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K. J. Collins, A. C. Jensen, J. J. Mallinson,
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Scrap tyres have been widely used around the world to construct artificial reefs. They are a popular construction material, being readily available at no cost, durable, and with large void spaces. However, published information about the environmental impact of tyres in the marine environment is limited. When used, successful colonization by epibiota and mobile species seems to be taken as empirical proof of their suitability. In 1998, an experimental scrap tyre artificial reef was constructed in Poole Bay to provide data on the environmental impact of the material. Epibiotic colonization is being monitored for comparison with that on concrete control modules deployed at the same time. Samples of the epibiota have been analysed for heavy metals and organic compounds. Results from the first year of deployment are presented.

Keywords: artificial reef, colonization, environmental impact, leaching, tyre.

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K. J. Collins, A. C. Jensen. J. J. Mallinson, V. Roenelle, and I. P. Smith: School of Ocean and Earth Science, University of Southampton, Southampton SO14 3ZH, England, UK; e-mail: kjc@soc.soton.ac.uk

Introduction

Millions of tyres are produced each year around the world, and waste tyres pose an enormous disposal problem. In the UK, about 37 million tyres are replaced each year (EA, 1998). Of these, some 30% were re-treaded for reuse, 27% were used as fuel (e.g. cement kilns and electricity generation), and 16% were reused whole or as granulated particles, leaving the remainder for disposal in stockpile or landfill. Tyres have been stockpiled in massive land dumps where they pose a serious fire risk. Once alight, they generate smoke, toxic fumes, oils, and liquids, and the fires are difficult to extinguish. This is a worldwide problem, and has led, for instance, to a proposed European Union ban on their use in land-waste burial sites. The longevity, resistance, and shape of tyres has been exploited for many marine construction applications (review by Collins *et al.*, 1995): breakwaters (onshore and offshore), retaining walls in harbours and estuaries, and artificial reefs for fishery enhancement. Underwater, tyres are protected from ultraviolet degradation and are in a neutral, stable chemical environment, which may limit leaching. Two extensive artificial reef bibliographies (Stanton *et al.*, 1985; Berger, 1993) list some 60 tyre breakwater papers and over 200 references to tyre reefs, and describe tyre reefs from North America, the Caribbean, Europe, the Middle East, Asia/Pacific, and Australia. They appear to be particularly popular in the southwest Pacific. Stone *et al.* (1975) list some 40 US east coast reefs, which in total have utilized 700 000 tyres. A subsequent review (McGurrin, 1988) lists 73 tyre reefs along the Atlantic seaboard of the USA. Tyres are relatively buoyant in sea water, and initial attempts to construct tyre reefs in the USA were poorly engineered and quickly washed ashore by storms. This led to restrictions or banning in some states (e.g. California and Washington; Stone, 1985). McGurrin's (1988) review of Atlantic reefs describes the successful concrete ballasting of tyre units employed in different programmes in various States.

The majority of papers concerning tyre artificial reefs concentrate on fish populations and catches. However, when considering their potential environmental impact in the marine environment, the growth of organisms on the tyre surface may be more revealing than the mobile fauna, as their exposure to any chemical release is greater. Colonization by a range of flora and fauna has been described by many authors (e.g. Gordon, 1972; Tsuda and Kami, 1973; Alfieri, 1975; Alcala *et al.*, 1981; Gomez, 1982; Prince *et al.*, 1986; Vyshkvartsev and Lebedev, 1990; and Reimers and Branden, 1994).

Tyres are manufactured from a wide range of chemical compounds, which vary between type, manufacturer, date of production and country of origin. Both natural rubber and synthetic polymers (e.g. butadiene) are used in their production, with large quantities of carbon black as a reinforcing agent and filler. Oils are used to aid mixing of the components and to modify physical properties. Vulcanizing agents such as sulphur, zinc oxide, and organic peroxides enable the polymerization reactions at elevated temperature during manufacture. Accelerators (e.g. thiazole compounds) and retarders are added to control the rate of these reactions, while antidegradants extend the life of the rubber.

