Laser Diffraction Particle Size Distribution of North American Turfgrass Horse Racing Surfaces

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Highlights

- Laser diffraction analysis of soil particle size distribution is uniquely suited for active turf racetracks.
- Eight standard sampling locations are shown to be sufficient for characterizing a racing surface.
- Differences between the three archetypes of turfgrass racing surfaces were significant using laser diffraction.
- There is a need for consensus on the proper handling of organic content in samples.

Abstract. *Significant research has focused on North American dirt and synthetic Thoroughbred racing surfaces. Turfgrass racing surfaces have received less consideration. Basic information, including climate and turfgrass species, can be documented relatively easily. However, a key characteristic, the particle size distribution of the growing medium, is not readily available for turf tracks. Particle size distribution and the deviation from nominal values are important to infiltration rate, shear strength, and turf health, as well as being critical for the selection of top-dressing and divot repair sand. The primary difficulty with obtaining the particle size distribution is the relatively large quantity of material required for traditional sedimentation test methods. Sampling an active racing surface could present a risk to the horses and riders. Laser diffraction testing methods present an opportunity to use much smaller samples. The use of smaller samples introduces new questions about the ability of a small sample to represent a large area, such as a racetrack. Tests were carried out with high resolution sampling at one racetrack. By sampling a large number of locations, 96 locations on a single racetrack, the variability of the track could be evaluated, and an eight-sample protocol was developed. Using the eight-location protocol, 22 additional turf racetracks throughout North America were sampled. A total of 23 turf racetracks were tested, representing all three of the designs used for North American turf racetracks. By looking at the three different track designs: engineered profile, engineered profile with fiber, and native soil, appropriate testing parameters and measurements were identified. While the primary objective was to understand turf racetracks, this unique data set also provided a method to investigate the applicability of laser diffraction for the analysis of soil samples. Mineralogy and organic content had previously been identified as important in the measurement of particle size distribution using laser diffraction. Mineralogy and organic content were determined for samples from each surface using X-ray diffraction (XRD) and loss on ignition. The PSD of the three types of turfgrass horse racing surfaces showed significant differences between native soil (N), engineered surfaces without synthetic fibers (EWOF), and engineered surfaces with synthetic fibers (EWF). These basic design descriptions were also found to be sufficient for making reasonable estimates of the settings used in the machine configuration and sample preparation. A single refractive index was used for the entire range of samples in this group; however, the sample quantity tested was different for the three different types of track designs.*

Keywords. *: Horse, Laser diffraction, Racing, Soil, Thoroughbred, Turf, Turfgrass.*

While thoroughbred racing has been part of American life since the colonial era, the risks to human and equine athletes have become an important concern. Of particular concern are catastrophic injuries, which are defined in The Jockey Club's Equine Injury Database as death or euthanasia of the horse within 72 hours of a race (The Jockey Club, 2022). While the causes of catastrophic Thoroughbred injuries are multi-factorial, the consistency of the racing surface is generally accepted as one of the factors that affects every horse on the track

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(Peterson et al., 2012). While the literature often focuses on equine athletes, jockeys were also found to be "171 times more likely to be injured when they rode a horse that died in a race" (Hitchens et al., 2014). In particular, the condition or "going" of turf racing surfaces has been shown to directly impact the likelihood of injury to the horse (Georgopoulos and Parkin, 2016; Hitchens et al., 2019; Rosanowski et al., 2018) and jockey (Hitchens et al., 2010). While a consistent racing surface is one of many factors impacting risk to the horse and rider, it is part of the overall focus on safety.

The current understanding of requirements for consistent racing surfaces includes maintenance, materials, base considerations, and moisture content (Peterson et al., 2012). The dynamics of the hoof-surface interaction (Thomason and Peterson, 2008) and the magnitude of the loads on the hoof are particularly important to understand for horse racing surfaces (Setterbo et al., 2009), since the loads are much higher and applied at a higher loading rate than the surfaces used for human athletes. The majority of racing in the United States and Canada is conducted on dirt and synthetic surfaces. However, the percentage of races conducted on turf surfaces in North America has increased significantly in recent years (The Jockey Club, 2022). At the same time, the understanding of turf racing from countries in which turf is the primary racing surface does not always apply to horse racing in North America. North American races are conducted in a counterclockwise direction on oval tracks. Some turf tracks may have as many as 8,000 starts over meets that can last nearly 200 days per year (The Jockey Club, 2022). At the same time, North American turf racing is rarely conducted on wet turf surfaces since turf tracks have adjacent dirt or synthetic surfaces to transfer the races, which can protect the turf from damage. The amount of time after a rainstorm during which races are moved to other surfaces is both an economic and a safety consideration. The recovery time after a storm is influenced by the design of the track, with native soils typically being the slowest to recover from rain and fiber reinforced sand being the fastest. The most common surface is a bespoke sand surface with some fine material used to increase the shear strength.

The composition and closely related mechanical properties of dirt racetracks have been shown to vary by geography and climate, at least in part because of the need to maintain a consistent moisture content in the track (Mahaffey et al., 2012). Geographic and climate trends may also apply to turfgrass racing surfaces. The surface composition will influence the surface's resistance to compaction, soil water retention, hydraulic conductivity, and the ability to grow healthy turf, which produces a dense network of root fibers that reinforce the footing. The particle size distribution of the growing media, soil mineralogy, amount of organic matter present, and turfgrass species cultivated all combine to produce a unique set of conditions that influence the hoof-surface interaction. Knowledge of a racing surface's composition is critical for the purpose of ongoing maintenance decisions, including irrigation and topdressing. The selection of topdressing material will prevent layering and enhance drainage. Using topdressing material with a narrow particle size distribution that matches the mean value of the existing particle size distribution will maintain or enhance track drainage. Matching existing sand for divot repair will also help provide a more consistent racing surface.

A primary reason that the particle size distribution has not been reported for existing turf racetracks is the requirement to remove a large specimen for particle size analysis by the common sedimentation methods. Given the potential for spatial variation in the surface, the removal of several large samples is particularly difficult. Areas of concern in the track where damage or contamination has occurred can also be evaluated if small samples can be removed. Compared to sedimentation methods, soil testing performed using laser diffraction requires only a small specimen and also has reduced analysis time and increased repeatability (Eshel et al., 2004). Specimens tested using laser diffraction are well suited to removal from turf racetracks and sports surfaces since the samples removed can be the same size as cores, which are commonly extracted during aeration. Aeration is a common cultural practice for turf racetracks to reduce compaction of the surface and encourage root growth (Dalsgaard et al., 2020).

