

# Contents

<b>1</b>	<b>Review of literature</b>	<b>1</b>
1.1	Performance of baseball infield surfaces . . . . .	3
1.2	Laboratory tests of soil behavior and physical properties . . . . .	5
1.3	Behavior of artificial soil mixtures . . . . .	18

## 1 Review of literature

```
library(tidyverse)
library(measurements)
library(latex2exp)
library(scales)
```

```
##
## Attaching package: 'scales'

## The following object is masked from 'package:purrr':
##
##      discard

## The following object is masked from 'package:readr':
##
##      col_factor
```

```
library(ImaginR)
```

```
## Loading required package: imager

## Loading required package: magrittr

##
## Attaching package: 'magrittr'

## The following object is masked from 'package:purrr':
##
##      set_names

## The following object is masked from 'package:tidyr':
##
##      extract

##
## Attaching package: 'imager'
```

```
## The following object is masked from 'package:magrittr':  
##  
##   add
```

```
## The following object is masked from 'package:cowplot':  
##  
##   draw_text
```

```
## The following object is masked from 'package:stringr':  
##  
##   boundary
```

```
## The following object is masked from 'package:tidyr':  
##  
##   fill
```

```
## The following objects are masked from 'package:stats':  
##  
##   convolve, spectrum
```

```
## The following object is masked from 'package:graphics':  
##  
##   frame
```

```
## The following object is masked from 'package:base':  
##  
##   save.image
```

```
library(imager)  
library(here)
```

```
## here() starts at C:/Users/ecm200/OneDrive - The Pennsylvania State University/PSU2019-present/A_inf_2
```

```
library(cowplot)  
library(baseballr)
```

```
## Registered S3 method overwritten by 'quantmod':  
##   method      from  
##   as.zoo.data.frame zoo
```

```
library(ecmfuns)  
library(balldensityplots)  
library(magick)
```

```
## Linking to ImageMagick 6.9.11.34  
## Enabled features: cairo, freetype, fftw, ghostscript, lcms, pango, rsvg, webp  
## Disabled features: fontconfig, x11
```

```
library(DescTools)
theme_set(theme_cowplot())
```

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

### 1.1 Performance of baseball/softball infields

### 1.2 Laboratory tests of soil behavior and physical properties

### 1.3 Design and properties of artificial soil mixtures

## 1.1 Performance of baseball infield surfaces

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). Footing and ball response are the main surface properties of interest to the athlete and the grounds manager.

Published research on baseball infields is relatively scant. Studies relevant to footing and ball response are summarized below.

---

### 1.1.1 Footing

**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 [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 [Nigg1990]. Excessive rotational traction is associated with lower extremity injuries, but traction differences among shoe types are often larger than those across surface types [Serensits2014]. Clear-cut thresholds separating acceptable and unacceptable 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.

@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.

@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.

**1.1.1.2 The “corkboard effect”** The nature of cleat indentations could be considered an element of footing. However, this topic has not been studied in scientific experiments and no primary literature is available. A description has been provided in the problem description portion of this proposal (Section ??). @Zwaska2007 also described the corkboard concept and other desirable properties of the infield skin.

### 1.1.2 Ball response

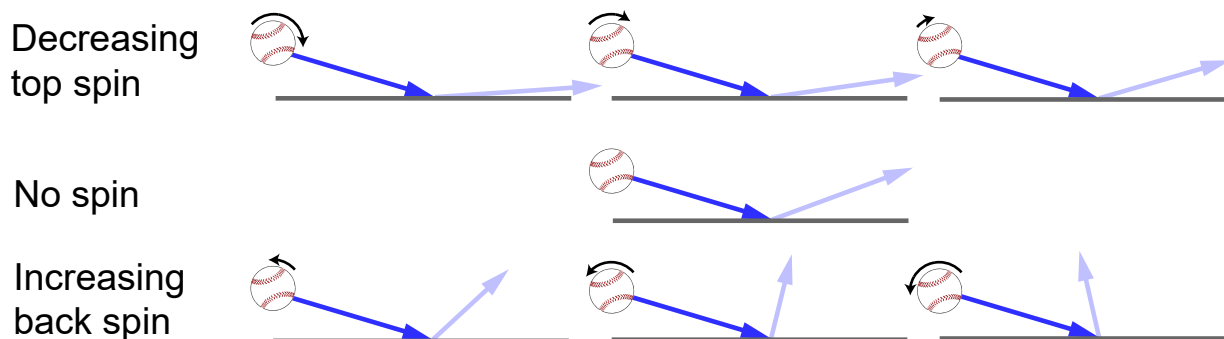
The reaction of a baseball upon contact with the surface plays a key role in the outcome of competition (recall Figures ??-??). As with footing, limited research is available on infield ball response.

@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. @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 [-@Brosnan2011]. Higher bulk density ( $\rho_{\text{bulk}}$ ) increased surface pace, although the range of bulk densities tested (1.2-1.8 Mg m<sup>-3</sup>) 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 1). 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 [-@Daish1972]. Alternatively, when friction is low, the ball will skid through impact and retain some of its original spin.

```
knitr::include_graphics("images/illustrations/ball_spin_effect/daish_fig_9.2_redraw.pdf")
```



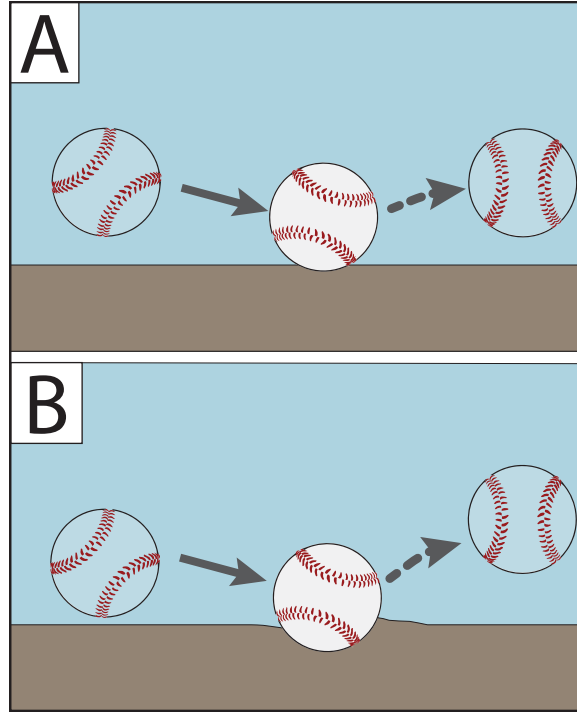
**Figure 1:** Initial spin will influence a ball's release angle following impact. Adapted from Daish, 1972.

When soil stiffness is low, the ball produces a notable deformation of the surface (Figure 2). An important consequence of the larger deformation is that the contact area between the ball and the surface is increased. This prolongs the impact duration and allows friction more time to operate [-@Daish1972]. This may be the critical feature which links hardness, bounce, pace, and ball spin. As the ball releases, it rolls up the saucer-like depression created by its own impact. This yields a slightly steeper release angle relative to that of a more rigid soil surface (Figure 2).

```
knitr::include_graphics('images/illustrations/ball_indentation_release_angle/ball_indentation_release_angle.png')
```

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 [-@Baker2006].

A laboratory study on surface friction of cricket soils was made by @Adams2001a. This experiment mixed the same clayey soil with 6 types of coarse amendments. All final mixes had sand contents between 30 and



**Figure 2:** 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.

40% by mass. Ball-to-surface friction was highest for the mix containing sand between 125-60  $\mu$ m. 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.

## 1.2 Laboratory tests of soil behavior and physical properties

The goal of laboratory soil testing is to assess or predict the properties of a soil in the field. Many laboratory soil tests are costly and time-intensive. 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 their precision and accuracy. This section summarizes literature on the two classes of laboratory tests pertinent to infield soils: plasticity tests and particle size analysis.

