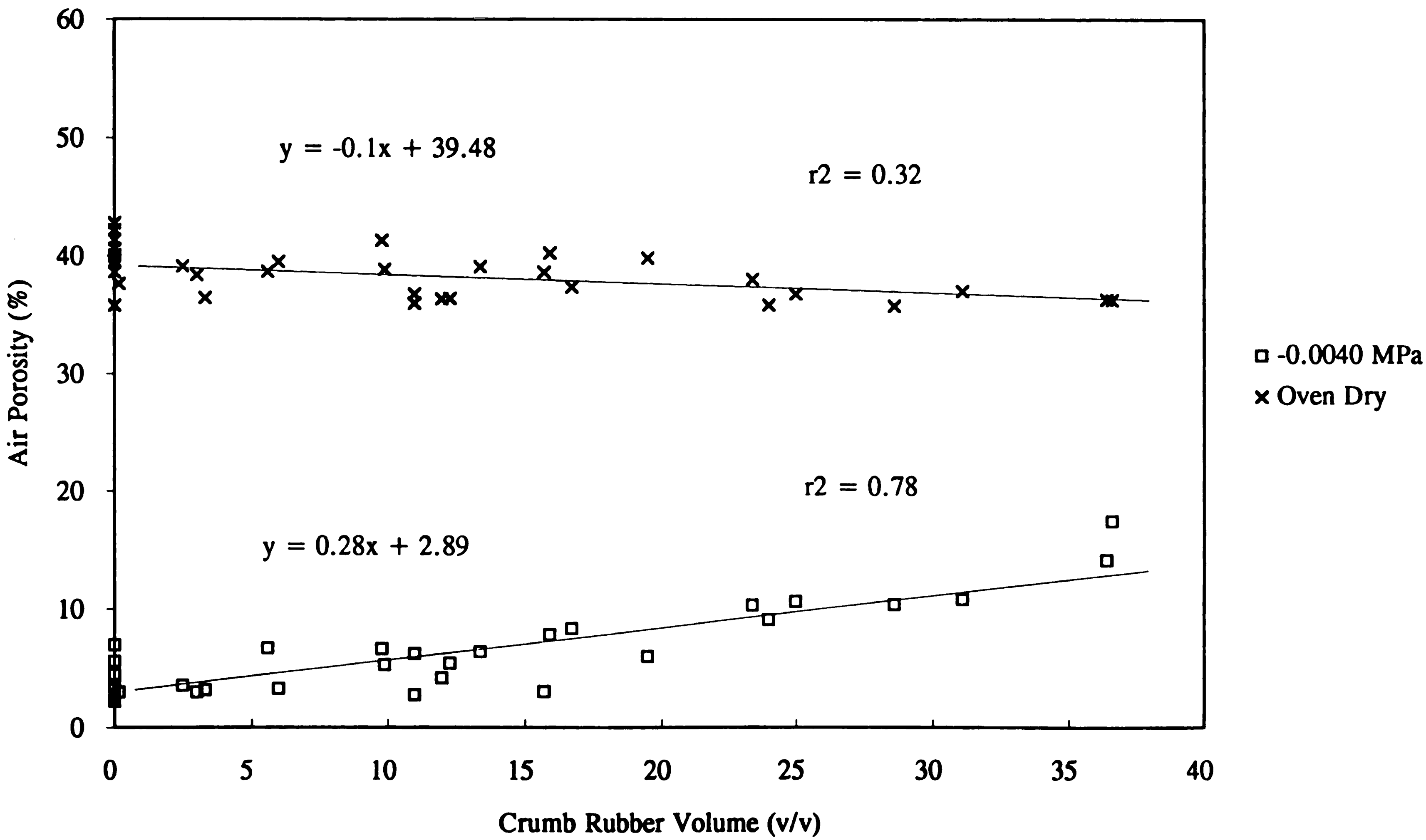



Fig. 8. Air-filled porosity as a function of volumetric proportion on incorporated crumb rubber at -0.0040 MPa matric potential and oven dry on a trafficked perennial ryegrass stand at the HTRC, 1993.

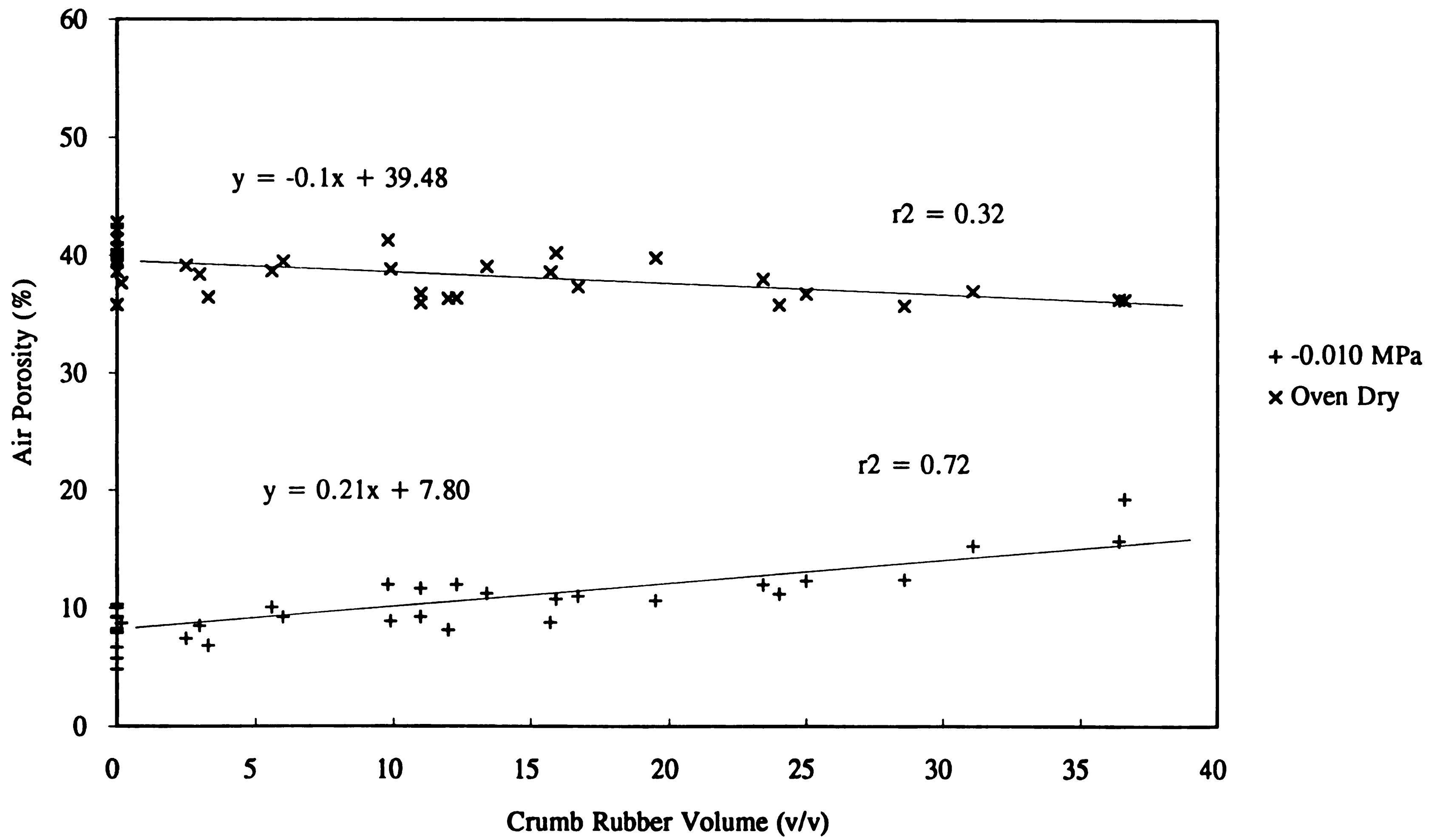



Fig. 9. Air-filled porosity as a function of volumetric proportion on incorporated crumb rubber at -0.010 MPa matric potential and oven dry on a trafficked perennial ryegrass stand at the HTRC, 1993.

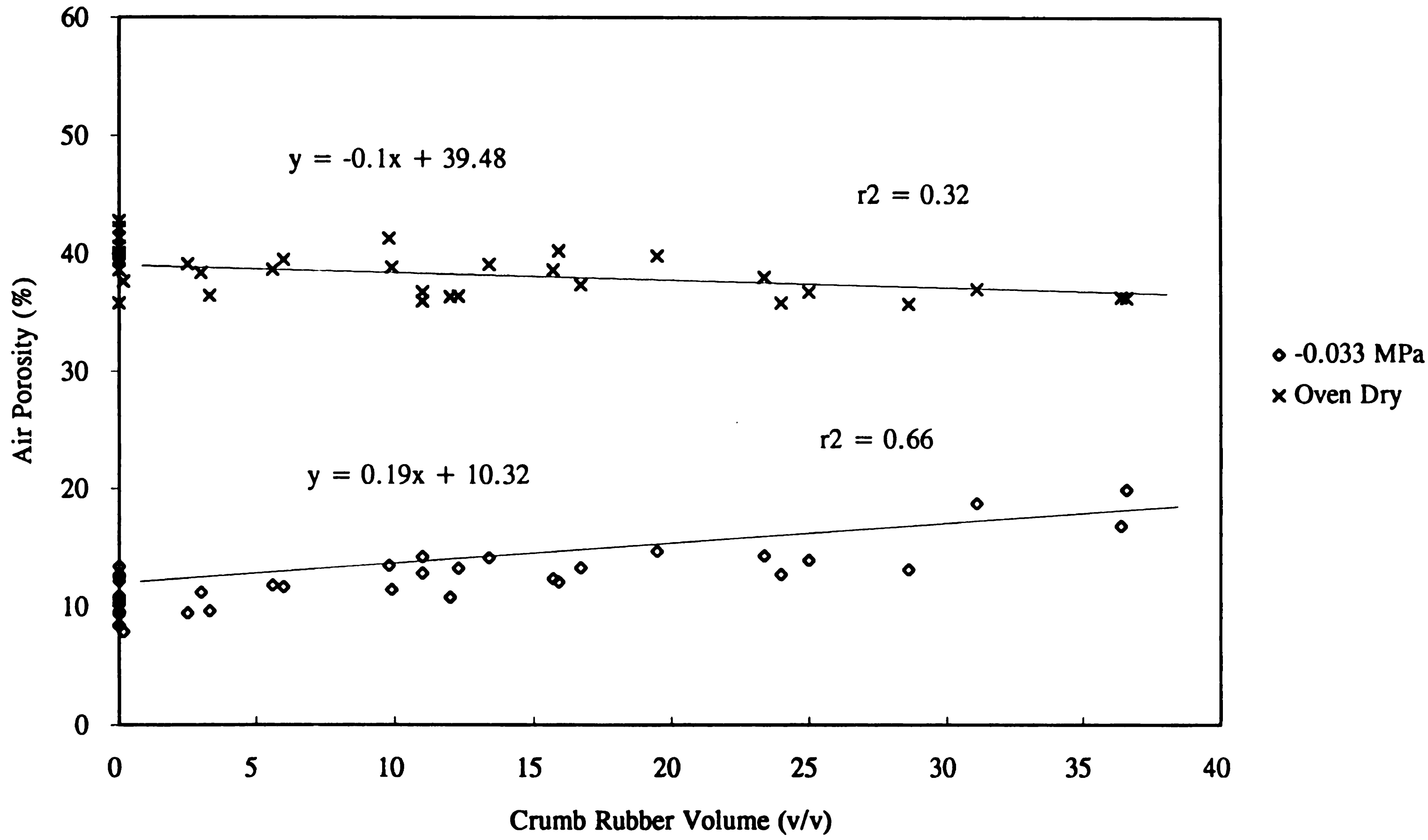



Fig. 10. Air-filled porosity as a function of volumetric proportion on incorporated crumb rubber at -0.033 MPa matric potential and oven dry on a trafficked perennial ryegrass stand at the HTRC, 1993.

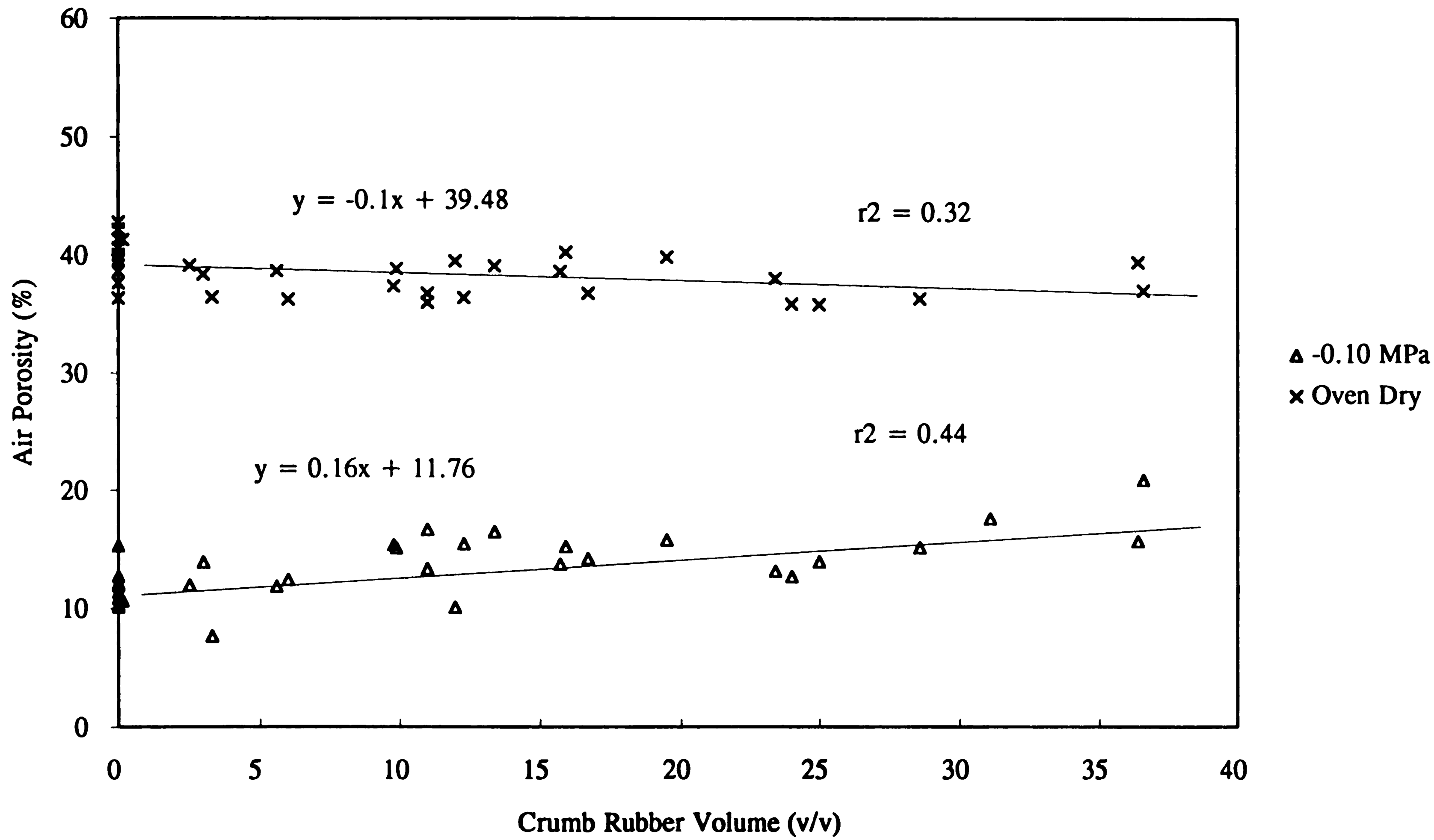



Fig. 11. Air-filled porosity as a function of volumetric proportion on incorporated crumb rubber at -0.10 MPa matric potential and oven dry on a trafficked perennial ryegrass stand at the HTRC, 1993.

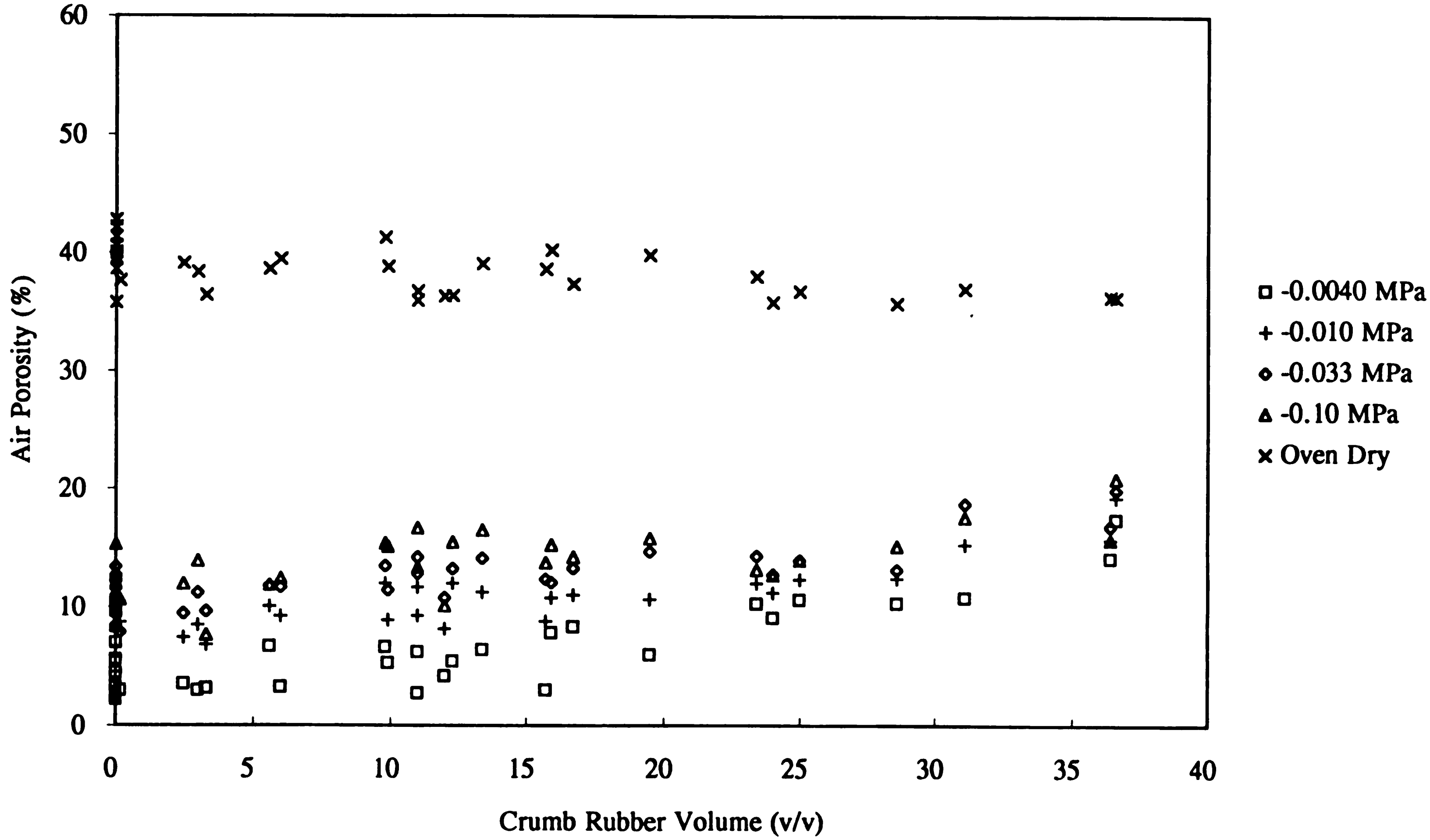



Fig. 12. Air-filled porosity as a function of volumetric proportions on incorporated crumb rubber at -0.0040, -0.010, -0.033, -0.10 MPa versus oven dry on a trafficked perennial ryegrass stand at the HTRC, 1993.

Table 14. Effects of crumb rubber volume rates and incorporation depths on soil nutrient concentrations at depths of 0-7.6 cm, 7.6-15.2 cm, and 15.2-22.8 cm on a perennial ryegrass stand (Exp II) on 10 August 1994 at the Hancock Turfgrass Research Center.

| | Soil Nutrient Concentration | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | B | Zn | Cd | Mn | Cu | Pb | Ni | Fe | Cr | Na |
| Incorporation Depths | | | | | | | | | | |
| 7.6 cm | 0.8 | 11.2 | 0.3 | 89.7 | 1.9 | 2.8 | 1.7 | 129.5 | 0.3 | 98.5 |
| 15.2 cm | 0.8 | 28.6 | 0.3 | 99.7 | 2.0 | 2.9 | 1.8 | 131.5 | 0.3 | 103.1 |
| Significance[†] | -NS- | * | -NS- | * | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Volume (v/v) | | | | | | | | | | |
| 0% | 0.7 | 3.4 | 0.3 | 87.8 | 2.0 | 2.8 | 1.6 | 122.8 | 0.3 | 99.3 |
| 20% | 0.7 | 20.5 | 0.3 | 97.0 | 1.9 | 2.8 | 1.8 | 124.0 | 0.3 | 96.6 |
| 40% | 0.9 | 33.6 | 0.3 | 98.6 | 1.9 | 2.8 | 1.8 | 119.9 | 0.3 | 103.0 |
| LSD (0.05) | 0.3 | 5.7 | -NS- | 7.3 | -NS- | -NS- | 0.2 | -NS- | -NS- | -NS- |
| Sampling Depth | | | | | | | | | | |
| 0-7.6 cm | 0.8 | 49.8 | 0.3 | 112.7 | 2.2 | 3.1 | 2.0 | 128.2 | 0.3 | 107.2 |
| 7.6-15.2 cm | 0.9 | 5.8 | 0.3 | 86.3 | 1.8 | 2.6 | 1.6 | 123.9 | 0.3 | 101.5 |
| 15.2-22.8 cm | 0.6 | 4.0 | 0.3 | 85.1 | 1.9 | 2.7 | 1.6 | 139.5 | 0.3 | 93.6 |
| LSD (0.05) | -NS- | 4.4 | -NS- | 5.6 | 0.2 | 0.2 | 0.2 | -NS- | -NS- | -NS- |

[†] * indicates a significant difference at a 0.05 level
NS = not significant

Interactions of incorporation depths, crumb rubber volumes, and sampling depths are listed on Tables 15 and 16. These interactions all stem from inconsistency of the rubber.

### *Summary*

Tilling rubber into the soil profile was very labor intensive, costly, and time consuming. However, field measurements recorded did provide insight on the dynamics crumb rubber can provide in improving playing surface characteristics.

It was noted throughout the study, impact absorption values tended to be lower and shear values higher on Kentucky bluegrass versus perennial ryegrass, this could be primarily due to the thatch (or mat) layer of Poa pratensis L. The thatch above the soil profile for the Kentucky bluegrass masked many field paramenters, and consequently may have inhibited the effectiveness of crumb rubber.

When incorporated into the ground, crumb rubber was able to improve soil physical properties. However, there was no increase observed in turfgrass density and quality regardless of improvements in the soil profile. Soil nutrient concentrations revealed higher differences for zinc and manganese among crumb rubber volumes. While the increases are attributed to the crumb rubber incorporated into the soil, all concentrations were in acceptable ranges as well as no movement through the soil profile.

