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Characterization of three plastic forms: Plasticoncrete, plastimetal and plastisessiles

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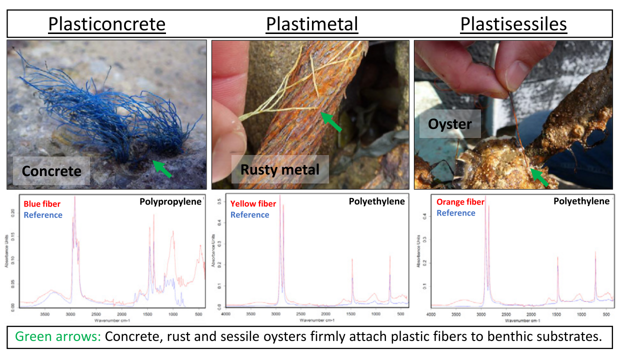
HIGHLIGHTS

- First records of plasticoncrete, plastimetal and plastisessiles worldwide
- Plasticoncrete is plastic hardened with concrete.
- Plastimetal consists of plastic rusted with metal.
- Plastisessiles are sessile invertebrates attaching plastic to benthic substrates.
- Coastal waves and onshore winds drive plasticoncrete deposition in beach sand.

GRAPHICAL ABSTRACT



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ABSTRACT

Plastic forms, including plastiglomerate, pyroplastic, plasticrusts, anthropoquinas, plastistone and plastitar, were recorded worldwide. These plastic forms derive from geochemical or geophysical interactions such as heat-induced plastic fusion with rock in campfires, incomplete plastic combustion, water motion-driven plastic abrasion in the rocky intertidal zone, plastic deposition in hardened sediments and plastic bonding with tar. Thereby, these interactions can profoundly influence the fate of plastics in the environment. This study characterized three novel plastic forms (plasticoncrete, plastimetal and plastisessiles) discovered on Helgoland island (North Sea). Plasticoncrete consisted of common polyethylene (PE) and polypropylene (PP) fibers hardened in concrete. Plastimetal included PE fibers rusted with metal. Plastisessiles consisted of PE fibers attached to benthic substrates by sessile invertebrates (oysters and polychaetes). Plasticoncrete and plastimetal are the first plastic forms composed of two man-made materials. Plastisessiles show that plastic forms not only result from human- or environment-mediated interactions but also from biological interactions between invertebrates and plastic. All plastic forms (bulk density ≥ 1.4 g/cm^3) sunk during floating tests and hardly changed their positions during a 13-day field experiment and 153- to 306-day field monitorings, indicating their local formation, limited mobility and longevity. Still, experimentally detached plastic fibers floated, confirming that the formation of these plastic forms influences the fate of plastic fibers in the environment. Furthermore, the experiment showed that plasticoncrete got deposited in beach sand under wavy and windy conditions, indicating that coastal waves and onshore winds drive plasticoncrete deposition in coastal sediments. We also provide first records of plasticoncrete on Mallorca island (Mediterranean Sea) and plastimetal on Hikoshima island (Sea of Japan), respectively, which show that these plastic forms are no local phenomena. Thereby, our study

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contributes to the growing fundamental knowledge of plastic forms that is essential to understand the role and fate of these pollutants in coastal habitats worldwide.

1. Introduction

In recent years, several plastic forms, including plastiglomerate (Corcoran et al., 2014), pyroplastic (Turner et al., 2019), plasticrusts (Gestoso et al., 2019), anthropoquinas (Fernandino et al., 2020), plastistone (Santos et al., 2022) and plastitar (Domínguez-Hernández et al., 2022), were characterized. Plastiglomerate is a solid bond (agglomerate) consisting of melted plastic attached to rock or (in)organic material (Corcoran et al., 2014). Pyroplastic is burned, melted and weathered plastic with a rock-like appearance (Turner et al., 2019). Plastiglomerate and pyroplastic have been related to (un)intentional and incomplete plastic combustion in beach campfires, debris incineration fires and ship fires (Corcoran et al., 2014; Turner et al., 2019; de Vos et al., 2022). Plasticrusts consist of plastic encrusting rocky intertidal habitats (Gestoso et al., 2019) and can derive from plastics being abraded on intertidal rocks by water motion (Ellrich et al., 2023). Beachrocks containing man-made material (García-Garmilla, 1990; Arrieta et al., 2011; Irabien et al., 2015), such as plastic (Fernandino et al., 2020), result from the hardening of coastal sediments (Danjo and Kawasaki, 2014) and were termed anthropoquinas (Fernandino et al., 2020). Plastistone is melted plastic resembling a stream of molten rock (Santos et al., 2022). Plastitar is a recent term for a plastic-containing tar matrix deposited on rocky substrate (Domínguez-Hernández et al., 2022) deriving from plastic bonding with crude oil residues (e.g., Wilber, 1987; Domínguez-Hernández et al., 2022). All these plastic forms result from human- or environment-mediated geochemical or geophysical interactions altering the properties of the plastics involved. Thereby, these interactions influence the fate of plastic in the environment. For instance, plastiglomerate has a higher bulk density than regular plastic and, therefore, higher chances of getting covered by beach sand in windy backshore habitats (Corcoran et al., 2014). Also, rock-like pyroplastic is more difficult to be detected during field surveys and beach clean-ups than regular plastic (Turner et al., 2019; de Vos et al., 2022; Furukuma et al., 2022). Furthermore, plastic forms have been reported in coastal, estuarine, freshwater and terrestrial habitats worldwide (Fig. S1) and the increasing frequency of plastic form records reported over the last 40 years from 1983 to 2023 (Fig. S2) highlights that plastic forms are a global phenomenon which has been largely overlooked for decades. Therefore, it is essential to characterize and term novel plastic forms to understand the role and effects of these pollutants in the environment and to enable the development of appropriate measures.

This study introduces three plastic forms that we recently discovered on Helgoland island (North Sea). Since these plastic forms have, to the very best of our knowledge, not been mentioned previously, we considered them novel and termed them plasticoncrete (plastic hardened in concrete), plastimetal (plastic rusted with metal), and plastisessiles (plastic attached to benthic substrates by sessile biogenic invertebrates). We (i) characterized these plastic forms using macro- and microscopic methods, (ii) verified that each of them contained plastic using Fourier-transform infrared (FTIR) spectroscopy, and (iii) confirmed their limited mobility by combining floating tests with bulk density measurements and experimentally tracking them in the field. Using plastic floating tests, we (iv) also examined whether the formation of these plastic forms influenced the floatability of the involved plastics. Furthermore, (v) since information on environmental influences on plastic forms is limited to floating plastic forms (Furukuma et al., 2022; Ellrich et al., 2023) and field experimental plastic form examinations are rare (Ellrich et al., 2023) but urgently needed to understand their fate in coastal habitats (Ellrich and Ehlers, 2022), we examined whether plasticoncrete gets deposited in coastal sediments. As plastiglomerate (bulk density: 1.5–2.4 g/cm^3) does not float (Furukuma et al., 2022) and plastiglomerate (1.7–2.8 g/cm^3) was detected covered in beach sand in backshore habitats (Corcoran et al., 2014), we tested the hypothesis that plasticoncrete (1.9–2.3 g/cm^3; see Results) can get deposited in beach sand. For that, we conducted an intertidal field experiment on Helgoland island under different environmental conditions (calm versus wavy/windy). Additionally, we (vi) provided first records of plasticoncrete in terrestrial habitats on Mallorca island (Mediterranean Sea) and (vii) first records of plastimetal in intertidal habitats on Hikoshima island (Sea of Japan). Finally, since an umbrella term for plastic forms is missing, we (viii) proposed plastic forms as umbrella term.