### 1.2.1 Plasticity tests

The behavior of fine-grained soil is markedly affected by its water content [Holtz2010]. Plasticity tests mark the water contents where behavioral thresholds occur for a given soil. This section reviews the tests’ history, methodology, and potential shortcomings.

**1.2.1.1 Origins of Atterberg limit test methods** The earliest test methods for soil plasticity were developed by Atterberg [Atterberg1911; Atterberg1974]. Plasticity<sup>1</sup> is the tendency of a material to

<sup>1</sup>from the Greek *plastikos*, “to mold or form”

deform under an applied load, without fracturing into multiple pieces, and to retain its new shape when the load is removed [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. He termed the upper boundary the ‘flow limit,’ at which two batches of soil paste flowed together when jarred. He defined the lower boundary as the ‘rolling limit,’ when the soil had dried enough to become brittle and could no longer be rolled into thin threads. The difference between the flow limit and the rolling limit was 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. These were:

- 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 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 distinction will be considered further in the section on soil toughness (??).

Atterberg’s work has never been fully appreciated in his own discipline of agricultural soil science. His test methods were improved and standardized by geotechnical engineers [Terzaghi1926; Casagrande1932]. Terzaghi1926 acknowledged the arbitrary nature of the tests but emphasized that their importance for preliminary soil investigations. He pointed out the value 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.’” - Terzaghi1926

**1.2.1.2 Modern protocols for Atterberg limits** Standard test methods typically pair the plastic and liquid limit tests. In the United States the relevant standards are ASTM D4318 2018 and AASHTO 2020 while BS 1377 1990 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.

**1.2.1.2.1 Liquid limit** The liquid limit test described by Atterberg 1911 lacked reproducibility because it required the operator to manually agitate the soil. A mechanical test method was first presented by Casagrande 1932 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 13 mm (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.<sup>2</sup> 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 [Sherwood1970a]

---

<sup>2</sup>These methods are purportedly traceable to the Russian researcher Piotr Vasilje [wikipediafallcone2021], although the author has been unable to verify this claim in primary literature because Vasilje’s work has not been translated to English.

2. Provide a more straightforward estimate of the soil's undrained shear strength [Haigh2016]
3. Ability to determine the liquid limit for some low-plasticity soils which cannot be tested with the Casagrande cup [Sherwood1970a; Sivapullaiah1985]

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 [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 [Holtz2010; OKelly2017].

**1.2.1.2.2 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.

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

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

Atterberg limit tests can be performed rapidly and require only simple equipment and few 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 their utility. This section outlines research on the precision and accuracy of the tests.

## 1.2.3 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.

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.

```
source("supplemental_R_scripts/Sherwood_1970_plots_facet_style.R")
```

```
##
## -- Column specification -----
## cols(
##   lab = col_character(),
##   soil = col_character(),
##   PL = col_double(),
##   LL = col_double()
## )
```

```

##
## -- Column specification -----
## cols(
##   soil = col_character(),
##   replication = col_double(),
##   PL = col_double(),
##   LL = col_double()
## )

##
## -- Column specification -----
## cols(
##   operator = col_character(),
##   method = col_character(),
##   B = col_double(),
##   G = col_double(),
##   W = col_double()
## )

##
## -- Column specification -----
## cols(
##   soil = col_character(),
##   test = col_character(),
##   comparison = col_character(),
##   mean = col_double(),
##   sd = col_double(),
##   cov = col_double()
## )

##
## -- Column specification -----
## cols(
##   replication = col_double(),
##   test = col_character(),
##   B = col_double(),
##   G = col_double(),
##   W = col_double()
## )

##
## -- Column specification -----
## cols(
##   operator = col_character(),
##   B = col_double(),
##   G = col_double(),
##   W = col_double()
## )

##
## -- Column specification -----
## cols(
##   soil = col_character(),

```



```

##   test = col_character(),
##   comparison = col_character(),
##   mean = col_double(),
##   sd = col_double(),
##   cov = col_double()
## )

##
## -- Column specification -----
## cols(
##   replication = col_double(),
##   test = col_character(),
##   B = col_double(),
##   G = col_double(),
##   W = col_double()
## )

##
## -- Column specification -----
## cols(
##   lab = col_character(),
##   soilB = col_double(),
##   soilG = col_double(),
##   soilW = col_double()
## )

## `summarise()` has grouped output by 'test_condition', 'soil'. You can override using the `.groups` a

## `summarise()` has grouped output by 'test_condition', 'soil', 'test'. You can override using the `.g

## `summarise()` has grouped output by 'test_condition', 'soil'. You can override using the `.groups` a
## `summarise()` has grouped output by 'test_condition', 'soil'. You can override using the `.groups` a
## `summarise()` has grouped output by 'test_condition', 'soil'. You can override using the `.groups` a

## `summarise()` has grouped output by 'test'. You can override using the `.groups` argument.

## `summarise()` has grouped output by 'soil'. You can override using the `.groups` argument.

```

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 3 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 3 also shows 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 clustered around their mean with maximum deviations of 1.2 units for the liquid limit and 0.9 units for the plastic limit.

```
att_lims_variation_plot
```

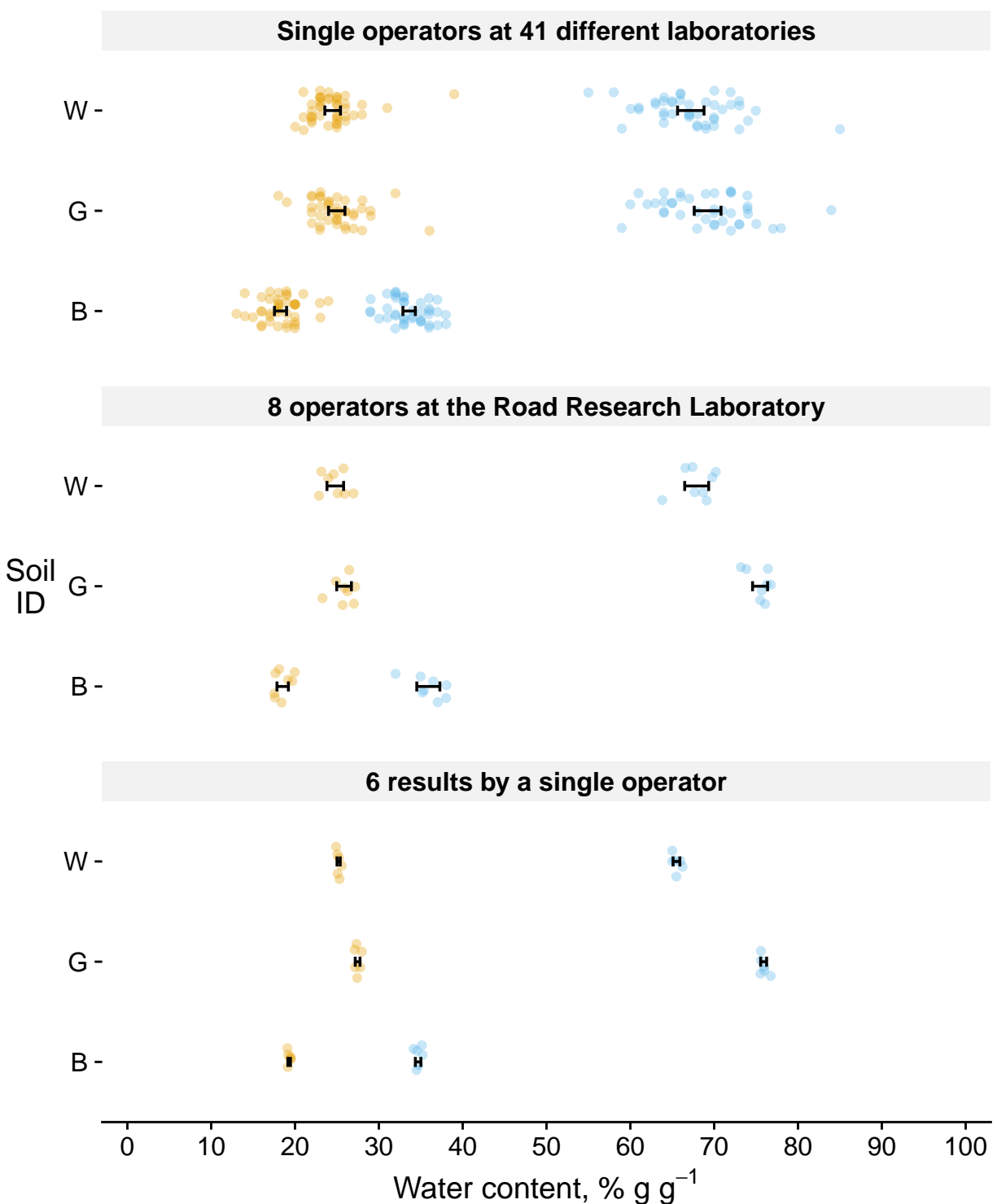
```

## Warning: Removed 8 rows containing non-finite
## values (stat_summary).

