TECHNICAL ARTICLE

The Effect of Temperature on the Tangent Modulus of Granular Composite Sport Surfaces

J.W. Bridge[1,2,3], M.L. Peterson[2,3], and C.W. McIlwraith[4]

1 Department of Manufacturing and Mechanical Engineering, Oregon Institute of Technology, Klamath Falls, OR
2 Department of Mechanical Engineering, University of Maine, Orono, ME
3 Racing Surfaces Testing Laboratory, Orono, ME
4 Gail Holmes Equine Orthopaedic Research Center, Department of Clinical Sciences, Colorado State University, Fort Collins,CO

Keywords
Tangent Modulus, Vertical Stiffness, Granular Composites, Paraffin and Microcrystalline Wax, Synthetic Horse Tracks

Correspondence
J.W. Bridge,
Department of Manufacturing and Mechanical Engineering,
Oregon Institute of Technology, Klamath Falls, OR 97601
Email: john.bridge@oit.edu

Received: March 26, 2012; accepted: July 4, 2012

doi:10.1111/j.1747-1567.2012.00851.x

Abstract

A series of tests were conducted to determine the tangent modulus (vertical stiffness) values for a wax-coated granular composite material. This material is commonly used as the surface for Thoroughbred horse racetracks. The tangent modulus is important in the vertical loading of the surface by the hoof for a highly nonlinear material. Test temperatures span a range from 0 to 64°C and include the thermal transition regions of the wax coating obtained from differential scanning calorimetry tests. These temperatures also include the range of temperatures that are encountered during use. Creep tests were conducted to obtain steady-state strain conditions at loads ranging from 0.89 to 4.45 kN, the latter load approximating the weight of a Thoroughbred racehorse. Through-transmission ultrasonic waves were utilized to determine the tangent modulus values. The tangent moduli ranged from 74 to 573 MPa for the conditions tested. For all loads tested, a large decrease in modulus and decrease in material nonlinearity occurred as temperatures increased from 20 to 32°C. This temperature range matches the first thermal transition temperature for the wax coating of the track material. The results of this work provide a basis for racetrack maintenance decisions that can eliminate potentially adverse temperature effects and may reduce equine injuries.

Introduction

To date, nine Thoroughbred horse racetracks in North America have switched from dirt surfaces to synthetic granular composite surfaces in an effort to reduce equine injuries (although one has recently switched back to dirt). Subsequent synthetic track injury reports have been promising; for example, following the 2005–2006 winter–spring meet at Turfway Park in Kentucky, fatal equine racing injuries dropped from 24 to 3.[1] Racing data collected in California between 2004 and 2009 has shown an average reduction in Thoroughbred fatalities from 3.09 per 1000 racing starts on dirt surfaces to 1.95 per 1000 racing starts on synthetic surfaces.[2] These statistics may be attributed, in part, to an improved track base installed during the replacement of the existing dirt tracks but also due to a more consistent racing surface.[3,4] The consistency of the synthetic tracks is influenced by the hydrophobic wax (or polymer)-coated materials that reduce the effect of moisture, a primary variable in traditional dirt and turf surfaces.[5]

The construction of the synthetic track systems generally consists of an approximately 250-mm thick layer of synthetic granular track material that rests on porous macadam (asphalt) or other porous geotextile. Under this layer is stone/aggregate that covers a network of drainage pipes.[6,7] The synthetic material differs from dirt used in conventional tracks as it generally contains silica sand, polymer fibers, and rubber particles all of which is coated with a hydrocarbon paraffin-based, high-oil content wax. One representative track manufacturer cites percentages (by mass) of material constituents as: >50% sand, <5% fibers, 0–15% rubber, and 5% wax.[8] Soxhlet extraction tests of a California synthetic racetrack surface at 10 locations around the track gives a combined sand and rubber mass percentage of 85%, 7% fibers, and 8% wax.[9] Laboratory tests performed by authors on five synthetic racetrack surfaces show wax contents ranging from 5 to 7.3% by mass.[10] Other tests by same authors have also verified the loss of the wax binder over time, thus requiring the periodic reapplication of wax on the track surface. The sand, fibers, and rubber can differ in type, size, and shape, and the wax binder can also vary in hydrocarbon composition.

