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Project Zero

Comparative Testing of Antifouling Coatings

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Comparative testing of antifouling coatings

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1 Introduction

On request of Project Zero, Endures B.V. has investigated the efficacy, torque properties, and surface characterisation of 6 different fouling control coatings. These consist of three fouling release coatings (FRC), one slow polishing antifouling coating, one hard matrix antifouling coating, and one unknown coating. Efficacy tests lasted for 25 weeks and included the peak fouling season. Inspections of the coatings were done every 5 weeks for a total of 5 inspection dates. Concurrently, coated discs were exposed to biofouling growth for 12 weeks and subsequently spun on a friction disc machine to measure the effects of attached biofouling organisms on torque and the capabilities of the coatings to release the attached species. Additionally, a second set of coated discs was aged for 10 weeks to investigate the effects of immersion without biofouling growth on torque and surface characterisation parameters.

The following terminology is used in this document:

Biofouling: A general term that groups all types of sessile marine organisms settled on manmade surfaces.

Biofilm: A thin layer of molecules, bacteria, unicellular algae and spores/larvae, also referred to as microfouling or slime.

Sessile: Incapable of movement on its own, often attached to structures.

Motile: Capable of motion.

Macrofouling: Sessile macro-organisms (such as algae, barnacles, mussels, tunicates, sponges, algae, and bryozoan). – See Appendix A

Soft fouling: Sessile macro-organisms without hard structures, often more easily removed than hard fouling organisms – See Appendix A

Hard fouling: Sessile marine organisms with calcareous bodies (such as barnacles, mussels, tubeworms, and oysters). – See Appendix A

Hydrophilic: Capable of interacting with water

Hydrophobic: Incapable of interacting with water

Amphiphilic: Containing both hydrophilic and hydrophobic structures

Acronyms:

FRC: Fouling Release Coating
PVC: Polyvinyl Chloride
FDM: Friction Disc Machine
Ra: Average roughness profile height deviations
DFT: Dry Film Thickness
t_0: Timepoint before the experimental phase (aging or raft exposure), where the discs were in pristine condition
t_e: Timepoint after the discs were aged or exposed on the raft

2 Materials and Methods

2.1 Efficacy Testing Through 'Static' Raft Exposure

Six commercially available fouling control paints were applied on PVC panels (300 X 250 mm) by the paint manufacturers. These panels, in addition to uncoated control PVC panels, were exposed in triplicate on the exposure raft in the Den Helder harbour for 25 weeks. Inspections were done every 5 weeks for a total of 5 inspections dates (Table 1). Each coating was given a specific identifier name (Table 2). Each replica was given a label and was placed at a different depth (200mm-1100mm) (Figure 1, Table 3).

Table 1: Static raft exposure inspection dates

Inspection moment	Date	Time (weeks)
T0 (mounting of panels)	02/05/24	0
T1	06/06/24	5
T2	11/07/24	10
T3	13/08/24	15
T4	19/09/24	20
T5	24/10/24	25

Table 2: Coating paint identifier names

Fouling control paint name	Coating identifier in the document	Technology
Hempablue 87750 – 19990	Hempablue	Biocide-free FRC
Nautix A4 T-Speed	Nautix	Biocide-based hard matrix antifouling
Jotun (coating unknown)	Jotun	Unknown
Trilux 33	Trilux	Biocide-based slow polishing antifouling
Intersleek 1100SR	Intersleek	Biocide-free FRC
Hempaguard X7 89900 – 19740	Hempaguard	Biocide-based FRC

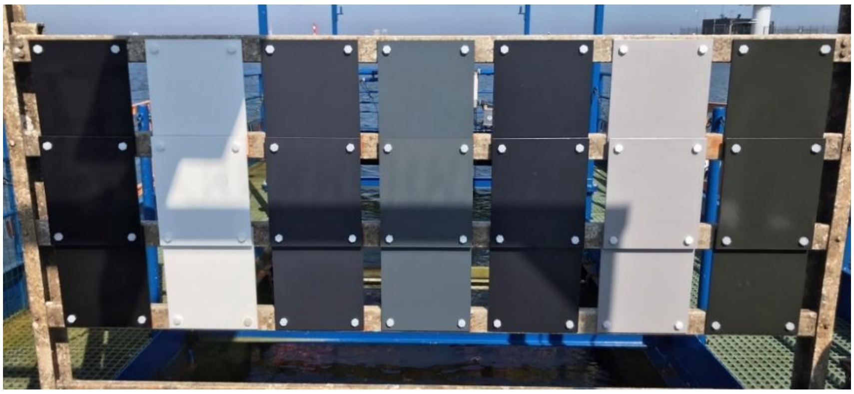

Figure 1: Raft exposure panel placement before immersion for the 'static' exposure tests – from left to right: Hempablue, Nautix, Jotun, PVC (control), Trilux, Intersleek and Hempaguard. Three replicas of each coating are stacked vertically and denoted as A, B, and C from top to bottom.

Table 3: Schematic representation of the panel placements at different depths during the 'static' exposure tests.

Depth (cm)	1	2	3	4	5	6	7
20-50	Hempablue A	Nautix A	Jotun A	Control A	Trilux A	Intersleek A	Hempaguard A
50-80	Hempablue B	Nautix B	Jotun B	Control B	Trilux B	Intersleek B	Hempaguard B
80-110	Hempablue C	Nautix C	Jotun C	Control C	Trilux C	Intersleek C	Hempaguard C

Visual identification of biofouling (biofouling coverage) was done according to a method based on ASTM D 6990 – 20 and section 5.7.1.2.3 in the ECHA Guidance Document of April 2018. The most common fouling taxa found in the Den Helder harbour are summarised in Table 4.

Table 4: Different groups of fouling organisms common in the Den Helder harbour.

Soft fouling	Hard fouling
Biofilm/slime	Barnacles
Algae	Mussels
Hydroids	Tubeworms
Tunicates	Bryozoa

Only primary fouling, i.e. organisms directly adhering to the painted surface, are taken into account. Additionally, biofouling growth on the edges of the panels is not included in the assessment to remove influences from organisms growing from the uncoated racks.

2.2 Aging Of Discs

Twelve coated aluminium discs (6 coatings in duplicate) with a diameter 230 mm and a thickness of 5 mm were aged on a rotating device for 10 weeks. Coatings were named according to Table 2 and given a label of A (Aging) with numbers 1 and 2 denoting different replicas. Discs were continuously spun at 900 rpm throughout the duration of the aging period. Natural seawater was constantly refreshed and supplied via a flow-through system. Friction Disc Machine (FDM) and surface characterization measurements were taken before (t_0) and after (t_e) the aging period (see section 2.4 and 2.5).

2.3 'Static' Raft Exposure Of Discs

Twelve coated discs (6 coatings in duplicate) were exposed on the raft for 12 weeks (Figure 2, Table 5). Coatings were named according to Table 2 and given a label of R (Raft) with numbers 1 and 2 denoting replicas. FDM and surface characterization measurements were taken before (t_0) and after (t_e) the raft exposure. After the exposure period on the raft, the back and the sides of the discs was cleaned to only measure the effect on torque generated from the front side. Each disc was measured twice on the FDM, the first to identify the effect of fouling on torque and the second to measure the effect on torque of the remaining fouling which did not get released during the first run. Analysis was done by comparing torque values from run 1 and 2 after raft exposure with the torque data from the aged discs. This allowed for the investigation of increased torque caused by biofouling growth, and accounted for any changes of the coating due water intake or general exposure to water.

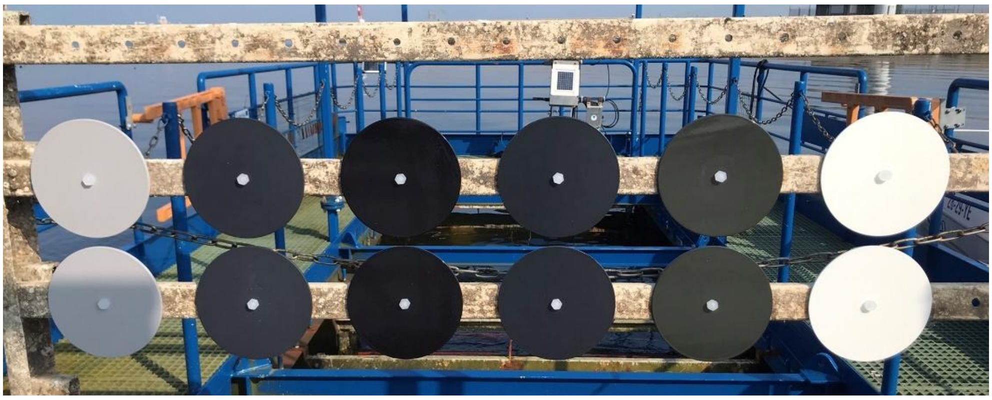

Figure 2: Disc placement during the raft exposure before immersion for the 'static' exposure tests and subsequent FDM measurements – from left to right: Intersleek, Jotun, Hempablue, Trilux, Hempaguard. Two replicas of each coating are stacked vertically and denoted as R1 (top) and R2 (bottom). The front of the discs are pictured.

Table 5: Positions of coated disc on the raft.