```

## Relative uncertainty among replicated plasticity tests

● Plastic limit    ● Liquid limit



Error bars span 95% confidence interval of the mean.  
Data re-plotted from Sherwood, 1970 (Tables 1, 3, 4).

**Figure 3:** Reproducibility is excellent for a single operator, fair among operators in the same lab, and relatively poor across laboratories.

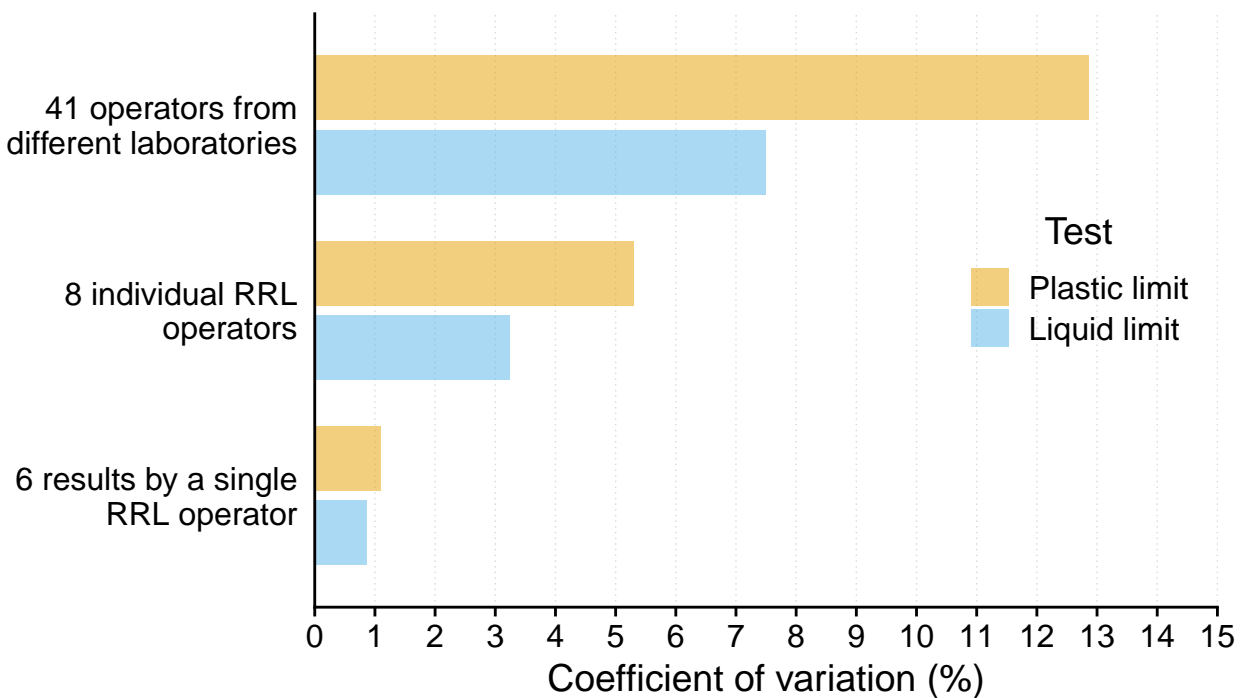
```
## Warning: Removed 8 rows containing missing
## values (geom_point).
```

The spread of data points in Figure 3 could be seen as misleading because the number of replicates was fewer for the within-lab and within-operator studies than the inter-lab study. Therefore it is useful to compare the coefficients of variation (COV) for the three studies. Figure 4 shows that the smaller range of results for a single lab or single operator is due to better precision and not to fewer samples being tested. Compared to the inter-lab study, the COV for one operator's replicates are smaller by a factor of \_\_\_\_\_. 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.

```
knitr::opts_chunk$set(fig.pos = "b")
att_limbs_cov_plot
```

## Coefficients of variation among replicated plasticity tests

Data re-plotted from Sherwood, 1970 (Tables 5 and 8).  
Bars represent mean COV across soils B, G, and W.



**Figure 4:** Atterberg limit tests are much more repeatable by a single operator than across operators or labs.

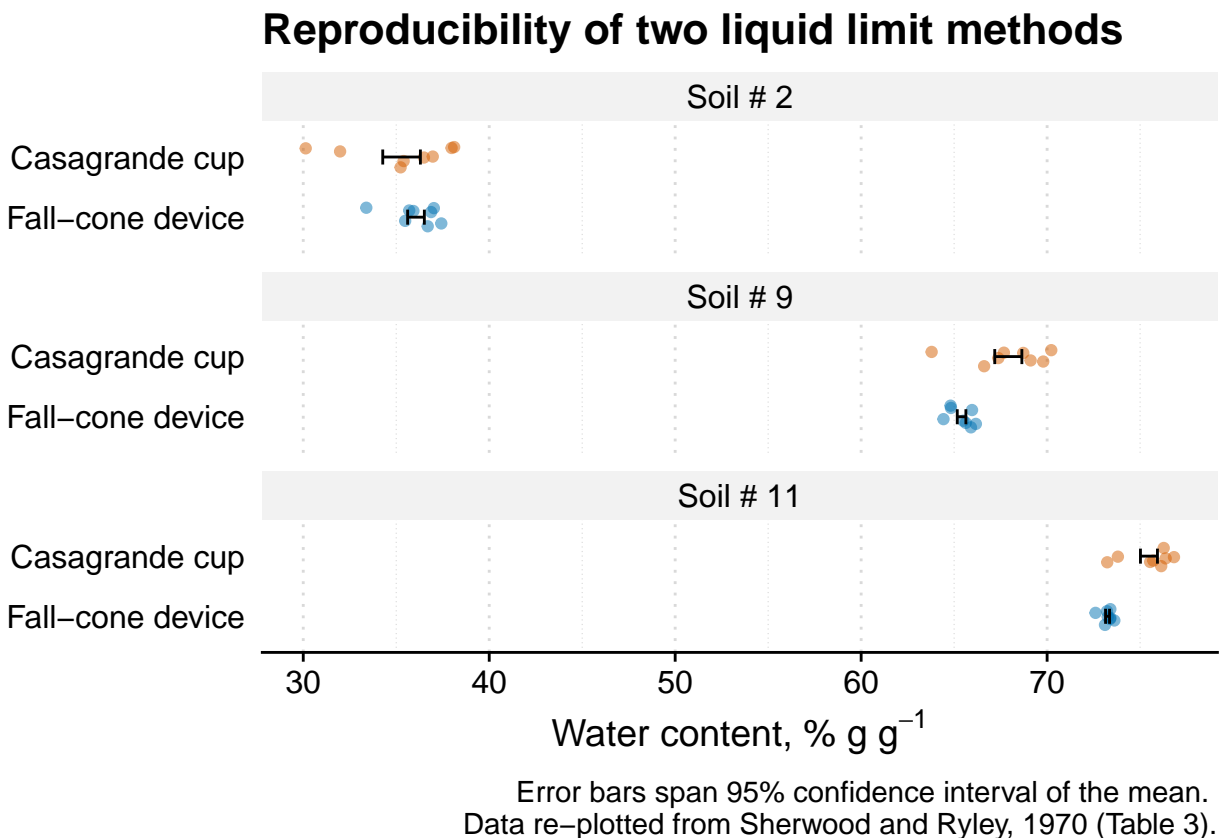
The liquid limit involves a mechanical device whereas the plastic limit test introduces a greater degree of operator judgment. One could expect better agreement for the liquid limit and this is clearly borne out in Figures 3-4.

