MRS Communications (2021) 11:256–260
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https://doi.org/10.1557/s43579-021-00017-z

MRS Communications

Research Letter

Development of an environmentally-durable, low-friction coating

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(Received 3 December 2020; accepted 26 January 2021; published online: 25 February 2021)

Abstract

In this communication, we highlight the development of a new coating that offers environmental durability and low-friction characteristics by exploiting the low interfacial bond strength of fillers with lamellar structures. The water-based coating has low volatile organic compound (VOC) content (< 50 g/L), offers the ability to be pigmented, demonstrates resilience against accelerated aging exposures, and exhibits even lower friction with extended weathering. The low-friction coating provides a simple method for modifying surface properties, and has the potential to complement Jersey walls by inhibiting vertical climb and thus decreasing the probability of vehicular roll-over upon impact.

Introduction

An environmentally-durable, low-friction coating has the ability to enhance the performance of highway barriers used to better protect drivers and construction workers throughout state and federal highways. The Federal Highway Administration utilizes robust barriers to separate lanes of traffic, minimize distraction associated with oncoming headlight glare, form a protective barrier in construction zones, and limit crossover interaction between vehicles in the event of an accident. The barriers, often referred to as Jersey walls, are designed to withstand significant mechanical impact, and are available in concrete and plastic material types,[1,2] with a sloped or tapered face intended to minimize vehicular roll-over on impact. While the design has proven effective, a number of cases exist where the angle of impact dictates the protective value of the sloped barrier.[3] Although the barriers are typically uncoated, low-friction coatings have the ability to complement the effectiveness of the Jersey wall design by limiting the vertical climb of a car's wheel up the face of the barrier.

Background

Development of a low-friction coating required the investigation of substrate materials, commercially available products, evaluation of many types of dry lubricant fillers, along with consideration of a compatible and durable binder system. To properly formulate a functional, low-friction coating, the research started with examination of a variety of substrate materials in order to establish a threshold for our low-friction standard. The dynamic friction of the substrates, including concrete masonry block, steel, Teflon, and wet glass was measured in units of British Pendulum Number (BPN). Table SI highlights measured skid resistance values for the substrate materials of interest. From the substrate assessment, a threshold rating of 34 BPN was established, with Teflon being the low-friction reference material. It is important note that low-friction and anti-stick are not synonymous properties. Friction and release are very different effects, and having one does not guarantee the other. In this instance, using Teflon as a standard for low-friction helps to establish a performance goal. Lower skid resistance values translate to lower friction coefficients, the primary performance metric for the coating being developed.

Commercially available binders designed as anti-stick or sacrificial/erosion coatings were procured and their skid resistance was measured. Evaluation of the commercial products (Table SII) revealed friction values much higher than the desired threshold, with results in the range of 74–100+ BPN. Consequently, development of a low-friction coating that makes use of dry lubricant fillers with lamellae structures infused into binders to create slippery surfaces became the focus. It was hypothesized that the inclusion of dry lubricant fillers would assist with stabilizing coating performance over time.

In addition, environmental impact was considered in the process of developing the low-friction coating. We sought to develop an environmentally benign coating, with volatile organic compounds (VOC) content less than 50 grams per liter. To the best of our knowledge, this is the first demonstration of a water-based coating that is environmentally-durable, non-corrosive, non-flammable, non-staining, low VOC, and offers a skid resistance less than 34 BPN, with the ability to color-match formulations.

Material selection and experimental approach

The key to achieving a low-friction coating required the use of layered structured mineral fillers (LSMF). The lamellar features offer low-friction properties due to their low interfacial bond strength that enable slip under weak forces. The motivation for selecting LSMF materials stemmed from prior knowledge associated with anti-fouling paints. Anti-fouling paints inhibit the growth of marine organisms on boat hulls because the outer layer slowly wears away, a concept sometimes referred to as "sloughing". We decided to take advantage of the sloughing traits of LSMF materials to produce a water-based coating system that offers improved performance over current classes of functional coatings. Examples of LSMF are graphite, hexagonal boron nitride, talc, and molybdenum disulfide. The fillers were blended into a water-based acrylic paint and evaluated over a concentration range of 5–65 wt%. Figure 1 shows a scanning electron microscopy (SEM) image of the graphite and talc particles, which were determined to be the most effective fillers for our applications of interest, along with a diagram outlining the structural mechanism by which slipperiness is achieved. When a compressive load is applied to coatings containing the respective fillers, the lamellae structures slide under weak shear forces and adhere to sliding surfaces, thus making them slippery and ideal for low-friction applications. All formulated paints were easily applied using standard brushing, rolling, and spraying techniques on concrete and/or metal substrates. No thinning of the formulation was required, and all painted substrates were allowed to dry for 48 h before further testing. Should the coating become used as a treatment for Jersey barriers, it could be touched up or re-applied as would normal paint, with no extraordinary surface preparation required.

