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Benthic community establishment on different concrete mixtures introduced to a German deep-water port

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Abstract

Concrete is a widely used building material in coastal constructions worldwide. However, limited natural resources used in the production process, as well as high CO₂-emission due to the calcination process of limestone and the thermal energy demand for Portland cement clinker production, raise the demand for alternative constituents. Alternative mixture types should be environmentally friendly and, at best, mimic natural hard substrates. Here five different concrete mixtures, containing different cements (Portland cement and blast furnace cements) and aggregates (sand, gravel, iron ore and metallurgical slags) were made. Three replicate cubes (15 × 15 × 15 cm) of each type were then deployed in a German deep-water Port, the JadeWeserPort, to study benthic community establishment after one year. Results are compared to a similar experiment conducted in a natural hard ground environment (Helgoland Island, Germany). Results indicate marked differences in settled communities in the Port site compared to natural environments. At the Port site community composition did not differ with the concrete mixtures. Surface orientation of the cubes (front/top/back) revealed significant differences in species abundances and compositions. Cubes hold more neobiota in the Port site than in natural hard ground environments. Implications for the usage of new concrete mixtures are discussed.

Keywords: Coastal constructions, Succession, Fouling communities

Introduction

Coastal infrastructures do not function as surrogate for natural marine habitats. Even though artificial structures act as key anthropogenic drivers of environmental change to coastal habitats worldwide [1], ecological consequences of their introduction to the marine environment, to date, have received relatively little attention [2–8]. However, there is a growing consensus that artificial structures are different to natural rocky shores or biogenic reefs [1, 2, 9–13]. In most instances, coastal

infrastructure is built in areas which otherwise are characterised as soft bottom habitats; here the change in species composition, abundance and diversity through the change of the natural habitat origin becomes particularly clear [14].

While natural habitats slope gently or have heterogeneous topography, artificial constructions frequently provide vertical habitat [6, 15–17]. This can lead to increased densities of certain species and to an increasing strength of interspecific interactions [1, 18]. Understanding of how species do or do not use artificial structures is still in its infancy. To date, the characteristics of communities that are likely to establish on or near artificial structures are not predictable [1]. Observation of the community establishment on newly introduced artificial structures

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thus helps to understand the ecological value of a structure itself.

The release of artificial substrata initiates primary succession. Primary succession starts with physiochemical events and occurs on very small spatial scales. Physiochemical events are followed by a biological colonization by bacteria and diatoms [19]. From this point on, succession is regarded as a continuous process with changing trajectories, deflected by both physical and biological processes. A temporary “final stage” of succession, where most of the substrata is covered by macrofauna organisms > 1 cm and subsequently only small changes occur, is reached after approximately one year of deployment in most cases [19]. Further studies on succession of coastal infrastructure can be found, for instance, in biofouling literature, where processes are extensively discussed [20–23].

Newly raised artificial structures are susceptible to invasion, first of all, because of the new, open space [24–27]. Further reasons for invasion can be poor environmental conditions, frequent disturbances, or support of activities linked to the introduction of exotic species (e.g. shipping, aquaculture) [1]. Especially globalization and extended marine traffic within the last century, together with an increase in infrastructure on coasts worldwide, increase the risks of introducing non-indigenous species, so called neobiota [1]. This is especially true for artificial structures in big ports, which are connected to shipping routes worldwide. Neobiota generally appear in greater proportions on artificial structures than in adjacent natural habitats [25] potentially due to a higher tolerance to environmental stressors [28], reduced competitive interactions with extant species and or by lower mortality by predation [29, 30].

Closely connected systems of artificial structures for example along the European coastlines, provide additional dispersal routes for neobiota, also causing drastic changes to natural environments close by [2, 25]. For example, *Undaria pinnatifida*, a brown algae species native to East Asian shores, was introduced into the Mediterranean in 1971 with Pacific oysters. Intentional introduction from there to the French Atlantic coast 12 years later led to a gradual spread to the British Isles and recently to the North Sea [31]. Environmental agencies worldwide are monitoring species causing such changes to the natural marine environment, particularly under the European Water Framework Directive and the Marine Strategy Framework Directive.

European coastlines are covered by 22.000 km² of concrete or asphalt [32–34]. Due to its availability, durability (50–100 years), formability and low in price, concrete has become one of the most important construction materials worldwide [35]. However, the availability of natural

resources, commonly used in aggregates, are limited [36–38]. The reduction of Portland cement production and the increase of supplementary cementitious materials, like granulated blast furnace slags, a byproduct of pig iron production, is a desired achievement in the cement industry [39–41]. The use of slags from metal production (e.g. steel, copper) is promising. These offer technical advantages due to their mineral properties, and have been used in road construction and armor stones for decades [42]. For aquatic environments, their usage is controversial because of the potential for uncontrolled leaching of heavy metals out of pure slag stones [43]. The European concrete standards regulations are not standardized on the usage of aggregates, thus the usage depends on assessments in specific projects.

