Evan’s PhD thesis proposal

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# 1 Overview

Baseball fields are built from soil. Therefore, soil behavior determines the safety and function of the field. The purpose of this dissertation is to assess and improve the behavior of soil mixtures used on baseball infields.

The production of soil mixtures has received much study. However, there are no published experiments on this topic as it pertains to baseball and softball fields.

This thesis proposal is organized into four sections:

[**Purpose and objectives**](#purpose-objectives): A broad description of the scope and aims of the project

[**Definition of terms**](#definition-of-terms): Explicit meanings of verbiage used this document (these may vary across scientific fields)

[**Review of literature**](#lit-review): A summary of scientific research pertaining to baseball/softball fields, laboratory soil testing methods, and the behavior of artificial soil mixtures

[**Proposed experiments**](#proposed-experiments): The planned course of laboratory research, organized as anticipated publication units

# 2 Purpose and Objectives

## 2.1 Purpose

The motive for initiating this research is simple: baseball has an important influence on our American culture and economy, yet science has paid little attention to the surface on which it is played. The safety, enjoyment, and economic value of baseball fields can be improved applying the scientific method to this topic

## 2.2 Objectives

The objectives of my thesis are twofold: (1) create a new way to assess infield soil performance, and (2) use the new framework to design improved soil mixtures.

**My intent is to answer these open-ended questions:**

1. How can infield soil performance be objectively quantified?
2. How can the performance of infield soils be improved? 3 Can a rational basis for mix design be developed to reflect soil behavior?
3. Which lab tests best to predict the performance of a mix?

**The anticipated outcomes from this research are:**

1. New laboratory methods for measuring the behavior of baseball and softball infield soils
2. A quantitative framework for designing new infield mixes and amending existing infields
3. Refereed journal publications, trade magazine articles, and technical presentations
4. Software which can be used beyond this project’s scope and lifespan

# 3 Definition of terms

**clay**: a soil material which can be reshaped or molded when moist and which retains develops high strength when dry

**clay-size**: an individual mineral grain which settles in through a column of fluid at the same rate as a spherical particle having 2 μm diameter

**sand**: a soil material which is predominantly composed of mineral particles having sieve diameters between 53 and 2000 μm

**packing fraction**: the volume fraction occupied by solids, normalized to the total soil volume (1-void fraction);

# 4 Review of literature

This literature review is organized into three sections to address the following topics:

**4.1** [**Function and performance of baseball/softball infields**](#infield-performance)

**4.2** [**Laboratory test methods pertinent to the problems of interest**](#lab-methods-review)

**4.3** [**Design and properties of artificial soil mixtures**](#artificial-soil-mixtures)

## 4.1 Function and performance of baseball infields

In baseball and softball, athletes engage with the playing surface in two ways: directly (by running, pivoting, and sliding) and indirectly (by fielding batted balls).

Existing research on this topic is relatively scant. This section describes the few published research studies and outlines the general goals of a baseball grounds manager.

### 4.1.1 Qualitative description of the importance of the infield

Portions of a baseball field are termed **skin** if they comprise bare soil rather than natural grass or synthetic turf. The pitcher’s mound and the area immediately surrounding home plate are considered distinct; these are constructed and maintained somewhat differently from the infield skin. However, this thesis will not treat the mound or home plate areas in detail, so in this document the terms “skin” and “infield skin” are used interchangeably.

A full-size baseball field occupies ~ 1 ha. Roughly 75% of this total area is surfaced with natural turfgrass or synthetic turf. An additional ~ 15% is occupied by the warning track, which is alerts players that they are nearing the wall by its changing feel underfoot. Only about 10% of the total playing surface is occupied by the infield skin.

To motivate the significance of the infield skin, consider Figures 4.1-4.3.[[1]](#footnote-25) All the offensive players, the four infielders, and the pitcher and catcher are standing on skinned areas. A large majority of important plays occur here, so the funds and effort devoted to maintaining this area are disproportionately large.

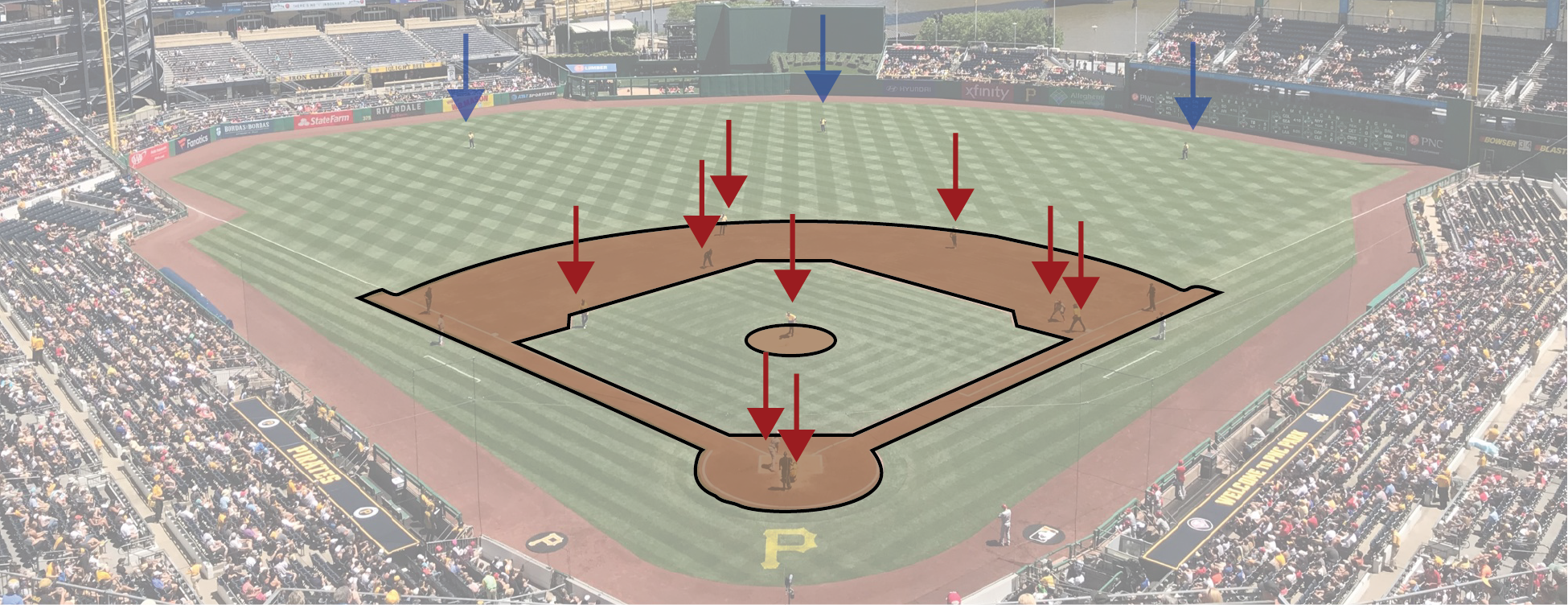


Figure 4.1: Locations of players during a professional baseball game. Note the paucity of players on turf (blue arrows) compared to bare soil/skin areas (red arrows).

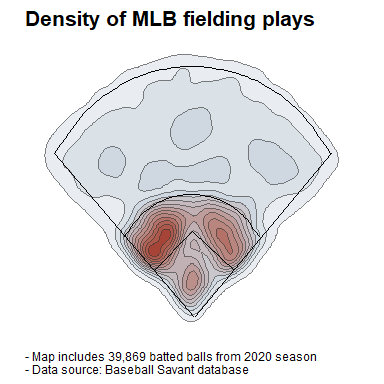


Figure 4.2: Data from actual MLB contests support the intuition that most play occurs on the infield skin.

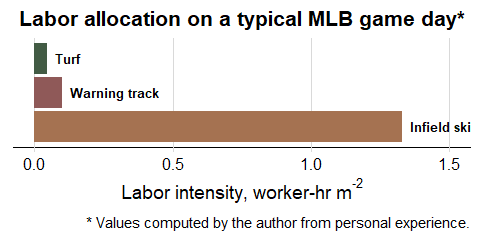


Figure 4.3: The infield skin consumes a majority of inputs despite comprising less than 10 percent of the playing surface area.

At the professional level, great efforts are made to sustain the infield in a playable condition. If a game is cancelled due to field conditions, the host franchise stands to lose several hundred thousand dollars. Therefore, every attempt is made to keep the field in a playable condition and complete the game. At the youth level, most revenue is also driven by concessions and repeated cancellations of tournaments or games may undermine the sustinability of the organization’s finances. Many facilities generate a large portion of annual revenue over only a handful of concentrated events (for example, a 3-day tournament).

The median MLB player salary in 2019 was x , with x players earning over $20 million. In a very real sense, elite athletes bodies are the most valued asset of an MLB franchise. Every effort must be made to ensure that player injuries are prevented so a team’s investment is not squandered due to lost playing time. A safe infield surface is a must.

Toughness is an important property of an infield soil. When the soil offers adequate resistance to foot traffic, play may continue during rain. Once the resistance is lowered enough to make footing unsafe, the game is halted, and the grounds crew covers the field with an impermeable tarp to prevent further saturation. Rain delays and postponements lead to lost revenue and create schedule conflicts at both the professional and recreational levels. Moreover, deployment of the tarp during rainfall is dangerous and physically difficult. Even when weather conditions are favorable, high toughness allows the groundskeeper a wider range of water contents to provide excellent playability. This minimizes mistakes when hand-watering the infield.

The groundskeeper is unable to add water to the infield once the game has begun. In hot and dry weather., the soil dries and becomes excessively hard as the game progresses, affecting ball response and also inducing brittle bulking from cleat (Ch. \_\_). Therefore soil toughness also allows the soil to retain its plastic behavior as soil moisture is reduced.

The main surface properties of interest to the athlete (and therefore to the grounds manager) are footing and ball response. Each can be further subdivided.

#### 4.1.1.1 Footing

##### 4.1.1.1.1 Traction

Traction allows the athlete to run, change directions, and perform other maneuvers without slipping, sliding, or otherwise losing control. Traction is distinct from planar friction because of the presence of studs or other gripping aids on the players’ footwear ([McNitt et al., 1997](#ref-McNitt1997a)). Even when using machine tests (rather than human subjects), measuring traction is complicated by nonlinear interactions between surface type, shoe type, and loading weights ([Nigg, 1990](#ref-Nigg1990)). Excessive rotational traction is associated with lower extremity injuries, but traction differences among shoe types are often larger than those across surface types ([Serensits and McNitt, 2014](#ref-Serensits2014)). Clear-cut thresholds separating acceptable and unaccpetable traction have not been established.

Most athletic field research has focused on natural grass and synthetic turf. There are two published accounts of traction measurements on infield skin surfaces.

[Goodall et al.](#ref-Goodall2005) ([2005](#ref-Goodall2005)) measured traction on plots constructed from 5 different soils blended with 4 rates of calcined clay. Higher traction levels were reported for silty and loamy soils than for sandier soils. Mixing the soil with calcined clay prior to plot construction had no effect on traction. No relationship was found between traction and water content, although only 3 water contents were tested.