Also, a more improved method of introducing crumb rubber to the soil turf environment must be investigated. A three to four month quarantine was rendered for proper turfgrass development. Plus, results from the first two years were skewed due

Table 15. Incorporation depth by crumb rubber volume by sampling depth interaction means for zinc and manganese soil concentrations on 10 August, 1994 at the Hancock Turfgrass Research Center.

| Incorporation Depth x Crumb Rubber Volume | Zn | Mn |
|---|---|---|
| 7.6 cm, 0% | 3.6 | 86.3 |
| 7.6 cm, 20% | 12.1 | 90.5 |
| 7.6 cm, 40% | 17.4 | 94.3 |
| 15.2 cm, 0% | 3.1 | 89.2 |
| 15.2 cm, 20% | 28.9 | 103.5 |
| 15.2 cm, 40% | 49.7 | 102.8 |
| LSD (0.05) | 8.0 | 10.2 |
| **Incorporation Depth x Sampling Depth** | | |
| 7.6 cm, 0-7.6 cm | 26.5 | 99.9 |
| 7.6 cm, 7.6-15.2 cm | 3.5 | 84.6 |
| 7.6 cm, 15.2-22.8 cm | 3.7 | 84.6 |
| 15.2 cm, 0-7.6 cm | 73.2 | 125.4 |
| 15.2 cm, 7.6-15.2 cm | 8.2 | 88.0 |
| 15.2 cm, 15.2-22.8 cm | 4.3 | 85.6 |
| LSD (0.05) | 6.2 | 7.9 |
| **Crumb Rubber Volume x Sampling Depth** | | |
| 0%, 0-7.6 cm | 5.4 | 93.0 |
| 0%, 7.6-15.2 cm | 1.6 | 85.3 |
| 0%, 15.2-22.8 cm | 3.0 | 85.0 |
| 20%, 0-7.6 cm | 51.8 | 117.3 |
| 20%, 7.6-15.2 cm | 5.7 | 86.5 |
| 20%, 15.2-22.8 cm | 4.0 | 87.1 |
| 40%, 0-7.6 cm | 85.3 | 124.2 |
| 40%, 7.6-15.2 cm | 10.2 | 87.2 |
| 40%, 15.2-22.8 cm | 5.2 | 84.3 |
| LSD (0.05) | 10.1 | 12.5 |

Table 16. Incorporation depth by crumb rubber volume by sampling depth interaction means for zinc and managanese soil concentrations on a trafficked perennial ryegrass stand on 10 August, 1994 at the Hancock Turfgrass Research Center.

| Incorporation Depth x Crumb Rubber Volume x Sampling Depth | Zn | Mn |
|---|---|---|
| 7.6 cm, 0%, 0-7.6 cm | 6.0 | 94.4 |
| 7.6 cm, 0%, 7.6-15.2 cm | 2.6 | 80.5 |
| 7.6 cm, 0%, 15.2-22.8 cm | 2.2 | 83.9 |
| 15.2 cm, 0%, 0-7.6 cm | 31.0 | 100.4 |
| 15.2 cm, 0%, 7.6-15.2 cm | 1.7 | 85.3 |
| 15.2 cm, 0%, 15.2-22.8 cm | 3.8 | 85.9 |
| 7.6 cm, 20%, 0-7.6 cm | 39.8 | 107.3 |
| 7.6 cm, 20%, 7.6-15.2 cm | 6.8 | 90.2 |
| 7.6 cm, 20%, 15.2-22.8 cm | 5.6 | 85.5 |
| 15.2 cm, 20%, 0-7.6 cm | 4.8 | 91.7 |
| 15.2 cm, 20%, 7.6-15.2 cm | 0.7 | 90.1 |
| 15.2 cm, 20%, 15.2-22.8 cm | 3.9 | 86.0 |
| 7.6 cm, 40%, 0-7.6 cm | 72.5 | 134.2 |
| 7.6 cm, 40%, 7.6-15.2 cm | 9.8 | 87.8 |
| 7.6 cm, 40%, 15.2-22.8 cm | 4.3 | 88.4 |
| 15.2 cm, 40%, 0-7.6 cm | 130.9 | 141.1 |
| 15.2 cm, 40%, 7.6-15.2 cm | 13.6 | 84.1 |
| 15.2 cm, 40%, 15.2-22.8 cm | 4.7 | 83.1 |
| LSD (0.05) | 13.8 | 17.7 |

to the lack of soil settling. However, after two years, a reduction in soil compaction and improved turfgrass quality was observed.

Chapter 2

# Core cultivation as a tool to incorporate crumb rubber into high traffic turfgrass areas

## ABSTRACT

Crumb rubber, incorporated into the soil profile, has shown potential in reducing compaction and decreasing surface hardness. However, incorporation methods other than conventional tilling need investigation. A study was initiated in a 2x6 randomized complete block design with three replicates at the Hancock Turfgrass Research Center (HTRC). Two crumb rubber sizes (2.00/0.84mm and 6 mm) and six cultivation treatments (four core cultivated crumb rubber treatments, conventional rubber tilling, and core cultivation with no rubber) were incorporated into on a 2-year old stand of Lolium perenne var. 'Dandy'. Traffic treaments were applied by the Brinkman Traffic Simulator (BTS) with an average of 7 passes per week during the 1993 and 1994 fall seasons. Data collected included surface hardness, traction, soil moisture, surface and soil temperatures, and quality and density ratings. Data showed minimal differences in surface characteristics measurements. Root mass was greater in the coring holes with crumb rubber filled into these holes. There were significant differences between particle sizes. Turfgrass density and overall quality were higher for the core cultivated crumb rubber treatments which implemented a regime of five cultivations versus 10 cultivations per treatment.

***Introduction***

Cultivation is a commonly used tool which aids in the process of temporarily relieving soil and plant stresses (Kuipers, 1963). In terms of turfgrass cultivation, the two main stresses that are relieved or alleviated are soil compaction and thatch accumulation. Cultivation is a process in which minimial disruption takes place within the turf/soil profile environment (Beard 1973). Rieke and Murphy (1989) cited many key advantages in cultivation, such as, relieving soil compaction, decreasing thatch accumulation, breaking up soil layers, and a tool used to re-establish areas and/or modify them with topdressing. Furthermore, they cited benefits from cultivating an area, such as, improving soil/root relationships (increase root mass, oxygen levels, and infiltration rates) and providing "a softer, more resilient surface". However, Rogers and Waddington (1990), when evaluating playing surface characteristics, found core cultivation to provide minimal relief of surface hardness. Therefore, the use of crumb rubber may enhance the benefits that cultivation can provide and facilitate a softer, more resilient surface.

A commonly used method, rototilling provided the opportunity to re-establish a highly compacted soil profile and improve the plant relationships. This also allowed for the use of soil amendments to be implemented to improve soil physical properties and subsequently improve plant responses especially in high traffic areas (refer to Chapter 1, Introduction). However, rototilling has become quite costly and labor intensive. Excessive tilling also destoys soil structure, and the area must have time for soil settling and proper turfgrass re-establishment and development (Lee and Rieke, 1993).

Turgeon (1980) referred to several forms of turfgrass cultivation including, slicing, spiking, coring and deep soil aerification. One other newly developed cultivation method has been the use of a high pressure water injection machine for cultivation (WIC) which will not disrupt the turfgrass surface and has been ideal for closely mowed turf, such as a putting greens (Murphy, 1990). Miller (1994) evaluated surface hardness after using the WIC. He reported water injection decreased surface hardness, but it was inconclusive if this was a direct effect of the shattering of the soil profile or an increase in soil moisture.

The objective of this study was to evaulate crumb rubber as a soil amendment by incorporating it through core cultivation. Results from Chapter 1 reported there was no significant difference between tilling depths of crumb rubber and that greater than a 20% (v/v) was best for improved soil/plant relationships and reducing surface hardness. It was imperative to find a more efficient management practice that would decrease the time for re-establishing a playing field which would improve its playabilty and aesthetics and decrease the potential for surface-related injuries.

### *Materials and Methods*

A study was established on a 2-year old stand of Lolium perenne v. 'Dandy', on 29 July 1993, at the Hancock Turfgrass Research Center (HTRC) at Michigan State University, East Lansing, Michigan. The soil was a Capac loam containing 61% sand, 23% silt, and 16 % clay (Fine-loamy, mixed mesic aeric, Ochracualfs).

Crumb rubber (6.00 mm and 2.00/0.84 mm) (Table 17a) was used as a soil amendment in a variety of cultivation treatments in a 2x6 randomized complete block design. Treatments 1 and 2, were core cultivated, 5 and 10 times, respectively, topdressed with crumb rubber and dragged in for even distribution; treatments 3 and 4, were topdressed with crumb rubber in between every two or three passes of core cultivations, 5 and 10 times, respectively; treatment 5 employed the conventional crumb rubber incorporation method (strip the sod, rototill rubber in at a 7.6 cm depth at a 20% v/v rate, and resod with prior turfgrass stand), and treatment 6 was a check plot (core cultivation 5 times; no rubber). A treatment list is presented in Table 17b. Individual plot size was 5.4 m x 1.8 m.

On 22 July 1993, the plot was overseeded at 98 kg $ha^{-1}$ with Lolium perenne v. 'Dandy'. Fertilization was applied before and after the core cultivation of crumb rubber into the soil profile. Before core cultivation, 24.5 kg N $ha^{-1}$ each of sulfur-coated urea (35-0-0) and ureaformaldehyde (38-0-0) were broadcasted. After core cultivation, 16.3 kg N $ha^{-1}$ of urea (46-0-0) was broadcast at weekly intervals on 28 July, 6 August, and 12 August. Also on 23 August, 24.5 kg N $ha^{-1}$ of 25-0-25 was broadcast over the plot. Phosphorous was not added as they were at sufficient levels throughout the study as indicated by soil tests. On 16 May 1994, the plot was slit-seeded at 109 kg $ha^{-1}$ of Lolium perenne L. var. 'Dandy'and fertilized with a 19-19-19 at 37 kg N $ha^{-1}$.

After establishment, the mowing height was 38 mm and mowed three times a week. Irrigation and pest management was applied on a need only basis.

Table 17a. Crumb rubber sieve analysis for the crumb rubber core cultivation and topdressing studies, 1993.

| | Particle Size | |
|---|---|---|
| | 6.00 mm | 2.00/0.84 mm |
| | ----------- % ---------- | |
| Category (Size range) | | |
| Gravel (> 2mm) | 93.3 | 16.6 |
| Very Coarse (1-2mm) | 3.7 | 39.4 |
| Coarse (1-0.50mm) | 1.5 | 17.5 |
| Medium (0.50-0.25mm) | 1.3 | 22.4 |
| Fine (0.25-0.10mm) | 0.2 | 3.8 |
| Very Fine (0.10-0.05mm) | 0.0 | 0.3 |

Table 17b. Cultivation treatments for the core cultivation study using crumb rubber as a soil amendment, 1993.

Treatments

1. Cored 5x + topdress + drag (C5TD)

2. Cored 10x + topdress + drag (C10TD)

3. Topdress rubber between 5x cored (TR5)

4. Topdress rubber between 10x cored (TR10)

5. Strip sod + till rubber 3" + resodded (1991-92 method) (SSR)

6. Check (Cored 5x; no rubber) (NOR)

To cultivate the treatments, the plot was mowed at 13 mm with a Toro 223D (Bloomington, MN) deck mower (deck was 1.7m wide). Each scheduled treatment area was core cultivated with a Jacobsen Greens King (Racine, WI) with a tine size having an inner diameter of 9.6 mm. After the cultivation treatments were performed, the treatment area was dragged in for as even distribution as possible and then rolled with an Olathe Greens roller (Olathe, KS). The rubber particles would settle down either into the coring hole or the soil surface. The particle density of crumb rubber was 1.2 g/cc (Epps, 1994) versus soil particle density being 2.65 g/cc (Hillel, 1980).

Traffic treatments were applied with the Brinkman Traffic Simulator (BTS) (See Chapter 1, Materials and Methods). In 1993, traffic treatments were made from 26 August to 14 November, and in 1994, from 5 September to 15 November. In 1994, new traffic lane was initiated due to its close proximity to the original crumb rubber experiments (Poa pratensis L. and Lolium perenne L., Chapter 1), thus switching traffic lanes in between experiments was not pratical. For both years, an average of eight and ten passes were applied per week, respectively. The total number of games simulated per year were 48 games.

In 1993, data was collected on trafficked surfaces on 18 August, 17 September, 1 October, 13 October, 25 October, and 15 November, and non-traffic dates were inclusive except for 18 August. In 1994, data was collected on 19 July, 24 August, 13 September, 4 October, 28 October, and 11 November on trafficked surfaces only.

Impact absorption was collected by the Clegg Impact Soil Tester (CIT) (Lafayette Instruments Co., Lafayette, IN) using the 2.25 kg hammer (See Chapter 1, Materials and Methods). In 1994, the CIT readout box was replaced with the Brüel and Kjaer 2515 Vibration Analyzer, and the values [peak deceleration ($G_{max}$), time to peak deceleration (Tp), total duration of impact (Tt), and rebound ratio (rr%)] recorded were an average of four measurements except on 18 August (CIT readout box with hammer dropped three times) and 17 September (Brüel and Kjaer Analyzer with hammer dropped three times) (Rogers and Waddington, 1992). Shear resistance was measured with the Eijkelkamp Shearvane Type 1B (Henderson, 1986). The value recorded (Nm) was an average of three measurements. Surface and soil temperatures (7.6cm) were recorded with a Barnant 115 Thermocoupler Thermometer (°C). Soil water content (kg $kg^{-1}$) readings were measured by the Gravimetric method (Gardner, 1965). Three soil samples (7.6 cm) per treatment were used for this method. Ball bounce was measured from a height of 3 meters (Canaway, 1985). The soccer ball used was an official 1990 FIFA soccer ball (pressure range of ball 0.9 bar - 1.1 bar) at a pressure of 0.95 - 1.0 bar.

Root sampling was taken on 22 November 1993 and 7 November 1994. In 1993, three samples were taken from the traffic and non-traffic areas at three depths of 0-5 cm, 5-10 cm, and 10-15 cm. The probe area was 5.1 $cm^2$. In 1994, treatments C5TD, C10TD, TR5, and NORUB were evaluated for root density. Four samples were taken from the traffic area from four depths of 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm. The area of the probe was 7.5 $cm^2$. Roots were separated from the soil by the hydropneumatic elutriation system (Smucker et al, 1982). Roots were weighed, ashed at 500°C for five hours, and then reweighed.

Bulk density (Blake and Hartage, 1986) and air porosity (Danielson and Sutherland, 1986) were measured from two undisturbed samples removed from each treatment in 22 November 1994. The core sample was 45.8 $cm^2$ by 7.6 cm deep but did not exclude crumb rubber in the coring holes. Samples were taken below the thatch/rubber layer. Air porosity was measured as the soil water lost from saturation to matric potentials of -0.0040, -0.010, -0.033, -0.10 MPa, and oven dry (105°C) in the laboratory in Febraury 1995. Saturated hydraulic conductivity was measured using a constant head (Klute and Dirksen, 1986).

Turfgrass density was recorded on 3 September, 1, 7, and 25 October 1993 and 23 August, 4 October, and 4 December 1994. Density ratings were rated on a scale of 0 - 100%. In 1994 (same dates as density ratings), turfgrass quality ratings were rated on a scale from 1 - 9; 1 = brown (or dead), 9 = excellent and
6 = acceptable.

Results from all measurements were analyzed using the MSTAT analysis of variance and the least significance difference (LSD) test at the 0.05 level.

***Results and Discussion***

Surface hardness characteristics are listed on Tables 18-20. In 1993, peak deceleration values (Table 18) had no significant differences between particle sizes for the traffic and non-traffic areas. However, there was a significant difference in surface hardness among cultivation treatments for every testing date in the trafficked area except 15 November. Furthermore, there was a significant difference among treatments for every testing date in the non-trafficked areas. In 1994, peak deceleration values (Table 19) had no significant difference between particle sizes except on 4

Table 18. Effects of crumb rubber particle size and cultivation treatments on peak deceleration ($G_{max}$) on a trafficked and non-trafficked perennial ryegrass stand at the Hancock Turfgrass Research Center, 1993.

| | Trafficked Areas | | | | | Non Trafficked Areas | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 17 Sept | 1 Oct | 13 Oct | 25 Oct | 15 Nov | 17 Sept | 1 Oct | 13 Oct | 25 Oct | 15 Nov |
| | $G_{max}$ | | | | | | | | | |
| Particle Size (mm) | | | | | | | | | | |
| 6.00 | 64 | 55 | 95 | 79 | 59 | 66 | 63 | 84 | 75 | 67 |
| 2.00/0.84 | 62 | 54 | 94 | 77 | 58 | 64 | 62 | 82 | 74 | 65 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Treatment | | | | | | | | | | |
| C5TD | 64 | 57 | 91 | 78 | 57 | 65 | 64 | 81 | 70 | 64 |
| C10TD | 67 | 59 | 91 | 79 | 61 | 70 | 66 | 93 | 81 | 72 |
| TR5 | 63 | 53 | 88 | 72 | 58 | 66 | 64 | 79 | 73 | 65 |
| TR10 | 67 | 58 | 96 | 82 | 60 | 71 | 70 | 86 | 81 | 70 |
| SSR | 55 | 46 | 93 | 75 | 57 | 53 | 49 | 73 | 66 | 56 |
| NOR | 65 | 56 | 106 | 82 | 58 | 67 | 63 | 88 | 76 | 66 |
| LSD (0.05) | 6 | 6 | 9 | 5 | -NS- | 7 | 6 | 7 | 6 | 6 |
| Soil Water (kg $kg^{-1}$) | .228 | .249 | .192 | .204 | .272 | .233 | .243 | .183 | .211† | .262 |
| Games Simulated | 11 | 22 | 30 | 37 | 48 | 11 | 22 | 30 | 37 | 48 |

NS = not significant
† soil water significant between particle sizes at the 0.05 level.

Table 19. Effects of crumb rubber particle size and cultivation treatments on peak deceleration ($G_{max}$) and ball bounce (%) on a trafficked perennial ryegrass stand at the Hancock Turfgrass Research Center, 1994.

| | Peak Deceleration | | | | | | Ball Bounce | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 19 Jul | 24 Aug | 13 Sept | 4 Oct | 28 Oct | 11 Nov | 24 Aug | 13 Sept | 4 Oct | 11 Nov |
| | $G_{max}$ | | | | | | % | | | |
| Particle Size (mm) | | | | | | | | | | |
| 6.00 | 85 | 70 | 98 | 62 | 83 | 53 | 39 | 41 | 39 | 37 |
| 2.00/0.84 | 87 | 70 | 102 | 60 | 85 | 53 | 40 | 41 | 39 | 39 |
| Significance[†] | -NS- | -NS- | -NS- | * | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Treatment | | | | | | | | | | |
| C5TD | 79 | 68 | 95 | 61 | 82 | 54 | 38 | 40 | 38 | 38 |
| C10TD | 89 | 70 | 95 | 63 | 82 | 54 | 39 | 42 | 39 | 39 |
| TR5 | 81 | 66 | 104 | 62 | 83 | 52 | 38 | 40 | 38 | 37 |
| TR10 | 89 | 69 | 102 | 60 | 83 | 53 | 39 | 41 | 39 | 38 |
| SSR | 88 | 75 | 102 | 64 | 85 | 54 | 41 | 41 | 37 | 35 |
| NOR | 89 | 71 | 102 | 59 | 89 | 52 | 40 | 42 | 44 | 40 |
| LSD (0.05) | -NS- | 5 | -NS- | 3 | 4 | -NS- | -NS- | -NS- | 3 | -NS- |
| Soil Water (kg $kg^{-1}$) | 0.167 | 0.189[§] | 0.137 | 0.200 | 0.170[‡] | 0.205 | 0.189 | 0.137 | 0.200 | 0.205 |
| Games Simulated | 0 | 0 | 8 | 24 | 40 | 46 | 0 | 8 | 24 | 46 |

[†] * indicates a significant difference at the 0.05 level.
[‡] indicates a significant difference between particle size at the 0.05 level.
[§] indicates a significant difference among cultivated treatments at the 0.05 level.
NS = not significant

October. However, three out of the six testing dates showed a significant difference among cultivation treatments.

Rogers and Waddington (1990) reported similar results when measuring surface hardness after core cultivation. A reduction in $G_{max}$ was minimal and temporary for the NOR treatment versus the crumb rubber treatments especially when soil moisture was low. Treatments C5TD and TR5 had lower peak deceleration values than treatments C10TD and TR10. This could possibly be due to cultivating twice as much and forming a hardpan underneath, regardless of crumb rubber absorbing impact at the surface.

Ball bounce (Table 19), another surface hardness characteristic, showed no differences between particle sizes. There were no significant differences among treatments except on 4 October.

To further describe surface hardness characteristics, time to peak deceleration, duration of impact, and rebound ratio were recorded in 1994 in addition to peak deceleration as listed on Table 20. For time to peak deceleration, there were no significant differences between particle sizes nor among core cultivated crumb rubber treatments except on 28 October. For duration of impact, there were no significant differences between particle sizes. Also, there were no significant differences among core cultivated crumb rubber treatments except on 28 October. For rebound ratio, there were no significant differences between particle sizes except on 4 October. There were no significant differences among core cultivated crumb rubber treatments except for 4 October and 28 October. However, an interaction is also listed 4 October (Table 20) for rebound ratio revealing importance of the 2.00/0.84 mm size.

Table 20. Effects of crumb rubber particle size and cultivation treatments on time to peak deceleration (ms), duration of impact (ms),and rebound ratio (%) on a trafficked perennial ryegrass stand at the Hancock Turfgrass Research Center, 1994.

| | Time to peak deceleration | | | | Total duration of impact | | | | Rebound ratio | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 13 Sept | 4 Oct | 28 Oct | 11 Nov | 13 Sept | 4 Oct | 28 Oct | 11 Nov | 13 Sept | 4 Oct | 28 Oct | 11 Nov |
| Particle Size (mm) | | | | | | | | | | | | |
| 6.00 | 3.5 | 5.7 | 4.1 | 6.1 | 6.6 | 10.4 | 7.7 | 11.0 | 28.6 | 26.2 | 28.1 | 21.8 |
| 2.00/0.84 | 3.7 | 5.5 | 4.2 | 6.1 | 6.9 | 10.3 | 7.9 | 11.2 | 29.1 | 27.8 | 28.1 | 21.1 |
| Significance† | -NS- | -NS- | * | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | * | -NS- | -NS- |
| Treatment | | | | | | | | | | | | |
| C5TD | 3.9 | 5.8 | 4.3 | 6.0 | 7.1 | 10.5 | 8.1 | 11.1 | 31.1 | 28.2 | 29.5 | 23.4 |
| C10TD | 3.8 | 5.6 | 4.3 | 5.9 | 7.2 | 10.2 | 8.1 | 11.1 | 31.1 | 28.4 | 30.1 | 21.7 |
| TR5 | 3.6 | 5.7 | 4.4 | 6.2 | 6.7 | 10.4 | 8.1 | 11.4 | 30.6 | 27.8 | 30.6 | 21.5 |
| TR10 | 3.6 | 5.7 | 4.2 | 6.1 | 6.7 | 10.5 | 7.8 | 11.3 | 28.3 | 27.2 | 28.0 | 22.2 |
| SSR | 3.4 | 5.2 | 4.0 | 6.1 | 6.5 | 9.9 | 7.8 | 10.9 | 25.8 | 26.5 | 26.3 | 21.3 |
| NOR | 3.4 | 5.6 | 3.7 | 6.2 | 6.4 | 10.3 | 7.0 | 10.8 | 26.3 | 24.0 | 24.1 | 18.8 |
| LSD (0.05) | -NS- | -NS- | 0.2 | -NS- | -NS- | -NS- | 0.6 | -NS- | -NS- | 1.0 | 3.0 | -NS- |
| Interaction | | | | | | | | | | | | |
| 6.00, C5TD | | | | | | | | | | 26.5 | | |
| 6.00, C10TD | | | | | | | | | | 26.9 | | |
| 6.00, TR5 | | | | | | | | | | 27.4 | | |
| 6.00, TR10 | | | | | | | | | | 26.7 | | |
| 6.00, SSR | | | | | | | | | | 26.6 | | |
| 6.00, NOR | | | | | | | | | | 23.3 | | |
| 2.00/0.84, C5TD | | | | | | | | | | 29.8 | | |
| 2.00/0.84, C10TD | | | | | | | | | | 29.9 | | |
| 2.00/0.84, TR5 | | | | | | | | | | 28.2 | | |
| 2.00/0.84, TR10 | | | | | | | | | | 27.6 | | |
| 2.00/0.84, SSR | | | | | | | | | | 26.4 | | |
| 2.00/0.84, NOR | | | | | | | | | | 24.7 | | |
| LSD (0.05) | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | 0.2 | -NS- | -NS- |

† * indicates a significant difference at the 0.05 level, NS = not significant

Soil moisture was 0.137, 0.200, 0.170, and 0.205 kg $kg^{-1}$ for 13 September, 4 October, 28 October, and 11 November, respectively.

In 1994, surface hardness characteristic data had significant differences among crumb rubber cultivated treatments showing crumb rubber core cultivated having longer time values and higher rebound ratios These types of values translated to softer, more resilient surfaces as reported by Rogers and Waddington (1992). This trend was evident throughout the fall although not always statistically significant.