A separate study by @Sherwood1970a showed that the fall-cone method has better inter-operator reproducibility. Figure 5 shows the spread of the 6 replicated tests for each method. The coefficient of variation among operators was about half that of the Casagrande method.

```
source("supplemental_R_scripts/Sherwood_Ryley_1970_plot.R")
```

```
##
## -- Column specification -----
## cols(
##   operator = col_character(),
##   method = col_character(),
##   `2` = col_double(),
##   `9` = col_double(),
##   `11` = col_double(),
##   test = col_character()
## )
```

```
sherwood_ryley_1970_table3_plot
```



**Figure 5:** 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, @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.

**1.2.3.1 Sources of error in Atterberg limit methods** 1.2.3 described the expected uncertainties associated with Atterberg limit results. It is next useful to explore the sources of these errors so they can be avoided as much as possible. 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 [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 source receives less attention than the test mechanics. 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 [Brady2007].

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

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 ( $w_{opt}$ ). The effect was small;  $\Delta w_{opt}$  was only ~0.5% when using granular/pelletized bentonite and not detectable for powdered bentonite. The effect of mixing procedure was more apparent. Mixing water with the sand prior to adding the bentonite increased  $w_{opt}$  by up to 2% compared with mixing the soil components dry and adding the water last.  $w_{max}$  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.

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 ° C. 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 cured with water before beginning the test. ASTM D4318-2018 prohibits drying above 60 ° C and requires a minimum 16-hour curing time.

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.

**1.2.3.1.2 Apparatus-related errors** 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.

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 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 @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 [@ASTMD43182018]. This finding suggests a large fraction 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 drop height caused by a loose locking screw [@Sherwood1970]. The drop height must be frequently calibrated to ensure accurate results [@ASTMD43182018].

#### 1.2.3.1.3 Operator technique errors 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 [@Casagrande1958]. Cutting a uniform groove can be especially challenging for soils containing sand [@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 [@ASTMD43182018]. Inadequate mixing of the specimen can also contribute to erroneous blow counts and water content determinations.

#### Plastic limit

Sources of error include the operator's rolling path, judgement of the crumbling condition, and weighing errors in the water content determination.

**1.2.3.2 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 [@Barnes2013]. @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. @Bobrowski1992 also stated 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. The Bobrowski-Griekspoor device was criticized by @Barnes2013, who cited the data of @Rashid2008 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 @Temyingyong2002. Their device used two acrylic plates similar to @Bobrowski1992 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.

@Temyingyong2002 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.

@Barnes2009 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-Maroto2015a described a plastic limit test in which 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 (2017???) 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

### 1.2.4 Soil toughness

Toughness is a conspicuous feature of clay soils. It plays an important role on the infield skin because the soil must be both stiff and ductile to achieve the corkboard effect. This section describes the nature of toughness and research which has measured or modeled it for clay soils.

**1.2.4.1 Definitions of toughness** 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. @Barnes2013; @Barnes2013b). Toughness is a measure of work and bears units of energy per unit volume ( $\text{Jm}^3$ ) [@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 [@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 1.2.1.1), and Casagrande noted [-@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 is not a test of shear strength or toughness. It merely reflects the water content at which a drying soil becomes brittle. Regrettably, the distinction has been blurred by authors who report the plastic limit as the water content corresponding to a particular value of cone penetration (for example, @Whyte1982). Reported values of peak strength at the plastic limit differ by up to 2 orders of magnitude [@Haigh2013]. There is no unique shear strength at the plastic limit.

@Barnes2009 described an apparatus which measures soil toughness directly. Barnes later published a series of papers on the toughness of clays in their pure state, admixed with sand and silt, or blended with other clays [-@Barnes2013; -@Barnes2013b; -@Barnes2018]. The Barnes device was originally intended to reduce variability in operator technique during the plastic limit test. Barnes realized that stress and strain could

be measured during the test and these could be translated to toughness. This work comprises the only published research which directly measured the toughness of clay soils.

Major findings by Barnes [-@Barnes2009; -@Barnes2013; -@Barnes2013b; -@Barnes2018] included :

1. New characteristic water contents and indices can be defined in terms of toughness. For example, the toughness coefficient is the rate of change in toughness as a function of water content.
2. Both clay-size content and clay-mineral content affect toughness. The general order of decreasing toughness at the plastic limit was montmorillonite > illite > kaolinite.
3. The addition of coarse particles decreased toughness by diluting the clay content. For equal ‘matrix water content’ (i.e. water per unit clay-size material) coarse particles *increased* toughness because of the increased work required to shear them through the viscous clay matrix. However, maximum toughness was lower for mixed soils because the presence of coarse particles brought the onset of brittle failure at a higher water content due to interparticle interference. these raised the plastic limit relative to the pure clay.
4. Some clays undergo strain-hardening during the rolling procedure, while others exhibit strain-softening behavior.
5. The toughness of clays does not obey the linear law of mixtures. Mixing two clays together will not result in a mixture whose behavior does not rellproportions. In other words, the behavior of the mixture cannot be predicted by a simple linear interpolation between the two pure materials.

The Barnes apparatus marks a significant advance, but it represents only one means of measuring soil toughness. Because it is a single, unique apparatus there is no information about the reproducibility of its results across operators. There is also no research comparing its results with other 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 limit does not represent the true limit of ductile behavior; it merely establishes an arbitrary if useful threshold for a single type of deformation. A soil can undergo ductile strain even when its water content lies below the plastic limit. This is readily observed when classifying soils with the USDA field texture evaluation. This method involves forming a ribbon with the thumb and fingers. A soil can often be “ribboned” but will crumble if rolled. This highlights the arbitrary nature of the thread rolling test and its cyclic shearing which tends to force air to the center of the thread.

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)).

**1.2.4.2 Computing toughness from index properties** @Casagrande1932 described the relationship of toughness to soil testing and classification:

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

The language above suggests Casagrande favored the use of a direct toughness measurement, but he also derived a formula to estimate a soil’s toughness.