To evaluate the large number of coatings produced, a standard procedure to measure frictional properties in accordance with ASTM E303[4] was followed, except for the use of water on the surface. Skid resistance values were obtained by using the British pendulum friction tester to measure the dynamic friction between a rubber slider and the test surface, in units of BPN. We also analyzed the coefficient of friction associated with the coatings to further validate slip performance. The test set-up and method were designed with guidance from ASTM D1894 (Standard Test Method for Static and Kinetic Coefficients of Friction of Plastic Film and Sheeting) and ASTM D2394 (Standard Test Methods for Simulated Service Testing of Wood and Wood-Based Finish Flooring), Section 33. Furthermore, the test method was formulated using ASTM G115 (Standard Guide for Measuring and Reporting Friction Coefficients) as a reference.

Although skid resistance is the primary metric, the coating was subjected to a series of environmental tests to confirm that the coating would withstand real-life conditions. As a result, a variety of outdoor exposure and environmental tests were performed including UV light, thermal cycling, high-temperature, low-temperature, humidity, flammability, flame spread, blowing wind, blowing sand, rain, shelf-life, freeze-thaw (in-can), and accelerated life trials via Weather-Ometer. The exposure conditions and associated methodologies are outlined in Table SIII.

Results

Skid resistance

Figure 2 shows the skid resistance of the developed low-friction formulation after outdoor weathering. The skid resistance of the coating was below that of Teflon, yielding performance better than the goal of 34 BPN. In addition, the performance improves with weathering time, demonstrating even greater benefit. These measurements provided initial confidence in support of the hypothesis; however, subsequent development to optimize performance was also explored and implemented.

Pigmenting

Following the characterization and performance evaluation, we explored tinting the low-friction coating using various pigments. Because our starting formulation offers a light base,

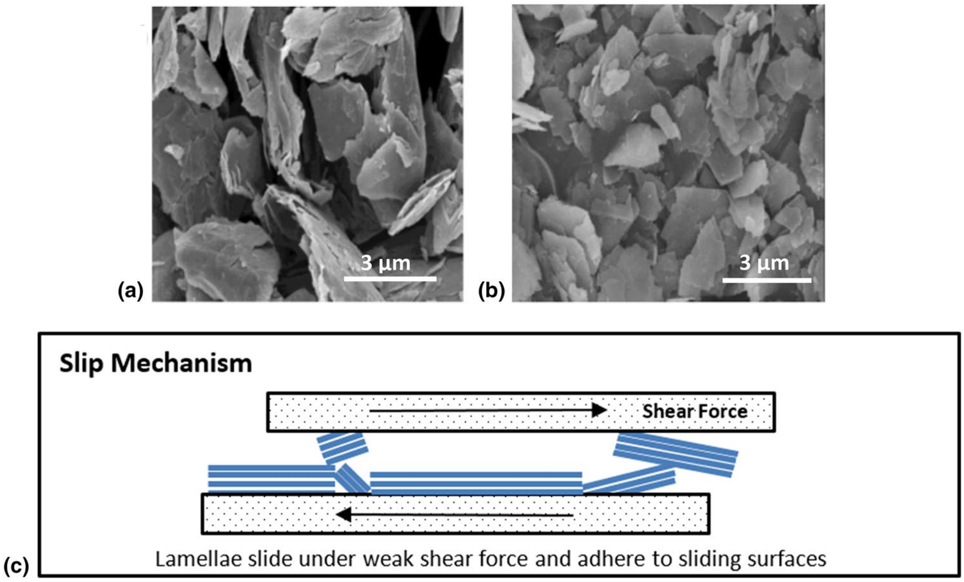

Figure 1. SEM images of LSMF for (a) graphite and (b) talc with (c) lamellae diagram of slip mechanism.