[Brosnan et al.](#ref-Brosnan2011) ([2011](#ref-Brosnan2011)) measured traction on research plots of the same infield soil subjected to various treatments. Traction was increased by soil compaction and decreased by surficial additions of calcined clay.

##### 4.1.1.1.2 The brittle-ductile transition and the “corkboard effect”

Minimal surface disruption is a crucial element of infield quality. A smooth playing surface ensures the game’s outcome is decided by the players’ performance alone and not influenced by chance events such as an errant ball bounce.

Grounds managers consider ideal infield performance as follows: an athlete’s studded footwear readily penetrates the soil at footstrike. The soil provides adequate resistance as the athlete completes his or her maneuver. The cleats release from the surface without separating any soil solids from the zone surrounding them. No material adheres to the studs or sole of the shoe. Thus, surface deformation is limited to a small indentation matching the shape of the stud. This phenomenon is known as “cleat-in, cleat-out” or "the corkboard effect[[2]](#footnote-30).“ In contrast, a poor-quality infield is one on which larger clods of soil are readily chipped out of the surface or easily fragmented into powder.

Figure 4.4 depicts the importance of the corkboard phenomenon. Small, narrow cleat indentations are unlikely to deflect a ball from its initial path, while larger depressions excavated by player’s cleats (or the soil clods themselves) are impediments which tend to produce an errant bounce.

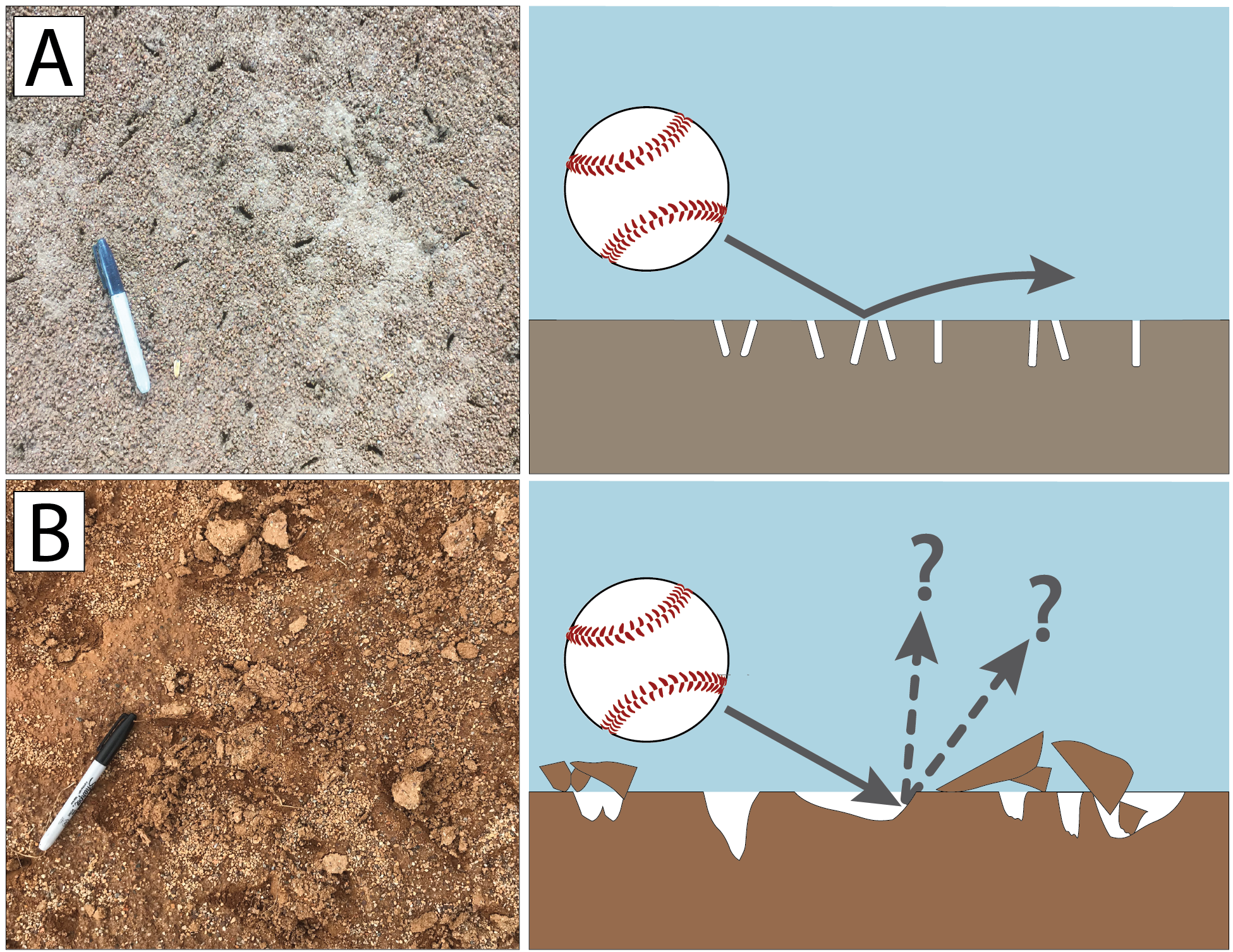


Figure 4.4: (A) The “cleat-in, cleat-out” effect ensures predictable ball response. (B) Cleat indentations and soil clods inhibit a smooth and predictable ball path.

A given infield soil moves between these states as its water content changes. This change in state is formally termed the brittle-ductile transition. The brittle-ductile transition is examined further in the 4.2 section, but a brief description is provided below to establish its important link to infield performance.

A skilled grounds crew takes great care to maintain the soil at the desired moisture. Water is manually added with hoses, and rain is kept off using a large tarpaulin. Soil water content can only be controlled during field preparation; after the game begins, no further adjustments can be made and weather conditions determine the rate of water loss or gain.

Grounds managers have observed that some soils undergo the brittle-ductile transition rapidly, while other soils can withstand a longer drying period before the behavior change occurs. Therefore, it seems plausible that infield soils could be designed to maximize the range of water content over which the corkboard phenomenon will persist.

Some amount of yield must occur for a player’s cleats to penetrate the soil surface. The mode of yield depends on the water content and the packing arrangement of the soil particles. Yield may be one of two types:

1. brittle yield: microcracks propagate through the soil skeleton, eventually coalescing to fracture the soil mass into discrete fragments. These clods adjust their positions to accommodate the cleats and are usually ejected from the depression as the shoe releases. Crumbling or cracking of soil is controlled by the distribution of imperfections or “weakest links” in the soil matrix ([Dexter, 2004](#ref-Dexter2004)). In general, brittle deformation attenuates less energy than ductile deformation ([Kuipers, 1984](#ref-Kuipers1984)).

or

1. ductile yield: soil particles are re-arranged to accommodate the cleat, but the soil mass behaves as a continuum. The remolded zone around the indentation is likely to be small and more uniform with space ([Deepa et al., 2013](#ref-Deepa2013)). Ductile behavior is usually associated with higher mechanical strain and more generation of heat ([Perez, 2017](#ref-Perez2017)). The terms ductile and plastic[[3]](#footnote-32) are used synonymously.

A second important consequence of a ductile yield mode is that if a batted baseball *does* contact a cleat indentation, the surface will deform a second time. Changes to the ball’s trajectory will be minimal. This scenario is preferred to a more rigid collision in which the ball is re-directed, possibly leading to a misplay or injury (Figure 4.4).

It is emphasized that no scientific investigations of the corkboard effect have been performed. It is a solely qualitative description of soil behavior, and at present no metrics exist for its study.

### 4.1.2 Ball response

The reaction of a baseball upon contact with the surface plays a key role in the outcome of competition (recall Figures 4.3-4.2). As for footing, limited research is available on infield ball response.

[Goodall et al.](#ref-Goodall2005) ([2005](#ref-Goodall2005)) is the only published account of controlled research on multiple infield soils. The authors installed 5 soils which were commercially available within the northeastern United States. Static and dynamic ball friction were measured along with traction and other soil properties. The authors found that increases in water content raised the coefficients of static and dynamic friction between the ball and the soil surface. The increase was likely due to greater ball penetration, increasing the contact area between the ball and the surface and also prolonging their interaction. [Goodall et al.](#ref-Goodall2005) ([2005](#ref-Goodall2005)) suggested that surface pace may be more related to friction than to hardness. This agrees with intuition because the main component of a ground ball’s velocity is horizontal (nearly coplanar with the surface), favoring the importance of horizontal friction rather than vertical rebound. Incorporation of calcined clay (particle size 0.5 - 2 mm) also decreased friction, especially for finer-textured soils.

Brosnan et al. studied the effects of construction and maintenance activities on infield surface pace ([2011](#ref-Brosnan2011)). Higher bulk density (ρbulk) increased surface pace, although the range of bulk densities tested (1.2-1.8 Mg m-3) was beneath values typically encountered on infield skins (author’s personal observation; data not shown). Water content was negatively correlated with surface pace, but no attempt was made to intentionally alter water content among plots. This study was performed on a single soil material.

The effect of ball spin may be large or small depending on the playing surface properties. If the ball-surface friction coefficient is high, the ball will roll through impact and its release angle will be altered (Figure 4.5). The new spin rate will be determined by the incoming velocity and the friction coefficient. Sidespin imparted by the bowler will readily grip the surface and alter its horizontal path ([Daish, 1972](#ref-Daish1972)). Alternatively, when friction is low, the ball will skid through impact and retain some of its original spin.

![Figure 4.5: Initial spin will influence a ball’s release angle following impact. Adapted from Daish, 1972.](data:application/pdf;base64,)

Figure 4.5: Initial spin will influence a ball’s release angle following impact. Adapted from Daish, 1972.

When soil stiffness is low, the ball produces a notable deformation of the pitch. This prolongs the duration of the impact and gives friction more time to operate. As the ball releases, it rolls up the saucer-like depression created by the impact. This yields a slightly steeper release angle relative to that of a more rigid soil surface (Figure 4.6).

![Figure 4.6: A. A rigid soil surface produces a lower release angle, provided no imperfections are present in the surface. B. A surface with lower stiffness encourages the ball to roll out of the shallow depression created by impact, leading to a slightly steeper release angle.](data:application/pdf;base64,)

Figure 4.6: A. A rigid soil surface produces a lower release angle, provided no imperfections are present in the surface. B. A surface with lower stiffness encourages the ball to roll out of the shallow depression created by impact, leading to a slightly steeper release angle.

Infield soil bear some similarity to cricket pitches and these have been researched more extensively. Ball response is influenced by soil bulk density, clay content, water content, organic matter, and particle size distribution ([Baker, 2006](#ref-Baker2006)).

A laboratory study on surface friction of cricket soils was made by [Adams and Young](#ref-Adams2001a) ([2001](#ref-Adams2001a)). This experiment mixed the same clayey soil with 6 types of coarse amendments. All final mixes had sand contents between 30 and 40% by mass. Ball-to-surface friction was highest for the mix containing sand between 125-60 μm. Lower friction was measured for soils with coarser or finer amendments. Using a suede-type leather increased friction relative to polished leather, implying that the degree of wear on the ball may influence surface pace.

