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Living with artificial grass: A knowledge update

Part 1: Basic science

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ABSTRACT

Part I of this two part study reviews the development and characteristics of artificial grass, and the influence of this surface on the American football player.

Artificial grass was initially developed to provide city children with increased play space and thus enable them to maintain a fitness level equal to their peers in more rural locales. Today, artificial grass fields allow for increased use when field availability is limited, or for a grass substitute where grass will not grow. However, epidemiologic studies suggest that there is an increased risk of lower extremity injury to the football athlete playing on an artificial grass field. By reviewing available studies, a knowledge base can be formed that can serve to direct future investigations concerning the influence of artificial grass surfaces and injury and, ultimately, how that influence can be affected.

Twenty-five years ago a field made of a grass substitute was installed in a covered sport facility for the first time.[47] Today artificial grass is played on throughout the world by professional and amateur athletes. However, after a quarter century of use, artificial grass has not been totally accepted; it has been both praised and maligned. Whether or not it is safe for the athlete, or influences the games played on it, is still a subject of controversy.

Artificial grass has undeniable advantages. Where land is limited, field use is high, or the climate is harsh, artificial grass withstands use better than natural grass.[37] When funds are limited, decreased maintenance costs may make an artificial grass field more attractive. In contrast are the concerns over alterations in field characteristics as well as a concern that playing on artificial grass will increase the risk for injury. Studies quantifying the physical effects of artificial grass on athletes have been undertaken, but the conclusions reached have been inconsistent.

The goals of this Phase I report are two-fold. In Part 1, we shall review the development, material characteristics, mechanical properties, and costs of artificial grass. In Part 2, we shall review all available epidemiologic studies of the effect of artificial grass on American football players. With this review we have been able to form a knowledge base that can be used to clarify the key issues concerning artificial grass and can serve as a starting point for future epidemiologic investigations.

HISTORY

After the Korean War, the Ford Foundation evaluated the factors that influenced the physical well-being of young people. A review of military induction examinations from American recruits indicated that rural inductees were in better physical condition than their urban counterparts.[18, 28, 37, 47] It was concluded that this difference was due to a lack of suitable play areas for urban children.[47] In 1960, the Educational Facilities Laboratory (EFL) was created by the Ford Foundation to pioneer work in school-plant development.[47] Led by Harold Gores, the EFL began to evaluate methods for the construction of rooftop playgrounds. Monsanto, Minnesota Mining & Manufacturing (3M; St. Paul, MN) and Cabin Crafts Carpets (Dalton, GA) were given design parameters for the construction of the rooftop play areas.[47] Chemstrand (Pensacola, FL), a subsidary of Monsanto, had already been working with synthetic fibers for use in carpeting to be installed in schools and other public

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buildings. From this work they developed an artificial surface, ChemGrass. With a $200,000 grant from the EFL, an experimental ChemGrass field was installed in the fieldhouse of the Moses Brown School in Providence, Rhode Island, in 1964.[18, 28, 37, 47] This was the first artificial indoor surface and it is still in use.

The Astrodome in Houston, Texas, was completed in 1965. Because the glare from the roof's skylights was blinding Houston Astros' outfielders, the skylights were painted over. Without sunlight, the grass inside the Astrodome died, and the playing surface turned into hard dirt.[51] To resolve this dilemma a medium-pile, artificial surface, Monsanto AstroTurf, was laid over the dirt floor. The surface was modified a year later, in 1967, when a rubber pad was placed between the synthetic turf and the floor.[51] Outdoor artificial surfaces were first installed in 1967 by Monsanto at High School Memorial Stadium in Seattle, Washington, and at Indiana State University in Terre Haute, Indiana.[37, 51] By 1980, AstroTurf (Appendix 1) had been installed in over 300 fields in the United States as well as abroad.[18, 30, 46]

In 1960, 3M had begun research on an all-weather track for horse racing.[28] While not successful as a surface for horse racing, the track was modified slightly and put to use as a running surface called Tartan Track. This surface was used for the track events in the 1968 Olympic Games in Mexico City. Tartan Turf (Appendix 1), designed for field sports, became the next entrant in the artificial surface market. It was initially installed at university playing fields in Tennessee and Wisconsin.[46] In 1974, 3M abandoned the production of its Tartan products because of increasing production costs, limited markets, limited revenues, and negative publicity concerning the risk to athletes playing on the surface.[28]

PolyTurf (Appendix 1) was created by American Bilt-Rite (Wellesley, MA). One of its earliest installations was in Miami's Orange Bowl followed by Foxboro Stadium, Springfield College, Cornell University, Tulane University, and Boston College.[37] Not long after its installation, the surface at the Orange Bowl suffered from problems with plasticizer migration and split seams.[28] American Bilt-Rite ceased production of Polyturf in 1973, claiming only unprofitability as the reason for discontinuance.