2. Material and methods

2.1. Surveyed boulder fields on Helgoland island, North Sea

For our study, we surveyed three rocky intertidal boulder fields located along the Nordostmole, Augustamole and Ostkaje breakwaters on Helgoland island, German Bight, North Sea (hereafter: Helgoland) for plastic forms (Fig. S3) in winter and summer 2022 (Table S1). The Nordostmole and Augustamole boulder fields are moderately wave-exposed (Jungblut et al., 2017), whereas the Ostkaje boulder field is located in the wave-sheltered Helgoland harbor basin (Fig. S4). All boulder fields derive from post-World War 2 bulk fills (KFKI, 1990) and contain reinforced concrete fragments of destroyed harbor, coastal and bunker fortifications, broken concrete tetrapods, rusty metal beams and rods, granite boulders, bricks, cobbles, pebbles and sand (Fig. S5). All boulder fields are covered by seaweed canopies (*Fucus serratus* at Nordostmole and Augustamole in contrast to *Ascophyllum nodosum* at Ostkaje owing to the different wave exposure regimes of these locations; Reichert et al., 2008) and plastic fibers are common (O'Hanlon et al., 2019; Fig. S6). We focussed on these three boulder fields because access to other boulder fields on the northern and western Helgoland coast (Bartsch and Tittley, 2004) is currently blocked by a large rocky debris heap and a wide construction site, respectively (Fig. S7). On Helgoland, harbor and coastal fortifications were first installed in 1908 (KFKI, 1990) and were maintained over the years (WSV, 2023) with the latest comprehensive harbor repair conducted from 2012 to 2021 (HGH, 2021). Furthermore, there are several ongoing coastal clean-ups (Eggers, 2023a; Eggers, 2023b) and construction projects across the island (Helgoland, 2022; Fig. S3). Sessile benthic invertebrates, such as introduced Pacific oysters (*Magallana gigas,* formerly *Crassostrea gigas*) and native tube-building polychaetes (*Spirobranchus triqueter*, formerly *Pomatoceros triqueter*), are common around Helgoland with highest oyster densities in wave-sheltered intertidal habitats (Reichert et al., 2013; Zwerschke et al., 2013; Teschke et al., 2020) and highest polychaete densities in low intertidal and subtidal habitats (Klöckner, 1976; Gillandt, 1979; Michaelis et al., 2019; Becker et al., 2020).

2.2. Field surveys

In each boulder field, we surveyed four parallel transects along the respective breakwater ($n = 12$ transects in total). These transects were located in the supra, high, mid and low intertidal zones (Fig. S4). Transect length was 64 m at Nordostmole, 25 m at Augustamole and 72 m at Ostkaje. Transect width was 1 m. We surveyed each transect twice (Table S1). Thus, 1288 m^2 were surveyed. We performed all surveys under calm and mostly dry conditions by thoroughly examining the entire top layer of each transect for plastic forms (Ellrich and Ehlers, 2022). Additionally, we measured Pacific oyster abundance (oysters / dm^2) and estimated plastic fiber abundance (plastic fiber balls / m^2) along each mid intertidal transect on 5 March 2022. For that, we counted all oysters in 30 random quadrats (20 cm × 20 cm) per transect (Teschke et al., 2020) and all plastic fiber balls per transect (Furukuma et al., 2022).

2.3. Macro-, micro- and spectroscopic examinations

At the lab, we carefully rinsed our samples in tap water, let them dry at room temperature for 6 h and documented them using a digital camera. We measured maximum length (x-axis: the longest axis), maximum height (y-axis: the thickest section of the axis perpendicular to the x-axis) and maximum width (z-axis: the thickest section of the axis perpendicular to the x- and y-axes) of each sample using a folding ruler. We measured the weight of each sample with a balance (EW 6200-2NM, Kern, Balingen, Germany for samples <3 kg; Digital Body Scale, Grundig, Kleve, Germany for samples ≥3 kg). We measured the maximum length of the shortest and the longest plastic fiber contained in each sample using a ruler. Concerning the plastisessiles, we additionally measured the length (x-axis: from the hinge to the narrowest edge), width (y-axis: the axis perpendicular to the x-axis at its widest section) and height (z-axis: the axis perpendicular to the y-axis at its thickest section) of each Pacific oyster (Fig. 3A-D) using digital callipers (Digi-Met, Helios Preisser, Gammertingen, Germany). We also measured the length of the polychaete tube (Fig. 3E, F) using a cotton string and a ruler and its width using the callipers. We identified the sessile invertebrates using a field guide (Hayward and Ryland, 2017). To examine plastic form floatability, we performed plastic form floating tests by putting each sample in a seawater (salinity: 30.6 ppt) filled plastic box. Objects with a higher density than seawater (1.03 g/cm^3) sink. When a sample sunk, we measured its volume by putting the sample in a tap water filled plastic box to calculate its bulk density (g/cm^3; Furukuma et al., 2022).

For plastic floating tests, microscopic and spectroscopic analyses, we cut small plastic pieces (i.e., fibers or chips) out of each sample using a scalpel. We performed the plastic floating tests just like the aforementioned plastic form floating tests. We measured the thickness of 16 fibers under a digital microscope (VHX-2000, Keyence, Osaka, Japan) at 20× to 200× magnification (Ehlers et al., 2021) by taking three thickness measurements randomly along each fiber and calculating the average (± SD) thickness of each fiber. For that we used eight fibers from the plasticoncretes and eight plastic fibers from the plastisessiles (i.e., seven fibers from the oysters and one fiber from the polychaete; see Results). All fibers, except the polychaete fiber (Fig. 3G, H), were picked at random. Regarding some very large plasticoncretes and plastimetals, we took pictures in the field, measured their dimensions (where possible) and collected plastic samples as described above. Additionally, we collected fibers, that we frequently detected entangling seaweeds and rusty metal rods around Helgoland, for floating tests and spectroscopic analyses and counted the number of fiber-entangled rusty metal rods.

To identify the polymer types of the examined plastics, we used a Fourier-transform infrared (FTIR) spectroscope (Vertex 70, Bruker, Ettlingen, Germany). We performed all FTIR measurements in attenuated total reflectance (ATR) mode using a wavenumber range between 4000 and 370 cm^{-1} with eight co-added scans and a spectral resolution of 4 cm^{-1} (Ehlers et al., 2021). For polymer identification, we compared the obtained FTIR spectra with the Bruker spectral library using Opus 8.5 software (Bruker, Ettlingen, Germany). In total, we conducted 65 FTIR measurements on plasticoncrete (n = 23 plastic samples), plastimetal (n = 5), plastisessiles (n = 7), fibers from seaweeds (n = 12) and rusty metal rods (n = 13) collected on Helgoland as well as plasticoncrete (n = 3) collected on Mallorca island (Section 2.6) and plastimetal (n = 2) collected on Hikoshima island (Section 2.7).