### 4.1.3 Summary of the infield skin’s value

The infield skin is a crucial component of baseball’s competitive and business operations. A professional grounds crew expends significant effort to maintain the soil water content within this relatively narrow range. An ideal infield surface exhibits a combination of plasticity and stiffness. The soil must readily deform around the cleats so that they are not rejected, but it must also provide enough resistance to prevent the athlete from sliding.

### 4.1.4 Use of artificial soil mixtures on baseball infields

Baseball was first played in the early 19th century, but the definitive origins of the game are likely lost to history ([Walker et al., 1994](#ref-Walker1994)). The earliest recorded attempt to alter the physical properties of an infield soil was by Harry Wright in 1875. Wright and his contemporaries incorporated various materials into their infield soils to enhance stability, firmness, or drainage of the playing surface. Amendments included organic debris (straw, ashes) and and inorganic materials (sand, lime, cinders) ([Morris, 2007](#ref-Morris2007)).

Infield soil mixes were produced off-site and imported beginning in the 1960s ?Zwasksa?.

Popularity of engineered infield mixes has grown markedly since 2005 and today the majority of professional stadia utilize an engineered soil for their infield skin.

## 4.2 Laboratory tests of soil behavior and physical properties

The goal of laboratory soil testing is to assess or predict the properties of the soil in the field. Many laboratory soil tests are time-consuming and costly. Results from simpler tests are commonly used as surrogate markers for the information yielded by more intensive tests. The methodology underlying these “surrogate” tests has been studied extensively because much is riding on the tests’ precision and accuracy. This section summarizes literature on the laboratory test methods pertinent to infield soils.

### 4.2.1 Atterberg limit tests

#### 4.2.1.1 Origins of Atterberg test methods

The earliest test methods for soil plasticity were developed by Atterberg ([1911](#ref-Atterberg1911); [1974](#ref-Atterberg1974)). Plasticity is the tendency of a material to deform under an applied load, without fracturing into multiple pieces, and to retain its new shape when the load is removed ([Andrade et al., 2011](#ref-Andrade2011)). Atterberg noted that plasticity is easy to observe but does not lend itself to simple measurement. He showed that soil was plastic only within a finite range of water content which differed for every soil. The upper boundary was defined as the flow limit, at which two batches of soil paste flowed together when jarred. The lower boundary was defined as the rolling limit, when the soil had dried enough so it became brittle and could no longer be rolled into thin threads. He termed the difference between the lower limit of viscous flow and the rolling limit the “plasticity number.” Today these are known as the liquid limit, plastic limit, and plasticity index. He defined 3 additional consistency limits, though none are widely used today.

* Upper limit of viscous flow: soil flows easily, similar to water
* Adhesion limit: soil no longer adheres to a metal implement
* Cohesion limit: lumps of soil can be no longer pressed together with one’s fingers

Atterberg concluded that his ‘plasticity number’ was the most reliable means of measuring plasticity but also pointed out that it gave no information about the effort required to deform the soil. He considered the effort needed to remold the soil a separate property, which translates to English as ‘viscosity;’ this property was later called ‘toughness’ by [Casagrande](#ref-Casagrande1932) ([1932](#ref-Casagrande1932)).

Atterberg’s work has never been fully appreciated in his own discipline of soil science, but his test methods were improved and standardized by geotechnical engineers ([Terzaghi, 1926](#ref-Terzaghi1926); [Casagrande, 1932](#ref-Casagrande1932)). [Terzaghi](#ref-Terzaghi1926) ([1926](#ref-Terzaghi1926)) acknowledged the arbitrary nature of the tests but emphasized that their value for preliminary soil investigations. He pointed out the importance of the tests lied in quantifying an observable phenomenon:

“Every engineer should develop the habit of expressing the plasticity and grain-size characteristics of soils by numerical values rather than adjectives…..the degree of plasticity should be indicated by the estimated value of the plasticity index and not by the words ‘trace of plasticity’ or ‘highly plastic.’” - [Terzaghi et al.](#ref-Terzaghi1996) ([1996](#ref-Terzaghi1996))

Of Atterberg’s original 5 limits, only (2) and (4) are in use today and they are termed the liquid and plastic limits respectively. The following sections detail the mechanics underlying these tests and their limitations.

#### 4.2.1.2 Methods in current use

Standard test methods typically pair the plastic and liquid limit tests. In the United States the relevant standards are [ASTM International](#ref-ASTMD43182018) ([2018](#ref-ASTMD43182018)) and [AASHTO](#ref-AASHTO2020) ([2020](#ref-AASHTO2020)) while [British Standards Institute](#ref-BS13771990) ([1990](#ref-BS13771990)) is typically cited in Europe. The United States methods use the Casagrande method to determine the liquid limit while the British method uses a fall-cone device; these are briefly described below. The plastic limit tests described in the three standards are essentially identical.

##### 4.2.1.2.1 Liquid limit

The liquid limit test described by [Atterberg](#ref-Atterberg1911) ([1911](#ref-Atterberg1911)) lacked reproducibility because it required the operator to manually agitate the soil. A mechanical test method was first presented by [Casagrande](#ref-Casagrande1932) ([1932](#ref-Casagrande1932)) and the method has undergone little alteration up to the present. The Casagrande apparatus comprises a brass cup fixed to a rotating cam. A groove is cut in the soil paste. The soil paste is agitated by dropping the cup against a hard rubber base until the soil begins to flow and the groove closes over a span of 1.25 cm (1/2 in). Casagrande arbitrarily defined the liquid limit as the water content needed to close the groove after 25 blows. Several trials are made and the water content is plotted against the natural logarithm of blow count. The water content to produce 25 blows is interpolated from this curve.

Several fall-cone methods have been proposed for determining the liquid limit.[[4]](#footnote-43) The fall-cone methods offer several advantages over the Casagrande method and have been widely adopted internationally. Merits of the fall-cone methods include:

1. Less operator dependency ([Sherwood and Ryley, 1970](#ref-Sherwood1970a))
2. Give a more straightforward estimate of the soil’s undrained shear strength ([Haigh, 2016](#ref-Haigh2016))
3. Ability to determine the liquid limit for some low-plasticity soils which cannot be tested with the Casagrande cup ([Sherwood and Ryley, 1970](#ref-Sherwood1970a))

The British Standard is the most widely-used fall-cone method and considers the liquid limit as the water content at which an 80g cone with a single-sided angle of 30° penetrates the sample to a depth of 20 mm ([British Standards Institute, 1990](#ref-BS13771990)). Unfortunately, other nations have developed similar methods with different cone masses and angles and comparing results is challenging. Empirical correlations have been established to convert between the Casagrande LL and the fall-cone LL. For soils with LL under 100, the two methods give good agreement but for higher-LL soils the cone yields lower LL values ([Holtz et al., 2010](#ref-Holtz2010); [O’Kelly et al., 2017](#ref-OKelly2017)).

##### 4.2.1.2.2 Plastic limit

Atterberg’s original plastic limit test remains essentially unchanged. After performing the liquid limit test, a ~5 g sample of soil is gradually dried by gentle blow drying and re-molding. Once the soil can be molded without sticking to the operator’s skin, the soil is rolled into a thread of 3.2 mm diameter, broken apart, and pressed into a new lump. This process is repeated until the soil crumbles when the rolling action is applied. The plastic limit is the water content at which the soil can no longer be rolled out.

[Terzaghi](#ref-Terzaghi1926) ([1926](#ref-Terzaghi1926)) introduced the use of a fixed thread diameter of 1/8" (3.2 mm), although its significance has been recently questioned by [Barnes](#ref-Barnes2013) ([2013a](#ref-Barnes2013)). The stability of the soil thread is related to the maximum particle diameter and the rolling technique. [Barnes](#ref-Barnes2013) ([2013a](#ref-Barnes2013)) argued that emphasis should be shifted away from a specific thread diameter and toward observation of the thread during the test.

### 4.2.2 Nature and magnitude of errors associated with Atterberg limits

Atterberg limit tests can be performed rapidly and require only simple equipment and no consumables. They also correlate reasonably well with other soil properties such as shear strength, compressibility, and permeability. Unfortunately there are multiple sources of error associated with the tests and these are often raised as critiques of the utility of the test results. This section outlines research on the precision and accuracy of the tests.

### 4.2.3 Reproducibility and repeatability

Reproducibility is defined as achieving the same result for the same sample by multiple test operators. Repeatability is achieving the same result through multiple trials of the same sample by the same operator.

[Sherwood](#ref-Sherwood1970) ([1970](#ref-Sherwood1970)) conducted a detailed investigation on the reproducibility and repeatability of laboratory soil tests. Three soils termed B, G, and W were pulverized and riffled repeatedly to ensure their homogeneity. The samples were sent to 41 laboratories which performed several tests on them, including the Atterberg limits. The tests were replicated by multiple operators at the Road Research Laboratory and by a single operator to compare the variation among each means of replication.

Results differed widely across laboratories, but agreement was much better for operators trained in the same lab and better still for repeated tests by the same operator. Figure 4.7 shows that extreme values for the liquid limit differed across labs by as much as 30 units. Plastic limit values varied by up to 19 units (30-40% of their mean values). Figure 4.7 shows that variation across eight individuals employed by the Road Research Laboratory at the time of the study. These technicians were considered highly experienced and the spread of their results was much smaller than that across laboratories. Repeatability was better still for a single operator; all six results are tightly clusered around their mean with maximum deviations of 1.2 units for the liquid limit and 0.9 units for the plastic limit.

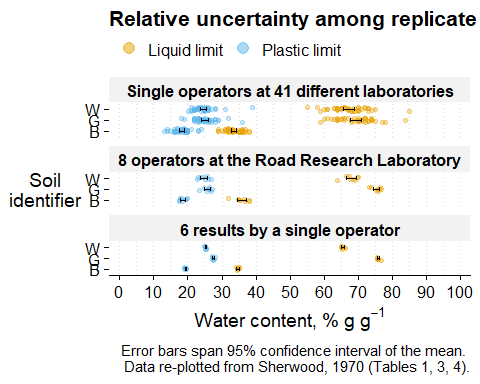


Figure 4.7: Reproducibility is excellent for a single operator, fair among operators in the same lab, and relatively poor across laboratories.

The spread of data points in ?? could be misleading because the number of replicates was much lower for the within-lab and within-operator studies. Therefore it is also useful to compare the coefficients of variation for the three studies. Figure 4.8 shows that the small range of data points for the single lab or single operator is not due only to fewer samples being tested; the coefficients of variation for one operator’s replicates are smaller by a factor of 3 to 10. The coefficient of variation was remarkably consistent across soils: the three materials had COV values of 7.2, 7.5, and 7.9% for the liquid limit and 12.9, 12.8, and 12.8% for the plastic limit. Evidently, the uncertainty associated with a single test result is not a function of soil type.

