Development of marine antifouling performance in hard fouling-release coatings

Allanique T. Hunter, Aaron J. Cogger, Kristyn Boutilier, Kylie H. Curnew, Katherine Purvis, Alexis Trevors, and Russell C. Wyeth*

Department of Biology, St. Francis Xavier University, 2321 Notre Dame Avenue, Antigonish, Nova Scotia, B2G 2W5, Canada

*Corresponding author at: Department of Biology, St. Francis Xavier University, 2321 Notre Dame Avenue, Antigonish, Nova Scotia, B2G 2W5, Canada. Email address: rwyeth@stfx.ca.

Abstract

Marine biofouling is a substantial economic and environmental issue. Hard fouling-release coatings present a promising solution, combining fouling-release characteristics with durability. This study tested proprietary hard fouling-release prototype coatings from GIT Coatings, Inc. alongside uncoated controls, colour controls, and commercial performance standards. Three successive experiments combined static and dynamic flow conditions at one or more sites in Nova Scotia. Initially, biofouling percent cover and cleanability for prototype coatings were comparable to untreated controls. By the final experiment, prototype coatings had significantly lower percent covers than both uncoated controls and the durability performance comparison (Ecospeed). Furthermore, several prototype hard fouling-release coatings had comparable percent cover (and possibly cleanability) to the fouling-release performance comparison (Intersleek). The results indicate that hard fouling-release coatings with potentially greater durability and longevity can achieve similar fouling-release performance as commercial fouling-release coatings. Further tests are needed to determine if unintended toxicity contributes to the antifouling effects.

Keywords: marine biofouling; antifouling; macrofouling; fouling-release; durability; recruitment

Running head: Marine hard fouling-release coating development

Introduction

Marine biofouling is the unwanted attachment and growth of organisms on submerged surfaces. This phenomenon is known to impact the functionality and longevity of marine infrastructure, with notable examples being vessel hulls and aquaculture infrastructure (Bannister et al. 2019; Dürr et al. 2022) . As a consequence of the drag large amounts of fouling can create on vessels, fuel consumption is greatly increased, driving up both monetary costs and carbon emissions (Davidson et al. 2016). For aquaculture, large amounts of fouling can damage equipment and harm farmed species (Braithwaite and McEvoy 2005). In addition to economic disruption, fouling on vessel hulls and aquaculture equipment is a vector for transporting invasive species to new areas (Ruiz et al. 2015; Davidson et al. 2016). The cumulative effect of these impacts make biofouling a major issue in maritime industries.

The numerous negative impacts of marine biofouling have led to a multi-faceted effort to create procedures and products that prevent or remove unwanted growth on vessels. The most promising anti-fouling paints can employ two strategies to reduce fouling buildup: biocidal agents and fouling release. Biocidal products employ materials toxic to organisms, such as copper, to kill and remove attached organisms. Fouling release coatings utilize low surface energy materials to both mechanically interfere with initial attachment to surfaces and reduce the force required to remove fouling that still manages to grow (Lejars et al. 2012; Hu et al. 2020; Wu et al. 2022). Although a range of coatings have succeeded in limiting the impacts from biofouling growth, issues can arise when these coatings affect more than the intended fouling targets and enter the wider marine environment (Antizar-Ladislao 2008). Indeed, tributylin , a widely used and effective antifouling compound, was banned internationally for its negative environmental effects (Uc-Peraza et al. 2022). As a result, there has been a renewed interest in creating effective coatings that minimally impact the marine environment. The characteristics of an ideal antifouling coating include minimal environmental impacts and accumulation, antifouling efficacy against multiple species and in multiple environments, long-term durability, and cost effectiveness for widespread use (Yebra et al. 2004; Lejars et al. 2012; Nurioglu et al. 2015; Hu et al. 2020; Gu et al. 2020).

A key challenge for fouling-release coatings has been balancing low attachment strengths for biofouling versus durability of the coating (Leonardi and Ober 2019). Surfaces with low surface energy and high elastic modulus substantially reduce the strength of biofouling attachment (Lejars et al. 2012; Hu et al. 2020; Wu et al. 2022). However, such coatings are often relatively soft, and therefore are susceptible to mechanical damage (Dahlgren et al. 2022). This is particularly the case for siloxane-based surfaces that have been a primary focus of past studies exploring fouling-release coatings. Nonetheless, a number of commercial siloxane-based coating have been developed (Lagerström et al. 2022). Development of fouling-release coatings with greater durability will likely be a valuable additional option for protecting vessels hulls and other similar applications. Coatings with greater durability would have increased longevity as they would have greater resistance to physical damage or erosion over time. Indeed, the importance of durability (and longevity) are a clear implication of the latest International Maritime Organization recommendations regarding proactive and reactive cleaning of biofouling on ship hulls (International Maritime Organization 2024).

A variety of recent studies have explored several different approaches to increasing durability of fouling release coatings. Mechanical properties contributing to overall durability, including adhesion (to the coated surface), resistance to abrasion, and hardness have all been considered alongside the surface performance with regard to reducing attachment strengths (reviewed in Pistone et al. 2021). Improvements in durability for siloxane-based coatings have particularly been achieved by adding either metallic nanoparticles or co-polymers to the coating formulations. Durability benefits have also been reported via other changes; for example, adding either siloxane-based gel particles or polysaccharides to siloxane-based resins (Eslami et al. 2019; Wanka et al. 2020). Alternatively, coatings using either epoxy or urethane resins are inherently more durable to begin with, and thus numerous studies have attempted to use additives or formulation modifications to improve their fouling-release characteristics (Pistone et al. 2021; Poornima Vijayan et al. 2022). Finally, a number of studies exploring the use of sol-gel chemistries involving methacrylate have also found fouling-release performance comparable to the siloxane-based coatings, while achieving a categorically different level of hardness (Gunari et al. 2011; Chen et al. 2020; Vignesh et al. 2020). The shared aim for these studies is to maintain surface properties that limit biofouling attachment, while improving coating performance with respect to maintaining adhesion and resisting both abrasion and fracturing.

GIT Coatings (Dartmouth, Canada) is a materials engineering company that is developing polymeric coatings with both fouling-release characteristics and improved hardness over siloxane-based coatings. The exact formulas of the GIT coatings are confidential, and their basic formulation changed substantially over three generations of prototype coatings involved in this study. The first generation of coatings were epoxy resins based on either phenylalkamine or a hybrid combining phelyalkamine and polyamide. The second generation switched to a combination of aminosilane and phenylakamine epoxy resin. The third generation were a proprietary combination of epoxy and silicone resins. In all generations, the coatings incorporated other additives that varied amongst the different coatings in each generation. As with other members of the antifouling industry, the ultimate goal was to develop a coating that limited growth on marine vessels while avoiding negative side effects to non-target marine organisms.