Laser diffraction is based on a different set of assumptions compared to sedimentation methods. Sedimentation methods include sieve-pipette and sieve-hydrometer methods (Gee and Bauder, 1986). A relatively large sample, 100 g in the case of high sand content mixtures, is typical. These methods have been used extensively in the soil science community over many years, in spite of the labor required (Fisher et al., 2017). The analysis of sedimentation methods is based on Stokes' law, which assumes that spherical particles are suspended in solution. Clay particles do not fit this assumption well since they may have aspect ratios of 100 or more (Veghte and Freedman, 2014). Sedimentation results are reported as a percent of the mass of the sample (Gee and Bauder, 1986). Laser diffraction, in contrast, is based on the scattering of light and thus the volume of the material rather than the mass (Sperazza et al., 2004). The differences between volume and mass are minimal for sand since the density of most of the minerals is similar. However, this distinction has a significant effect on samples with organic material because of differences between the densities of mineral soil particles and organic matter. Furthermore, laser diffraction has been shown to report higher percentages of silt and lower percentages of clay compared to sedimentation results for equivalent samples (Yang et al., 2019).

This article explores the use of laser diffraction to measure the particle size distribution of the growing medium used in turfgrass surfaces used for Thoroughbred racing. General characteristics of the racing surfaces, such as turfgrass grown, climate factors, and mineralogy, are documented in order to facilitate future testing by identifying factors that may impact the results. The suitability of this method for this testing application is considered for turf profiles typically used in horse racing.

Materials and Methods

Turf Course Descriptions and Sampling Locations

Track Descriptions

Soil samples collected from 23 turfgrass racing surfaces across North America represent the three commonly used track designs. Specifically, these designs are identified as native soil (N), engineered surfaces without synthetic fibers (EWOF), and engineered surfaces with synthetic fibers (EWF). The native soil racetracks have not received any significant modifications to their profile. EWF racing surfaces have either been significantly modified or completely renovated and incorporate the use of synthetic fibers to increase shear strength (Henderson et al., 2009). EWOF racing surfaces have either been significantly modified or completely renovated and do not incorporate the use of synthetic fibers. The turf racetracks sampled for this study are Aqueduct Racetrack Inner (AQUI), Aqueduct Racetrack Outer (AQUO), Belmont Park Inner (BELI), Belmont Park Outer (BELO), Churchill Downs (CD), Del Mar Thoroughbred Club (DM), Ellis Park (EP), Fair Grounds Race Course (FG), Golden Gate Fields (GG), Gulfstream Park Inner (GPI), Keeneland Race Course (KEE), Laurel Park (LRL), Oklahoma Training Track (OKTT), Pimlico Race Course (PIM), Palm Meadows Training Center (PMTC), Parx Racing (PRX), Remington Park (RP), Santa Anita Park (SA), Saratoga Race Course Inner (SARI), Saratoga Race Course Outer (SARO), Woodbine Racetrack Inner (WOI), Woodbine Racetrack Outer (WOO), and Woodbine Racetrack Training (WOT).

Table 1 details the location and climate data for all 23 racetracks. This information can help provide a framework for understanding cultural practices and maintenance

Table 1. Summary of track locations, climate data, turfgrasses grown, and archetype.

		Annual Precipitation (cm)		Annual Mean Temp (°C)		Annual Avg High Temp (°C)		Annual Avg Low Temp (°C)					
Track	City, State	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Turfgrass Species 1	Turfgrass Species 2	Fiber, Y/N/T[a]	Archetype
AQUI	Jamaica, NY	1142.7	209.9	13.1	0.57	17.1	0.62	9.1	0.54	Kentucky Bluegrass	…	N	EWOF
AQUO	Jamaica, NY	1142.7	209.9	13.1	0.57	17.1	0.62	9.1	0.54	Kentucky Bluegrass	…	N	EWOF
BELI	Elmont, NY	1173.3	250.2	13.9	0.75	17.7	0.76	10.1	0.77	Kentucky Bluegrass	…	N	EWOF
BELO	Elmont, NY	1173.3	250.2	13.9	0.75	17.7	0.76	10.1	0.77	Kentucky Bluegrass	…	N	EWOF
CD	Louisville, KY	1362.5	249.8	15.2	0.75	20.4	0.83	10.0	0.73	Tall Fescue[b]	Kentucky Bluegrass[b]	Y	EWF
DM	Del Mar, CA	246.7	92.5	16.5	0.76	19.6	0.84	13.5	0.72	Bermudagrass	…	Y	EWF
EP	Henderson, KY	1339.2	261.9	14.2	0.79	19.8	1.03	8.7	0.60	Bermudagrass	…	N	N
FG	New Orleans, LA	1662.6	172.5	21.9	0.76	26.5	0.73	17.3	0.85	Bermudagrass	Perennial Ryegrass[c]	Y	EWF
GG	Berkeley, CA	552.1	260.5	14.8	0.66	19.3	1.50	10.4	1.03	Kentucky Bluegrass	Perennial Ryegrass	Y	EWF
GPI	Hallandale Beach, FL	1700.1	318.4	25.0	0.34	28.7	0.31	21.3	0.43	Bermudagrass	…	N	EWOF
KEE	Lexington, KY	1402.2	242.3	13.8	0.72	19.2	0.86	8.3	0.65	Tall Fescue	Kentucky Bluegrass	Y	EWF
LRL	Laurel, MD	1177.5	252.6	13.7	0.61	18.9	0.69	8.4	0.61	Tall Fescue	Kentucky Bluegrass	N	EWOF
OKTT	Saratoga Springs, NY	1164.0	146.4	9.3	1.21	15.2	1.06	3.4	1.41	Kentucky Bluegrass	Tall Fescue	N	EWOF
PIM	Baltimore, MD	1236.9	285.8	13.9	0.80	19.3	0.88	8.5	0.76	Tall Fescue	Kentucky Bluegrass	N	N
PMTC	Boynton Beach, FL	1606.8	280.6	24.5	0.59	29.0	0.41	20.1	0.96	Bermudagrass	…	N	EWOF
PRX	Bensalem, PA	1364.4	251.7	12.2	0.59	18.0	0.66	6.4	0.65	Tall Fescue	Kentucky Bluegrass	T	EWOF
RP	Oklahoma City, OK	980.2	267.9	16.4	0.86	22.7	1.05	10.0	0.72	Bermudagrass	Perennial Ryegrass[c]	N	EWOF
SA	Arcadia, CA	372.1	150.8	17.2	0.71	21.5	0.72	12.9	0.77	Bermudagrass	Perennial Ryegrass[c]	Y	EWF
SARI	Saratoga Springs, NY	1164.0	146.4	9.3	1.21	15.2	1.06	3.4	1.41	Kentucky Bluegrass	Tall Fescue	N	EWOF
SARO	Saratoga Springs, NY	1164.0	146.4	9.3	1.21	15.2	1.06	3.4	1.41	Kentucky Bluegrass	Tall Fescue	N	EWOF
WOI	Toronto, Ontario, Canada	885.1	99.1	9.5	0.96	14.0	1.00	4.9	0.96	Kentucky Bluegrass	Perennial Ryegrass	Y	EWF
WOO	Toronto, Ontario, Canada	885.1	99.1	9.5	0.96	14.0	1.00	4.9	0.96	Kentucky Bluegrass	Perennial Ryegrass	N	EWOF
WOT	Toronto, Ontario, Canada	885.1	99.1	9.5	0.96	14.0	1.00	4.9	0.96	Kentucky Bluegrass	Perennial Ryegrass	N	N

[a] The presence or absence of fiber is denoted as Y = Yes, N = No, and T = Trace for minor, trace amounts of fiber present in samples.