Depth (cm)	1	2	3	4	5	6
40-60	Intersleek R1	Jotun R1	Hempablue R1	Trilux R1	Hempaguard R1	Nautix R1
70-90	Intersleek R2	Jotun R2	Hempablue R2	Trilux R2	Hempaguard R2	Nautix R2

2.4 Friction Disc Machine (FDM)

The FDM rotated the discs at varying RPM speeds while logging the torque required to maintain the specified RPM. The RPM speeds ranged from 500 to 1500 with incremental steps of 200. Each RPM was maintained for 2 minutes. Measurements of torque were taken every second. An example of the friction rotation protocol is displayed in Figure 3. Only the last minute of each RPM step was used for analysis to ensure steady state conditions. FDM measurements were conducted on the discs prior to exposure (t_0) and after raft exposure (twice) or aging (once) (t_e).

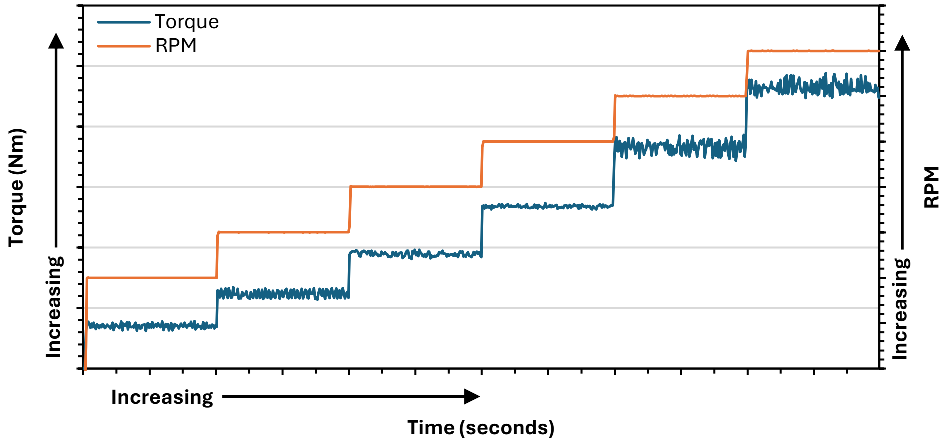

Figure 3: Example of the friction rotation protocol used for the coated discs. Only the last minute per speed step was analysed.

2.5 Surface characterisation

2.5.1 Surface Roughness

Surface roughness measurements were conducted at t_0 (coating as received by the client) for both exposures (Raft and Aging). For the discs exposed on the raft, surface roughness was measured after the second run. For the aged discs, measurements were taken after the first (and only) run. Measurements were conducted in pre-specified locations on each disc. In order to achieve this, a mask was used before and after the treatment (aging and raft exposure) to ensure that subsequent measurement were performed at the same location. Measurements were taken at three different distances from the centre of the disc (45 mm, 75 mm, 105 mm), across four directions on the discs. Three measurements were done per location for a total of 36 measurements per disc. Roughness measurements were taken three times per location using a Surtronic® Duo II Surface Roughness Meter for a total of 36 measurements per panel. The surface parameter measured (*Ra*) signifies the average profile height deviations.

2.5.2 *Coating Thickness*

Coating thickness (Dry Film Thickness, DFT) measurements were conducted at t_0 (coating as received by the client) for both exposures (Raft and Aging). For the discs exposed on the raft, measurements were conducted after the second FDM run. Measurements were conducted in pre-specified locations on each disc. In order to achieve this, a mask was used before and after the treatment (aging and raft exposure) to ensure that subsequent measurement were performed at the same location. Measurements were taken at three different distances from the centre of the disc (45 mm, 75 mm, 105 mm), across four directions on the discs. Three measurements were done per location for a total of 36 measurements per disc. DFT measurements were conducted using a DUALSCOPE® MP0®R thickness meter.

3 Results

3.1 Raft Exposure: Antifouling Efficacy Test

3.1.1 Inspection T1: June 6th 2024

During the first visual inspection, 5 weeks after immersion (T1, Table 1), biofouling growth and coverage varied between and within coatings (Figure 4). All coatings displayed biofilm (aka slime) growth. Macrofouling taxa attached to the coatings included algae, tunicates, hydroids, and bryozoa (Figure 5). Along with a high coverage of hydroids, barnacles were present on the uncoated PVC panels.

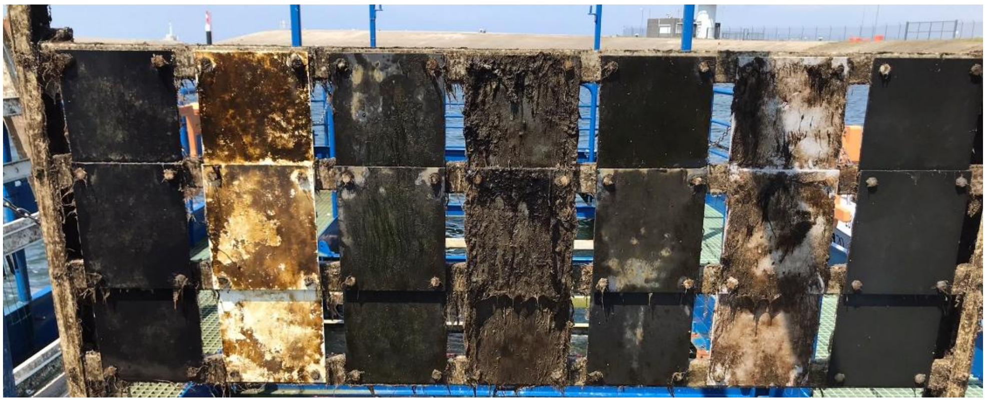

Figure 4: Biofouling growth on coated panels after 5 weeks of exposure (T1) – from left to right: Hempablue, Nautix, Jotun, PVC (control), Trilux, Intersleek and Hempaguard. Three replicas of each coating are stacked vertically and denoted as A, B, and C from top to bottom.

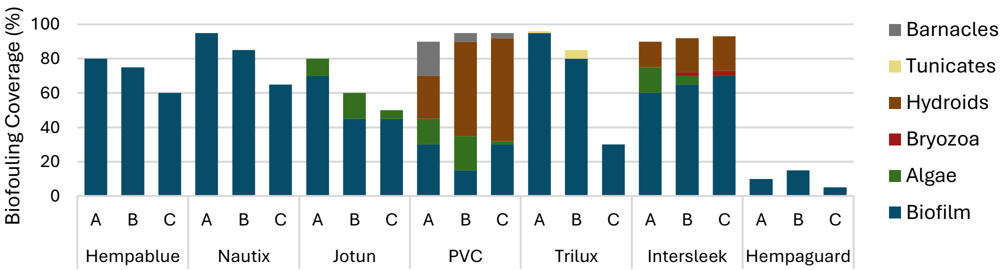

Figure 5: Biofouling coverage (%) during T1 per replica of each coated panel and the uncoated PVC panels. The edges of the panels are not included in the assessment of biofouling coverage. A, B, C indicate different replicas.

Hempablue, Nautix, and Hempaguard only had biofilm growth, with Hempaguard having the lowest coverage of biofilm. Jotun showed attachment of filamentous green algae (Figure 6). Trilux had growth of young tunicates on replica A and B. All three replicas also had macroalgae growth, however due to the size of the macroalgae it is considered as a part of the biofilm (in accordance with ECHA 2018). Intersleek was colonised by hydroids and some bryozoa. Biofouling coverage decreased with depth for certain coatings (Hempablue, Nautix, Trilux). All paints were able to prevent barnacle attachment, although their growth on the uncoated PVC panels did not indicate a high settlement pressure when compared to other taxa on T1.

Figure 6: Algae growth on Jotun A (left) and B (right) during the first inspection date (T1). Note that macroalgae coverage is calculated using only the initial attachment points.

When calculating fouling rating for the efficacy test according to the ASTM 6990 D – 20 standard, biofilm coverage plays a minimal role. Therefore, a separate graph without biofilm coverage is displayed (Figure 7). Biofouling coverage, when not taking biofilm into account, shows that Intersleek had moderate levels of macrofouling. Hydroids and bryozoa were seen on Intersleek which were not seen on any of the other coated panels.

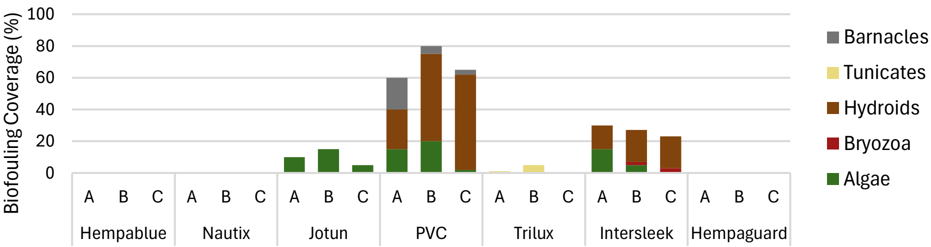

Figure 7: Macrofouling coverage (%) during T1 per replica of each coated panel and the uncoated PVC panels. Does not include biofilm. The edges of the panels are not included in the assessment of biofouling coverage. A, B, C indicate different replicas.

