Proceedings of the SEM Annual Conference
June 7-10, 2010 Indianapolis, Indiana USA

Dynamic Strain Rate Response with Changing Temperatures for Wax-Coated Granular Composites

J. W. Bridge[1,2,3]
M. L. Peterson[2,3]
C. W. McIlwraith[4]
[1]Associate Professor, Dept. of Engineering, Maine Maritime Academy, Castine, Maine 04420
john.bridge@mma.edu
[2]Department of Mechanical Engineering, University of Maine, Orono, ME 04469
[3]Racetrack Surfaces Testing Laboratory, Orono, ME 04473
[4]Gail Holmes Equine Orthopaedic Research Center, Department of Clinical Sciences, Colorado State University, Fort Collins, CO 80523

ABSTRACT

Triaxial tests were conducted at varying load rates and temperatures for a wax-coated granular composite material. This material is used as a surface for Thoroughbred horse racing. The purpose of the test is to examine how the shear strength of a synthetic track responds to changing strain rates. The temperatures used correspond to the temperatures of the surfaces during operations. These same temperatures have been shown using differential scanning calorimetry to correspond to thermal transition regions for the wax used to coat the sand in these surfaces. Preliminary results show that these tracks are sensitive to both an increase in the rate of loading and the temperature. However there may be an upper strain rate limit where temperature effects diminish. At low strain rates, temperature affects the dynamic strengthening response, while at higher strain rates; the dynamic load governs the strength response.

KEYWORDS: granular composites, dynamic strain rate, triaxial shear strength, paraffin and microcrystalline wax, synthetic horse tracks

INTRODUCTION

Synthetic granular composite materials are being used in many Thoroughbred horse race tracks in the United States and other parts of the world. In one case, their use was mandated by the state of California in 2007 due to testimony that these tracks were significantly safer than traditional dirt tracks [1]. One of the California synthetic tracks showed a 75% reduction in catastrophic horse injuries during the first year as compared to the previous year racing on a dirt track [2]. There are several vendors of the synthetic track materials used in the U.S. with track compositions generally consisting of silica sand (>70%), polymer fibers (<5%), and rubber particles (0-15%) all coated with a paraffin-based, high oil content wax [3,4]. The oil content in a recent study of several synthetic race tracks, to include the track location in this study, ranged from 34 to over 44% by mass [5].

Previous work investigated the composition and thermal transition characteristics of the wax coating as well as the static shear strength of actual track samples tested at operational temperatures [5,6]. Operational temperatures during the summer at one synthetic track surface in Southern California had been observed to range from 18^{o}C to over 50^{o}C over a 4-day period [7]. These earlier tests demonstrated that the wax-coatings have a definitive effect on the material properties of the track surfaces as the thermal transitions of the wax are encountered. This effect has also been shown through a correlation of 6-furlong (201 m) race times and temperatures [8]. For example, there is an increase in the track static shear strength as the wax in the materials experience melting during temperatures between 20 and 50°C [5]. This temperature range, well within racing operational limits, encompassed the first differential scanning calorimetry (DSC) thermal transition region for the extracted track waxes analyzed in the previous study. Figure 1 shows the DSC curve for one operational synthetic track sampled in March 2009, Figure 2 shows the corresponding quasi-static shear strengths that correspond to the transition temperatures in the DSC curve. Note that during the first DSC thermal transition region, the shear strength increases from 16.4 to 18.7°C, resulting in a peak strength increase of over 12%. The strength decreases as the end of the first transition region is reached but increases again as the second transition region is encountered.