The US National Artificial Reef Plan (Stone, 1985) includes tyres as a reef construction material noting that no toxic effects attributable to leaching or decomposition have been demonstrated. However, there is little published information about the leaching of compounds either in sea or fresh water. There is considerable interest in the use of shredded tyre in road construction both as a base and when mixed with asphalt. Related leaching studies have been carried out (Eldin and Senouci, 1992). An indirect study was undertaken by Stone *et al.* (1975) using fish kept in flowing water tanks with tyres. Hartwell *et al.* (1998) used a range of salinities in leaching studies and bioassays with minnows (*Cyprinodon variegatus*) and shrimp (*Palaemonetes pugio*) and found that toxicity decreased with increasing salinity.

So far, millions of tyres used in marine artificial reefs around the world have been colonized by marine organisms without apparent ill effects. However, until detailed environmental compatibility studies have been carried out, the UK or any other European country will not sanction their use in the sea. In 1993, concrete filled compressed scrap tyre bales "rubber rocks" were proposed for use in building offshore breakwaters off the Holdemess coast, northeast UK. If accepted, this could have been a self-financing coastal defence scheme using the disposal fees to pay for the preparation and deployment of the rubber rocks, something of a first in the UK. A preliminary study (Collins *et al.*, 1995) noted the release of zinc and polycyclic aromatic compounds from tyres in laboratory seawater leaching studies. We describe results from a follow-up study in the field with the following objectives: (1) to characterize tyre leachates in sea water in the laboratory, (2) deploy waste tyre and concrete control reef modules in the sea, (3) monitor the biological colonization of these modules, and (4) assess the bioaccumulation of tyre compounds in the epibiota.

Methods

We followed the marine environmental evaluation procedure developed for cement stabilized coal ash in which, after a series of laboratory trials (physical, chemical, and biological), an experimental structure was deployed in Poole Bay, off the central south coast of England (Collins *et al.*, 1994; Jensen *et al.*, 1994).

In July 1998, tyre modules and concrete control modules were deployed alongside the existing cement stabilized coal ash reef study site in 12 m of water in Poole Bay. Five hundred scrap tyres were formed into three types of modules: (1) concrete-filled single tyres (2), stacks of 6/7 car tyres forming a cylinder filled with concrete ("rubber rocks"), and (3) open lattice structures (tetrahedra) using either 4 or 13 tyres held together by stainless steel bolts and with the basal tyres filled with concrete (Figure 1). Concrete blocks ($20 \times 20 \times 40$ cm) were used as the control surface. The reef was arranged (in the same way as the earlier coal ash reef) as 8 separate units, each 5 m across by 1 m high replicating each of the three tyre structures and the concrete control.

The reef was monitored at approximately 2-monthly intervals, by scuba diving, to study the colonization of the tyre surfaces, in comparison with concrete, by observing and collecting organisms plus close-up photography (Nikonos V camera, flash, 28-mm lens and Nikonos close-up kit). Typically, eight photographs were taken on both horizontal and vertical surfaces on two tyre units (rubber rock and tetrahedra) and two concrete control units. The techniques used have been described by Jensen *et al.* (1994). Organisms growing on and around the structures were collected, care being taken to avoid removing surface tyre or concrete with the sample, for chemical analysis. Heavy metals were measured by flame atomic absorption spectrometry (Pye Unicam SP9) of nitric acid digests (see, for details, Collins *et al.*, 1994).

Results

The mean metal (Zn, Cu, Pb, and Cd) concentrations within four individual epibiotic species (Hydroida: *Halecium* sp.; Bryozoa: *Bugula fabellata*; Ascidia: *Styela clava*, and *Ascidiella aspersa*) sampled after 11 months by substratum are shown in Figure 2. GLM ANOVA indicated highly significant effects of substratum, species, and their interactions for most metals (Table 1a), but post hoc Tukey tests showed that highly significant substrate differences in metal content were largely restricted to *Halecium* sp. (Table 1b).