3.1.2 Inspection T2: July 11th 2024

After 10 weeks of exposure (T2) (Figure 8,9), barnacles were able to settle on Nautix and Trilux (Figure 10, 11), however they were more prevalent on Nautix. Hempablue and Hempaguard were the only coatings without any macrofouling. In addition, Hempablue had a slightly lower biofilm coverage when compared to T1. Mussels started attaching to the PVC panels, indicating a settlement pressure from these taxa. However, they were not able to attach to any of the coated panels. Algal coverage only includes the attachment area, the increase in length is not reflected in the biofouling coverage. Intersleek coverage changed from mainly hydroids to mainly algae, and had a decrease in total biofouling coverage compared to T1.

Figure 8: Biofouling growth on coated panels after 10 weeks of exposure (T2) – from left to right: Hempablue, Nautix, Jotun, PVC (control), Trilux, Intersleek and Hempaguard. Three replicas of each coating are stacked vertically and denoted as A, B, and C from top to bottom.

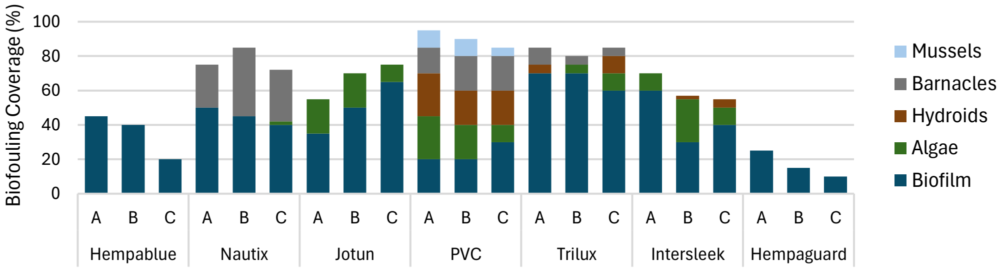

Figure 9: Biofouling coverage (%) during T2 per replica of each coated panel and the uncoated PVC panels. The edges of the panels are not included in the assessment of biofouling coverage. A, B, C indicate different replicas.

When looking at the coverage of macrofouling taxa (Figure 10), Nautix had the highest coverage, consisting predominantly of barnacles. Jotun, Trilux and Intersleek had a relatively low fouling coverage consisting of mainly algae for Jotun and Intersleek, and barnacles for Trilux.

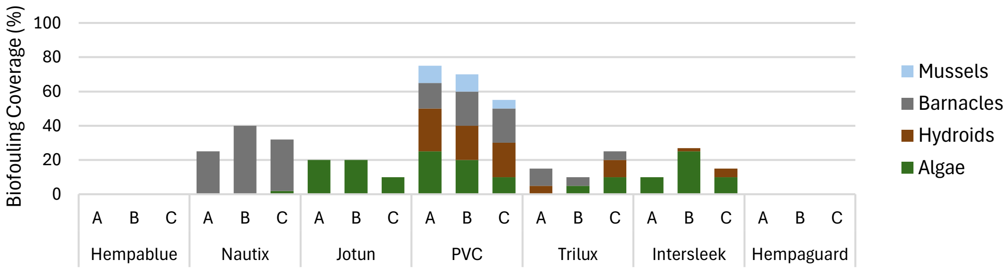

Figure 10: Macrofouling coverage (%) during T2 per replica of each coated panel and the uncoated PVC panels. Does not include biofilm. The edges of the panels are not included in the assessment of biofouling coverage. A, B, C indicate different replicas.

Figure 11: Left: Nautix B T2 with barnacle growth. Algae was attached to the barnacles but not to the panel. Right: Trilux A T2 with barnacle growth and hydroids.

3.1.3 Inspection T3: August 13th 2024

After 15 weeks of exposure (T3), the Hempablue panels had a moderate biofilm level, with the deepest replica (Hempablue C) having the least amount of biofilm (Figure 12, 13). Nautix still showed high levels of barnacle settlement, with slight attachment of tunicates, hydroids, and algae. Jotun displayed comparable biofouling coverage to T2, with some attachment of barnacles and tunicates. Tunicates were able to grow on Trilux as well. Taxa coverage and diversity was high for Intersleek, where bryozoa, barnacles, and tubeworms were able to attach, which were rarely seen on this coating during T1 and T2. Hempaguard had the lowest biofilm growth and no macrofouling taxa were attached on them. The PVC panels displayed growth of tunicates, barnacles, and mussels.

Figure 12: Biofouling growth on coated panels after 15 weeks of exposure (T3) – from left to right: Hempablue, Nautix, Jotun, PVC (control), Trilux, Intersleek and Hempaguard. Three replicas of each coating are stacked vertically and denoted as A, B, and C from top to bottom.

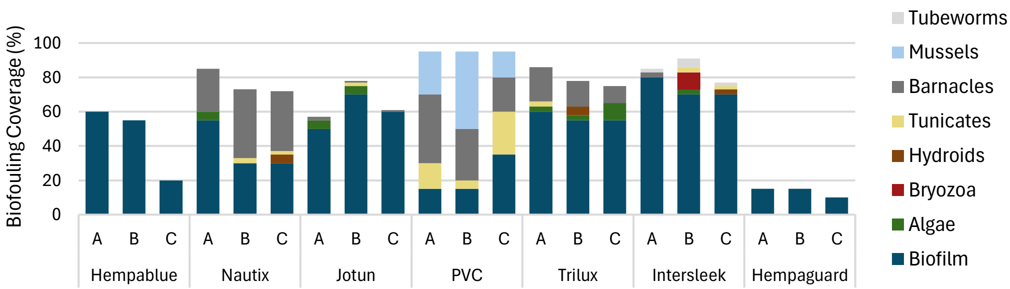

Figure 13: Biofouling coverage (%) during T3 per replica of each coated panel and the uncoated PVC panels. The edges of the panels are not included in the assessment of biofouling coverage. A, B, C indicate different replicas.

Assessment of macrofouling surface area coverage (Figure 14) showed that Nautix and Trilux had a relatively high coverage of barnacles, comparable to the level of growth on the PVC panels. Macrofouling growth on the Jotun panels was relatively low, and lower than previous inspections. Intersleek had lower macrofouling growth than Nautix and Trilux but had calcareous species which were not seen on the other coatings (tubeworms and bryozoa).

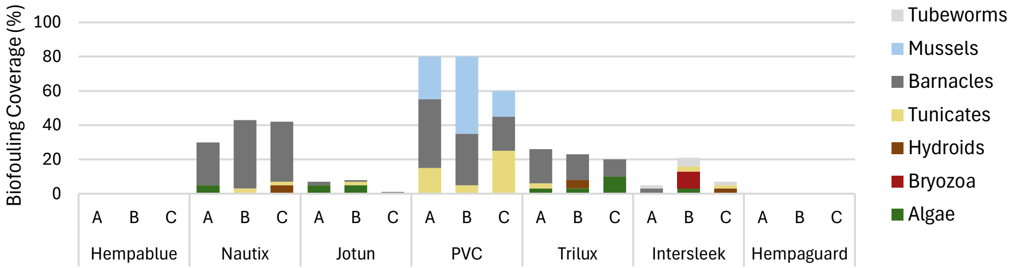

Figure 14: Macrofouling coverage (%) during T3 per replica of each coated panel and the uncoated PVC panels. Does not include biofilm. The edges of the panels are not included in the assessment of biofouling coverage. A, B, C stands for different replicas.

3.1.4 *Inspection T4: September 19th 2024*

After 20 weeks of exposure (T4), Hempablue displayed slightly higher biofilm growth than previous dates but still showed resilience towards the attachment of macrofouling species (Figure 15, 16). All three Nautix panels were highly fouled with tunicates (Figure 17, 18). The barnacles seen in previous time points were likely covered by the tunicates, which made characterization of the barnacles difficult. While Jotun was covered with algae during T1 to T3, algae were absent from Jotun panels during T4. Jotun and Trilux, were covered with amphipods and their mud tubes. Since these motile species are rarely seen on ship hulls and are likely an artifact of static exposure experiments, they are not taken into account for the biofouling coverage (in accordance to ASTM D 6990 – 20 and ECHA, 2018). Barnacles were seen on Trilux beneath the mud tubes, and in small amounts on the PVC panels. Tunicates were seen on all Trilux and Intersleek replicas. Macrofouling coverage on Intersleek B was high, with growth of tunicates, bryozoa and tubeworms (Figure 18). Tubeworms were only seen on the Intersleek panels throughout the exposure period. Hempaguard displayed an increase in biofilm coverage compared to previous dates, especially in replica B. However, they still displayed the lowest growth on average and prevented macrofouling taxa from attaching. PVC panels displayed high levels of mussel growth, along with tunicates, hydroids and barnacles, although the barnacles were most likely dead. Since the dead barnacles when attached on a ship’s hull can still have an effect on drag and are difficult to remove, they are still considered in the fouling evaluation.

Figure 15: Biofouling growth on coated panels after 20 weeks of exposure (T4) – from left to right: Hempablue, Nautix, Jotun, PVC (control), Trilux, Intersleek and Hempaguard. Three replicas of each coating are stacked vertically and denoted as A, B, and C from top to bottom.