[b] CD was renovated in the summer of 2020 to bermudagrass with a perennial ryegrass overseed for winter coverage. References to CD in this paper are based on the track prior to renovations.

[c] Denotes this grass is overseeded for winter coverage and removed in the spring Sampling Locations.

schedules. Annual precipitation, average annual temperature, average annual maximum temperature, and average annual minimum temperature information was obtained from the National Centers for Environmental Information for the ten-year period of 2011 through 2020 (NCEI, 2021).

The suitability of laser diffraction testing requires the ability to measure the range of soil types used for the turfgrass or turfgrasses cultivated as well as dealing with materials that may include the use of synthetic reinforcing fibers. Table 1 also details the track design, or archetype, of each surface along with the turfgrasses cultivated, which were documented based on sample observations and verified by consulting with the racetrack superintendents.

Two sampling protocols were used: high spatial resolution sampling was used for one track and a lower resolution spatial sampling on the additional 22 turf tracks. Spatial variation in the composition, both radially from the inside rail and circumferentially, from one pole to another, is of interest since it can affect the shear strength and moisture content. To help determine the number of samples required to characterize the surface, a total of 96 samples were collected from Keeneland Racecourse (KEE). Specifically, samples were collected at every 1/16th mile pole at distances of 1 m, 4.8 m, 8.6 m, 12.4 m, 16.2 m, and 20 m from the innermost rail location. However, as the track is only 18m wide at the 3/8 pole, that was the outermost location sampled at that position. The basic set of eight samples, like those collected at the other tracks, were also taken from the most trafficked area of the racetrack to be compared with the full set of 96 samples.

For the remaining 22 turf tracks, eight samples from the most highly trafficked areas were collected and labeled with the collection date, racetrack, and sampling location. These eight standard sampling locations were the 3/4 pole, 1/2 pole, 1/4 pole, and the wire at distances of 1 m and 8.6 m from the innermost rail position. The innermost rail position is always used as a reference, as the inside rail is moved periodically to manage wear and damage from the hooves on the surface during the race meet. Figure 1 depicts the eight standard sampling locations.

For all samples collected, a 22 mm diameter sampling probe was inserted multiple times to a depth of 150 to 200 mm within a 0.5 m radius of each nominal sampling location shown figure 1. The probe was sized to be comparable

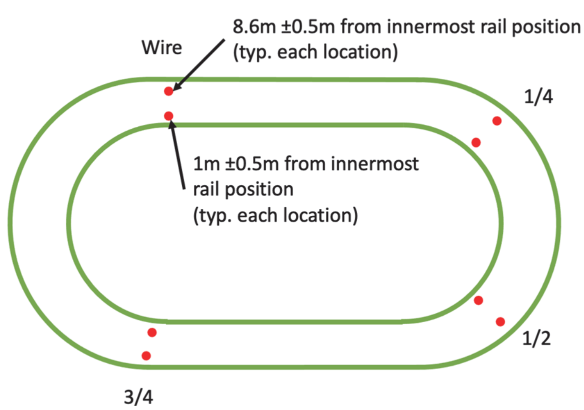

Figure 1. Standard soil sampling locations for turfgrass racing surfaces.

to the holes produced from hollow tine aeration, which is part of normal maintenance.

Testing Methods

Particle Size Distribution of Soil

Sample Preparation

Samples were weighed on a balance and oven-dried for 16 hours at 60°C to remove moisture. Samples were weighed upon removal from the oven, gently crushed, and sieved to <2 mm. The mass of material greater than 2 mm retained in the sieve was recorded. The laser diffraction particle size analyzer cannot accept particles larger than 2 mm. Macroscopic organic particles such as turf biomass and any synthetic fibers (if present) were also removed with tweezers and documented.

Samples from each racetrack were prepared for testing to determine the appropriate quantity of materials to be used for testing. Sample quantities were determined based on the manufacturer's recommended obscuration value of 10% to 20%. For each surface, different quantities of dried soil were measured into a test tube with a mass tolerance of ±0.01 g. 2 mL of a 50 g/L sodium hexametaphosphate (SHMP) solution and 10 mL of distilled water were then added for each gram of dry soil. Samples were then placed on an end over end shaker for 16 hours. Sample preparation, including the use of chemical dispersants and end-over-end shaking, is consistent with prior soil research (DiStefano et al., 2010; Fisher et al., 2017). From testing the different samples, the largest specimen size that produced the required obscuration was then chosen as the nominal sample size for samples tested for that racetrack. Three replicate samples of the appropriate size from each sampling location were then prepared using the same methods as the trial runs described in this section.

Laser Diffraction Analysis

Laser diffraction testing was performed using a Mastersizer 3000 fitted with the Hydro LV attachment (Malvern Panalytical Ltd., Malvern, UK). Samples were sonicated in the laser diffraction instrument at 100% power (40 W) for 60 seconds (DiStefano et al., 2010; Fisher et al., 2017). Nonspherical particle mode was selected for the particle type, and Mie theory was used for the analysis. The optical settings were 1.544 for the refractive index and 0.01 for the absorption index. The refractive index of 1.544 was based on a weighted average of the refractive index of 80% quartz and 20% feldspar (Eshel et al., 2004). The mineralogy estimate is supported by the X-ray diffraction testing results. The absorption index of 0.01 has also been used successfully in the analysis of soils (Fisher et al., 2017). Both the refractive and absorption indexes were confirmed to generate sufficiently low weighted residual values in all measurements. According to the manufacturer, a weighted residual under 1% implies that the calculated data is reasonably well-fitted to the measurement data, whereas weighted residuals greater than 1% may indicate adjustments to the refractive and absorption indices are necessary. The dispersant used was distilled water, and its refractive index was set to 1.33. Five measurements were recorded for each sample, and the average of those five measurements was reported. The process was then repeated for three replicated samples from each sampling location.

The data output calculated includes statistical parameters of D_{10} (tenth percentile), D_{50} (median grain size), and D_{90} (ninetieth percentile), as well as percent by volume reported in several size classes. The lower boundaries of each of those groups are 0.01 µm, 2 µm, 4 µm, 10 µm, 20 µm, 32 µm, 40 µm, 53 µm, 74 µm, 105 µm, 149 µm, 250 µm, 420 µm, 500 µm, 1000 µm, 1410 µm, 2000 µm, 2380 µm, and 2830 µm to allow comparison to historical data or other available sports field data (Mahaffey et al., 2012).

Organic Matter Analysis

Apart from large turf biomass in the samples, organic material was not removed prior to laser diffraction analysis. Previous research has shown a marginal effect of organic matter removal (DiStefano et al., 2010). Specifically, samples varying from 0.32% to 7.18% organic matter were shown to produce a small underestimation of clay content when laser diffraction was performed on samples when organic matter was not removed from the sample. More recently, removing organic carbon has been shown to negatively affect the agreement between laser diffraction results and sedimentation methods (Fisher et al., 2017).