Omniturf (Division of Sportec, Kenmore, NY; Appendix 1) was installed at the Hattem Hockey Club in Holland in 1981 and a year later on the home field of the Queens Park Rangers football club of the United Kingdom football league.[39, 48] In this country, Omniturf was initially installed at the University of Oregon in 1984.[39] Since then, it has been installed successfully at various universities and high schools.

Poligras (Appendix 1), a product of the Adolff Company in West Germany, is a first-generation artificial surface primarily found in soccer and field hockey stadia in Europe. Poligras started production in the United States (Poligras USA Inc., Clearwater, FL) with their first installation at Colgate University in 1987.[41] Sporturf (Appendix 1), a product of All-Pro Athletic Surfaces, produces both first-generation and second-generation artificial surfaces.[1] These surfaces have been in use across the United States since 1982.[1] Today, AstroTurf and All-Pro Athletic Surfaces are those most widely used, but other companies continue to find places in the American market.

ARTIFICIAL TURF CHARACTERISTICS

Fiber ribbons and wear surfaces

The fibers that collectively make up the surface of an artificial playing field are most effectively produced from an extruded monofilament ribbon.[49] The majority of these fibers are rectangular in cross-section. Two thermoplastics are used principally for the formation of the ribbon and ultimately the structural fiber: nylon and polypropylene.[26, 49]

Nylon is a linear thermoplastic polyamide capable of forming a fiber.[49] To help it improve its resistance to the environment, nylon is usually modified by additives.[49] Pigments are added to give the fiber the desired color.

Polypropylene is a linear hydrocarbon polymer.[49] For outdoor use, it requires both stabilizers and antioxidants. After the final compound is formed, it is extruded through a slit dye, forming a film. Tapes of the appropriate width are produced by multiple blade slitters or air knives. The tapes are then stretched. This orients them, and influences the degree of crystallinity.[49]

Once a suitable fiber is created it is incorporated into the wear surface system by merging it with the carpet backing. This final product can be knitted, woven, or tufted. Knitted carpets are formed by tying each fiber into the carpet backing.[18, 43] The knitted fiber, and its backing, in effect become a single unit. A woven carpet backing is created by interlacing warp and filler threads while the pile fibers are inserted along the warp threads. A tufted surface is formed by passing the pile fiber through a separately prepared backing.[49] The fiber is fixed to the backing by applying a binder coating of polyurethane or a synthetic rubber to lock the fiber in place.

The resistance of a pile fiber to pullout (tuft lock) from a knitted carpet construct is excellent, and may exceed the tensile strength of the fiber. A woven system's resistance to pile pullout is less than that of a knitted system and is dependent on the type of weave employed. The tuft lock of tufted products is variable and depends directly on the binder.[27]

The dimensional stability of a wear surface, that is the resistance of a carpet to movement and distortion, varies with the construction technique.[27] Tufted carpets are quite stable, while knitted ones are less stable than woven or tufted surfaces.[27] A binder can be applied to woven or knitted products to add to their dimensional stability.

In general, the structural architecture of artificial turf surfaces are either first-generation or second-generation types.[27] With first-generation artificial turfs, the fibers are the playing surface. This is accomplished by creating a wear surface that has a high density of grass fibers. Architectural components and design can vary, but the grass fibers support the athlete and the ball. Second-generation systems use granular infills for the playing surface. Less densely ar-

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ranged fibers act to stabilize the granular infill, improve appearance, and create appropriate ball roll characteristics.[27] The fibers of these second-generation systems are longer than their first-generation counterparts. They are often tufted through a porous backing and held in place by a porous binder. The reported advantages of sand-filled systems include "reduced footlock," reduced fire sensitivity, and decreased carpet movement because of the substantial weight of the granular infill.[27]

Shock pads and undersurface

Beneath the wear surface of both first-generation and second-generation fields is the shock pad. Variations in shock pad design alter ball roll and bounce characteristics and influence player-surface interactions. Because of that influence, when an artificial turf field is installed outdoors, the shock pad must maintain its desired characteristics throughout the entire range of climatic conditions.