Shear resistance values are listed on Tables 21 and 22. In 1993, shear resistance values in the trafficked and non-trafficked areas (Table 21) showed no significant differences between particle sizes. In the trafficked areas, there was a significant difference among cultivated treatments for all four testing dates. In the non-trafficked areas, for three out of the four testing dates, there was a significant difference among cultivated treatments. In 1994 (Table 20), there were no significant differnces between particle sizes except on 19 July and 13 September. There were no significant differences among cultivated treatments except on 4 October.

In 1993, after the crumb rubber was incorporated through core cultivation and before it stabilized, there were lower shear resistance values versus SSR and NOR treatments. This trend did not continue in 1994, and higher shear resistance values resulted. However, there were little differences among treatments in 1994 versus 1993.

In 1993, shear resistance values for SSR and NOR treatments were significantly higher than the core cultivated crumb rubber treatments, for both the traffic and non-traffic areas. The advantage of these two treatments was the pre-existing mature turf plants in the treatments. However, it was observed that plugs from the shearvane were pulled out of the surface from the SSR treatment throughout the experiment (as would

Table 21. Effects of crumb rubber particle size and cultivation treatments on shear resistance (N m) on a trafficked and non-trafficked perennial ryegrass stand at the Hancock Turfgrass Research Center, 1993.

| | Trafficked Areas | | | | Non-Trafficked Areas | | | |
|---|---|---|---|---|---|---|---|---|
| | 17 Sept | 1 Oct | 13 Oct | 25 Oct | 17 Sept | 1 Oct | 13 Oct | 25 Oct |
| Particle Size (mm) | | | | | | | | |
| 6.00 | 15.3 | 14.6 | 15.7 | 13.0 | 19.0 | 19.9 | 18.8 | 17.8 |
| 2.00/0.84 | 15.4 | 14.6 | 17.5 | 13.6 | 18.8 | 19.9 | 19.9 | 16.7 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Treatment | | | | | | | | |
| C5TD | 14.1 | 13.7 | 12.2 | 12.2 | 17.0 | 19.1 | 16.0 | 14.9 |
| C10TD | 13.9 | 13.4 | 16.1 | 11.7 | 17.6 | 18.8 | 18.9 | 16.2 |
| TR5 | 14.7 | 13.7 | 14.9 | 10.9 | 18.6 | 19.7 | 18.1 | 15.7 |
| TR10 | 14.4 | 13.8 | 15.8 | 12.9 | 18.6 | 20.4 | 20.1 | 16.3 |
| SSR | 17.7 | 16.7 | 20.3 | 16.1 | 20.7 | 21.0 | 20.9 | 20.0 |
| NOR | 17.3 | 16.5 | 20.5 | 16.4 | 20.9 | 20.2 | 22.0 | 20.4 |
| LSD (0.05) | 1.9 | 1.3 | 2.5 | 1.7 | 1.6 | -NS- | 2.9 | 1.8 |
| Interaction | | | | | | | | |
| 6.00, C5TD | | | | | | | 14.8 | |
| 6.00, C10TD | | | | | | | 16.4 | |
| 6.00, TR5 | | | | | | | 16.9 | |
| 6.00, TR10 | | | | | | | 18.6 | |
| 6.00, SSR | | | | | | | 23.3 | |
| 6.00, NOR | | | | | | | 22.8 | |
| 2.00/0.84, C5TD | | | | | | | 17.2 | |
| 2.00/0.84, C10TD | | | | | | | 21.3 | |
| 2.00/0.84, TR5 | | | | | | | 19.2 | |
| 2.00/0.84, TR10 | | | | | | | 21.7 | |
| 2.00/0.84, SSR | | | | | | | 18.4 | |
| 2.00/0.84, NOR | | | | | | | 21.2 | |
| LSD (0.05) | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | 4.1 | -NS- |

NS = not significant

Table 22. Effects of crumb rubber particle size and cultivation treatments on shear resistance (N m) on a trafficked perennial ryegrass stand the Hancock Turfgrass Research Center, 1994.

| | 19 Jul | 24 Aug | 13 Sept | 4 Oct | 28 Oct | 11 Nov |
|---|---|---|---|---|---|---|
| | ---------- | | N m | | ---------- | |
| Particle Size (mm) | | | | | | |
| 6.00 | 21.0 | 15.8 | 20.1 | 19.4 | 22.4 | 16.4 |
| 2.00/0.84 | 19.1 | 15.1 | 18.4 | 18.6 | 21.8 | 17.0 |
| Significance† | * | -NS- | * | -NS- | -NS- | -NS- |
| Treatment | | | | | | |
| C5TD | 20.3 | 14.7 | 17.3 | 18.8 | 22.6 | 17.8 |
| C10TD | 20.1 | 16.1 | 19.8 | 20.1 | 20.8 | 16.6 |
| TR5 | 19.6 | 15.7 | 19.7 | 20.2 | 22.3 | 16.7 |
| TR10 | 21.3 | 15.7 | 19.5 | 18.9 | 22.9 | 16.5 |
| SSR | 18.5 | 15.3 | 19.7 | 19.0 | 22.3 | 16.6 |
| NOR | 20.8 | 15.3 | 19.6 | 17.0 | 21.6 | 16.3 |
| LSD (0.05) | -NS- | -NS- | -NS- | 2.1 | -NS- | -NS- |

† * indicates a significant difference at the 0.05 level.
NS = not significant

be observed on a new athletic field that was sodded and has not fully established in a short period of time). Furthermore, with the sod intact, the shearvane appartus could "dig into" the turf/soil interface and produce a high traction value. Due to the weakening of the plant, round turf plugs, the shape of the shearvane, were removed from the surface. The core cultivated crumb rubber treatments started from this point as well except crumb rubber could impede proper turfgrass development. In 1993, turfgrass growth for these treatments were not as fully developed, and consequently had lower shear resistance values. However, in 1994, the turfgrass had time to recover and regrow thus allowing for better establishment of the turf especially for the core cultivated crumb rubber treatments.

Surface and soil temperatures are listed on Tables 23-25. In 1993, for both surface and soil temperatures in trafficked areas (Table 23), there were no significant differences between particle sizes. For surface temperatures, there were no significant differences among cultivated treatments. For soil temperatures, there were no significant differences among cultivated treatments except on 18 August and 1 October. Although significant, the differences would likely have little bearing on root growth or development at this time of year. For non-trafficked areas (Table 24), for both surface and soil temperatures, there were no significant differences between particle sizes. Also, for both temperatures, there were no significant differences among cultivated treatments except for soil temperatures on 1 October. In 1994, for both surface and soil temperatures (Table 25), there were no significant differences between particle sizes, Also, for both temperatures, there were no significant differences among

Table 23. Effects of crumb rubber particle size and cultivation treatment on surface and soil temperatures (°C) at the 7.6 cm depth on a trafficked perennial ryegrass stand at the Hancock Turfgrass Research Center, 1993.

| | Surface Temperatures | | | | | Soil Temperatures | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 18 Aug | 1 Oct | 13 Oct | 25 Oct | 15 Nov | 18 Aug | 1 Oct | 13 Oct | 25 Oct | 15 Nov |
| Particle Size (mm) | | | | | | | | | | |
| 6.00 | 34.4 | 13.8 | 13.9 | 16.5 | 5.1 | 27.3 | 12.1 | 11.8 | 14.8 | 7.6 |
| 2.00/0.84 | 34.6 | 13.7 | 14.3 | 16.4 | 5.1 | 27.4 | 12.0 | 11.8 | 15.0 | 7.6 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Treatment | | | | | | | | | | |
| C5TD | 34.7 | 13.9 | 14.2 | 16.4 | 5.1 | 27.2 | 12.1 | 12.0 | 14.5 | 7.7 |
| C10TD | 35.1 | 13.5 | 14.3 | 16.1 | 5.2 | 27.8 | 12.0 | 11.8 | 15.2 | 7.6 |
| TR5 | 35.0 | 13.8 | 14.4 | 16.6 | 5.3 | 26.8 | 12.2 | 11.8 | 14.0 | 7.7 |
| TR10 | 34.6 | 13.9 | 14.4 | 16.5 | 5.0 | 27.8 | 12.1 | 11.9 | 14.9 | 7.6 |
| SSR | 33.9 | 13.6 | 13.4 | 16.5 | 5.1 | 27.0 | 12.0 | 11.5 | 15.0 | 7.5 |
| NOR | 33.7 | 13.7 | 13.8 | 16.4 | 5.2 | 27.3 | 12.0 | 11.8 | 15.6 | 7.5 |
| LSD (0.05) | -NS- | -NS- | -NS- | -NS- | -NS- | 0.5 | 0.1 | -NS- | -NS- | -NS- |
| Interaction | | | | | | | | | | |
| 6.00, C5TD | | | | | | | 12.0 | | | |
| 6.00, C10TD | | | | | | | 12.0 | | | |
| 6.00, TR5 | | | | | | | 12.3 | | | |
| 6.00, TR10 | | | | | | | 12.1 | | | |
| 6.00, SSR | | | | | | | 12.0 | | | |
| 6.00, NOR | | | | | | | 11.9 | | | |
| 2.00/0.84, C5TD | | | | | | | 12.1 | | | |
| 2.00/0.84, C10TD | | | | | | | 11.9 | | | |
| 2.00/0.84, TR5 | | | | | | | 12.0 | | | |
| 2.00/0.84, TR10 | | | | | | | 12.0 | | | |
| 2.00/0.84, SSR | | | | | | | 12.0 | | | |
| 2.00/0.84, NOR | | | | | | | 12.0 | | | |
| LSD (0.05) | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | 0.1 | -NS- | -NS- | -NS- |

NS = not signficant

Table 24. Effects of crumb rubber particle size and cultivation treatments on surface and soil temperatures (°C) at the 7.6 cm depth on a non-trafficked perennial ryegrass stand at the Hancock Turfgrass Research Center, 1993.

| | Surface Temperatures | | | | Soil Temperatures | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 Oct | 13 Oct | 25 Oct | 15 Nov | 1 Oct | 13 Oct | 25 Oct | 15 Nov |
| | °C | | | | | | | |
| Particle Size (mm) | | | | | | | | |
| 6.00 | 11.9 | 10.6 | 17.0 | 5.1 | 12.6 | 12.0 | 13.2 | 8.0 |
| 2.00/0.84 | 11.8 | 10.8 | 16.9 | 5.2 | 12.6 | 12.1 | 13.4 | 8.0 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Treatment | | | | | | | | |
| C5TD | 11.9 | 10.4 | 16.7 | 5.1 | 12.7 | 12.2 | 13.2 | 8.0 |
| C10TD | 11.9 | 11.0 | 17.4 | 5.1 | 12.5 | 12.1 | 13.5 | 7.9 |
| TR5 | 11.9 | 10.7 | 16.9 | 5.2 | 12.7 | 12.0 | 13.3 | 8.0 |
| TR10 | 11.9 | 10.7 | 17.5 | 5.1 | 12.7 | 12.2 | 13.5 | 7.9 |
| SSR | 11.7 | 10.6 | 16.8 | 5.2 | 12.5 | 11.9 | 13.1 | 8.0 |
| NOR | 11.8 | 10.7 | 16.4 | 5.3 | 12.6 | 12.0 | 13.2 | 7.9 |
| LSD (0.05) | -NS- | -NS- | -NS- | -NS- | 0.2 | -NS- | -NS- | -NS- |

NS = not significant

Table 25. Effects of crumb rubber particle size and cultivation treatments on surface and soil temperatures (°C) at the 7.6 cm depth on a trafficked perennial ryegrass stand at the Hancock Turfgrass Research Center, 1994.

| | Surface Temperatures | | | | Soil Temperatures | | | |
|---|---|---|---|---|---|---|---|---|
| | 24 Aug | 13 Sept | 4 Oct | 11 Nov | 24 Aug | 13 Sept | 4 Oct | 11 Nov |
| Particle Size (mm) | | | | | | | | |
| 6.00 | 22.8 | 17.9 | 21.2 | 9.1 | 19.3 | 19.1 | 13.3 | 8.0 |
| 2.00/0.84 | 22.9 | 17.9 | 21.4 | 9.1 | 19.3 | 19.1 | 13.3 | 8.0 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Treatment | | | | | | | | |
| C5TD | 23.0 | 17.7 | 21.3 | 9.4 | 19.3 | 19.1 | 13.5 | 8.2 |
| C10TD | 22.8 | 18.0 | 21.1 | 8.9 | 19.3 | 19.1 | 13.4 | 8.0 |
| TR5 | 23.0 | 17.9 | 21.3 | 8.9 | 19.4 | 19.1 | 13.4 | 8.1 |
| TR10 | 23.1 | 17.8 | 20.4 | 9.2 | 19.3 | 19.1 | 13.3 | 8.0 |
| SSR | 22.5 | 18.0 | 21.7 | 9.0 | 19.0 | 19.1 | 13.0 | 7.9 |
| NOR | 22.6 | 17.8 | 21.9 | 9.3 | 19.3 | 19.2 | 13.2 | 8.1 |
| LSD (0.05) | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | 0.5 | -NS- |
| Interaction | | | | | | | | |
| 6.00, C5TD | | | | | | 19.2 | | |
| 6.00, C10TD | | | | | | 19.0 | | |
| 6.00, TR5 | | | | | | 19.1 | | |
| 6.00, TR10 | | | | | | 19.2 | | |
| 6.00, SSR | | | | | | 19.3 | | |
| 6.00, NOR | | | | | | 19.1 | | |
| 2.00/0.84, C5TD | | | | | | 19.0 | | |
| 2.00/0.84, C10TD | | | | | | 19.2 | | |
| 2.00/0.84, TR5 | | | | | | 19.1 | | |
| 2.00/0.84, TR10 | | | | | | 19.1 | | |
| 2.00/0.84, SSR | | | | | | 19.1 | | |
| 2.00/0.84, NOR | | | | | | 19.3 | | |
| LSD (0.05) | -NS- | -NS- | -NS- | -NS- | -NS- | 0.2 | -NS- | -NS- |

NS = not significant

cultivated treatments except for soil temperatures on 4 October. Interactions resulted from soil temperatures on 1 October 1993 (Table 23) and 13 September 1994 (Table 25).

Root mass values are listed on Tables 26 and 27. In 1993, for traffic and non-traffic areas, there were no significant differences in root mass between particle sizes except in the non-traffic areas at the 0-5 cm sampling depth. There were no significant differences in root mass among cultivated treatments.

In 1994 (Table 27), there were no significant differences in root mass between particle sizes except at the 0-2.5 cm and the 0-15 cm (total) sampling depths. There were no significant differences among cultivated treatments.

In 1993 and 1994, the 2.00/0.84 mm size promoted a larger root mass in both the traffic and non-traffic areas. The top 2-3 cm are considered the most compacted area in recreational turf (Morgan et al., 1966; O'Neil and Carrow, 1982). O'Neil and Carrow (1983), when evaluating perennial ryegrass, reported root weights decreased as compaction levels increased due to a decrease in oxygen and an increase in soil strength. However, additions of crumb rubber allowed for root growth to be substantially higher versus the NOR treatment.

In 1994, only certain cultivation treatments were selected based on the better field measurements and overall quality, and observation from the 1993 data. A larger root mass was evident with the cultivated core crumb rubber treatments versus the NORUB treatment although not statistically significant (Table 27).

Bulk density, air-filled porosity, and saturated hydraulic conductivity values were measured in 1994 and are listed in Table 28. For bulk density, there were no

Table 26. Effects of crumb rubber particles sizes and core cultivation treatments on root mass ($g * cm^{-3}$)on a trafficked and non-trafficked perennial ryegrass stand on 22 November 1993 after 48 simulated football games at the Hancock Turfgrass Research Center.

| | Trafficked Areas | | | Non-Trafficked Areas | | |
|---|---|---|---|---|---|---|
| | 0-5 cm | 5-10 cm | 10-15 cm | 0-5 cm | 5-10 cm | 10-15 cm |
| | $g * cm^{-3}$ | | | | | |
| Particle Sizes | | | | | | |
| 6.00 mm | 0.56 | 0.14 | 0.09 | 0.54 | 0.14 | 0.09 |
| 2.00/0.84 mm | 0.70 | 0.17 | 0.09 | 0.71 | 0.20 | 0.10 |
| Significance† | -NS- | -NS- | -NS- | * | -NS- | -NS- |
| Treatments | | | | | | |
| C5TD | 0.67 | 0.18 | 0.09 | 0.87 | 0.17 | 0.09 |
| C10TD | 0.74 | 0.12 | 0.08 | 0.55 | 0.13 | 0.08 |
| TR5 | 0.53 | 0.15 | 0.08 | 0.60 | 0.17 | 0.09 |
| TR10 | 0.64 | 0.14 | 0.10 | 0.63 | 0.16 | 0.09 |
| SSR | 0.58 | 0.12 | 0.07 | 0.52 | 0.13 | 0.09 |
| NOR | 0.60 | 0.22 | 0.09 | 0.60 | 0.25 | 0.12 |
| LSD(0.05) | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |

NS = not significant
† indicates a significant difference at the 0.05 level.

Table 27. Effects of crumb rubber particle size and cultivation treatments on root mass (g * cm$^{-3}$)on a trafficked perennial ryegrass stand on 7 November 1994 after 44 simulated football games at the Hancock Turfgrass Research Center.

| | 0-2.5 cm | 2.5-5 cm | 5-10 cm | 10-15 cm | Total |
|---|---|---|---|---|---|
| | | | ---------- g * cm$^{-3}$ ---------- | | |
| Particle Sizes | | | | | |
| 6.00 mm | 0.52 | 0.21 | 0.22 | 0.12 | 1.07 |
| 2.00/0.84 mm | 0.69 | 0.28 | 0.25 | 0.14 | 1.36 |
| Signficance[†] | * | -NS- | -NS- | -NS- | * |
| Treatments | | | | | |
| C5TD | 0.62 | 0.23 | 0.21 | 0.12 | 1.18 |
| C10TD | 0.60 | 0.23 | 0.25 | 0.15 | 1.23 |
| TR5 | 0.75 | 0.30 | 0.25 | 0.13 | 1.43 |
| NOR | 0.45 | 0.22 | 0.22 | 0.13 | 1.02 |
| LSD (0.05) | -NS- | -NS- | -NS- | -NS- | -NS- |

NS = not significant

[†]* indicates a significant difference at the 0.05 level.

significant differences between particle sizes nor among cultivated treatments. For air-filled porosity, there were no differences between particle sizes nor among cultivated treatements. For saturated hydraulic conductivity, there were no significant differences between particle sizes nor among cultivated treatments.

Turfgrass density ratings are listed on Table 29 and 30. In 1993 and 1994, there were no significant differences in turfgrass density between particle sizes, but there were significant differences among cultivated treatments for every testing date. As traffic increased throughout the experiment, the core cultivated crumb rubber treatments promoted a higher turfgrass density versus the SSR and NOR treatments. These density observations also help supplement the explanation of shear values from the SSR and NOR treatments being weaker and pulling plugs consistently throughout the experiement even though shear resistance values were higher than the other treatments. The number of cultivation passes or timing of incorporation of rubber during the cultivation process made no statistical difference in terms of turfgrass density throughout the experiment.

Turfgrass quality ratings are also listed on Table 30. There were no significant differences between particle sizes, but there were significant differences among cultivated treatments. The core cultivated crumb rubber treatments were significantly higher than the SSR and NOR treatments except on 23 August before traffic simulation. Both treatments did not have the crumb rubber in the top 2-3 cm to aid in reducing surface hardness and promoting better turfgrass growth and quality.

Table 28. Effects of crumb rubber particle size and cultivation treatments on bulk density ($g * cm^{-3}$), air porosity (%), and saturated hydraulic conductivity ($cm * hr^{-1}$) on a trafficked perennial ryegrass stand on 22 November 1994 at the Hancock Turfgrass Research Center.

| | Bulk Density | Matric Potentials | | | | | Sat. Hydraulic Cond. |
|---|---|---|---|---|---|---|---|
| | $g * cm^{-1}$ | -0.0040 | -0.010 | -0.033 | -0.10 | O.D | $cm * hr^{-1}$ |
| | | ---------- MPa --------- | | | | | |
| **Crumb Rubber Particle Sizes (mm)** | | | | | | | |
| 6 mm | 1.65 | 6.5 | 10.3 | 13.6 | 13.9 | 41.7 | 4 |
| 2.0/0.84 mm | 1.65 | 6.4 | 9.2 | 12.1 | 13.3 | 41.3 | 6 |
| Significance† | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| **Cultivation Treatments** | | | | | | | |
| C5TD | 1.66 | 6.6 | 10.3 | 13.7 | 13.9 | 41.9 | 3 |
| C10TD | 1.64 | 6.6 | 9.6 | 13.5 | 13.4 | 41.2 | 3 |
| TR5 | 1.65 | 6.3 | 9.5 | 13.4 | 13.3 | 41.1 | 4 |
| NOR | 1.65 | 6.2 | 9.6 | 10.8 | 13.7 | 41.8 | 8 |
| LSD (0.05) | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |

NS = not significant
O.D. = Oven Dry

Table 29. Effects of crumb rubber particle size and cultivation treatments on turfgrass density ratings on a trafficked perennial ryegrass stand at the Hancock Turfgrass Research Center, 1993.

| | Density Ratings | | | |
|---|---|---|---|---|
| | 3 Sept | 1 Oct | 7 Oct | 25 Oct |
| Particle Size (mm) | | | | |
| 6.00 | 57 | 44 | 27 | 21 |
| 2.00/0.84 | 58 | 44 | 28 | 22 |
| Significance[†] | -NS- | -NS- | -NS- | -NS- |
| Treatment | | | | |
| C5TD | 63 | 53 | 35 | 26 |
| C10TD | 58 | 42 | 24 | 23 |
| TR5 | 77 | 47 | 33 | 26 |
| TR10 | 70 | 47 | 32 | 26 |
| SSR | N/A | 38 | 20 | 15 |
| NOR | 77 | 38 | 23 | 17 |
| LSD (0.05) | 10 | 10 | 9 | 5 |
| Games Simulated | 3 | 20 | 25 | 37 |

NS = not significant
N/A = Treatment was not included in density rating because area was sodded.

Table 30. Effects of crumb rubber particle size and cultivation treatments on turfgrass density and quality ratings on a trafficked perennial ryegrass stand at the Hancock Turfgrass Research Center, 1994.

| | Density Ratings | | | Quality Ratings | | |
|---|---|---|---|---|---|---|
| | 23 Aug | 4 Oct | 4 Dec | 23 Aug | 4 Oct | 4 Dec |
| Particle Size (mm) | | | | | | |
| 6.00 | 99 | 63 | 46 | 7.6 | 6.2 | 4.2 |
| 2.00/0.84 | 99 | 64 | 52 | 7.7 | 6.3 | 4.6 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Treatment | | | | | | |
| C5TD | 99 | 72 | 60 | 7.7 | 6.8 | 5.0 |
| C10TD | 99 | 67 | 52 | 7.8 | 6.4 | 4.6 |
| TR5 | 99 | 70 | 65 | 7.7 | 6.7 | 5.3 |
| TR10 | 98 | 67 | 52 | 7.5 | 6.7 | 4.6 |
| SSR | 98 | 48 | 32 | 7.4 | 5.0 | 3.4 |
| NOR | 100 | 58 | 31 | 7.8 | 6.0 | 3.5 |
| LSD (0.05) | 1 | 6 | 14 | 0.2 | 0.9 | 0.8 |
| Games Simulated | 0 | 24 | 48 | 0 | 24 | 48 |

NS = not significant
Density Ratings Scale was 0-100%
Quality Ratings Scale was 1-9; 1 = brown (low density, dead), 9 = excellent (high density, green), and 6 = acceptable.

*Summary*

Core cultivation has proven to be effective in introducing crumb rubber to the soil turf environment to reduce surface hardness, improve shear resistance, and density and increase quality ratings while not removing the field out of play. Although timing is crucial in any effective management scheme, core cultivating crumb rubber, using a 20% v/v rate can improve playing surface characteristics and overall turfgrass quality. Results in the first year after incorporation had lower shear resistance values for core cultivated crumb rubber treatments versus SSR and NOR treatments However, these qualities started to dissipate towards the end of the first year, and by the second year, crumb rubber revealed the importance of improving surface hardness characteristics and improving traction under traffic conditions.