Prior work has shown reliable results using laser diffraction without the need to pretreat samples when testing samples with a moderate amount of organic carbon (Fisher et al., 2017). To verify the range of organic content in the samples, soil from each sampling location was submitted to a loss on ignition procedure to determine organic content (ASTM, 2020). Approximately 100 g of dry soil was measured into a crucible and placed into a 440°C oven for 14.5 hours to burn off organic matter. Samples were weighed to determine the percent loss by mass of organic content.

X-ray Diffraction Analysis

For X-ray diffraction analysis, one mixed sample was created from each racetrack. This was done by combining 4.5 g ±0.5 g from each of the eight standard locations described previously. The mixed sample was then sent to an outside lab for X-ray diffraction analysis (K/T GeoServices, Inc., Gunnison, Colorado). The method for the procedure employed is described in Bish and Reynolds (2018) and Post and Bish (2018) and was also used for dirt racetrack testing (Mahaffey et al., 2012).

Statistical Methods

The statistical analysis used to test the hypotheses listed in this paper was conducted using a general mixed model estimation (R Development Core Team, 2022). The first hypothesis was tested by comparing the standard eight sampling locations to the full set of 96 samples collected at KEE. Since there were three laser diffraction measurements per sampling location, a repeated measures ANOVA was performed to compare the mean values of the D_{10}, D_{50}, D_{90}, and volume fraction results from each size category detailed. As there was only one measurement each for organic content and the percentage of material in excess of 2 mm, a simple linear model was used to compare those mean values using ANOVA. Significance was set at $p<0.05$. The variation was also investigated by calculating the percentage of the range seen in the 96 samples that was evident in the sample size of eight. To test the second hypothesis, the racetracks were grouped into archetypes based on observations of the soil composition, including the presence or absence of synthetic fiber. Again, since there were three laser diffraction measurements per sampling location, a repeated measures ANOVA was performed to compare the mean values of each archetype for the D_{10}, D_{50}, D_{90}, and volume fraction results from each size category detailed, and a simple linear model was used to compare the organic content and the percentage of material in excess of 2 mm. When significant differences were detected ($p<0.05$), pairwise comparisons were performed using Tukey's honestly significant difference (HSD) test. To investigate the variation between racing surfaces, all numeric response variables were also included in a principal component analysis (PCA) using the prcomp function (R Development Core Team, 2022). The data were centered and scaled as part of the analysis.

Results

Laser Diffraction Results

A summary of 552 total laser diffraction measurements and 24 samples from 23 different racetracks is shown in the appendix in table A1. The mean D_{10}, D_{50}, and D_{90} values for all tracks were 8.41 µm, 93.08 µm, and 420.04 µm respectively, with standard deviations of 4.78 µm, 75.64 µm, and 149.76 µm respectively. Values for KEE in the table represent the eight standard sampling locations, not the larger 96 sample size.

A total of 816 laser diffraction measurements were made, including the 88 additional samples collected for testing the first hypothesis. 138 of those measurements were outside of the 10%-20% obscuration range. No measurements were flagged by the Malvern software for data quality concerns. A target obscuration range of 10%-20% was used, which resulted in samples sizes ranging from 0.25 g to 2.5 g. The weighted residuals reported had an average of 0.25 with an overall range of 0.10-0.80 for all measurements.

Differences in laser obscuration and the weighted residual were evident between the different track designs, which in turn influenced the size of the sample to be tested. In general, samples with a greater percentage of fine materials necessitated the use of a smaller sample to achieve the required laser obscuration (fig. 2).

Organic Matter

Table A2 in the appendix shows a summary of percent organic matter by mass for each racetrack using the eight standard sampling locations. The mean organic matter content was 5.47% by mass, with a standard deviation of 3.19%. The range of all measurements recorded was from 1.31% to 17.56%.

Mineralogy

The mineralogy of the surfaces is shown in table 2. The less abundant minerals, including amphibole, hematite, kaolinite, chlorite, R0 ordered mixed-layer illite/smectite with

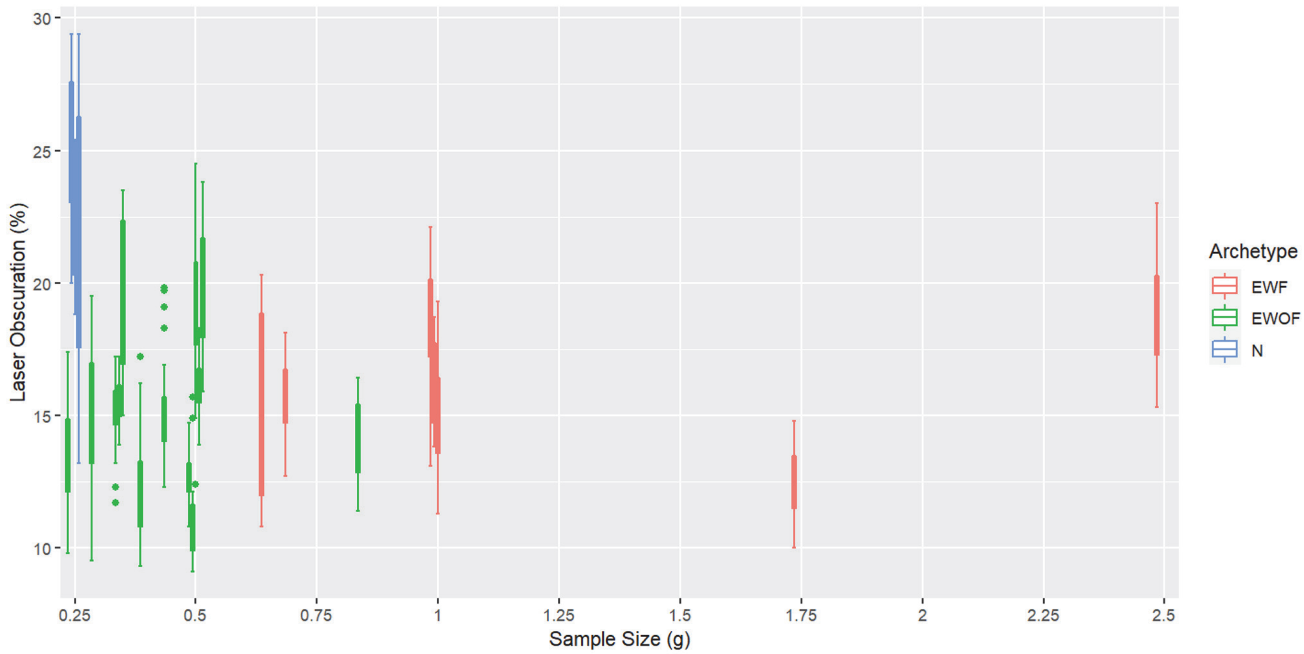

Figure 2. Plot of laser obscuration vs. sample size for each racetrack.

Table 2. Percent by mass mineralogy information for each racing surface.