Initial recruitment of fouling organisms occurred rapidly after reef deployment. Within 3 weeks, 7 species of drift algae, including brown (*Laminaria* sp.) and red algae (*Brongniartella byssoides* and *Chondria dasyphylla*)

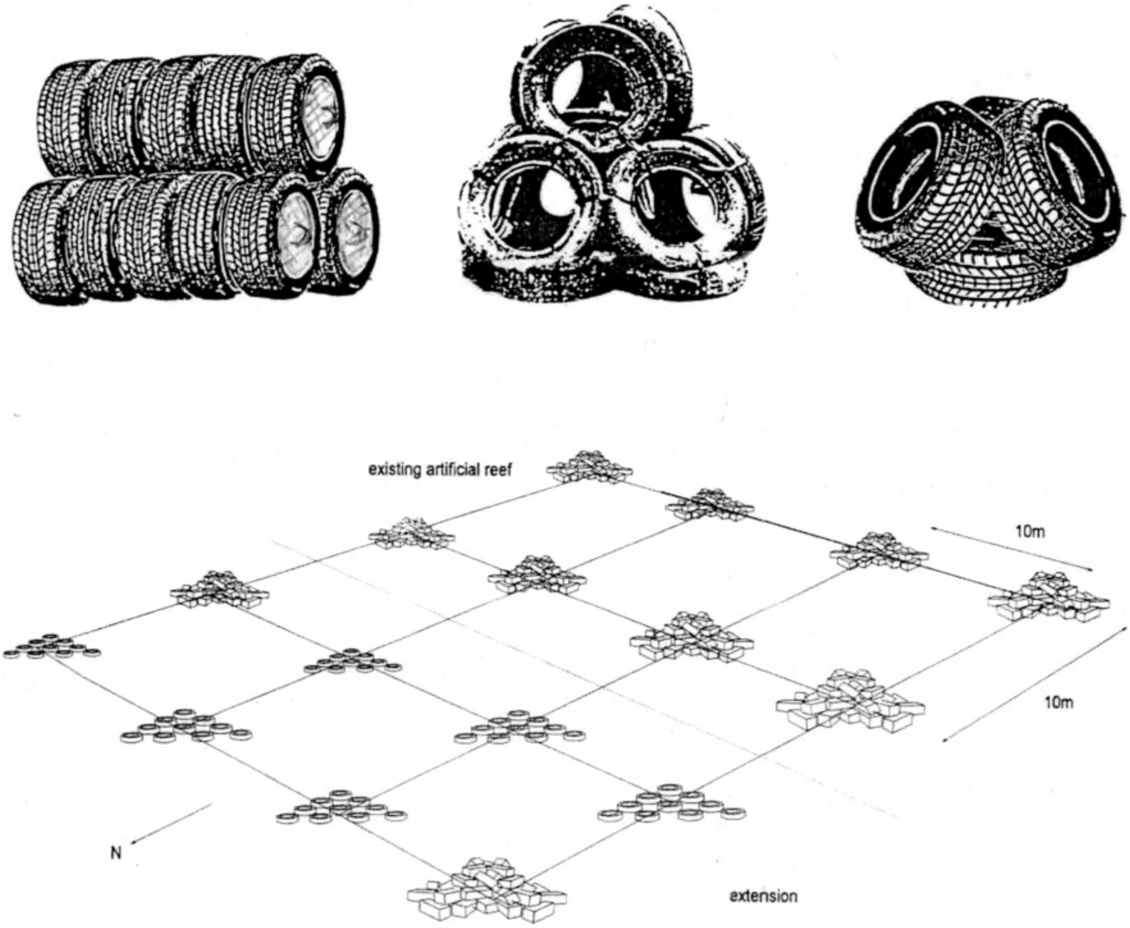

Figure 1. Configuration of the artificial reef and of the "rubber rock", large and small tetrahedral tyre modules.

re-attached on both concrete and tyre surfaces and continued growing. New settlement of algae occurred at the same time: fine brown algae (*Taonia atomaria*) and red algae (*Antithamnion* sp. and some 1–2 cm shoots of *C. dasyphylla*) developed all over horizontal surfaces and to a lesser extent on vertical surfaces.