The following study closely relates to the results of a succession experiment on concrete cubes made of different mixtures which contained different cements (Portland cement and blast furnace cements) and aggregates (natural sand, gravel, iron ore and metallurgical slags). The cubes for this study were deployed in an underwater experimental area and test facility within a natural hard ground environment near Helgoland Island in the German Bight [44]. In order to compare succession on natural and artificial structures, we report here on a settlement experiment on concrete cubes made of the same mixtures and deployed in the same time span as in Becker et al. [44], but in a completely different environment; the JadeWeserPort as an example of a recently erected artificial habitat (Wilhelmshaven, Germany). Here, it is most likely that additional marine coastal infrastructure will be built, and further anthropogenic influences are to be expected.

Taking the JadeWeserPort as a representative example of a recently established artificial infrastructure with high anthropogenic impact, this study focuses on the following questions:

- (1) Are there differences in the benthic communities settled on different mixture types after one year of deployment in an anthropogenically influenced area?
- (2) Are observed patterns different to succession studies in a natural hard ground area (e.g. near Helgoland Island)? How do both areas differ in terms of species composition on the concrete blocks?
- (3) Are there implications for the usability of alternative concrete constituents in marine constructions?

Material and methods

Deployment site and experimental design

The JadeWeserPort is the most eastern deep-water port from the “Nordrange”, it is the most important

continental European Ports of the North Sea [45] and is tide-independent up to 18 m water depth (Fig. 1a). Port construction started in 2008; in April 2012 its trial operation started and it has been running official business since September 2012 [45]. It holds 130 hectare of Container Terminal out of 340 hectare total area. It has a turnover capacity of 2.7 million TEU/Year [46]. In 2019, transfer of 29.29 Mio t were documented, which is +7% compared to 2018 [47]. The neobiota report of the German coast line 2014 [48] reports a total of 116 taxa for the JadeWeserPort, of which 17 were neobiota to the German North Sea coastline.

The deployment site of the concrete cubes was in a separated part of the harbor, the service port. In total, 15 concrete cubes (15 × 15 × 15 cm) made of five different concrete mixtures, were fixed on five steel—PVC-frames (1 m × 0.25 × 0.30 m). Each frame was rigged with three cubes. The different mixtures were randomly placed in the frames, with the exception that none of the different mixtures were present in the same frame twice (Fig. 1b). The frames were deployed from swimming pontoons in April 9th, 2017 and submerged ~1.5 m beneath the surface and fixed by ropes.

The swimming pontoons had previously been reported as the species richest habitat of the harbor [48]. Here, a total of 63 Taxa was found, 14 of them were neobiota [48]. It was further reported that eight out of the 14 neobiota were only found at the JadeWeserPort pontoons.

Concrete mixtures

Concretes used in the experiments fulfill the requirements for exposure class “XS2” (marine structures being permanently under water) defined in the

non-standardised EU concrete standard EN 206. The cement content was 320 kg/m³ and the water/cement ratio was 0.5 in all cases.

Mixtures differed in the used cement types and aggregates. In mixture 1—mixture 3, a Portland cement CEM I 42.5 R and two blast furnace cements CEM III/A 42.5 N and CEM III/B 42.5 N were used as binders. Natural sand (2.64 kg/dm³), gravel (2.64 kg/dm³) and iron ore “MagnaDense” (4.90 kg/dm³) were used in slightly different concentrations (Table 1). In mixture 4 and 5, blast furnace cement (CEM III/B 42.5 N) was combined with two metallurgical slags (a copper slag “Iron Silicate” and an electric arc furnace slag “EOS” with 3.80 kg/m³ and 3.60 kg/m³) as aggregates (Table 1). All cements used fulfilled the requirements of the European cement standard EN 197-1. Since blast furnace cements provide a very dense structure with a low capillary porosity, they are commonly used for durable concrete structures in the marine environment [33, 49, 50].

In accordance with EN 12390-2, the “Institut für Baustoffforschung FEhS Duisburg” produced three cubes (15 × 15 × 15 cm³) of each of the five different mixtures (M1–M5) in February 2017. The cubes were stored 1 day in their mold, 6 days under water, and then under constant climate conditions at 20 °C and 65% relative moisture. At the end of March 2017, they were transported to Wilhelmshaven.

The concretes’ compressive strengths were measured in accordance with EN 12390-3 after 2 and 28 days of casting. The results are shown in Table 2. M5, the mixture with the electric arc furnace slag aggregate, had a significantly higher strength after 28 days, due to the very high grain strength of EOS.