Track	Quartz	K-Feldspar	Plagioclase	Calcite	Dolomite	Illite & Mica	Other
AQUI	85.8	2.6	6.3	0	1.3	3.2	0.8
AQUO	84.4	4.2	4.7	1	1.8	3.2	0.7
BELI	80.8	5.8	8.4	0	0	2.8	2.2
BELO	82.7	3.5	7.4	0	1.2	4.3	0.9
CD	68.2	2.4	6.9	6.7	11	2.2	2.6
DM	48.9	15.7	24.8	1.2	1	6	2.4
EP	69.3	3.9	6.8	0.3	0	11.3	8.4
FG	94.1	2.3	0.8	1.2	0	1.2	0.4
GG	91.5	2.9	2.4	0	0	2.7	0.5
GPI	82.1	0	0	17	0	0.7	0.2
KEE	64.9	6	9.9	5.3	10	2.7	1.2
LRL	95.1	0.8	0.5	0	0	1.9	1.7
OKTT	70.3	10.9	12.3	0	0.8	4.4	1.3
PIM	83.7	3.3	1.8	0.4	0	5.8	5.0
PMTC	82.7	0	0	15.3	0	1.5	0.5
PRX	94	1.4	0.6	0.3	0.7	2.1	0.9
RP	77.6	11.7	7.2	0	0	1.7	1.8
SA	45.6	17.1	27.2	0	0	6.5	3.6
SARI	71.1	10.5	12.5	0	0	3.2	2.7
SARO	72.2	8.4	12.6	0	0	4.2	2.6
WOI	44.8	15.1	32.5	0.4	0	2.9	4.3
WOO	37.5	8.3	23.1	18.4	4.7	3.1	4.9
WOT	44.3	9.9	22.1	3.4	4.9	7.1	8.3

90% smectite layers, and R3 ordered mixed-layer illite/smectite with 15% smectite layers, were condensed into the column labeled “Other.” This information is included in the appendix (table A3).

Hypotheses

Hypothesis 1 – Number of Samples Per Racing Surface

By determining if the mean values obtained from eight samples were significantly different from the full 96 samples collected, the ability to use fewer samples is evaluated. Table 3 shows a summary of laser diffraction results from testing at KEE comparing the eight standard sampling locations to the full set of 96 samples. This data includes the averages and standard deviations for laser obscuration, weighted residual, and the D_{10}, D_{50}, and D_{90} values. Of the 96 samples analyzed, 91 were able to achieve a desirable obscuration with 1.00 g sample size. Three of the remaining specimens were reduced to 0.25 g and two were reduced to 0.50 g to achieve a suitable obscuration value.

Statistical analysis from the repeated measures ANOVA yielded p-values ranging from 0.25 to 0.97 for the 24 categories observed (table 4). None of the p-values were less than 0.05 as a 95% confidence in significantly different mean values, which indicates that eight samples can accurately characterize the mean value for each parameter measured in this study. The results of the percentage of variation captured in eight samples are shown in the appendix (table A4). Those values range from 6.5% to 80.0% if non-zero values are ignored due to the very low amount of material observed in the 2000 μm, 2380 μm, and 2830 μm size classes.

Table 3. Summary of laser diffraction results for N=8 and N=96 at KEE.

Sample Size	Obscuration (%) Mean	Obscuration (%) Standard Deviation	Weighted Residual Mean	Weighted Residual Standard Deviation	D_{10} (µm) Mean	D_{10} (µm) Standard Deviation	D_{50} (µm) Mean	D_{50} (µm) Standard Deviation	D_{90} (µm) Mean	D_{90} (µm) Standard Deviation
N=8	15.2	1.94	0.20	0.02	10.4	1.06	100.8	16.71	534.7	48.83
N=96	16.5	2.54	0.22	0.07	10.2	1.98	93.2	27.4	506.4	80.58

Table 4. P-values for hypothesis 1.

Parameter	D_{10} (µm)	D_{50} (µm)	D_{90} (µm)	Percent Retained. All Values in µm.																			% OM	% >2 mm
				0.01	2	4	10	20	32	40	53	74	105	149	250	420	500	1000	1410	2000	2380	2830		
p-value	0.97	0.94	0.89	0.97	0.97	0.97	0.97	0.96	0.90	0.87	0.89	0.92	0.94	0.96	0.92	0.89	0.82	0.77	0.88	0.84	0.83	0.87	0.25	0.82

Hypothesis 2 – Archetypes of Turfgrass Horse Racing Surfaces

The three different turf track designs used in North American horse racing were evaluated. For each racetrack design archetype (table 1), a statistically significant difference in mean values for all parameters was found. Table 5 provides the D_{10}, D_{50}, and D_{90} values as well as percent sand, silt, clay, organic content, and the percentage of material greater than 2 mm. As the p-values in tables 5 and 6 indicate, there is a significant difference between the mean values for all of the parameters among the three designs. The only parameter that did not have a clear separation among the three archetypes was the percentage of material greater than 2 mm. The Tukey's HSD values in table 5 for that parameter indicate that while there is a significant difference between the EWF and N archetypes, the EWOF archetype is technically indistinguishable from the other two.

Table 6 shows further breakdowns of the silt and sand sized particle results from laser diffraction analysis. Again, the p values indicate a significant difference between the mean values for each parameter. As the Tukey's HSD values in table 6 indicate, though, there is some overlap among the archetypes depending on the exact size category in question. In the silt range, there is a clear distinction between the EWF archetype having significantly lower mean values than the EWOF archetype, which also has a lower mean value than the N archetype (EWF<EWOF<N) for the 2 µm, 4 µm, 10µm, 20 µm, and 32 µm size classes. For the 40 µm class, however, while the EWF archetype is again lower than the other two, EWF and N are technically indistinguishable from each other (EWF<EWOF=N). There were detectable differences for each class of sand as well. The EWF archetype contains a higher amount of material, while the EWOF and N archetypes contain progressively less (N<EWOF<EWF) for the 250 µm, 420 µm, and 500 µm classes. The separation is not as clear between the EWOF and N archetypes in the 1000 µm and 1410 µm sizes (N=EWOF<EWF) because there is so little material in both archetypes. Across the 53 µm, 73 µm, 105 µm, and 149 µm size classes, the EWOF archetype has the most material, while the N archetype trends downward in comparison and the EWF archetype trends upward as you go up in particle size.

Four principal components from the PCA analysis, PC1, PC2, PC3, and PC4, explain 48.5%, 17.7%, 15.1%, and 7.5% of the overall variation between racing surfaces, respectively. Figure 3 is a biplot of the first two principal components of the PCA. Variables that have a significant contribution (greater than 0.2 or less than -0.2) to PC1 or PC2 are displayed as vectors in figure 3. A full list of contributions from each parameter measured in this study to each PC is shown in table A5 in the appendix.

