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Ice Engineering

U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire

Evaluation of Coatings for Icing Control at Hydraulic Structures

Adhesion of ice to surfaces creates problems for many industries, including hydropower and navigation. At present, ice removal techniques are costly, hazardous, and time-consuming. Andersson and Andersson (1992) reported that one hydropower station in Sweden had ice-related costs averaging $0.2 million per year over a 10-year period. Annual maintenance costs incurred at Corps of Engineer projects as a result of ice problems were estimated to be $33 million in 1992 (Haynes et al. 1993). Numerous commercially available materials, coatings, and paints are advertised to have low friction or non-stick properties. Some of these coatings are also marketed as icephobic (i.e., significantly lowering the adhesion strength of ice). We have measured the ice adhesion strength for many of these coatings and materials in the laboratory to rank their relative performance (e.g., Haehnel and Mulherin 1998). Our most recent study focused on the suitability of these materials and coatings for controlling icing at hydraulic structures.

We measured the ice adhesion strength of common paints used by the Corps of Engineers to protect steel members on hydraulic structures and compared their performance to the low-adhesion coatings. Both vinyl-based paints (used at freshwater projects) and epoxy paints (mainly salt/brackish water applications) were evaluated. Because the paints used by the Corps have been primarily developed for their high durability, it was considered unlikely that the low-adhesion coatings would replace them, but, instead, would be applied over the Corps paints to reduce ice adhesion to the surface. Consequently, our laboratory tests were designed to simulate this condition, and icephobic coatings were layered over samples that already had the Corps paints applied.

An alternate means of protection might be to clad an area with a low-adhesion material. Consequently, several candidate plastic cladding materials, such as Teflon, acetal, and polyurethane, were evaluated in this study as well.

Test procedure

Table 1 lists the paints, low-adhesion coatings, and materials evaluated in this study and in the past. We evaluated the materials and coatings in the laboratory at CRREL using a shear test apparatus (Fig. 1). The apparatus configuration is a cone test, which is typically used to evaluate the performance of adhesive joints (Anderson et al. 1977). In this configuration, an adhesive is used to bond concentric cones of variable angle and then an axial load is applied, so that the cones are pulled apart. By varying the cone angle, the relative amounts of shear and tension being applied to the adhesive joint can be controlled. We test using a cone angle of 0° (two concentric cylinders), which predominantly loads the adhesive in shear. In our tests ice is used as the adhesive. The inner cylinder (or pile) is either made of the material to be evaluated or coated with a candidate icephobic material. Once the sample is frozen, it is placed in the test apparatus (Fig. 1) and loaded until the ice–pile bond fails. The measured load at the time of bond failure is used to compute the shear strength of the joint (the maximum force divided by pile–ice contact area). This is our indicator of the adhesive strength of the ice bonded to the material of interest. Details of this test procedure are given in Haehnel and Mulherin (1998). These tests were all conducted at –10°C.

Results

Figure 2 shows the relative adhesive strength of the ice bonded to the coatings and materials listed in Table 1. Test results from the present study are indicated in yellow. In Figure 2, we grouped our results according to the test pile's base material: plastic, stainless steel, carbon steel, or aluminum. The height of each bar indicates the average failure stress measured for each material, while the vertical lines indicate the range in measured values. Teflon and polyethylene had the lowest average adhesion strengths, as do the commercial coatings WC-1-ICE and Kiss-Cote, which were each applied to

Table 1. Materials and coatings evaluated at CRREL using a 0° cone test to measure the adhesive shear strength of ice.