Root mass improved with additions of crumb rubber with a 2.00/0.84 mm particle size. As compaction levels increased, root mass was able to be consistent for the core cultivated crumb rubber treatments versus the NOR treatment. Furthermore, turfgrass density and quality for these subsequent treatments were significantly higher as the fall season progressed.

Regardless of being core cultivated five or 10 times into the soil profile crumb rubber can stabilize the playing surface and provide a more consistent palying surface. The importance of this soil amendment can not be over-stated because it can be used as a tool to be integrated into a management program, and can be incorporated without taking the field out of play for an extended period of time.

Chapter 3

# Crumb rubber as a topdressing for athletic fields and high traffic turf areas

## ABSTRACT

Crumb rubber has shown to be an effective in reducing compaction and surface hardness. However, to successfully incorporate crumb rubber into the soil, a field must be quarantined for at least three to four months for proper turfgrass development. Therefore, a topdressing study with crumb rubber was initiated at the Hancock Turfgrass Research Center at Michigan State University in East Lansing, MI in fall 1993. A 2x5 randomized complete block design with three replications was implemented with two particle sizes levels (6.00 mm and 2.00/0.84 mm) and five crumb rubber topdressing treatments (0.0, 17.1, 34.2, 44.1, and 88.2 t * $ha^{-1}$). In both 1993 and 1994, 48 games were simulated by the Brinkman Traffic Simulator (BTS). Field measurements taken were impact absorption, shear resistance, soil moisture, soil and surface temperatures, and ball bounce. Turfgrass color, density and quality ratings were also observed. Impact absorption values were significant among treatments in 1993. This could be due to increasing the crumb rubber amounts throughout the fall season (Sept.-Nov.). In 1994, impact values were not significantly different among treatments. However, time to peak, impact duration, and rebound ratio were significantly different among treatments.

*Introduction*

Topdressing plays many roles in enhancing the turfgrass environment. Among these benefits include thatch control, smoother surface, modification of the surface soil and winter protection (Beard, 1973). Goss (1977) defined topdressing as,

> " Topdressing may be defined as a surface application of any growth medium intended to perform some of the following functions: correct putting surfaces; develop firmer, drier surfaces; increase infiltration rates of water; help relieve hard, compacted surfaces; increase air porosity (noncapillary pore space); aid thatch decomposition; prevent surface puddling; provide cover for overseeding; supply nutrients; modify topsoils..."

Putting greens and sports fields profit from this maintenance practice, primarily because they are high traffic areas and emphasize the importance of a smooth and uniform playing surface.

With a reduction in infiltration, a decrease in soil aeration and an increase in disease and weeds, putting green quality subsides (Rossi and Skogley, 1987). To remedy these adverse effects, Madison and Davis (1970) suggested that applications of sand topdressing (3 cu. yd./1000ft$^2$), should be light and frequent and at the same time matching the growth of the plant (roughly every three weeks during the active growing season of the year).

Although thatch can be detrimental to a turfgrass setting (Latham, 1955), it also can be advatageous in low amounts (Sartain and Volk, 1984). Numerous studies have been conducted on modifying thatch through various management practices, such as, core cultivation and/or topdressing (Eggens, 1980; White and Dickens, 1984;

Fermanian et al., 1993; Christians et al., 1993). In doing so, thatch can be resilient and reduce compaction in traffic sites (Hurto and Turgeon, 1978). They also observed thatch being porous and fibrous thus emphasizing the importance of a management strategy of light and frequent irrigation as to not dry out the thatch. Furthermore, Sartain and Volk (1984) cited other positive effects, such as, insulating any soil temperature extremes and reducing weeds. Nevertheless, in relation to sportsfields, Rogers and Waddington (1992) observed the importance of thatch in reducing impact absorption. Impact ($G_{max}$) values were signficantly higher with full turf versus bare soil in a Kentucky bluegrass turf. Turfgrasses that do not form a thatch layer (i.e. Lolium perenne) may have more exaggerated responses to playing field measurements (Refer to Chapter 1).

Madison and Davis (1970) reported that topdressing was the "most important practice" to implement under high traffic conditions due to the forementioned qualities. Furthermore Davis (1984) reported that sportsfields tend to become heavily trafficked and the need of some heavy topdressing was important. However, the most intensively worn areas by mid-season are past the point of repair, and topdressing will not alleviate the problem. Additionally, sand has more abrasive edges leading to scarification of the crown tissue area (Beard, 1973). Topdressing applied too frequent and/or heavy can produce a layer which is "hard and abrasive" to the turfgrass plant (Gibeault, 1978). The abrasive action of the sand can be detriemental to the turfgrass if the plant is weak and not actively growing or in areas that are under low light conditions (i.e. shade) and subsequently reduced growing and recuperative conditions. This effect is magnified on low to medium use sportsfields. With the absence of turf, the playing quality and aesthetics are dramatically reduced which can ultimately lead to player injuries (Harper, et al., 1984; Rogers, et al., 1990). Furthermore, van Wijk (1980) reported that ball roll and ball bounce should be directly influenced by the smoothness and resiliency of the playing surface. One method to investigate the improvement of surface characteristics was to employ the use of crumb rubber as a topdressing to act as a thatch/topdressing without the abrasive properties.

The objective of this study was to find a more efficient management practice of incorporating crumb rubber to the soil/turf environment. By reducing surface hardness and decreasing the susceptibility of compaction, the playing field would have an improvement in playability and aesthetics while potentially reducing surface related injuries.

### *Materials and Methods*

A trial plot was established on an 80% sand : 20 % peat mix (v/v) (Figure 13) at the Hancock Turfgrass Research Center (HTRC) at Michigan State University, East Lansing, Michigan on 29 July 1993. Crumb rubber was topdressed in a 2x5 randomized complete block design with three replications. There were two levels of crumb rubber (6.00 mm and 2.00/0.84 mm) (Table 15) and five topdressing treatment rates (0.0, 5.7, 11.4, 14.7 and 29.4 t * $ha^{-1}$ of crumb rubber added to the surface on 29 July, 11 September and 5 October in 1993. Crumb rubber treatments reached final levels at 0.0, 17.1, 34.2, 44.1, and 88.2 t * $ha^{-1}$. Crumb rubber was not topdressed in 1994.). Crumb rubber was topdressed with a Scott's rotary spreader (Marysville, OH)

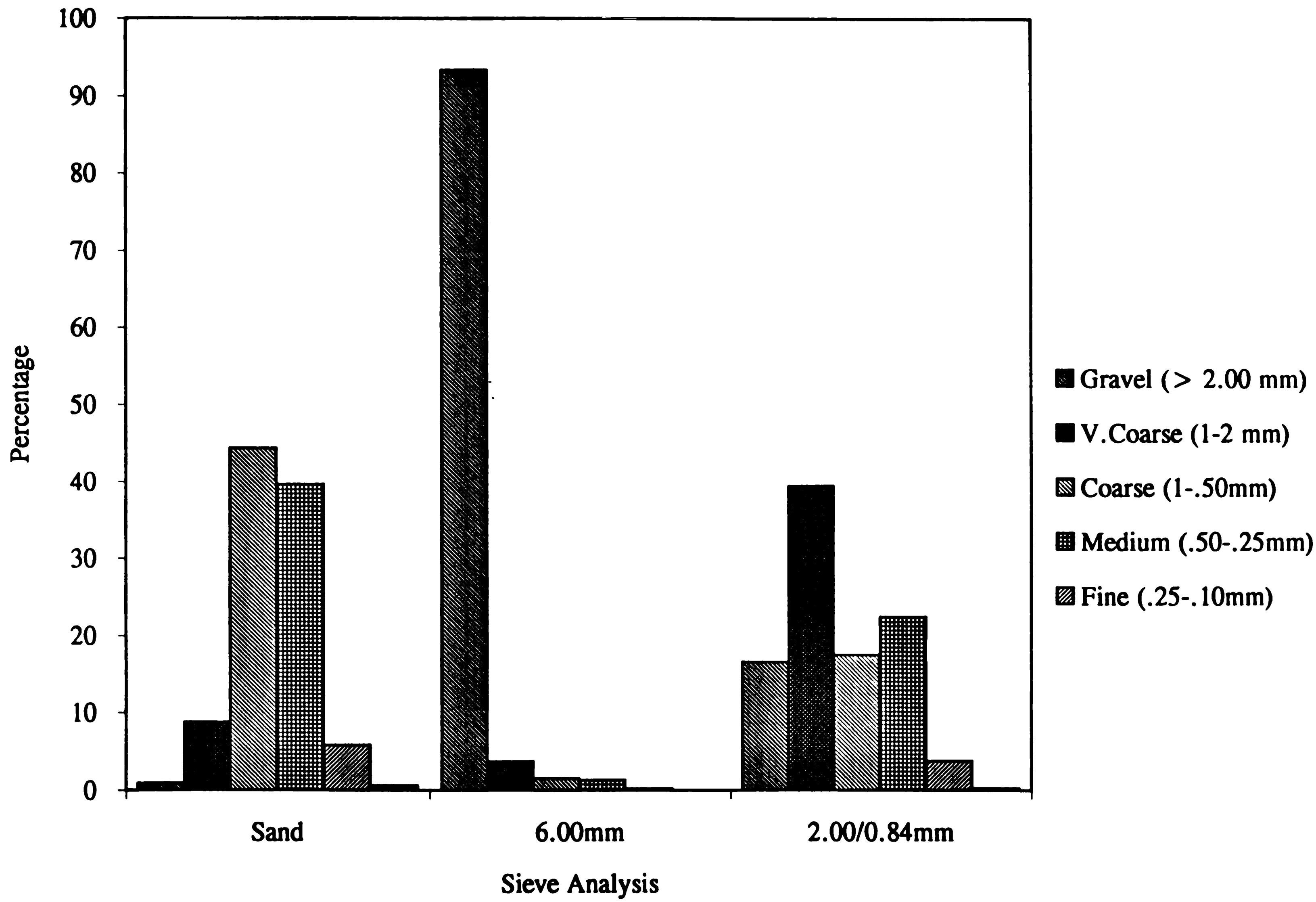



Fig. 13. Sieve analysis of sand (80:20, sand:peat mix), 6.00 mm size, and 2.00/0.84 mm size for the crumb rubber topdressing study at the Hancock Turfgrass Research Center, 1993.

and then dragged in for as even distribution as possible on a 85% Lolium perenne var. 'Dandy', 'Target', and 'Delray' and 15% Poa pratensis var. 'Argyle', 'Rugby', and 'Midnight' turfgrass stand. On 16 May 1994, trafficked lanes were slit-seeded with Lolium perenne var. Dandy at 53.9 kg * $ha^{-1}$. Treatment areas were 3.0m by 3.6m. Mowing height was at 38 mm and mowed three times a week with a Ransomes Triplex mower in 1993 and a Toro rotary deck mower (1.5 m deck) in 1994. Pest control and irrigation were applied on a need only basis. The rubber particles eventually settled down to the soil surface because of being lighter or having a lower particle density: [(rubber's particle density is 1.2 g/cc (Epps, 1994) versus soil particle density being 2.65 g/cc) (Hillel, 1980)].

Traffic treatments were made with the Brinkman Traffic Simulator (BTS) (Cockerham, 1989). In 1993, traffic treatments were made from 26 August to 14 November and from 5 September to 15 November in 1994. An average of eight and ten passes were made per week, respectively. The total number of games simulated per year were 48 games, respectively.

In 1993, data was collected on traffic surfaces on 18 August, 11 September, 20 September, 29 September, 22 October, 5 November, 19 November, and 3 December, and on non-traffic surfaces inclusive of the previous dates except 18 August, 5 November, 19 November, and 3 December in 1993. In 1994, data was collected on 2 June, 27 July, 15 September, 6 October, 17 October, 27 October, 10 November, and 30 December on trafficked surfaces only.

Impact absorption was collected by the Clegg Impact Soil Tester (Lafayette Instruments Co., Lafayette, IN) using the 2.25kg hammer. In 1993, an average from three measurements was recorded as transmitted to a hand-held read-out box as well as in 1994 on 2 June, 27 July, and 30 December. On other dates in 1994, impact absorption values were recorded with the Brüel and Kjaer 2515 Vibration Analyzer. This instrument allowed for further evaluation of surface hardness characteristics (Rogers and Waddington, 1990). These parameters included time to peak (Tp), duration of impact (Tt) (both measured in milliseconds), and rebound ratio (%).The values recorded were an average of four measurements except on 15 September when three measurements were recorded. In both years, the hammer was dropped randomly throughout the plot from a height of 0.46m (Rogers and Waddington, 1990). Soil water content (kg $kg^{-1}$) readings were provided by the Gravimetric method (Gardner, 1986). Shear resistance was measured with the Eijkelkamp Shearvane Type 1B. The value recorded (Nm) was an average of three measurements. Surface and soil temperatures (7.6cm) were recorded by the Barnant 115 Thermocoupler Thermometer ($^{o}$C). In 1994, additional surface temperatures were recorded on 7 April, and soil temperature on 19 April. Three soil samples (7.6 cm) per treatment were used for this method. Ball bounce measurements were taken and dropped from a height of 3 meters (Canaway, 1985). The soccer ball used was an official 1990 FIFA soccer ball (pressure range of ball 0.9 bar - 1.1 bar) at a pressure of 0.95 - 1.0 bar.

Clippings yields were taken from the treatments on 1.92$m^2$ on 2 October in 1993, and 20 April, 9 August and 20 October in 1994. The area of the clippings removed was 1.92 $m^2$. The mower used was a John Deere SR21 (Moline, IL) set at a mowing height of 38mm. Turf was allowed to grow for an extended periods of time in order to magnify the clipping yield measurements. Clippings were collected, dried for

24 hours at 60°C, and weighed. Clipping analysis of elements was ground to a 40 mesh size, and 0.5 gram was weighed out from each treatment and then ashed at 500°C. Ash was digested for one hour in a nitic acid/lithium chloride solution and analyzed for nutrient content (Zn, Fe, Mn, Cu, Mo, B, Mg, Ca, K, and P) by the ARC D.C. Plasma Emission Spectrophotometer V-B (Evelron, PA).

Root sampling was taken in November 1993. In 1993, root samples were collected: five samples were taken from the traffic areas at four depths 0-5 cm, 5-10 cm, 10-15 cm, and 15-20 cm. The area of the probe was $4.9 cm^2$. Roots were separated from the soil by the hydropneumatic elutriation system (Smucker et al, 1982). Roots were weighed, ashed at 500°C for five hours and then reweighed.

Turf density, color and overall quality ratings were recorded in 1993 and 1994. Density ratings were rated on a scale of 0 - 100%. Color and overall quality ratings were rated a scale from 1 - 9; 1 = brown (or dead), 9 = excellent and 6 = acceptable.

Results from both experiments were analyzed using the MSTAT analysis of variance and the least significance difference (LSD) test at the 0.05 level.

***Results and Discussion***

Surface hardness values are listed in Tables 31-33. Peak deceleration values, for 1993 (Table 31), in the traffic areas, had no significant differences between particle sizes except on 20 September while five out of 7 dates had significant differences among treatments. As crumb rubber rates exceeded $44.1 t * ha^{-1}$, the peak deceleration

Table 31. Effects of crumb rubber particle size and topdressing rates on peak deceleration ($G_{max}$) on a trafficked and non-trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Turfgrass Research Center, 1993.

| | Trafficked Areas | | | | | | | Non-Trafficked Areas | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 11 Sep | 20 Sep | 29 Sep | 22 Oct | 5 Nov | 19 Nov | 3 Dec | 11 Sep | 20 Sep | 29 Sep | 22 Oct |
| | $G_{max}$ | | | | | | | | | | |
| **Particle Size (mm)** | | | | | | | | | | | |
| 6.00 | 71 | 67 | 65 | 67 | 66 | 79 | 68 | 73 | 70 | 62 | 63 |
| 2.00/0.84 | 72 | 70 | 66 | 67 | 68 | 79 | 69 | 77 | 72 | 66 | 64 |
| Significance† | -NS- | * | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | * | -NS- |
| **Crumb Rubber Rates ($t\ ha^{-1}$)** | | | | | | | | | | | |
| 0.0 | 70 | 71 | 67 | 69 | 68 | 83 | 67 | 77 | 75 | 69 | 71 |
| 17.1 | 73 | 70 | 66 | 72 | 70 | 79 | 72 | 75 | 74 | 67 | 67 |
| 34.2 | 74 | 72 | 69 | 71 | 72 | 76 | 73 | 76 | 72 | 65 | 63 |
| 44.1 | 72 | 68 | 64 | 66 | 66 | 78 | 70 | 74 | 70 | 62 | 61 |
| 88.2 | 70 | 63 | 61 | 56 | 61 | 79 | 60 | 73 | 65 | 57 | 54 |
| LSD (0.05) | -NS- | 3 | 4 | 3 | 5 | -NS- | 5 | -NS- | 5 | 5 | 6 |
| Soil Water, ($kg\ kg^{-1}$) | N/A‡ | 0.174 | 0.202 | 0.218 | 0.172 | 0.189 | 0.202£ | N/A‡ | 0.168 | 0.201§ | 0.223§ |
| **Interaction** | | | | | | | | | | | |
| 6.00, 0.0 | 68 | | | | | | | | 73 | | |
| 6.00, 17.1 | 70 | | | | | | | | 73 | | |
| 6.00, 34.2 | 71 | | | | | | | | 68 | | |
| 6.00, 44.1 | 72 | | | | | | | | 69 | | |
| 6.00, 88.2 | 72 | | | | | | | | 69 | | |
| 2.00/0.84, 0.0 | 72 | | | | | | | | 78 | | |
| 2.00/0.84, 17.1 | 75 | | | | | | | | 76 | | |
| 2.00/0.84, 34.2 | 77 | | | | | | | | 77 | | |
| 2.00/0.84, 44.1 | 71 | | | | | | | | 71 | | |
| 2.00/0.84, 88.2 | 68 | | | | | | | | 61 | | |
| LSD (0.05) | 5 | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | 7 | -NS- | -NS- |

NS = not significant, † * indicates a significant difference at a 0.05 level
‡ soil water not available, £ soil water significant between particle sizes at the 0.05 level.
§ soil water significant among treatments at the 0.05 level

values decreased from the control. Peak deceleration values on non-traffic areas had no significant differences between particle sizes except on 29 September. Also, three out of four dates had significant differences among crumb rubber treatments except on 11 September. Soil moisture was not available on 11 September for either traffic and non-traffic areas. Crumb rubber particle size x rate under trafficked conditions on 11 September 1993 (Figure 14) shows the relevance of particle size. Although this was early in the experiment (topdressing rates were only only at 0.0. 5.7, 11.4, 14.7, and 29.4 t * $ha^{-1}$, one third of the total amount), as the topdressing rate increased, the 2.00/0.84 mm size was able to reach the soil surface quicker and cushion the surface. The 6.00 mm size may not have reached the surface as quickly thus the particles were still above the soil surface but in and around the turfgrass canopy, and consequently, surface hardness measurements were not as responsive as the smaller rubber particles.

In 1994, peak deceleration values (Table 32) had no significant differences between particles sizes. There were also no significant differences among crumb rubber topdressing treatments except 2 June and 27 July. To explain this, crumb rubber was topdressed in 1993, and was not topdressed in 1994 because topdressing rates were not going to surpass 50% of the mowing height or 19.0mm. Thus, not all the crumb rubber particles had settled down to the soil surface to protect the crown tissue area of the plant. Thus, impact values, in 1993, were significant among treatments due to the crumb rubber particles being in direct contact with the CIT. Thus a direct cushioning effect was taking place. However, in 1994, the crumb rubber particles settled down to the soil surface, and peak deceleration value were not significant once traffic was initiated.

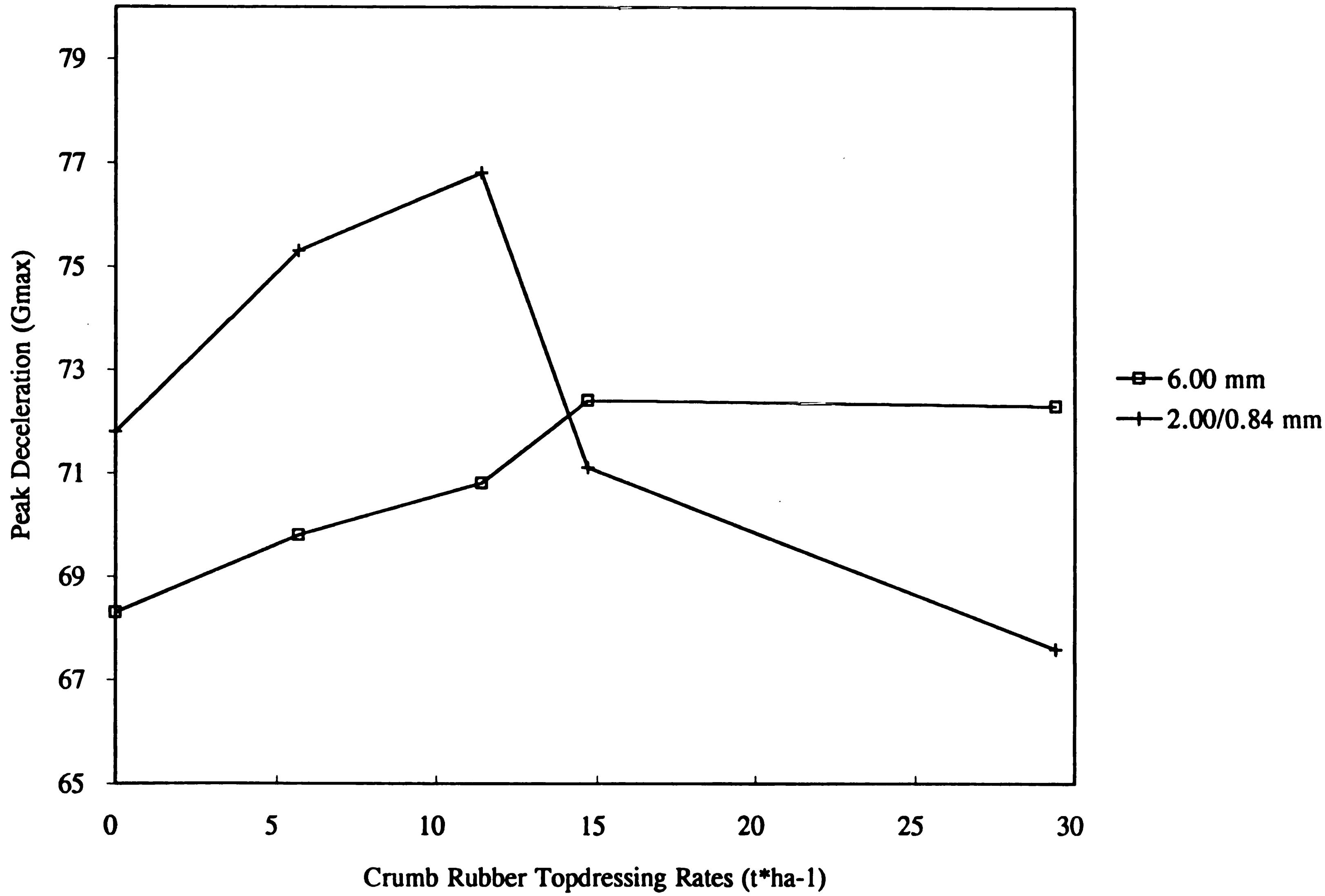



Fig. 14. Effects of peak deceleration on particle size x topdressing rate interaction on a trafficked Kentucky bluegrass/perennial ryegrass stand on 11 September 1993 at the HTRC.