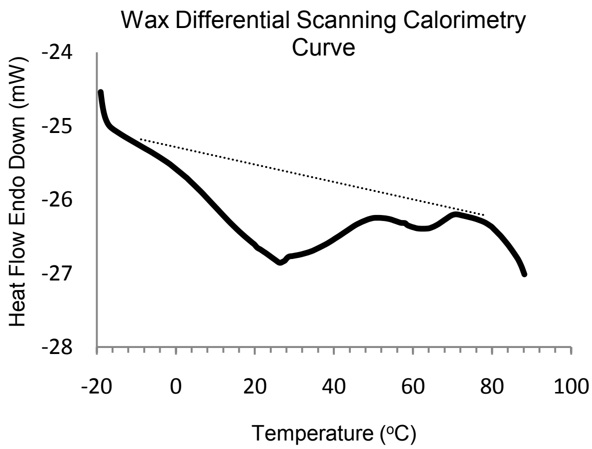

Fig. 1 DSC of extracted wax, Arlington Park, Arlington Heights, Illinois, 3-9-09.

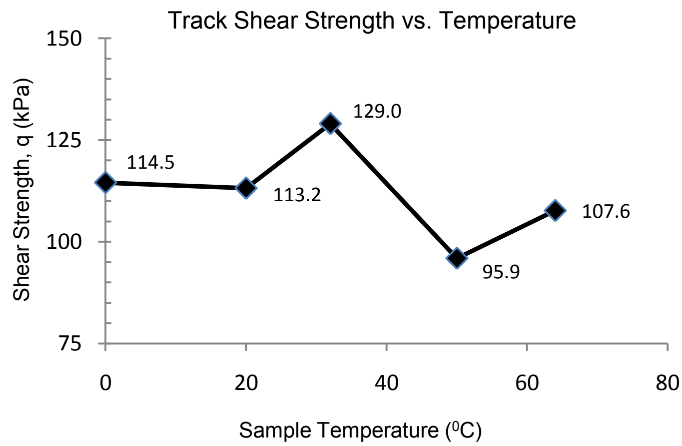

Fig. 2 Triaxial shear strength for Arlington Park, Arlington Heights, Illinois, 3-9-09.

The current study examines the effect of increasing the rate of loading on one operational synthetic race track surface at two potential operating temperatures.

MATERIALS AND METHODS

Track samples were taken from Arlington Park race track in Arlington Park, Arlington Heights, Illinois on September 27, 2009. The track had been in continual use for over 2 years. The samples were removed from the top 76.2 mm (3 in) of the track using a 75 mm-diameter sampling probe. The wax was extracted from a portion of the samples. The oil content of the wax was determined and gas chromatography (GC) and DSC tests were performed on the wax (with oil) to characterize the wax molecular carbon number distribution and thermal response. Dynamic shear strength tests were conducted on the remainder of the original track samples.

Wax Extraction and Oil Content Determination

The wax content by mass percent for each original wax-coated sample was determined using a high-purity iso-octane solvent extraction procedure described in an earlier paper [6]. Oil extraction tests were performed to measure the amount of oil present in the wax extracted from the Arlington Park race track. Tests were performed in accordance with ASTM D 3235 [9] using toluene and methyl ethyl ketone solvent extraction.

Gas Chromatography

Gas chromatography analyses of the extracted wax (with oil) were performed based on ASTM D 5442 [10] using a Hewlett Packard 5890 Series II Gas Chromatograph with flame ionization detector. Hydrogen was used as the carrier gas. The column used was a J&W Scientific capillary column DB-1HT, 30 m, with 0.32 mm inner diameter and 0.1-micron film thickness. Detector gasses employed were hydrogen at 30 ml/min and air at 400-450 ml/min. These tests give general carbon number distributions of petroleum waxes from C17 through C44 and higher. Normal and non-normal (isomer) hydrocarbon molecule mass percents are reported and results are used to help interpret DSC thermal behavior and to make comparisons between waxes.

Differential Scanning Calorimetry

Differential scanning calorimetry of the extracted wax was performed in a PerkinElmer Pyris1 with power compensation under nitrogen flow (ml/min). Two samples (9-11 mg weighed to 0.1 mg precision) of each 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 D 4419 [11]. Transition ranges and melting 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.