In this study, three generations of prototype fouling-release coatings produced by GIT Coatings were tested. Each generation of coatings had their material properties characterized and were then field tested to evaluate relative performance amongst several different formulation variants as well as compare their performance against commercially available coatings. The first commercial comparison, Intersleek is a silane-based coating that is used for its fouling release properties (International Marine Coatings, 2024). The second coating, Ecospeed, is a glass platelet composite that is highly durable but does not have any antifouling properties (Subsea

Industries, 2024). In total, field tests of 16 different coating prototypes prepared by GIT Coatings were conducted over three successive deployments targeting one or more marine biofouling communities found around Nova Scotia, Canada. Coatings were applied to primed steel plates and tested in either static or dynamic conditions. Antifouling capabilities for each protoype were assessed through observing the change of and total growth percent cover on each plate over the span of the experimental deployment, as well as through the relative presence of each fouling species. Cleanability tests of attachment strength were also completed at the end of each deployment.

Materials and Methods

Hard fouling-release coatings

All hard fouling-release coatings were prepared by GIT Coatings, Inc. (previously Graphite Innovation and Technologies, Inc.;Halifax, Nova Scotia, Canada). As key details of the recipes are proprietary information, only a summary of the coating preparation is provided, along with internal batch codes to identify the coatings (Table 1). Coatings varied with regard to the primary resin polymers, curing agents, fillers, dyes and other additives. Coatings were applied to primed steel plates (20 x 10 x 0.5 cm) with holes drilled in the corners for securing them during deployment.

Surface Characterization Tests

A series of surface characterization tests were conducted on treatment plates for each coating type before deployment. Contact angle was measured using a goniometer and associated software (Ossila, Ltd). Relative hardness compared coating hardness to graphite pencil tips, based on ISO 15184. A sharpened graphite pencil was clamped in a horizontal wheeled cart that held the pencil precisely at a 45 degree angle, with the tip resting on the coating surface. The cart was manually moved a short distance (approx. 1cm) across the plate, without pushing down, and the coating was then inspected for damage. By testing a series of graphite pencils of increasing hardness and noting which hardness was the first to cause damage, coating hardness was scored on a scale from 1(softest) to 20 (hardest; based on the 20 available degrees of pencil hardness). Wet coefficient of friction was measured using a tribometer (model 925 DCOF, American Slip Meter Inc). Average surface roughness (Ra) was measured using a surface roughness tester (VTSYIQI Lab Measuring Instruments).

Field Experiments

Three experiments were conducted over three successive years (2020, 2021 and 2022), each with a different set of hard fouling-release coatings (Table 1). In the first experiment, four sites were used to increase the diversity of biofouling organisms, while only one of the sites (which had the highest diversity) was used for the second and third experiments (Table 2). In each experiment, the efficacy of the hard fouling-release coatings was compared to one or two commercially available performance comparisons (also applied to primed steel plates) as well as bare acrylic colour-matched controls (Ells et al. 2016) and/or bare PVC controls (all with similar dimensions as the steel plates). Plates were strung into a series of frames constructed from plastic pipe (either PVC or ABS) and deployed off docks at the same depth (between 1 and 3 m, depending on the site). Plate positions within each frame were randomized, with equal numbers of plates for each treatment in each frame. Tests could either be in a static environment, with plates subjected only to natural tidal and wind-generated water movement or in a dynamic environment, with frames placed downstream from a fixed electric trolling motor (Endura Max, Minn Kota Item # 1352156M) that produced turbulent water flow parallel to the surface of the plates (1.5 – 2 m s^{-1} as measured by *in situ* video of dye transport ~10 cm from the plate surfaces). The goal with the static and dynamic conditions was not to compare effectiveness in the different environments (there was not enough space for adequate replication), but instead to diversify the hydrodynamic conditions under which biofouling developed on all treatments.

Experiment 1 tested three hard fouling-release coatings in static environments at four sites (Table 2) from July 10 or 11, 2020 for 7 weeks at site A, 10 weeks at site B, 10 weeks at site C, and 6 weeks at site D. Twelve plates of each treatment and both bare black acrylic and PVC controls were tested at each site. One site had an additional 12 plates coated with Intersleek IS1100SR (International, Akzo Nobel N.V.) included in the test. Experiment 2 tested seven hard fouling-release coatings in a dynamic environment at one site, from July 17, 2021 for 8.5 weeks. Twelve replicates were tested for each coating, as well as for both smooth and sanded white acrylic (colour controls), bare PVC, Intersleek, and Ecospeed (Subsea Industries, Inc.). Experiment 3 tested six hard fouling-release coatings in both static and dynamic environments, from May 24, 2022 for 12 weeks. Sixteen replicate plates were tested for each treatment as well as for white acrylic (colour controls), Intersleek, and Ecospeed, all evenly split between static and dynamic environments. Initial analyses showed no clear patterns differentiating the two environments, and thus static vs dynamic environment was not included as a factor in the analyses.

Photo Analysis

Plate images were used to calculate biofouling percent cover over time for all treatments and controls. Methods were similar to Wilson et al (2024). Briefly, images were cropped and scaled to an identical resolution in FIJI (Schindelin et al. 2012), and then used CoralNet (Beijbom et al. 2012; Beijbom 2015; Williams et al. 2019) to quantify biofouling coverage for each plate (with all observations validated by a human observer). Biofouling species (or bare plate) was identified (see lists in Table 2) for 49 points spread in a stratified random distribution over each image, and total percent cover was estimated from the proportion of points identified as an organism rather than background plate.

Cleanability

At the end of each experiment (only at site B in experiment 1), cleanability tests were conducted. These followed the principle of assessing remaining biofouling after stepped increases in water pressure applied to the plates, as outlined in Swain and Schultz (1996). A DeWALT DXPW3625 pressure washer was used with the spray nozzle held 25 cm above the center of the plate. An inline pressure gauge was added and used the built-in pressure regulator to expose the plates to three different pressures (30 sec each, in ascending order: 250, 500, and 750 PSI (equivalent to 1.7, 2.4, and 4.1 MPa). Photos were taken in between each pressure increment, and processed as above to determine percent cover after each pressure increment.