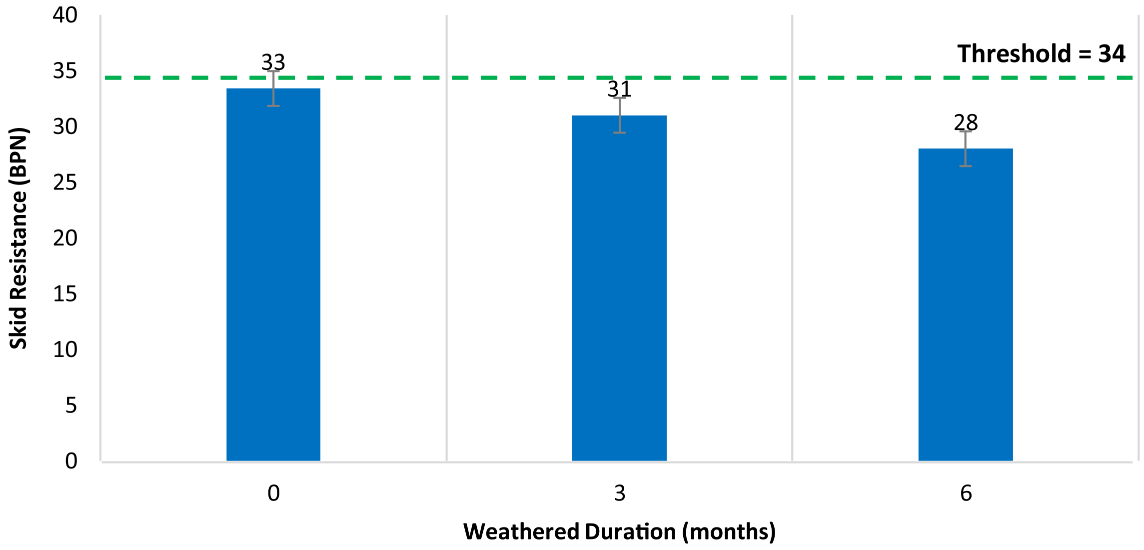

Figure 2. Skid resistance of the developed low-friction coating for 0, 3, and 6 months of outdoor weathering. All data was collected in triplicate.

colors become a viable option. There are two types of pigments used in coating formulations that offer high opacity, organic and inorganic. Organic pigments have a bright appearance and offer high tinting strength, but are relatively expensive. Inorganic pigments are duller in appearance and have lower tinting strength, but are lower in cost. To maximize the efficacy of the pigments, both organic and inorganic pigments were incorporated into the light base formula. Recognizing that some colors fade more than others, we opted to explore red pigments because red is typically a challenging color due to fading. Figure S3 provides a visual for assessment of the low-friction formulation, along with the pigmented organic and inorganic red pigments. Skid resistance tests revealed an average value of 29 BPN for the red pigmented panels.

Anti-graffiti properties

There was also interest in evaluating the graffiti resistance of the low-friction coating, as it is not uncommon for walls to be defaced with paint or other materials along roads and highways. The test method was formulated using ASTM D6578 (Standard Practice for Determination of Graffiti Resistance) as a reference. In Fig. S4, blue crayon, black marker, ballpoint pen, red alkyd spray paint, and lipstick were used to deface several painted metal coupons. Cleaning techniques ranging from dry wiping to light surface treatment were explored, and we discovered that all graffiti was able to be removed, except in the case of oil-rich materials like lipstick where a light stain was left behind.

Volatile organic compound content

VOC, a measure of solvent concentration released into air during application or after the paint has dried, was calculated and measured directly. There are currently regulations restricting the amount of solvent in coatings, but VOC levels less than 100 g/L (0.83 lb/gal) are often classified as environmentally friendly coatings. Achieving a VOC level less than 50 g/L (0.41 lb/gal) results in a coating that can be applied anywhere, without restrictions. The VOC of the light base formulation was measured in accordance with Environmental Protection Agency (EPA) Method 24.[10]