DISCUSSION

The goal of this paper was to evaluate the use of laser diffraction to measure the particle size distribution of

Table 5. Overview of comparisons between EWF, EWOF, and N archetypes.[d]

Archetype	D_{10} (µm)	D_{50} (µm)	D_{90} (µm)	Sand[a,b]	Silt[a,b]	Clay[a,b]	%OM[c]	%>2 mm[c]
EWF	13.0 (5.5) A	165.3 (92.0) A	578.2 (111.6) A	67.5 (12.7) A	32.1 (12.5) C	0.3 (0.2) C	3.2 (0.01) C	4.1 (0.05) A
EWOF	6.9 (2.5) B	70.5 (33.0) B	392.3 (59.7) B	52.5 (9.6) B	46.5 (9.5) B	1.0 (0.6) B	6.0 (0.03) B	3.0 (0.02) AB
N	4.1 (0.7) C	22.2 (6.9) C	171.0 (60.4) C	27.5 (7.8) C	70.4 (7.0) A	2.1 (0.8) A	8.2 (0.04) A	1.7 (0.02) B
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0352

[a] These values are percent by volume.

[b Particle size ranges for each category correspond to USDA values of 53 µm – 2 mm for sand, 2 µm – 53 µm for silt, and <2 µm for clay.

[c] These values are percent by mass.

[d] All data shown is mean value, (standard deviation), and an identifying letter from Tukey's HSD. Within a column, archetypes with the same identifying letter are not significantly different.

Table 6. Comparison of EWF, EWOF, and N archetypes for percent retained in each size class of silt and sand sized particles.[a]

Archetype	Silt 2 µm	Silt 4 µm	Silt 10 µm	Silt 20 µm	Silt 32 µm	Silt 40 µm	Sand 53 µm	Sand 73 µm	Sand 105 µm	Sand 149 µm	Sand 250 µm	Sand 420 µm	Sand 500 µm	Sand 1000 µm	Sand 1410 µm
EWF	2.2	6.9	8.5	6.9	3.4	4.3	5.1	5.4	5.8	12.3	18.1	6.0	13.6	1.1	0.2
	(1.0) C	(3.2) C	(3.7) C	(2.7) C	(1.2) C	(1.4) B	(1.7) B	(1.9) B	(2.0) B	(3.5) A	(6.5) A	(2.2) A	(5.2) A	(1.3) A	(0.4) A
EWOF	4.2	11.7	12.1	9.0	4.3	5.3	6.1	6.3	6.8	11.9	12.6	3.4	5.3	0.1	0.0
	(1.4) B	(3.3) B	(3.1) B	(2.2) B	(1.0) B	(1.3) A	(1.7) A	(1.8) A	(1.8) A	(3.7) A	(3.8) B	(1.0) B	(2.1) B	(0.3) B	(0.1) B
N	7.9	20.2	18.7	12.3	5.3	5.9	6.1	5.4	4.4	5.2	4.4	1.0	1.1	0.0	0.0
	(1.9) A	(3.5) A	(2.0) A	(0.8) A	(0.5) A	(0.9) A	(1.3) A	(1.5) B	(1.4) C	(1.9) B	(1.5) C	(0.4) C	(0.9) C	(0.0) B	(0.0) B
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0011	0.0014	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0001

[a] All data shown is mean value, (standard deviation), and an identifying letter from Tukey's HSD. Within a column, archetypes with the same identifying letter are not significantly different.

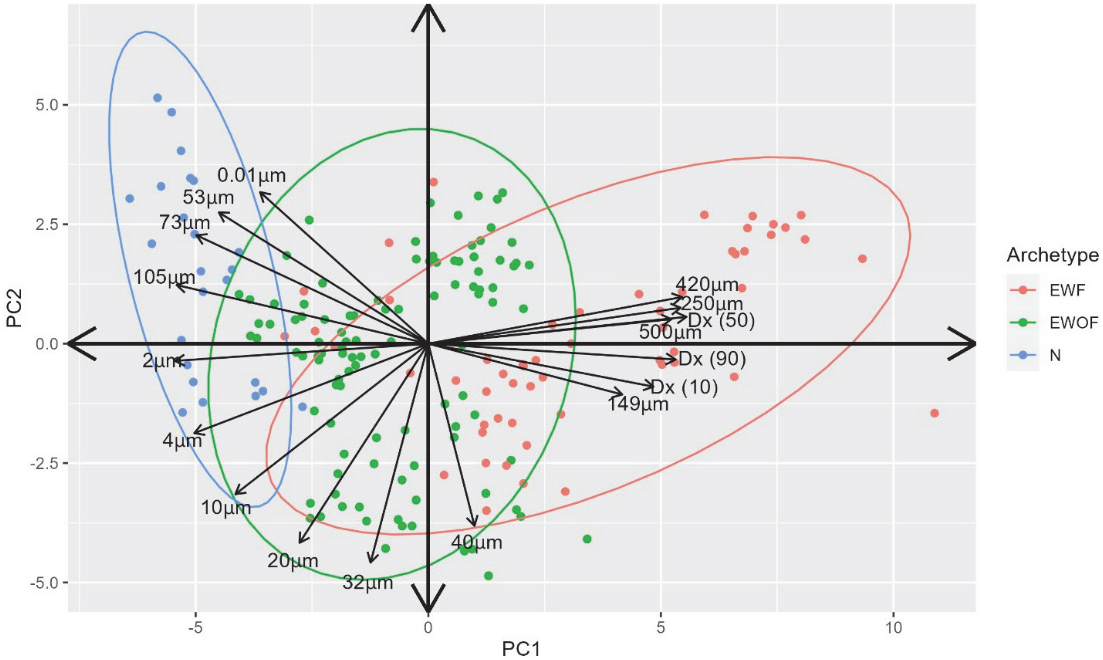

Figure 3. PCA of particle size distribution variables along the first two principal components.

growing medium used in turfgrass surfaces for Thoroughbred racing. Underlying characteristics such as turfgrasses grown, climate factors, organic content, and mineralogy are documented to identify factors that may impact the results. To support the use of laser diffraction for the application of turfgrass horse racing surfaces, two hypotheses were suggested: that a racing surface could be characterized by using eight sampling locations and that there were three different surface design archetypes. Both of these hypotheses were accepted.

The number of samples required and the effect of various other factors, including mineralogy and organic, will all influence the results from the characterization of the racetrack. Comparison to sedimentation methods has been addressed by other investigators (Yang et al., 2019), as well as the effects of mineralogy (Eshel et al., 2004) and organic content (DiStefano et al., 2010; Fisher et al., 2017). However, because of limitations to the sample size that can safely be removed from an operational turf racetrack and the resulting risk to horse and rider, laser diffraction testing provides the baseline data to separate the three types of tracks. Laser diffraction will also allow the mean particle size to be characterized using a small number of samples in order to facilitate the selection of sand for top dressing and repairs.

Laser Diffraction

The first thing to consider for the suitability of this method is to determine if standard test conditions can be met. The weighted residual values shown in table A1 are consistent with manufacturer recommendations. This supports the use of a refractive index of 1.544 and an absorption index of 0.01. Table A1 also displays obscuration values which comply with the manufacturer's recommendations in most cases. A notable exception to that is the three tracks in the N archetype, that could not achieve below 20% obscuration even when a 0.25 g sample size was used.

Figure 2 shows the relationship between the amount of material required to meet the target obscuration value and the track design. For future testing of Thoroughbred turf racing surfaces, knowledge of the general type of material and track design may be sufficient to estimate the specimen size required for testing. A more accurate estimate or sample quantity to be used for laser diffraction analysis reduces the number of sample size trials required.