Table 32. Effects of crumb rubber particle size and topdressing rates on peak deceleration ($G_{max}$) on a trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Turfgrass Research Center, 1994.

| | Peak Deceleration | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2 Jun | 27 Jul | 15 Sep | 6 Oct | 17 Oct | 10 Nov | 30 Dec |
| | $G_{max}$ | | | | | | |
| **Particle Size (mm)** | | | | | | | |
| 6.00 | 60 | 68 | 66 | 66 | 69 | 60 | 139 |
| 2.00/0.84 | 60 | 69 | 67 | 67 | 69 | 62 | 133 |
| Significance† | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| **Crumb Rubber Rates ($t\ ha^{-1}$)** | | | | | | | |
| 0.0 | 64 | 76 | 66 | 65 | 67 | 58 | 193 |
| 17.1 | 62 | 72 | 68 | 65 | 70 | 60 | 160 |
| 34.2 | 62 | 69 | 67 | 68 | 71 | 62 | 136 |
| 44.1 | 60 | 67 | 67 | 67 | 69 | 62 | 114 |
| 88.2 | 54 | 60 | 63 | 66 | 68 | 62 | 78 |
| LSD (0.05) | 6 | 6 | -NS- | -NS- | -NS- | -NS- | 18 |
| Soil Water, ($kg\ kg^{-1}$) | 0.124 | 0.120 | 0.163 | 0.141 | 0.121 | 0.123 | 0.132 |
| **Interaction** | | | | | | | |
| 6.00, 0.0 | 60 | 72 | | | | | |
| 6.00, 17.1 | 59 | 70 | | | | | |
| 6.00, 34.2 | 60 | 65 | | | | | |
| 6.00, 44.1 | 63 | 73 | | | | | |
| 6.00, 88.2 | 59 | 63 | | | | | |
| 2.00/0.84, 0.0 | 68 | 79 | | | | | |
| 2.00/0.84, 17.1 | 64 | 74 | | | | | |
| 2.00/0.84, 34.2 | 63 | 74 | | | | | |
| 2.00/0.84, 44.1 | 57 | 60 | | | | | |
| 2.00/0.84, 88.2 | 49 | 58 | | | | | |
| LSD (0.05) | 8 | 8 | -NS- | -NS- | -NS- | -NS- | -NS- |

† * indicates a significant difference at the 0.05 level, NS = not significant

Surface hardness characteristics are listed in Table 33. There were no differences between particle size for total duration of impact. However, for all four testing dates, there were significant differences among crumb rubber treatments. Interactions between particle size and rate were reported for three of the four dates. For time to peak deceleration, there were no significant differences between particle sizes, but there were significant differences among crumb rubber treatments for every test date. Interactions were reported for three out of the four testing dates. For rebound ratio, three out of four testing dates showed a significant difference between particle sizes. There was a significant difference among crumb rubber treatments for every testing date. No interactions were reported except on 6 October.

For duration of impact and time to peak deceleration, the interactions revealed both the importance of the particle size and the topdressing rate. The 2.00/0.84 mm size tended to have lower times (indication of a harder surface, Rogers and Waddington, 1992) when the topdressing rate was below or at 34.2 t * $ha^{-1}$. However, once the rate was at or above 44.1 t * $ha^{-1}$, the 2.00/0.84 mm size had higher times (an indication of a softer surface). Furthermore, the duration of impact and time to peak deceleration tended to increase steadily as topdressing rates increased. Rebound ratio was critical in showing that as crumb rubber rates increased, a more resilient surface resulted. Also, rebound ratio revealed that the 2.00/0.84 mm particle size influenced the incremental rates as the rates increased. For all testing dates, the 2.00/0.84 mm size and the 88.2 t * ha-1 always provided a higher rebound ratio (also note that for every test date 2.00/0.84 mm size provided significantly higher rebound ratios except on 17 October). By having smaller particles at the higher rates, the particles "acted

...eleration (ms) and rebound

Table 33. Effects of crumb rubber particle size and topdressing rates on duration of impact (ms), time to peak deceleration (ms) and rebound ratio (%) on a trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Turfgrass Research Center, 1994.

| | duration of impact | | | | time to peak deceleration | | | | rebound ratio | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 15 Sep | 6 Oct | 17 Oct | 10 Nov | 15 Sep | 6 Oct | 17 Oct | 10 Nov | 15 Sept | 6 Oct | 17 Oct | 10 Nov |
| | ms | | | | ms | | | | % | | | |
| **Particle Size (mm)** | | | | | | | | | | | | |
| 6.00 | 9.9 | 9.8 | 9.5 | 10.3 | 5.4 | 5.4 | 5.2 | 5.7 | 28.5 | 26.5 | 28.6 | 21.6 |
| 2.00/0.84 | 10.0 | 9.9 | 9.7 | 10.2 | 5.5 | 5.6 | 5.3 | 5.8 | 30.2 | 28.8 | 29.8 | 23.6 |
| Significance† | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | * | * | -NS- | * |
| **Crumb Rubber Rates (t ha$^{-1}$)** | | | | | | | | | | | | |
| 0.0 | 9.3 | 9.3 | 8.9 | 10.1 | 5.3 | 5.2 | 5.0 | 5.6 | 23.2 | 21.5 | 21.0 | 16.8 |
| 17.1 | 9.3 | 9.5 | 8.9 | 9.7 | 5.1 | 5.5 | 5.0 | 6.1 | 25.9 | 22.6 | 24.4 | 18.1 |
| 34.2 | 9.7 | 9.5 | 9.4 | 9.4 | 5.3 | 5.4 | 5.2 | 5.5 | 28.6 | 27.2 | 28.8 | 21.0 |
| 44.1 | 9.9 | 9.9 | 9.8 | 10.5 | 5.4 | 5.5 | 5.3 | 5.7 | 31.1 | 30.1 | 31.7 | 25.7 |
| 88.2 | 11.5 | 11.0 | 11.0 | 11.1 | 6.2 | 6.0 | 5.8 | 5.8 | 38.1 | 36.8 | 40.1 | 31.4 |
| LSD (0.05) | 0.6 | 0.5 | 0.4 | 1.0 | 0.3 | 0.5 | 0.3 | 0.4 | 2.0 | 2.0 | 3.0 | 3.0 |
| **Particle Size x Rate** | | | | | | | | | | | | |
| 6.00, 0.0 | 9.2 | 9.7 | 9.2 | 9.5 | 5.1 | 5.4 | 5.2 | 5.4 | 23.2 | 21.8 | 22.5 | 16.4 |
| 6.00, 17.1 | 9.5 | 9.6 | 9.0 | 9.8 | 5.3 | 5.5 | 5.1 | 5.8 | 24.9 | 21.6 | 23.3 | 17.5 |
| 6.00, 34.2 | 10.0 | 9.7 | 9.6 | 10.2 | 5.5 | 5.4 | 5.2 | 5.7 | 28.3 | 26.1 | 28.3 | 18.6 |
| 6.00, 44.1 | 9.6 | 9.5 | 9.3 | 10.7 | 5.3 | 5.2 | 5.2 | 5.8 | 30.0 | 28.7 | 30.5 | 25.7 |
| 6.00, 88.2 | 10.9 | 10.5 | 10.3 | 11.0 | 5.8 | 5.6 | 5.5 | 5.6 | 36.3 | 34.2 | 38.5 | 29.9 |
| 2.00/0.84, 0.0 | 9.5 | 8.9 | 8.6 | 10.6 | 5.4 | 5.0 | 4.8 | 5.7 | 23.2 | 21.3 | 19.5 | 17.3 |
| 2.00/0.84, 17.1 | 9.1 | 9.3 | 8.8 | 9.6 | 5.0 | 5.4 | 5.0 | 6.4 | 26.8 | 23.6 | 25.6 | 18.7 |
| 2.00/0.84, 34.2 | 9.5 | 9.4 | 9.1 | 9.5 | 5.2 | 5.4 | 5.1 | 5.3 | 28.9 | 28.3 | 29.3 | 23.3 |
| 2.00/0.84, 44.1 | 10.1 | 10.3 | 10.2 | 10.2 | 5.4 | 5.6 | 5.5 | 5.6 | 32.1 | 31.4 | 32.9 | 25.6 |
| 2.00/0.84, 88.2 | 12.0 | 11.4 | 11.6 | 11.1 | 6.6 | 6.5 | 6.1 | 6.0 | 39.9 | 39.4 | 41.6 | 32.9 |
| LSD (0.05) | 0.8 | 0.8 | 0.6 | -NS- | 0.4 | -NS- | 0.4 | 0.4 | -NS- | 2.0 | -NS- | -NS- |

† * indicates a significant difference at the 0.05 level
NS = not significant

together" and moved quicker to the soil surface filling in space thus providing a softer and more resilent surface. Figure 14 reveals this early in the experiment in 1993. The 6.00 mm size took longer to get to the soil surface and cannot move as freely (due to the particle size and the tillering of the plant; before commencing experiment, plots had a 100% density), consequently there are more gaps between the crumb rubber particles. Furthermore, once the crown tissue has elongated and grown upward, crumb rubber could move downward easier (Crumb rubber was topdressed in the fall when air temperatures decrease and growth slows down.)

Rogers and Waddington (1992) evaluated surface hardness on a variety of soil and turf surfaces. They reported not only on the significance of peak deceleration, but were able to define differences between $G_{max}$ values even though these values may not be statistically significant. Other surface parameters of great importance included time to peak deceleration, duration of peak deceleration, and rebound ratio. By evaluating time (in milliseconds) and rebound ratio (%), the higher the number the softer, more resilient the surface thus not simply relying on only one value.

In 1993, ball bounce values (Table 34) had no significant differences between particle sizes except 5 November. Treatments were significant for every testing date except 29 September. In 1994, ball bounce values had two out of four dates with significant differences between particle sizes. Also, ball bounce values were significant among crumb rubber treatments for every testing date. For both years, ball bounce showed that as crumb rubber rates increased, values decreased thus providing a softer surface. Figure 15 shows an interaction on how the particle size was more influential than the topdressing rate. For the 6.00 mm size, no matter the topdressing rate, the

Table 34. Effects of crumb rubber particle size and topdressing rates on ball bounce (%) on a trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Turfgrass Research Center, 1993 and 1994.

| | 1993 | | 1994 | | | |
|---|---|---|---|---|---|---|
| | 20 Sept | 4 Nov | 2 Jun | 15 Sept | 6 Oct | 10 Nov |
| | | | % | | | |
| Particle Size (mm) | | | | | | |
| 6.00 | 34.8 | 40.3 | 38.0 | 39.2 | 37.9 | 40.1 |
| 2.00/0.84 | 35.3 | 37.7 | 35.6 | 37.6 | 38.7 | 39.5 |
| Significance† | -NS- | * | * | * | -NS- | -NS- |
| Crumb Rubber Rates ($t\ ha^{-1}$) | | | | | | |
| 0.0 | 36.8 | 42.8 | 39.4 | 40.9 | 40.0 | 41.1 |
| 17.1 | 36.4 | 41.2 | 38.4 | 39.5 | 39.8 | 41.7 |
| 34.2 | 34.2 | 39.4 | 36.5 | 37.6 | 38.0 | 42.0 |
| 44.1 | 36.4 | 38.9 | 36.4 | 37.7 | 38.1 | 38.6 |
| 88.2 | 31.5 | 32.8 | 33.4 | 36.2 | 35.8 | 35.6 |
| LSD (0.05) | 3.3 | 2.5 | 3.2 | 2.6 | 2.7 | 3.9 |
| Interaction | | | | | | |
| 6.00, 0.0 | | | | 38.8 | | |
| 6.00, 17.1 | | | | 40.4 | | |
| 6.00, 34.2 | | | | 39.1 | | |
| 6.00, 44.1 | | | | 38.8 | | |
| 6.00, 88.2 | | | | 38.9 | | |
| 2.00/0.84, 0.0 | | | | 42.9 | | |
| 2.00/0.84, 17.1 | | | | 38.7 | | |
| 2.00/0.84, 34.2 | | | | 36.1 | | |
| 2.00/0.84, 44.1 | | | | 36.6 | | |
| 2.00/0.84, 88.2 | | | | 33.5 | | |
| LSD (0.05) | -NS- | -NS- | -NS- | 4 | -NS- | -NS- |

NS = not significant, † * indicates a significant difference at a 0.05 level

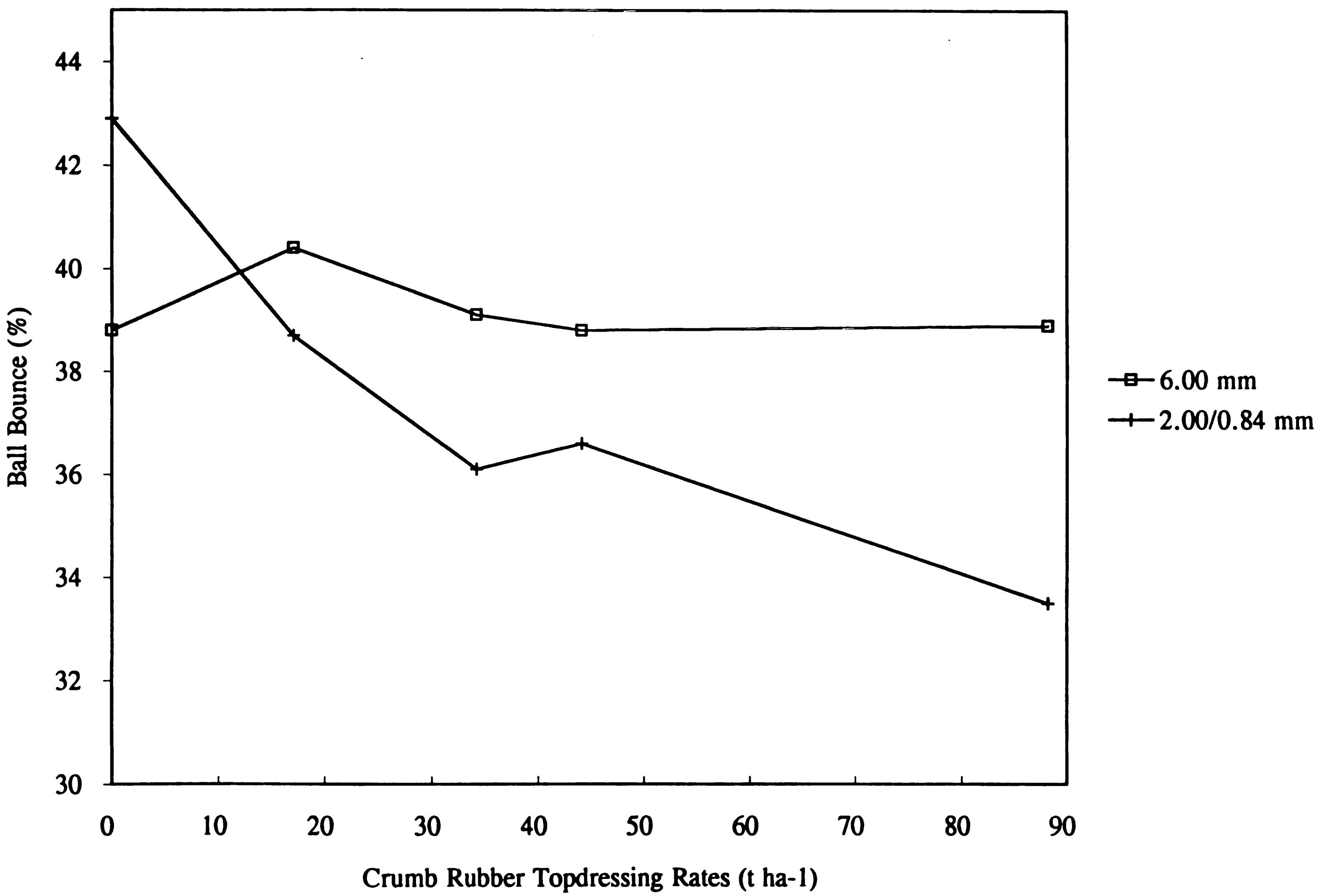



Fig. 15. Effects of the particle size x topdressing rate interaction on ball bounce on a trafficked Kentucky bluegrass/perennial ryegrass stand on 15 September 1994 at the HTRC.

ball bounce values were consistent. However, for the 2.00/0.84 mm size, values dropped as the topdressing rate increased. Thus implying the 2.00/0.84 mm size blend of smaller particles "acting together" and providing a softer surface. This trend continued out the rest of the 1994 season.

For 1993, shear resistance values (Table 35), in the trafficked areas had no significant differences between particle sizes except on 22 October. There were significant differences among treatment values for every testing date. In the non-trafficked areas, there was no significant differences between particle sizes except on 22 October. There were significant differences among treatment values for every testing date. In 1994, three out of six testing dates revealed a significant difference between crumb rubber particle sizes, in the trafficked areas (Table 36). Furthermore, there were significant differences among treatment values for all testing dates.

Shear resistance values indicated, in 1993, that as crumb rubber rates increased, shearvane values decreased. However, in 1994, as crumb rubber rates increased, shearvane values increased and stabilized. Crumb rubber was topdressed in 1993, and not in 1994. Crumb rubber particles were still in and around the turf canopy and still had not reached the soil surface. This hinderance of the crumb rubber particles, in and around the canopy, affecting the shearvane can also be revealed in the non-traffic area in 1993 (Table 35). However, after a growing season in 1994, the crumb rubber particles had reached the soil surface and were simutaneously protecting the crown tissue area of the plant thus not allowing for damage to this vital area. Furthermore, with the wide range of particle sizes of crumb rubber, especially with the 2.00/0.84 mm size, offered additional stability for increasing shearing.

Table 35. Effects of crumb rubber particle size and topdressing rates on shear resistance (N m) on a trafficked and non-trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Turfgrass Research Center, 1993

| | Trafficked Areas | | | | Non-Trafficked Areas | | |
|---|---|---|---|---|---|---|---|
| | 20 Sep | 29 Sep | 22 Oct | 5 Nov | 20 Sep | 29 Sep | 22 Oct |
| | --------------- N m --------------- | | | | | | |
| Particle Size (mm) | | | | | | | |
| 6.00 | 21.4 | 21.1 | 16.0 | 14.0 | 22.7 | 24.5 | 17.8 |
| 2.00/0.84 | 22.3 | 21.2 | 17.5 | 15.7 | 24.1 | 25.0 | 20.2 |
| Significance† | -NS- | -NS- | * | -NS- | -NS- | -NS- | * |
| Crumb Rubber Rates ($t\ ha^{-1}$) | | | | | | | |
| 0.0 | 25.6 | 24.4 | 20.7 | 17.6 | 28.5 | 28.9 | 27.1 |
| 17.1 | 23.7 | 24.7 | 20.2 | 17.0 | 26.2 | 28.5 | 20.8 |
| 34.2 | 22.5 | 21.6 | 15.3 | 16.2 | 24.3 | 25.7 | 17.2 |
| 44.1 | 22.1 | 21.1 | 15.3 | 13.3 | 22.6 | 23.3 | 15.7 |
| 88.2 | 15.0 | 14.0 | 12.2 | 10.3 | 15.4 | 17.3 | 14.2 |
| LSD (0.05) | 2.3 | 3.3 | 2.2 | 2.8 | 2.3 | 2.1 | 3.1 |

† * indicates a significant difference at a 0.05 level
NS = not significant

Table 36. Effects of crumb rubber particle size and topdressing rates on shear resistance (N m) on a trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Turfgrass Research Center, 1994.

| | 2 Jun | 27 Jul | 15 Sep | 6 Oct | 27 Oct | 10 Nov |
|---|---|---|---|---|---|---|
| | --------------------- | | | N m | | --------------------- |
| Particle Size (mm) | | | | | | |
| 6.00 | 15.5 | 15.6 | 17.2 | 19.2 | 17.5 | 14.2 |
| 2.00/0.84 | 16.1 | 18.3 | 19.0 | 20.0 | 19.2 | 14.7 |
| Significance† | -NS- | * | * | -NS- | * | -NS- |
| Crumb Rubber Rates (t ha$^{-1}$) | | | | | | |
| 0.0 | 19.2 | 19.3 | 17.6 | 17.0 | 16.2 | 11.9 |
| 17.1 | 19.1 | 19.1 | 19.7 | 18.7 | 16.3 | 15.3 |
| 34.2 | 15.4 | 17.1 | 18.4 | 21.1 | 19.1 | 13.7 |
| 44.1 | 14.4 | 15.9 | 18.8 | 20.2 | 20.7 | 16.0 |
| 88.2 | 10.8 | 13.6 | 16.1 | 20.9 | 19.6 | 15.4 |
| LSD (0.05) | 1.8 | 2.1 | 2.2 | 2.4 | 2.6 | 2.1 |

† * indicates a significant difference at the 0.05 level
NS = not significant

In 1993, soil temperatures (Table 37) had no significant differences between particle sizes in both the traffic and non-traffic areas, However, in the traffic areas, five out of 7 testing dates had significant differences among treatmant values. In the non-traffic areas, there were no differences among treatment values. In 1994, soil temperatures (Table 38) had no significant differences between particle sizes except on 19 April and 15 September, in the traffic areas. There were significant differences among treatment values for five out of 8 testing dates.

In 1993, when crumb rubber was topdressed, as topdressing rates increased thus did the soil temperatures, In 1994, on 20 April, the opposite effect took place. Lower crumb rubber rates (0.0, 17.1, and 34.2 t $ha^{-1}$) had a lower turfgrass density (Table 46) thus the soil was exposed and was warming up. However, higher crumb rubber rates had a higher density, and the crumb rubber was acting like a blanket from the sun. Thus the rubber had to conduct the heat to the soil.

In 1993, surface temperatures (Table 39) in the traffic areas were not significant between particle sizes except on 5 November. There were four out of six testing dates with significant differences among treatmants. In the non-traffic areas, values between particle sizes were not significant as well as among crumb rubber treatments. In 1994, surface temperatures (Table 40), in the traffic areas, had no significant differences between particle sizes. There were no significant differences among treatment values except for 2 June, 15 September, 17 October, and 30 December. The trend, in 1994, indicated as crumb rubber treataments increased, surface temperatures increased as well.