The formula assumes a semi-logarithmic relationship between water content and shear strength exists over the whole range of plasticity. It uses the flow index derived from the liquid limit test to extrapolate the shear strength at the plastic limit. A steeper flow curve indicates less change in shear strength for a unit increase in water content. @Casagrande1932 derived the following formula for what he termed the ‘toughness index’:

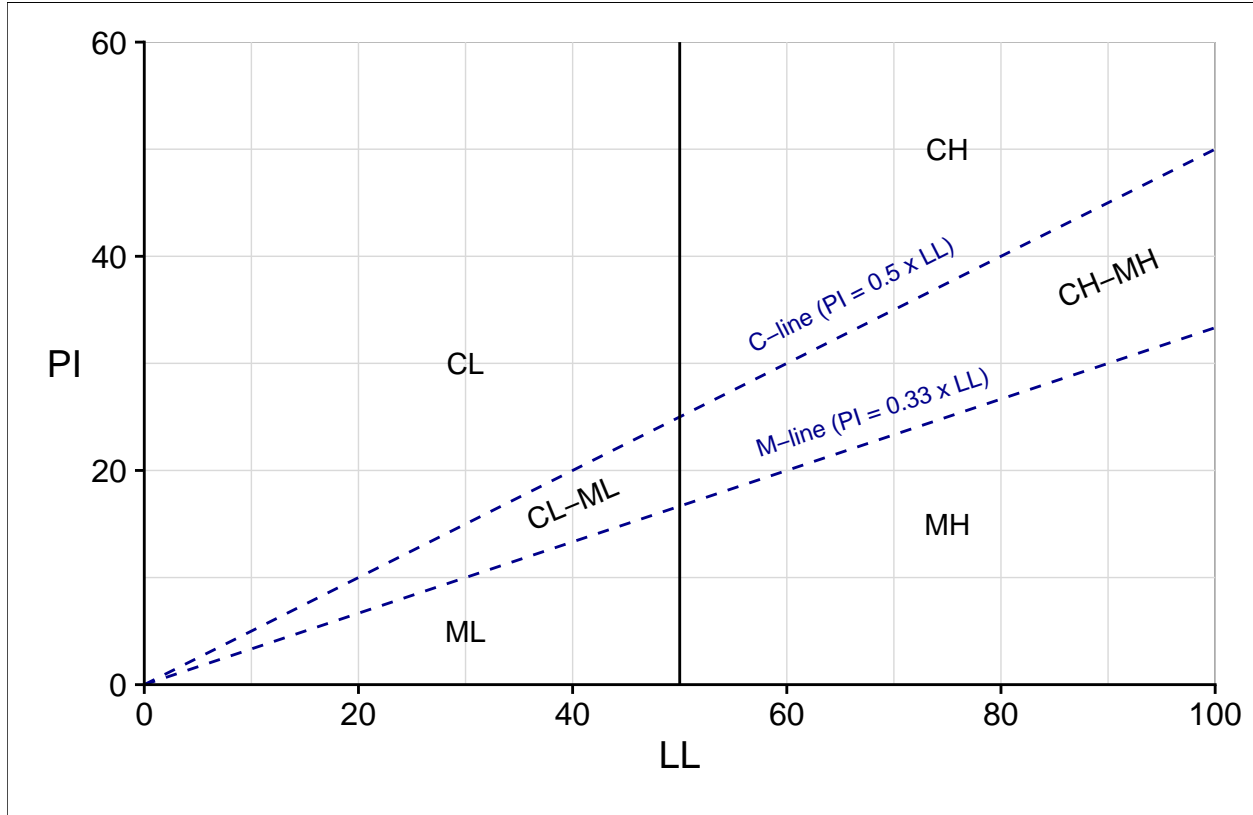


$$I_t = \frac{PI}{F}$$

where  $I_t$  is the toughness index,  $PI$  is the plasticity index, and  $F$  is the slope of the flow curve.

@Moreno-Maroto2018 used data from @Barnes2013 to develop an empirical equation for computing maximum toughness ( $T_{max}$ ) from the plastic and liquid limits of a specimen ?? . @Moreno-Maroto2018 also suggested a new basis for classifying fine-grained soils from their toughness equation (Figure 6 and qualitative observations [@Moreno-Maroto2017]).

```
source('draw_moreno-maroto_chart.R')
moreno_maroto_chart
```



**Figure 6:** Soil classification chart proposed by Moreno-Maroto and Alonso-Azcárate (2018). Toughness data from Barnes (2013) and the empirical equation from Moreno-Maroto and Alonso-Azcárate (2018) were used to define the positions of the C-line and M-line.

They retained the existing groups in the USCS but added additional groups for soils intermediate between silts and clays. The new chart eliminated the A-line and instead defined two lines to separate clays from intermediate soils and intermediate soils from silts. The lines were drawn on the basis of toughness computed from their equation and converted to LL and PL values.

Moreno-Maroto and Alonso-Azcárate later compared their own classification system with other systems based on plasticity [@Moreno-Maroto2021]. They noted that USCS tends to classify soils with high liquid limits but low toughness as clays and argued that toughness is the most defining feature of clay and behavior of these soils is more silt-like. They favored their own use of a quantitative property (toughness) to classify soils rather than the empirical A-line used by USCS. The author considers this claim to be rather circular

because any attempt to classify soils into groups invokes a degree of arbitrariness. The slopes of the C-line and M-line closely match the toughness classification given by @Barnes2009, but these too are arbitrary. Another limitation of the system described by @Moreno-Maroto2018 is that toughness is computed from an empirical equation and not measured directly. However, the emphasis on toughness by @Moreno-Maroto2018; @Moreno-Maroto2021 is valid and should be explored further.

@Vinod2017 also used data from @Barnes2013 to form an empirical correlation. Their objective was to predict the optimum moisture content for compaction at any compaction effort without actually performing a Proctor-style compaction test. They hypothesized that the optimum water content for compaction could be predicted from another property defined by @Barnes2013, termed the toughness limit. Barnes defined the toughness limit as the water content where a soil changes from an unworkable, adhesive consistency to a state having measurable toughness. @Vinod2017 first correlated the toughness limits of the 59 soils tested by @Barnes2013 with their respective liquidity indexes ( $I_L$ , defined as  $I_L = LL - PL$ ). @Vinod2017 found that the average position of the toughness limit was  $PL + 0.42 \cdot I_L$ . In other words, the toughness limit was 42% of the way between the plastic and liquid limits. This correlation was then used to develop an empirical equation to predict the optimum water content from the plastic limit, liquid limit, and compaction energy. The authors reported a good correlation, but the spread of their data shows that the optimum water content measured with an actual compaction test routinely differed by 5-10% from the value predicted by their equation. Although such an equation may be useful for a cursory investigation, the idea that it could replace compaction testing seems spurious.

**1.2.4.3 Summary: toughness research** The toughness of soil has not been studied extensively. Toughness is the total work needed to deform a specimen to failure. Work by G. Barnes has produced a useful device which directly measures toughness during a thread-rolling procedure. Empirical correlations can estimate soil toughness, but these should be validated with further experimentation.

## 1.2.5 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.

@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 7. 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.

## 1.2.6 Summary: laboratory tests of soil behavior and physical properties

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. \_\_\_\_\_

## 1.3 Behavior of artificial soil mixtures

Soil mixtures for baseball and softball fields typically contain two materials - a sand and a fine-grained soil. This section summarizes research about how the components of a soil mixture affect its behavior. Table ?? also shows that researchers have evaluated soil mixtures using a variety of analyses. This review focuses on studies which have measured compaction, Atterberg limits, shear strength, and toughness because these

properties are the tests most relevant to baseball and softball infields. Other methods which have been utilized include permeability, static compressibility, and pore size distribution.

In this section, the first topic outlined is the rationale for using engineered soils. Next, the concept of the transitional fines content is introduced. Third, specific research studies on coarse-fine mixtures are discussed. Finally, artificial mixtures containing multiple clay types are reviewed. For brevity, in this section the term “clay” simply refers to the fine-grained mixture component and does not connote any specific definition of texture, particle size, plasticity, or mineralogy.

### 1.3.1 Rationale for producing engineered soils

Natural materials do not always meet the requirements for a particular use. Natural soils<sup>3</sup> are commonly excavated and blended to benefit their physical or chemical properties [Brady2007]. The purpose of blending multiple soils is to create a mixture with properties not exhibited by any naturally occurring soil. These soils have been termed engineered soils [Thompson2008a]. Potters and brick masons were the likely first in antiquity to develop engineered soils using simple intuition and experience. Un-fired bricks containing clay mixed with organic residues have been dated to over 9,000 years before the present [Staubach2005]. Engineered soils are now used for agricultural, horticultural, geotechnical, environmental, and recreational purposes [Leake2014].