One month after deployment, a few specimens of fruiting hydroids (*Laomedea fexuosa* and *Plumularia setacea*) and bryozoans (*Bicellaria ciliata* and *Bugula fabellata*) had colonized tyre surfaces. Algae grew rapidly into recognizable specimens. By the end of August 1998, small specimens of the calcareous tube worm *Pomatocerous triqueter* and the sabellariid polychaete *Sabellaria spinulosa* had recruited onto concrete and tyre units. Hydroids continued to grow and fruit, with new species recruiting (*Tubularia indivisa*). Bryozoans spread to most of the tyre units. The algal and hydroid cover continued to develop, particularly on higher surfaces.

By mid-October (3 months after deployment), all tyre units were dominated by well-grown and fruiting hydroids. New hydroid species had recruited, among them *Halecium halecium* and *Sertularella gaudichaudi*, the latter being frequently recorded with *Plumularia setacea* and *T. indivisa*. Upper surfaces supported a denser cover than those closer to the seabed. Small ascidians (*Ascidiella aspersa*) and didemnids (*Lissochum perforatum*), both pioneering species, had colonized concrete and tyre units, and so had the barnacle *Elminius modestus*. Hydroids, bryozoans, and ascidians were growing and spreading fast on the tyres. On concrete, hydroids were more patchy, erect bryozoans were found as individual clumps, and encrusting bryozoans as small patches. Algae such as *T. atomaria* and *Chondria* sp. had not developed further since the end of August.

In December (5 months after deployment), all units were still hydroid dominated with some bryozoans and a few ascidians, barnacles, and worms. There were signs of dieback of some species, especially algae undergoing a typical winter decline. *P. triqueter* and barnacles were present on all the tyre units. In mid-March 1999, the reef showed signs of regrowth of hydroids (*P. setacea*