The purpose of this study is to determine the effect of normal operational temperatures on the tangent modulus or ''vertical stiffness'' of the racetrack surface at a range of applied loads. The tangent modulus gives an indication of the softness or hardness of a material, such as a wax-coated granular composite, that exhibits nonlinear stress–strain behavior and no set yield point.[11] There can be a significant span in daily racetrack operating surface temperatures. At the Del Mar, California synthetic racetrack, summer daily track surface temperatures were found to fluctuate from 20 to over 50°C (68–122°F) over a 4-day period.[12] Previous work with samples taken from the same track as this study involved analyzing the thermal characteristics of the wax coating using differential scanning calorimeter (DSC) and its effect on the triaxial shear strength.[10,11] It was found that the shear strength of the track corresponds to the DSC thermal transition regions of the wax coatings that also encompass typical racetrack operational temperatures. An initial increase in shear strength occurs as the track material warms and the transition melting temperature peak is approached—but drops quickly prior to reaching this temperature.[11] Both shear strength and tangent modulus are involved in the hoof–track interactions present during the impact, stance, and breakover phases of a horse's gait during racing. While the shear strength involves the ability of a track surface to withstand horizontal hoof deceleration forces that lead to ''cuppy'' (low-shear strength) or ''fast'' (high-shear strength) tracks, the tangent modulus corresponds to the vertical response of the track.[13,14] By understanding how temperature affects the tangent modulus (in addition to the shear strength), the potential exists to further improve track consistency even under varying environmental conditions thus reducing equine injuries.

Materials and Methods

Sample synthetic material was collected from the newly installed surface of a Thoroughbred horse racetrack in the Midwestern USA in April 2007. This track was originally a dirt track and had just been replaced by a wax-coated granular composite track system (Polytrack®Elite, Martin Collins Surfaces and Footings, LLC, Lexington, Kentucky).

Several tests were required to characterize the material prior to measuring the tangent modulus. The sample material was thoroughly dried in a vacuum oven at 100°C to remove water so that weight percent could be determined from wax extraction tests. The wax content by mass percent was determined using a high-purity isooctane solvent extraction procedure involving multiple track sample/solvent mixings, the use of an ultrasonic bath, decanting, and vacuum oven evaporation at 100°C.[10] DSC tests and creep stabilization tests were used to develop a testing protocol. The DSC test described below was used to determine the most important tangent modulus test temperatures. The creep stabilization and tangent modulus ultrasonic tests were performed using dried track material with 4% moisture added to simulate the typical moisture content of operational synthetic tracks.

Differential scanning calorimetry

DSC of the extracted wax was performed in a PerkinElmer Pyris1 with power compensation under nitrogen flow (20 mL/min). Two samples (9–11 mg weighed to 0.1 mg precision) of the wax were prepared in aluminum sample pans and heated from 20 to 93.3°C, 93.3 to −30°C, then −30 to 93.3°C. The thermal sequence of the tests used was consistent with the standards for DSC wax testing ASTM D4419.[15] Thermal transition ranges and peak temperatures were taken from the second heating run and are plotted with thermal endotherms pointing downwards. The endotherms indicate the melting enthalpies of the wax samples as heat is absorbed during melting.

Creep and tangent modulus tests

A series of constant load creep tests and tangent modulus tests were conducted using a specially designed temperature and load-controlled apparatus. This apparatus is shown in Figure 1 and consists of an 89-mm inner diameter, 189 mm tall aluminum cylinder with an outside water circulation cavity. A 100 psi pressure regulated air cylinder actuator

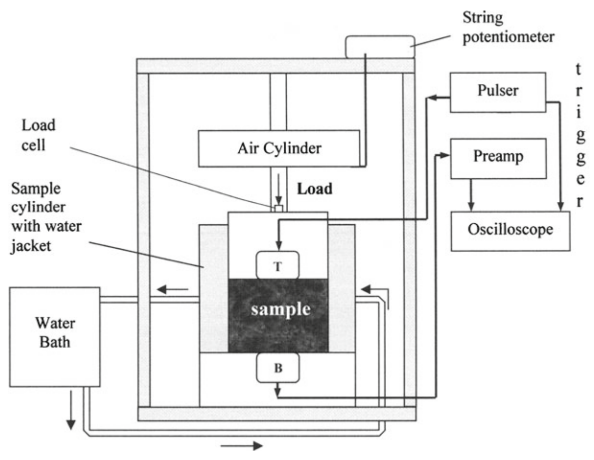

Figure 1 Schematic diagram of the tangent modulus apparatus. An aluminum cylinder with water jacket compartment contains the compacted track sample. Ultrasonic transducers are shown on the top and bottom of the sample ("T" and "B"). The air cylinder assembly applies a constant load to the sample while the water bath maintains temperature.