Triaxial Shear Compression Tests

Triaxial shear tests were performed to acquire track shear strength values at varying strain rates and temperatures. The tests were conducted with a screw type universal testing machine (Instron 4465, Norwood, MA, USA) based on the procedures outlined in ASTM D4767 used to characterize cohesive soils under foundations or structures. This test was modified to address the characteristics of a synthetic granular composite [12]. A consolidated, drained condition was incorporated as well as a temperature-controlled system to simulate the track operational conditions. Test confining pressures were also chosen to correspond to the depth of the critical stress field in the track. These pressures are based on the general maintenance conditions of a granular composite racetrack and the dynamic loads imposed by the forelegs of a galloping Thoroughbred horse [13]. The strength parameters involved and equation describing interactions of the sand internal friction angle and cohesion are explained in a previous paper [5]. The test setup is show in Figure 3 with accompanying component diagram.

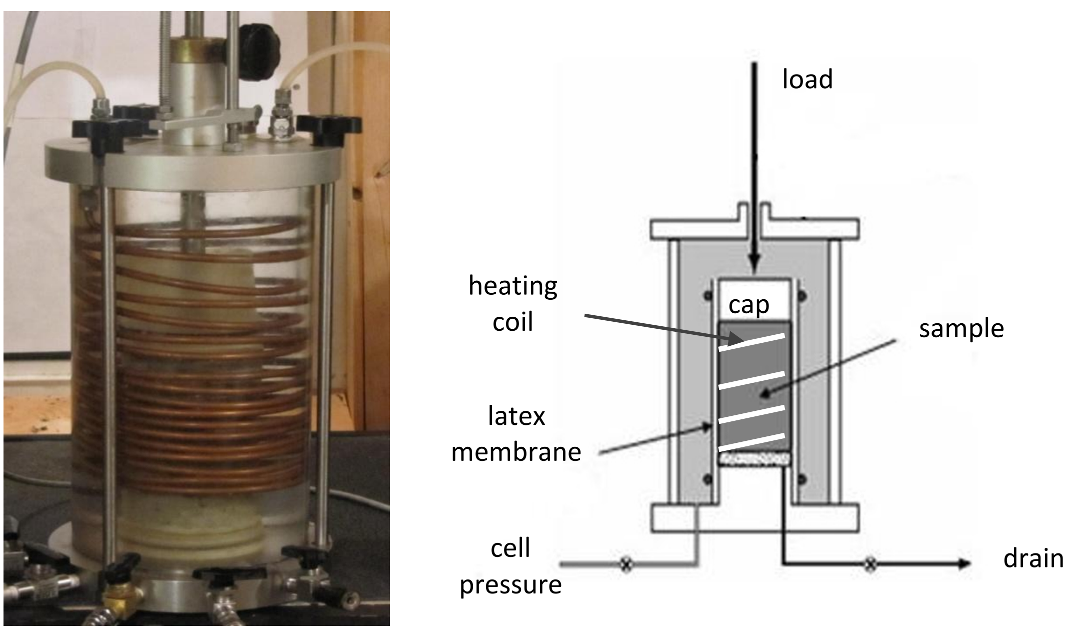

Fig. 3 Triaxial shear test setup showing sample within pressurized, temperature-controlled water test cell.

Samples to be tested were initially dried for a minimum of 24 hours prior to adding 4% moisture by mass. The 4% moisture is typical of the operating moisture content for synthetic tracks. Samples 70 mm in diameter were tightly packed in 25.4 mm compacted layer increments to a sample height of 152 mm. The tests were performed at 0.853, 10 and 100 mm/min loading rates under confining pressures of 35, 70, and 103 Pa (5, 10 and 15 psi).

The 0.853 mm/min strain rate chosen corresponds to the quasi-static load rate previously used when regularly reporting quasi-static synthetic track shear strengths[1]. The confining pressure used to report shear strength data is 103 Pa. The test temperatures selected were 20 and 50°C and based on the range of the first thermal transition region exhibited in the DSC curve. Temperature was controlled using a 0 to 100°C refrigerated water bath (Thermo Fisher Scientific, model RTE-17, Newington, NH, USA) that cycled water through the triaxial cell via a copper coil.