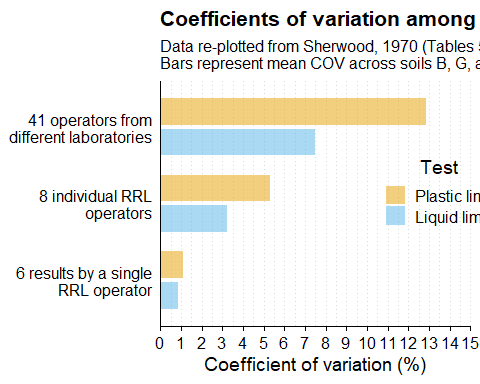


Figure 4.8: Atterberg limit tests are much more repeatable by a single operator than across operators or labs.

The liquid limit involves a mechanical device whereas the plastic limit test introduces a greater degree of operator judgment. One might expect better agreement for the liquid limit and this is clearly borne out in Figures 4.7-4.8.

A separate study by [Sherwood and Ryley](#ref-Sherwood1970a) ([1970](#ref-Sherwood1970a)) showed that the fall-cone method has better inter-operator reproducibility. The coefficient of variation among operators was about half that of the Casagrande method.

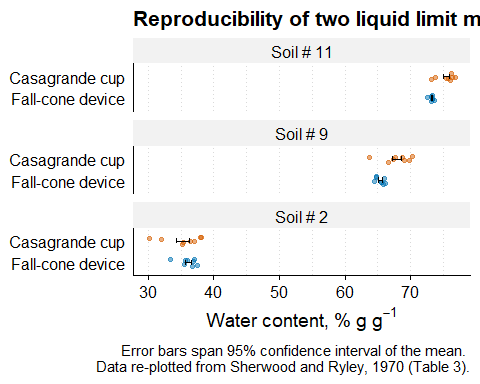


Figure 4.9: The fall-cone method is less variable across operators than the Casagrande cup

Sherwood summarized the results of the round-robin testing with a warning about not only the Atterberg limits, but all the soil physical tests evaluated in his study:

“The results of this investigation….are for the most part rather disturbing, since it is clear that none of them can be used without quite wide tolerances being placed on the values obtained.”

In summary, [Sherwood](#ref-Sherwood1970) ([1970](#ref-Sherwood1970)) showed that most soil physical tests are quite repeatable so long as they are performed by an experienced operator with a well-tuned apparatus and careful workmanship.

#### 4.2.3.1 Sources of error in Atterberg limit methods

4.2.3 described the expected uncertainties associated wtih Atterberg limit results. It is next useful to exploe the sources of these errors so they can be avoided as much as possibke. The tests depend heavily on an accurate determination of the water content. Clean workmanship is essential to avoid flakes of dry soil contaminating the fresh specimen ([Barnes, 2013a](#ref-Barnes2013)). The laboratory balance in use must be of sufficient sensitivity and calibrated frequently. The water content determination may comprise a substantial source of error during the tests, although this uncertainty is often ignored. Figure \_\_\_ shows a distribution of 50 replicate water content determinations from the same specimen near its LL (data collected by the author). Even with thorough mixing and the use of a milligram balance, Figure \_\_\_ indicates one should expect a standard deviation of ~0.2% water content when sampled from an ostensibly homogenous specimen.

Besides measuring the water content, three chief sources of laboratory error for the Atterberg limits include:

1. specimen preparation
2. proper function/calibration of test apparatus
3. operator technique Each is outlined in the following sections.

Note that these do not include sampling practices, which are carried out prior to laboratory testing and normally comprise a larger source of error than any laboratory procedure ([Brady and Weil, 2007](#ref-Brady2007)).

##### 4.2.3.1.1 Specimen preparation

The means by which a soil specimen is mixed and handled can affect the results obtained from physical tests.

[Howell et al.](#ref-Howell1997) ([1997](#ref-Howell1997)) performed compaction tests on sand-bentonite mixtures produced with different preparation methods. They showed that a longer “curing” time after adding water slightly increased the optimum water content for compaction (opt). The effect was small; %delta;wopt was only ~ 0.5% when using granular/pelletized bentonite and not detectable for powedered bentonite. The effect of mixing procedure was more apparent. Mixing water with the sand prior to adding the bentonite increased opt by up to 2% compared with mixing the soil components dry and adding the water last. ρmax was also lower when the water was added before the bentonite. Evidently, the water was more apt to associate with the sand in the latter procedure.

[Armstrong and Petry](#ref-Armstrong1986) ([1986](#ref-Armstrong1986)) tested 13 means of preparing soil specimens for Atterberg limit tests. They reported a 4 % water content increase of in the liquid limit due to oven-drying at either 60 or 110 &degC. This was attributed to difficulty in re-hydrating the clay mineral surfaces and micropores. If the soil was oven-dried, the liquid limit was increased by curing the sample for 24 hours after adding water. A further but marginal LL increase was noted for a 48-hour cure time. The relevant finding is that soil specimens should not be oven-dried prior to testing and should be thoroughly wetted to near their liquid limit before beginning the test. [ASTM International](#ref-ASTMD43182018) ([2018](#ref-ASTMD43182018)) prohibits drying above 60 °C and requires a minimum 16-hour curing time.

[Dumbleton](#ref-Dumbleton1966a) ([1966](#ref-Dumbleton1966a)) tested the effect of mixing duration on Atterberg limits of several soils. The liquid limit continued to increase for up to 3 hours of mixing time. The effect was only observed for specific soils, namely those containing iron-oxide cements. The cements were evidently degraded by the longer agitation time because non-cemented London clay showed no change after more mixing. No information was provided about the actual mixing procedure, though one could assume it was performed by hand with a spatula or similar tool.

##### 4.2.3.1.2 Apparatus-related errors

[Casagrande](#ref-Casagrande1958) ([1958](#ref-Casagrande1958)) expressed regret that his original design did not quantitatively specify the rubber base’s properties. This led to disparities among the devices produced by various manufacturers, and they yielded different liquid limits despite being otherwise identical.

[Sherwood](#ref-Sherwood1970) ([1970](#ref-Sherwood1970)) concluded that so long as a standard test device is used, differences in operator technique comprise a larger source of error than the device itself. However, a recent survey by [Haigh](#ref-Haigh2016) ([2016](#ref-Haigh2016)) confirmed that the hardness and resilience of the rubber base does vary widely across national specifications. Even within a rubber type (hard or soft), the coefficient of variation in rubber hardness was around 20%. Analytical solutions by [Haigh](#ref-Haigh2016) ([2016](#ref-Haigh2016)) predict that a 20% deviation in base stiffness yields a change in the liquid limit of 2-3% of its value (i.e. coefficient of variation). This variability is similar to the standard deviation reported by an ASTM reproducibility study across 14 labs ([ASTM International, 2018](#ref-ASTMD43182018)), suggesting a large amount of inter-laboratory variability could be due simply to variation in the rubber base properties of the devices employed.

Assuming the device meets specification, the most common error sources with the Casagrande apparatus are a worn grooving tool and variability in in drop height caused by a loose locking screw ([Sherwood, 1970](#ref-Sherwood1970)). The drop height must be frequently calibrated to ensure accurate results ([ASTM International, 2018](#ref-ASTMD43182018)).

##### 4.2.3.1.3 Operator technique errors

###### 4.2.3.1.3.1 Liquid limit

The means by which the groove is cut and the rate at which the cam is agitated will affect the flow of the soil. Every effort must be made to maintain the tool in an orthogonal position to the cup surface throughout the action ([Casagrande, 1958](#ref-Casagrande1958)). Cutting a uniform grove can be especially challenging for soils containing sand ([Sherwood and Ryley, 1970](#ref-Sherwood1970a)); the larger sand particles tend to be torn from the groove’s sides, making it wider and more ragged. The cam should be agitated at a constant rate of 2 blows per second ([ASTM International, 2018](#ref-ASTMD43182018)). Inadequate mixing of the specimen can also contribute to erroneous blow counts and water content determinations.

###### 4.2.3.1.3.2 Plastic limit

Sources of error include the operator technique, operator judgement, and weighing errors in the water content determination.

#### 4.2.3.2 Attempts to improve plastic limit test

Most attempts to improve the plastic limit test have focused on mechanizing the thread-rolling procedure in hopes of improving its reproducibility across operators. Test operators utilize different combinations of force, speed, and displacement when rolling the soil. Collectively these variables were termed ‘rolling path’ by ([Barnes, 2013a](#ref-Barnes2013)). [Bobrowski and Griekspoor](#ref-Bobrowski1992) ([1992](#ref-Bobrowski1992)) described a simple apparatus to aid the operator in producing a thread of precisely 3.2 mm. The device consists of a flat plexiglass plate which is used to roll the thread, rather than the operator’s hand. (Bobrowski and Griekspoor, 1992) also state that paper should be affixed to the base of the device to prevent the thread from sliding and to expedite the drying process. Use of this device is allowed, but not mandated, in the current version of ASTM D4318. This device has been criticized by (Barnes, 2013), who cited the data of (Rashid et al., 2008) to assert the rolling device produces excessively rapid drying and eliminates the soil thread from the view of the operator.

A fully mechanized thread rolling apparatus was developed by (Temyingyong et al., 2002). Their device used two acrylic plates similar to (Bobrowski and Griekspoor, 1992) and added a DC motor to apply the rolling action. The DC voltage was adjusted to control the rolling speed, and the downward force was altered by the addition of weights to the upper plate. They found that the initial diameter of the soil mass explained a larger amount of variation in the test result than did factors which might be ascribed to the subjective manual method (speed and pressure). The device still appears to be a significant improvement over the hand-rolling method; unfortunately, the device is not commercially available and its use has not been adopted by governing bodies. Barnes (2009) introduced a novel thread-rolling apparatus which allows precise control of the load applied to the soil thread. The device comprises two stainless steel plates: a fixed base and an upper loading plate which is manually oscillated. The load is adjusted by sliding a weight ballast along the side of the device opposite the handle. The further the ballast weight is from a pivot point, the lesser the load on the soil thread. The device is still operated by hand and a constant rate of rolling must be maintained through careful operation. A thin smear of petrolatum is used on the stainless steel plates to encourage extrusion of the soil thread. A number of other useful properties have been developed with this device, as described in the section of this review on soil toughness. Moreno-Marato and Alonso-Azcàrate described a plastic limit test in a soil thread is bent rather than rolled. The soil is wetted to a moldable consistency and flattened to ~3 mm. A special slicing tool is used to create a rectangular prism of soil having precise dimensions of 3 mm x 3mm x 50 mm. The specimen is then rounded into a cylindrical thread using the same tool. The thread is carefully bent about its center, which is anchored around a stainless steel cylinder. When the thread begins to crack, a caliper is used to measure the distance between the two ends of the thread. The test is repeated for at least two other water contents and the water content of the threads is plotted against the displacement with segmented regression. The shallower segment is extrapolated to zero displacement and this water content is taken as the plastic limit.

Moreno-Marato and Alonso-Azcàrate also described a faster version of their original thread-bending test. In this version only a single thread is prepared and its displacement and water content are extrapolated to zero displacement using an empirical equation. This test meets the original requirements of any plastic limit test which could replace the current method, namely:

1. Rapid
2. repeatable
3. Operator-independent

Many soil tests have been developed with the goal of supplanting the Atterberg limits. However, in the author’s view, these tests are unlikely to be abandoned because of the abundance of data which has accumulated from their use and the speed with which they can be performed.