(Bimba FM-1710, Monee, IL) is used to apply load. A pair of 1 MHz 25-mm diameter longitudinal piezoelectric contact transducers (Panametric V102-RM, Waltham, MA) is mounted internally inside the piston and directly beneath the cylinder. The transducers were used to generate and receive the ultrasonic pulse and were driven by a high-voltage pulse generator (Panametrics 5072PR, Waltham, MA) with the receiving transmitter connected with a preamplifier (Panametrics 5660, Waltham, MA) to the signal acquisition by a 500 megasample/s digitizing oscilloscope (Tektronix TDS320, Beaverton, OR). Load was measured with an 8.9 kN load cell (Futek LLW200, Irvine, CA) and displacement was measured using a 0–10 VDC 127 mm string potentiometer (Celesco PT1DC-5, Chatsworth, CA). Temperature was maintained by a 0–100°C digital refrigerated water bath (ThermoFisher RTE-17, Waltham, MA). LabView data acquisition software (National Instruments, Austin, TX) was used to interface with the oscilloscope. Tests were conducted at 0, 20, 32, 50, and 64°C under loads ranging from 0.89 to 4.45 kN (200–1000 lb).

Approximately, 500 g of material was prepared for compaction for both creep and tangent modulus tests. Rubber pieces with dimensions greater than 10 mm were removed in an effort to ensure consistency between tests. Because of the location of the built-in lower contact transducer, the Proctor ASTM D698 compaction method[16] for soils (uses a dropped mass) was not utilized. Instead, samples were hand compacted with a 32-mm diameter rubber tamper using six sample lifts of approximately 83 g per lift. The resulting sample thickness after compaction was approximately 50 mm and sample bulk densities from hand tamping were within 1% of tests using the Proctor method. After compaction, the sample cylinder was connected to the rest of the test assembly and allowed to equilibrate for 1 h at each temperature before load application. The 1 h equilibrium time for the sample to reach temperature was confirmed via a range of tests with embedded thermocouples inside the sample/cylinder that confirmed consistent temperature through the thickness of the sample.[12]

Strain versus time tests were conducted at each temperature and load to determine the times at which the creep rates stabilized. Once minimum wait times were established to reach fixed creep conditions, the resulting sample displacements were recorded and sample densities were calculated from the volume of the samples since each test was performed based on a known sample mass. Tangent modulus tests were then conducted by transmitting longitudinal ultrasonic waves through each sample at each temperature and incremental load (with wait times appropriate for creep stabilization). The first wave arrival time (the start of the first peak relative to the trigger signal) was recorded for all the tests. Using the same main time base on the oscilloscope display, longitudinal sound waves were also transmitted through a 172 mm long, 82.6 mm diameter Aluminum 6061 reference sample and the first arrival time was recorded. The expression for a longitudinal wave velocity through an unbounded sample c_s is as follows:

$$c_s = \sqrt{\frac{E(1-\upsilon)}{\rho(1+\upsilon)(1-2\upsilon)}}, \tag{1}$$

where E is the tangent modulus, υ is Poisson's ratio, and ρ is the sample density. The Poisson's ratio for this granular track material was estimated to be similar to that of a medium dense sand falling between 0.25 and 0.40.[17] Data are reported using a value of 0.30. For each temperature and load tested, the relative time delay in ultrasonic wave arrival time for the track sample and aluminum reference was calculated using a cross-correlation algorithm. The peak of the cross-correlation corresponds to the relative time delay between the signals. The application of cross-correlation has been shown to increase accuracy in the measurement of ultrasonic wave velocity to the order of the sampling rate in many cases.[18] The cross-correlation is as follows:

$$C_{rs}(t) = \Sigma_{-\infty}^{\infty} R(\tau) S(\tau - t). \tag{2}$$

The relative time delay, t, of the track and reference signals corresponds to the point where the function $C_{rs}(t)$ has reached maximum amplitude, τ_a. The relative delay time found by cross-correlation is then defined with respect to the sample and reference transit time relationships:

$$t = \frac{\Delta x_s}{c_s} - \frac{x_{al}}{c_{al}}, \tag{3}$$

where the ultrasonic velocity c_{al} through the aluminum reference sample, the sample and reference thicknesses Δx_s and Δx_{al}, and t are all presumed known. Using t calculated with accuracy based on the sample rate of 2 MS/s, the velocity of the ultrasonic wave in the sample (c_s) is found from:

$$c_s = \frac{\Delta x_s c_{al}}{\Delta x_{al} + c_{al} t}. \tag{4}$$

By equating Eqs. 1 and 4, the tangent modulus E is calculated:

$$E = \left(\frac{\Delta x_s c_{al}}{\Delta x_{al} + c_{al} t} \right)^2 \frac{\rho(1+\upsilon)(1-2\upsilon)}{1-\upsilon}. \tag{5}$$

After the series of tests at temperatures and loads were completed, through-transmission ultrasonic tests were repeated using different samples from the same track material at both 20 and 50°C to check for variability. A test for moisture loss at 50°C and the resulting effect on the tangent modulus was also conducted.

Results and Discussion

The wax extracted from the test material used was 8.15% by mass. The DSC curve for the extracted wax is shown in Figure 2 and shows two major thermal transition regions spanning the approximate range of −1.0 to 50°C and 52 to 78°C. The first and second transition peaks occurred at 27 and 64°C±0.5°C, respectively. These results are consistent with DSCs of samples taken from the same track in March 2009 and are notable for the relatively smooth transitions that result in smaller and more gradual changes in the track material with temperature.[11] The wax glass transition temperature is estimated to be approximately 9°C.[19]

The results from the constant load creep tests at 0 and 64°C are displayed in Figure 3. The initial strain and creep stabilization times for the intermediate 20, 32, and 50°C tests are similar in appearance and fall between the tests shown. The initial strain under increasing load application increases with temperature and exhibited a 265% increase in strain at the highest temperature tested (64°C) as compared

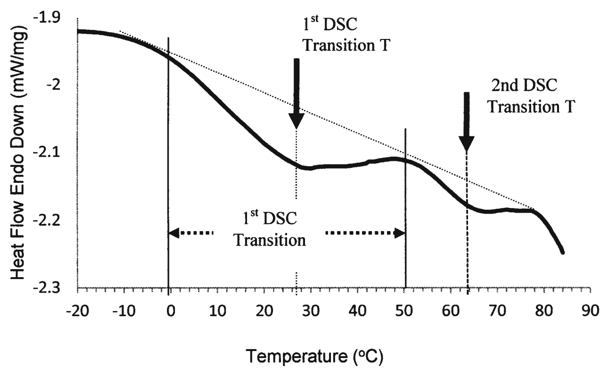

Figure 2 DSC curve of synthetic racetrack extracted wax.

to the initial strain at the lowest temperature tested (0°C). While the time necessary to reach equilibrium creep conditions is reduced as load and temperature increase, the total strain increases with temperature and load. This is reasonable because the viscosity of the wax coating decreases with temperature and particle reorientation is likely to be inhibited when the wax is viscous. However, the relationship is not simple because the interaction of granular materials is complex and depends on other factors such as particle shape, size distribution, and particle bonding mechanics. For all of the samples tested, steady-state creep conditions were reached in 15 min or less at all temperatures considered. Ultrasonic measurements were made at 20 min after the sample was loaded.

For the tangent modulus, 25 measurements were made at five temperatures and five loads. The results of the tangent modulus tests are listed in Table 1 and graphed in Figure 4. The thermal transitions from the DSC curve are also marked on the graph in Figure 4.