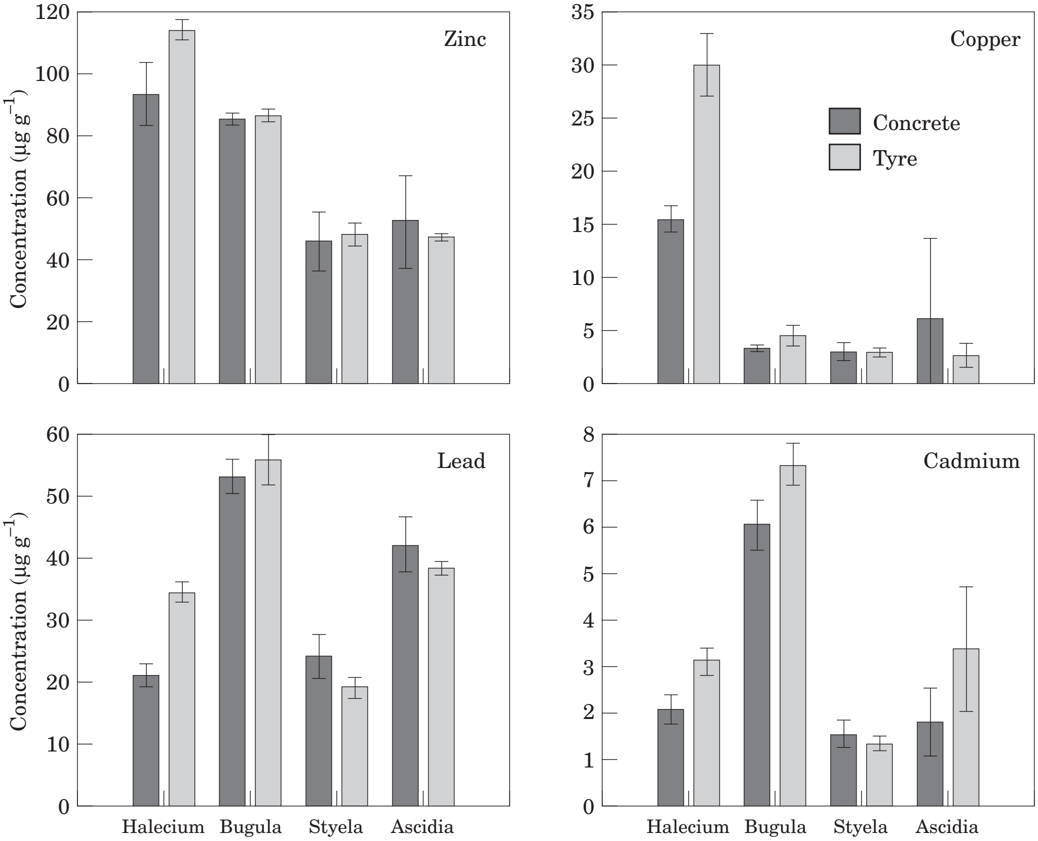

Figure 2. Concentrations (± 1 s.d.; n=10) of heavy metals in hydroids (*Halecium* sp.), bryozoans (*Bugula flabellata*), and ascidians (*Styela clava* and *Ascidiella aspersa*) collected from tyre and concrete surfaces after 11 months.

Table 1. Results (a) from General Linear Model ANOVA (F-ratio and p-values) of effects of substrate, species, and their interaction and (b) from Tukey multiple comparison tests (T-value and p-value) on heavy metal concentrations within four species of epibiota (*significant difference at p<0.05).

Source	d.f.	Zinc F/T	Zinc p	Copper F/T	Copper p	Lead F/T	Lead p	Cadmium F/T	Cadmium p
a. ANOVA									
Substratum	1	192.9	<0.001*	302.3	<0.001*	366.5	<0.001*	227.7	<0.001*
Species	3	4.6	0.038*	18.6	<0.001*	3.8	0.057	26.1	<0.001
Substratum* species	3	9.94	<0.001*	49.1	<0.001*	40.4	<0.001	3.5	0.024*
Residuals	40								
b. Tukey tests									
Ascidiella aspersa		− 1.0	0.97	− 2.2	0.39	− 2.7	0.16	3.4	0.03
Bugula flabellata		0.3	1.00	0.9	0.98	1.8	0.64	4.4	0.002
Halecium sp.		7.2	<0.001*	15.9	<0.001*	12.9	<0.001*	5.0	<0.001*
Styela clava		0.5	1.00	− 0.0	1.00	− 2.4	0.26	− 0.6	1.00

and *H. halecium*) from the previous year as well as new growth. The ascidian *Molgula* sp. was occasionally present on concrete, but was absent on tyres. By April 1999, tyre units were dominated by hydroids and bryozoans, the latter being numerous and growing up on all surfaces. Didemnids (*Didemnum maculosum* and *L. perforatum*) were numerous on concrete but not on tyres.

Increasing density of epifauna and flora provided greater opportunity for grazing by mobile species. For

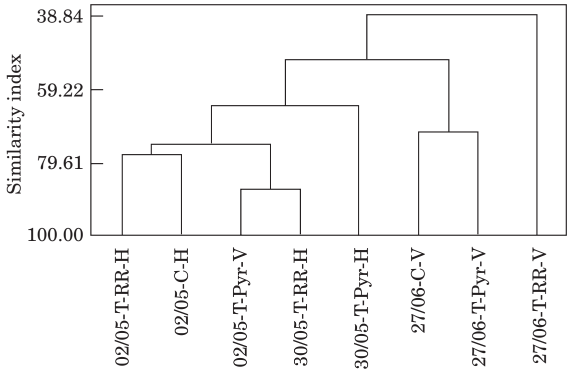

Figure 3. Similarity dendrogram based on cluster analysis of the epibiotic fauna on horizontal and vertical monitoring surfaces, sampled over three monitoring events (Codes: 2 May, 30 May, and 27 June 1999; C: concrete; T: tyre; RR: rubber rock; Pyr: tetrahedra; H: horizontal surface; V: vertical surface).