Statistical Analysis

Percent cover for both field test and cleanability data involved repeated measures. Initial testing indicated substantial departures from normality, and thus a non-parametric aligned-rank transform analysis (ARTool) was chosen (Kay et al. 2021; Elkin et al. 2021). This allowed us to test for statistical differences in percent cover between treatments, between time points or pressure increments, and whether the effect of treatments depended on time or pressure increments. Data for each experiment and site combination were analysed separately, and each model included main effects for treatment, time (or pressure increment), their interaction, and a random effect of plate. Post hoc contrast tests were conducted to determine the significance of specific differences among the treatments. For experiment 1, analysis as limited to just time points during the growth portions of the fouling curves for each site. For experiments 2 and 3, which showed growth even at the end of deployment, all time points were analysed. Differences in biofouling were assessed by determining whether different treatments had more or less fouling over all time points analysed. Thus, the primary focus for determining differences among coatings were the main effects of treatment. All analyses were conducted using R and RStudio, supported by the following packages: tidyverse, readxl, ggplot2, magrittr, ggpubr, lemon, rcompanion, and ARTool (Wickham 2009; Kay et al. 2021; Wickham and et al. 2021; Signorell et al. 2021; Mangiafico 2022).

Results

Surface Characteristics

Surface characteristics of the hard fouling-release coatings varied quite widely (Table 1). With regard to hardness, the two performance comparisons were the hardest (Ecospeed) and softest (Intersleek) coatings tested. Prototype hard fouling-release coatings with varying hardnesses were included in experiments 1 and 2 ranging from almost as hard as Ecospeed to intermediate hardness between Ecospeed and Intersleek. In experiment 3, hardness was consistently intermediate for all prototype coatings tested. With regard to the other characteristics measured, prototype coatings tested in Experiment 1 varied in contact angle (neither wet coefficient of friction nor roughness was measured for this group of coatings). In experiment 2, coatings varied with regard to all three other characteristics: contact angle, wet coefficient of friction and roughness. Finally, in experiment 3, variation among coatings was reduced, with relatively consistent contact angles (and hardness), in particular.

Experiment 1 - Site A

Biofouling at this site was mostly the compound ascidian *Botrylloides violaceus*. Biofouling development under static conditions followed a typical sigmoidal growth pattern over time until an unexplained die-off occurred after 34 days of deployment (Figure 1A). (No correspondence was observed with either temperature or rainfall patterns that could have led to a severe drop in salinity, and no known release of pollution coincided with the die-off either.) From this point onwards, percent cover continually decreased until the experiment ended. Before the die-off occurred, all three hard fouling-release treatments had significantly less fouling than controls (PVC and Black Acrylic; no commercial performance comparisons were tested; Table 3). Hard fouling-release coating 128.2 clearly had the lowest percent cover, and was significantly lower than the other hard fouling-release coatings between 6 and 36 days after deployment. The two other hard fouling-release coatings (122.15 and 125.3) showed no significant difference between each other in biofouling.

Experiment 1 – Site B

Plates at this site were primarily colonized by the ascidian *Ciona intestinalis.* Growth in total percent cover in static conditions followed a typical sigmoidal pattern until completion of the experiment (Figure 1B). There were no significant differences between any of the hard fouling-release coatings or control treatments (PVC and black acrylic), and no performance comparisons were tested.

In contrast, hard fouling-release coatings showed much poorer cleanability than the control treatments. All treatments began with close to 100% percent cover prior to pressure washing. Over successively greater pressures, percent cover on the hard fouling-release coatings decreased significantly less than on the control treatments, and ultimately had greater biofouling than the controls after the highest wash pressure (Figure 2A; Table 4).

Experiment 1-Site C

Biofouling under the static conditions at this site was more diverse, with the greatest cover from *C. intestinalis*, but also *Botrylloides violaceus*, and two bryozoans, *Bugula* sp. and *Membranipora membranacea*, This site was the only site in Experiment 1 to include Intersleek as a commercial performance comparison. Intersleek outperformed all hard fouling-release coatings and controls, significantly reducing total percent cover (Figure 1C; Figure 3; Table 3). Among the hard fouling-release coatings, there were no significant differences in percent cover, although coatings 122.15 and 128.2 did show significant reductions in percent cover compared to the black acrylic control treatment (but not to the PVC control treatment).

Experiment 1 - Site D

This site was fouled exclusively with the mussel *Mytilus edulis*. Plates deployed in the static conditions at this site experienced a rapid increase in biofouling from day 6 through day 27 when percent cover had reached 100% (Figure 1D). Treatments 125.3 and 128.2 appeared to delay biofouling by a couple days, however, there were no significant difference between any of the treatments (when analysing the growth period from days 6 to 28). No performance comparisons were deployed at this site.

Experiment 2 - Site C

The hydroid *Ectopleura larynx* was the predominant species in this experiment, with smaller contributions from *C. intestinalis*, *B. violaceus* and *Bugula* sp. Overall, percent cover under the exclusively dynamic conditions again followed a typical sigmoidal growth pattern, although variability was substantially higher (Figure 4). Unfortunately, no significant differences were found between control treatments and either Intersleek or any of the hard fouling-release coatings (Table 3). Percent cover on the best performing hard fouling-release coating, 208.5B, was not significantly different from cover on Intersleek, but was significantly lower than the two worst performing hard fouling-release coatings, 208.1, and 208.3 (Figures 3 and 4).

Not surprisingly, cleanability data was similarly unclear. The most obvious pattern was that the greatest decreases in percent cover following pressure washing tended to occur for treatments with the greatest precent cover prior to washing (Figure 2B). Intersleek and one hard fouling-release coating (208.5B) had the lowest fouling to start with, and both decreased to close to zero percent cover after the first (and lowest) wash pressure. Other hard fouling-release coatings began with a range of percent covers, spanning less, comparable or more percent cover than the controls (PVC and white acrylic). As washing pressure was increased, they (and Ecospeed) all followed close to parallel decreases in percent cover, with those with the least cover initially tending to achieve the lowest percent cover after the highest wash pressure. Statistical comparisons of the decreases for the different treatments showed substantial overlap among most of the treatments (Table 4). Overall, then, the data are consistent with hard fouling-release coatings having similar cleanability to that of Intersleek, and no worse than uncoated control surfaces (and Ecospeed).

Experiment 3 - Site C

In this experiment, *E. larynx* was again the predominant fouling species, with *Ciona intestinalis* also abundant. All hard fouling-release coatings performed better than uncoated controls, and one achieved reductions in biofouling comparable to Intersleek. Intersleek had significantly less fouling than all control treatments and all but one of the hard fouling-release treatments (Figure 5, Table 3). Compared to Intersleek, coating 250.3 did have more total fouling later in sampling (Figures 3 and 5), but over the entire experiment the difference was not statistically significant. At the same time, coating 250.3 had significantly less biofouling cover than either Ecospeed or white acrylic, and also had less than coatings 250.5 and 250.6C. Among the other hard fouling-release treatments, no substantial differences were found, while most had significantly less fouling than Ecospeed, and all had significantly less than white acrylic.