2.4. Plasticoncrete field experiment and monitoring of environmental conditions

To examine whether plasticoncrete can get deposited in beach sand, we placed seven plasticoncretes (plasticoncretes$_{1-4,\ 6-8}$) on a mid intertidal sand patch in the Nordostmole boulder field on 9 January 2022 and monitored plasticoncrete burial depth relative to the patch surface using a folding ruler on 15 and 22 January 2022. We then removed all plasticoncretes from the field and stored them at the lab since heavy winter storms were predicted for the following weeks (DWD, 2022a).

To study environmental influences on plasticoncrete deposition depth, we monitored environmental conditions using wave height data recorded half-hourly by a buoy off Helgoland (Helgoland North: 54.219100, 7.818483; BSH, 2022), local tidal amplitude information provided twice a day (Helgoland: 54.183000, 7.883000; Tide and Current Predictor, 2022) and wind direction, wind speed and precipitation data recorded hourly by the local weather station (Helgoland: 54.170000, 7.890000; DWD, 2022b) during two consecutive periods: 9–15 January 2022 (period 1) and 15–22 January 2022 (period 2). We focused on onshore winds blowing across the open North Sea from 290° to 330° (Jungblut et al., 2017) because the Nordostmole boulder field is protected from winds blowing from other directions by the Nordostmole breakwater, the island and the Nordmole breakwater (Fig. S3). We analyzed this environmental data by calculating wave height ranges, average (± SE) tidal amplitudes, onshore wind durations, average (± SE) onshore wind speeds and average (± SE) precipitation per day for periods 1 and 2.

2.5. Plastic form experimental monitoring, collection, maintenance and preservation

To monitor whether plastimetals and plastisessiles remain in the same positions, we left three plastimetals (plastimetals$_{1,3,5}$) and nine plastisessiles (plastisessiles$_{1-9}$) in the Ostkaje boulder field over 153 days from 6 February 2022 to 9 July 2022 and recorded their positions on both dates. During that period, we checked the plastimetals and plastisessiles weekly. Subsequently, we maintained the plastisessiles in an outdoor tank with seawater flowthrough until their examination (Section 2.3) and preservation at −18 °C. We also tracked one plasticoncrete (plasticoncrete$_9$), that was too large to be collected (i.e., 180 cm × 140 cm × 60 cm, L × W × H), in a wave-sheltered spot in the Nordostmole mid intertidal zone over 306 days from 10 July 2022 to 12 May 2023.

2.6. Plasticoncrete field surveys in terrestrial habitats on Mallorca island, Mediterranean Sea

To examine whether plasticoncrete also occurs in terrestrial habitats, we surveyed supra intertidal habitats on Mallorca, Balearic Islands, Mediterranean Sea. We did that since we detected one plasticoncrete in a supra intertidal quay wall in Portocolomb on 12 February 2023 by chance. For our examinations, we surveyed one supra intertidal transect (length: 60 m, width: 1 m) in Portocolomb (39.425839, 3.263814) on the same day and another one (length: 575 m, width: 1 m) in Cala Rajada (39.707667, 3.460100) on 18 February 2023 as described in Section 2.2. Thus, 635 m^2 were surveyed. We took pictures of the detected plasticoncretes using a digital camera, collected plasticoncrete samples (i.e., plastic fibers and fragments) in padded bags for transportation to the lab in Koblenz, Germany (Furukuma et al., 2022) and examined them spectroscopically as explained in Section 2.3.

2.7. Plastimetal field surveys in intertidal habitats on Hikoshima island, Sea of Japan

Finally, to investigate plastimetal occurrence on other coasts, we surveyed rocky intertidal habitats along the Sea of Japan coastline in Nishiyama-cho (33.942389, 130.880528), Hikoshima island, Shimonoseki City, Yamaguchi Prefecture, Honshu, Japan. For that, we searched 8360 m^2 of coastline on 25 March 2023 for plastimetals, took pictures of all detected plastimetals, examined them macroscopically as explained in Section 2.3, collected plastic fiber samples from each plastimetal and mailed them to Koblenz for spectroscopic analysis.

3. Results

3.1. Plasticoncrete, plastimetal and plastisessile examinations, floating test results and fiber examinations on Helgoland

On Helgoland, we detected 13 plasticoncretes$_{1-13}$ (Fig. 1), five plastimetals$_{1-5}$ (Fig. 2), ten plastisessiles$_{1-10}$ (Fig. 3), numerous plastic

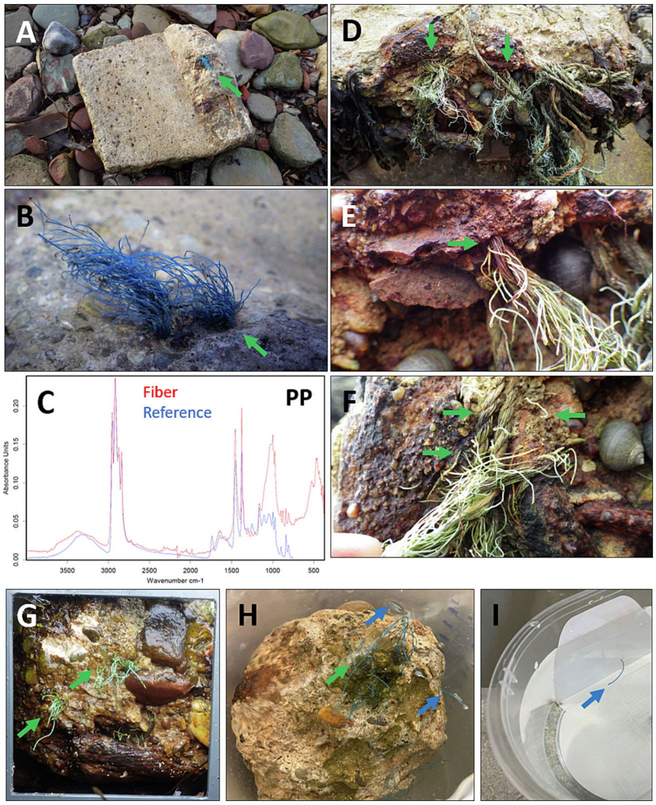

Fig. 1. Plasticoncretes on Helgoland. A) Plasticoncrete$_1$ at Nordostmole. B) Close-up of the blue plasticoncrete$_1$ fibers. C) The blue plasticoncrete$_1$ fibers consisted of polypropylene (PP). The measured PP spectrum is depicted in red and the reference spectrum from the Bruker database is depicted in blue. D—F) Yellow plasticoncrete$_9$ polyethylene (PE) ropes and fibers at Nordostmole. G) The green PE fibers of plasticoncrete$_{12}$ at Augustamole. The size of the gray quadrat is 10 cm × 10 cm. H) Sunken plasticoncrete$_8$ during the bulk density measurement. The contained blue PE fibers floated in tap water. I) Floating blue PP fiber detached from plasticoncrete$_1$ during the floating test in seawater. The green arrows point at plastic ropes and fibers contained in concrete and the blue arrows point at floating plastic fibers.

fibers entangling seaweeds (Fig. S6) and 26 rusty metal rods entangled in plastic fibers (Fig. S8).

Plasticoncretes$_{2–12}$ consisted of concrete containing polyethylene (PE) fibers. Plasticoncretes$_{1,13}$ consisted of concrete and polypropylene (PP) fibers (Fig. 1A-C). Plasticoncrete length, weight and bulk density ranges were 11.5 to 55.5 cm, 0.46 to 21.65 kg and 1.9 to 2.3 g/cm^3. The weight and bulk density of the two largest plasticoncretes (plasticoncrete$_5$: 300 cm × 280 cm × 90 cm; L × W × H; plasticoncrete$_9$: 180 cm × 140 cm × 60 cm) could not be determined.