### 4.2.4 Toughness tests

Toughness is a conspicuous feature of clay soils. This section describes the nature of toughness and attempts to measure it for soils.

In mechanics, toughness is the total effort or work required to deform a specimen to its failure condition. It is mathematically defined as the area beneath a stress-strain curve up to failure. This integral is traditionally computed over the entire material test, but the strain range may be arbitrarily defined for a specific problem (e.g. [Barnes](#ref-Barnes2013) ([2013a](#ref-Barnes2013)); [Barnes](#ref-Barnes2013b) ([2013b](#ref-Barnes2013b))). Toughness is a measure of work and bears units of energy per unit volume () ([Mamlouk and Zaniewski., 2006](#ref-Mamlouk2006)).

A large peak strength does not necessarily imply a material is tough. A brittle material may have a high strength, but because it fails at low strain the toughness is relatively low. Conversely, a ductile material which deforms to very high strain levels may be quite tough despite its low ultimate strength ([Mamlouk and Zaniewski., 2006](#ref-Mamlouk2006)).

Many fine-textured soils exhibit ductile behavior, but their strength in this state varies widely. This observation is known by those who work intimately with clay in trades such as pottery production or earthworks. Atterberg himself noted that his ‘plasticity number’ did not provide information on the toughness of the soil (Section 4.2.1.1), and Casagrande noted ([1932](#ref-Casagrande1932)):

“There is a wide variation in the shearing resistance of different soils at the plastic limit. This difference may be felt by hand when performing the plastic limit test on various soils….the toughness of a clay at its plastic limit may therefore be described as the maximum stiffness or shearing resistance which it can acquire without losing its plasticity.”

The plastic limit therefore reflects only the water content at which a drying soil becomes brittle, and on its own should not be considered a measure of soil strength or toughness. This distinction has been blurred in academic literature, where the plastic limit is sometimes reported as the water content corresponding to a particular value of cone penetration (e.g. [Whyte](#ref-Whyte1982) ([1982](#ref-Whyte1982))). In reality, reported values of peak strength at the plastic limit differ by up to 2 orders of magnitude ([Haigh et al., 2013](#ref-Haigh2013)).

The literature on shear strength and compressive strength is rich, but these studies focus on the peak load at failure and give little mention to energy dissipation up to failure. In most engineering applications little to no strain is desired. A baseball field differs because a small amount of deformation to the soil is desirable (Section @ref(#corkboard-section)).

Few attempts have been made to measure soil toughness directly. G. Barnes published a series of papers descibing an apparatus which replicates the plastic limit hand-rolling procedure ([2009](#ref-Barnes2009), [2013a](#ref-Barnes2013); [2013b](#ref-Barnes2013b), [2018](#ref-Barnes2018)). This work comprises the only published research which directly measured the toughness of clay soils.

Major findings by Barnes included:

It must be acknowledged that while the Barnes apparatus marks a significant advance, it represents but one means of measuring soil toughness. Clays exhibit toughness during many types of strain, not only the harmonic thread-rolling typical of the plastic limit test which the Barnes device seeks to emulate. Similarly, the plastic liimit does not represent the true limit of ductile behavior; it merely establishes an arbitratry if useful threshold for a single type of deformation. Soil can exhibit ductile strain even when its water content lies below the plastic limit. This is readily observed when classifying soils with the USDA hand method, which involves making a ribbon with the thumb and fingers. The soil can still be “ribboned” but will crumble if rolled.

#### 4.2.4.1 Computing toughness from index properties

Data from [Barnes](#ref-Barnes2013) ([2013a](#ref-Barnes2013)) and ([2018](#ref-Barnes2018)) have been re-analyzed by other authors to develop empirical equations for predicting toughness.

from other soil properties ([Vinod and Sreelekshmy Pillai, 2017](#ref-Vinod2017); [Moreno-Maroto and Alonso-Azcárate, 2018](#ref-Moreno-Maroto2018)) and even used to suggest a new system for classifying soils based on toughness ([Moreno-Maroto et al., 2021](#ref-Moreno-Maroto2021)). However, because the Barnes device is a unique apparatus, no attempts have been published to confirm its replicability across other operators or to compare its results with other means of measuring soil toughness.

The flow index is the slope of a line plotting water content against the natural log of blow count in the liquid limit test. A steeper flow curve indicates less change in shear strength for a unit increase in water content. [Casagrande](#ref-Casagrande1932) ([1932](#ref-Casagrande1932)) used this to derive a formula he termed the ‘toughness index’:

where is the toughness index, is the plasticity index, and is the slope of the flow curve.

“In order to classify clays according to their toughness it would be necessary to determine the shearing resistance at the plastic limit by means ofa direct shearing tet or an unconfined compression test.”

In the hypothetical sense any test which applies a known load and measures a deformation could be used to measure toughness. [Barnes](#ref-Barnes2013) ([2013a](#ref-Barnes2013)) suggested his apparatus would correlate well with the Moisture Condition Value test, which is the logarithm of the number of blows needed to compact a fixed mass of soil to a pre-determined volume.

### 4.2.5 Particle size analysis

At the time of writing, particle size analysis is the only means of soil testing which has been applied to infield soils. Mechanical analysis is relatively rapid and inexpensive, and it has been used as a surrogate marker for nearly every aspect of soil science. A tremendous amount of data has accumulated with particle size analysis as its basis. It is useful to examine the principles which underlie the analysis and the development of the techniques, and to identify potential sources of error during the tests.

[Brosnan and McNitt](#ref-Brosnan2008a) ([2008](#ref-Brosnan2008a)) surveyed the surface conditions of the infield skin on extant playing fields at three maintenance levels. Particle size analyses were performed on soil sampled from each infield skin. The USDA soil texture of those samples is plotted in 4.10. These soils were sampled from the upper 13 mm and contained large granules of calcined clay infield conditioner; therefore, the texture measured with this method is coarser than the “true” texture of the base soil.

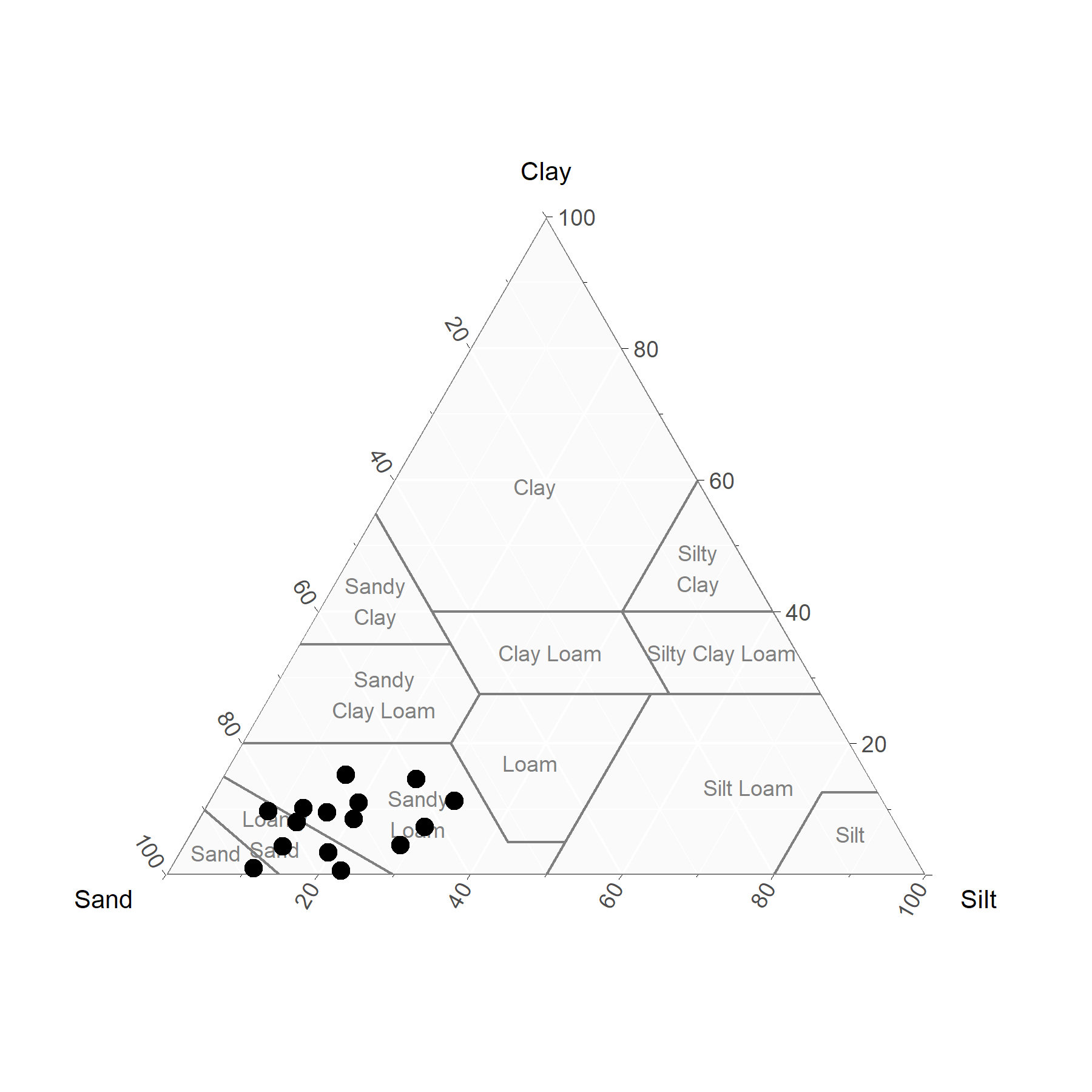


Figure 4.10: Infield soils suyveyed by Brosnan (2008a)

## 4.3 Design and properties of artificial soil mixtures

Natural soil materials are excavated and deliberately blended for many uses. Potting mixes and green roof media are the largest means of production by volume (reference ??). The purpose of blending multiple soil materials is to create a product having properties not exhibited by any naturally occurring soil material. Even if the desired properties *could* be found in a single naturally occurring material, the properties of natural soils are subject to spatial variation. In such a scenario, the properties of the mixture can be held constant simply by adjusting the ratio of the components.

A rtificial sand-clay mixtures usually contain two components, but some studies have combined sand with two clays to form a three-way mixture. Several methods have been employed to test the engineering behavior of sand-clay mixtures. Atterberg limits are the most popular due to their relative speed and low cost. Compaction and shear tests are also common. Other properties which have been studied include permeability, static compressibility, and pore size distribution.

This section describes prior research pertaining to the behavior of sand-clay mixtures in laboratory tests.

### 4.3.1 pasted from word 2021-1-28

An engineered soil is defined as an artificial mixture of two or more natural soils for a specific application. The purpose of manufacturing an engineered soil is to obtain a material which exhibits properties superior to those of any naturally occurring soil.

Artificial mixtures of sand with clay have been studied extensively. .