Results and Discussion

The wax extracted from the Arlington Park track material was found to be 9.24 % by mass and oil content was calculated at 41% by mass. The GC and DSC results with endothermic peaks are depicted in Figures 4 and 5. The GC has a bimodal isomer carbon number distribution (CND) and a very spread out normal CND. The mass percents of the normal and isomeric hydrocarbon molecules are 17.8 and 82.2 % respectively. The first DSC thermal transition begins at approximately 0°C and ends at 49°C. The second transition region begins at 53°C and ends at 66°C. The DSC nominal transition peak temperatures for each transition region are located at approximately 30 and 60°C respectively.

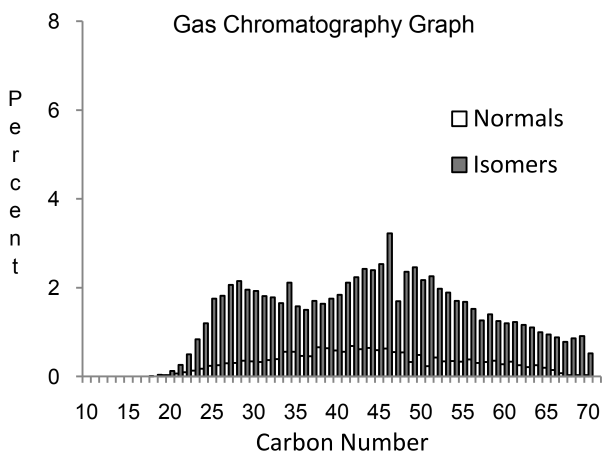

Fig. 4 GC graph of Arlington Park extracted Wax, 9-27-09.

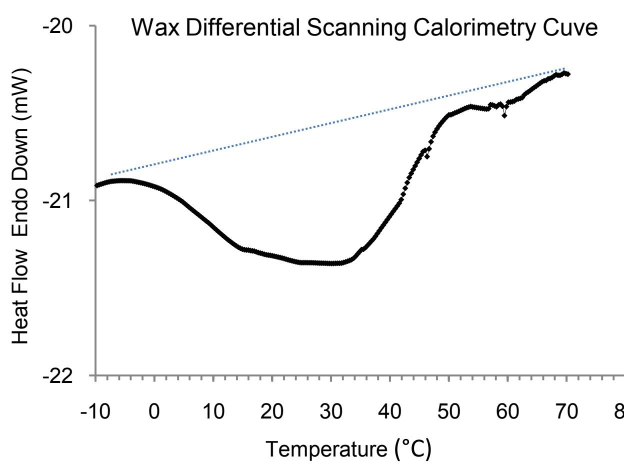

Fig. 5 DSC curve for Arlington Park extracted Wax, 9-27-09.

The results of the dynamic triaxial shear tests are shown in Figure 6. The data was extracted from Mohr-Coulomb p-q trend lines and strength envelopes as outlined in ASTM D 4767 [12]. The p-q trend lines had very high coefficient of determination r^2 values (0.999 average). There was a gradual increase in shear strength at both 20 and 50°C testing temperatures as load rates increased.

[1]Testing results obtained at the Race Track Surfaces Laboratory, Orono, Maine, Mar 2009 - Dec 2009.