Plastimetals$_{1,2,3,5}$ consisted of metal rods rusted together with PE fibers (Fig. 2). Plastimetal$_4$ was a metal beam rusted with a PE fragment (Fig. S9). Plastimetal length, weight and bulk density ranges were 15.3 to 77.5 cm, 0.11 to 0.92 kg and 1.4 to 5.6 g/cm^3. Plastimetals$_{2,4}$ protruded from reinforced concrete blocks. Therefore, their weights and bulk densities could not be measured.

Plastisessiles$_{1–9}$ were introduced Pacific oysters (*Magallana gigas*) attaching PE ropes and fibers to metal, rock, concrete and conspecifics (Fig. 3A-F). Plastisessiles$_{1–5}$ consisted of five single oysters that attached blue, green and orange PE fibers to a metal rod (120 cm × 3 cm × 3 cm). Another 23 oysters were attached to that rod and tightly entangled in PE rope and fibers of the same colors. Total weight and bulk density were 3.43 kg and 2.8 g/cm^3. Plastisessiles$_{6\ \&\ 7}$ were single oysters attaching green and orange PE fibers to rock and concrete, respectively. In the single oysters, shell length ranged from 4.6 to 9.5 cm, shell width from 2.7 to 6.7 cm and shell height from 1.9 to 4.0 cm. Plastisessile$_6$ bulk density was

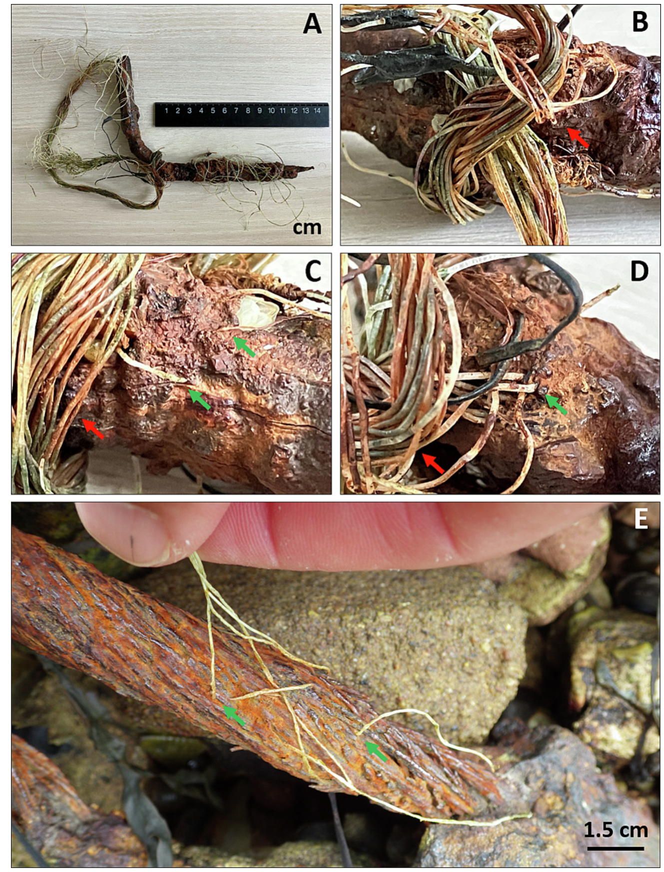

Fig. 2. Plastimetals on Helgoland. A) Plastimetal$_1$ (from Nordostmole) overview. B—D) Plastimetal$_1$ close-ups. The red arrows point at polyethylene (PE) fibers entangling the rusty metal rod and the green arrows point at PE fibers rusted together with the rod. E) Plastimetal$_3$ at Augustamole.

1.6 g/cm^3. Plastisessiles$_{8\ \&\ 9}$ were an oyster clump (8.5 cm × 8 cm × 5 cm) composed of two oysters that included orange PE rope and fibers. Plastisessile$_{10}$ was the calcareous tube of a native polychaete (*Spirobranchus triqueter*) attaching a white PE fiber to concrete (Fig. 3G, H, S10D). Plastisessile$_{10}$ length, weight and bulk density were 7.3 cm, 0.06 kg and 1.4 g/cm^3. The polychaete tube length was 5.1 cm and its average (± SD) diameter was 0.28 ± 0.12 cm (n = 3 thickness measurements taken at random along the tube).

All plastic forms sunk during floating tests (Fig. 1H, Table S2) whereas all plastics detached from the plastic forms floated (Fig. 1I, Table S2). All plastic fibers collected from seaweeds and rusty metal rods around Helgoland consisted of PE or PP (Fig. S6, S8) and floated in seawater (Table S2). Plastic fiber length ranged from 0.2 to 25 cm in plasticoncrete, from 0.5 to 25 cm in plastimetal and from 0.5 to 20 cm in plastisessiles (Table S2). Average plastic fiber diameter (± SD) ranged from 278 ± 4 to 593 ± 15 μm in plasticoncrete and from 266 ± 19 to 479 ± 16 μm in plastisessiles (Table S4).

Further details on plastic form height, width, volume, bulk density as well as the shape, length, color and polymer type of the contained plastics are provided in Table S2. Pacific oyster shell lengths, widths and heights are contained in Table S3. Plastic fiber diameters are summarized in Table S4.

3.2. Pacific oyster and plastic fiber ball abundance

Average (± SE) Pacific oyster abundance was 0.01 ± 0.01 oysters/dm^2 at Nordostmole, 0.03 ± 0.01 oysters/dm^2 at Augustamole and 0.38 ± 0.08 oysters/dm^2 at Ostkaje (Table S5). Average plastic fiber ball abundance was 0.39 fiber balls/m^2 (n = 25 fiber balls) at Nordostmole, 0.44 fiber balls/m^2

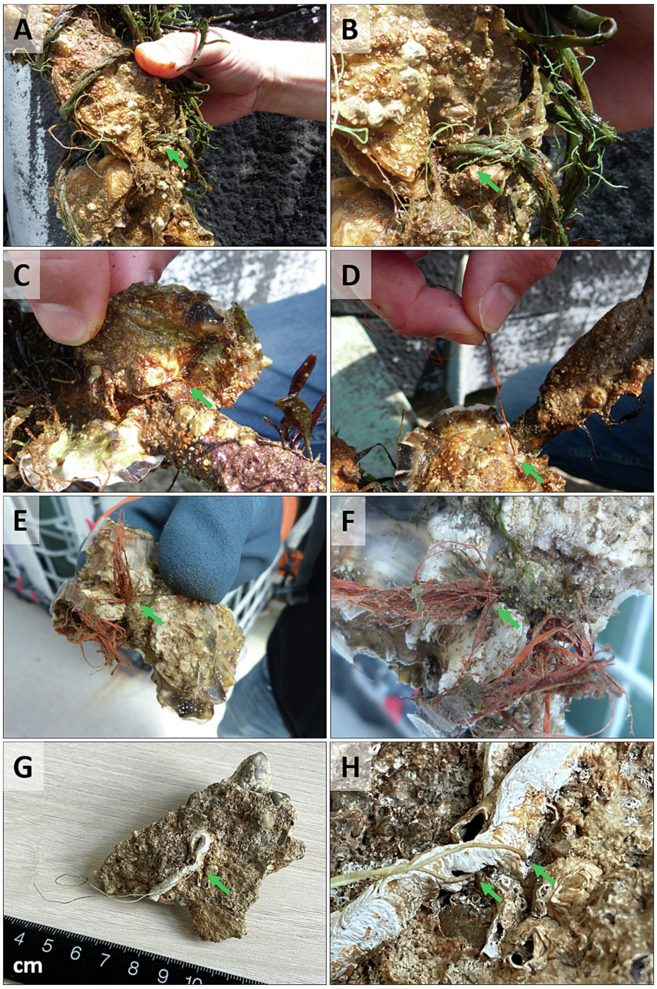

Fig. 3. Plastisessiles on Helgoland. A, B) Pacific oysters (*M. gigas*) entangled in green polyethylene (PE) ropes and fibers. C - F) Pacific oysters firmly attaching orange PE fibers. G, H) The calcareous tube of the polychaete (*S. triqueter*) attaching a white PE fiber to concrete. The green arrows point at firmly attached PE ropes and fibers.