The ultrasonic transmission time repeatability tests, performed at 20 and 50°C, showed the greatest variability at 0.89 kN, the lowest load tested. These results are shown in Figure 5. The largest time difference at this load was 10.5 μs at 50°C (7.2% change). However, at the higher loads, the largest difference for both 20 and 50°C repeat tests decreased to 3.5 μs (less than 5%) with generally decreasing delay times as loads increased. It is suggested that the higher variance in through-transmission time at the lowest applied load can be attributed to the decreased ability for the granular material to compact efficiently. Post-test moisture content measured for the 50°C series of tests was found to decrease from 4 to 3.5% from the initial values. This difference is thought to be primarily from mixing losses during preparation of the sample rather than from evaporation effects because

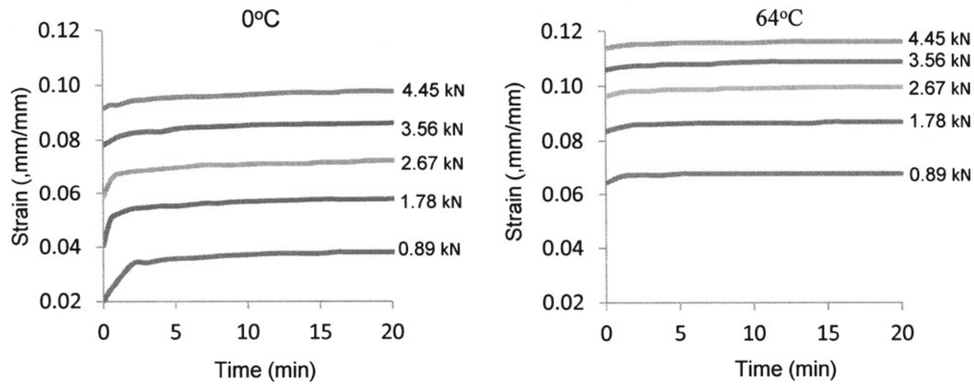

Figure 3 Constant load creep curves of synthetic racetrack bulk sample at 0 and 64°C under 0.89 to 4.45 kN (200–1000 lb) loads.

Table 1 Tangent modulus at varying temperature and loads

	Tangent modulus (MPa)				
Temp Load (kN)	0°C	20°C	32°C	50°C	64°C
0.89	228	141	94	75	74
1.78	331	246	149	122	114
2.67	418	319	195	151	136
3.56	505	410	233	174	156
4.45	573	533	275	190	167

the sample is enclosed in a metal cylinder throughout testing. The potentially small loss of moisture during the 50°C tests is not expected to significantly impact the overall tangent modulus results but is reported to ensure consistency in testing.

In examining the tangent modulus results in Figure 4, the maximum value of the tangent modulus occurs at the lowest tested temperature, 0°C, for all loads, and decreases as the temperature increases (as expected). At 0°C the wax coating is below the glass transition temperature and will be in a state which will contribute to the higher measured modulus.[20] The greatest material nonlinearity also occurs at 0°C, with a 354 MPa span. From the lowest to highest load, the greatest change in modulus with temperature occurs over the relatively narrow 20 to 32°C temperature range which corresponds to the first DSC thermal transition region. The first nominal transition temperature lies within this nonlinear temperature band.

This narrow, nonlinear response temperature span corresponds to common track surface temperatures that occur regularly on tracks throughout North America.[21] At cooler temperatures, the wax is

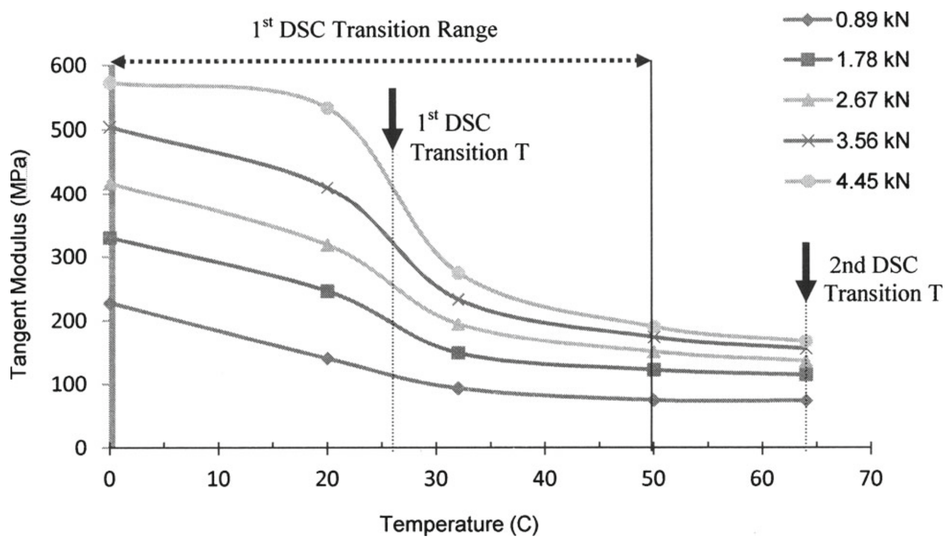

Figure 4 Tangent modulus at temperatures and loads ranging from 20 to 64°C and 0.89 to 4.45 kN (200 to 1000 lb).