#### 4.3.1.1 Definition of the Transitional Fines Content

In a coarse-grained soil, applied loads are transmitted through a skeleton of grain-to-grain contacts. The behavior of the soil is relatively independent of water content. A minor addition of fine particles will not alter the soil’s behavior so long as the fines fit comfortably within the large voids. Once sufficient fines are added, they begin to participate in the force chain and with further additions the coarse grains become completely suspended in a matrix of fines. At this point the soil’s behavior will be dominated by the fines and the coarse grains act only as inert inclusions. The percent fines by where the soil behavior changes from that of the sand to that of the fines has been termed the “transitional fines content.” It should be pointed out that there is no single, unique value at which the behavioral threshold occurs - it is a *transition* which occurs continuously. Regardless, it can be useful to distill the transition to a single number or range of numbers representing the percent fines which cause the transition. There are several means to identify this value.

Reported values of transitional fines content range from 15 to 45% by dry mass [reference??]. There is no universal mass-based fines percent which defines the TFC because (1) the transition depends on the behavioral threshold of interest (for example, compressibility, shear strength, or permeability), and (2), a unique ratio exists for every combination of coarse-grained and fine-grained components because particle packing depends on the grain-size distribution of each component, the plasticity of the fines, the means of compaction or consolidation, and the state of effective stress.(Zuo and Baudet, 2015)

The TFC has been variously defined based on: derived values from phase relations and index properties (Thevanayagam, 1998; Monkul and Ozden, 2007; Cabalar, 2011), the minimum global void ratio in compaction experiments (Lade et al., 1998; Ueda et al., 2011), undrained shear strength(Thevanayagam, 1998; Vallejo and Mawby, 2000; Dafalla, 2013; Nagaraj, 2016; Cabalar and Mustafa, 2017; Kim et al., 2018), parameters of the normal compression line or critical state line,(Cabalar, 2011; Carrera et al., 2011; Shipton and Coop, 2012) and liquefaction potential (Lade and Yamamuro, 1997).

### 4.3.2 Importance of distinction between volumetric and mass relations

In an artificial mixture of two or more soils, the relative amounts of each components may be compared on a volumetric or mass basis. The dry mass of solids is considered a more absolute measure of the quantity of each component, as these never change despite fluctuations in water content or bulk density. The ratios or percentage to which the component fractions are normalized should also be made explicit. The most common means to express the amount of each component is to set the total dry mass of the mixture equal to 100% : % sand=g\_sand/(g\_sand+g\_clay ) However, others have advocated for enumerating the amount of sand to the amount of clay. For example, if 40 grams sand are added to 100 grams clay, this mixture would be termed 40% sand. This approach is analogous to computing water content as the mass of water related to the mass of dry soil. It is scarcely used in scientific literature.  
% sand=g\_sand/g\_clay Mass-based ratios are the most rational basis for mixing and testing, yet the behavior of the soil is governed by particle-to-particle relations in physical space. Therefore volumetric relations provide a more accurate depiction of the soil’s behavior, especially when the mixture components have very different specific gravities.

The importance of intergranular void ratio An important variable in the behavior of sand-clay mixtures is the configuration of the sand grains within the bulk soil matrix. The term intergranular void ratio was introduced by (Thevanayagam, 1998) to enumerate the configuration of the coarse grains in a soil mixture. The intergranular void ratio is derived from phase relations (Fig \_\_) by treating the solid fines as voids within the bulk volume, which is held equal to unity.

The intergranular void ratio may be compared with the minimum and maximum void ratio of the pure sand as determined by standard test methods. When the intergranular void ratio exceeds that of the host sand, it is considered that the soil’s behavior will no longer be governed solely by the coarse grain contacts.

Factors influencing the transitional fines content Size ratio TFC values may be computed analytically from phase relations and minimum/maximum void ratios, yet derived values rarely coincide with those observed in experiments(Zuo and Baudet, 2015). In practice, observed volumetric packing densities (i.e. volumetric solid fraction) are always lower than the theoretical maximum because the calculations rely on simplifying assumptions which are unlikely to be satisfied(Zuo and Baudet, 2015). These assumptions are: The fines are “infinitely small” The coarse grains are smooth spheres Both the coarse and fine soils are packed to their respective optimum densities  
Observed packing densities in experiments range from 60% to 95% of the theoretical maximum(Furnas, 931; McGeary, 1961; Zuo and Baudet, 2015). An important element of the discrepancy between calculations and experiments is the size ratio between the coarse and fine components (Lade et al., 1998; Ueda et al., 2011). The size ratio is given as: R=〖D\_50〗\_sand/〖D\_50〗\_fines The agreement between calculation and experiment is enhanced with increasing size ratio(Lade et al., 1998; Zuo and Baudet, 2015). If the coarse and fine soils have similar mean grain sizes, mis-fitting and lodging of fines between the coarse grains is responsible for creating additional voids. (Lade et al., 1998) showed that when R < 7, an increase in R imparts a relatively steep increase in packing density. Additionally, (Lade et al., 1998) showed analytically that a void between closely packed spheres of equal sizes has a diameter of ~ 1/6.4 that of the large particles. Therefore, there is a fundamental reason for the abrupt change in slope at R~7. The effect is lessened once R > 7, and the observed void ratio approaches the theoretical maximum asymptotically. Numerical simulations indicate the intergranular void ratio practically independent of 〖D\_50〗\_fines when R > 100. (Ueda et al., 2011)

Uniformity of each component

The theoretical maximum packing density of a two-component mixture is increased when the maximum density of each component is greater. If the mean grain size is suficintly different bewtewne the two components, a wider widening the particle size distribution within each individual component will increase the packing density of each component without causing the fines to interfere with packing of the sand.

Number of mix components As the number of components in the mixture increases, the achievable packing density asymptotically approaches the specific gravity of the solids (zero void space). A four-component mixture by (McGeary, 1961) achieved a volumetric packing density of 0.951 (less than 5 % porosity). This extreme density was only achieved in the experiments by first vibrating the coarsest component to its maximum density, then adding the next finer component and vibrating until it fully penetrated the remaining voids. Plasticity of fines The majority of research on TFC mixtures has focused on sand mixed with nonplastic fines. This likely reflects the greater engineering liquefaction potential of silt and also the relative speed at which the experiments can be performed. Mixtures of sand with silt are easily vibrated to their maximum density in an air-dry condition, while investigations of sand mixed with plastic clay require more time- and labor-intensive proctor compaction methods. Plasticity index is positively correlated with optimum water content for compaction(Sridharan and Nagaraj, 2005; Verma and Kumar, 2019). Therefore, in a compaction experiment, a higher plasticity clay would be expected to have a lower mass percent of fines, as more of the intergranular space is occupied by water rather than clay solids.

Method of compaction/ compaction energy

Mixtures subjected to static compression in an oedometer exhibit typical void ratio vs. log pressure curves. When this method of volume reduction is used, higher ultimate density values are attained than when using dynamic compaction, such as in the standard and modified Proctor tests. The difference in packing can probably be attributed to more complete evacuation of air from the voids. Transitional fines content- how to define? Volume vs mass (again) Maximum density Behavior- undrained strength?

A qualitative definition of the transitional fines content is when the behavior of a soil mixture becomes more similar to the behavior of the fines alone than the sand alone. A transition in actual soil behavior, however defined, is of greater practical interest than a surrogate marker such as void ratio [which is more aptly considered a state parameter than an index property].

Atterberg limits of sand-clay mixtures The Atterberg tests have been used to assess the behavior of sand-clay mixtures. Although the tests are intended to characterize silts and clays, the test results also reflect the size and shape of the sand fraction in an artificial sand-clay mixture. This section summarizes research on the Atterberg limits of artificial soil mixtures. Two-component mixtures (sand with a single type of clay material) and three-component mixtures (sand with two forms of clay material) are both discussed. For brevity, in this section the term “clay” is used to mean the fine-grained soil component of the mixture and does not connote any particle size definition.  ***The term “clay” connotes varied meanings to different fields. In this dissertation, in the spirit of brevity, I use the term “clay” in this dissertation in its colloquial sense- that is a fine-grained soil material that can be shaped and molded. When soil mixtures are made one does not typically consider only the fraction of mineral solids having < 2 μm equivalent Stoke’s diameter. Instead, the mix is made on the basis of a specified ratio between 2 or more soils which are combined.*** \_

Two-component mixtures of clay and coarse additions Seed et al., 1964a (Seed et al., 1964) investigated Atterberg limits of sand-clay mixtures. Three types of clay (kaolinite, illite, and Ca-bentonite) were mixed with varying amounts of sand. All of the sand was < 425 μm in accordance with the standard test methods.

For the high-swelling bentonite, the liquid limits of the sand-clay mixtures were inversely proportional to sand content. In other words, the water content per unit clay material remained constant. This relationship was also observed for the illite clay. A linear relation was observed for the kaolinite clay up to 50 % sand, but the liquid limit test could not be performed on the 75 % sand-25 % kaolinite mixture, so whether the liner decline holds above 50 % sand could not be evaluated.

The slopes of these liquid limit vs. sand content lines differed by clay type; the authors showed that the slope was in close agreement with the Skempton activity of the clay, computed as (LL/ % < 2 μm). This relationship also held regardless of whether a single clay was mixed with the sand or if the sand was mixed with two types of clay (further discussed in the following section).

The plastic limit of the bentonite-sand mixtures also followed a linear relationship with increasing sand, up to the highest percent sand tested (75%). In contrast, the illite and kaolinite clays showed a linear relation only at lower sand contents. At sand content of 50% or higher, the plastic limits were higher than would be predicted by a simple linear regression line. This suggests the sand grains began to play a role in the soil’s behavior.

A precise estimate of the inflection point for the PL-sand content curve could not be established because of the small number of sand contents investigated. The authors tested only 4 sand contents for the illite clay and 3 sand contents for the kaolinite clay, so the precise terminus of a linear trend could have occurred anywhere between 25 and 75% sand.

[Sivapullaiah and Sridharan](#ref-Sivapullaiah1985) ([1985](#ref-Sivapullaiah1985)) published similar findings on the effects of adding sand to pure clay materials. If the sand grains act solely as inert inclusions, the liquid limit of the sand-clay mixture should decrease in exact proportion to the sand content. [Sivapullaiah and Sridharan](#ref-Sivapullaiah1985) ([1985](#ref-Sivapullaiah1985)) termed this effect the “linear law of mixtures.” They showed that the linear law is only valid for sand-clay mixtures within a range of sand contents. Evidence is given as (1) liquid limits which are systematically higher than predicted by the linear law and (2) Plastic limits actually *increasing* with greater sand content once 60% sand was reached. The linear law was also shown to be invalid for mixes of bentonite with two types of silt in several ratios.

[Sivapullaiah and Sridharan](#ref-Sivapullaiah1985) ([1985](#ref-Sivapullaiah1985)) clearly demonstrated that the linear law is not valid over the full range of 0-100% clay, but only one data points was collected between 0 and 60% sand. At these low sand contents, the shape of the liquid limit vs. sand content curve (linear or curvilinear) cannot be definitively stated from their data.