Control over the mixing process also permits a nearly identical soil to be produced repeatedly. When natural variation is encountered in the raw materials, the mixture may be adjusted so its final properties do not vary. The nature of soil solids is wide-ranging. Because these materials may be combined in any ratio, it is easy to imagine the nearly infinite number of possible soil mixtures.

The raw components incorporated into a mixture depend on its intended use. Materials which retain plant-available water and nutrients are favored for agricultural or horticultural operations. These include fired or expanded ceramic granules and various types of organic matter. Soil mixtures produced for engineering applications are usually limited to inorganic components. Gravel, sand, soil, coal ash, and lime are common components.

```
#.... %>%
#
```

```
# kableExtra::kbl(caption = 'Selected studies on behavior of coarse-fine soil mixtures. Measured physical
```

### 1.3.2 Transitional fines content of coarse-fine mixtures

Loads applied to a coarse-grained soil are transmitted through a skeleton of grain-to-grain contacts. The soil’s behavior 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.

If 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. The soil’s behavior becomes dominated by the fines with the coarse grains acting only as inert inclusions. This threshold has been termed the transitional fines content (TFC). The global void ratio also increases with fines content > TFC because solid sand particles are displaced by an equivalent volume of fines and inter-fine voids. The transitional fines content (TFC) is relevant to most infield mixes because they have fines content near the TFC. Infield soils are transitional materials because they must exhibit the plasticity of a fine-grained soil but the dimensional stability and workability of a coarse-grained soil.

It is important to acknowledge that the TFC is not a universal number. The majority of studies report values between 20 and 30% fines by dry mass with extreme values range 15 to 45% [Zuo2015; ]. The TFC value varies across mixtures because (1) it depends on the behavioral threshold of interest (for example,

<sup>3</sup>Here the term “soil” refers to a particular soil **material**, in contrast to a pedogenic definition which encompasses a characteristic arrangement of horizons and other features. See Section @ref(#definition-of-terms), Definition of Terms.

**Table 1:** Selected studies on the transitional fines content (TFC) of coarse-fine mixtures. Methods used to identify the TFC depends on the problem of interest.

Reference	Type of 'fines'	Tests performed
Cabalar (2011)	fine sand	consolidation (oedometer); dry shear strength (direct shear test)
Carrera (2011)	low-plasticity silt	oedometer, undrained shear strength (triaxial test)
Lade et al. (1998)	fine sand; nonplastic silt	minimum void ratio; undrained shear strength (triaxial test); liquefaction potential
Monkul and Ozden (2007)	kaolinite clay	consolidation (oedometer)
Thevanayagam (1998)	nonplastic silt	minimum void ratio; undrained shear strength (triaxial test)
Ueda et al. (2011)	fine sand	numerical modeling; dry shear strength (direct shear test)
Vallejo and Mawby (2000)	kaolinite clay	minimum void ratio; dry shear strength (direct shear test)

compressibility, shear strength, or permeability), and (2), a unique ratio exists for every combination of coarse-grained and fine-grained components. The total state of 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 [Zuo2015].

Researchers have defined the TFC using several methods (Table 1). A few examples include: calculations from phase relations and index properties [Thevanayagam1998; Monkul2007; Cabalar2011], the minimum global void ratio following compaction [Lade1998; Ueda2011], undrained shear strength during triaxial tests [Thevanayagam1998; Vallejo2000; Cabalar2017; Kim2018], parameters of the normal compression line or critical state line, [Cabalar2011; Carrera2011; Shipton2012] and liquefaction potential [Lade1997].

```
tfc_definition_methods <- readr::read_csv("data/lit-review-data/tables/selected_transitional_fines_content.csv")
dplyr::mutate(Reference = paste0(Citation, " (", year, ") "))%>%
dplyr::arrange(Citation) %>%
dplyr::select(Reference, `Type of 'fines'`, `Tests performed`, `Reported TFC ( % by mass)`) %>%
kableExtra::kbl(caption = 'Selected studies on the transitional fines content (TFC) of coarse-fine mixtures')
kableExtra::kable_styling()
```

```
##
## -- Column specification -----
## cols(
##   Citation = col_character(),
##   year = col_double(),
##   `Type of 'fines'` = col_character(),
##   `Tests performed` = col_character(),
##   `Reported TFC ( % by mass)` = col_character()
## )
```

```
tfc_definition_methods
```

**1.3.2.1 Maximum density and intergranular void ratio** The term intergranular void ratio was introduced by Thevanayagam1998 to describe the configuration of large grains in a coarse-fine mixture. Intergranular void ratio may be derived from phase relations (Fig 1.3.2.1) by considering 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 void ratio of the pure sand. When the void ratio of the granular phase surpasses that of the host sand, behavior will no longer be governed by contact between coarse grains.

\*\* good verbiage here : \*\* Minimum porosity of a mixture occurs when the fines and their interfine voids are just sufficient to fill the sand skeleton's larger voids. Many authors have defined the TFC as the fines content which produces the lowest total void space. This approach may not reflect the actual behavior of the soil because the global void ratio may not reach its minimum until  $e_{sand}$  has already exceeded the minimum  $e_{sand}$  for the host sand alone. The coarser grains act mostly independent of one another and behavior is already governed by the fines, thus the transition occurs at a lower fines content than would be suggested by the global void ratio [Cabalar2011].

**1.3.2.2 Size ratio** The theoretical maximum density of a coarse-fine mixture is determined by the maximum possible density of each component in its pure state. If the fines are assumed to be infinitely small, the global solids volume or packing fraction is

$$V_{solids} = 1 - n_{global} = 1 - [n_{coarse} \cdot n_{fines}] \quad (1)$$

where  $n_{global}$  is the global porosity,  $n_{coarse}$  and  $n_{fines}$  represent the porosity of each component when packed to their respective maximum densities.

For example, a sand having a minimum porosity of 0.35 and a clay having a minimum porosity of 0.4, the theoretical maximum packing fraction of the mixture is  $1 - [0.35 \cdot 0.4] = 0.86$  i.e. 14% porosity. Measured packing fractions in experiments are always lower than the theoretical maximum because the calculations rely on simplifying assumptions which are unlikely to be satisfied [Zuo2015]. Observed packing fractions in experiments range from 60% to 95% of the theoretical maximum [Furnas1931; McGeary1961; Zuo2015].

The size ratio between the coarse and fine components partially explains the discrepancy between calculated and experimental values [Lade1998; Ueda2011]. In Equation (1), it is assumed that the fines are infinitely small. The size ratio  $R$  was given by Lade1998 as the ratio between the mean grain size of each component:

$$R = \frac{D_{50 \text{ sand}}}{D_{50 \text{ fines}}} \quad (2)$$

The disparity between calculations and experiments increases with decreasing size ratio [Lade1998; Zuo2015]. If the coarse and fine soils have similar  $D_{50}$ , lodging of fines between the coarse grains is responsible for creating additional voids. A meta-analysis by Lade1998 concluded that if  $R < 7$ , any increase in the size ratio imparts a relatively steep increase in packing density (see Figure 8).

```
knitr::include_graphics('images/illustrations/Lade_1998_Figure_7/Lade_1998_Figure_7.pdf')
```

Additionally, Lade1998 showed that a void between closely packed spheres of equal sizes has a diameter of  $\sim \frac{1}{6.4}$  that of the large particles. Therefore, there is a fundamental reason for the abrupt change in slope at  $R \sim 7$ . For further increases in  $R$ , the observed void ratio slowly decreases toward its theoretical minimum. Numerical simulations indicate the intergranular void ratio is practically independent of  $D_{50 \text{ fines}}$  when  $R > 100$  [Ueda2011].