Material	Composition
Paints and coatings	
Kiss-Cote	Kiss-Cote 1083 (polydimethyl siloxane) used on aluminum samples and Kiss-Cote MegaGuard (polydimethyl siloxane) used on steel samples
Polyurethane paint	BMS (Boeing Material Spec) 10-60 polyurethane over BMS 10-11 epoxy primer
Rod-Coil-A	Developmental Foster-Miller Rod-Coil-A
Rod-Coil	Developmental Foster-Miller Rod-Coil coating
Wearlon	Water-based, methyl silicone copolymer epoxy
PSX-700	Siloxane and polyurethane epoxy
TroyGuard acrylic urethane	Fluoropolymer suspension and mineral spirits in clear urethane
TroyGuard/polyurethane	Fluoropolymer suspension and mineral spirits in BMS 10-60 polyurethane
Inertia 160	Trimethyl hexamethylenediamine epoxy
Envelon	Resin-based ethylene acrylic acid copolymer thermoplastic
Slip plate	Natural graphite coating in mineral spirits
WC-1-ICE	Saturated polyester resins in fluoropolyol with PTFE and organofunctional silicone fluid additives, modified with a fluorotelomer intermediate, and activated with a trimer of HDI
SA-RIP-4004	Saturated polyester resins modified with fluorotelomer intermediates activated with a biuret of HDI
Corps paints	
V-103c	Vinyl resin, type 3 (20), carbon black (1.5), diisodecyl phthalate (3.4), methyl isobutyl ketone (36.0), toluene (39.1% by weight)
V-766e	Vinyl resin, type 3 (5.6) and type 4 (11.6), titanium dioxide and carbon black (13.0), diisodecyl phthalate (2.9), methyl isobutyl ketone (32.0), toluene (34.7) ortho phosphoric acid (0.2% by weight)
V-102e	Vinyl resin, type 3 (18.2), aluminum powder (8.3), diisodecyl phthalate (3.1) methyl isobutyl ketone (33.8), toluene (36.6% by weight)
C-200a	Coal tar epoxy
MIL-P-24441C Type III	Polyamide epoxy
Materials	
Teflon	Polytetrafluoroethylene (PTFE) thermoplastic
Polyethylene	Ultra-high molecular weight polyethylene thermoplastic
Acetal	Acetal copolymer thermoplastic
Dupont Delrin	Polyoxymethylene homopolymer thermoplastic
Carbon steel	Cold rolled 1018
Stainless steel	Type 410
Aluminum	Type 7075

aluminum piles. On carbon steel piles, we found that the V-103c vinyl paint performed as well as PSX-700. Furthermore, using the Wilcoxon Ranked Sum test we found that there was no statistical difference, at $\alpha = 0.05$ (95% confidence level), between the performance of the V-103c black and any of the coatings applied to it. However, there was a statistical difference between C-200a alone and C-200a with TroyGuard applied over it.

Although the V-103c paint appears to have very low ice adhesion, this is not generally true for the other paints typically used by the Corps. The white and gray vinyl paint V-766e and aluminum vinyl paint V-102e had average adhesion strengths that were only 20–25% less than bare carbon steel, and epoxies C-200a and MIL-P-24441C Type III have adhesion strengths about the same as bare carbon steel. We found that the engineered coatings appeared to reduce the adhesion strength for the C-200a coal tar epoxy, with both PSX700 and TroyGuard reducing the adhesion strength by about 40 percent.

Most of our tests were conducted on pristine samples. However, a few of the plastics had been previously mounted outside during winter at the top of Mount Washington, New Hampshire, and were exposed to atmospheric and ultraviolet

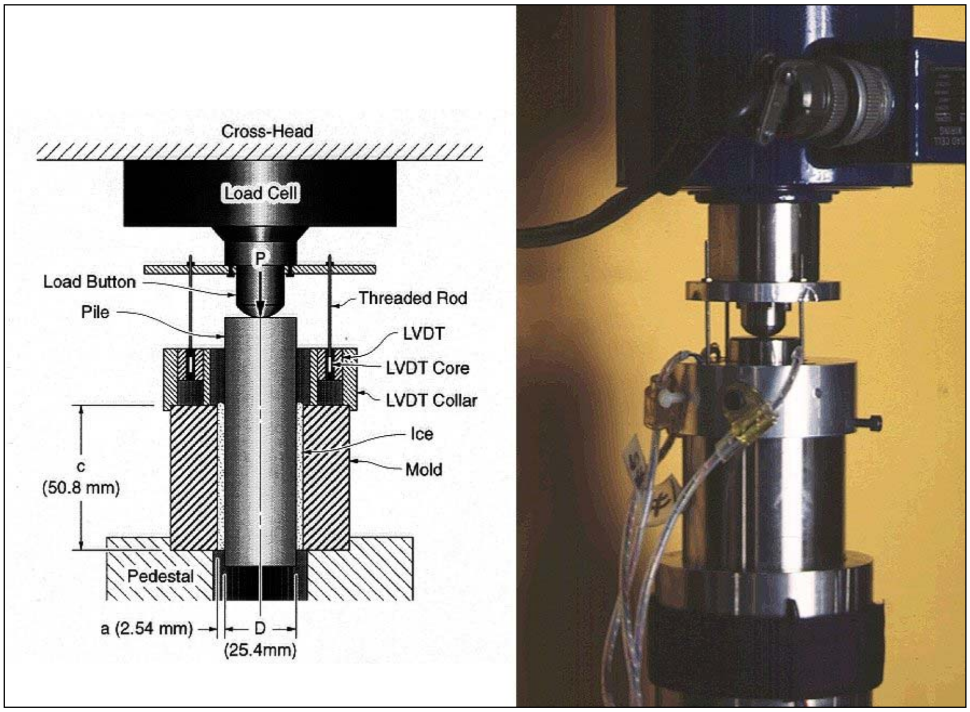

Figure 1. 0° cone test apparatus.

weathering. The number of days of weathering is indicated in parentheses following the plastic's name (Fig. 2). Initial results showed that the effect of weathering could significantly increase ice adhesion strength. Most notably, the adhesion strength for polyethylene increased by over a factor of two after being exposed to sunlight and atmospheric conditions for only 28 days.