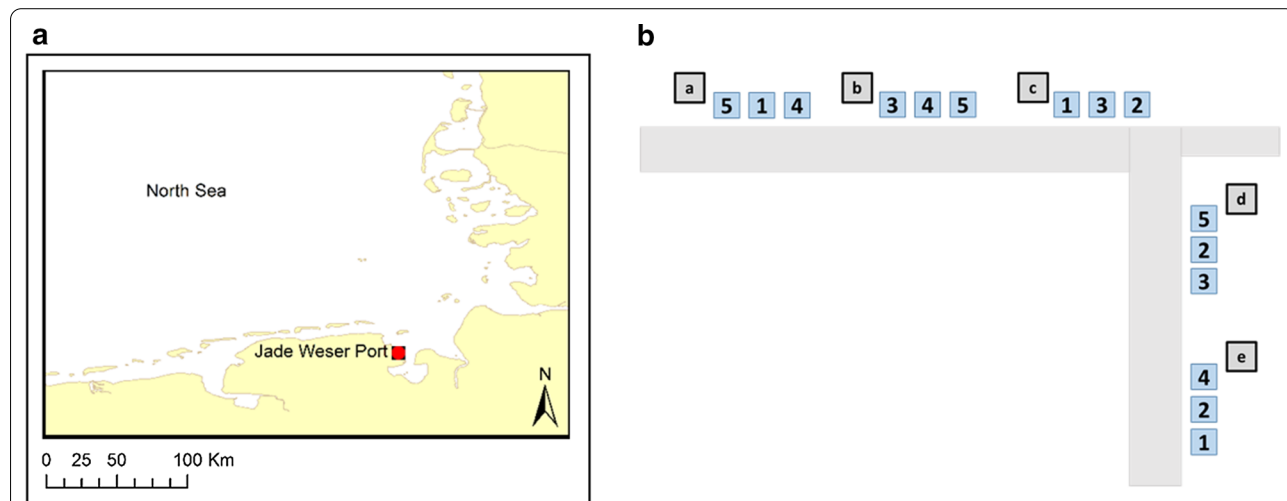


Fig. 1 Deployment site and experimental set up—**a** Location of the JadeWeserPort; tiles were deployed in the service port. **b** Order of frames **a–e**; numbers 1–5 show the location of the different concrete mixtures

Table 1 Composition of the different concrete mixtures M1–M5

Mixture	Cement type	[kg/m ³]	Water [kg/m ³]	w/c—ratio	Aggregates					
					Type	[kg/m ³]	Art			
M1	CEM I 42,5R	320	160	0.5	Sand 0–2 mm	667	Gravel 2–8 mm	95	Magnadens 20 s	2122
M2	CEM III/A 42,5 N	320	160	0.5	Sand 0–2 mm	664	Gravel 2–8 mm	95	Magnadens 20 s	2112
M3	CEM III/B 42,5 N-LH/SR/NA	320	160	0.5	Sand 0–2 mm	662	Gravel 2–8 mm	95	Magnadens 20 s	2107
M4	CEM III/B 42,5 N-LH/SR/NA	320	160	0.5	Iron silicate 0–5 mm	1361	Iron silicate 5–22 mm	1358	–	–
M5	CEM III/B 42,5 N-LH/SR/NA	320	160	0.5	Sand 0–2 mm	284	EOS	2193	–	–

Ingredients of cements (CEM I 42,5R; CEM III/A 42,5 N; CEM III/B 42,5 N-LH/SR/NA) and aggregates (sand, gravel, magnadens, iron silicate, EOS) are given in kg/m³

Sampling procedure and analysis

The concrete cubes were retrieved on April 16th, 2018, after a one year deployment (April 9th, 2017–April 16th, 2018). Until evaluation, they were stored in darkness in saltwater at ~ 10 °C. The cubes were examined in the lab from April 16th 2018 to April 19th 2018. Three cube sides, the top, front and backside, were evaluated. The front side is defined as the cube side, which points in the direction of the open water, the back side is defined as the cube side, which points to the pontoon (Fig. 1b). All macrofauna and algal species present on the top, front and backside of the concrete cubes (15 × 15 cm) were recorded. Additionally, each side was photographically documented. Species were determined to the lowest possible taxonomic level and for smaller species, abundance and coverage were recorded using a smaller grid (1 cm² = 0.44% coverage of the total area).

For comparison of the different sides and mixture types, only coverage data was used in the statistical analysis. Mobile macrofauna species or species with less than five individuals per cube side were excluded from the analysis. One community was summed up as “mat”, including species of juvenile Phaeophyceae and cyanobacterial communities, as well as diatoms species. They formed a visible crust on the cubes.

All neobiota were identified according to neobiota catalogues [51, 52]. Categories (K1–K3) were assigned accordingly: K1 Neobiota with a known strong impact on the environment. K2 Neobiota with a known strong impact on the environment, but this impact is still not present on regional coasts. K3 Neobiota with to date unknown consequences to the environment [51].