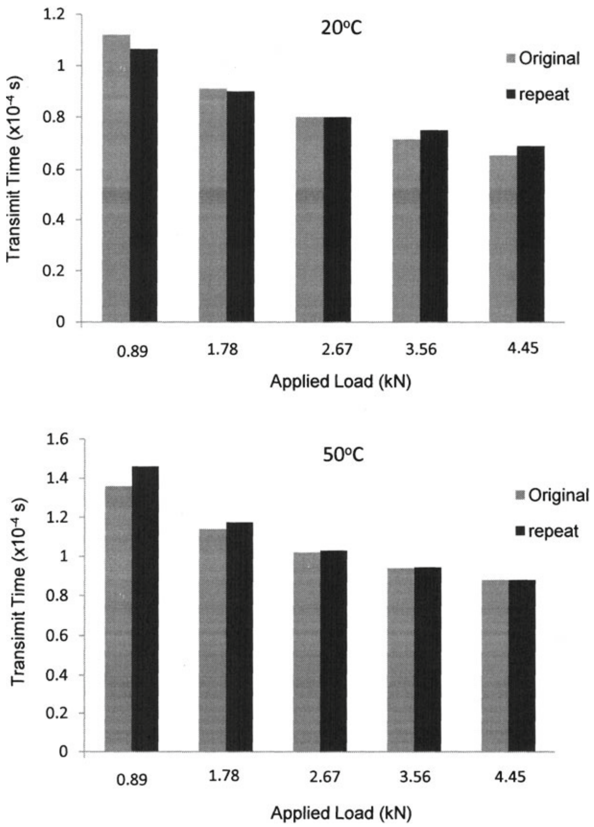

Figure 5 Ultrasonic transmission time repeatability tests at 20 and 50°C.

cohesive and facilitates mechanical interlocking and frictional resistance of the sand grains, polymer fibers, and rubber particulate under load. However, this interlocking frictional resistance appears to lessen significantly as the wax coating progresses through melting at higher temperatures and loads. The wax coating of these synthetic tracks is analogous to the bituminous binders used in asphaltic granular mixtures that soften and become less cohesive as temperatures warm.[22] It has been shown that the stiffness of petroleum-based, bituminous granular mixtures is temperature-dependent and the frictional interlocking of coarse aggregate is impeded at higher temperatures.[22] In several studies involving asphalt mixtures, the resilient modulus has been demonstrated to decrease by as much as 90% between 10 and 40°C as the binder softens.[23] Similar thermal-induced mechanisms for loss of stiffness appear to be occurring with the wax-coated materials in racetrack synthetic surfaces.

The variation in tangent modulus (vertical stiffness) with increasing temperature observed for the synthetic track sample is hypothesized to be a major contributor to racing performance at synthetic racetracks. For example, tests conducted at the Del Mar, California track showed slower afternoon race times, as compared to faster morning times when the track is cooler.[21] In this study, the surface temperature range from morning to afternoon was approximately 20 to 50°C, which overlaps the 20 to 32°C nonlinear tangent modulus region shown in Figure 4.

For temperatures above 32°C, the tangent modulus rate of decrease with temperature increase is reduced. The tangent modulus curves beyond 32°C generally exhibit high linearity for the 2.67–4.45 kN (600–1000 lb) load levels with coefficients of determination r^2 values greater than 0.99. The r^2 value for the 1.78 kN (400 lb) curve after 32°C is 0.95. This lower sensitivity at higher temperatures suggests that vertical stiffness and subsequent impact on racing performance would be more consistent after the DSC nominal transition temperature is reached. It is hypothesized that after this transition temperature, the majority of wax has transitioned from solid to liquid and the ability for further sand particle rearrangement is greatly reduced. The smaller negative slope of the modulus versus temperature curves indicate that the remaining wax solid is gradually melting as the second DSC nominal transition temperature (64°C) is approached.