With regard to cleanability, the clearest pattern was again that greater decreases in percent cover with pressure washing tended to be associated with higher initial biofouling cover. Three hard fouling-release treatments, one of which was coating 250.3, joined Intersleek in having essentially zero percent cover following cleaning with the lowest pressure (Figure 2C). Among the other hard fouling-release treatments, all but one had achieved near-zero percent cover after the highest wash pressure. Based on the amount percent cover decreased between pressures, white acrylic had the greatest cleanability, and over several pressure increments (Table 4), several of the hard fouling-release coatings had comparable (i.e. not significantly different) decreases in percent cover. Only Ecospeed showed substantial fouling after the highest was pressure, but presumably because it started with such high percent cover, none of the decreases in biofouling on hard fouling-release coatings were significantly greater. In summary, then, within the limitations set by having differing initial fouling levels, hard fouling-release coatings did not have worse cleanability than either Intersleek or white acrylic, while Ecospeed did have less cleanability.

Discussion

Hard fouling-release coatings developed by GIT Coatings improved with regard to fouling prevention in each successive experiment. By design, the prototype coatings were prepared with greater hardness than Intersleek, the commercially-available fouling-release performance comparison. With regard to antifouling performance, the first experiment showed that the first set of prototype hard fouling-release coatings were comparable to untreated controls in performance, with percent covers reaching close to saturation (>75%) at their peak. Experiment 2 was largely inconclusive, although trends in the data suggest prototype coatings might have somewhat better performance than untreated controls. In contrast, by the end of the final experiment, the new hard fouling-release coatings had significantly lower percent covers compared to the durability control (Ecospeed) and the untreated acrylic control. Furthermore, several hard fouling-release coatings were comparable to the fouling-release performance control (Intersleek). Although absolute hardness was not measured, the relative measures confirmed hardness values were intermediate between the two performance comparisons. Intersleek is a soft coating with excellent fouling release characteristics. Ecospeed is a hard coating with no fouling-release characteristics. Thus, the final prototype coatings produced by GIT Coatings, Inc. for experiment 3 can be considered as hard fouling-release coatings.

Cleanability results were less clear cut, but are at least consistent with improvements over the three successive experiments. An ideal cleanability test would have all coatings saturated with biofouling and then compare the reduction in biofouling as wash pressure is increased. Unfortunately, only the first experiment fulfilled this ideal, and its results showed lower cleanability for the hard fouling-release coatings in comparison to uncoated acrylic and PVC. In experiments two and three, saturation was not achieved for most or all treatments. In these later experiments, treatments that had the most initial fouling (BC208-3 and Ecospeed) also retained the most fouling after pressure washing. In this situation, coatings that have high cleanability but low initial percent cover could have a lesser decrease in percent cover simply because they are reduced to zero percent cover, and cannot demonstrate their full potential for cleanability. This is almost certainly the case for the Intersleek performance comparison coating in experiments 2 and 3. Thus, for the hard fouling-release coatings in those experiments, the conclusion for those coatings that had similar percent cover to uncoated control plates is that their cleanability was no worse than the uncoated controls, with both types have similar decreases in percent cover as wash pressure increases. On the other hand, for those coatings that had initial percent cover similar to Intersleek, cleanability was no worse than Intersleek, with zero percent cover achieved with the same increases in wash pressure. Crucially, though, is unknown whether cleanability of the hard fouling-release coatings would be similar to Intersleek, if the biofouling cover was saturated on the coatings. Nonetheless, there is a clear pattern of improved cleanability of the hard fouling-release coatings between experiments 1, 2 and 3, with similar or better cleanability than uncoated controls and Ecospeed, and possibly as good cleanability as Intersleek. Future tests of cleanability should be delayed until percent cover saturates on all treatments.

The improvement across experiments corresponds with changes in the coating formulations. Unfortunately, since the formulations are proprietary, coating information is limited to what is publicly available on the composition of the coatings from Safety Data Sheets. A key aspect of the coating development was changes in the resins and curing agents used for the hard fouling-release coatings in each experiment. Epoxy resins cured with polyamide and a mixture of phenalkamine polyamide were used in experiment 1, an aminosilane epoxy was used in experiment 2, and a combination of epoxy and silicone resins was used in experiment 3. Whether these changes are responsible for the improved performance is not clear, as other (proprietary) changes were made to the coatings between experiments.

There was little correspondence between the performance of hard fouling-release coatings and their surface characteristics. Both within and between experiments, there were no consistencies with regard to contact angle, wet coefficient of friction, or roughness for coatings either with good performance or with poor performance. The only pattern that has some support was in experiment 2, when the hardest coatings (208.1 and 208.3) performed relatively poorly, in clear opposition to the strong performance of Intersleek which is relatively soft. This is consistent with past studies that have shown softer, more compliant surfaces can have better fouling-release properties (Hu et al. 2020; Wu et al. 2022). Given that increasing hardness is key to improving durability (Leonardi and Ober 2019; Pistone et al. 2021), further development of hard fouling-release coatings will require optimization to balance fouling-release and durability. Indeed, the coatings tested in experiment 3 were part of the first efforts in this regard.

Another potential explanation for the varying results relative to physical characteristics is that chemical characteristics (particularly the possibility of unintended chemical leaching) were driving some of the antifouling performance (Filip et al. 2016; Lagerström et al. 2022). This could be via either direct effects of any leached chemicals on the macroscopic biofouling species or via induced changes in biofilms which then produce differences in the biofouling community based on settlement preferences of the macroscopic fouling species (Hadfield 2011; Freckelton et al. 2017). Thus, reduced biofouling relative to the controls in the experiments reported here could either be a consequence of reduced attachment strengths as suggested by the cleanability measurements, or toxicity, or both. Further tests with both microbial and macroscopic fouling species are thus recommended for hard fouling release coatings to better understand the relative contributions of reduced attachment strength *versus* reduced growth or mortality arising from toxicity. In addition, toxicity assays with biofilms as well as larvae and settled adults of major biofouling taxa will be important for insight into possible broader environmental impacts of hard fouling-release coatings.

Colour of the coatings may have had some influence on their relative performance (Ells et al. 2016). Typically, lighter coatings should have less biofouling, given the general preference for darker surfaces shown by many marine invertebrate larvae. Thus, lighter coatings were expected to have less fouling. Consistent with this expectation, there was a clear trend with more fouling on black acrylic than grey PVC in experiment 1 at both site D and especially at site C, but in neither case was the pattern statistically significant. In contrast, at site B, the opposite pattern occurred with more fouling on the lighter PVC. In experiment 2, grey PVC had consistently higher fouling than white acrylic as might be expected, but again the percent cover on the two was not statistically distinguishable. Overall, the findings suggest there may have been a subtle effect of surface colour (or brightness) that would require greater replication to reveal as significant in a single experiment. However, there remains the possibility that chemical or physical features of the different materials that are confounded with colours are causing the effects. Given these uncertain results, inclusion of differing colour controls was abandoned in experiment 3.