The effect of sand particle size on the behavior of sand-clay mixtures was also tested by [Sivapullaiah and Sridharan](#ref-Sivapullaiah1985) ([1985](#ref-Sivapullaiah1985)). The size of the added sand particles affected both the liquid and plastic limits. Mixes with coarser sand (425 μm – 150 μm) adhered more closely to the linear law of mixtures than finer sand containing only particles 150 μm – 75 μm. Mixes containing bentonite and silt (rather than sand) deviated further still from the linear law.

[Sivapullaiah and Sridharan](#ref-Sivapullaiah1985) ([1985](#ref-Sivapullaiah1985)) also isolated the effect of sand particle shape on the Atterberg limits of sand-clay mixtures. Bentonite clay was mixed with equal amounts of either angular or round sand of the same particle size fraction (150 μm – 75 μm). Sand contents ranged from 20 - 95 %. There was no discernable difference in the liquid or plastic limit due to particle shape.

Dumbleton and West (1966a, 1966b, 1970) (Dumbleton, 1966) investigated the liquid and plastic limits of two types of clay mixed with 5 types of coarse particles in various quantities. Silt and sand additions reduced the liquid limit and plastic limit. On an absolute scale, the water content at the liquid limit was changed more substantially than the plastic limit. However, on a relative scale (i.e. compared to characteristic water contents of the pure clay), adding sand or silt produced a similar *relative* change in both characteristic water contents. Their montmorillonite clay was more affected by sand additions than their kaolinite. This is somewhat contrary to other studies which find montmorillonite to be a more “active” clay mineral (citation).

The degree of the coarse particles’ influence on the test results was inversely related to particle size. In other words, for the same percent coarse addition, the degree of influence on the plasticity of a mix was silt > fine sand > coarse sand. The shape of the coarse particles mixed with the clays also affected the results of [Dumbleton](#ref-Dumbleton1966a) ([1966](#ref-Dumbleton1966a)). For the same mass percent of coarse addition, the increase in the plastic limit was platy mica silt > bulky quartz silt angular quartz sand > round quartz sand. The authors attributed the difference to irregularly-shaped particles having higher surface area and requiring more water to coat the particles. This finding contradicts that of [Sivapullaiah and Sridharan](#ref-Sivapullaiah1985) ([1985](#ref-Sivapullaiah1985)), whose data showed no difference between angular and round sands of the same sieve diameter. Were the experiment conducted to higher sand content, it is possible an effect of particle shape would have been observed.

(Dumbleton and West, 1966) furthered their investigation of the coarse fraction’s influence on Atterberg limits. Increasing departure from spherical and round particles tended to raise both the liquid and plastic limits by roughly equivalent amounts. Although the coarse fraction had a measurable influence, the authors determined the nature of the clay material was the more important variable.

[Barnes](#ref-Barnes2013) ([2013a](#ref-Barnes2013)) tested mixes of London clay with sand (two different size fractions) or silt, in 10% increments of coarse particles from 0 to 100% clay.

* Casagrande 1932
* Barnes dissertation
* Mixtures of clays together and non-linear behavior
* Clay and pottery books.

Three-component mixtures of sand with two types of clay The work of (Seed et al., 1964) on relatively pure clay minerals mixed with sand was discussed above. A more complex relationship was observed when two types of clay were mixed together before adding sand. Seed et al. also extended the problem to three-component mixes in which two types of clay were first combined in varying ratios and the resultant mixture further blended with different amounts of sand. The plastic and liquid limits of the mixtures did not lie on a linear interpolation between those of the pure clay endmembers.

Three types of clay (kaolinite, illite, and Ca-smectite) were investigated. For mixes of kaolinite with either illite or smectite, a nearly linear relationship was observed. For example, a mix with a mass percent 50% kaolinite and 50% illite had a liquid limit halfway between the liquid limits of each individual clay. Mixtures of smectite with illite did not adhere to a simple linear relationship. The LL of the mixtures were always lower than would be predicted. Small additions of illite to montmorillonite lowered the LL by more than expected, and small additions of smectite to illite raised the LL by less than would be expected. The response of the plastic limit to smectite additions were more complex. With small bentonite additions, the plastic limit was lower than expected, while for larger bentonite additions the PL was higher than expected. Seed et al. noted that if a mass-weighted value of Skempton activity was used instead of pure mass percent, ????

\_\_ [Sivapullaiah and Sridharan](#ref-Sivapullaiah1985) ([1985](#ref-Sivapullaiah1985)) showed that their linear law was not valid for mixtures of bentonite with kaolinite. The liquid limit of the mixture was always lower than would be expected from the linear law. This implies an interaction between the clay mineral particles.

#### 4.3.2.1 Notable research gaps to address in this project:

There are no data available on the brittle and ductile response of soil to cleated baseball shoes. Data pertaining to sand-clay mixes only have tested sand with particle sieve diameters of < 425 μm The transitional fines content of sand mixed with plastic fines has scarcely been explored The effect of silt-to-clay ratio has been championed yet without systematic evaluation for the same type of extant clay minerals.

Quantitative analysis has not been applied to the toughness of clays, save for the studies of Barnes who used a cyclic shearing mode similar to that of the standard hand-rolling plastic limit test. In addition, the range of acceptable strain values for a given engineering problem significantly changes the toughness computation. For highly ductile materials, the failure strain is extremely high, and an unacceptably large deformation may be incurred before a failure criterion is reached. In the standard unconfined compression test, the test is halted at 20% strain if a clear peak has not been reached. Toughness is computed as the integral of the stress strain curve from zero strain all the way up to the failure strain. In contrast, Barnes elected to define the toughness of clays as a definite integral from the soil thread diameter of 6 mm down to 4 mm, because in this region deformation of the soil thread was considered to be relatively stable and the stress-strain curves extend with only slight curvature. However this approach may underestimate the toughness of more brittle specimens because the energy dissipated at low strain but high stress is not included in the calculation. It is evident that the strain range chosen for the toughness calculation can substantially change the conclusions about toughness, and one must select the failure criterion carefully based on the problem of interest.

# 5 Proposed experiments and papers

This section details the planned research, much of which has already begun. Figure \_\_ outlines envisaged timelines for these experiments. Many of the tests will be performed on the same soil mixtures and the experiments, while separate, have substantial overlap. Therefore the testing program will be structured to minimize bottlenecks. In other words, multiple experiments will be in progress at a given time because some of the protocols involve wait times (i.e. for several hours or overnight) during which other lab tasks can be performed.

## 5.1 Dissertation chapter 1: A novel method for measuring surface deformation of baseball and softball infield skin soils

### 5.1.1 Principal research questions

1. Can differences among infield mixes be observed in a laboratory test without using human subjects?
2. How can performance be quantified?
3. How can the method be made objective and repeatable?

### 5.1.2 Hypotheses

1. The “cleat-in, cleat-out” phenomenon (described in Section @ref(#corkboard-effect)) can be duplicated using a machine and a laboratory-sized soil specimen.
2. The means by which the soil specimen is prepared will affect the test result. Therefore, a protocol must be developed which adequately emulates the real procedures used for construction and maintenance of infield skins. Furthermore, the method must simulate outdoor conditions to adjust the soil water content.
3. Subjectivity can be minimized by relying on 3D scanning technology to measure the response of the soil.
4. Morphpometrics may be classified by means of the property they depend on; each metric will be minimized at similar water content but their sensitivity (i.e. *relative* magnitudes) will differ in this order: surface-area > volume > curvature.

### 5.1.3 Materials and Methods

A mechanical apparatus has been developed to emulate a baseball or softball athlete’s foot-to-surface interaction (Figure 5.1). The device was designed and fabricated between May 2019 and March 2020 with service from the Penn State Engineering Services Shop.



The apparatus comprises a pneumatic cylinder which combines high travel speed and precise control of the peak load.

### 5.1.4 Timeline

The device was designed and fabricated between May 2019 and March 2020. Calibration and tuning of the machine is ongoing. The first set of mixtures is scheduled to be tested in Nov 2020. The goal is to complete all tests with this device by the end of 2021.

## 5.2 Dissertation chapter 2: Toughness of clay soil near the plastic limit using unconfined compression tests

### 5.2.1 Principal research questions

1. Can soil toughness be measured using unconfined compression tests?
2. How does toughness change as a function of water content for different types of clay soils?
3. How does the toughness-water content relationship change as sand is added to the clays?

### 5.2.2 Hypotheses

1. Soil toughness can be measured with unconfined compression tests. By testing both specimens dry and wet of the plastic limit, one can interpolate their maximum toughness, which occurs at the plastic limit (i.e. onset of brittle fracturing).
2. Higher plasticity soils will have less change in toughness for a unit change in water content. The maximum toughness of the clay types will be in order of montmorillonite >> mixed-layer/illite > kaolinite > iron-oxide rich > high-silt soil.
3. Clays with higher maximum toughness will require more sand to reduce their toughness. Because they maintain similar toughness over a broader range of water content, the behavior of the soil is less affected by sand additions.

### 5.2.3 Materials and Methods

The same mixtures tested in 5.1 will be used for this study. Five fine-grained soils will be mixed with a single sand in multiple ratios. These same fine-grained soils will then be mixed with quartz silt to produce soil mixtures having identical sand content and silt-to-clay ratios but different clay minerals.

The soils will be wetted to their adhesion limit and packed into a steel tube with a dynamic compaction effort similar to that in the Modified Proctor test ([ASTM International, 2015](#ref-ASTMD15572015)). The soil will be packed in a single lift to minimize heterogeneities in the specimen which could arise due to lack of binding between successive lifts. Preparing the specimens in a relatively soft condition also ensures minimal air entrapment. For each mixture, 6 replicate cylinders will be prepared.

The specimens will be extruded with a manual hydraulic bottle jack (Figure 5.3). One specimen will be immediately sealed in an air-tight plastic bag. The rest will be air dried under a loose polyethylene sheet to slow the rate of drying. The specimens will be dried to progressively lower water contents, with the final specimen being completely air-dried. The goal is to evaluate the full range of water contents where ductile behavior is observed and to bracketing the plastic limit.



Figure 5.3: Bottle jack specimen extruder for preparing compression test specimens.

The specimens will be subjected to unconfined compression tests at the Penn State Civil Infrastructure Testing and Evaluation Laboratory. Axial strain and nominal stress will be recorded up to 20% strain or an abrupt failure criterion. The water content of the specimen will then be determined.

A smooth curve will be fitted to the stress-strain curve using general additive models in the R language for statistical computing ([R-Core-Team, 2020](#ref-baseR)). Toughness will be computed as a definite integral up failure.

Toughness will be plotted against water content, and a second curve will be used to determine the rate of change in toughness per unit water content. It is anticipated that this relationsip will follow a semi-logarithmic shape, as for the Barnes apparatus ([Barnes, 2013a](#ref-Barnes2013)). Figure ?? shows such a plot.

Finally, the coefficients from the toughness-water content relationship for each sample can be analyzed as a function of sand content and clay type. This two-way model will permit the toughness slope to be computed for any soil based on its initial toughness.

### 5.2.4 Timeline

These tests will be completed beginning in Fall 2021 and continue through April of 2022.