Most shock pads are made from flexible foams (open or closed cell) derived from a variety of plastics and rubbers. In addition, suitable shock pads can be made from porous bound synthetic rubbers, fibrous mats, particulate systems, or a combination of these.[27] Open cell foams (sponges) tend to fill with water, and can freeze during cold weather, making the pad significantly harder.[23] Similarly, the gas in closed cell foams is also affected by temperature as is the material used in the cell walls.

In general the shock pad undersurfaces of American football fields are made of closed-cell foams of polyurethane, polyvinyl chloride, or cross-linked polyethylene.[36] The density of the foam depends on the amount of gas incorporated in the foam. The flexibility of the foam is dependent on the degree of cross-linking present.

Polyurethane and polyvinyl chloride are made into foams by adding materials that liberate gas (blowing agents). Polyvinyl chloride pastes can be whipped or agitated to generate bubbles or carbon dioxide can be added under pressure to create the foam.

The purpose of these materials as an undersurface is identical: to produce in conjunction with the artificial turf a surface with playing characteristics as close as possible to natural grass.

Structural properties

A number of structural properties contribute to the play characteristics of a surface (Appendix 2). Two of these properties, shock absorbancy and adhesion at the shoe-surface interface, are of particular interest. The American Society for Testing and Materials (ASTM) designation F355-86 describes a test to measure the shock-absorbing characteristics, impact force-time relationships, and rebound properties of certain playing systems.[7,18,36] The test can be applied to both natural and artificial playing surfaces. The results of this test quantify the cushioning properties of an individual play surface.[7]

The test design F355-86 is based on investigations by the U.S. automobile industry. In 1968, Daniel[36] proposed that a flat impacting surface provided a more accurate measure of impact attenuation by the human facial plane. The parameters of this test were influenced by the investigations of Reid et al.[42] For these investigations an accelerometer was fixed to the helmet of an American football player. The resulting data suggested that 85% of the impacts sustained by the head of an American football player were of 54 Nm or less.[18,42] Using Daniel's test device, this was equivalent to the effect of dropping a missile weighing 20 pounds from a height of 2 feet.

In the ASTM procedure, a missile (of known shape and weight) is impacted at a specified velocity. A transducer in the missile monitors the acceleration time-history of the impact. Procedure A employs a cylindrical missile. Procedures B and C use a hemispherical missile and an ANSI (American National Standards Institute) head form, respectively.[7] The test allows for determination of a value G, the ratio of magnitude of missile acceleration during impact to the acceleration of gravity.[40] G_{max} is the maximum value of G encountered at impact. The severity index is an arbitrary parameter equal to[36]

$$\text{Severity index} = \int_0^t G^{2.5}\,dt$$

Because $\log_{10}G_{max}$ and the severity index correlate well for a given playing surface, most investigators rely on G_{max} values for analysis. Some values for G_{max} are indicated in Table 1.

Nigg[38] has expressed concern over this test method. He believes that the result is influenced significantly by the dropping missile, the drop height, and the area of contact. Further, he suggests that the deceleration forces measured in a drop test do not correlate well with the impact forces measured during specific movements of an athlete on these surfaces. Because of such discrepancies, he advocates alterations of the test methods.

Although it is not clear whether present test methods accurately assess the "hardness" of a field, it is known that this quality can be adjusted by changing the characteristics of the wear surface and the pad. In effect, a field can be tuned to create a desired set of conditions depending on whether the field will impact with bodies or baseballs.