The same trend was evident for the weathered acetal and Delrin samples, though the differences were not as great. The differences were statistically significant ($\alpha = 0.05$) for polyethylene, while not so for acetal and Delrin. To further study the effect of weathering on ice adhesion, the pristine plastic and coated carbon steel samples were mounted in a navigation lock chamber on the Mississippi River near St. Louis, Missouri (Lock and Dam 25), and exposed to field conditions, including cyclical wetting and drying, and abrasion from moving ice, sediment, and debris for the duration of the 2001–2002 winter and spring seasons. In late summer 2002, they will be returned to CRREL for retesting, so that their adhesion strengths can be compared to the results in Figure 2. Concurrently, 3-m × 2.4-m test patches of PSX-700, WC-1-ICE, and TroyGuard EX527 will be applied to the lock chamber wall at Lock and Dam 25; their durability and performance will be monitored over the upcoming years.

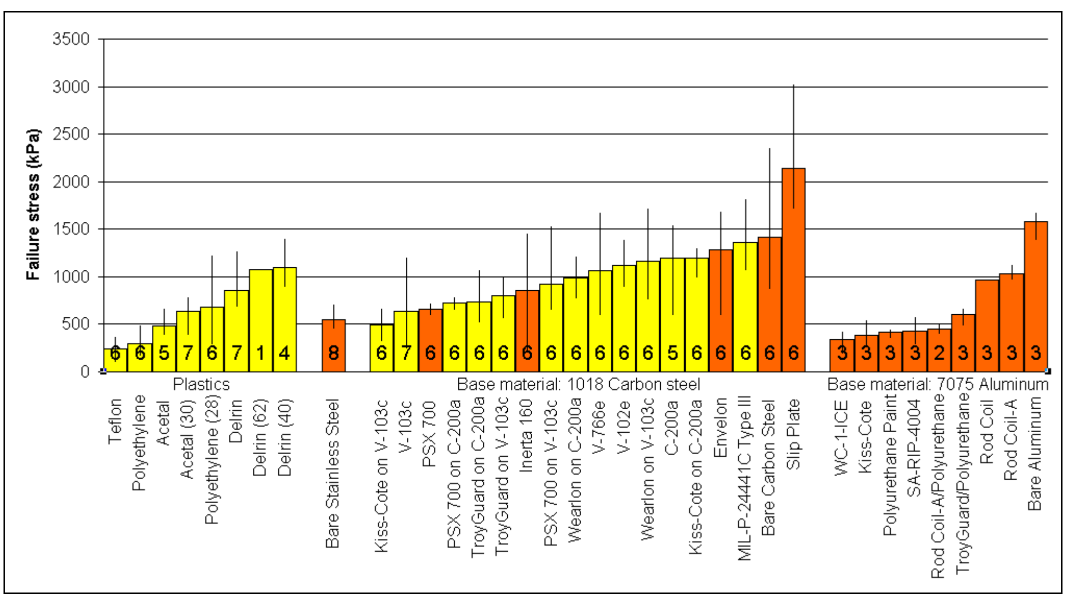

Figure 2. Shear adhesion strength of ice bonded to various materials and coatings. Yellow bars indicate new tests done under this study. Numbers in bars indicate sample size. Numbers in parentheses indicate number of days samples were weathered atop Mount Washington.

All of the tests conducted to date have shown that the adhesive shear strength of ice bonded to a variety of materials and coatings varies less than an order of magnitude. For the pristine plastic samples, the variation in adhesion strength between Teflon (lowest bond strength) to Delrin (highest bond strength) is less than a factor of four. Similarly, the bond strength of ice to carbon steel painted with V-103c is approximately three times lower than that of bare carbon steel, and the adhesion to bare aluminum is about five times higher than that to WC-1-ICE over aluminum. Although these reductions in ice strength are significant, they are not be significant enough to eliminate the need for additional methods of ice removal. More appropriately, low-energy materials should be considered as system enhancements for other methods, such as heat, electro-expulsive panels, or steam lances and pike poles.

Conclusions

There are a number of new commercially available icephobic coatings that provide a significant reduction in ice bond strength. Some of the coatings and paints that we have tested to date have one-half to one-third the ice adhesion strength of bare metal. Plastic cladding materials perform slightly better. The long-term performance, or durability of both plastics and coatings, has still to be evaluated. Durability tests are in progress.

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