In the calculated VOC assessment, we included all of the non-exempt solvents, and assumed that all solvents would be released into air upon film formation. The VOC was calculated in view of the following formula:

$$\mathrm{VOC} = \frac{\text{Weight of Non Exempt Portion of Formula}}{\text{Total Formulation Volume} - \text{Volume of Exempt Solvent}}$$

In EPA Method 24, the sample was heated to remove all solvent, yielding the actual percent solid. Realistically, not all solvents that exist in the formula will be released into air, as some solvents react with the binder or become entrapped in the binder matrix, thus becoming part of the dry film and consequently being classified as a non-fugitive solvent. This assumption is usually the basis for the differences between the calculated and measured VOC, but the measured EPA method values are of greatest interest. The VOC values for the light base formulation are presented in Table SIV. Based on the findings, the measured VOC in the light low-friction coating is substantially lower than 50 g/L, and thus the coating can be categorized as near-zero VOC.

Environmental testing

Following the series of environmental exposures, the skid resistance of our low-friction paint was measured. Figure 3 shows the performance of the formulation for each exposure.

All measurements were below the threshold of 34 BPN and comparable to the unexposed control sample. In general, the skid resistance of the formulation increased after exposures where water was involved and decreased after hot or dry exposures. We suspect that this is closely related to microstructure of the LSMFs, which allow for absorption of water, thus impacting slip performance. Environmental tests also provided details that helped with the optimization of the formulation for color-fastness. Based on the tests conducted, painted substrates proved durable for 6+ months of outdoor exposure and an accelerated lifetime of at least 1-year via Weather-Ometer.

The overall results reveal that the formulation has a lower friction than Teflon, is environmentally-durable, and useful as an anti-graffiti material, thus demonstrating its viability.

Coefficient of friction

As an additional validation metric to the skid resistance testing, which provides a quick measure of kinetic friction, it was desirable to design and implement a test that could provide greater detail about the friction response of the formulation under different conditions. Various test methodologies were explored to directly measure the coefficient of friction (COF), both static and kinetic, for the finalized formulation on primed concrete masonry blocks and metal substrates.

A simple image of the test set-up is shown in Fig. S5. The test involves pulling a sled across a substrate. In this case, the sled was made of steel with rubber mounted to the bottom. Rubber, as part of a tribological system, is known to exhibit atypical behaviors that violate common rules of friction.[11] Thus, it was important to validate the test set-up and results without the use of rubber, ahead of the planned trials. Validation of the test set-up was conducted using a steel-on-steel system, as outlined in Fig. S6.

Bare concrete masonry block and metal substrates were tested as a control. Both types of substrates were coated with the Rustoleum water-based epoxy as a baseline for a standard exterior paint. Substrates were also coated with a commercial-off-the-shelf (COTS) sloughing paint product, Slip Plate #3, as a commercial baseline. Finally, substrates were coated with the developed low-friction formulation for experimental evaluation against the baselines.

The test matrix showing the experimental plan is shown in Table SV. For each of the coating-substrate pairs (“samples”), at least three runs were repeated on the same sample. Multiple runs were executed to elucidate any wear effects, and the performance was shown to be repeatable, which provided sufficient data for statistical confidence.

As shown in Fig. 4 and Figure S7, the kinetic COF data revealed that the developed low-friction formulation reduces the COF by up to nearly 60% on concrete compared to a COTS exterior paint (Rustoleum Water-based Epoxy). Moreover, the low-friction paint has a greater impact (reduction of COF) on the primed concrete substrates than on steel.

Conclusion

Based on the measured skid performance, environmental results, and COF analysis, we have demonstrated the viability and durability of a new water-based, low VOC, anti-graffiti, low-friction coating. Given the measured reduction in friction on concrete, this coating proves effective for treatment of Jersey walls. Additional test and evaluation data can be found in the supplementary material which accompanies this document. Future work will involve evaluation and adaptation of the low-friction coating for applications such as launch systems, farm equipment, boat hulls, and others. The coating described herein is patent pending.