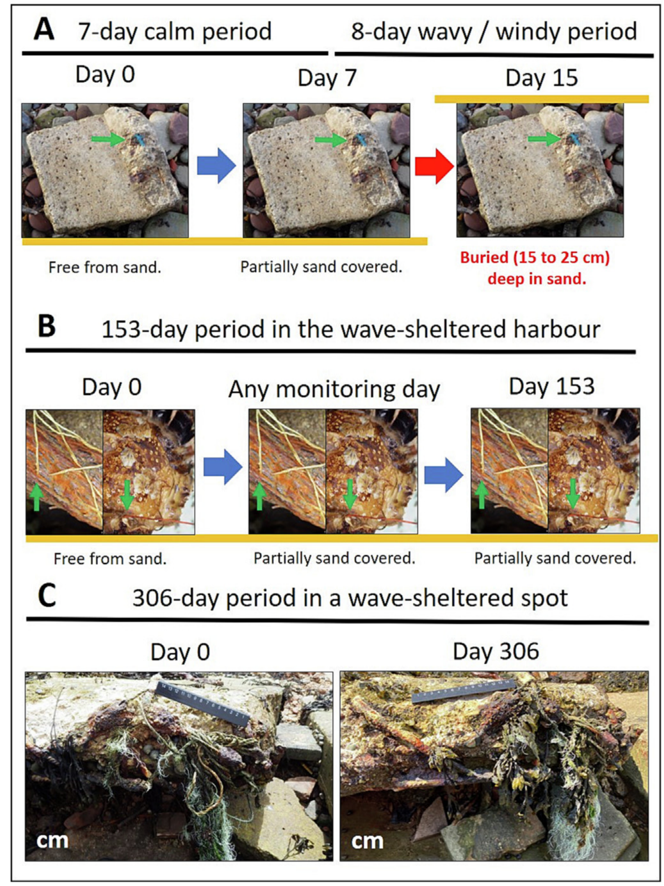

Fig. 4. Summary of the plasticoncrete field experiment and the plastimetal, plastisessile and plasticoncrete field monitorings on Helgoland. A) Plasticoncretes were located on the beach surface after the 7-day calm period and buried 15 to 25 cm deep in beach sand at the end of the consecutive 8-day wavy and windy period. B) Plastimetals and plastisessiles hardly changed their positions and were only partially covered by beach sand during the 153-day long monitoring in the wave-sheltered Ostkaje boulder field in the Helgoland harbor basin. C) The large plasticoncrete$_9$ in the wave-sheltered spot of the Nordostmole boulder field. The green arrows point at plastic fibers contained in the plasticoncrete, plastimetal and plastisessiles.

(n = 19) at Augustamole, and 0.43 fiber balls/m^2 (n = 31) at Ostkaje. Thus, Pacific oyster abundance decreased with wave exposure (which matched with earlier findings on Helgoland; Reichert et al., 2013; Zwerschke et al., 2013; Teschke et al., 2020), whereas plastic fiber abundance was unrelated to wave exposure.

3.3. Plasticoncrete field experiment and environmental conditions during the experiment

During and after the field experiment in the wave-exposed Nordostmole boulder field, all seven plasticoncretes$_{1–4,\ 6–8}$ were recovered approximately where we had put them at the beginning of the experiment in the mid intertidal zone. All plasticoncretes were located on the beach surface partially covered by sand at the end of period 1, whereas all of them were deposited below the beach surface fully covered by a 15 to 25 cm thick wet sand layer at the end of period 2 (Fig. 4A).

Wave height ranged between 0.2 and 1.3 m during period 1 and between 0.4 and 2.7 m during period 2. Wave heights >1.3 m occurred for 65.5 h (41 % of the time) during period 2. Wave height peaked during period 2 on 20 January 2022 (Fig. S11). Average (± SE) tidal amplitude was 2.20 ± 0.05 m during period 1 and 2.26 ± 0.03 m during period 2. Onshore winds occurred for 34 h (23 % of the time) during period 1 and for 75 h (47 % of the time) during period 2. Average (± SE) onshore wind speed was 4.5 ± 0.3 m/s (range: 1.9–9.1 m/s; light to fresh breeze) during period 1 and 9.5 ± 0.4 m/s (range: 3.3–16.4 m/s; light breeze to strong wind) during period 2. Onshore wind speed also peaked during period 2 on 20 January 2022. Average (± SE) precipitation per day ranged between mostly no rain and occasional light rain (2.08 ± 0.64 mm/h) during period 1 and mostly no rain and rare light rain (0.79 ± 0.39 mm/h) during period 2. Heavy rain was restricted to 4 h during period 1 (range: 9–19 mm/h) and 1 h during period 2 (9 mm/h). Thus, period 2 was clearly wavier and windier than period 1 and both periods were similar in tidal amplitude and precipitation.

3.4. Plastimetal, plastisessile and plasticoncrete field monitorings

In the wave-sheltered Ostkaje boulder field, all plastimetals$_{1,3,5}$ and plastisessiles$_{1–9}$ were monitored over 153 days and recovered where we had put them at the beginning of the monitoring. Occasionally, some were covered by the seaweed (*Ascophyllum nodosum*) canopy but all of them were hardly covered with sand (Fig. 4B). The large plasticoncrete$_9$ tracked in the wave-sheltered spot in the Nordostmole boulder field did not move and did not show any apparent changes after 306 days (Fig. 4C).