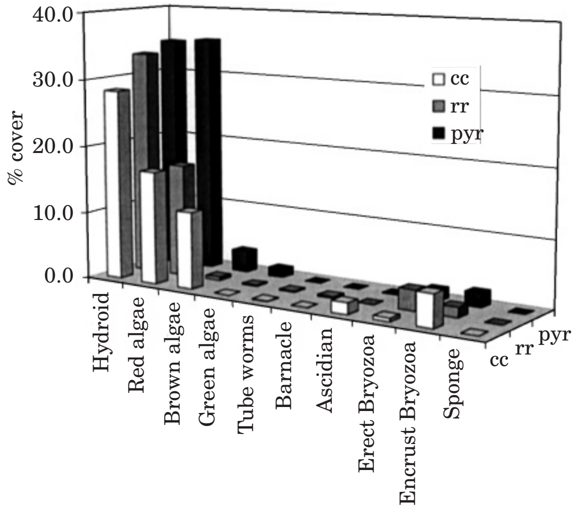

Figure 4. Percentage cover of different epibiotic groups on horizontal surfaces derived from the photographic monitoring data on 30 May 1999 (cc: concrete; rr: rubber rock, pyr: tetrahedra; hydroids, red, brown and green algae, tube worms, barnacles, ascidians, encrusted and erect bryozoans and sponges).

example, some tyre surfaces were browsed by Corkwing wrasse (*Crenilabrus melops*) and cleared from their attached barnacles.

Cluster analysis (Minitab package) was used to examine the photographic monitoring data set (May–June 1999, 10–11 months after deployment), giving a qualitative overview of the major colonization patterns (Figure 3). Vertical surfaces of the rubber rock units appeared to differ greatly from the rest of the monitoring surfaces. Overall, the differences between horizontal and vertical surfaces appeared to be larger than those between tyre and control units, because the former largely clustered into two groups.

Figure 4 shows the percentage cover of different epibiotic groups on the horizontal surfaces in May 1999, derived from the photographic monitoring data and a summary of statistical analysis is given in Table 2. All horizontal surfaces were dominated by hydroids and then red algae. By the end of May 1999, red algae had grown well, particularly on tyre units. Algae cover on horizontal surfaces of the tetrahedral units had increased sixfold. There were no significant differences ($p>0.05$) between concrete and tyre substratum for most epibiotic groups, with the exception of brown algae, which were far more developed on concrete surfaces. No significant differences were found between horizontal surfaces of rubber rock and tetrahedral units for any group. Significant differences were found between concrete units and rubber rock units for encrusted bryozoans and for erect bryozoans, both having a higher percentage cover (6 × and 2 × , respectively) on concrete units than on rubber rock units. However, no significant difference was found between concrete and tetrahedral units, suggesting a structure type effect rather than a substratum type effect. Red algae percentage cover was twice higher on tetrahedral units than on concrete units. However, no significant difference was found between concrete and rubber rock units, again supporting a structure type effect. Among the other species, the ascidian *Molgula* sp. was abundant in late May on the concrete centre of filled tyres and spreading around. Few sponges had recruited (*Scypha cifata* on tyres and *Leucoselenia complicata* on concrete).

In early June 1999, the tyre reef was covered in filamentous red and brown algae on all upper surfaces. Bryozoans (particularly *Scrupocellaria scruposa*) dominated, followed by algae and hydroids. Cover was virtually complete on both concrete and tyre surfaces. Some tyres had their top covered by masses of barnacles (*E. modestus* and *Balanius crenatus*).