In summary, the findings here show it is possible for a harder fouling-release coatings to be developed with antifouling characteristics approaching those of a softer, commercially available fouling-release coating. Indeed, these findings are consistent with the assertion that the first commercially-available hard fouling-release coatings are being produced by GIT Coatings, Inc. Further effort seems warranted to optimize the trade-off between durability and fouling-release capabilities (Eslami et al. 2019). More detailed analysis of the coating physical characteristics would be helpful, including more rigorous hardness tests than the pencil test use here, as well as microscopic examination of the coating surfaces. Tests focused on quantifying both fouling cover, durability, and surface characteristics over longer periods of time (months or years) would particularly help to assess how those characteristics could translate into greater longevity than less durable coatings (Lin et al. 2024). Additional testing would also be useful in different environments with differing biofouling communities (Swain et al. 2000; MacKenzie et al. 2019; Whitworth et al. 2023). A particular priority should be to determine effectiveness against hard fouling species such as barnacles, and also more thorough testing of cleanability than was achieved here. Lastly, systematic assessment of any toxicity effects of both current and future formulations will always be needed to verify that antifouling performance is indeed arising from fouling-release characteristics, and to support any claims of reduced environmental effects.

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Declaration of Interest

The authors declare that there are no known conflicts of interest associated with this publication and there has been no financial support for this work that could have influenced its outcome. Employees of GIT Coatings did participate in preparation and characterization of the coatings and could theoretically benefit from findings that support the efficacy of the hard fouling-release coatings. However, all relevant data collection and analysis of the coating performances was funded by external research grants and conducted by authors affiliated with St. Francis Xavier University for whom no such potential benefit exists.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author, RCW, upon reasonable request.

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Tables with Captions

Table 1. Characteristics of hard fouling-release coatings prepared by GIT Coatings, Inc. as well as for commercial coatings tested for performance comparison. Characteristics include coating resin, curing agent, contact angle (CA), relative hardness (a pencil test based on ISO 15184), wet coefficient of friction (WCOF), roughness (Ra), and colour. Abbreviations: Phenalkamine (Phenalk); Polyamine (PolyA); Aminosilane (Am Sil).

Expt	**Coating**	**Resin**	**Curing Agent**	**CA (°)**	**Hardness**	**WCOF**	**Ra (µm)**	**Colour**
1	122.15	Epoxy	Phenalk	95	9	NA	NA	Black
1	128.2	Epoxy	PolyA/Phenalk	110-113	4	NA	NA	Black
1	125.3	Epoxy	PolyA/Phenalk	116	2	NA	NA	Black
2	207	Epoxy	Am Sil/Phenalk	110-115	11	0.13±0.02	0.19	White
2	208.1	Epoxy	Am Sil/Phenalk	105-110	2	0.14±0.02	0.09	White
2	208.3	Epoxy	Am Sil/Phenalk	95-100	1	0.08±0.02	0.70	White
2	208.4	Epoxy	Am Sil/Phenalk	85-90	8	0.08±0.02	0.20	White
2	208.5B	Epoxy	Am Sil/Phenalk	100-105	11	0.15±0.02	1.72	White
2	208.6B	Epoxy	Am Sil/Phenalk	80-90	11	0.13±0.05	1.07	White
2	208.7	Epoxy	Am Sil/Phenalk	90-100	8	0.11±0.01	0.34	White
3	250.1	Mix of Epoxy and Silicone Resins*		106	9	0.189	1.96	White
3	251.4	Mix of Epoxy and Silicone Resins*		104	9	0.147	0.41	Red
3	250.3	Mix of Epoxy and Silicone Resins*		109	9	0.153	2.48	Blue
3	251.5	Mix of Epoxy and Silicone Resins*		106	9	0.228	0.36	Black
3	250.5	Mix of Epoxy and Silicone Resins*		109.5	9	0.123	2.22	White
3	250.6C	Mix of Epoxy and Silicone Resins*		110.2	9	0.124	3.06	White
Commercial coatings for performance comparison								
2 and 3	IS1100SR	Silane*	*	108	15	0.113	0.11	Red
2 and 3	Ecospeed	Vinyl epoxy*	*	67	1	0.194	6.62	Grey

* details unavailable for proprietary information

Table 2. Characteristics of the four sites used across the three experiments.

Site	**Expts**	**Location**	**Latitude & Longitude**	**Type**	**Flow Conditions**	**Tidal Exchange**	**Water Temperature** (°C)	**Species Present**
A	1	Cribbons Pt.	45°45’21’’N 61°53’49”W	Marina with rock breakwater	Static	±1.2 m	17 – 23	*Botrylloides violaceus*, *Botryllus schlosseri*, *Bugula* sp., filamentous algae
B	1	Petit de Grat	45°30’26”N 60°57’38”W	Marina with rock breakwater	Static	±1.3 m	15 – 21	*Botrylloides violaceus*, *Botryllus schlosseri*, *Bugula* sp., *Ciona intestinalis*, filamentous algae
C	1,2,3	Port Hawkesbury	45°36’49”N 61°21’56”W	Marina with floating breakwater	Static & Dynamic	±1.4 m	1: 13 - 21, 2: 14 - 22, 3: 5 – 22	*Botrylloides violaceus*, *Botryllus schlosseri*, *Bugula* sp., *Ciona intestinalis*, *Membranipora membranacea*, *Ectopleura larynx*, *Metridium senile*, filamentous algae
D	1	Waycobah	45°57’7”N 61°7’28”W	Aquaculture site with no breakwater	Static	±0.1 m	17 - 23	*Mytilus edulis*, filamentous algae

Table 3. Statistical analysis of biofouling total percent cover on the treatments over time, including main effects for treatment and time, and their interaction. For the main effect of treatment, homogenous subsets are indicated by lower case letters for each of the treatments. Treatments include hard fouling-release coatings (alphanumeric codes), commercial performance comparisons (Intersleek, IS; and Ecospeed, ES), and controls (black acrylic, BA; white acrylic, WA; and bare polyvinyl chloride, PVC).