Data processing and statistical analysis

Statistical analysis were performed using the statistical PRIMER package, v6 [53] and PERMANOVA + add on PRIMER v6 [54]. Univariate 1-way PERMANOVA tests, based on square root transformed coverage data, as well as multivariate analysis of the transformed data via PERMANOVA pair-wise tests, based on Bray–Curtis similarity, were performed. P-values yield the exact test of the null hypothesis. This means, the probability of rejecting the null hypothesis is exactly equal to the chosen significant level of 0.05. The chance of false positive findings

(type I error) is 5% [54]. MDS plots were used to show trends in multivariate data. DIVERSE tool and similarity percentage routine (SIMPER) analysis were used to determine differences in species communities. Mean coverage and standard deviations were calculated in R v.3.3.2 [55]. Coverage values over 100% were found due to the horizontal and partially overlapping distribution of species.

Results

Benthic flora and fauna

After one year of deployment, 32 macrofauna and algal taxa were identified in total on all concrete cubes. Five of these taxa belong to the group of neobiota (K1 = 1 species and two species classified as K2 and K3). With five different taxa, Mollusca represented the most diverse group, followed by Arthropoda (4), Phaeophyceae (4), and Rhodophyta (4). Other taxonomic groups were represented two or less taxa per group (Table 3). The following statistical analysis include %-coverage of nine taxa and one taxa named “mat” (which includes 3 juvenile species of Phaeophyceae and diatoms).

Differences between the observed mixtures and sides

Permanova revealed no differences in community composition for the different mixtures (M1–M5), but confirmed highly significant differences ($P = 0.0001$) between macrofauna and algal communities of the top side (T), the front side (F), and the back side (B) of the cubes (Table 4).

Differences between the observed sides of the concrete cubes were also shown by the MDS plot of square root transformed coverage data (Fig. 2). Permanova pair-wise test confirmed significant differences between all sides (T-F $P = 0.0001$, T-B $P = 0.0001$, F-B $P = 0.0001$).

Side effect

Taxa numbers are similar between the Top and Front sides (T: 4.31 ± 0.91 ; F: 4.62 ± 0.62), only the Back differed with one taxa less (B: 3.31 ± 0.46). The Top sides of the cubes revealed lower mean coverages ($51.23 \pm 19.04\%$) compared to the Front ($118.54 \pm 21.69\%$) and Back ($97.38 \pm 29.77\%$) sides (Table 5). Shannon–Wiener index H' was highest for the Top sides (1.07 ± 0.15). For the Front sides, a Shannon–Wiener index of 0.97 ± 0.19 , and for the Back sides, a Shannon–Wiener index H' of 0.88 ± 0.13 was calculated. Evenness J' was 0.75 ± 0.15 for the Top sides, 0.63 ± 0.1 for the Front sides, and 0.74 ± 0.11 for the Back sides of the cubes (Table 5). SIMPER analysis indicated differences in species communities between the sides. While the Top communities were dominated by red algae *Polysiphonia nigrescens* (46.33%), followed

Table 2 Compressive strength $f_{c, \text{cube}}$ of the concrete mixtures M1–M5 in N/mm² after 2 and 28 days under constant climate conditions at 20 °C and 65% relative moisture