The geometrical calculations by Lade1998 assume a single particle size for each mix component. The packing density  $V_s$  of a two-component mixture is further increased when each individual component is well-graded. Reed1995 provided solutions for the optimum density of multi-phase mixtures when each has a log-normal particle size curve.

**1.3.2.3 Mixtures with more than 2 phases** Additional voids may be filled by in a coarse-fine mixture by adding progressively smaller particles. The overall void volume approaches zero as more components are added. McGeary1961 achieved a volumetric packing density of 0.951 (less than 5% porosity) with a four-component mixture. This extremely high packing density could only be achieved 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. @McGeary1961 noted that this mixture could still be poured from its container.

**1.3.2.4 Plasticity of fines** Most research on the transitional fines content has focused on sand mixed with nonplastic fines. This research bias is likely due to the high liquefaction risk posed by silts. It also may reflect the speed at which the experiments can be performed. Mixtures of sand with silt can be vibrated to their maximum density in an air-dry condition, while investigations of sand mixed with plastic clay require more laborious dynamic compaction methods [ASTMD4253-16; ASTMD698-12e2]. Plasticity index has been positively correlated with optimum water content for compaction [Sridharan2005a; Verma2019]. Therefore, by increasing the plasticity of the fines, one would expect the maximum achievable density of a sand-clay mix to occur at a lower fines content. Compared to a low-plasticity clay, more of the intergranular space is occupied by water in a zero-air voids condition ( $S_e = 1$ ).

**1.3.2.5 Method of compaction/consolidation** Mixtures subjected to static compression in an oedometer exhibit typical void ratio vs. log pressure curves. When this method is used, higher ultimate density values are attained compared to dynamic compaction tests. The difference in ultimate density can be attributed to more complete evacuation of air from the voids. A soil compacted at its optimum water content typically retains air in 5-15% of its void volume ( $S_e = 0.85 - 0.95$ ) [Holtz2010]. Slow consolidation from a saturated condition generates a higher final density because there is no entrapped air. Oedometer experiments on artificial soil mixtures probably have less practical significance than compaction experiments because engineered soils are usually installed in an unsaturated condition.

#### 1.3.2.6 Transitional fines content summary

- There is no universal value for the TFC (for example, 70 %);. Values range from 15-45 % by mass and are specific to a given mixture, specimen preparation method, and problem of interest.
- Factors affecting the TFC value in a binary mixture include sand gradation, plasticity of the fines, compaction energy, and behavioral parameter of interest.
- Soil mixtures are described by mass, but descriptions of behavioral thresholds are best specified using volumetric relations. This accounts for the presence of void volumes and specific gravity differences between the solids.
- Calculations provide a useful starting point or estimation of the TFC, but experiments are required for a more precise solution.

### 1.3.3 Effect of coarse fraction on mix behavior

**1.3.3.1 Effect of sand content** @Seed1964a 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  $\mu$ m.

The liquid limits of the sand-bentonite 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. Therefore, it was not clear whether the linear relationship would have persisted above 50 % sand.

@Seed1964a showed that the slopes of liquid limit vs. sand content lines differed by clay type. The slopes were in close agreement with the Skempton activity of the clay, computed as  $\frac{LL}{\% < 2 \mu m}$ . The relationship to clay activity held regardless of whether the sand was mixed with a single clay or a pre-blended clay mixture.

The plastic limit of the bentonite-sand mixtures also followed a linear relationship with increasing sand, up to the highest percent sand tested (75%). The illite and kaolinite clays showed a linear relation only at low sand contents. With sand content of 50% or higher, the plastic limits were higher than would be predicted by a simple linear regression line. This suggests that 50% sand is enough for the sand grains to affect the soil's behavior.

A more precise curve of PL vs. sand content could not be established because of the small number of sand contents tested. The authors tested only 4 sand contents for the illite clay and 3 sand contents for the kaolinite clay, so a departure from the linear trend could have begun anywhere between 25 and 75% sand.

@Dumbleton1966a measured the Atterberg limits of 2 types of clay mixed with 5 types of coarse particles. Both kaolinite and montmorillonite showed linear decreases in their Atterberg limits up to 50 % sand. Few conclusions can be drawn for higher sand contents; with 75% sand the kaolinite evidently became nonplastic but montmorillonite had a measurable liquid and plastic limit. Like @Seed1964a, the researchers tested only 4 sand contents so the shape of the relationship cannot be clearly discerned above 50% sand.

@Sivapullaiah1985 also studied mixes of sand with pure clay materials. In such a mixture, if the sand grains act merely as inclusions within the clay-water matrix, the liquid limit of the mixture should decrease in direct proportion to sand content. @Sivapullaiah1985 termed this effect the “linear law of mixtures.” Like @Seed1964a, @Sivapullaiah1985 showed that the linear law is only valid up to a maximum sand content which depends on clay type. Evidence was given as (1) liquid limits which are systematically higher than predicted by the linear law, and (2) plastic limits *increasing* with greater sand content once 60% sand was reached, rather than decreasing as expected.

@Sivapullaiah1985 clearly demonstrated that the linear law is not valid over the full range of 0-100% clay, but only one data point was collected between 0 and 60% sand. Therefore, the shape of the liquid limit vs. sand content curve below 60% sand cannot be discerned from their data.

@Nagaraj2016 and effect of sand size and clay type on shear strength of sand-clay mixtures ...[[[[]]]]

**1.3.3.2 Effect of sand/silt particle size** The influence of coarse particle additions' particle size was tested by @Sivapullaiah1985. For equal sand percentages, both the liquid and plastic limits were affected by the size of the added sand particles. Mixes containing coarser sand (425  $\mu$ m – 150  $\mu$ m) adhered more closely to the linear law of mixtures than finer sand having only particles 150  $\mu$ m – 75  $\mu$ m. Mixes containing silt (rather than sand) deviated even further from the linear law.

@Dumbleton1966b mixed kaolinite or montmorillonite with either coarse sand, fine sand, or silt. For the same percent 'coarse addition,' coarse sand caused a smaller change in the Atterberg limits while fine sand had a larger effect, and the effect of silt was even greater.

@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. Finer particles decreased a mixture's toughness at its plastic limit. @Barnes2013 argued that increased the clay's toughness was higher at a given 'matrix water content' (water per unit <2mm fraction), but this is a somewhat abstract idea because water is also associated with particles > <2mm. reflected only when all the soils were above their respective plastic limits.

**1.3.3.3 Effect of sand particle shape** @Sivapullaiah1985 found no effect of sand particle shape on the Atterberg limits. Bentonite clay was mixed with equal amounts of either angular or round sand of the same particle size fraction (150  $\mu$ m – 75  $\mu$ m). Sand contents ranged from 20 - 95 %. There was no discernible difference in the liquid or plastic limits.

Dumbleton and West [-@Dumbleton1966b] studied the influence of the coarse fraction's shape on Atterberg limits. Increasing departure from spherical and round particles tended to raise both the liquid and plastic limits by roughly equivalent amounts. 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 differs from that of @Sivapullaiah1985, whose data showed no difference between angular and round sands of the same sieve diameter.

**1.3.3.4 Effect of sand uniformity** The uniformity of sand included in soil mixtures has not been studied extensively. @Dumbleton1966b found that mixes made with broadly-graded sand had similar Atterberg limits to mixes containing sand from a single mesh size. However, a detailed particle size distribution was not given in this study so it is difficult to know how large the difference in uniformity was between the sands. It could be assumed that 100% of the sand passed the #40 sieve (425  $\mu$ m) because this is the standard range of allowed sand sizes in Atterberg limit tests. If this were the case, the range of sand particle diameters would only fall between  $\sim$ 50 to 425  $\mu$ m. This narrow range precludes efficient particle packing (see Section @ref(#tfc-size-ratio)); it is possible the uniformity would play a bigger role if coarser sand were used in the mixture.