The shoe-surface interface

An athlete's skills are limited by the quality of the fixation of that player to his present playing surface. Usually, the

TABLE 1
Shock absorbancy of playing surfaces[a]

Surface	G_{max}
Ideal grass field	70–90
Wet/muddy field	60–65
Frozen ground	150–275
Compact clay	150–250
Wet sand	135–150
Synthetic turf	70–100
5-year-old synthetic turf	150–175

[a] Source: Milner.[36]

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athlete plays at the limit of that adhesion.[31] As a result of that difference in adhesion, a football athlete moves faster on synthetic turf than on natural grass.[31]

It is at the shoe-surface interface where player-surface interaction can be most dramatically affected. But there is a trade off. Any increase in fixation increases the risk of injury. Unlike a natural surface where fixation on a given field is predominately dictated by the footwear, on an artificial surface it is possible to influence both sides of the fixation interaction, the shoe and the surface.

Hanley[50] recognized that increasing foot fixation resulted in forces on the leg that were capable of inducing injury. Torg et al.[50] were able to show that modification of the cleat size, shape, and action could influence the number of lower extremity injuries on grass fields. Surveying local high schools, they learned that players who wore ⅜ inch soccer-style cleats had significantly reduced incidence and severity of knee injuries when compared to players who wore conventional ¾ inch seven-cleated football shoes.

In an attempt to quantify the shoe-surface relationship, Torg et al. developed a test device in which a prosthetic foot was mounted on a stainless-steel shaft. A torque wrench was used to apply a rotational force to the prosthetic foot. A variable axial load was applied to the shaft in such a way that the load was shared equally by the prosthetic heel and forefoot. The rotational force (F) needed for rotating the shoe through a known arc was measured for a particular load (w). Using the relationship $r = F/w$, a release coefficient (r) was measured for a variety of shoe types and surfaces. The high release coefficient recorded for seven-cleated football shoes correlated well with previous field tests. No difference in release coefficient was noted for soccer-style cleats (⅜ × ½ inch) whether evaluated on grass or on AstroTurf. The release coefficient of conventional football cleats (¾ inch) were significantly lower on artificial surfaces than on grass, but they were not as low as soccer cleats on artificial surfaces.

The grip index is an alternative method of quantifying the fixation of a shoe to a surface. Using a drag-test apparatus, the force required to initiate the forward translation of a weighted shoe was determined (grip index = force/load).[18] With this system, Milner (personal communication, 1989) demonstrated that the seven-cleated football shoe with ¾ inch cleats, when tested on grass, had the highest grip index of any of the shoe-surface combinations tested. However, when tested on artificial surfaces, the seven-cleated shoe had the same traction characteristics of a conventional leather shoe. Use of multicleated soccer shoes on artificial surfaces had values that were 50% higher than the seven-cleated shoe.

Drag tests conducted by Stanitski et al.[46] evaluated the amount of friction resistance to sliding at the shoe-surface interface. Four surfaces and four shoes with architecturally different soles were tested. Tests indicated that both the sole architecture and the playing surface influenced the coefficient of sliding friction. Of the four surfaces tested (Polyturf, AstroTurf, Tartan Turf, and natural grass), Polyturf required the greatest force for the initiation of motion at the shoe-surface interface. AstroTurf required less force, and grass the least. Tartan Turf yielded characteristics close to that of grass. None of the four surfaces tested demonstrated any grain effects, that is, drag-test results were independent of the direction the test was conducted.

Bonstingl et al.[19] evaluated torques developed at the shoe-surface interface. Their test apparatus used a weighted pendulum to apply an instantaneous torque to a simulated leg. An artificial foot at the end of the leg rotated on a sample playing surface as a result of the impact. Strain gauges measured the "effective" torque at the shoe-surface interface. The static load on the leg, the energy of impact, and the foot stance were variables. Shoes, outsole designs, and playing surfaces were evaluated. In general, a full-foot stance position developed 70% more torque than toe stance. As the load increased on the simulated leg, torques increased. Again, the seven-cleated, conventional football shoe was found to develop significantly more torque than any other shoe-surface combination tested. Multicleated turf shoes were found to develop high torques in the toe-stance position on the artificial surfaces tested. They concluded that the total effective cleat surface area was related to the "effective" torque developed.

Andreasson et al.[2] recorded the torque that developed between a variety of shoes and Poligrass. They constructed a test apparatus that simultaneously measured the frictional forces and torque at the shoe-surface interface, at varying speeds, at an applied load of 241 N, and with varying shoe positions. They found that the distribution of material at the heel and toe, as well as the material itself, influenced the torque developed by the shoe-surface interaction. They postulated that architectural arrangements that balance the frictional forces experienced by the toe and the heel of a shoe will result in a balanced shoe that will not twist when it slides. This is feasible on a surface like artificial turf that is defined and consistent.