Conclusions

The particular granular composite racetrack surface analyzed in this study was chosen because the relatively shallow wax DSC thermal transition peaks (as compared to other waxes used in synthetic surfaces) suggest that this synthetic surface shows relatively modest changes in mechanical properties with temperature. This would make this racetrack even more consistent than other synthetic tracks, which are generally less variable than dirt tracks due to the inherent insensitivity to moisture content. However, over the relatively narrow temperature span of 12 degrees between 20 and 32°C, the track shows quite dramatic changes in both material nonlinearity and tangent modulus. This temperature range is within the normal operation range of the racetrack. This softening of the surface with increasing temperature may affect horse race performance as illustrated in a Del Mar, California synthetic track study that showed consistently slower afternoon 6-furlong race times when temperatures were warmer.[21]

Although a softer surface may reduce the velocity of a horse as confirmed in another study,[24] softer surfaces do reduce hoof oscillations and may lead to fewer repetitive hoof injuries.[25] Softer surfaces have also been shown to reduce peak hoof impact forces and accelerations during hoof landings; one study shows that a loose top cushion of 50 mm or more can reduce impact forces by 40–60%.[26] Thus a softer surface may alter the load transfer from the ground to the hoof and the propagation of forces to the bones, tendons, and ligaments of the horse's leg.[27]

Future work will examine maintenance procedures that may assist in providing a more consistent surface over a larger range of temperatures. These procedures may include the addition of wax/oil additives aimed at increasing the melting temperature of the wax and delaying or decreasing the nonlinear, abrupt changes in tangent modulus. Additional procedures may also include watering the track and mechanical surface harrowing to help maintain the surface temperature at predetermined limits based on the DSC thermal characteristics of the wax coating.

Acknowledgments

The authors are grateful to the Grayson-Jockey Club Research Foundation and to the Churchill Downs ''Safety from Start to Finish'' initiative for primary funding for this research. The testing for this research was performed at the non-profit Racing Surfaces Testing Laboratory in Orono, Maine which is supported by a coalition of Thoroughbred racing tracks and industry organizations.