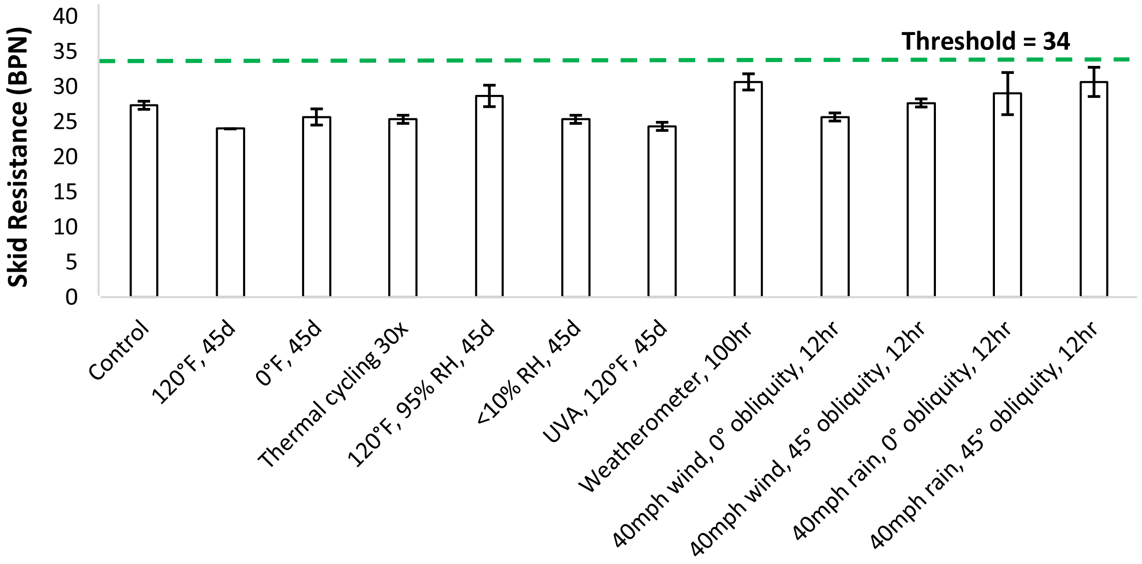

Figure 3. Skid resistance values for the developed low-friction coating after environmental exposure.

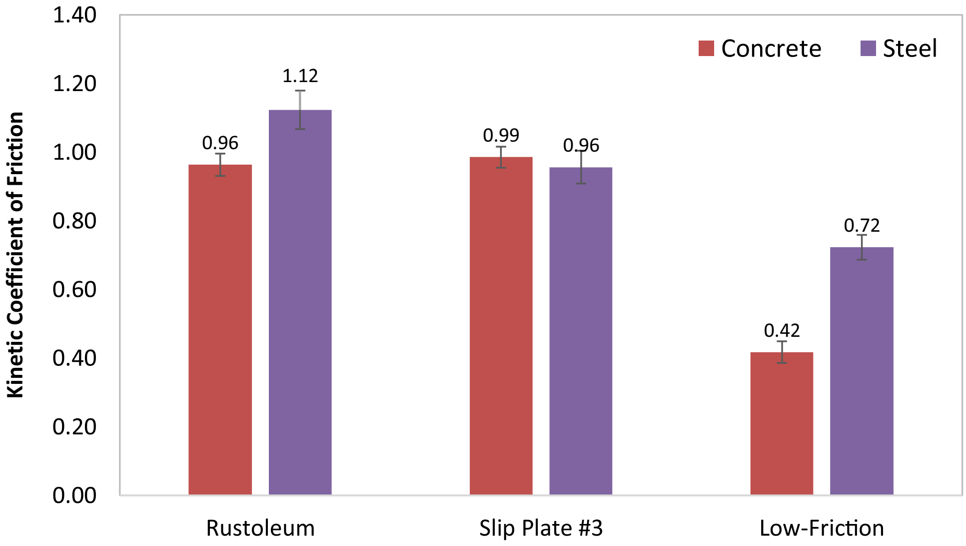

Figure 4. Comparison of Kinetic COF for All Coating-Substrate Pairs, including the developed low-friction coating.

Acknowledgments

The team would like to acknowledge Cavin Mooers and Eddie Gienger of the Research and Exploratory Development Department at The Johns Hopkins University Applied Physics Laboratory for the SEM analyses associated with the selected LSMF materials and for the COF testing, respectively. Financial support for this work was provided by the U.S. Department of State (Contract No. SAQMMA16C0355).

Compliance with ethical standards

Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Supplementary information

The online version of this article (https://doi.org/10.1557/s43579-021-00017-z) contains supplementary material, which is available to authorized users.

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