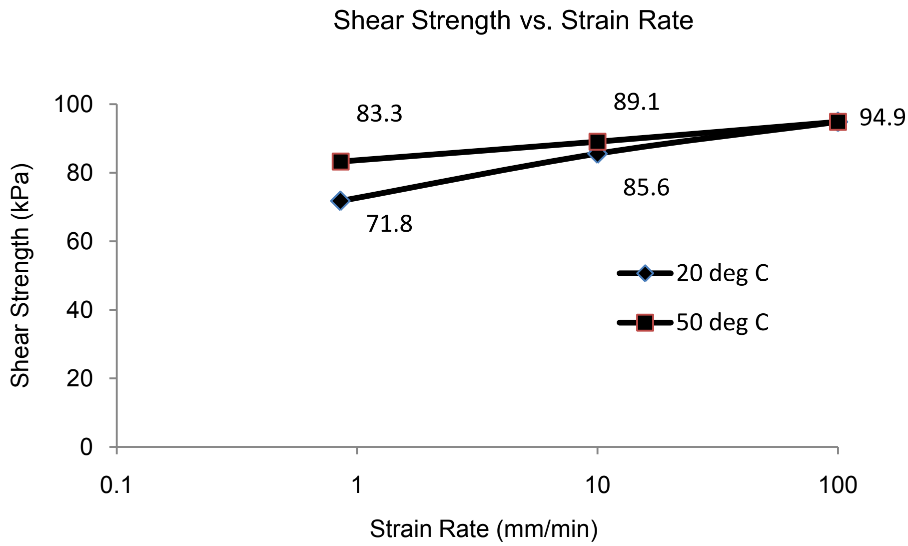

Fig. 6 Triaxial shear strength versus strain rate for Arlington Park track samples at 20 and 50°C.

The wax percent and high oil content reported are consistent with amounts found in earlier track synthetic wax studies and contribute to the wide GC carbon number distributions and DSC thermal transition regions. The GC bimodal CNDs suggest a blend of two waxes in the Arlington Park track samples. The high GC isomer percentage, coupled with CNDs extending beyond C60 (11% by mass), confirm the high-oil content in addition to the presence of complex, higher molecular weight hydrocarbon solids such as microcrystalline wax [14]. The DSC shows the largest fraction of wax undergoing complete melting at approximately 30°C and the remaining smaller fraction melting at 60°C. This melting behavior translates to a cumulative softening of the race track as these temperatures are approached.

The melting of the wax coating also contributes to a track strengthening effect at a range of temperatures as shown in the triaxial shear strengths in Figure 6. The 13.7% increase in strength between samples at the 0.853 mm/min strain rate is consistent with previously reported results for another Arlington Park sample at these temperatures [5]. As the strain rates increase from 0.853 mm/min to 10 mm/min, the 20°C samples show a 16.1 % increase in strength while the 50°C samples only shows a 4.8% increase. From 10 to 100 mm/min, the percent increase in strength narrows with shear strengths reaching almost the same levels (85.6 vs. 89.1 kPa). At the 100 mm/min strain rate, the shear strengths are identical for both temperatures (94.9 kPa). At the 20°C temperature, there is a total dynamic strengthening effect of 24.1% from 0.853 to 100 mm/min, while at 50°C the total dynamic strengthening is only 12.1%. However, the temperature only appears to affect the shear strength at low strain rates (less than 1 mm/min); the strength levels at the two temperatures quickly converge at the 10 and 100 mm/min strain rates. This suggests that at very low strain rates, increasing temperature has a greater effect as the wax-coated material becomes more fluid and coats the track constituents - enabling them to compact more easily under load. At lower temperatures under low strain rate conditions, a smaller percentage of the wax is melted and there is more time for particles to rearrange and subsequently, lower strength is exhibited. However, this temperature-induced viscoelastic response at lower strain rates diminishes with increasing dynamic load where the strain rate now governs the shear strength response.

The results of this work show that there is a complex relationship between the strain rate and the temperature of the material. This relationship is not surprising because of the well-established time temperature superposition effects in polymers [15]. From this understanding it is expected that the increase in temperature is equivalent to a decrease in time interval. This effect is clear from the results. The implications of this effect are also profound for interpretation of the biomechanical impacts of the surface on the horse. Different loading rates are experienced in the front and rear legs of the horse, since the deceleration of the center of mass of the horse occurs in the front with propulsion primarily in the hind limbs. As a result, the strain rate applied to the surface may be higher in the front limbs than in the rear. Thus, the length of the stride and relative support provided by the surface in the front and rear may be affected by temperature. This suggests that an improved understanding of the hoof landing and loading rates will need to be investigated as a part of the development of safer racing surfaces.