Valiant (unpublished data, 1987) evaluated the minimum needs of a soccer shoe outsole. Ground reaction forces and moments were measured during straight line running, lateral movements, and pivoting. He determined that the greatest shear forces were developed in the anterior direction while stopping. Physical traction tests measured a coefficient of kinetic friction for the shoe on AstroTurf to be 1.6. Force trials produced values significantly lower than this. Similarly, rotational traction characteristics of the shoe exceeded the torques developed voluntarily during pivoting movements. He concluded that the reduction of rotational frictional characteristics of the shoe would likely reduce the risk to the athlete.

ECONOMICS

Contributing to the construction costs of an artificial turf field are the cost of the purchase or renovation of the field site, the asphalt base, the wear surface, the drainage system, and the initial purchase of the maintenance system.[45] Quite

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variable is the cost of the labor force required to accomplish the job. Climatic conditions will influence initial design considerations and ultimately the cost of the structure.[1, 18, 39, 41] A tropical, snowy, or rainy climate make necessary certain adjustments in recommended construction. A northern winter may require an underground heating system to assist with snow melting. If large amounts of rainfall are expected, a drainage system must be included in the plan.

The operating costs of a field vary greatly. Sweeping is required and spot cleaning may be necessary. Some manufacturers recommend flooding the field once a year to help remove the accumulation of dirt.

A valuable method for comparing the cost of a field to a community is a cost per use equation[21]: field used × hours used = cost per use. An expanded form of the cost per use equation includes the number of participants, resulting in a cost per participant hour statistic.[29, 33–35] Because of an artificial field's ability to tolerate high use, the cost per participant hour often falls far below that of a similar natural grass field. This difference is less apparent with fields having low demands like those in professional stadia.

INJURY—NEW MALADIES

After the initial installations of artificial surface fields, concern arose over the effect of those fields on the athletes that played on them. Early investigations suggested that artificial surfaces were not only influencing the rates of injuries commonly seen, but were actually responsible for an entirely new set of injury patterns.

A 1978 review of the Pacific 8 football conference by Larson and Osternig[32] indicated that bursitis of the prepatellar and olecranon bursae were far more common on artificial surfaces. Prevention and reduction of severity was readily accomplished by application of pads to the joints at risk. As play on artificial surfaces became more commonplace, players and trainers learned to accommodate to the surface by adjusting their technique and changing their dress.

Turf toe remains a problem. It is likely that soft tissue injuries of the great toe are directly related to play on artificial turf. In 1976 Bowers and Martin[20] termed sprains of the plantar capsule ligament complex of the metatarsophalangeal (MTP) joint of the great toe as "turf toe." They suggested that the mechanism of injury was hyperextension of the MTP joint producing the sprain. They attributed the injury to the hardness of the playing field and the flexibility of playing shoes.

Doller[24, 25] defined turf toe as an acute traumatic bursitis of the first MTP joint associated with a tendinitis of the extensor and flexor hallicus longus. He attributed this to adjustments made by the great toe while running on artificial fields. Shoe wear and hard surfaces were again considered contributory to the problem. Coker et al.[22] indicated that even though the occurrence of ankle sprains was more common than toe injury, the latter injury was far more disabling. They determined by questionnaire and experience that both the shoe and surface were responsible for the injury. A review by Rodeo et al.[44] suggests that inappropriate fit may contribute to the malady as well as the very flexible forefoot region of multicleated turf shoes. The flexibility fails to protect the first MTP joint from hyperextension, allowing for overload and disruption of the capsuloligamentous complex.

SUMMARY

As artificial grass fields become more commonplace it is important that we fully understand the structural characteristics of these playing surfaces. Insight into the properties of a field will enable the engineer, athlete, and physician to create a design that optimizes both performance and safety. It was the goal of this section of our paper to describe the structure and the nature of that structure that forms an artificial grass field. From this review it seems likely that manipulations of field characteristics are not only possible, but essential, if player safety is to be maximized. In Part II of our paper we will review the ramifications of these characteristics on the player.