## 5.3 Dissertation chapter 3: Effect of oversize particles on Atterberg limits of artificial sand-clay mixtures

### 5.3.1 Principal research questions

1. Can Atterberg limit tests be performed when sand particles up to 2 mm sieve diameter are included in a soil?
2. What is the effect of using coarser or finer sand?
3. What is the effect of sand uniformity?

### 5.3.2 Hypotheses

1. The tests can be performed using identical methodology to ASTM D4318 with the 425 μ washing step eliminated
2. The liquid limit will be lower for coarser sand due to reduced surface area of the sand particles relative to finer sand.
3. Coarser sand will cause greater particle interference in the plastic limit thread as it nears its 3.2 mm diameter. The thread will crumble prematurely, raising the plastic limit value.
4. The combined effect of (2) and (3) will yield a smaller plasticity index for coarser sand. The results of the experiment can be used to apply a correction for the presence of oversize particles without their removal prior to testing.

### 5.3.3 Materials and Methods

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### 5.3.4 Timeline

The experiments were begun in March of 2020 during the initial COVID-19 stay-at-home order. Data collection is nearing completion.

## 5.4 Dissertation chapter 4: A critical appraisal of particle size analysis as a proxy for infield soil behavior

### 5.4.1 Principal research questions

1. Can particle size distribution (PSD) be accurately measured using a range of laboratory techniques?
2. Does the increased PSD resolution from laser diffraction provide useful information about an infield mix?
3. What particle size metrics are the best and worst predictors of infield performance?

### 5.4.2 Hypotheses

1. Specimen pre-treatment will drastically alter the results of a particle size test. This uncertainty is associated with the test protocol and is independent of operator performance. The hydrometer and pipette yield similar results, but the laser diffraction method requires an empirical correlation to permit comparison with older methods. The most important step is the physical disaggregation of the soil; ultrasonic dispersion will yield higher clay percentages than stirring or shaking methods.
2. Laser diffraction allows rapid analyses of more size fractions than sedimentation analyses, and the amount of fine clay will correlate with infield performance.
3. Even with the larger dataset produced with laser diffraction, considering the silt and clay fractions will correlate only loosely with infield performance as measured in

### 5.4.3 Materials and methods

#### 5.4.3.1 Experiment 1

5 soils will be tested using 3 pre-treatment protocols:

1. ASTM D7928; milkshake mixer method ([American Society for Testing Materials, 2017](#ref-ASTMD79282017))
2. ASTM D7928; overnight shaker method ([American Society for Testing Materials, 2017](#ref-ASTMD79282017))
3. ASTM D7928; ultrasonic dispersion method ([American Society for Testing Materials, 2017](#ref-ASTMD79282017))

These will each be sampled with the pipette method, considered the standard technique for mechanical analysis in soil science ([Gee and Or, 2002](#ref-Gee2002)).

Soils dispersed with method (3) will also be subjected to 4 additional sampling methods:

1. pipette analysis with samples removed at 20, 5, 2, and 0.2 μm equivalent spherical diameters; sand tested with sieve method
2. hydrometer analysis with measurements taken for 20, 5, and 2 μm equivalent spherical diameters; sand tested with sieve method
3. laser diffraction analysis for fine fraction and either:
4. sand fraction analyzed with sieve method
5. sand fraction analyzed with dry laser diffraction method

All tests will be replicated 5 times to allow statistical comparison.

The author has already developed software for the data management and analysis tasks involved for these experiments. The data can be batch-analyzed, reducing the time for data processing to virtually zero. In total, these experiments sum to 175 total analyses.

### 5.4.4 Timeline

These experiments will be conducted throughout 2021, primarily during the summer and early fall. Current lab capacity is to test 12 specimens per workday, so the experiments equate to 15 full days of testing.

## 5.5 Dissertation chapter 5: A rational basis for the design of soil mixtures used on baseball and softball infields

### 5.5.1 Principal research questions

1. How can better infield mixes be designed?
2. How can the performance of an existing mix be improved without replacing it?
3. What criteria best relate to infield performance, defined as the range of water contents where the soil is both plastic and stiff enough to support athletic maneuvers?

### 5.5.2 Hypotheses

1. Infield mix design should start with the toughness of an available clay soil, not the final sand %.
2. The level of play and maintenance budget will dictate the desired toughness level.
3. The upper bound of the amount of clay soil component that should be included in the mix is a function of the dry shear strength of the mix because it is this property that governs the workability of the mix (i.e. the ability to groom it with implements and hand tools)
4. If a given toughness level is desired, the % sand needed to achieve this can be computed from empirical equations.
5. Ideally, toughness should be directly measured when designing a new mix; however it can also be estimated from an empirical correlation with the Atterberg limits
6. Particle size analysis is acceptable for quality control purposes, but not for design. Only once a desired blend of a particular sand with a particular clay is established through toughness testing can a definite ratio of sand-size particles to fines be defined for that mix.
7. Amending existing soils should be done on the basis of plastictity rather than silt-to-clay ratio. The resulting mixture’s properties will not be a linear interpolation between the two; thus a calibration of Atterberg limit results may be required by making several mixtures (for example 0, 20, 40, 60, 80, and 100% of soil A with the implied amount of soil B) to determine the proper amendment ratio.

### 5.5.3 Materials and Methods

This paper is primarily a synthesis of the methods papers described above. It will combine the methods into a single framework for designing infield mixes. Simple metrics will be defined, and the framework will be tested by using materials which were *not* tested in the other experiments to validate the theory’s merit.

### 5.5.4 Timeline

This is the final paper I will write as it encompasses all the lab work and other publications. I anticipate writing it in the second half of 2022.

The end game/envisaged process of mix design:

1. Decide what toughness value you want - this is determined by the level of play and maintenance capability.
2. Test the toughness of the pure “clay” (or estimate it from the empirical equation published by [Moreno-Maroto and Alonso-Azcárate](#ref-Moreno-Maroto2018) ([2018](#ref-Moreno-Maroto2018)), or hopefully via an even better equation I will make with my compression test method for toughness)
3. Use an empirical equation I will develop to interpolate along the dose-respone curve of toughness vs. sand content. It will probably be linear for coarse sand and non-linear for finer sand. Probably I would need to develop multiple equations based on the properties of the sand….either choose from two or three equations (i.e. sand too fine, sand ok, sand excellent), or what would be even better (but probably beyond the scope of my own project and therefore a great starter for one of my future grad students) is to represent the sand variable as something continuous, such as mean particle diameter, or better yet specific surface area (could derive this from PSA curve with a correctly-fitted model) and then you would have *two* continuous variables with which to form the dose-response curve. Anyway, you interpolate on this curve to get the sand-clay ratio you want, then make the mixture from that ratio. In this way the properties of the resultant mixture are not only replicable, they are precisely controllable. You have your hand on the dial!

Basically you end up with a line plotting toughness against % sand. The nature of the line is determined by : 1. the intercept of the line is determined by the initial toughness (i.e. that of the “pure” clay soil component) which is in turn determined by the mineralogy and particle size of the clay soil component. 2. the slope is determined *both* by the type of clay (i.e. the slope is a function of toughness; tougher clays will not be dilluted as easily; they will retain their toughness at higher sand contents; their slopes will be shallower) **and** the type of sand (i.e. the slope is a function of sand type, but only above ~20% sand)

Generally speaking, the larger the athletes the higher the toughness you want. The maximum toughness that can be used as an infield mix is governed by the strength of dry clods because they have to be draggable. This is complicated by the use of conditioner because they will increase the friability of the soil when used on a real infield. So you can use a base soil which has slightly higher toughness than would really be acceptable if there were no conditioner around….but how much higher is a hard question to answer. To find out you would have to do a conditioner titration on the soils which bracket this transition.

# 6 Appendix

Table 6.1: Field preparation tasks for a typical MLB game day.

Field area

Task

Prep time

Participants

Approx. duration (minutes)

Game mound/bullpen

repair bullpens

Daytime

1

60

Game mound/bullpen

repair bullpens

Pre-game

4

15

Game mound/bullpen

repair bullpens

Postgame

3

45

Game mound/bullpen

repair game mound

Daytime

0

0

Game mound/bullpen

repair game mound

Pre-game

2

15

Game mound/bullpen

repair game mound

Postgame

2

30

Home plate

repair home plate

Daytime

0

0

Home plate

repair home plate

Pre-game

2

30

Home plate

repair home plate

Postgame

2

30

Infield skin

add conditioner to skin

Daytime

2

15

Infield skin

add conditioner to skin

Pre-game

2

5

Infield skin

add conditioner to skin

Postgame

0

0

Infield skin

drag skin

Daytime

1

60

Infield skin

drag skin

Pre-game

3

10

Infield skin

drag skin

Postgame

1

30

Infield skin

paint infield skin lines

Daytime

0

0

Infield skin

paint infield skin lines

Pre-game

3

10

Infield skin

paint infield skin lines

Postgame

0

0

Infield skin

pull full-field tarp

Daytime

8

20

Infield skin

pull full-field tarp

Pre-game

0

0

Infield skin

pull full-field tarp

Postgame

15

10

Infield skin

rake skin edges/baselines

Daytime

1

60

Infield skin

rake skin edges/baselines

Pre-game

2

10

Infield skin

rake skin edges/baselines

Postgame

1

30

Infield skin

hand water skin

Daytime

3

15

Infield skin

hand water skin

Pre-game

6

15

Infield skin

hand water skin

Postgame

3

15

Turf

hand water turf

Daytime

2

30

Turf

hand water turf

Pre-game

0

0

Turf

hand water turf

Postgame

0

0

Turf

mow infield and foul areas

Daytime

1

90

Turf

mow infield and foul areas

Pre-game

0

0

Turf

mow infield and foul areas

Postgame

0

0

Turf

mow outfield

Daytime

1

75

Turf

mow outfield

Pre-game

0

0

Turf

mow outfield

Postgame

0

0

Turf

paint foul lines on turf

Daytime

1

20

Turf

paint foul lines on turf

Pre-game

0

0

Turf

paint foul lines on turf

Postgame

0

0

Warning track

drag track

Daytime

1

20

Warning track

drag track

Pre-game

3

10

Warning track

drag track

Postgame

0

0

Warning track

paint foul lines on track

Daytime

0

0

Warning track

paint foul lines on track

Pre-game

3

10

Warning track

paint foul lines on track

Postgame

0

0

Warning track

water track

Daytime

2

20

Warning track

water track

Pre-game

0

0

Warning track

water track

Postgame

0

0

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1. Data used to compute the values in Figure 4.3 are compiled in the Appendix, see Table 6.1 [↑](#footnote-ref-25)
2. named for its similarity to the experience of removing a thumbtack from a bulletin board. [↑](#footnote-ref-30)
3. from the Greek *plastikos*, “to mold or form” [↑](#footnote-ref-32)
4. These methods are purportedly traceable to the Russian researcher Piotr Vasilje [Wikipedia](#ref-wikipediafallcone2021), although the author has been unable to verify this claim in primary literature because Vasilje’s work has not been translated to English. [↑](#footnote-ref-43)