3.5. Plasticoncrete occurrence in terrestrial habitats on Mallorca, Mediterranean Sea

We detected three plasticoncretes$_{14–16}$ in supra intertidal habitats on Mallorca island. Plasticoncrete$_{14}$ was a green PE rope contained in a

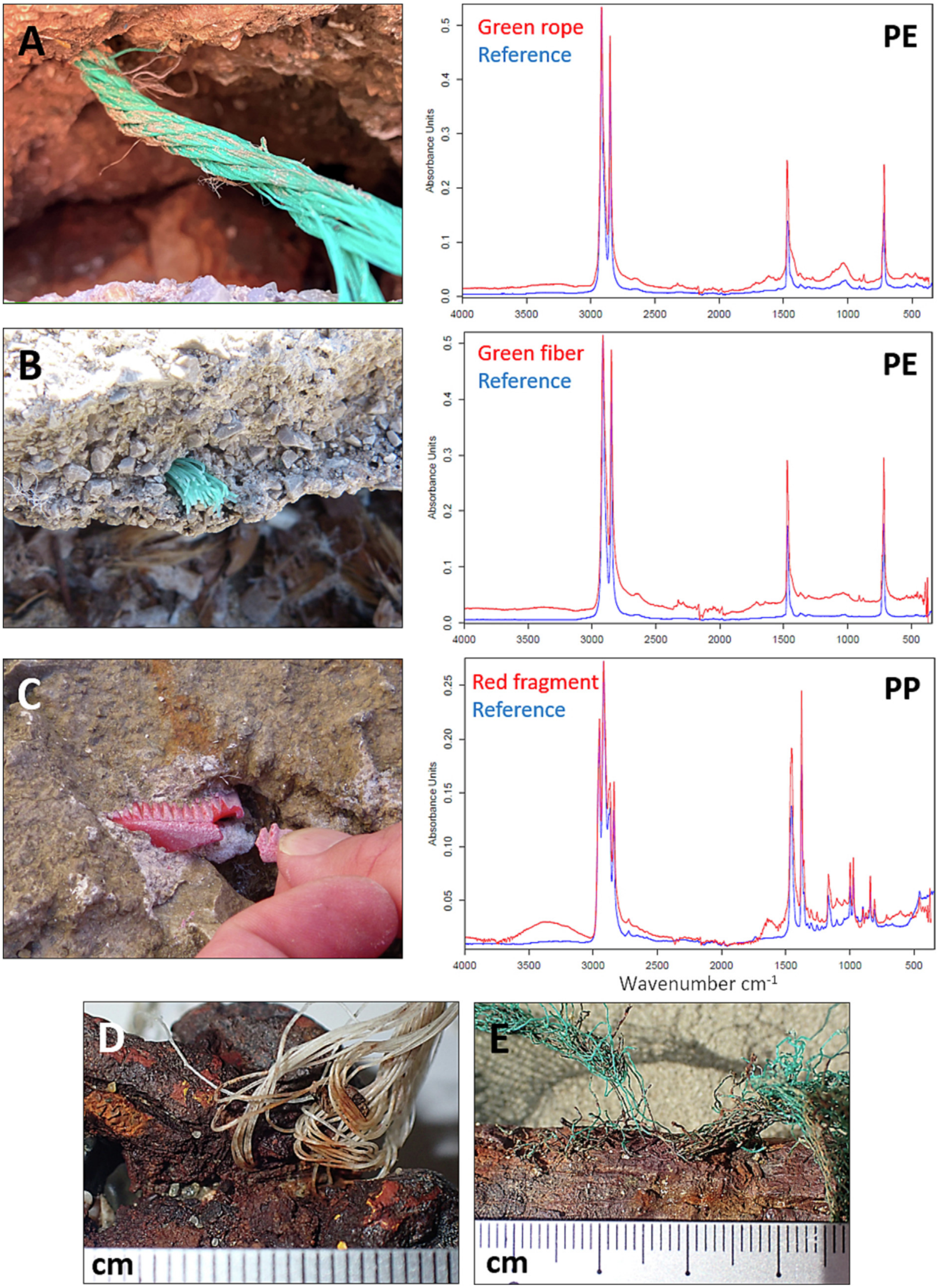

Fig. 5. Plasticoncretes in terrestrial habitats on Mallorca and plastimetals in intertidal habitats on Hikoshima. A) Green polyethylene (PE) rope contained in a concrete quay wall at Portocolomb. B) Green PE fibers contained in a concrete terrace at Cala Rajada. C) Red polypropylene (PP) fragment contained in concrete stairs at Cala Rajada. The measured plastic spectra are depicted in red and the reference spectra from the Bruker data base are depicted in blue. D) White PE fibers contained in a rusted metal clump on Hikoshima. E) Green PE mesh rusted with a metal rod on Hikoshima.

concrete quay wall in Portocolom (39.425925, 3.263888; Fig. 5A), plasticoncrete$_{15}$ consisted of green PE fibers enclosed in a concrete terrace in Cala Rajada (39.706306, 3.458558; Fig. 5B) and plasticoncrete$_{16}$ was a concrete staircase in Cala Rajada containing red PP fragments (39.707666, 3.460412; Fig. 5C).

3.6. Plastimetal occurrence in intertidal habitats on Hikoshima, Sea of Japan

We found two plastimetals$_{6\ \&\ 7}$ in the rocky Nishiyama-cho mid intertidal zone on Hikoshima island. Plastimetal$_6$ consisted of white PE fishing line entangling a metal clump and being encrusted in rust (Fig. 5D). Plastimetal$_7$ was a metal rod entangled in and rusted together with green PE fishing net (Fig. 5E). Further details on plastimetals$_{6\ \&\ 7}$ are summarized in Table S2.

4. Discussion

4.1. Plasticoncrete, plastimetal and plastisessiles differ from previously reported plastic forms

Our study provides the first records and characterizations of plasticoncrete (plastic hardened in concrete), plastimetal (plastic rusted with metal) and plastisessiles (plastic attached to benthic substrates by sessile invertebrates) worldwide. These plastic forms did not consist of the same components as plastiglomerate (plastic, rock, inorganic and/or organic materials; Corcoran et al., 2014), pyroplastic (plastic, Turner et al., 2019), plasticrusts (plastic, intertidal rock; Gestoso et al., 2019), anthropoquinas (plastic, beachrock; Fernandino et al., 2020), plastistone (plastic; Santos et al., 2022) and plastitar (plastic, tar / crude oil; Gregory, 1983; Wilber, 1987; Turner and Holmes, 2011; Domínguez-Hernández et al., 2022). They also did not show any signs of plastic melting (as in plastiglomerate, pyroplastic and plastistone; Corcoran et al., 2014; Turner et al., 2019; Ehlers and Ellrich, 2020; De-la-Torre et al., 2022; Furukuma et al., 2022; Santos et al., 2022; Rakib et al., 2023), plastic abrasion (as in plasticrusts; Gestoso et al., 2019; Ehlers and Ellrich, 2020; Ehlers et al., 2021; Ellrich et al., 2023) or plastic interactions with beachrock (as in anthropoquinas; Fernandino et al., 2020) or tar (as in plastitar; Gregory, 1983; Wilber, 1987; Turner and Holmes, 2011; Domínguez-Hernández et al., 2022). Plasticoncrete and plastimetal are the first plastic forms that each consists of two man-made materials (plastic and concrete, plastic and metal) whereas all previously reported plastic forms contained only plastic as artificial component. These findings also indicate that plasticoncrete and plastimetal must form geochemically through cement hydration and metal corrosion, respectively. Furthermore, plastisessiles indicate, for the first time, that plastic forms derive not only from geochemical and geophysical processes but also from biological interactions between plastic particles and sessile invertebrates. These comparisons unequivocally differentiate plasticoncrete, plastimetal and plastisessiles from all previously characterized plastic forms and from each other. In addition, the terms plasticoncrete, plastimetal and plastisessiles correspond with most previously introduced plastic form terms (i.e., plastiglomerate, plasticrust, plastistone, plastitar) and most proposed terms for predicted plastic forms (e.g., plasticoal; Rangel-Buitrago et al., 2022). Thereby, these terms clearly associate plasticoncrete, plastimetal and plastisessiles with plastic forms and follow the call for a unified plastic vocabulary to help facilitating the communication among scientists, resource managers, policy-makers and the public (Haram et al., 2020).