	M1	M2	M3	M4	M5
2 days	43.5	40.1	41.1	41.7	43.5
28 days	59.1	58.4	56.4	60.4	72.0

Table 3 List of macrofauna and algal taxa found on the concrete cubes

Phylum/class	Order	Family	Species	Neobiota
Arthropoda	Amphipoda	Gammaridae	<i>Gammarus spec</i>	
	Decapoda	Cancridae	<i>Cancer pagurus</i>	
	Sessila	Austrobalanidae	<i>Austrominius modestus</i>	K2
Bryozoa	Cheilostomatida	Bugulidae	<i>Balanus crenatus</i>	
		Electridae	<i>Crisularia purpurotincta</i>	
Chlorophyta	Ulvales	Ulvaceae	<i>Ulva spp</i>	
	Ulvales	Ulotrichaceae	<i>Acrosiphonia arcta</i>	
Chordata	Stolidobranchia	Styelidae	<i>Botryllus schlosseri</i>	K3
Cnidaria	Actiniaria	Actiniidae	<i>Urticina juv</i>	
			<i>Urticina felina</i>	
Echinodermata	Forcipulatida	Asteriidae	<i>Asterias rubens</i>	
Hydrozoa	Anthoathecata	Tubulariidae	<i>Tubularia indivisa</i>	
			"Club polyp"	
Mollusca	Littorinimorpha	Calyptreaeidae	<i>Crepidula fornicata</i>	K2
	Mytilida	Mytilidae	<i>Mytilus edulis</i>	
	Nudibranchia	Onchidorididae	<i>Onchidoris bilamellata</i> + <i>Gelege</i>	
	Ostreida	Ostreidae	<i>Crassostrea gigas</i>	K1
	Trochida	Trochidae	<i>Gibbula spec</i>	
Phaeophyceae (mat)	Ectocarpales	Acinetosporaceae	<i>Hincksia hincksiae</i>	
			<i>Pilayella spp</i>	
			<i>Pilayella littoralis</i>	
Polychaeta	Phyllodocida	Ectocarpaceae	<i>Ectocarpus siliculosus</i>	
			Polynoidae	<i>Harmothoe glabra</i>
Porifera	Terebellida	Terebellidae	<i>Harmothoe antilopes</i>	
			"Polychaete mud tube"s	
Rhodophyta	Suberitida	Halichondriidae	<i>Halichondria (Halichondria) panicea</i>	
Rhodophyta	Bonnemaisoniales	Bonnemaisoniaceae	<i>Bonnemaisonia hamifera</i>	K3
	Ceramiales	Rhodomelaceae	<i>Ceramium rubrum</i>	
		Rhodomelaceae	<i>Polysiphonia nigrescens</i>	
	Corallinales	Lithothamniaceae	<i>Phymatolithon spp</i>	

Tube dwelling diatoms

Species %-coverage included in the JadeWeserPort analysis are shown in bold. Species of the Phylum Phaeophyceae and diatoms built a mat cover on the cubes and were included as such in the statistical analysis. Risk categories are given (K1–K3) [51]

Table 4 Results of Permanova on square root transformed coverage data showing differences in macrofauna and algal communities between different sides (Top vs Front vs. Back)

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms
Sides	2	23,183	11,592	27.763	0.0001**	9940
Mixture	4	2094	523.5	1.2539	0.275	9929
Sides x mixture	8	1603.3	200.41	0.48002	0.955	9923
Res	24	10,020	417.52			
Total	38	38,455				

No differences were present for mixtures (M1–M5). Analysis implies no interaction between side effect and mixtures effect. Meaning that the effect within side and mixtures is the same within the tested groups

df degrees of freedom, SS sum of squares, MS mean sum of squares, Pseudo F pseudo-F ratio. Significance levels P(perm) are based on 9999 permutations (significance levels: *significant (p ≤ 0.05), **highly significant (p ≤ 0.005)). Unique perms indicate how many unique values of the test statistic were obtained under permutation