Expt & Effect	**F**	**Df**	***P*-value**	**Treatments**										
Expt 1 Site A				128.2	122.15	125.3	BA	PVC						
Treatment	30.6	4,55	<0.001	a	b	b	c	c						
Time	440.5	3,165	<0.001											
Interaction	10.2	12,165	<0.001											
Expt 1 Site B				128.2	122.15	125.3	BA	PVC						
Treatment	1.69	4,55	0.166	a	a	a	a	a						
Time	319.37	6,330	<0.001											
Interaction	1.33	24,330	0.140											
Expt 1 Site C				128.2	122.15	125.3	BA	PVC	IS					
Treatment	16.49	5,66	<0.001	b	b	bc	c	bc	a					
Time	853.32	5,330	<0.001											
Interaction	9.82	25,330	<0.001											
Expt 1 Site D				128.2	122.15	125.3	BA	PVC						
Treatment	14.87	4,54	<0.001	a	ab	a	c	bc						
Time	1314.62	2,108	<0.001											
Interaction	10.57	8,108	<0.001											

Expt 2 Site C				207	208.1	208.3	208.4	208.5B	208.6B	208.7	ECO	PVC	WA	IS
Treatment	3.84	11,132	<0.001	ab	b	b	ab	a	ab	ab	ab	ab	ab	a
Time	131.70	8,1056	<0.001											
Interaction	3.49	88,1056	<0.001											
Expt 3 Site C				250.1	250.3	250.5	250.6C	251.4	251.5	ECO	WA	IS		
Treatment	25.08	8,135	<0.001	bcd	ab	cde	de	bcd	bc	ef	f	a		
Time	251.82	12,1602	<0.001											
Interaction	11.64	96,1602	<0.001											

Table 4. Statistical analysis of cleanability of the treatments, including main effects for treatment and pressure, and their interaction. Interaction contrasts, comparing treatments with respect to how percent cover changed between pressure levels are used to create homogenous subsets among the treatments (indicated by lower case letters for each pair of pressures). Treatments include hard fouling-release coatings (alphanumeric codes), commercial performance comparisons (Intersleek, IS; and Ecospeed, ES), and controls (black acrylic, BA; white acrylic, WA; and bare polyvinyl chloride, PVC). .

Expt & Effect	**F**	**Df**	***P*-value**	**Treatment**										
Expt 1 Site B				128.2	122.15	125.3	BA	PVC						
Treatment	22.21	4,25	<0.001											
Pressure	113.58	3,75	<0.001											
Interaction	10.86	12,75	<0.001											
Pressure pairs														
0-250				a	a	a	a	a						
0-500				a	a	a	b	b						
0-750				b	b	a	c	c						
250-500				ac	ab	c	d	bd						
250-750				c	a	b	d	ad						
500-750				a	a	b	a	a						

Expt 2 Site C				207	208.1	208.3	208.4	208.5B	208.6B	208.7	ECO	PVC	WA	IS
Treatment	4.74	11,132	<0.001											
Pressure	152.71	3,396	<0.001											
Interaction	4.10	33,396	<0.001											
Pressure pairs														
0-250				bc	c	c	bc	a	ab	bc	bc	bc	bc	a
0-500				cd	de	e	de	a	bc	de	cd	de	de	ab
0-750				bc	de	e	cde	a	b	cd	bc	cde	cde	a
250-500				a	a	a	a	a	a	a	a	a	a	a
250-750				abc	c	c	c	ab	abc	c	abc	c	c	a
500-750				a	a	a	a	a	a	a	a	a	a	a
Expt 3 Site C				250.1	250.3	250.5	250.6C	251.4	251.5	ECO	WA	IS		
Treatment	26.35	8,135	<0.001											
Pressure	208.60	3,404	<0.001											
Interaction	7.84	24,404	<0.001											
Pressure pairss														
0-250				cd	bc	b	d	b	b	bcd	cd	a		
0-500				de	bc	cd	de	bc	b	de	e	a		
0-750				c	b	c	c	b	b	c	d	a		
250-500				abc	a	abc	ab	a	a	bc	c	a		
250-750				ab	a	ab	a	a	a	bc	c	a		
500-750				a	a	a	a	a	a	a	a	a		

Figures with Captions

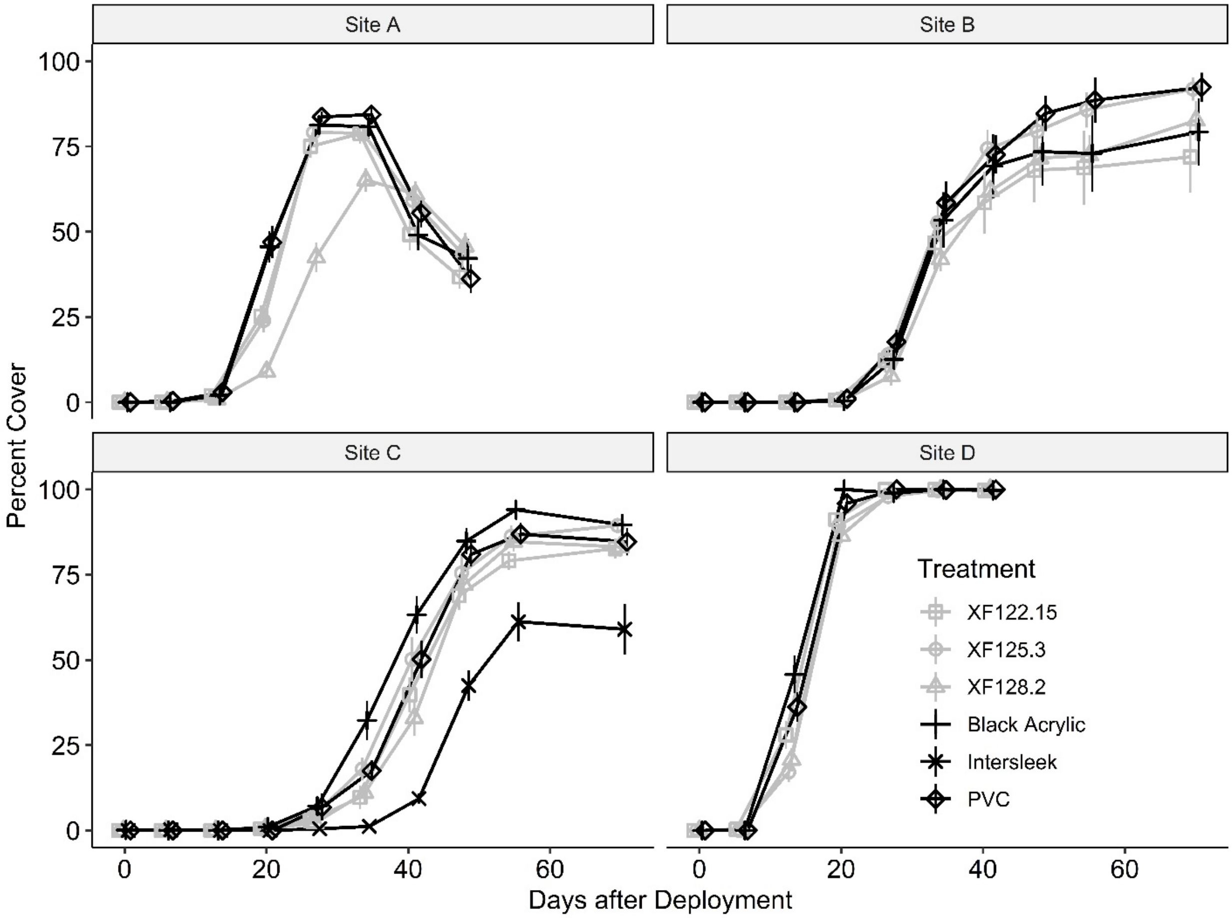

Figure 1. Biofouling percent cover in experiment 1 (conducted at four sites: A, B, C and D). Three hard fouling-release coatings (grey lines) were compared against a commercial performance comparison (Intersleek, only at Site C) and two bare controls (grey PVC and black acrylic).