Organic Matter

Samples were tested using loss on ignition to determine their organic content, with the mean organic content of each racetrack ranging from 1.7% to 12.8% (table A2). The relatively wide range of organic content suggests that pretreatment may be justified based on the significantly different densities of organic matter and mineral soil particles. While laser diffraction without pretreatment can detect differences in surface composition, a standard method for the racing industry should explicitly define how samples should be pretreated. Several methods have been shown to properly remove organic matter in soil samples, should it be deemed warranted (Mikutta et al., 2005).

Mineralogy

Mineralogy results are relevant to the selection of the correct refractive index for the testing as well as being relevant to understanding the wear behavior of the material (Lopez et al., 2018). With quartz content ranging from 44.3% to 95.1%, the range of mineralogy in the sand is quite large. However, the refractive index of K-Feldspar and Plagioclase is sufficiently close to that of quartz that adjustments may not be required (Pichler and Schmitt-Riegraf, 1997). The higher quartz content sand will generally be more durable in use, although other factors such as shape may be relevant (Whitmore and Strom, 2017).

Hypothesis Testing

Hypothesis 1 – Number of Samples Per Racing Surface

Given the size of the specimens being tested from each location, the ability to characterize the entire racing surface is a particular concern. Specifically, is it possible to accurately represent a surface using eight locations? For this testing, the Keeneland racetrack was selected since it included a surface that was designed with a crown on the racetrack surface. The area outside of the crown is not used for racing and contains a higher percentage of native soil. The Keeneland racetrack thus represents one of the more challenging surfaces to characterize, despite its role as one of the premier racetracks for turf and dirt racing. The results show that while small differences in the track are evident, the track surface, in particular the racing surface, is well represented by using eight samples when comparing mean values for every parameter measured in this study. This is particularly important for the selection of appropriate topdressing material. By selecting topdressing material that matches the mean values for a racetrack, potential layering concerns and the resulting drainage issues can be mitigated. The selection of divot repair material as well as top dressing materials that match the mean value of the existing track will reduce variation in the racing surface.

Eight samples were shown to have less variation in every size category observed than the 96 samples collected at Keeneland. A great deal of this can be attributed to the fact that many of these samples were collected in areas of the track not used on race days that are known to remain native soil. Rarely is it feasible for 96 (or more) samples to be collected at regular time intervals for the purpose of making ongoing maintenance decisions. Providing the understanding that eight samples accurately characterize the mean values for a racetrack but not the total variation is a useful finding for this industry, as it helps guide the decision making process.

Hypothesis 2 – Archetypes of Turfgrass Horse Racing Surfaces

Using eight samples from standard locations at 23 racetracks, laser diffraction was able to detect differences in the designs of the racetracks. The detection of the differences in design and usage was possible, although a number of these racetracks had been in regular use for several decades with minimal alterations. The PCA is presented as a means for interpreting the sources of variation between racetracks. While the PCA results support the grouping of racetracks into the three archetypes, it also opens the door to retrospective epidemiological studies of Thoroughbred injuries. The four principal components, which represent more than 85% of the total variation, are linear combinations of all the values used in the analysis. To the extent that any of the composition terms may be relevant to the performance or safety of the surface, this suggests that all the values will need to be retained, at least in the initial analysis.

Laser diffraction testing of turf racetracks opens up a range of possibilities for horse racing. The result of this study is not only the development of baseline data for 23 major racetracks in North America but also a method that can now be used as a diagnostic tool for future efforts. Based on the understanding of the different particle size distributions as well as the range of distribution for each surface, the potential influence on infiltration rate would be large. The infiltration rate would in turn influence the amount of water available for the turf growth as well as the recovery of the turf from rainfall. The dynamic response of the surface could, with an open structure and fiber, potentially be consistent over a much wider range of conditions. Recovery from significant rain events would also be facilitated by a free draining surface. The dynamic response is measured by the Orono Biomechanical Surface Tester (ASTM, 2019; Peterson et al., 2008). Simpler devices have also been used for quality control for new construction as well as having the potential for daily monitoring of surfaces (Blanco et al., 2021). The protocol for determining the particle size distribution of an active turf racetrack, in combination with daily surface measurements, has the potential to contribute to efforts to enhance the safety of the horse and rider.

Conclusion

Laser diffraction has previously been shown to be a viable alternative to sedimentation methods for measuring the particle size distribution on turf racetracks. Unlike sedimentation methods, laser diffraction can be performed using small samples, which makes it possible to test turf Thoroughbred racetracks that are used for active racing. No other test method allows this type of testing to be done. This study showed that those samples, sometimes as small as 0.25 g and using eight standard locations, were able to successfully characterize the average particle size of the materials in the track for relatively homogenous surfaces. This method provides baseline data that can be used for the design of new racetracks and for the renovation and maintenance of existing turf racetracks.

The development of methods to ensure the consistency of all types of racing surfaces is potentially important for the safety of the horse and rider. By allowing small samples to be taken at areas of concern with minimal disturbance to the racing surface, variation in the surface, including differences in materials with depth, localized accumulation of fine material and even sand wear can be evaluated. The overall response of the track to rain can then be compared to areas where lower infiltration rates are observed.

Some of the testing parameters may also need to be considered further. Most importantly, there is a need for consensus on the handling of organic content. The data from the present study may help in areas of testing when larger ranges of organic or fine material are encountered. Reporting on the mineralogy and organic content of these samples is intended to provide additional information for future work looking at applications with a wider range of these values compared to the relative consistency of the surfaces used in Thoroughbred horse racing.

Future work with other natural turf surfaces presents opportunities to use laser diffraction in other applications for natural sports fields as well as for infill material used on synthetic playing surfaces. For material with a higher organic or clay content, attention will need to be paid to obscuration and weighted residuals measured during testing.

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APPENDIX

Table A1. Summary of laser diffraction analysis results for each racetrack.