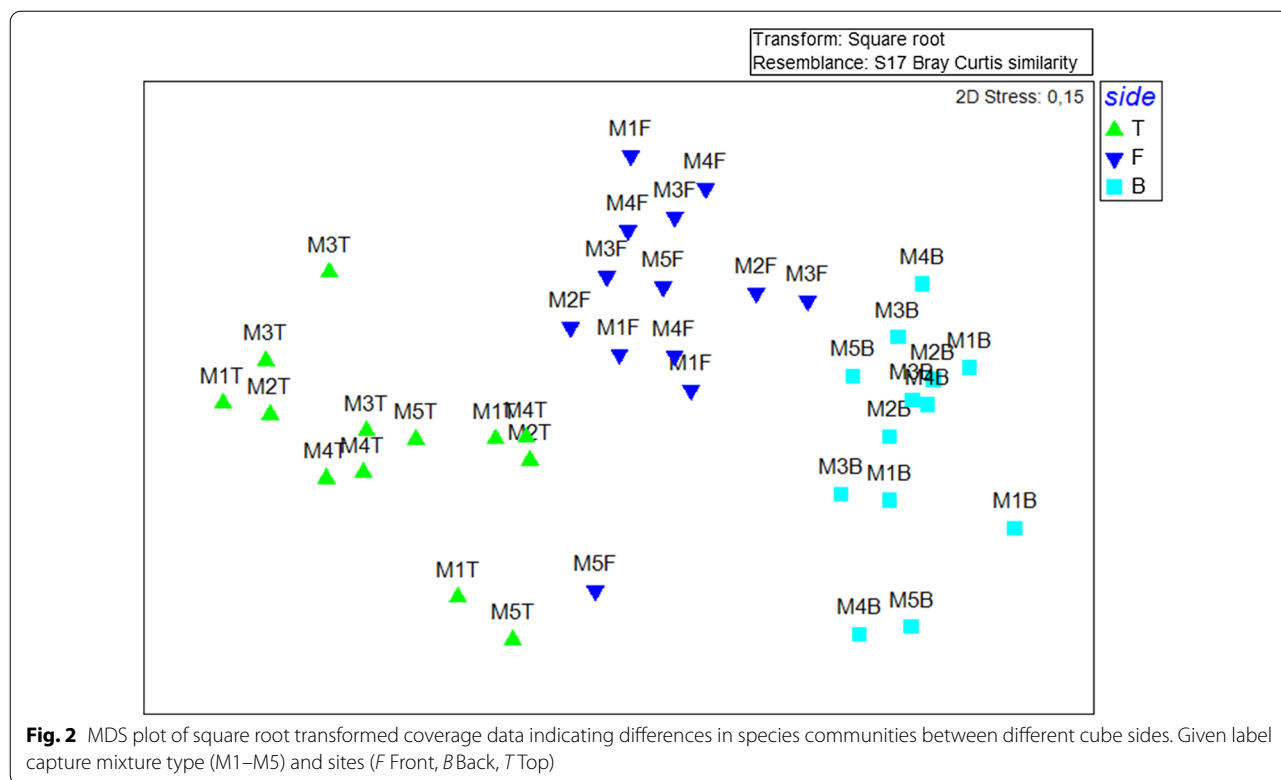


Fig. 2 MDS plot of square root transformed coverage data indicating differences in species communities between different cube sides. Given label capture mixture type (M1–M5) and sites (F Front, B Back, T Top)

Table 5 Results of DIVERSE and SIMPER analysis for the top, front and back sides of the cubes

Site	Top	Front	Back
Mean taxa per side	4.31 (0.99)	4.62 (0.68)	3.31 (0.5)
Mean coverage [%]	51.23 (20.63)	118.54 (23.5)	97.38 (32.25)
Shannon–Wiener index H'	1.07 (0.29)	0.97 (0.21)	0.88 (0.14)
Eveness J'	0.75 (0.16)	0.63 (0.1)	0.74 (0.12)
Species communities resulting from SIMPER analysis	<i>Polysiphonia nigrescens</i> (46.33) mat (26.20) <i>Balanus crenatus</i> (14.23) "Polychaete mud tubes" (10.17)	mat (56.39) <i>Polysiphonia nigrescens</i> (22.93) <i>Balanus crenatus</i> (10.52) <i>Crisularia purpurotincta</i> (7.28)	mat (48.47) <i>Balanus crenatus</i> (29.94) <i>Crisularia purpurotincta</i> (21.07)

Shown are mean taxa, mean coverage, Shannon–Wiener index H' and Eveness J'. Standard deviations are shown in brackets. SIMPER analysis shows characterizing macrofauna and algal species, and to which percentage they contribution to the communities (in brackets) on the different sites

by mat species (26.20%), *Balanus crenatus* (14.23%) and "Polychaete mud tubes" (10.17%), the Front sides were dominated by the mat species (56.39%), *Polysiphonia nigrescens* (22.93%), *Balanus crenatus* (10.52%), and *Crisularia purpurotincta* (7.28). The Back sides, like the Front sides, were also dominated by mat

species (48.47%) but then followed by *Balanus crenatus* (29.94%) and *Crisularia purpurotincta* (21.07%) (Table 5).

Neobiota in the JadeWeserPort

Five out of the total of 32 taxa found on the concrete cubes were recorded as neobiota, belonging to all of the three different risk categories: K1—*Crassostera gigas*; K2—*Austrominius modestus*, *Crepidula fornicata*; K3—*Botryllus schlosseri*, *Bonnemaisonia hamifera* (Table 3). Abundances of *Crassostera gigas* were low being found on 6 out of 45 cube sides, with less than five individuals per side. Abundances of *Austrominius modestus* were also low being found on 1 out of 45 cube sides, with less than five individuals per side. In 26 out of 45 cube sides, individuals of *Crepidula fornicata* were present at densities of 1–4 individuals per side, however on three sides, 10–25 individuals were present. Abundances of *Botryllus schlosseri* were low with three small colonies found on 5 sides. *Bonnemaisonia hamifera* was found on 13 out of 45 cube sides, with coverage mostly less than 5% per side but one side was found with 30%.

Discussion

The findings within this study contribute to a better understanding of the process of settlement of benthic communities on artificial constructions, and further

highlight that these structures cannot act as surrogates to natural grounds. In the context of a continuously increasing activity of constructing new marine coastal infrastructure [32–34], the investigation of new concrete mixtures is necessary with regards to resource efficiency, sustainability and economical aspects. There is more than one concrete type which can be used in coastal constructions, to safeguard natural resources. Testing different mixtures in the natural environment, is not only important for the evaluation of ecological impacts, but also concerning durability and static requirements.