Table 37. Effects of crumb rubber particle size and topdressing rates on soil temperatures (°C) at the 7.6 cm depth on a trafficked and non-trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Turfgrass Research Center, 1993.

| | Trafficked Areas | | | | | | | Non-Trafficked Areas | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 18 Aug | 20 Sep | 29 Sep | 22 Oct | 5 Nov | 19 Nov | 3 Dec | 20 Sep | 29 Sep | 22 Oct |
| | °C | | | | | | | | | |
| Particle Size (mm) | | | | | | | | | | |
| 6.00 | 24.9 | 17.4 | 14.2 | 9.5 | 8.1 | 4.2 | 3.5 | 15.7 | 14.7 | 14.3 |
| 2.00/0.84 | 24.5 | 17.3 | 14.1 | 10.0 | 8.1 | 4.2 | 3.4 | 15.7 | 14.9 | 14.7 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Rates (t $ha^{-1}$) | | | | | | | | | | |
| 0.0 | 24.3 | 17.1 | 13.9 | 8.7 | 7.7 | 4.0 | 3.2 | 15.9 | 14.7 | 14.5 |
| 17.1 | 25.3 | 17.3 | 14.0 | 9.3 | 8.0 | 4.1 | 3.4 | 15.8 | 14.6 | 13.9 |
| 34.2 | 24.6 | 17.4 | 14.2 | 10.8 | 8.2 | 4.2 | 3.4 | 15.5 | 14.7 | 14.5 |
| 44.1 | 24.9 | 17.4 | 14.2 | 9.8 | 8.2 | 4.3 | 3.6 | 15.7 | 15.0 | 14.5 |
| 88.2 | 24.5 | 17.7 | 14.5 | 10.5 | 8.5 | 4.3 | 3.8 | 15.7 | 15.1 | 15.1 |
| LSD (0.05) | -NS- | 0.4 | 0.4 | 2.2 | 0.3 | -NS- | 0.3 | -NS- | -NS- | -NS- |

NS = not significant

‡ Aug 18 traffic treatments had not been initiated

Table 38. Effects of crumb rubber particle size and topdressing rates on soil temperatures (°C) at the 7.6 cm depth on a trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Turfgrass Research Center, 1994.

| | 19 Apr | 2 Jun | 27 Jul | 15 Sep | 6 Oct | 17 Oct | 27 Oct | 10 Nov |
|---|---|---|---|---|---|---|---|---|
| | | | | °C | | | | |
| Particle Size (mm) | | | | | | | | |
| 6.00 | 17.6 | 19.9 | 21.6 | 23.9 | 13.7 | 14.9 | 11.3 | 9.0 |
| 2.00/0.84 | 16.6 | 19.8 | 21.5 | 23.6 | 13.7 | 14.9 | 11.3 | 9.0 |
| Significance† | * | -NS- | -NS- | * | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Rates (t $ha^{-1}$) | | | | | | | | |
| 0.0 | 17.6 | 20.3 | 21.6 | 24.3 | 13.8 | 15.4 | 11.3 | 8.9 |
| 17.1 | 17.6 | 20.5 | 21.6 | 24.1 | 13.8 | 15.0 | 11.2 | 8.9 |
| 34.2 | 17.1 | 19.8 | 21.6 | 23.8 | 13.6 | 15.0 | 11.2 | 8.9 |
| 44.1 | 16.8 | 19.6 | 21.6 | 23.7 | 13.7 | 14.8 | 11.2 | 9.0 |
| 88.2 | 16.2 | 19.0 | 21.4 | 23.0 | 13.7 | 14.4 | 11.3 | 9.4 |
| LSD (0.05) | 0.8 | 0.7 | 0.1 | 0.2 | -NS- | 0.3 | -NS- | -NS- |
| Interaction | | | | | | | | |
| 6.00, 0.0 | 17.5 | | | | | | | |
| 6.00, 17.1 | 17.9 | | | | | | | |
| 6.00, 34.2 | 17.8 | | | | | | | |
| 6.00, 44.1 | 17.8 | | | | | | | |
| 6.00, 88.2 | 16.9 | | | | | | | |
| 2.00/0.84, 0.0 | 17.8 | | | | | | | |
| 2.00/0.84, 17.1 | 17.5 | | | | | | | |
| 2.00/0.84, 34.2 | 17.0 | | | | | | | |
| 2.00/0.84, 44.1 | 16.5 | | | | | | | |
| 2.00/0.84, 88.2 | 16.0 | | | | | | | |
| LSD (0.05) | 1.0 | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |

† * indicates a significant difference at the 0.05 level, NS = not significant

Table 39. Effects of crumb rubber particle size and topdressing rates on surface temperatures (°C) on a trafficked and non-trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Turfgrass Research Center, 1993.

| | Trafficked Areas | | | | | | Non-Trafficked Areas | | |
|---|---|---|---|---|---|---|---|---|---|
| | 18 Aug | 20 Sep | 29 Sep | 22 Oct | 5 Nov | 3 Dec | 20 Sep | 29 Sep | 22 Oct |
| | °C | | | | | | | | |
| Particle Size (mm) | | | | | | | | | |
| 6.00 | 29.2 | 14.9 | 14.1 | 9.4 | 7.9 | 3.9 | 17.5 | 14.2 | 9.9 |
| 2.00/0.84 | 29.3 | 14.9 | 14.1 | 9.3 | 8.0 | 3.9 | 17.4 | 14.2 | 9.9 |
| Significance† | -NS- | -NS- | -NS- | -NS- | * | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Rates ($t\ ha^{-1}$) | | | | | | | | | |
| 0.0 | 28.3 | 15.0 | 13.9 | 8.6 | 7.8 | 3.8 | 17.2 | 14.0 | 9.6 |
| 17.1 | 28.9 | 15.0 | 14.1 | 9.6 | 7.8 | 3.9 | 17.3 | 14.0 | 10.0 |
| 34.2 | 29.5 | 14.9 | 14.0 | 9.4 | 8.0 | 3.9 | 17.5 | 14.3 | 9.8 |
| 44.1 | 29.9 | 14.9 | 14.1 | 9.4 | 8.0 | 3.9 | 17.5 | 14.1 | 9.8 |
| 88.2 | 29.9 | 14.7 | 14.3 | 10.3 | 8.0 | 4.1 | 17.6 | 14.3 | 10.2 |
| LSD (0.05) | 1.8 | -NS- | 0.5 | 1.5 | 0.2 | -NS- | -NS- | -NS- | -NS- |

NS= not significant
† * indicates a significant difference at the 0.05 level
‡ 18 Aug traffic treatments had not been initiated

Table 40. Effects of crumb rubber particle size and topdressing rates on surface temperatures (°C) on a trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Turfgrass Research Center, 1994.

| | 7 Apr | 2 Jun | 27 Jul | 15 Sep | 6 Oct | 17 Oct | 27 Oct | 10 Nov | 30 Dec |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | °C | | | | |
| Particle Size (mm) | | | | | | | | | |
| 6.00 | 17.6 | 24.7 | 21.7 | 30.2 | 18.5 | 23.3 | 15.3 | 8.6 | 1.7 |
| 2.00/0.84 | 17.1 | 24.7 | 21.6 | 30.3 | 18.3 | 23.4 | 15.0 | 8.8 | 1.2 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Rates ($t\ ha^{-1}$) | | | | | | | | | |
| 0.0 | 15.8 | 23.9 | 21.9 | 30.1 | 17.9 | 22.1 | 15.0 | 8.7 | 0.7 |
| 17.1 | 16.6 | 24.7 | 21.5 | 30.0 | 18.3 | 23.3 | 14.9 | 8.7 | 0.7 |
| 34.2 | 17.4 | 24.9 | 21.6 | 30.2 | 18.5 | 23.1 | 15.2 | 8.7 | 1.8 |
| 44.1 | 17.1 | 24.9 | 21.5 | 29.9 | 18.3 | 23.8 | 15.1 | 8.7 | 0.9 |
| 88.2 | 19.9 | 25.2 | 21.8 | 30.9 | 18.9 | 24.3 | 15.5 | 8.8 | 3.6 |
| LSD (0.05) | -NS- | 0.6 | -NS- | 0.6 | -NS- | 1.1 | -NS- | -NS- | 0.9 |
| Interaction | | | | | | | | | |
| 6.00, 0.0 | | 24.0 | | | | | | | |
| 6.00, 17.1 | | 24.7 | | | | | | | |
| 6.00, 34.2 | | 24.7 | | | | | | | |
| 6.00, 44.1 | | 24.4 | | | | | | | |
| 6.00, 88.2 | | 25.8 | | | | | | | |
| 2.00/0.84, 0.0 | | 23.8 | | | | | | | |
| 2.00/0.84, 17.1 | | 24.7 | | | | | | | |
| 2.00/0.84, 34.2 | | 25.2 | | | | | | | |
| 2.00/0.84, 44.1 | | 25.3 | | | | | | | |
| 2.00/0.84, 88.2 | | 24.7 | | | | | | | |
| LSD (0.05) | -NS- | 0.9 | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |

NS = not significant

In the traffic areas, clipping yields (Table 41) were not significant between particles sizes. There were no significant differences among topdressing treatments except for 20 April and 9 August in 1994. In the non-traffic areas, clipping yields were not significant between particle sizes nor among treatments

The trend of the clipping yields indicates that as crumb rubber rates increase, clipping yields increased as well. This would probably be due to the retainment of turfgrass density during the traffic season. In the spring time (20 April), clipping yields for the highest rate was 2x more than the second highest rate. Due to the crumb rubber at the surface, surface temperatures increase, and, as a result, a higher density and earlier spring green-up was observed. However in the summer (9 August) when no traffic was being applied, the opposite trend took place. It was observed that fertilizers were being trapped in the crumb rubber layer. As crumb rubber thickness increases, this effect was more pronounced.

Analysis of clippings were taken on 2 October 1993 (Table 42) and 20 April 1994 (Table 43). On 2 October, there were no significant differences between particle sizes except for copper. There were no significant differences among crumb rubber treatments. On 20 April, there were no significant differences between particle sizes nor among crumb rubber treatments.

Root mass values are listed on Table 44. There were no significant differences between particle sizes for any of the sampling depths. There were no significant differences among crumb rubber treatments except for 0-5 cm sampling depth. van Wijk (1980) observed 99% of the roots were in the top 5 cm of the soil profile. In recreational turf, the top 2-3 cm is the most compacted soil layer (Morgan et al., 1966;

Table 41. Effects of crumb rubber particle size and topdressing rates on clipping yields (g * $m^{-2}$) on a trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Turfgrass Research Center, 1994.

| | Traffic | | | | Non-Traffic | | |
|---|---|---|---|---|---|---|---|
| | 1993 | 1994 | | | 1993 | 1994 | |
| | 2 Oct† | 20 Apr | 9 Aug | 20 Oct | 2 Oct | 20 Apr | 9 Aug |
| | grams * $m^{-2}$ | | | | | | |
| Particle Size (mm) | | | | | | | |
| 6.00 | 0.8 | 1.2 | 6.7 | 0.5 | 9.8 | 6.2 | 5.3 |
| 2.00/0.84 | 1.0 | 1.6 | 5.6 | 0.5 | 8.6 | 5.6 | 4.2 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Rates (t $ha^{-1}$) | | | | | | | |
| 0.0 | 0.7 | 0.4 | 7.4 | 0.4 | 7.3 | 4.7 | 6.9 |
| 17.1 | 0.9 | 0.7 | 7.4 | 0.4 | 9.6 | 6.2 | 5.6 |
| 34.2 | 0.7 | 0.7 | 5.4 | 0.5 | 8.3 | 4.6 | 3.9 |
| 44.1 | 1.0 | 1.6 | 6.1 | 0.7 | 10.0 | 7.1 | 4.5 |
| 88.2 | 1.2 | 3.4 | 4.5 | 0.7 | 10.9 | 6.9 | 3.0 |
| LSD (0.05) | -NS- | 0.9 | 1.8 | -NS- | -NS- | -NS- | -NS- |
| Interaction | | | | | | | |
| 6.00, 0.0 | 0.9 | 0.6 | | | | | |
| 6.00, 17.1 | 0.9 | 0.8 | | | | | |
| 6.00, 34.2 | 0.8 | 1.0 | | | | | |
| 6.00, 44.1 | 0.6 | 1.0 | | | | | |
| 6.00, 88.2 | 0.7 | 2.3 | | | | | |
| 2.00/0.84, 0.0 | 0.7 | 0.3 | | | | | |
| 2.00/0.84, 17.1 | 0.7 | 0.6 | | | | | |
| 2.00/0.84, 34.2 | 0.7 | 0.4 | | | | | |
| 2.00/0.84, 44.1 | 1.3 | 2.1 | | | | | |
| 2.00/0.84, 88.2 | 1.6 | 4.5 | | | | | |
| LSD (0.05) | 0.7 | 1.2 | -NS- | -NS- | -NS- | -NS- | -NS- |

NS = not significant, † = Crumb rubber rates were only 0.0, 11.4, 22.8, 29.4, and 58.8, respectively.

Table 42. Effects of crumb rubber particle size and topdressing rates on nutrient concentrations (ppm) on a trafficked Kentucky bluegrass/perennial ryegrass stand on 2 October 1993 at the Hancock Turfgrass Resarch Center.

| | Zn | Fe | B | P | Cu | Mn | Mg | Ca | Mo | K |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | ppm | | | | | | | |
| Particle Size (mm) | | | | | | | | | | |
| 6.00 | 115 | 297 | 6 | 3701 | 5 | 39 | 1356 | 2923 | 2 | 24192 |
| 2.00/0.84 | 177 | 354 | 7 | 3397 | 7 | 39 | 1420 | 3453 | 2 | 22273 |
| Significance† | -NS- | -NS- | -NS- | -NS- | * | -NS- | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Rates ($t\ ha^{-1}$) | | | | | | | | | | |
| 0.0 | 113 | 364 | 4 | 2876 | 4 | 41 | 1536 | 4369 | 2 | 18376 |
| 17.1 | 64 | 320 | 7 | 3691 | 5 | 44 | 1447 | 3234 | 2 | 23989 |
| 34.2 | 183 | 284 | 6 | 3433 | 6 | 37 | 1243 | 2613 | 1 | 21863 |
| 44.1 | 148 | 323 | 7 | 3619 | 7 | 38 | 1293 | 2841 | 2 | 24388 |
| 88.2 | 221 | 338 | 8 | 4127 | 9 | 38 | 1420 | 2882 | 2 | 27547 |
| LSD (0.05) | -NS- | -NS- | -NS- | -NS- | 3 | -NS- | -NS- | -NS- | -NS- | -NS- |

NS = not significant
† * indicates a significant difference at the 0.05 level.

Table 43. Effects of crumb rubber particle size and topdressing rates on nutrient concentrations (ppm) on a trafficked Kentucky bluegrass/perennial ryegrass stand on 20 April 1994 at the Hancock Turfgrass Resarch Center.

| | Zn | Fe | B | P | Cu | Mn | Mg | Ca | Mo | K |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | ppm | | | | | | | |
| Particle Size (mm) | | | | | | | | | | |
| 6.00 | 127 | 213 | 10 | 2561 | 11 | 28 | 1272 | 5120 | 3 | 14600 |
| 2.00/0.84 | 144 | 215 | 11 | 2542 | 12 | 26 | 1393 | 5171 | 3 | 14398 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Rates (t $ha^{-1}$) | | | | | | | | | | |
| 0.0 | 111 | 254 | 8 | 2153 | 17 | 239 | 1200 | 4167 | 2 | 11874 |
| 17.1 | 127 | 265 | 10 | 2631 | 10 | 29 | 1790 | 6941 | 4 | 15088 |
| 34.2 | 169 | 217 | 12 | 2592 | 11 | 26 | 1402 | 5741 | 3 | 15072 |
| 44.1 | 110 | 168 | 12 | 2512 | 10 | 27 | 1101 | 4317 | 3 | 14609 |
| 88.2 | 162 | 167 | 11 | 2868 | 10 | 31 | 1170 | 4560 | 3 | 15855 |
| LSD (0.05) | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |

NS = not significant

Table 44. Effects of crumb rubber particle size and topdressing rates on root mass (g * $cm^{-3}$) on a Kentucky bluegrass/perennial ryegrass stand on 13 November 1993 after 47 simulated footbal games at the Hancock Turfgrass Research Center, 1993.

| | 0-5 cm | 5-10 cm | 10-15 cm | 15-20cm | Total 0-20 cm |
|---|---|---|---|---|---|
| | ------------------ g * $cm^{-3}$ ---------------- | | | | |
| Particle Size (mm) | | | | | |
| 6.00 | 0.54 | 0.15 | 0.07 | 0.05 | 0.82 |
| 2.00/0.84 | 0.58 | 0.15 | 0.09 | 0.04 | 0.86 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Rates (t $ha^{-1}$) | | | | | |
| 0.0 | 0.30 | 0.16 | 0.07 | 0.03 | 0.56 |
| 17.1 | 0.45 | 0.14 | 0.09 | 0.05 | 0.73 |
| 34.2 | 0.59 | 0.13 | 0.07 | 0.08 | 0.87 |
| 44.1 | 0.62 | 0.17 | 0.09 | 0.04 | 0.92 |
| 88.2 | 0.86 | 0.17 | 0.06 | 0.03 | 1.12 |
| LSD (0.05) | 0.3 | -NS- | -NS- | -NS- | -NS- |
| Interaction | | | | | |
| 0.0 | 0.28 | | | | |
| 17.1 | 0.70 | | | | |
| 34.2 | 0.41 | | | | |
| 44.1 | 0.39 | | | | |
| 88.2 | 0.94 | | | | |
| 0.0 | 0.31 | | | | |
| 17.1 | 0.19 | | | | |
| 34.2 | 0.77 | | | | |
| 44.1 | 0.85 | | | | |
| 88.2 | 0.78 | | | | |
| LSD (0.05) | 0.32 | -NS- | -NS- | -NS- | -NS- |

NS = not significant

O' Neil and Carrow, 1980). Thurman and Porkorny (1966) observed less rooting in compacted soils versus uncompacted soils. However, as crumb rubber levels increased, rooting in the top 5cm increased incrementally. Crumb rubber was cushioning the soil surface from compacting and promoting root growth, and absorbing the impact. Thus as rooting increased, crumb rubber was absorbing the impact thereby decreasing the tendency for soil compaction and deterioration of the crown tissue area.

In 1993, color ratings (Table 45) had no significant differences between particle sizes except on 25 October and 15 November. Also, crumb rubber treatment values were significant among rates for three out of four dates. In 1994, there were no significant differences between particle sizes. There were no significant differences among treatment values.

Powlson and Jenkinson (1971) reported carbon disulphide, from rubber bungs, inhibited nitrification, and more specifically, *Nitrosomonas* being sensitive to the exposure of carbon disulphide. Therefore, crumb rubber may be impeding nitrification and by entrapping fertilizer prills, over time, nitrogen was released thus clipping yields and color ratings increased as crumb rubber rates increased.

There was an interaction between partice size and crumb rubber rates for density ratings (Table 46) (Figures 16 and 17). This can be attributed to the smaller particle size being able to move down to the soil surface quicker, and thus being able to protect the crown tissue area and subsequently improve the longevity of the treatment areas as crumb rubber rates increased. In 1994, there were no significant differences between particle sizes. However, there were four out of six testing dates that showed significant differences among treatment values. Figure 18 illustrates the decrease in density

Table 45. Effects of crumb rubber particle size and topdressing rates on color ratings on a trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Turfgrass Research Center, 1993 and 1994.

| | 1993 | | | | 1994 | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 22 Sep | 1 Oct | 25 Oct | 15 Nov | 4 Apr | 23 Aug | 30 Sept | 27 Oct | 4 Dec |
| Particle Size (mm) | | | | | | | | | |
| 6.00 | 6.2 | 6.2 | 6.3 | 3.8 | 4.9 | 8.2 | 7.1 | 5.9 | 4.6 |
| 2.00/0.84 | 5.9 | 5.8 | 5.6 | 3.2 | 3.9 | 8.2 | 7.0 | 5.9 | 4.4 |
| Significance† | -NS- | -NS- | * | * | * | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Rate ($t\ ha^{-1}$) | | | | | | | | | |
| 0.0 | 4.8 | 5.3 | 4.0 | 2.7 | 4.0 | 8.2 | 6.9 | 5.7 | 4.7 |
| 17.1 | 5.7 | 5.6 | 5.7 | 3.2 | 4.7 | 8.2 | 7.2 | 6.0 | 4.7 |
| 34.2 | 5.7 | 5.8 | 6.2 | 3.4 | 4.7 | 8.2 | 7.0 | 5.9 | 4.6 |
| 44.1 | 6.2 | 6.0 | 6.2 | 3.0 | 4.7 | 8.2 | 7.0 | 5.7 | 4.6 |
| 88.2 | 7.8 | 7.2 | 7.0 | 5.2 | 4.6 | 8.2 | 7.2 | 6.2 | 4.1 |
| LSD (0.05) | 1.0 | -NS- | 1.1 | 1.1 | -NS- | -NS- | -NS- | -NS- | -NS- |

NS = not significant
† * indicates a significant difference at a 0.05 level
Color ratings scale 1-9; 1=poor (low density; brown); 9=excellent (high density; green); 6=acceptable.

Table 46. Effects of crumb rubber particle size and topdressing rates on density ratings on a trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Turfgrass Research Center, 1993 and 1994.

| | 1993 | | 1994 | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 Oct | 25 Oct | 7 Apr | 20 Apr | 23 Aug | 30 Sep | 27 Oct | 4 Dec |
| Particle Size (mm) | | | | | | | | |
| 6.00 | 55 | 49 | 36 | 41 | 100 | 88 | 68 | 60 |
| 2.00/0.84 | 55 | 48 | 36 | 46 | 100 | 89 | 72 | 64 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Rates ($t\ ha^{-1}$) | | | | | | | | |
| 0.0 | 47 | 27 | 25 | 25 | 100 | 85 | 53 | 42 |
| 17.1 | 53 | 40 | 29 | 32 | 100 | 89 | 62 | 51 |
| 34.2 | 55 | 55 | 37 | 45 | 100 | 87 | 72 | 63 |
| 44.1 | 53 | 52 | 37 | 47 | 100 | 90 | 73 | 66 |
| 88.2 | 67 | 68 | 50 | 70 | 100 | 93 | 89 | 88 |
| LSD (0.05) | -NS- | 12 | -NS- | 15 | -NS- | 4 | 11 | 14 |
| Games Simulated | 20 | 37 | 0 | 0 | 0 | 22 | 40 | 48 |

NS = not significant
Density rating scale 0-100%

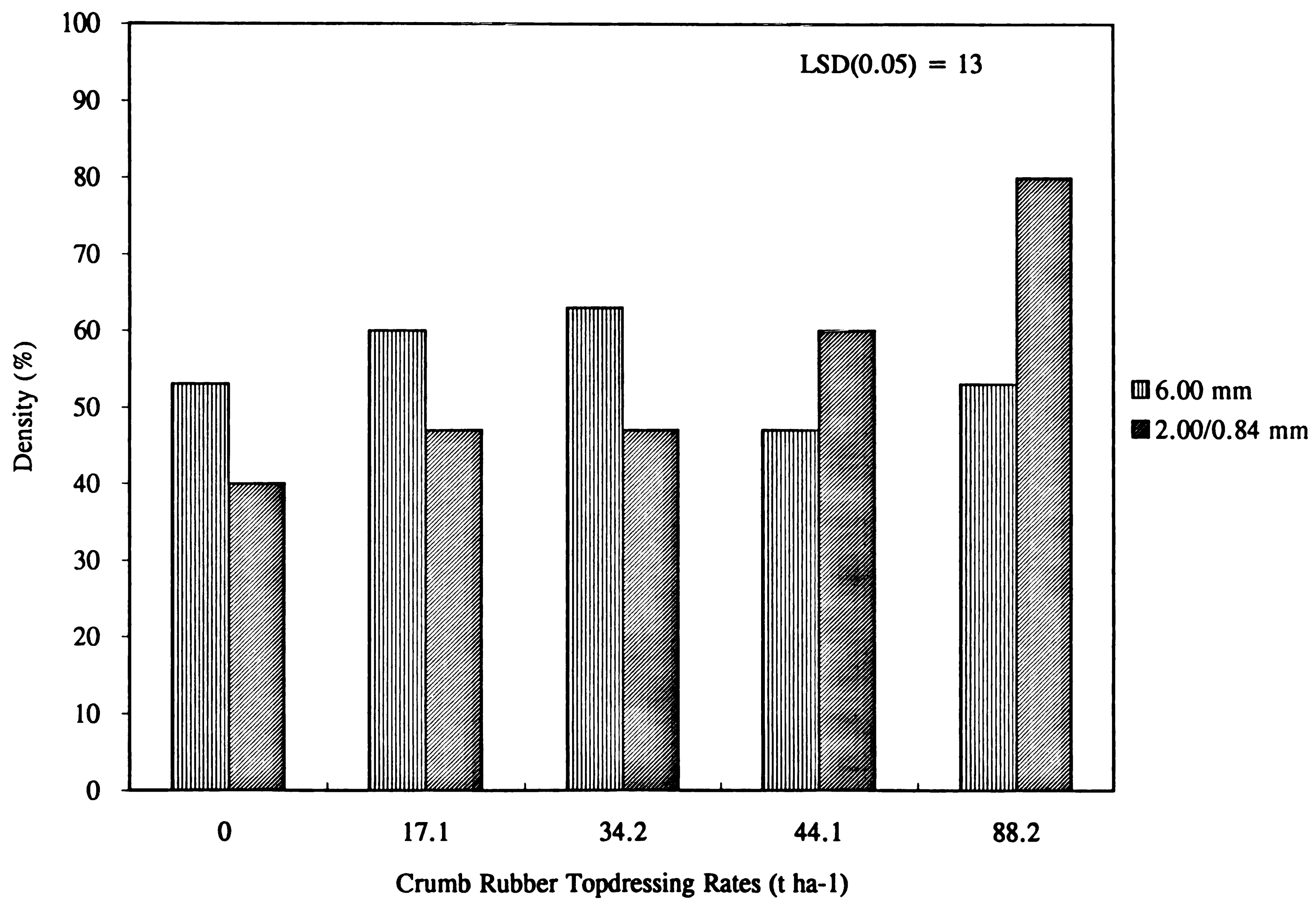



Fig. 16. Effects of density ratings on particle size x topdressing rate interaction on a trafficked Kentucky bluegrass/perennial ryegrass stand on 1 October 1993 at the HTRC.