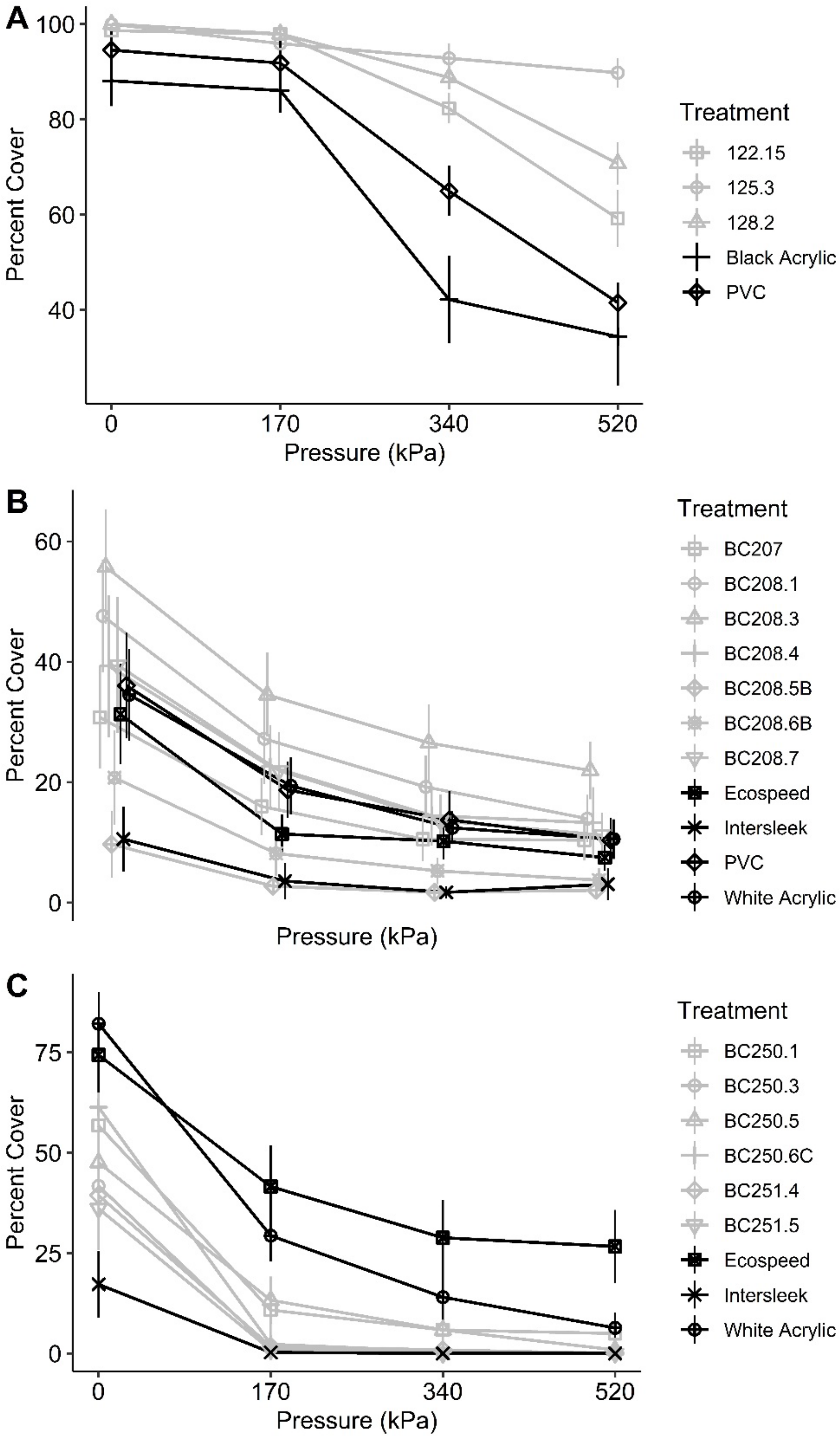

Figure 2. Cleanability measured by decline in fouling percent cover after successive pressure washing at increasing water pressures. A. Experiment 1 (Site B only). B. Experiment 2 (Site C). C. Experiment 3 (Site C). In each, hard fouling-release coatings (grey lines) were compared against one or more commercial performance comparisons and/or controls (black lines).