In the JadeWeserPort, concrete mixture type made no differences to settled communities after one year. However, surface orientation of the cubes (Front/Top/Back) revealed significant differences in species abundances and community compositions. In a similar experimental setting, however in a less anthropogenically shaped environment, Becker et al. [44] observed different results. Here, the same concrete mixtures were exposed within the same period of time to the natural subtidal hard ground conditions of Helgoland Island. Becker et al. [44] also observed significant differences of settlement communities depending on the surface orientation of the cubes, but also significant differences in settled communities between mixture types. They suggest that concrete mixture type is negligible in anthropogenically influenced sites but more study sites are needed to confirm this. Impacts of artificial material in inshore coastal hard bottom communities might not necessarily be the same as for Helgoland, which, due to its relatively isolated location in the German Bight is offshore character [56].

Constructions of marine artificial infrastructure have been influencing natural environmental conditions for decades, for instance by changes in water flow, contamination loads, noise etc., and have impacted species richness and diversity which cannot be readily reversed [1, 57]. In nearshore environments, fragmentation of rocky shore habitats by replacing natural rock with artificial substrata, leads to a loss of habitat and changes the characteristics of the remaining assemblages [58]. The subdivision into numerous smaller habitat patches results in an overall reduction in species richness [59]. Species present in anthropogenically influenced sites are characterized by a generally broad range of tolerance [1]. Changes, for instance in concrete ingredients, will probably be of minor importance to those species. Natural hard grounds, in contrast, hold higher numbers of propagules, species that are more specialized and react more sensitive to small range environmental changes [1, 13, 57]. This might result in more drastic and visible changes in the settling community structures depending on mixture types.

Species composition and abundances in anthropogenically influenced and natural sites

Artificial constructions like ports, are known to differ from natural hard grounds in terms of community composition and species densities [57, 60]. Studies on artificial constructions found reduced species richness compared to the neighbouring natural communities [1, 61–63].

For the cubes deployed in the JadeWeserPort, a total of 32 taxa was found. This is low, compared to a total of 51 taxa found on the cubes of the natural hard ground study site in Helgoland by Becker et al. [44]. Comparing results of taxa numbers given by other studies conducted in the JadeWeserPort and Helgoland, the trend towards lower species diversity in the port site is also observed. For the JadeWeserPort a total of 116 taxa [48] is reported where at the natural site Helgoland, up to 402 taxa can be found [64]. Other studies show similar results. For instance, a recent comparison of concrete jetties versus natural rocky shores of the Mediterranean revealed a total of 150 algal and faunal taxa, 77 were recorded on jetties while 140 were recorded on natural rocky shores [65].

The floating pontoons in the JadeWeserPort were reported as the habitat of the harbor richest in species [48]. With a total of 63 taxa, they held more than half of all taxa found in the port site. Studies on floating and fixed artificial structures suggest, that the motion of floating structures, like pontoons, influence species composition and abundances [66, 67]. In temperate regions, differences between floating and fixed structures were mainly due to increased abundances of species [25, 66–69]. For tropical environments, changes in community composition were observed as well, for instance, more filter feeding organisms were found on floating structures, compared to fixed habitats [66, 67]. This might be explained by higher water flow and turbulence through these structures. This trend is also reflected by community composition found for the pontoons in the JadeWeserPort by Rhode et al. [48].

Regarding species composition, only eight red and brown algal species were found in the JadeWeserPort. The red alga *Polysiphonia nigrescens* dominated over all others covering most of the front sites of the cubes after the second month of deployment. *Polysiphonia nigrescens* was missing on the back side of the cubes, and here, barnacles dominated the surface. The back side of the cubes is shaded by the pontoons and since algae species need light for growth, it is reasonable that they preferred the open water side. However, taxa numbers of algae found on the concrete cubes in the port are considerably lower, compared to the natural study site, where cubes were covered by 23 algal taxa after one year of deployment. The proximity to natural rocky coastlines or reefs

influence community characteristics on artificial constructions [57, 60]. The JadeWeserPort is surrounded by a mud flat environment. Thus, the pool of reproductive spores potentially reaching artificial structures to settle is low compared to the natural hard ground environments [13].

Water transparency in anthropogenic port sites is often considerably low, especially when a mud flat environment surrounds them. This is critical, as light availability is a main factor limiting the growth of algal species. Regular dredging activities in the port and in the channels close by, in combination with the regular tide flow, can increase the percentage of small mud particles in the water column [70–73]. In the JadeWeserPort, water transparency is already low in 0.5 to 1 m [48], as measured by Secchi depth. For the North Sea areas, water transparency increases with distance to the shore lines [74]. For the natural site Helgoland, mean water transparency lies already around 4–5 m Secchi depth [75, 76], a value which can hardly be measured in the proximity of anthropogenic construction sites.