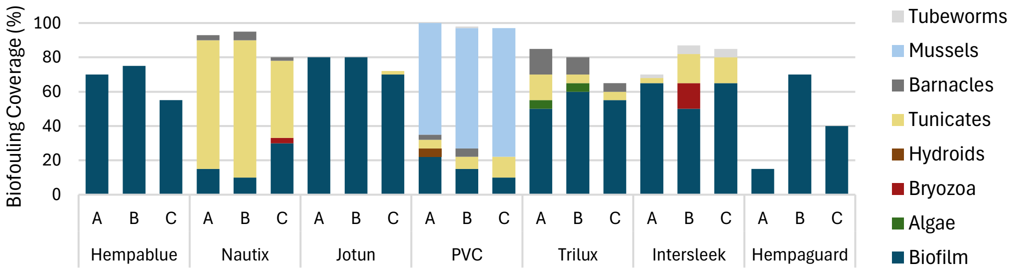

Figure 16: Biofouling coverage (%) during T4 per replica of each coated panel and the uncoated PVC panels. The edges of the panels are not included in the assessment of biofouling coverage. A, B, C stands for different replicas.

Nautix had a macrofouling coverage up to 85% (Figure 17). Intersleek B and C had slight increases in macrofouling growth compared to T3. Barnacle coverage on the Trilux coatings decreased slightly compared to T4, but this may have been due to the difficulty of assessing barnacle growth which was covered by other species and amphipod mud tubes.

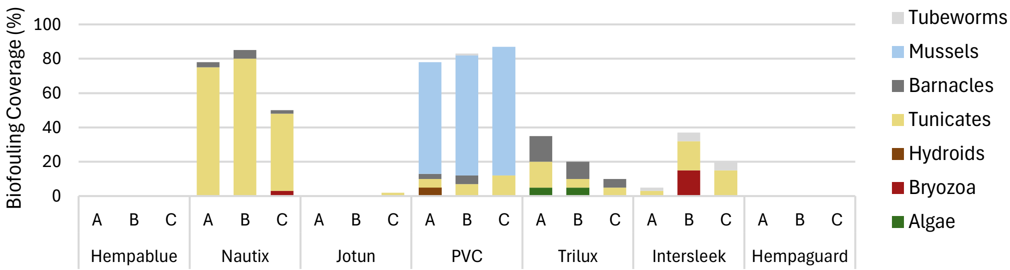

Figure 17: Macrofouling coverage (%) during T4 per replica of each coated panel and the uncoated PVC panels. Does not include biofilm. The edges of the panels are not included in the assessment of biofouling coverage. A, B, C stands for different replicas.

Figure 18: Closeups of macrofouling growth on panels during the T4 inspection. Solitary tunicate growth on Nautix B (left), Tubeworms and colonial tunicate growth on Intersleek C (right).

3.1.5 *Inspection T5: October 25th 2024*

After 25 weeks of exposure (T5), Hempablue maintained moderate levels of biofilm without any growth of macrofouling species (Figure 19, 20). Tunicate pressure had decreased on the Nautix panels and was instead replaced by amphipod mud tubes. The mud tubes were often present on or around barnacles, using their sturdy makeup as a foundation. Mud tubes were also present on Jotun and Trilux panels. While the mud tubes were surrounding barnacles on the Trilux panels, the Jotun panels were free of barnacles, resulting in a less sturdy attachment of the mud tubes directly on the coating. Aside from the mud tubes, the Jotun panels were only covered by biofilm with levels lower than previous dates for replicas B and C. The Trilux panels had barnacles attached to the coating, with secondary structures (mud tubes, green and red seaweed) growing over them. Intersleek panel B had high growth of bryozoa, along with several tubeworms. The bryozoa were absent on the Intersleek A replica. Hempaguard still displayed low levels of biofilm growth, however juvenile barnacles were found attached to the coating. While still in low numbers and size, this does indicate a potential for barnacles to attach to this coating after extended periods of idleness.

Figure 19: Biofouling growth on coated panels after 25 weeks of exposure (T5) – from left to right: Hempablue, Nautix, Jotun, PVC (control), Trilux, Intersleek and Hempaguard. Three replicas of each coating are stacked vertically and denoted as A, B, and C from top to bottom.

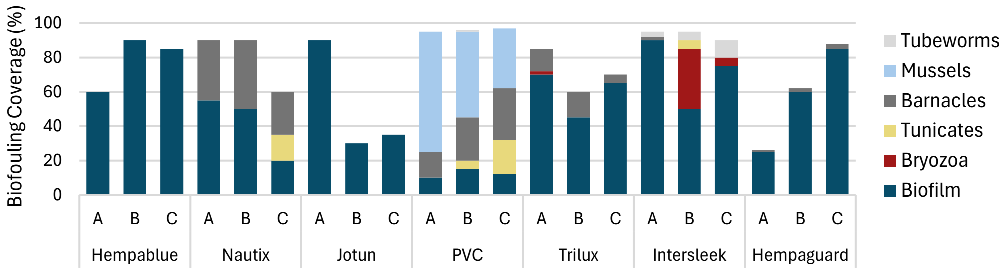

Figure 20: Biofouling coverage (%) during T5 per replica of each coated panel and the uncoated PVC panels. The edges of the panels are not included in the assessment of biofouling coverage. A, B, C stands for different replicas.

When assessing macrofouling coverage (Figure 21), Nautix displayed a lowered macrofouling coverage compared to T4, mainly due to the decrease in tunicates. Intersleek B had a large increase in bryozoa attachment.

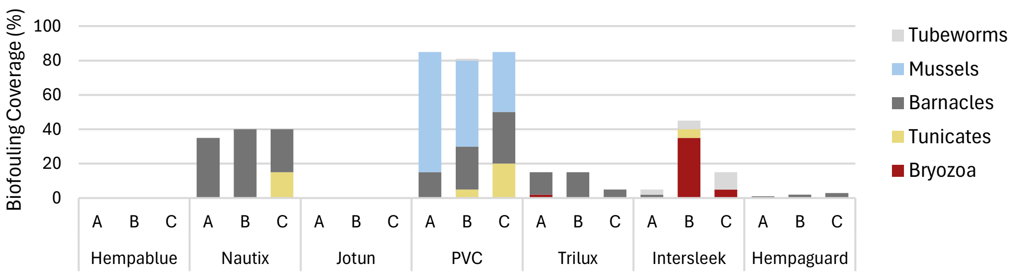

Figure 21: Macrofouling coverage (%) during T5 per replica of each coated panel and the uncoated PVC panels. Does not include biofilm. The edges of the panels are not included in the assessment of biofouling coverage. A, B, C stands for different replicas.

3.2 Dynamic Aging

3.2.1 Aging Roughness

Average surface roughness (*Ra*) of the different coatings was measured before (t_0) and after (t_e) aging coated discs for 10 weeks (Figure 22, Figure 23). *Ra* values were consistently lower for FRC (0,15 µm - 0,32 µm) compared to non-FRCs (0,85 µm - 1,65 µm).

Ra did not change considerably after aging for all the FRCs. Hempablue had the lowest average *Ra* (0,17 – 0,15 average *Ra* before and after aging respectively across both replicas) while Intersleek A2 had the highest average out of the FRCs (0,32 µm before and after).

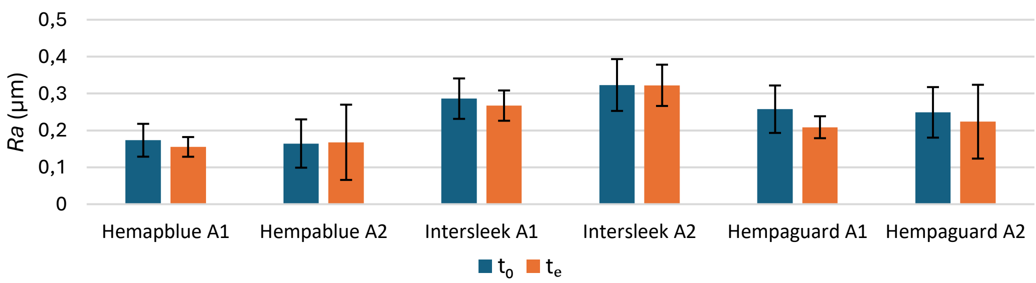

Figure 22: Roughness values (Ra) of FRCs before (t_0) and after (T_e) aging. Error bars indicate the standard deviation within each replica (N=36). A1 = Aging Replica 1, A2 = Aging Replica 2

For the non-FRCs (Figure 23), average *Ra* values were consistently lower after aging for each coating (average of 1,34 µm and 0,99 µm at t_0 and t_e respectively), however the averages were still within the standard deviation of each other except for Jotun A2, which had the largest effect of aging on surface roughness. Jotun had the highest surface roughness. Trilux and Nautix had comparable surface roughness values before aging, however Trilux discs had a lower roughness following the aging treatment compared to Nautix.