4.2. Plasticoncrete, plastimetal and plastisessiles influence the fate of plastic fibers in the environment

Polyethylene (PE) and polypropylene (PP) fibers typically float in seawater, due to their relatively low polymer density (PE: 0.9–1.0 g/cm^3; PP: 0.8–0.9 g/cm^3; Li et al., 2018), as confirmed by our plastic fiber floating tests (Section 3.1, Fig. 1I). Yet, our plastic form bulk density measurements and plastic form floating tests showed that all plasticoncretes, plastimetals and plastisessiles (bulk density: 1.35–5.56 g/cm^3) containing PE and PP fibers did not float in seawater (Section 3.1, Fig. 1H). We also found that all examined plasticoncretes, plastimetals and plastisessiles hardly changed their positions during the 13-day field experiment in the wave-exposed Nordostmole boulder field, the 153-day monitoring in the wave-sheltered Ostkaje boulder field and the 306-day monitoring in the wave-sheltered spot in the Nordostmole boulder field (Section 3.4). Thereby, our study clearly shows that plasticoncrete, plastimetal and plastisessile formation counteracts PE and PP fiber floatability, which constitutes a key property of these plastic fibers, and thereby influences the fate of these common plastics (Ostle et al., 2019; Int-Veen et al., 2021), that can derive from building material, maritime, fishery, aquaculture and restoration equipment (Szulc et al., 2015; Welden and Cowie, 2017; Comba et al., 2022; Walters et al., 2022; Wootton et al., 2022; Zhao et al., 2022), in coastal environments.

4.3. Plasticoncrete, plastimetal and plastisessiles derive from local and recent interactions

Due to their relatively high bulk density ($\geq$1.35 g/cm^3), plasticoncrete, plastimetal and plastisessiles sunk during the plastic form floating tests (Section 3.1, Fig. 1H) which indicated their limited mobility. Since Helgoland is located $\geq$48.5 km off the German North Sea coast, these results also reveal that all these plastic forms must have formed locally. Moreover, the fact that we made all findings in the top layer of the surveyed boulder fields suggests that all these plastic forms were formed recently.

Concrete is among the main building materials on Helgoland (Public Announcement Germany, 2018) which recommends that the plasticoncretes stem from ongoing harbor repair, coastal fortification or community construction measures (HGH, 2021; Helgoland, 2022). There are several construction sites (Fig. S3, S12A-C) and construction waste holders containing concrete and rusty metal remains across the island (Fig. S3, S12D-F). Based on these observations, we conclude that the detected plasticoncretes were formed during hydration-driven concrete preparation by (un)intentionally mixing cement, aggregates such as pebbles, water and plastic (Fig. 1) at local construction sites and that these plasticoncretes were later improperly disposed in the nearby boulder fields. These conclusions are corroborated by the facts that most plasticoncretes (84.6 %) were small (length: 18–55 cm), had a low weight (3–21.7 kg) and were, thus, transportable. Further support for these conclusions is provided by the fact that non-floating debris, which clearly resulted from building materials (Fig. S13), occurred in the Nordostmole boulder field. Interestingly, plastics have intentionally been used as spacers in concrete tetrapods for coastal protection on Helgoland (Fig. S14), concrete aggregates in building materials (Saikia and de Brito, 2012; Li et al., 2020), concrete fillers in construction (Pradeep et al., 2022; Rangel-Buitrago et al., 2023) and even potentially sustainable building materials (Mansour Habib Mansour and Ali, 2015; Lu et al., 2023). However, the variety of the plasticoncrete shapes (Fig. 1, 5A-C), the fact that plastic fibers cannot function as spacers, and the low plastic fiber to pebble aggregate ratio (Fig. 1G, H) support the notion that the detected plasticoncretes were created unintentionally which clearly differentiates them from intentionally created concrete building materials and constructions containing plastic. Overall, the proposed geochemical plasticoncrete formation process, that the plasticoncrete was formed during hydration-driven concrete preparation at construction sites on Helgoland, suggests that plasticoncrete can also occur in human-shaped terrestrial habitats including constructions, construction sites and construction waste holders. This conclusion is corroborated by our recent field observations on Mallorca island which detected plastic ropes, fibers and fragments firmly cemented into several coastal constructions including supra intertidal concrete quay walls, trails, terraces and stairs (Fig. 5A-C).

Historically, reinforced concrete (i.e., concrete containing steel; Gagg, 2014) and steel have been the main harbor, coastal and bunker fortification materials on Helgoland (KFKI, 1990) and enormous amounts of concrete and steel debris, which resulted from the total destruction of Helgoland in World War 2 (KFKI, 1990; Reuters, 2011), were used as bulk fills for harbor and coastal fortification measures during the post-war years to protect the island from storm surges (KFKI, 1990). Many of these bulk fills are still present (Fig. S5), concrete and rusty metal debris are common around the island (Fig. S5, S7A, S8, S12) and both materials can persist in marine environments for hundreds of years (Gagg, 2014; Moore III, 2015). Plastic entanglement is a widely documented phenomenon in mobile organisms (Laist, 1997; Gregory, 2009) and plastic fibers entangling seaweeds, that likely derive from water motion driven plastic-seaweed interactions (Cozzolino et al., 2020; Li et al., 2022), frequently occurred around Helgoland (Section 3.2; Fig. S6). Together, these historical facts and recent field observations suggest that plastimetal is formed by plastic rusting with metal in rocky intertidal boulder fields (Fig. 2) and that plastic fiber entanglement enhances this geochemical corrosion-driven plastimetal formation process since we detected 26 rusty metal rods entangled in plastic fibers (Fig. S8) and five plastimetals containing entangled and rusted plastic fibers (Fig. 2) but only one plastimetal containing a rusted plastic fragment (Fig. S9). Additionally, our recent plastimetal records on Hikoshima island confirmed that plastimetal resulting from plastic fiber entanglement occurs on that coast as well (Fig. 5D) and indicated that plastimetal can also result from metal being entangled by plastic mesh (Fig. 5E).