Apart from a higher diversity of algae, more Bryozoan species were found at the natural study site as well, compared to the JadeWeserPort [44]. In addition to water transparency, water contamination levels influence species diversity. The southern parts of the North Sea are under the influence of the rivers Elbe, Weser, Ems, Rhein, Schelde and Thames. Hence, contamination levels with respect to brackish water inflow and industrial loads through these rivers are higher compared to the isolated position of Helgoland Island [56]. Studies from the Red Sea coast show that bryozoan species react sensitively to environmental pollution, mainly heavy metal contamination in soils. Diversity of Bryozoan species was higher in unpolluted areas than in anthropogenically influenced coastal sites [77]. Although we did not assess heavy metal load at the study site, it is likely that a higher contamination level in port sites may influence species diversity.

For the JadeWeserPort, the barnacle *Balanus crenatus* were among the characteristic species, especially for the cubes' back sides. Barnacles are typical settling organisms on artificial structures worldwide [20–23, 78]. Within artificial constructions, barnacles prefer vertically orientated structures, but this can vary depending on sediment loads [79]. Other species typical for artificial constructions can be tube building polychaetes, like *Spirobranchus triqueter* or *Spirobis spirobis* for temperate regions, both missing from the JadeWeserPort study site [65, 79].

Neobiota

The experiments in the JadeWeserPort affirm a high invasion risk of artificial structures, as argued, for instance,

in Glasby et al. [80]. All five neobiota found in this study were also included in the total of 14 neobiota found on the pontoon site in the JadeWeserPort by Rhode et al. [48]. However, abundances of neobiota were still low, compared to dominating native species. A fast succession of native competitors, for instance *Polysiphonia nigrescens* might have prevented the settlement by neobiota.

Since 1954, the barnacle *Austrominius modestus* has been one of the main fouling species in German coastal waters [51]. After a series of mild winters and warm summers, exponential population growth was observed in several North Sea regions [51, 81]. This might become problematic with further increasing temperature due to climate change. A model on two competing barnacle species with different reproduction times (as would be the case for *Austrominius modestus* and *Balanus crenatus*) revealed a positive impact of warming waters for invasive species due to a reduced time period between the reproductive peaks of the species [82]. However, native species can be supported and positively influenced by the precise timing of the introduction of new substrates [82]. In the present study, the native barnacle *Balanus crenatus* still dominated on the cubes of the JadeWeserPort. The slipper snail *Crepidula fornicata*, also introduced from England where it spread to most European ports, has been established as part of the German marine fauna since 1934. Its abundance is still strongly reduced by cold winters [51]. On the cubes in the JadeWeserPort, the Pacific oyster *Crassostera gigas* was also found being introduced to the North Sea waters in the middle of the twentieth century where in the Wadden Sea, it replaced native mussel beds of *Mytilus edulis*. Hitherto, *Crassostera gigas* can be found along almost all European coastlines [51]. At the natural study site of Helgoland Becker et al. [44] observed two neobiota (*Botryllus schlosseri* and *Bonne-maisonia hamifera*) but they do not seem to have a negative impact on the natural environment [51].

There are several reasons given as to why artificial structures are particularly vulnerable to invasion. Those reasons entail a generally lower diversity of native species, reduced competitive interaction and predation risk, but also changes in environmental conditions, like a reduced water flow in more sheltered conditions [1]. For breakwaters along the coasts of Italy a spread of introduced green macroalgae has been found [12, 24]. Algae benefit from the wave-sheltered environments on the shoreward side of the breakwaters [12, 24]. Dafforn et al. [28] argue that filter-feeding invaders, which are often transported on ship hulls, could take advantage of being adapted to high shear stress by colonizing open space on moving substrata, for instance floating docks. Regarding reduced competitive interactions and predation risk, as postulated by the biotic resistance theory [29] and enemy

release hypotheses [30], it also needs to be taken into account that artificial structures always initiate primary succession when they are built or released to marine environments. It is difficult to predict, if neobiota will manage to replace native competitors in the long term. However, with ongoing climate change and global trade and transport it is likely that neobiota will succeed over native species [83, 84].

In conclusion, a general recommendation can be given with respect to the use of new concrete mixtures in marine constructions. As long as there is no significant difference in succession patterns and establishment of benthic communities between the new concrete mixtures and those which are commonly provided, and that leakage of environmental pollutants can be excluded, the new mixtures should be used for new constructions. This way, at least a more environmentally friendly production would be guaranteed. However, it is important to balance between costs and benefits of new concrete mixtures and building solutions may differ from case to case.

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Authors' contributions

L. R. Becker: conceptualization, methodology, validation, formal analysis, investigation, writing—original draft, writing—review and editing, project administration, visualization. K. Bischof: conceptualization, writing—review and editing, supervision. I. Kröncke: validation, writing—review and editing, supervision. A. Ehrenberg: conceptualization, methodology, resources, writing—review and editing. V. Feldrappé: methodology, resources, writing—review and editing. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

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Competing interests

The authors declare that they have no competing interests.

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