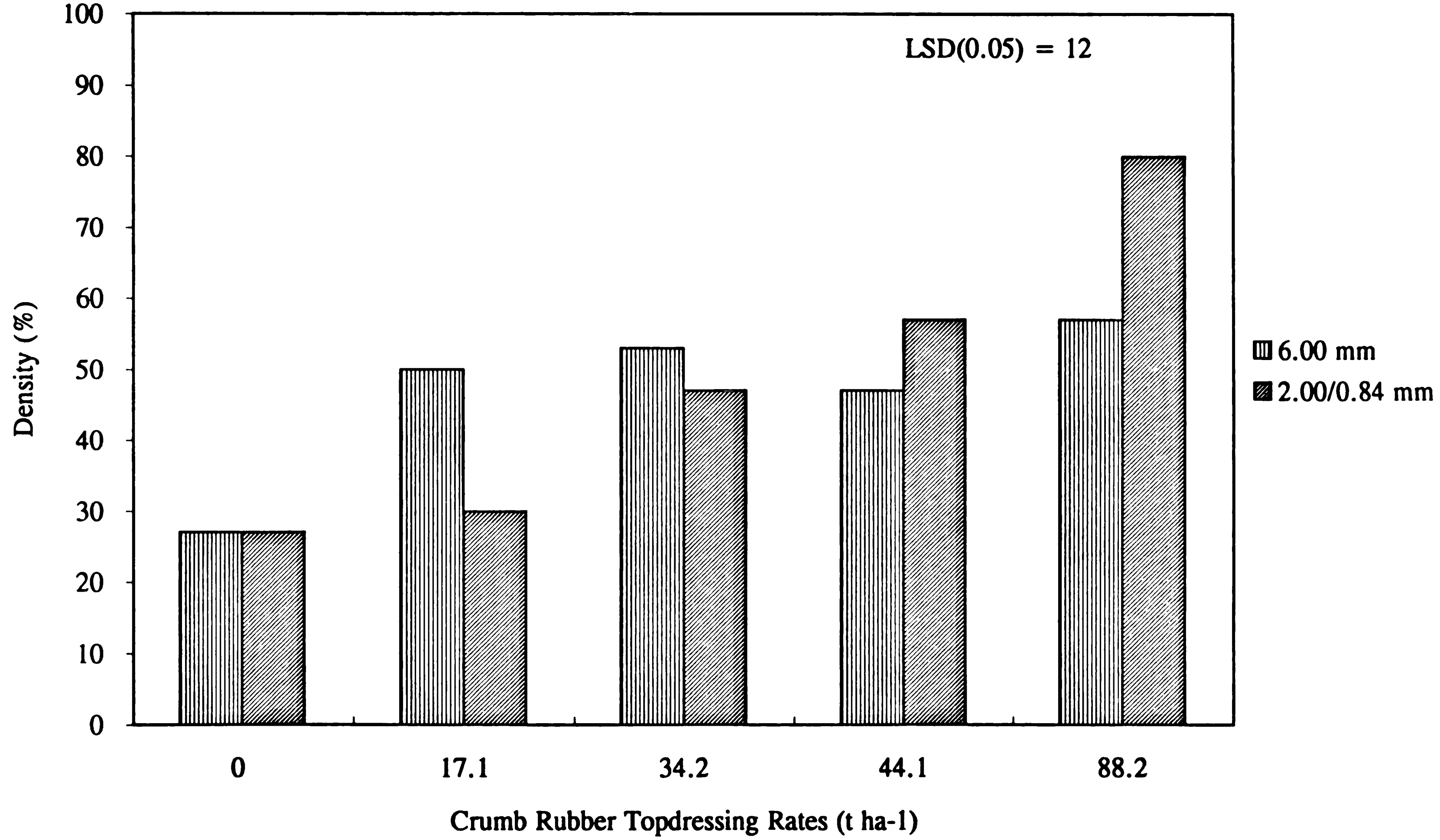



Fig. 17. Effects of density ratings on particle size x topdressing rate interaction on a trafficked Kentucky bluegrass/perennial ryegrass stand on 25 October 1993 at the HTRC.

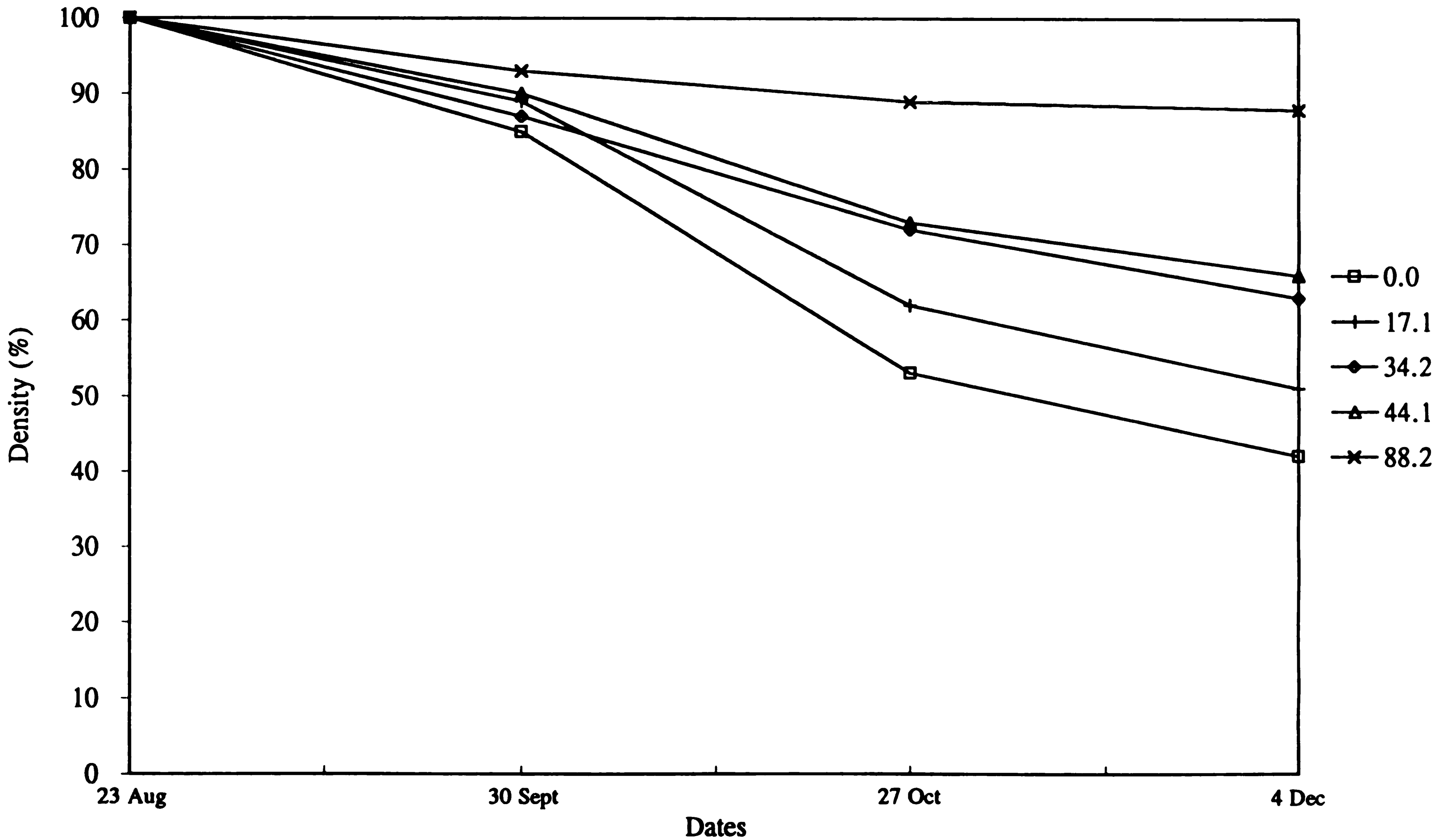



Fig. 18. Effects of particle size and topdressing rates on density ratings on a trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Turfgrass Research Center, 1994.

throughout the 1994 traffic season as crumb rubber rates increased. On 4 December, it was observed that color, for the highest rate of crumb rubber was lower than the other treatments. However, it was concluded that the grass was going dormant, but the density for the highest rate crumb rubber rate was near 90%.

In 1994, turfgrass quality ratings (Table 47) had no significant differences between particle sizes. However, there were three out of five testing dates that revealed significant differences among treatment values. As crumb rubber rates increased, overall turfgrass quality increased as well.

Figures 19 - 22 can further illustrate the effectiveness of crumb rubber protecting the crown tissue area at magnifications of 40x, 480x, 2600x, and 9400x as compared to sand. Figure 19 shows sand as looking relatively round and smooth versus crumb rubber revealing an erratic shape. However, as the magnification is increased the jaggedness and sharp, abrasive edges are revealed on the sand particle surface. Conversely, the magnification of the crumb rubber particle reveal the rounded and smooth edges on the crumb rubber particle surface. Beard (1973) noted a drawback to sand topdressing was the scarification of the crown tissue area. Due to the elastic prperties of the crumb rubber (Treloar, 1975) and the different densities (refer to Materials and Methods), crumb rubber can cushion and protect the crown tissue area of the plant thus improving the longevity of the turfgrass plant.

Table 47. Effects of crumb rubber particle size and topdressing rates on quality ratings on a trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Turfgrass Research Center, 1994.

| | Quality Ratings | | | | |
|---|---|---|---|---|---|
| | 20 Apr | 23 Aug | 30 Sep | 27 Oct | 4 Dec |
| Particle Size (mm) | | | | | |
| 6.00 | 4.7 | 8.7 | 7.2 | 5.9 | 4.6 |
| 2.00/0.84 | 5.0 | 8.7 | 7.2 | 6.1 | 4.8 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Rates (t $ha^{-1}$) | | | | | |
| 0.0 | 3.5 | 8.7 | 6.9 | 5.0 | 3.6 |
| 17.1 | 4.2 | 8.7 | 7.2 | 5.6 | 4.2 |
| 34.2 | 5.2 | 8.7 | 7.0 | 6.2 | 4.8 |
| 44.1 | 5.0 | 8.7 | 7.3 | 6.0 | 5.0 |
| 88.2 | 6.2 | 8.7 | 7.6 | 7.2 | 6.0 |
| LSD (0.05) | 1.3 | -NS- | -NS- | 0.8 | 0.9 |
| Games Simulated | 0 | 0 | 22 | 40 | 48 |

Quality ratings scale 1-9; 1=dead (low density; brown); 9=excellent (high density; dark green); 6=acceptable.
NS = not significant

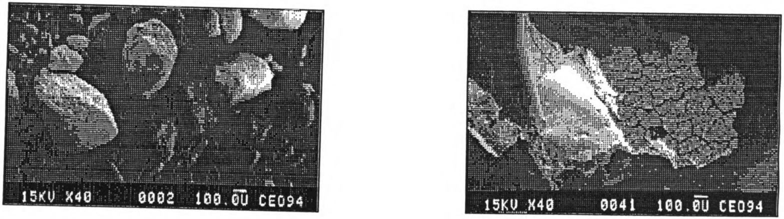
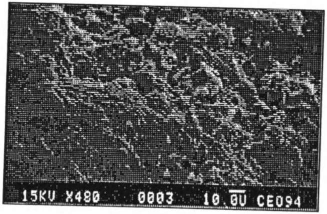



Figure 19. An electron microscope scan of sand versus crumb rubber at 40x, 1994.



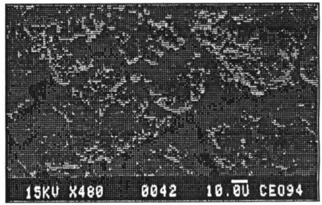
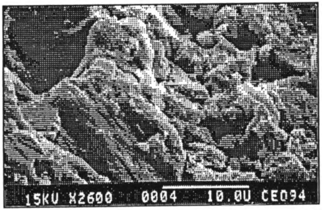




Figure 20. An electron microscope scan of sand versus crumb rubber at 480x, 1994.



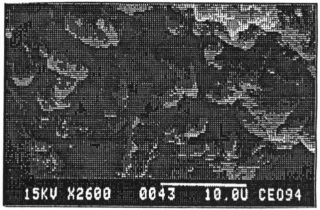




Figure 21. An electron microscope scan of sand versus crumb rubber at 2600x, 1994.

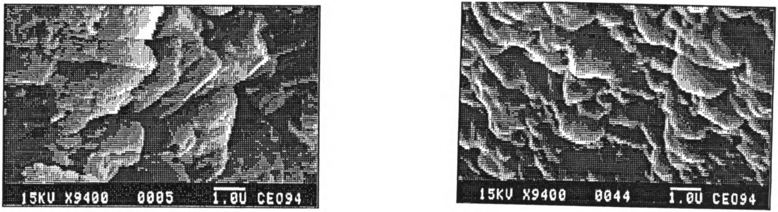



Figure 22. An electron microscope scan of sand versus crumb rubber at 9400x, 1994.

*Summary*

Topdressing crumb rubber proved to be the most effective management strategy to introduce crumb rubber to the soil/turf environment with respect to playing surface characteristics and overall turfgrass quality. Although the 2.00/0.84 mm size proved to be more effective particle size, the 6.00 mm size also proved to be worthy, at any topdressing rate, to improve playing surface characteristics. Due to the ease of application and being the least disruptive, in comparison to core cultivation, this was another advantage to highlight.

First year results showed a decrease in peak deceleration values (softer surface) and shear resistance values (less traction) as crumb rubber rates increased This can be primarily attributed to the application of crumb rubber during the fall season and the crumb rubber not settling down to the soil surface. However, by the second year, peak deceleration values were not significant between crumb rubber topdressing rates, but other surface hardness characteristics (time to peak deceleration, total time of duration, and rebound ratio) proved to be significant as crumb rubber rates increased thus providing a softer and more resilient surface. Furthermore, shear resistance values increased as crumb rubber rates increased thus correlating to a higher traction surface. Density ratings were near 90% throughout the 1994 season thus promoting a higher quality as crumb rubber rates increased.

As crumb rubber rates increased, improvements increased incrementally. However, these improvements can also be directly attributed the effectiveness of the

2.00/0.84 mm mesh size. This particle size was able to get to the soil surface quicker, protect the crown tissue, and improve the playing field quality and aethetics of its respective treatments.

The reasons for these improvements stem from the protecting of the crown tissue area of the turfgrass plant. The crown area is the point of regeneration for the new tillers and roots. Thus by protecting the plant, and providing an artificial thatch layer, the integrity of the sportsfield can be maintained for a longer period of time. Furthermore, surface dynamics of the crumb rubber was observed, noting the rounder and smoother edges versus sand. Therefore, it can be concluded, crumb rubber is not scarifying the plant and weakening the plant especially on sportfields and during a time of less optimal growth (spring and fall seasons).

With an increase in recreational sport activity (Watson, 1992) the gradual shift from artificial turf to natural grass (Berg, 1993), and an increase in concern for player safety and liability (Duff, 1995), pressures have increased on the turf manager to provide a high quality playing surface. However, by topdressing crumb rubber and using it as a "tool", integrated in a management program, the turf manager can improve the longevity and quality of the sportsfield while reducing the the potential of surface-related injuries.

# APPENDICES

# Appendix A

## The Marching Band Field Study

Results from a duplicate study from Chapter 2 are listed on Tables 48-53. The site of the experiment took place at the Michigan State University Marching Band practice field. The objective of the experiment was to evaluate the same treatments, but with less restrictions on the amount or time of traffic. The Michigan State Marching Band comprises from 125-150 members on the field at one time. Plus traffic was random throughout the field, and spikes were not implemented. This varies dramtically from the Chapter 2 study at the Hancock Turfgrass Research Center when the BTS, a spiked roller, was implemented and traffic treatments took place when weather conditions were not too extreme (too wet, too dry).

Field measurements taken were the same as the Chapter 2 study (surface hardness, traction, soil moisture, soil and surface temperatures) as well as turfgrass color, density, and quality ratings.

Table 48. Effects of crumb rubber particle size and cultivation treatments on peak deceleration ($G_{max}$) on the treatments and on the yardlines within the treatments on the Michigan State Marching Band practice field, 1993.

| | peak deceleration | | | | | | peak deceleration on the yardlines | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 21 Aug | 10 Sept | 24 Sept | 8 Oct | 4 Nov | 18 Nov | 10 Sept | 24 Sept | 8 Oct | 4 Nov | 18 Nov |
| Particle Size (mm) | | | | | | | | | | | |
| 6.00 | 82 | 70 | 63 | 100 | 82 | 63 | 83 | 84 | 110 | 99 | 78 |
| 2.00/0.84 | 82 | 67 | 63 | 99 | 80 | 63 | 83 | 81 | 111 | 98 | 76 |
| Significance† | -NS- | * | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Treatment | | | | | | | | | | | |
| C5TD | 80 | 66 | 64 | 97 | 78 | 60 | 81 | 82 | 108 | 96 | 74 |
| C10TD | 84 | 68 | 64 | 99 | 80 | 65 | 82 | 85 | 107 | 94 | 75 |
| TR5 | 86 | 70 | 66 | 101 | 83 | 60 | 85 | 85 | 115 | 98 | 75 |
| TR10 | 89 | 73 | 68 | 103 | 83 | 65 | 85 | 89 | 115 | 98 | 79 |
| SSR | 72 | 64 | 58 | 94 | 79 | 62 | 78 | 75 | 105 | 101 | 73 |
| NOR | 82 | 70 | 64 | 101 | 84 | 66 | 88 | 82 | 115 | 104 | 85 |
| LSD (0.05) | 8 | 7 | 4 | -NS- | -NS- | 4 | 6 | -NS- | 8 | -NS- | -NS- |
| Soil Water, (kg $kg^{-1}$) | 0.194 | 0.213 | 0.226 | 0.194 | 0.223 | 0.241 | 0.213 | 0.226 | 0.194 | 0.223 | 0.241 |
| Interaction | | | | | | | | | | | |
| 6.00, C5TD | | | | 97 | | | | | | | |
| 6.00, C10TD | | | | 93 | | | | | | | |
| 6.00, TR5 | | | | 106 | | | | | | | |
| 6.00, TR10 | | | | 108 | | | | | | | |
| 6.00, SSR | | | | 97 | | | | | | | |
| 6.00, NOR | | | | 97 | | | | | | | |
| 2.00/0.84, C5TD | | | | 97 | | | | | | | |
| 2.00/0.84, C10TD | | | | 104 | | | | | | | |
| 2.00/0.84, TR5 | | | | 95 | | | | | | | |
| 2.00/0.84, TR10 | | | | 98 | | | | | | | |
| 2.00/0.84, SSR | | | | 91 | | | | | | | |
| 2.00/0.84, NOR | | | | 105 | | | | | | | |
| LSD (0.05) | -NS- | -NS- | -NS- | 8 | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |

† * indicates a significant difference at the 0.05 level, and NS = not significant.

Table 49. Effects of crumb rubber particle size and cultivation treatments on soil moisture (kg kg$^{-1}$) on the Michigan State Marching Band practice field, 1993.

| | 21 Aug | 10 Sep | 24 Sep | 8 Oct | 4 Nov | 18 Nov |
|---|---|---|---|---|---|---|
| | ---------- kg kg$^{-1}$ ---------- | | | | | |
| Particle Size (mm) | | | | | | |
| 6.00 | 19.5 | 21.5 | 22.4 | 19.4 | 22.4 | 24.2 |
| 2.00/0.84 | 19.3 | 21.2 | 22.8 | 19.5 | 22.2 | 24.1 |
| Significance† | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Treatment | | | | | | |
| C5TD | 19.1 | 21.4 | 22.4 | 19.4 | 21.7 | 24.4 |
| C5TD | 19.4 | 21.3 | 22.8 | 18.9 | 22.7 | 24.6 |
| TR5 | 20.7 | 20.8 | 22.3 | 19.2 | 22.1 | 24.3 |
| TR10 | 18.5 | 21.0 | 21.6 | 19.1 | 22.1 | 23.6 |
| SSR | 19.2 | 22.0 | 23.4 | 19.6 | 22.4 | 24.4 |
| NOR | 19.6 | 21.6 | 23.2 | 20.6 | 23.0 | 23.6 |
| LSD (0.05) | 1.1 | -NS- | 0.9 | -NS- | 0.8 | -NS- |
| Interaction | | | | | | |
| 6.00, C5TD | 19.7 | 21.2 | 24.0 | 20.0 | 21.7 | 24.6 |
| 6.00, C10TD | 18.9 | 20.9 | 22.7 | 18.3 | 21.8 | 24.6 |
| 6.00, TR5 | 20.3 | 21.3 | 22.8 | 19.8 | 22.7 | 24.4 |
| 6.00, TR10 | 19.0 | 21.4 | 21.7 | 19.7 | 22.0 | 24.1 |
| 6.00, SSR | 18.7 | 21.3 | 22.7 | 19.0 | 22.4 | 24.4 |
| 6.00, NOR | 19.4 | 21.0 | 23.2 | 20.4 | 22.9 | 22.6 |
| 2.00/0.84, C5TD | 18.4 | 21.6 | 20.7 | 18.9 | 21.8 | 24.2 |
| 2.00/0.84, C10TD | 19.9 | 21.7 | 22.9 | 19.5 | 23.7 | 24.6 |
| 2.00/0.84, TR5 | 21.0 | 20.3 | 21.9 | 18.5 | 21.5 | 24.2 |
| 2.00/0.84, TR10 | 18.1 | 20.6 | 21.4 | 18.6 | 22.2 | 23.1 |
| 2.00/0.84, SSR | 19.6 | 22.7 | 24.0 | 20.2 | 22.4 | 24.4 |
| 2.00/0.84, NOR | 19.8 | 22.2 | 23.2 | 20.6 | 23.0 | 24.6 |
| LSD (0.05) | -NS- | -NS- | 1.2 | -NS- | 1.1 | -NS- |

NS = not significant

Table 50. Effects of crumb rubber particle size and cultivation treatments on shear resistance (N m) on the Michigan State Marching Band practice field, 1993 and 1994.

| | 1993 | | | | | 1994 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 21 Aug | 10 Sept | 24 Sept | 8 Oct | 4 Nov | 26 Jul | 9 Sept | 20 Sept | 3 Nov |
| | --------------- N m --------------- | | | | | | | | |
| Particle Size (mm) | | | | | | | | | |
| 6.00 | 11.9 | 15.5 | 18.1 | 19.1 | 14.0 | 13.1 | 14.1 | 12.0 | 18.0 |
| 2.00/0.84 | 13.5 | 15.7 | 18.9 | 19.8 | 15.2 | 14.2 | 14.3 | 12.6 | 18.4 |
| Significance† | * | -NS- | -NS- | -NS- | * | * | -NS- | -NS- | -NS- |
| Treatment | | | | | | | | | |
| C5TD | 11.5 | 13.9 | 17.4 | 16.2 | 13.6 | 12.8 | 14.1 | 11.5 | 18.5 |
| C10TD | 11.6 | 15.0 | 17.4 | 17.4 | 13.3 | 13.1 | 14.1 | 13.3 | 18.8 |
| TR5 | 11.8 | 16.0 | 19.2 | 17.8 | 13.7 | 13.7 | 13.9 | 11.7 | 17.8 |
| TR10 | 11.6 | 16.2 | 18.4 | 18.8 | 15.4 | 13.3 | 14.6 | 12.9 | 18.9 |
| SSR | 15.1 | 16.6 | 19.6 | 23.5 | 15.0 | 13.8 | 12.9 | 12.1 | 17.4 |
| NOR | 14.7 | 15.9 | 18.9 | 22.9 | 16.5 | 15.4 | 15.6 | 12.4 | 17.5 |
| LSD (0.05) | 1.6 | -NS- | -NS- | 2.6 | 1.7 | -NS- | -NS- | -NS- | -NS- |

† * indicates a significant difference at the 0.05 level.
NS = not significant

Table 51. Effects of crumb rubber particle size and cultivation treatments on surface and soil temperatures (°C) at the 7.6 cm depth on the Michigan State Marching Band practice field, 1993.

| | Surface Temperatures | | | | Soil Temperatures | | | |
|---|---|---|---|---|---|---|---|---|
| | 10 Sept | 8 Oct | 4 Nov | 18 Nov | 10 Sept | 8 Oct | 4 Nov | 18 Nov |
| | °C | | | | | | | |
| Particle Size (mm) | | | | | | | | |
| 6.00 | 18.8 | 16.0 | 10.3 | 7.0 | 17.4 | 14.3 | 9.0 | 3.7 |
| 2.00/0.84 | 19.1 | 16.1 | 10.3 | 6.9 | 17.5 | 14.4 | 9.0 | 3.6 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Treatment | | | | | | | | |
| C5TD | 18.6 | 16.3 | 10.3 | 6.8 | 17.4 | 14.3 | 9.0 | 3.8 |
| C10TD | 19.0 | 16.0 | 10.4 | 7.5 | 17.5 | 14.3 | 9.2 | 4.1 |
| TR5 | 19.5 | 16.0 | 10.3 | 6.6 | 17.5 | 14.4 | 8.9 | 3.3 |
| TR10 | 18.9 | 16.2 | 10.3 | 7.0 | 17.4 | 14.3 | 9.0 | 3.6 |
| SSR | 18.9 | 15.8 | 10.3 | 7.0 | 17.4 | 14.4 | 9.0 | 3.3 |
| NOR | 18.8 | 16.0 | 10.3 | 6.7 | 17.5 | 14.4 | 9.2 | 3.9 |
| LSD (0.05) | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |

NS = not significant

Table 52. Effects of crumb rubber particle size and cultivation treatments on peak deceleration ($G_{max}$) on the treatments and on the yardlines with the treatments on the Michigan State Marching Band practice field, 1994.

| | peak deceleration | | | | | peak deceleration on the yardlines | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 26 Jul | 9 Sept | 20 Sept | 13 Oct | 3 Nov | 9 Sept | 20 Sept | 13 Oct | 3 Nov |
| Particle Size (mm) | | | | | | | | | |
| 6.00 | 94 | 128 | 93 | 84 | 73 | 138 | 75 | 91 | 79 |
| 2.00/0.84 | 92 | 123 | 95 | 82 | 72 | 133 | 73 | 92 | 78 |
| Significance[†] | -NS- | * | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Treatment | | | | | | | | | |
| C5TD | 94 | 129 | 98 | 85 | 72 | 138 | 70 | 90 | 80 |
| C10TD | 95 | 125 | 95 | 83 | 74 | 129 | 77 | 94 | 77 |
| TR5 | 94 | 121 | 95 | 83 | 72 | 134 | 75 | 90 | 73 |
| TR10 | 95 | 125 | 91 | 84 | 72 | 137 | 79 | 93 | 78 |
| SSR | 89 | 124 | 91 | 80 | 70 | 133 | 73 | 92 | 81 |
| NOR | 91 | 129 | 93 | 82 | 74 | 140 | 72 | 90 | 81 |
| LSD (0.05) | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Soil Water, (kg $kg^{-1}$) | 0.151 | 0.139 | 0.156 | 0.225 | 0.259 | 0.139 | 0.156 | 0.225 | 0.259 |
| Interaction | | | | | | | | | |
| 6.00, C5TD | | 133 | | | | | | | |
| 6.00, C10TD | | 124 | | | | | | | |
| 6.00, TR5 | | 127 | | | | | | | |
| 6.00, TR10 | | 133 | | | | | | | |
| 6.00, SSR | | 123 | | | | | | | |
| 6.00, NOR | | 126 | | | | | | | |
| 2.00/0.84, C5TD | | 126 | | | | | | | |
| 2.00/0.84, C10TD | | 125 | | | | | | | |
| 2.00/0.84, TR5 | | 114 | | | | | | | |
| 2.00/0.84, TR10 | | 117 | | | | | | | |
| 2.00/0.84, SSR | | 124 | | | | | | | |
| 2.00/0.84, NOR | | 133 | | | | | | | |
| LSD (0.05) | -NS- | 10 | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |

[†] * indicates a significant difference at the 0.05 level, and NS = not significant

Table 53. Effects of crumb rubber particle size and cultivation treatments on time to peak deceleration (ms), duration of impact (ms),and rebound ratio (%) on the Michigan State Marching Band practice field, 1994.

| | Time to peak deceleration | | | | Total duration of impact | | | | Rebound ratio | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 9 Sept | 20 Sept | 13 Oct | 3 Nov | 9 Sept | 20 Sept | 13 Oct | 3 Nov | 20 Sept | 13 Oct | 3 Nov |
| **Particle Size (mm)** | | | | | | | | | | | |
| 6.00 | 2.6 | 3.7 | 3.7 | 4.3 | 5.0 | 7.5 | 7.8 | 9.1 | 35.9 | 35.7 | 35.4 |
| 2.00/0.84 | 2.7 | 3.5 | 3.9 | 4.4 | 5.4 | 7.2 | 8.1 | 9.2 | 36.9 | 37.0 | 34.9 |
| Significance[†] | * | -NS- | * | -NS- | * | -NS- | * | -NS- | -NS- | * | -NS- |
| **Treatment** | | | | | | | | | | | |
| C5TD | 2.7 | 3.4 | 3.7 | 4.4 | 5.2 | 6.9 | 7.8 | 9.3 | 37.4 | 37.3 | 35.9 |
| C10TD | 2.8 | 3.3 | 3.8 | 4.2 | 5.3 | 6.9 | 8.1 | 8.9 | 34.4 | 37.1 | 35.4 |
| TR5 | 2.8 | 3.5 | 3.9 | 4.5 | 5.6 | 7.2 | 8.1 | 9.3 | 35.8 | 36.4 | 35.4 |
| TR10 | 2.6 | 3.7 | 3.8 | 4.3 | 5.1 | 7.4 | 7.9 | 9.2 | 36.1 | 36.3 | 35.0 |
| SSR | 2.6 | 3.9 | 3.7 | 4.4 | 5.1 | 8.2 | 8.1 | 9.6 | 36.9 | 37.0 | 35.1 |
| NOR | 2.5 | 3.8 | 3.7 | 4.1 | 4.9 | 7.4 | 7.8 | 8.8 | 37.9 | 34.4 | 34.4 |
| LSD (0.05) | 0.2 | -NS- | -NS- | -NS- | 0.4 | -NS- | -NS- | -NS- | -NS- | 1.8 | -NS- |
| **Interaction** | | | | | | | | | | | |
| 6.00, C5TD | 2.6 | | | | 4.9 | | | | | 36.8 | |
| 6.00, C10TD | 2.8 | | | | 5.2 | | | | | 37.5 | |
| 6.00, TR5 | 2.7 | | | | 5.2 | | | | | 34.4 | |
| 6.00, TR10 | 2.4 | | | | 4.6 | | | | | 34.6 | |
| 6.00, SSR | 2.7 | | | | 5.2 | | | | | 36.3 | |
| 6.00, NOR | 2.4 | | | | 5.0 | | | | | 34.8 | |
| 2.00/0.84, C5TD | 2.7 | | | | 5.4 | | | | | 37.8 | |
| 2.00/0.84, C10TD | 2.7 | | | | 5.4 | | | | | 36.6 | |
| 2.00/0.84, TR5 | 3.0 | | | | 6.0 | | | | | 38.4 | |
| 2.00/0.84, TR10 | 2.8 | | | | 5.6 | | | | | 37.9 | |
| 2.00/0.84, SSR | 2.6 | | | | 5.0 | | | | | 37.7 | |
| 2.00/0.84, NOR | 2.5 | | | | 4.7 | | | | | 34.0 | |
| LSD (0.05) | 0.2 | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | 2.6 | -NS- |

[†] * indicates a significant difference at the 0.05 level, NS = not significant

## Appendix B

## The After Topdressing Study

Results from a topdressing study conducted adjacent to the study done in Chapter 3 are listed on Tables 54-61.

Material and methods are exactly the same , however crumb rubber was only topdressed on 11 September 1993.

The same field measurements were conducted on this study as was the Chapter 3 study as well as overall turfgrass ratings.

The objective of the experiment was to investigate the potential of crumb rubber improving playing field conditions and overall quality ratings **after** traffic had been applied.

Table 54. Effects of crumb rubber particle size and topdressing rates on peak deceleration ($G_{max}$) and ball bounce (%) on a trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Turfgrass Research Center, 1993.

| | 22 Oct | 5 Nov | 19 Nov | 3 Dec | 22 Oct |
|---|---|---|---|---|---|
| | ----------$G_{max}$---------- | | | | ---%--- |
| Particle Size (mm) | | | | | |
| 6.00 | 77 | 81 | 65 | 81 | 38 |
| 2.00/0.84 | 78 | 81 | 67 | 81 | 38 |
| Significance† | -NS- | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Rates (t ha$^{-1}$) | | | | | |
| 0.0 | 80 | 82 | 68 | 82 | 38 |
| 5.7 | 79 | 81 | 68 | 83 | 40 |
| 11.4 | 76 | 80 | 70 | 80 | 38 |
| 14.7 | 76 | 80 | 67 | 80 | 38 |
| 29.4 | 76 | 81 | 59 | 81 | 36 |
| LSD (0.05) | -NS- | -NS- | 6 | 4 | 2 |
| Soil Water, (kg kg$^{-1}$) | 0.172 | 0.148 | 0.193 | 0.158 | 0.172 |
| Interaction | | | | | |
| 6.00, 0.0 | | | | | 38 |
| 6.00, 5.7 | | | | | 39 |
| 6.00, 11.4 | | | | | 37 |
| 6.00, 14.7 | | | | | 38 |
| 6.00, 29.4 | | | | | 38 |
| 2.00/0.84, 0.0 | | | | | 38 |
| 2.00/0.84, 5.7 | | | | | 40 |
| 2.00/0.84, 11.4 | | | | | 40 |
| 2.00/0.84, 14.7 | | | | | 38 |
| 2.00/0.84, 29.4 | | | | | 33 |
| LSD (0.05) | -NS- | -NS- | -NS- | -NS- | 3 |

NS = not significant

Table 55. Effects of crumb rubber particle size and topdressing rates on shearvane values (N m) on a trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Turfgrass Research Center, 1993 and 1994.

| | 1993 | | 1994 | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 22 Oct | 4 Nov | 2 Jun | 27 Jul | 15 Sep | 6 Oct | 27 Oct | 10 Nov |
| | | | N m | | | | | |
| Particle Size (mm) | | | | | | | | |
| 6.00 | 23.7 | 24.1 | 25.0 | 17.4 | 20.5 | 22.1 | 21.8 | 16.4 |
| 2.00/0.84 | 24.5 | 24.6 | 25.1 | 19.2 | 22.5 | 22.1 | 21.0 | 15.8 |
| Significance† | -NS- | -NS- | -NS- | * | * | -NS- | -NS- | -NS- |
| Crumb Rubber Rates (t $ha^{-1}$) | | | | | | | | |
| 0.0 | 30.3 | 26.1 | 27.2 | 22.6 | 24.7 | 21.7 | 21.4 | 16.1 |
| 5.7 | 26.8 | 25.6 | 25.9 | 20.3 | 21.9 | 20.4 | 21.9 | 15.8 |
| 11.4 | 25.4 | 25.4 | 25.1 | 18.4 | 22.4 | 23.9 | 20.6 | 16.1 |
| 14.7 | 23.8 | 24.3 | 26.0 | 17.3 | 22.1 | 22.8 | 22.7 | 17.6 |
| 29.4 | 14.0 | 20.2 | 21.2 | 12.9 | 16.4 | 21.8 | 20.5 | 14.9 |
| LSD (0.05) | 4.3 | 3.7 | 3.0 | 3.0 | 2.2 | -NS- | -NS- | -NS- |
| Interaction | | | | | | | | |
| 6.00, 0.0 | | | | | | 21.6 | | |
| 6.00, 5.7 | | | | | | 19.4 | | |
| 6.00, 11.4 | | | | | | 27.4 | | |
| 6.00, 14.7 | | | | | | 23.4 | | |
| 6.00, 29.4 | | | | | | 18.8 | | |
| 2.00/0.84, 0.0 | | | | | | 21.9 | | |
| 2.00/0.84, 5.7 | | | | | | 21.3 | | |
| 2.00/0.84, 11.4 | | | | | | 20.3 | | |
| 2.00/0.84, 14.7 | | | | | | 22.1 | | |
| 2.00/0.84, 29.4 | | | | | | 24.9 | | |
| LSD (0.05) | -NS- | -NS- | -NS- | -NS- | -NS- | 5.3 | -NS- | -NS- |

† * indicates a significant difference at the 0.05 level, and NS = not significant.

Table 56. Effects of crumb rubber particle size and topdressing rates on color and density on a trafficked Kentucky bluegrass/perennial ryegrass turf at the Hancock Turfgrass Research Center, 1993

| | 25 Oct | 15 Nov | 25 Oct |
|---|---|---|---|
| | --- Color Ratings --- | | --- Density Ratings --- |
| Particle Size (mm) | | | |
| 6.00 | 4.4 | 2.4 | 29 |
| 2.00/0.84 | 3.7 | 2.1 | 30 |
| Significance† | * | * | -NS- |
| Crumb Rubber Rates (t ha$^{-1}$) | | | |
| 0.0 | 2.5 | 1.3 | 19 |
| 5.7 | 3.3 | 1.7 | 24 |
| 11.4 | 4.4 | 2.2 | 29 |
| 14.7 | 4.2 | 2.3 | 32 |
| 29.4 | 5.9 | 3.6 | 43 |
| LSD (0.05) | 0.9 | 0.4 | 6 |
| Interaction | | | |
| 6.00, 0.0 | 2.8 | 1.5 | 20 |
| 6.00, 17.1 | 3.8 | 1.7 | 28 |
| 6.00, 34.2 | 5.5 | 2.8 | 28 |
| 6.00, 44.1 | 4.5 | 2.7 | 35 |
| 6.00, 88.2 | 5.5 | 3.5 | 32 |
| 2.00/0.84, 0.0 | 2.2 | 1.2 | 18 |
| 2.00/0.84, 17.1 | 2.8 | 1.8 | 20 |
| 2.00/0.84, 34.2 | 3.3 | 1.7 | 30 |
| 2.00/0.84, 44.1 | 3.8 | 2.0 | 28 |
| 2.00/0.84, 88.2 | 6.3 | 3.7 | 53 |
| LSD (0.05) | 1.3 | 0.6 | 9 |

† * indicates a significant difference at a 0.05 level
NS = not significant
Quality Ratings Scale was 1-9; 1 = brown (low density, dead), 9 = excellent (high density, green), and 6 = acceptable.
Density Ratings Scale was 0-100%

Table 57. Effects of crumb rubber particle size and topdressing rates on peak deceleration ($G_{max}$) and ball bounce (%) on a trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Turfgrass Research Center, 1994.

| | peak deceleration | | | | | ball bounce | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2 Jun | 27 Jul | 15 Sep | 6 Oct | 27 Oct | 2 Jun | 15 Sep | 6 Oct | 10 Nov |
| **Particle Size (mm)** | | | | | | | | | |
| 6.00 | 65 | 74 | 77 | 76 | 75 | 37 | 38 | 38 | 38 |
| 2.00/0.84 | 65 | 75 | 78 | 77 | 76 | 36 | 39 | 38 | 39 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| **Crumb Rubber Rates ($t\ ha^{-1}$)** | | | | | | | | | |
| 0.0 | 69 | 79 | 79 | 78 | 77 | 36 | 39 | 40 | 39 |
| 5.7 | 66 | 72 | 78 | 77 | 73 | 36 | 40 | 41 | 40 |
| 11.4 | 64 | 75 | 76 | 76 | 76 | 37 | 39 | 37 | 37 |
| 14.7 | 64 | 75 | 77 | 78 | 75 | 37 | 37 | 37 | 39 |
| 29.4 | 60 | 70 | 79 | 74 | 76 | 35 | 36 | 37 | 37 |
| LSD (0.05) | 4 | 4 | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| **Interaction** | | | | | | | | | |
| 6.00, 0.0 | | 80 | | | | | | | |
| 6.00, 5.7 | | 70 | | | | | | | |
| 6.00, 11.4 | | 71 | | | | | | | |
| 6.00, 14.7 | | 73 | | | | | | | |
| 6.00, 29.4 | | 74 | | | | | | | |
| 2.00/0.84, 0.0 | | 77 | | | | | | | |
| 2.00/0.84, 5.7 | | 74 | | | | | | | |
| 2.00/0.84, 11.4 | | 80 | | | | | | | |
| 2.00/0.84, 14.7 | | 76 | | | | | | | |
| 2.00/0.84, 29.4 | | 67 | | | | | | | |
| LSD (0.05) | -NS- | 5 | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |

NS = not significant

Table 58. Effects of crumb rubber particle size and topdressing rates on time to peak deceleration (ms), total duration of impact (ms), and rebound ratio (%) on a trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Turfgrass Research Center, 1994.

| | Time to peak deceleration | | | Total duration of impact | | | Rebound ratio | | |
|---|---|---|---|---|---|---|---|---|---|
| | 15 Sep | 6 Oct | 27 Oct | 15 Sep | 6 Oct | 27 Oct | 15 Sep | 6 Oct | 27 Oct |
| | | ms | | | ms | | | % | |
| **Particle Size (mm)** | | | | | | | | | |
| 6.00 | 4.5 | 4.5 | 4.6 | 8.7 | 8.4 | 8.5 | 28.2 | 24.7 | 21.4 |
| 2.00/0.84 | 4.4 | 4.5 | 4.5 | 8.6 | 8.4 | 8.4 | 28.4 | 24.9 | 21.6 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| **Crumb Rubber Rates (mm)** | | | | | | | | | |
| 0.0 | 4.2 | 4.4 | 4.3 | 8.2 | 8.2 | 8.0 | 25.9 | 22.5 | 19.4 |
| 5.7 | 4.4 | 4.4 | 4.7 | 8.5 | 8.2 | 8.8 | 26.9 | 23.2 | 20.5 |
| 11.4 | 4.5 | 4.4 | 4.7 | 8.8 | 8.6 | 8.3 | 27.8 | 24.4 | 21.6 |
| 14.7 | 4.5 | 4.3 | 4.5 | 8.6 | 8.6 | 8.6 | 28.6 | 25.0 | 21.7 |
| 29.4 | 4.7 | 4.9 | 4.7 | 9.2 | 9.1 | 8.6 | 32.3 | 28.9 | 24.4 |
| LSD (0.05) | -NS- | 0.4 | 0.2 | 0.5 | 0.6 | -NS- | 2.0 | 2.0 | 2.0 |
| **Interaction** | | | | | | | | | |
| 6.00, 0.0 | | | | | | | 26.0 | | |
| 6.00, 5.7 | | | | | | | 26.3 | | |
| 6.00, 11.4 | | | | | | | 27.8 | | |
| 6.00, 14.7 | | | | | | | 28.6 | | |
| 6.00, 29.4 | | | | | | | 32.3 | | |
| 2.00/0.84, 0.0 | | | | | | | 25.8 | | |
| 2.00/0.84, 5.7 | | | | | | | 27.5 | | |
| 2.00/0.84, 11.4 | | | | | | | 26.5 | | |
| 2.00/0.84, 14.7 | | | | | | | 29.1 | | |
| 2.00/0.84, 29.4 | | | | | | | 33.3 | | |
| LSD (0.05) | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | 2.0 | -NS- | -NS- |

NS = not significant

Table 59. Effects of crumb rubber particle size and topdressing rates on color ratings on a trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Research Center, 1994.

| | 4 Apr | 23 Aug | 4 Oct | 4 Dec |
|---|---|---|---|---|
| Particle Size (mm) | | | | |
| 6.00 | 4.2 | 8.1 | 6.5 | 4.0 |
| 2.00/0.84 | 3.7 | 8.1 | 6.6 | 4.0 |
| Significance | -NS- | -NS- | -NS- | -NS- |
| | | | | |
| Crumb Rubber Rate (t $ha^{-1}$) | | | | |
| 0.0 | 2.8 | 8.2 | 6.7 | 3.9 |
| 5.7 | 3.4 | 8.0 | 6.2 | 4.0 |
| 11.4 | 3.9 | 8.2 | 6.7 | 4.1 |
| 14.7 | 4.2 | 8.2 | 6.7 | 4.0 |
| 29.4 | 5.3 | 8.1 | 6.7 | 4.0 |
| LSD (0.05) | 1.2 | -NS- | -NS- | -NS- |
| | | | | |
| Interaction | | | | |
| 6.00, 0.0 | 3.5 | 8.2 | 6.7 | 4.0 |
| 6.00, 5.7 | 3.8 | 7.8 | 5.8 | 4.2 |
| 6.00, 11.4 | 4.5 | 8.1 | 6.7 | 4.0 |
| 6.00, 14.7 | 3.7 | 8.2 | 6.8 | 3.9 |
| 6.00, 29.4 | 5.5 | 8.2 | 6.7 | 3.9 |
| 2.00/0.84, 0.0 | 2.2 | 8.1 | 6.7 | 3.9 |
| 2.00/0.84, 5.7 | 3.0 | 8.2 | 6.7 | 3.9 |
| 2.00/0.84, 11.4 | 3.3 | 8.2 | 6.7 | 4.2 |
| 2.00/0.84, 14.7 | 4.7 | 8.1 | 6.5 | 4.0 |
| 2.00/0.84, 29.4 | 5.2 | 7.9 | 6.7 | 4.0 |
| LSD (0.05) | -NS- | 0.2 | 0.4 | -NS- |

NS = not significant

Table 60. Effects of crumb rubber particle size and topdressing rates on density and quality ratings on a trafficked Kentucky bluegrass/perennial ryegrass stand at the Hancock Turfgrass Research Center, 1994.

| | Density Ratings | | | | Quality Ratings | | |
|---|---|---|---|---|---|---|---|
| | 7 Apr | 20 Apr | 4 Oct | 4 Dec | 20 Apr | 4 Oct | 4 Dec |
| Particle Size (mm) | | | | | | | |
| 6.00 | 30.3 | 41.3 | 67.3 | 58.7 | 5.4 | 6.5 | 4.0 |
| 2.00/0.84 | 26.7 | 37.7 | 69.3 | 58.7 | 5.0 | 6.7 | 4.0 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Rate (t $ha^{-1}$) | | | | | | | |
| 0.0 | 14.2 | 27.5 | 71.7 | 58.3 | 4.6 | 6.7 | 4.0 |
| 5.7 | 20.0 | 33.3 | 63.3 | 60.0 | 4.9 | 6.2 | 4.1 |
| 11.4 | 32.5 | 43.3 | 70.0 | 58.3 | 5.4 | 6.7 | 4.0 |
| 14.7 | 29.2 | 40.0 | 70.0 | 58.3 | 5.2 | 6.7 | 4.0 |
| 29.4 | 46.7 | 53.3 | 66.7 | 58.3 | 5.9 | 6.5 | 4.0 |
| LSD (0.05) | 13.6 | 12.6 | -NS- | -NS- | 0.7 | -NS- | -NS- |

NS = not significant

Table 61. Effects of crumb rubber particle size and topdressing rates on clipping yield (g * m$^{-2}$) on a trafficked and non-trafficked Kentucky bluegrass/perennial ryegrass turf at the Hancock Turfgrass Research Center, 1994.

| | Traffic | | | Non-Traffic | |
|---|---|---|---|---|---|
| | 21 Apr | 8 Aug | 20 Oct | 21 Apr | 8 Aug |
| | g * m$^{-2}$ | | | | |
| Particle Size (mm) | | | | | |
| 6.00 | 4.7 | 6.9 | 1.0 | 18.3 | 4.6 |
| 2.00/0.84 | 4.3 | 5.6 | 1.0 | 17.4 | 3.3 |
| Significance | -NS- | -NS- | -NS- | -NS- | -NS- |
| Crumb Rubber Rate (T ha$^{-1}$) | | | | | |
| 0.0 | 3.6 | 6.2 | 1.1 | 12.3 | 4.2 |
| 5.7 | 2.8 | 5.7 | 0.7 | 11.1 | 3.8 |
| 11.4 | 4.4 | 7.0 | 1.0 | 16.7 | 4.1 |
| 14.7 | 5.1 | 6.7 | 1.3 | 21.4 | 4.4 |
| 29.4 | 6.7 | 5.5 | 0.8 | 27.9 | 3.2 |
| LSD (0.05) | 1.9 | -NS- | -NS- | 8.8 | -NS- |
| Interaction | | | | | |
| 6.00, 0.0 | 5.3 | 7.4 | 1.2 | 14.3 | 6.0 |
| 6.00, 5.7 | 3.4 | 6.4 | 0.6 | 9.6 | 4.1 |
| 6.00, 11.4 | 5.4 | 7.0 | 1.4 | 18.6 | 4.2 |
| 6.00, 14.7 | 5.3 | 8.3 | 1.5 | 20.5 | 4.8 |
| 6.00, 29.4 | 4.1 | 5.3 | 0.6 | 28.7 | 3.6 |
| 2.00/0.84, 0.0 | 1.9 | 5.0 | 1.0 | 10.3 | 2.4 |
| 2.00/0.84, 5.7 | 2.2 | 4.9 | 0.9 | 12.7 | 3.4 |
| 2.00/0.84, 11.4 | 3.4 | 6.9 | 0.7 | 14.9 | 3.9 |
| 2.00/0.84, 14.7 | 4.9 | 5.2 | 1.1 | 22.3 | 4.0 |
| 2.00/0.84, 29.4 | 9.3 | 5.8 | 1.1 | 27.1 | 2.8 |
| LSD (0.05) | 2.7 | -NS- | 0.6 | -NS- | -NS- |

NS = not significant

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