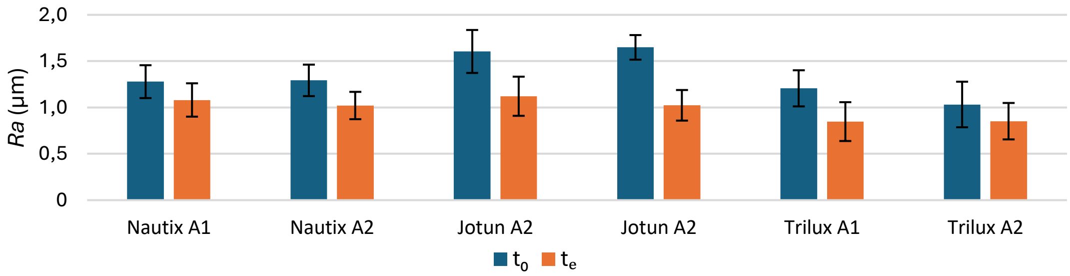

Figure 23: Roughness values (Ra) of non-FRCs before (t_0) and after (T_e) aging. Error bars indicate the standard deviation within each replica (N=36). A1 = Aging Replica 1, A2 = Aging Replica 2

3.2.2 *Aging Thickness*

Coating thickness was measured before and after aging. For the FRCs, Hempaguard had the lowest thickness (Figure 24). Hempablue and Intersleek had comparable levels of thickness. After 10 weeks of aging, no clear effect was observed on the thickness.

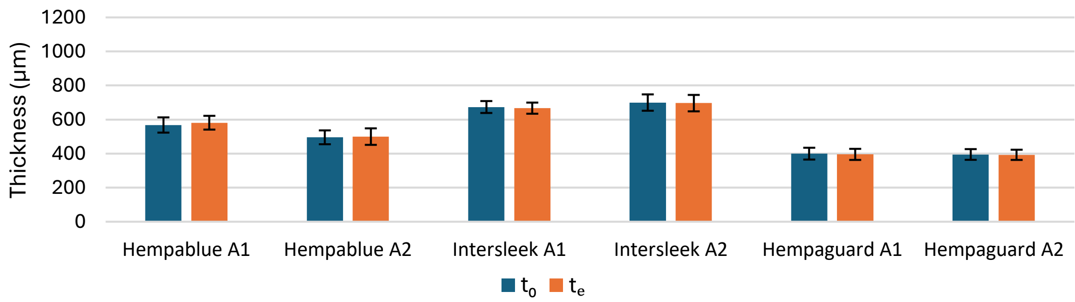

Figure 24: Thickness values (µm) of FRCs before (t_0) and after (T_e) aging. Error bars indicate the standard deviation within each replica (N=36). A1 = Aging Replica 1, A2 = Aging Replica 2

For the non-FRCs, Nautix had the lowest thickness while replica Trilux A1 had the highest thickness (Figure 25). Trilux had the largest difference between the two replicas. Dynamic aging for 10 weeks did not measurably affect the coating thickness.

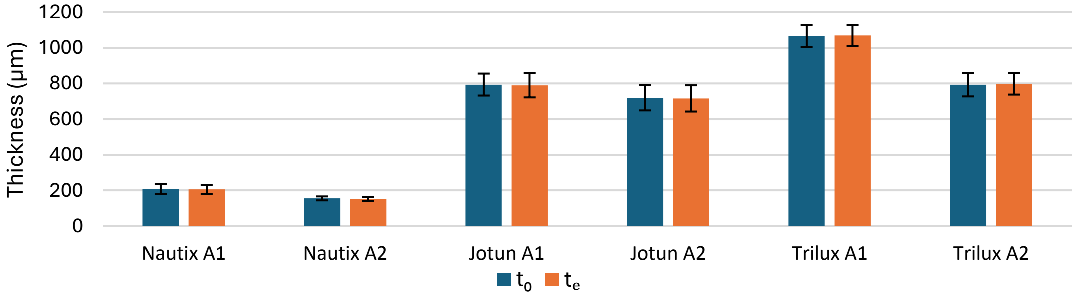

Figure 25: Thickness values (µm) of non-FRCs before (t_0) and after (T_e) aging. Error bars indicate the standard deviation within each replica (N=36). A1 = Aging Replica 1, A2 = Aging Replica 2

3.2.3 Aging FDM

The twelve coated discs were spun on the friction disc machine to measure torque over a range of RPM speeds (500 RPM – 1500 RPM). Measurements were done before and after aging for 10 weeks. FDM values (averaged over all RPM values) between t_0 and t_e (Figure 26) did not appear different from each other. Hempaguard A2 displayed a slight decrease in torque values after aging, but this is not the case for Hempaguard A1.

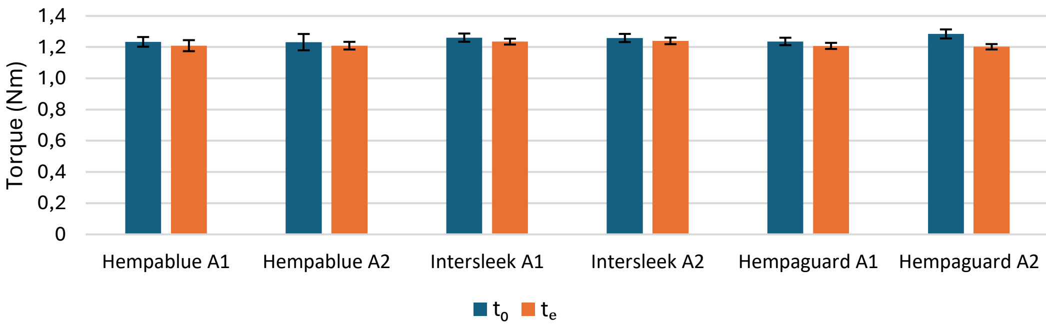

Figure 26: FDM torque values of FRCs before (t_0) and after (t_e) aging. Values from the different RPM values were averaged. Error bars indicate the average standard deviation across all RPM values. A = Aging, 1 and 2 denote replicas.

For the non-FRCs, torque values were relatively similar to the FRCs (Figure 27). A slight decrease in torque values after aging was seen for Jotun and Trilux.

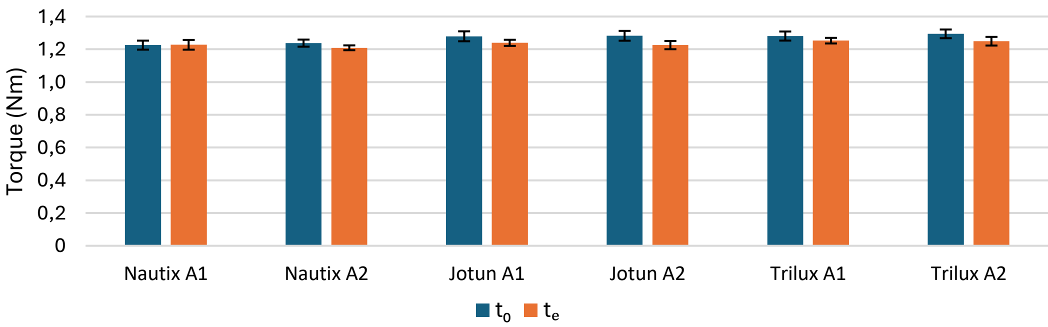

Figure 27: FDM torque values of non-FRC before (t_0) and after (t_e) aging. Values from the different RPM values were averaged. Error bars indicate the average standard deviation across all RPM values. A1 = Aging Replica 1, 2 = Aging Replica 2

3.3 Raft Exposure Of Coated Discs

3.3.1 Fouling Detachment During FDM

Coated discs were collected after 12 weeks of exposure on the raft. The discs had varying levels of fouling and responded differently to spinning in the FDM (Plate 1).

The Hempablue discs only had some slight growth of biofilm. Both replicas were able to release some of the attached biofilm after spinning on the FDM.

Intersleek R1 and R2 had biofilm growth and both had a tubeworm attached to the coatings. After run 1, Intersleek R1 was able to release most of the heavy biofilm but still had large coverage of light biofilm. It was also able to release the tubeworm. Intersleek R2 was able to release a similar amount of biofilm. However, it was not able to release the attached tubeworm.

Hempaguard R1 and R2 only had light biofilm coverage. After spinning, Hempaguard R1 and R2 were able to release a considerable amount of the attached biofilm.

Nautix R1 and R2 had biofilm, barnacles, tunicates, and algae. After the first FDM run, Nautix R1 was able to release the tunicates, algae, and some biofilm. Several barnacles were still attached after spinning. Nautix R2 had more barnacles attached initially but was not able to release many of them.

Jotun R1 and R2 had biofilm and macroalgae growth. Both replicas were able to release some of the biofilm but the attachment points (holdfasts) of the macroalgae remained attached after spinning (Figure 28).

Figure 28: Algae attached to Jotun (R2) after the first FDM run after 12 weeks of raft exposure

Trilux R1 was covered with biofilm, barnacles, algae, and tunicates while Trilux R2 had biofilm barnacles and algae. After spinning, Trilux R1 was able to release all tunicates and most of the algae, but still had a considerable amount of attached barnacles. Trilux R2 had a lower initial amount of barnacles but was able to release most of them. Some algae were still attached after spinning.

The second FDM run did not result in any additional release of fouling on any of the discs.