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APPENDIX 1

AstroTurf: ½ inch nylon ribbon pile of 500 denier on a polyester nylon mat which is double bonded to a ⅝ inch closed-cell nitrile rubber and polyvinyl chloride pad on an asphalt base. First-generation surface.[18]

Tartan Turf: ½ inch cut nylon pile surface of 40 to 60 denier on a knitted polyester backing, double bonded to an open cell ⅝ inch polyurethane pad over an asphalt base. First-generation surface.[46]

Polyturf: A first-generation artificial grass. A 3⁄16 inch polypropylene pile of 450 denier fibers matted on a polypropylene mat and single bonded to a ½ inch closed-cell nitrile rubber and polyvinyl chloride pad over an asphalt base.[46]

Omniturf: A second-generation surface. Of 1 inch, 10,000 denier polypropylene tufted fibers with a woven polypropylene backing, coated with durable polyurethane, infilled with a round angular-shaped silica sand over a 1 inch porous rubber and urethane underpad.[39]

Poligras: Polypropylene grass tapes, knitted together with high-strength polyester fibers and additional polyvinyl chloride (PVC) nap fixation and a welded-on profiled PVC resilient drain mat reinforced by an additional knitted inlay fabric.[41]

Sporturf: Tufted 7600 denier polypropylene fabric fibers attached to a single or double-layer primary backing. The shock pads are primarily cross-linked closed-cell, polyethylene foam.[1]

APPENDIX 2

ASTM publishes standard test methods for evaluation of components of products. The following is a list of the test methods applicable to artificial and grass surfaces.

1. D3575—Flexible cellular materials made from olefin polymers.[11] This test procedure allows for quality control of compression set, compression deflection, water absorption, energy absorption, thermal stability, tensile strength and elongation, density, buoyancy, constant compression creep, and dynamic cushioning.
2. F355—Shock-absorbing properties of playing surface systems and materials.[7] This test procedure allows for "measurement of certain shock-absorbing characteristics, the impact-force time relationships, and rebound properties."
3. D789—Determination of relative viscosity, melting point, and moisture content of polyamide.[6] This test procedure allows for "the determination of relative viscosity, melting point, and moisture content as they apply to polyamide."
4. D2859—Flammability of finished textile floor.[15] This test procedure allows for "the determination of the flammability of finished textile floor covering materials when exposed to an ignition source."
5. D395—Rubber property: compression set.[10] This test procedure allows for the evaluation of rubber when it "will be subjected to compressive stresses in air or liquid media."
6. D412—Rubber properties in tension.[4] This test procedure allows for testing the tension of rubber at various temperatures.
7. D418—Pile yarn floor covering construction.[12] This test procedure allows for quality control of component masses per unit area, number of binding sites per unit length, pile thickness (level and multilevel), pile yarn length, pile yarn mass, total mass, tuft length, and tuft height.
8. D1335—Tuft bind of pile floor coverings.[17] This pro-

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cedure allows for the "determination of the force required to pull a tuft completely out of a cut pile floor covering or to pull one or both legs of a loop free from the backing of looped pile floor covering."

9. D1667—Flexible cellular materials: vinyl chloride polymers and copolymers (closed-cell foam).[5] This test procedure allows for compression deflection, volume change on heat aging, water absorption, low-temperature changes in compressibility, and density.

10. D1682—Breaking load and elongation of textile fabrics.[16] This test procedure "determines the breaking load and elongation of textile fabrics."

11. D3676—Rubber cellular cushion used for carpet or rug underlay.[14] This specification provides requirements for "specific properties of compression set, compression resistance, delamination strength, and accelerated aging."

12. D2256—Tensile properties of yarn by the single-strand method.[3] This test procedure allows for the determination of tensile properties of yarn in various environments.

13. F1015—Relative abrasiveness of synthetic turf playing surface.[8] This test procedure allows for the "measurement of the relative abrasiveness of synthetic turf playing surfaces."

14. D3884—Abrasion resistance of textile fabrics.[13] This test procedure allows for "the determination of the abrasion resistance of textile fabrics."

15. D2240—Rubber property: durometer hardness.[9] This test procedure allows for "determining the indentation hardness of homogenous materials."

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