By the end of June, a thick cover of algae was present on all upper surfaces. Erect bryozoans were the dominant group on vertical surfaces of concrete and tetrahedral units and encrusting bryozoans on vertical surfaces of rubber rock units. There were no significant differences ($p>0.05$) between concrete and tyre substratum except for encrusting bryozoans.

Discussion

Previous studies (Collins *et al.*, 1994) have shown that the main heavy metal to leach from tyres is zinc, as might be expected, because this element typically represents in the order of 1–2% by weight. Elevated levels of zinc were found in the hydroids (*Halecium* spp.) from tyre surfaces

Table 2. Statistical analysis (GLM – F-ratio, Tukey multiple comparison test – T-value) comparing percentage cover for the dominant epibiotic groups on different substrata (*significant at p<0.05) for (A) May and (B) June 99.

Test factors		Ascidea	Hydroida	Encr. B.	Erect B.	Red A.	Brown A.
A. 30.5.99							
GLM CC, PYR, RR $F_{2,73}$		0.82	2.04	5.90	5.89	6.22	11.30
	p	0.45	0.14	0.004*	0.004*	0.003*	<0.001*
TukeyCC/PYR	T	− 0.03	1.94	1.14	− 3.25	2.76	− 3.84
	p	1.00	0.13	0.49	0.005*	0.02*	<0.041*
CC/RR	T	− 1.23	0.04	3.43	− 2.02	− 1.28	− 3.81
	p	0.44	1.00	0.003*	0.11	0.41	<0.001
PYR/2R	T	− 1.08	− 1.48	2.19	0.71	− 3.30	− 0.43
	p	0.53	0.31	0.08	0.76	0.004*	0.90
B. 27.6.99							
GLM CC, PYR, RR $F_{2,73}$		1.56	2.66	7.57	1.05	5.76	3.78
	p	0.21	0.08	0.001*	0.35	0.004*	0.03*
TukeyCC/PYR	T	0.74	1.78	2.38	− 0.09	2.47	− 2.75
	p	0.74	0.18	0.049*	1.00	0.04*	0.02*
CC/RR	T	− 1.30	− 0.84	3.66	− 1.40	− 1.45	− 0.85
	p	0.40	0.68	0.001*	0.34	0.32	0.67
PYR/RR	T	− 1.76	− 2.18	1.37	− 1.18	− 3.28	1.44
	p	0.19	0.08	0.36	0.47	0.004*	0.32

compared to those taken from concrete. The elevated concentrations of copper and lead in *Halecium* plus cadmium detected in the bryozoans (*Bugula*) cannot readily be explained, as these elements represent minor constituents in tyres (San Miguel *et al.*, 2002).

Three patterns of reef colonization have been identified: (1) seasonal variation was characterized by red algae and hydroids on the horizontal surfaces reaching a high cover in summer and decline in winter; (2) differences between colonization on vertical and horizontal surfaces are attributed to greater illumination (supporting more algae), and higher sediment loading on the horizontal surfaces; and (3) these differences were often greater between structural types (rubber rock and pyramid) than between substrates (concrete or tyre), which may reflect different water flows around and through the structures.

In a comparison of settlement on various materials, Laufle (1982) noted preferential settlement of hydroids on tyres. Fitzhardinge and Bailey-Brock (1989) compared the growth of corals on tyres, concrete, and metal in Hawaii and observed that the latter two substrates were more effective. One problem with tyres is that they can flex during storms and thus shed rigid epifauna.

The monitoring work continues (Collins *et al.*, 2001) to investigate if there are further changes in the relative uptake of heavy metals between epibiota on tyres and concrete. Laboratory studies (Collins *et al.*, 1995) suggest that leaching occurs from the outer surface of the rubber, a few microns deep, and rates of release will decrease with exposure time.

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