References

1. The Associated Press, ''Barbaro's Injury Spurs Interest in Polytrack,'' *NBC Sports* [Online]; May 25 (2006), URL http://nbcsports.msnbc.com/id/12976719/ns/sports-horse_racing// [accessed 16 June 2010]
2. Arthur, R.M., ''Comparison of Racing Fatality Rates on Dirt, Synthetic, and Turf at Four California Racetracks,'' *American Association of Equine Practitioners Proceedings* **56**:405 (2010).
3. Finley, B., ''Ground Control; The Real Truth about Synthetic Surfaces,'' *Thoroughbred Daily News Magazine* [Online], Winter (2010), URL http://thoroughbreddailynews.com [accessed 21 January 2010].
4. Peterson, M.L., and McIlwraith, C.W., ''Effect of Track Maintenance on Mechanical Properties of a Dirt Racetrack: A Preliminary Study,'' *Equine Veterinary Journal* **40**(1):2–3 (2008).
5. Ratzlaff, M.H., Hyde, M.L., Hutton, D.V., Rathgeber, R.A., and Balch, O.K., ''Interrelationships Between Moisture Content of the Track, Dynamic Properties of the Track and the Locomotor Forces Exerted by Galloping Horses,'' *Journal of Equine Veterinary Science* **17**:35–42 (1997).
6. Polytrack® Product Information, [Online] (2010), URL http://www.polytrack.com/ [accessed 1 January 2010].
7. Cushion Track Product Information, [Online], (2010), URL http://www.cushiontrackfooting.com/ [accessed 6 March 2010].
8. Polytrack I, *Material Safety Data Sheet*, Martin Collins Surfaces and Footings, LLC, Lexington, KY (2012).
9. Bardet, J.P., and Sanchez, J., ''Soxhlet Extraction Determination of Composition of Synthetic Soils,'' *Geotechnical Testing Journal* **34**(3):9 (2011).
10. Bridge, J.W., Peterson, M.L., Radford, D.W., and McIlwraith, C.W., ''Thermal Transitions in High Oil Content Petroleum-Based Wax Blends Used in Granular Sport Surfaces,'' *Thermochimica Acta Journal* **498**:106–111 (2010).
11. Bridge, J.W., Peterson, M.L., McIlwraith, C.W., and Beaumont, R.M., ''Temperature Effects on Triaxial Shear Strength of Granular Composites Sport Surfaces,'' *Journal of ASTM International* **7**(9):5–11 (2010).
12. Kuo, P., *Measurement of Modulus Change with Temperature of Synthetic Track Materials*, Masters Thesis, University of Maine, Orono, ME, Volume 16, pp. 37–40 (2008).
13. Dallap, B.L., ''The Horse-Racetrack Interface,'' *ACVS Veterinarian Symposium*, San Diego, CA; October 27, 2005.
14. Thomason, J.J., and Peterson, M.L., ''Biomechanical and Mechanical Investigations of the Hoof-Track Interface in Racing Horses,'' *Veterinary Clinical Equine Journal* **24**:53–77.
15. ASTM Standard D4419, ''Standard Test Method for Measurement of Transition Temperatures of Petroleum Waxes by Differential Scanning Calorimetry (DSC),'' *Annual Book of ASTM Standards*, Volume 5, ASTM International, West Conshohocken, PA (2005).
16. ASTM Standard D698, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3 (600 kN-m/m^3)),'' *Annual Book of ASTM Standards*, Volume **4**, ASTM International, West Conshohocken, PA (2007).
17. Trautmann, C.H., and Kulhawy, F.H., *CUFADA Computer Program for Compress and Uplift Foundation Analysis and Design, Report EL-4540-CMM*, Volume 16, Electrical Power and Research Institute, Palo Alto, CA (1987).
18. Peterson, M.L., ''A Method for Increased Accuracy of the Measurement of Relative Phase Velocity,'' *Ultrasonics Journal* **35**:17–29 (1997).
19. ASTM Standard E1356, ''Standard Test Method for Assignment of the Glass Transition Temperatures by

Differential Scanning Calorimetry,'' *Annual Book of ASTM Standards*, Volume 14, ASTM International, West Conshohocken, PA (2003).

20. Wineman, A.S., and Rajagopal, K.R., *Mechanical Response of Polymers*, Cambridge University Press, Cambridge, UK, pp. 255–256 (2000).
21. Peterson, M.L., Reiser, R.F., II, Kuo, P.H., Radford, D.W., and McIlwraith, C.W., ''The Effect of Temperature on Race Times on a Synthetic Surface,'' *Equine Veterinary Journal* **42**(4):351–357 (2010).
22. McNally, G.H., *Soil and Rock Construction Materials*, CRC Press, Boca Raton, FL, p. 211 (1998).
23. Hamzah, M., and Yi, T., ''Effects of Temperature on Resilient Modulus of Dense Asphalt Mixtures Incorporating Steel Slag Subjected to Short Term Oven Ageing,'' *World Academy of Science, Engineering and Technology* **46**:221–225 (2008).
24. Rogers, C.W., and Firth, E.C., ''Musculoskeletal Responses of 2-Year-Old Thoroughbred Horses to Early Training. 2. Measurement Error and Effect of Training Stage on the Relationship between Objective and Subjective Criteria of Training Workload,'' *New Zealand Veterinary Journal* **52**:272–279 (2004).
25. Salo, Z., Runciman, R.J., and Thomason, J.J., ''A Dynamic Model of a Horse Hoof at First Contact,'' *Biosystems Engineering* **103**:364–373 (2009).
26. Cheney, J.A., Shen, C.K., and Wheat, J.D., ''Relationship of Racetrack Surface to Lameness in the Thoroughbred Racehorse,'' *American Journal of Veterinarian Research* **34**(10):1285–1289 (1973).
27. Setterbo, J., Garcia, T., Campbell, I., Reese, J., Morgan, J., Kim, S., Hubbard, M., and Stover, S., ''Hoof Accelerations and Ground Reaction Forces of Thoroughbred Racehorses Measured on Dirt, Synthetic, and Turf Track Surfaces,'' *American Journal of Veterinarian Research* **70**(10):1220–1229 (2009).