### 1.3.4 Effect of mixing multiple clay types

When two clays are combined, the resultant mixture often has properties which are more reflective dominant dominated by one of the clays.

the resultant mixture has properties which do not necessarily reflect the proportions of the mixture. A small amount of a high-activity clay such as monmorillonite can dominate the behavior of the mixture. @Seed1964a extended their work on pure clays to three-component mixtures in which two types of clay were first mixed together before adding the sand.

Adding kaolinite to either illite or smectite had a nearly proportional effect on the Atterberg limits. 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. However, mixtures of smectite with illite did not adhere to this linear relationship. The liquid limits of smectite-illite mixes were always lower than predicted by the linear law. Small additions of illite to smectite lowered the LL by more than expected, and small additions of smectite to illite raised the LL by less than expected. An opposite effect was observed for the plastic limit. With small bentonite additions, the plastic limit was lower than expected, while for larger bentonite additions it was higher than expected.

Barnes study

Dumbleton and West

Ceramic textbooks :

Clay bodies for ceramic applications are commonly manufactured by adding a 1-3% bentonite {ref}. It is evident that a minute amount of one clay can drastically alter the behavior of a mixture. [ref??]

For equal sand contents, the plastic and liquid limits of the mixtures did not lie on a linear interpolation between those of the pure clay endmembers.

@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. This implies an interaction between the clay mineral particles.

### 1.3.5 Summary: behavior of artificial soil mixtures

Soils are often mixed to benefit their properties.

....

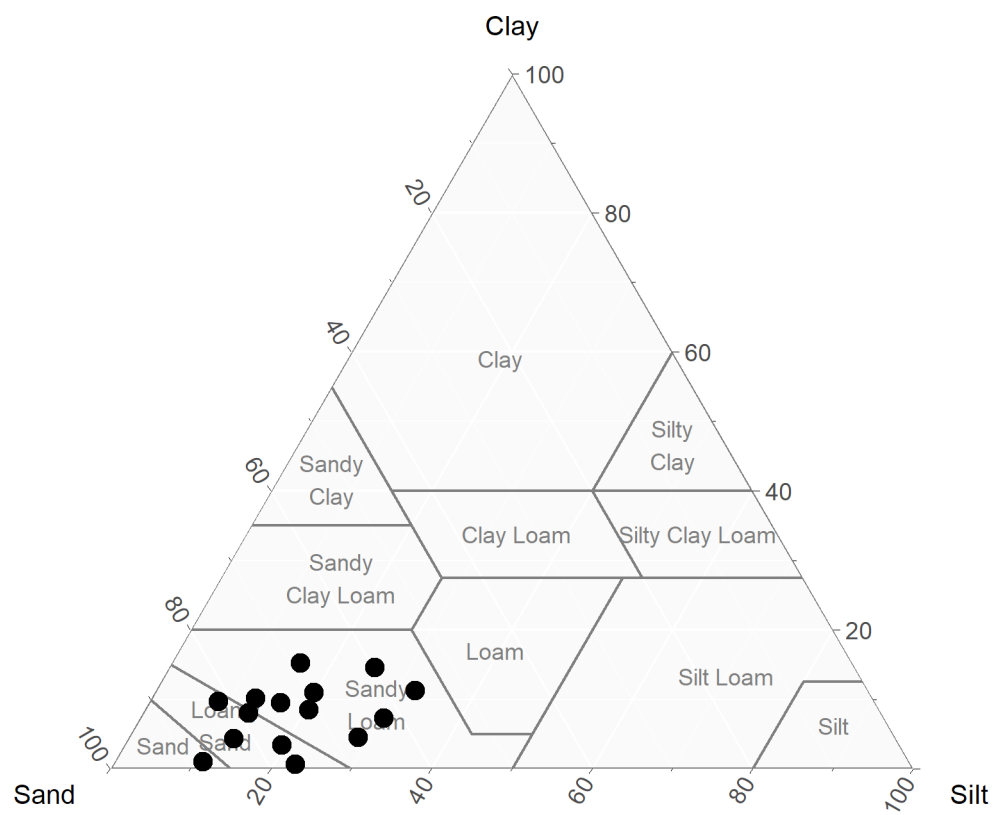
These findings collectively demonstrate the complex behavior that results when two or more soils are artificially mixed. This is particularly true when multiple clay types are combined. @Seed1964a concluded that this technique could be very useful in designing soil mixtures:

“Such a blending of two soils, producing a new soil with characteristics better than both of its constituents, would be an interesting addition to soil stabilization techniques.”

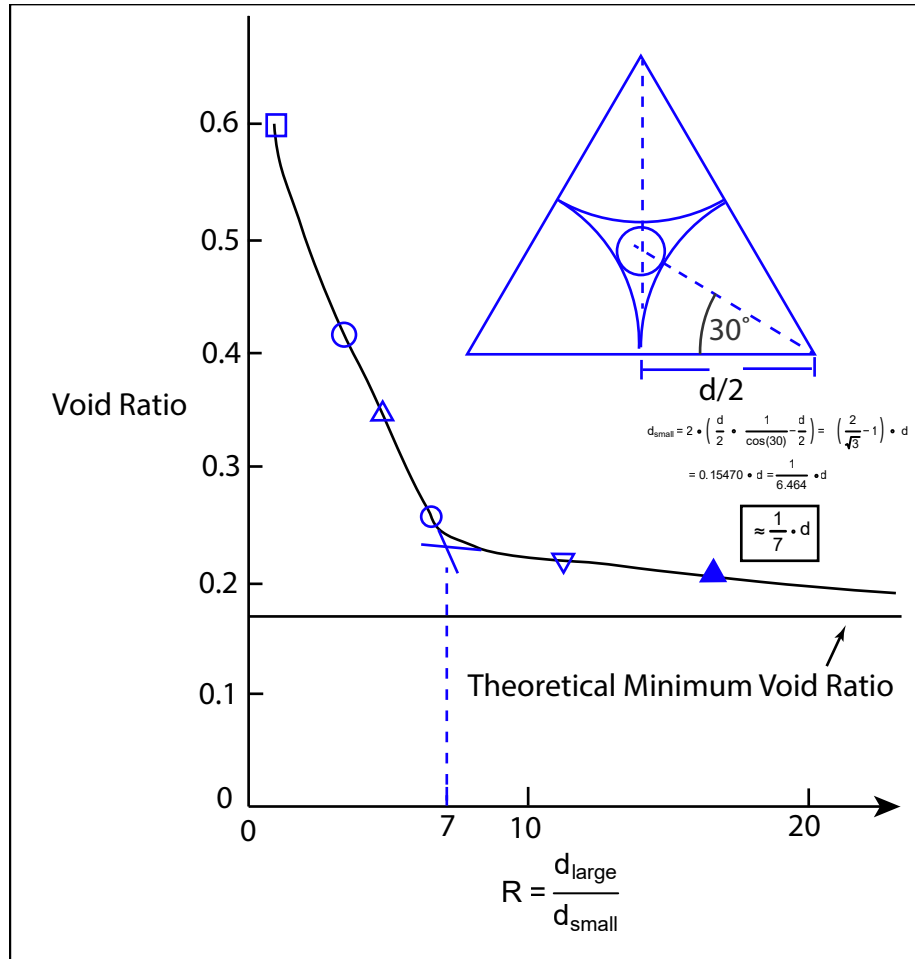


**1.3.5.1 Notable research gaps to address in this project:** There are no data available on the brittle and ductile response of soil to cleated baseball shoes. Data pertaining to sand-clay mixes only have tested sand with particle sieve diameters of  $< 425 \text{ }\mu\text{m}$ . The transitional fines 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.



**Figure 7:** Infield soils surveyed by Brosnan (2008a)



**Figure 8:** When the ratio of particle diameters is  $< 7$ , increases in the size ratio improve packing density. Above  $R$  of 7-10, little density increase is observed. Reproduced from Lade et al. (1998).