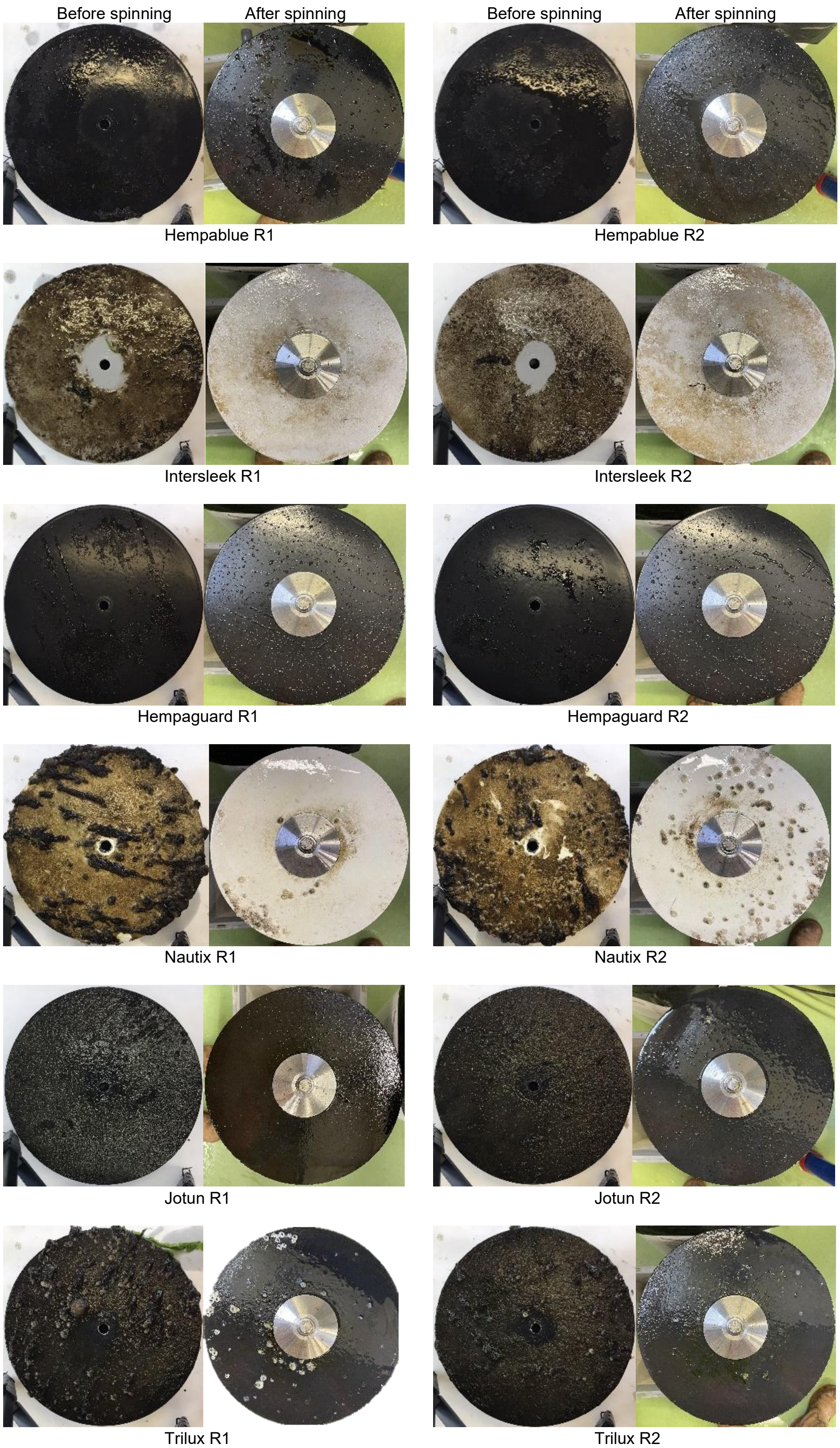

Plate 1: Discs that were exposed on the raft for 12 weeks, before and after spinning on the FDM for the first run.

3.3.2 *Surface Roughness Measurements*

Average surface roughness (*Ra*) of the coatings was measured before and after exposure on the raft. FRCs had lowered *Ra* values (average of 0,243 µm and 0,242 µm for t_0 and t_e respectively) (Figure 29) compared to the non-FRCs (average of 1,21 µm and 1,15 µm) (Figure 30). For FRCs, *Ra* values did not change considerable after raft exposure.

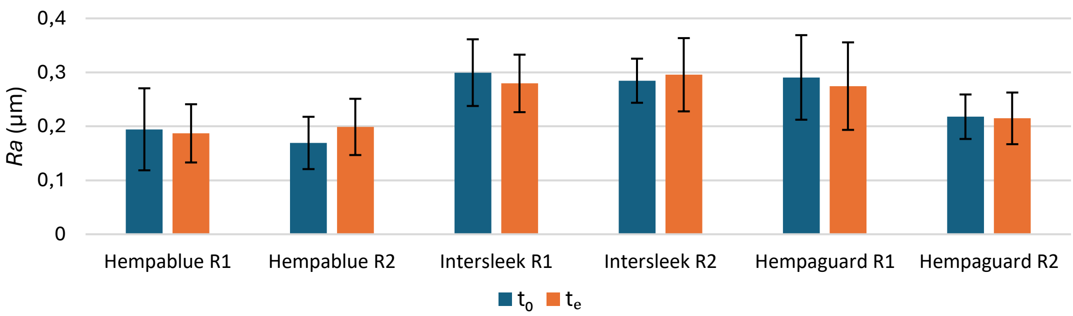

Figure 29: Roughness values (Ra) of FRCs before (t_0) and after (T_e) raft exposure. Error bars indicate the standard deviation within each replica (N=36). R1 = Raft Replica 1, R2 = Raft Replica 2

For the non-FRCs (Figure 30), average *Ra* values varied slightly before and after raft exposure, although always within the standard deviation. Jotun displayed slightly lowered *Ra* values after exposure for both replicas while Trilux R1 had a slightly higher surface roughness after exposure.

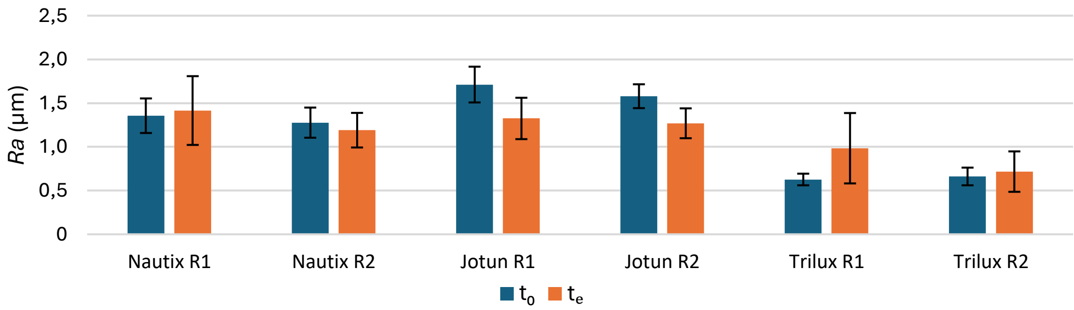

Figure 30: Roughness values (Ra) of non-FRCs before (t_0) and after (T_e) raft exposure. Error bars indicate the standard deviation within each replica (N=36). R1 = Raft Replica 1, R2 = Raft Replica 2

3.3.3 *Coating Thickness Measurements*

Coating thickness of the discs was measured before and after exposure of the coatings on the raft (Figure 31 and Figure 32). Exposure on the raft for 12 weeks did not alter coating thickness to a measurable degree in all FRCs and non-FRCs. FRCs had slightly lower thickness than non-FRCs, except for both replicas of Nautix, which had the thinnest coating application.

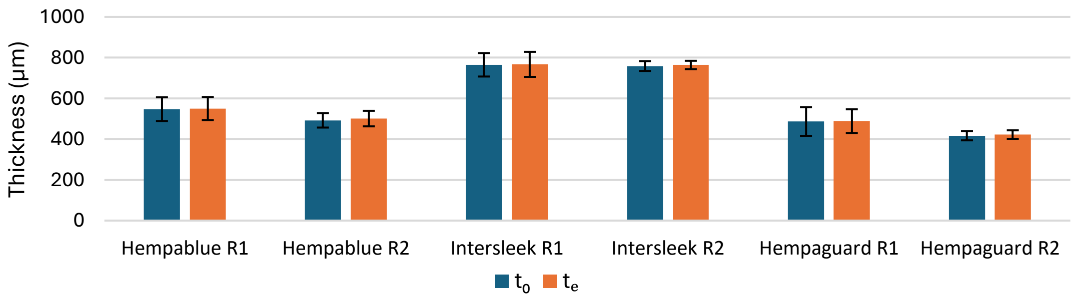

Figure 31: Thickness values (µm) of FRCs before (t_0) and after (T_e) raft exposure. Error bars indicate the standard deviation within each replica (N=36). R1 = Raft Replica 1, R2 = Raft Replica 2