Track	Sample Size (g)	Obscuration (%) Mean	Obscuration (%) Standard Deviation	Weighted Residual Mean	Weighted Residual Standard Deviation	D_{10} (μm) Mean	D_{10} (μm) Standard Deviation	D_{50} (μm) Mean	D_{50} (μm) Standard Deviation	D_{90} (μm) Mean	D_{90} (μm) Standard Deviation
AQUI	0.50	12.7	0.97	0.3	0.10	5.7	0.25	66.2	11.76	481.8	29.53
AQUO	0.50	11.2	1.84	0.3	0.10	6.5	0.55	100.2	25.53	470.0	31.65
BELI	0.30	14.7	2.65	0.3	0.04	5.5	0.18	34.9	7.74	363.9	60.37
BELO	0.25	13.4	1.97	0.3	0.04	5.2	0.39	29.8	4.46	343.5	57.44
CD	0.65	15.5	3.54	0.3	0.05	6.1	0.64	38.0	8.10	491.2	83.67
DM	1.00	18.5	2.53	0.2	0.04	11.4	1.40	110.7	14.48	542.7	70.69
EP	0.25	25.2	3.03	0.4	0.04	3.6	0.36	17.2	3.78	117.0	33.91
FG	2.50	18.8	2.09	0.2	0.07	21.3	3.77	256.9	31.28	568.8	32.61
GG	1.00	16.4	1.65	0.3	0.13	11.5	2.06	202.0	39.87	738.7	115.04
GPI	0.50	19.3	2.98	0.3	0.07	5.6	0.88	120.9	15.66	412.7	29.75
KEE	1.00	15.2	1.94	0.2	0.02	10.4	1.06	100.8	16.71	534.7	48.83
LRL	0.50	16.1	1.19	0.2	0.02	8.6	0.57	89.4	14.84	370.7	25.11
OKTT	0.35	15.1	1.32	0.2	0.05	5.8	0.52	48.8	6.47	353.4	36.02
PIM	0.25	22.1	1.96	0.5	0.07	3.8	0.34	19.3	2.57	171.2	32.47
PMTC	0.45	15.3	2.11	0.3	0.05	5.1	0.66	108.7	21.68	417.0	19.47
PRX	0.50	19.7	2.22	0.2	0.00	8.3	0.68	59.2	6.31	351.9	23.36
RP	0.85	14.0	1.50	0.2	0.05	13.4	1.31	108.5	9.18	439.2	44.23
SA	0.70	15.6	1.50	0.2	0.05	10.6	0.73	139.8	35.28	489.6	45.25
SARI	0.35	15.5	0.94	0.3	0.05	5.7	0.38	46.8	6.19	357.9	24.84
SARO	0.35	19.4	2.96	0.3	0.07	5.0	0.75	34.7	6.51	324.0	23.27
WOI	1.75	12.4	1.33	0.3	0.09	19.7	3.72	308.7	21.88	681.8	46.79
WOO	0.40	12.2	2.30	0.2	0.02	9.7	1.04	69.0	9.81	414.3	29.63
WOT	0.25	21.6	5.07	0.3	0.06	5.0	0.55	30.3	4.78	224.9	54.51

Table A2. Mean and standard deviation of percent organic matter by mass for each racetrack.

Track	Organic Matter (% by mass) Mean	Organic Matter (% by mass) Standard Deviation
AQUI	2.9	0.004
AQUO	2.3	0.004
BELI	7.6	0.027
BELO	7.7	0.008
CD	3.7	0.008
DM	3.4	0.006
EP	4.2	0.008
FG	1.7	0.003
GG	5.0	0.012
GPI	4.1	0.003
KEE	3.3	0.004
LRL	4.6	0.007
OKTT	6.8	0.015
PIM	7.5	0.012
PMTC	3.9	0.006
PRX	12.8	0.025
RP	4.7	0.010
SA	3.7	0.003
SARI	6.2	0.007
SARO	7.1	0.005
WOI	1.8	0.003
WOO	7.9	0.023
WOT	12.8	0.032

Table A3. Supplementary percent by mass mineralogy information (refer to table 2).

TRACK	Amphibole	Hematite	R0 M-L I/S (90%S)[a]	R3 M-L I/S (15%S)[b]	Kaolinite	Chlorite
AQUI	0	0	0	0	0.3	0.5
AQUO	0	0	0	0	0.4	0.3
BELI	1.3	0	0	0	0.4	0.5
BELO	0	0	0	0	0.3	0.6
CD	1.8	0	0	0	0.3	0.5
DM	1.2	0	0.6	0	0.3	0.3
EP	0	0	0	4.5	2.9	1
FG	0	0	0	0	0.2	0.2
GG	0	0	0	0	0.2	0.3
GPI	0	0.2	0	0	0	0
KEE	0	0	0	0	0.5	0.7
LRL	0	0	0	0	1.2	0.5
OKTT	0	0	0	0	0.5	0.8
PIM	0	1.6	0	0	2.5	0.9
PMTC	0	0	0	0	0.5	0
PRX	0	0	0	0	0.6	0.3
RP	0	0	1.3	0	0.2	0.3
SA	1.7	0	1.2	0	0.3	0.4
SARI	1.2	0	0	0	0.5	1
SARO	1.4	0	0	0	0.4	0.8
WOI	3.2	0	0	0	0.4	0.7
WOO	3.4	0	0	0.7	0.4	0.4
WOT	4.3	0	0	2.9	0.4	0.7

[a] R0 M-L I/S (90%S) = R0 Ordered Mixed-Layer Illite/Smectite with 90% Smectite Layers.

[b] R3 M-L I/S (15%S) = R3 Ordered Mixed-Layer Illite/Smectite with 15% Smectite Layers.

Table A4. Percentage of range shown in 96 samples that is covered by eight samples for KEE.

Parameter	Percentage of Total Range Shown With Eight Samples
D_{10}	21.0
D_{50}	24.7
D_{90}	22.6
2830 µm	0.0
2380µm	0.0
2000 µm	0.0
1410 µm	20.0
1000 µm	80.0
500 µm	35.1
420 µm	23.7
250 µm	18.1
149 µm	31.4
105 µm	34.4
74 µm	35.7
53 µm	29.9
40 µm	30.3
32 µm	29.3
20 µm	21.7
10 µm	14.9
4 µm	10.1
2 µm	8.4
0.01 µm	6.5
%OM	19.9
%>2 mm	58.5

Table A5. Contributions of each variable to the four principal components. Values greater than 0.2 or less than -0.2 are shown in bold.

Variable	PC1	PC2	PC3	PC4
D_{10}	**0.2420**	-0.0899	-0.0531	0.1104
D_{50}	**0.2775**	0.0562	-0.0165	-0.0074
D_{90}	**0.2658**	-0.0332	0.0593	**0.2075**
2830µm	0.0927	-0.0183	**0.4157**	-0.1097
2380µm	0.1089	-0.0591	**0.4389**	-0.1094
2000µm	0.1172	-0.0728	**0.4425**	-0.1225
1410µm	0.1260	-0.0742	**0.4224**	-0.0844
1000µm	0.1685	-0.0568	**0.3184**	0.0956
500µm	**0.2613**	0.0513	0.0559	**0.2782**
420µm	**0.2726**	0.0977	-0.0768	0.1514
250µm	**0.2713**	0.0753	-0.1519	-0.0387
149µm	**0.2085**	-0.1065	**-0.2096**	-0.3443
105µm	0.0496	**-0.3814**	-0.1382	-0.3409
73µm	-0.0621	**-0.4582**	-0.0537	-0.1054
53µm	-0.1384	**-0.4169**	-0.0024	0.0740
40µm	**-0.2073**	**-0.3151**	0.0377	0.1633
32µm	**-0.2515**	-0.1873	0.0730	0.1964
20µm	**-0.2723**	-0.0360	0.1033	0.1846
10µm	**-0.2705**	0.1228	0.1145	0.0888
4µm	**-0.2493**	**0.2271**	0.1003	-0.0669
2µm	**-0.2251**	**0.2748**	0.0786	-0.1563
0.01µm	-0.1808	**0.3174**	0.0421	-0.2406
% OM	-0.1751	-0.1809	0.0769	-0.0816
% >2 mm	-0.0207	-0.0129	-0.0042	**0.5793**