The strain rates tested in this study are considerably lower than those which occur in the surface when a horse gallops across it. However, this study clearly shows that strain rate effects cannot be neglected. The fact that temperature does not affect the material at the higher strain rates tested is not relevant based on previous race time data collected. Temperature has been clearly demonstrated to be an important factor in the speed of the horses and thus, has an effect on the material as well [8].

Conclusions

The dynamic shear strength of synthetic, wax-coated track materials appears to be influenced by temperature and the rate of loads imposed upon them. For the synthetic samples investigated, at the intermediate and post-melting temperatures tested, the shear strength increased with increasing strain rate. The higher temperature caused a change in shear strength only at the lowest strain rate applied (quasi-static) while at the higher strain rates (1 and 2 orders of magnitude higher), temperature effects diminished. It can be anticipated that for even higher strain rates, such as those caused by a Thoroughbred race horse, shear stresses will be much higher due to the higher strain rates. This will affect the biomechanical characteristics of a horse's leg impacting the surface. Future work will need to consider both accurate rates of loading and an improved understanding of the physiologically appropriate rates of loading. Higher strain rates (approaching 1000 mm/min) will be conducted as well as tests at additional thermal transition temperatures to confirm the material trends of the current study. The effects of differing strain rates on the material cohesion will also be examined. While this study is far from conclusive, it demonstrates that strain rate effects in these materials are significant and that further work is needed.

Acknowledgements

This work as been primarily funded by the Churchill Downs "Safety from Start to Finish" initiative. Additional support has come from the Grayson-Jockey Club Research Foundation for funding of the basic research as well as from Sean McColl of International Group Incorporated for gas chromatography tests. Work was performed at the non-profit Racing Surfaces Testing Laboratory which is supported by a coalition of Thoroughbred racing tracks and industry organizations.

References

[1] Allison, R., "Thoroughbred Racetracks Installing Synthetic Surfaces", JAVMA News [Online] April 1, 2007, http://www.avma.org/onlnews/javma'apr07/0070401o.asp (assessed Feb, 15, 2009).
[2] Shulman, L., *The Blood Horse*, 83, 2007, pp. 6975-6982.
[3] Polytrack® Product Information, [Online] 2010, http://www.polytrack.com/(accessed Jan 1,2010).
[4] Cushion Track Product Information, [Online] 2010, http://www.cushiontrackfooting.com/(accessed Mar 6, 2010).
[5] Bridge, J.W., Peterson, M.L., "Triaxial Effects on Triaxial Shear Strength of Granular Composites Sport Surfaces" (submitted to Journal of ASTM International, March 2010).
[6] 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", Thermochim. Acta 498, pp. 106-108, 2010.
[7] Kuo, P., "Measurement of Modulus Changes with Temperature of Synthetic Track Materials", Masters Thesis, University of Maine, p. 17, 2008.
[8] Peterson, M. L., McIlwraith, C. W., "The Effect of Temperature on 6-Furlong Times on a Synthetic Racing Surface", Equine Vet. J., 2009.
[9] ASTM Standard D3235: Standard Test Method for Solvent Extractables in Petroleum Waxes, Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA, 2002.
[10] ASTM Standard D5442: Standard Test Method for Analysis of Petroleum Waxes by Gas Chromatography, Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA, 2008.
[11] ASTM Standard D4419: Standard Test Method for Measurement of Transition Temperatures of Petroleum Waxes by Differential Scanning Calorimetry (DSC), Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA, 2005.
[12] ASTM Standard D4767: Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils, Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA, 2002.

[13] Wong, J. Y., Theory of Ground Vehicles, 2nd Ed., John Wiley & Sons, NY, 1995.
[14] The International Group Inc., Wax Overview [Online] 2006, www.igiwax.com/resource/Wax_Overview (accessed Nov, 2008).
[15] Ferry, J. D., Viscoelastic Properties of Polymers, Wiley, New York, 1980.