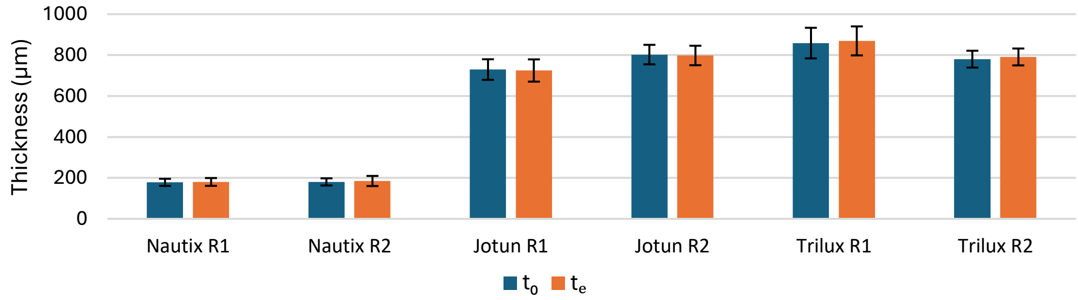

Figure 32: Thickness values (µm) of non-FRCs before (t_0) and after (T_e) raft exposure. Error bars indicate the standard deviation within each replica (N=36). R1 = Raft Replica 1, R2 = Raft Replica 2

3.3.4 *Torque Measurements*

Torque values after raft exposure were obtained for all coated discs (Figure 33). These values were compared with the data after aging. On average, the FRCs displayed lower effects of growth on torque after raft exposure compared to the non-FRCs. Considering the FRCs, an increase in 5,8% – 6,9% in torque was observed for Hempablue R1 and R2 respectively during run 1. The remaining fouling during run 2 had negligible effects on torque for both replicas. For Hempaguard R1, effects of growth on torque after raft exposure were minimal. For Hempaguard R2, an increase in torque is observed due to the growth during exposure, which was not released during spinning, resulting in a torque increase of ~7%.

Intersleek was the only FRC that had a thick biofilm, resulting in an average increase in torque when comparing the aging vs the raft discs. This difference ranged from 50,2% to 44,6% for Intersleek R1 and R2, respectively. After run 2, an increase of torque of 22,8% and 23,8% was observed due to the remaining biofilm growth for Intersleek R1 and R2 respectively.

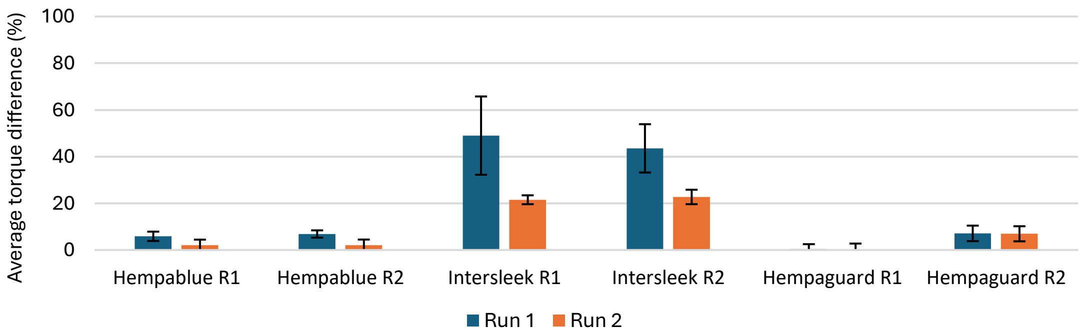

Figure 33: Average difference (%) in torque of FRCs between run 1 and 2 after raft exposure compared with values after aging. The different RPM data are averaged and denoted as error bars. R1 = Raft Replica 1, R2 = Raft Replica 2

Increases in torque for the non-FRCs ranged from 40,4% to 235,2% for run 1 and between 24,8% and 167,8% for run 2 (Figure 34). Nautix had the highest increases in torque due to attached growth. After spinning, part of growth on Nautix R1 was dislodged which was not observed for Nautix R2.

Jotun had the lowest torque increase out of all the non-FRCs and some of the attached fouling was released during run 1 (from 40,3% to 25,9% for Jotun R1, and from 49,7% to 32,2% for Jotun R2).

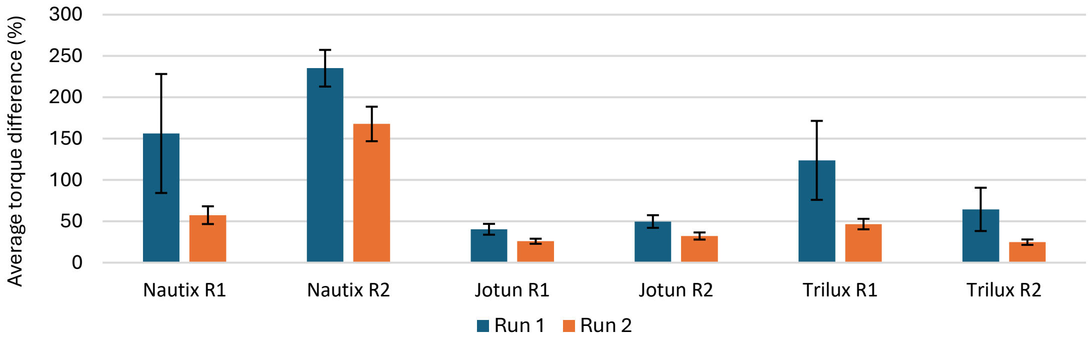

Figure 34: Average difference (%) in torque of non-FRCs between run 1 and 2 after raft exposure compared with values after aging. The different RPM data are averaged and denoted as error bars. R1 = Raft Replica 1, R2 = Raft Replica 2

4 Discussion

Accumulation of biofouling on hulls of ships can increase fuel consumption, lower vessel speed, and increase greenhouse gas (GHG) emissions (Figure 35, IMO, 2022). Additionally, species can be transported through hull fouling to areas outside of their natural range, and potentially cause impacts on local ecosystems. Other than impacts on the environment, attachment of biofouling on hulls can significantly increase vessel operating costs. Slight reductions in the accumulation of biofouling on ship hulls can reduce fuel expenditures by a significant amount (Schultz et al., 2011). Therefore, it is important to select appropriate fouling control coatings to protect the hull from marine growth. However, there is a large variety of different coating technologies with differing performances.

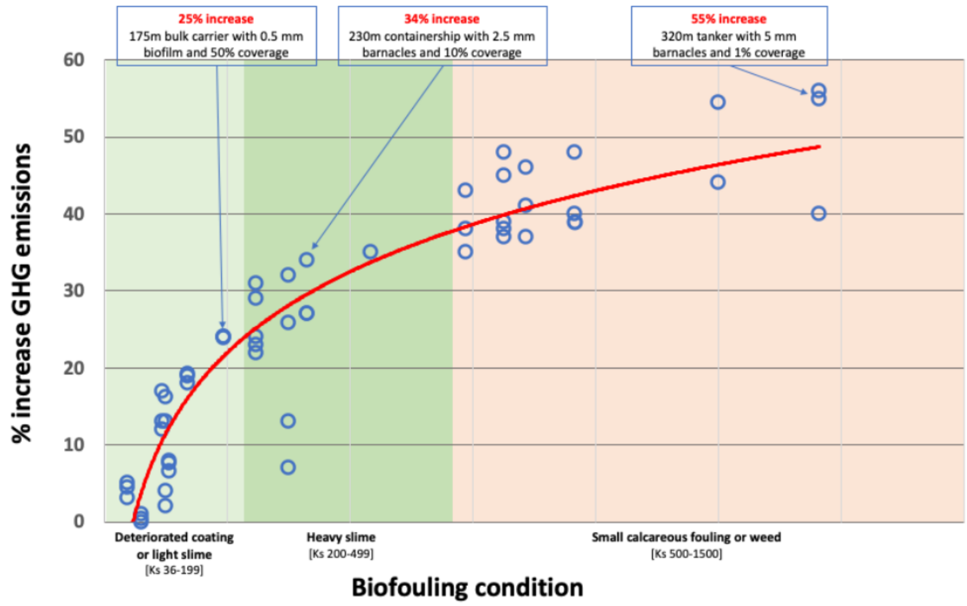

Figure 35: Impact of ship hull fouling on greenhouse gas (GHG) emissions. Each circle represents a different study (GEF-UNDP-IMO, 2022)

The efficacy of six antifouling coatings were tested in the Den Helder harbour. From the uncoated PVC control panels, it becomes apparent that panels without fouling control properties quickly get colonised by macrofouling organisms. The successional species composition changed over time and included biofilm, hydroids, algae, barnacles, and mussels. Species interactions (facilitation and competition for space and resources), as well as seasonality caused fluctuations in species composition (Dür & Thomason, 2009). Mussels appear to be a late-stage macrofouling group, preferring to grow on well-established communities. This successional pattern is to be expected in the North Sea, as well as in other areas of the world where similar taxa are found (Richmond & Seed, 1991).