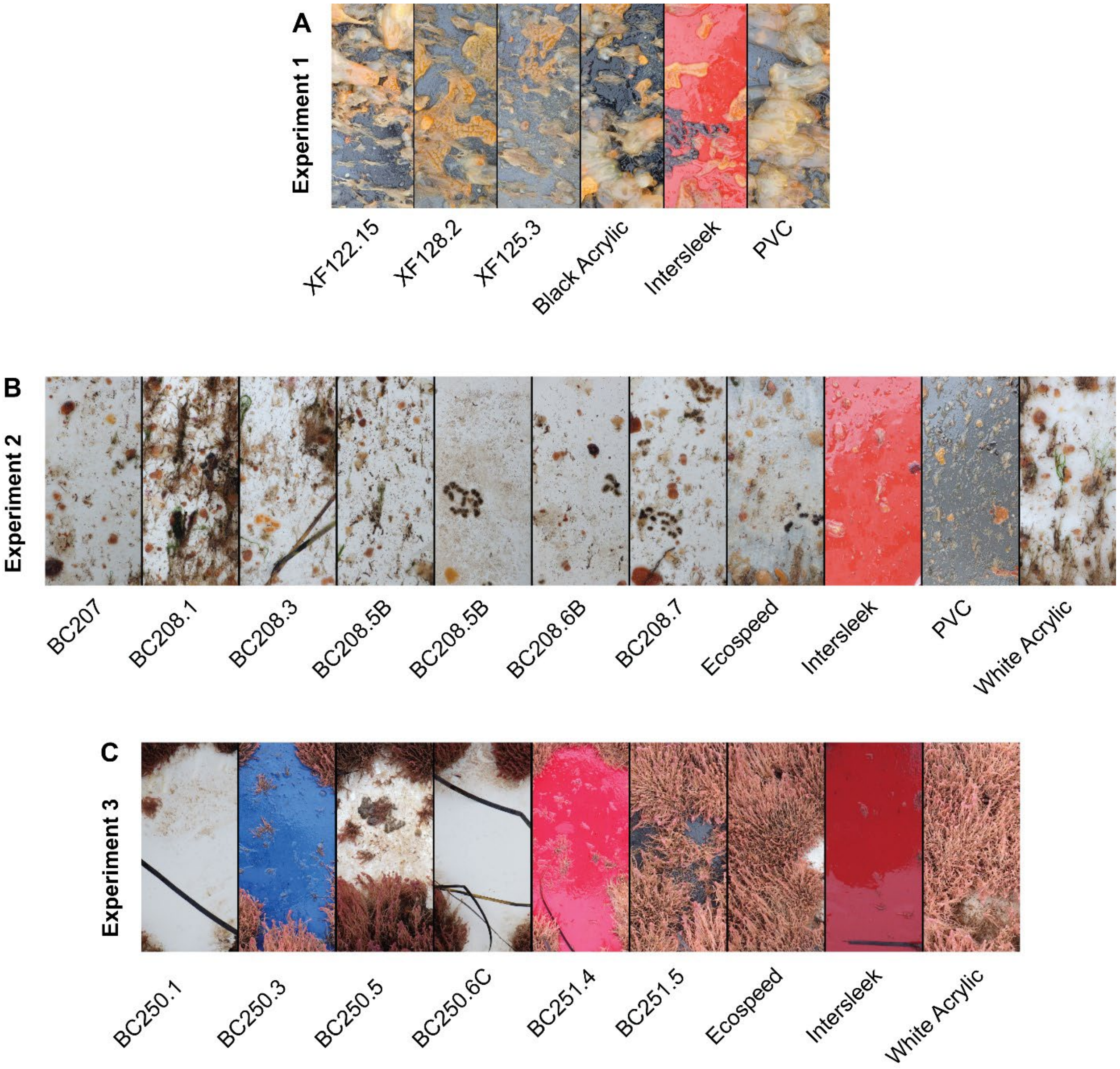

Figure 3. Examples of biofouling growth on the different coatings at the ends of the experiments. In each, the chosen plates were all deployed together in a single frame. A. Experiment 1, 70 days after deployment. B. Experiment 2, 60 days after deployment. C. Experiment 3, 86 days after deployment.

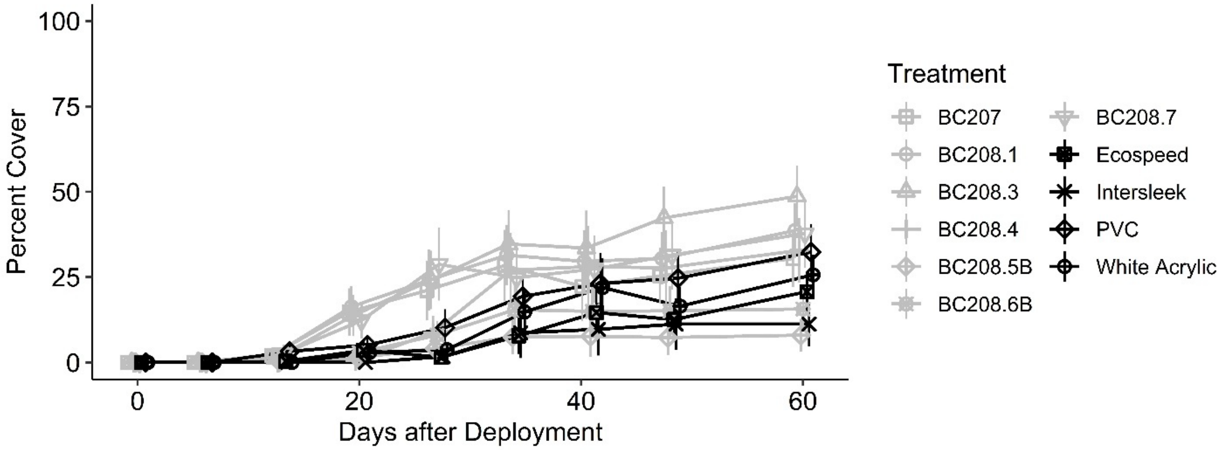

Figure 4. Biofouling percent cover in experiment 2 (site C). Seven hard fouling-release coatings (grey lines) were compared against two commercial performance comparisons (Intersleek and Ecospeed) and two bare controls (grey PVC and white acrylic).

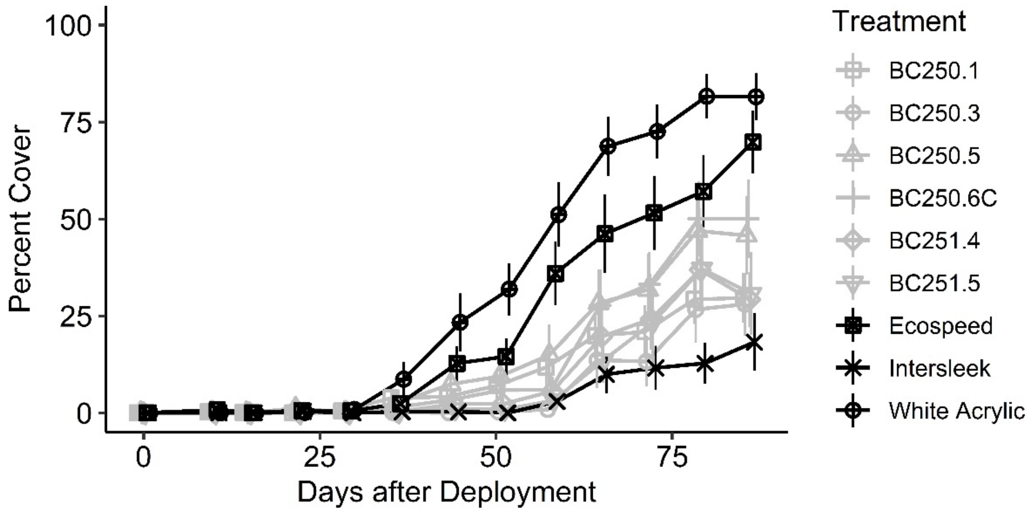

Figure 5. Biofouling percent cover in experiment 3 (site C). Six hard fouling-release coatings (grey lines) were compared against two commercial performance comparisons (Intersleek and Ecospeed) and