Due to the fouling control properties of the different coatings tested here, deviations from this pattern were observed on the coated panels. Coating control capacity varied per coating technology. The tested fouling control coatings can be divided into FRCs (Fouling Release Coatings) and non-FRCs, which consist of one slow polishing antifouling coating, one hard matrix antifouling coating, and a coating with an unknown mechanism. FRCs work through low surface-energy mechanisms, creating smooth surfaces which make adherence by biofouling organisms difficult (Lindholdt et al., 2015). These coatings achieve this through utilizing different coating surface properties, e.g. hydrophilic, hydrophobic, or amphiphilic (having both hydrophilic and hydrophobic properties) (Lagerström, et al., 2022). FRCs typically work best when applied to vessels moving at certain speeds. In order to release the loosely attached growth, higher speeds are required. While FRCs are initially created as a biocide-free alternative to biocide-based coatings, there are certain FRCs that contain biocides (often at low concentrations), including the Hempaguard (Hempaguard X7) coating from Hempel (Lagerström et al., 2022). Hempaguard X7 is a third generation FRC using the amphiphilic hydrogel technology (Sørensen et al., 2015, Thorlaksen et al., 2010). It contains the biocide copper pyrithione as an active ingredient. The best fouling control performance was observed by Hempaguard X7 and this may be attributed to its combined technological makeup (fouling release plus biocides). While growth during the field exposures on the Hempaguard coating was mainly limited to biofilm, during dynamic tests (FDM) biofilm was released leaving the coatings foul-free . This indicates that even biofilm is not strongly attached, resulting in a negligible effect on torque due to growth on ship hulls while in motion. The dynamic (FDM) results of Hempaguard R2 showed that the effect of growth on torque did not change between run 1 and run 2. While this may indicate that the attached biofilm is attached to a higher degree, it is likely that there was some attached residue which was not completely removed before the t_0 measurement. Therefore, rather than measuring the effect of growth on torque, the increased torque in Hempaguard R2 is potentially an artifact of the difference between the R2 and A2 discs during t_0, where the actual values should be similar to Hempaguard R1.

Hempablue is a newer generation FRC compared to Hempaguard X7 (Hempablue, 2024). It does not contain any biocide, however it illustrated a similar biofouling control capacity, except for a slightly lower capacity to prevent biofilm accumulation. This attached biofilm resulted in a ~2% increase in torque caused by tenacious biofilm which was not removed during the dynamic tests (FDM runs). When evaluating the 'static' raft tests it can be inferred that both Hempaguard and Hempablue performed well, however, at the end of the 25-week long 'static' raft exposure, juvenile barnacles were seen on the Hempaguard coatings.

While Intersleek (Intersleek 1100SR) is also an FRC, its fouling control capacity was not as extensive as the Hempel coatings. Intersleek uses a fluoropolymer technology with amphiphilic surface properties to create a smooth surface, and should be able to easily remove loosely attached fouling during sailing (Sørensen et al., 2015). However, the amount of fouling that was released from the coating during the dynamic tests (FDM runs) was similar or worse compared to some of the non-FRC coatings. The remaining fouling after two runs on the FDM resulted in ~20% increased torque, which can affect GHG emissions and fuel consumption to a high degree (Schultz et al., 2011). Part of this increase in torque is due to attachment of bryozoa, which are hard biofouling species that can adhere strongly to substrates. They have also been shown to facilitate the attachment of tubeworms (Riley & Ballerstedt, 2005), which was also observed on the Intersleek panels and discs.

Trilux 33 is a slow polishing antifouling coating which uses Biolux® technology, which includes the biocides copper thiocyanate and zinc pyrithione (Interlux, 2017). Zinc pyritione and copper thiocyanate are used to inhibit development of biofilm and macrofouling organisms (Soon et al., 2019; Vetere et al., 1997). However, it did not perform well during the dynamic tests, increasing torque up to ~50% during FDM measurements due to the attachment of biofouling organism.

While the Jotun coating performed the best out of the non-FRCs, it did not have a specific coating label, so it is unclear through which mechanism this coating works.

The limited fouling control performance of the non-FRCs may be attributed to the fact that the tests performed here were under 'static' conditions. For Trilux, the slow polishing mechanism through which the coating works may be diminished in 'static' conditions, potentially affecting its biocide release rate. For Nautix, the coating is meant to be used for high-speed sailing and is recommended to be cleaned regularly, meaning that 'static' conditions are not the primary application for this coating (Nautix, 2024, Swain, 2010). While thickness did not appear to change throughout the experiments for any coating during aging or raft exposure over a 12 week period, it is difficult to ascertain whether this had any effect on the biocide release.

4.1 Limitations

For the Nautix and Intersleek coatings, their white colour made biofilm growth stand out, allowing for easy identification of the biofilm coverage. The other coatings had a darker colour, which made it harder to quantify the biofilm coverage on these panels, resulting in a potential difference in biofilm coverage characterization.

During the inspections, the submerged rack with coated panels are briefly lifted out of the water to perform the biofouling characterization. While lifting the panels, it is possible that certain loosely attached growth is removed from the coatings, especially for the FRC coatings which work through smooth low-surface energy technologies. However, since these organisms would have been loosely attached, they would likely have been detached from ship hulls when achieving certain speed, likely not affecting torque in a considerable manner.

5 Mediterranean vs North Sea Biofouling Communities

While the current tests show the difference in fouling control properties against biofouling growth in the North Sea, performance of the coatings may be extrapolated to include other ecological areas, including the mediterranean. Comparisons in biofouling communities between the two areas indicate similar biofouling groups, albeit different species (Table 6, Terlizzi et al., 2000). Important macrofouling species in the mediterranean region include macroalgae, hydroids, sponges, tunicates, bryozoans, barnacles, mussels, and tubeworms (Terlizzi et al., 2000). Species composition changes over time and depends on the local biofouling pressure (Pierri et al., 2010; Richmond & Seed, 1991). In the Mediterranean, areas with high growth (e.g. ports) display a successional dynamic, where tunicates, bryozoa, and barnacles are followed by attachment of mussel species (Pierrie et al., 2010). The same successional pattern was observed during the current work, indicating a comparable biofouling community. Hildebrand (2004) investigated the effects of latitude on marine sessile species composition and showed that it was relatively weak. Although biofouling pressure could be higher due to higher temperatures in the mediterranean, the similar species composition would likely result in a similar coating performance range, as well as a comparable effect on hydrodynamic drag (Dürr & Thomason, 2009).

Table 6: Common taxa found in the North Sea and Mediterranean region, with examples of species from each region.

Common name	North Sea	Mediterranean
Mussels	*Mytiluis edulis*	*Mytilus Galloprovincialis*
Bryozoa (encrusting)	*Electra pilosa*	*Schizoporella errata*
Bryozoa (arborescent)	*Bugula neritina*	*Bugula neritina*
Cnidaria	*Obelia sp.*	*Tubularia sp*
Tubeworms	*Ficopomatus enigmaticus*	*Spirobranchus lamarckii*
Barnacles	*Semibalanus balanoides*	*Amphibalanus Amphitrite*
Tunicates (colonial)	*Botryllus schlosseri*	*Botryllus schlosseri*
Tunicates (solitary)	*Ciona intestinalis*	*Ciona intestinalis*
Tunicates (solitary)	*Styela clava*	*Styela canopus*

6 Conclusions and Recommendations

- Out of all fouling control coatings, Hempablue and Hempaguard performed best under both ‘static’ raft and dynamic tests (FDM).
- Out of the non-FRCs, Jotun had the best performance.
- Order of effectiveness, based on raft exposure, FDM release properties and torque values (left to right): Hempaguard > Hempablue > Jotun > Intersleek > Trilux > Nautix.
- Thickness did not change when comparing before and after the dynamic tests for both aging and raft exposure for any of the coatings.
- Roughness of non-FRCs slightly decreased after aging, while roughness of FRCs remained the same before and after aging. Raft exposure slightly increased the roughness of non-FRCs but did not affect the roughness of FRCs.
- North Sea biofouling taxa are likely comparable to the Mediterranean biofouling communities in complexity and consequently may affect torque in a similar manner.

7 References

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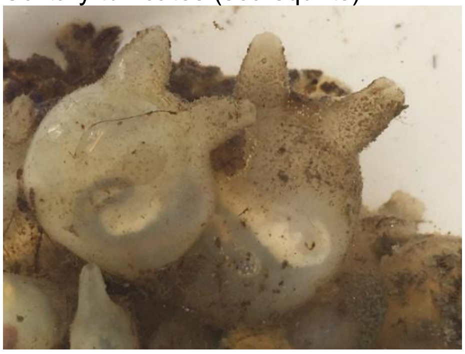
8 Appendix

8.1 Appendix A: Biofouling Organism Guide

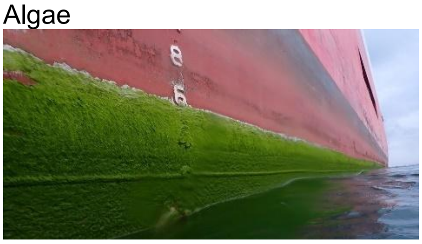
8.1.1 Soft fouling

Solitary tunicates (sea squirts)



Colonial tunicates

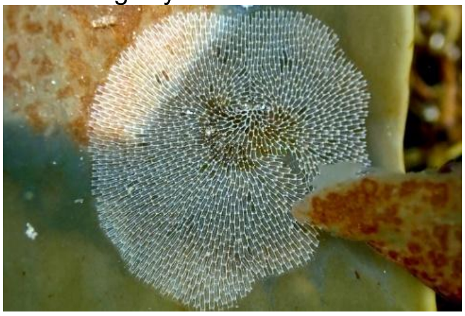
Algae



Hydroids

8.1.2 Hard fouling

Encrusting Bryozoa



Barnacles

Tube worms

Mussels