Plastisessiles must form by mobile invertebrate larvae settling on plastic or sessile invertebrates overgrowing plastic. Introduced Pacific oysters (*Magallana gigas*) were first recorded on Helgoland in spring 2003 (Franke and Gutow, 2004) and have been documented around the island since then (Reichert et al., 2013; Zwerschke et al., 2013; Teschke et al., 2020; this study). Native polychaetes (*Spirobranchus triqueter*) occur around Helgoland (Klöckner, 1976; Gillandt, 1979; Reichert and Buchholz, 2006; Zwerschke et al., 2013; Michaelis et al., 2019; Becker et al., 2020). Mobile Pacific oyster larvae settle to hard substrate by geochemically cementing themselves to rock, concrete, metal, plastic, mollusc or conspecific shells and metamorphosing to sessile oysters (Coon et al., 1990; Tamburri et al., 2007; Troost, 2010; Reichert et al., 2013; Hingant et al., 2023). Similarly, mobile polychaete larvae settle to such substrates and metamorphose to benthic polychaetes that secrete calcifying tubes which then remain permanently attached to the underlying substrate (Segrove, 1941; Klöckner, 1976; Turner et al., 2019; Michaelis et al., 2019; Becker et al., 2020). Settling oysters and polychaetes are tiny (*M. gigas*: 320 to 350 μm shell length, Coon et al., 1990; Miossec et al., 2009; *S. triqueter*: 300 μm tube length, Segrove, 1941) and, therefore, cannot attach plastic fibers (266 to 479 μm in diameter, 0.5 to 20 cm in length; Section 3.1) to benthic substrate by settling on them. However, young oysters and polychaetes have high growth rates (*M. gigas*: 6.3 mm shell length increase in six weeks, Pogoda et al., 2011; *S. triqueter*: 1.8 mm tube length increase in six weeks, Klöckner, 1976) which indicates that plastisessiles are formed by plastic fibers being overgrown by sessile invertebrates. Furthermore, Pacific oysters have complex shell surfaces that likely facilitate entanglement of plastic ropes and fibers (Fig. 3A, B) and their shells contain surface bound proteins attracting conspecific larvae seeking settlement (Sedanza et al., 2022). Accordingly, Pacific oysters are frequently overgrown by conspecifics (e.g., Troost, 2010; Reise et al., 2017) which leads to oyster clumping (Fig. 3E, F) and may favour plastisessile formation. Finally, the findings that all plastisessiles occurred in the wave-sheltered Ostkaje boulder field where Pacific oyster abundance was much higher than in the wave-exposed Nordostmole and Augustamole boulder fields (Section 3.2) suggests that Pacific oysters overgrowing plastic fibers is more common under wave-sheltered conditions.

4.4. Plasticoncrete deposition in coastal sediment is driven by coastal waves and onshore winds

Information on environmental influences on the fate of plastic forms is limited to floating pyroplastic (Furukuma et al., 2022) and detached plasticrusts (Ellrich et al., 2023) and field experiments with plastic forms are rare (Ellrich et al., 2023) but essential to understand the fate of plastic forms in the environment (Ellrich and Ehlers, 2022). Therefore, our field experiment in the wave-exposed Nordostmole boulder field (Fig. S3, S4A) examined whether non-floating plasticoncrete gets buried in coastal sediments under calm versus wavy and windy conditions. Our experiment showed that plasticoncrete got partially covered in beach sand in the mid intertidal zone during period 1 and got fully covered in wet sand under increasing wave height, onshore wind duration and wind speed during period 2 (Section 3.3, Fig. 4A, Fig. S11). These results show, for the first time, that plasticoncrete occurrence is not restricted to the beach surface. Moreover, these results show that high waves and strong onshore winds drive the vertical deposition of plasticoncrete in coastal sediments. This conclusion is corroborated by the findings that tidal amplitude was similar during periods 1 and 2 and that precipitation was mostly low and similar during both periods which suggest that tidal amplitude and precipitation did not influence plasticoncrete deposition (Section 3.3). This conclusion is also supported by our field monitorings in the wave-sheltered Ostkaje boulder field (Fig. S3, S4C) which showed that plastimetals and plastisessiles were hardly covered in beach sand (Section 3.4, Fig. 4B). Furthermore, these results suggest that other non-floating plastic forms with bulk densities similar to plasticoncrete (1.9 to 2.3 g/cm^3, Table S2), such as plastiglomerate (1.7 to 2.8 g/cm^3, Corcoran et al., 2014; 1.5 to 2.4 g/cm^3, Furukuma et al., 2022), dense pyroplastic (1.4 g/cm^3, Furukuma et al., 2022), plasticrusts encrusting sandstone cobbles (2.2 g/cm^3, Ellrich et al., 2023; this study), anthropoquinas (sedimentary rock: 1.2 to 3.3 g/cm^3, Manger, 1963), plastimetal (1.4 to 5.6 g/cm^3, Table S2), plastisessiles (1.4 to 2.8 g/cm^3, Table S2), and dense plastitar (clean tar floats in seawater whereas sand-encrusted tar gets buried in beach sand; Iliffe and Knap, 1979; Golik, 1982) can get buried in beach sand and that coastal waves and onshore winds influence the deposition of such plastic forms in coastal sediment.

4.5. Plasticoncrete, plastimetal and plastisessiles are no local phenomena

While our field observations on Helgoland enabled the conclusion that plasticoncretes, plastimetals and plastisessiles were formed locally (Section 4.2), multiple facts corroborate the notion that these plastic forms are not limited to Helgoland. For instance, cement, steel and plastic are produced and used globally and the production of these materials is continuously rising (Andrew, 2019; Geyer et al., 2017; Kang et al., 2022). Reinforced concrete and steel are used in harbor and coastline fortifications, seafaring, construction and industries worldwide (Moynihan and Allwood, 2012; Pranzini et al., 2015; Sujauddin et al., 2016). Plastic waste generation is increasing globally (Zhao et al., 2022) and plastic pollution is ubiquitous in aquatic environments (Su et al., 2022). Furthermore, plastic fibers, which constituted the most common plastic shape in plasticoncrete, plastimetal and plastisessiles on Helgoland (86 %), plasticoncrete on Mallorca (66 %) and plastimetal on Hikoshima (100 %), heavily contribute to marine plastic pollution (Ostle et al., 2019; Int-Veen et al., 2021). Also, Pacific oysters (*M. gigas*) have been introduced worldwide by international aquaculture (Martínez-García et al., 2022) with 618,140 ± 28,415 tons (mean ± SD) produced globally per year from 2010 to 2018 (FAO, 2020). Oysters are ecosystem engineers that form extensive oyster reefs along rocky and sandy coasts through settlement and growth (Walles et al., 2015; Herbert et al., 2016). Polychaetes (*S. triqueter*) occur from Northern Norway to Morocco (Hayward and Ryland, 2017) and, similar to oyster reefs, polychaete conspecifics can form dense and multi-layered calcareous tube beds on hard substrates through settlement and growth (e.g., Fig. 13 in Klöckner, 1976). Moreover, various common benthic invertebrates, such as blue mussels, tunicates and barnacles, settle and grow on plastics and form dense populations (Ehlers et al., 2018; Murphy et al., 2019; Yorisue et al., 2019; Fig. S15). Together with the proposed plasticoncrete, plastimetal and plastisessile formation processes (Section 4.2), our plasticoncrete findings on Mallorca (Fig. 5A-C) and plastimetal findings on Hikoshima (Fig. 5D, E), these facts strongly imply that plasticoncrete, plastimetal and plastisessiles are no local phenomena and that these plastic forms can occur in human-shaped coastal areas, such as construction sites, harbors, coastal fortifications, shipyards, −wrecks and -graveyards, oyster aquaculture and reef restoration sites, worldwide.

4.6. Recommendations for future research, coastal clean-ups, oyster aquaculture and reef restoration

To date, most plastic form records stem from marine coastal habitats (Fig. S1). Aside from plastitar (i.e., benthic plasto-tar crusts and pelagic plasto-tarballs on/off Bermuda; Wilber, 1987), only pyroplastic and plasticoncrete have been reported in marine coastal (Turner et al., 2019; Ehlers and Ellrich, 2020; Furukuma, 2021; De-la-Torre et al., 2022; de Vos et al., 2022; Ellrich and Ehlers, 2022; Furukuma et al., 2022; James et al., 2022; Lozoya et al., 2022; Santos et al., 2022; Sewwandi et al., 2022a; Sewwandi et al., 2022b; Fig. 1A-G) and terrestrial habitats (Cyvin et al., 2021; Fig. 5A-C). Similarly, information on plastiglomerate is limited to marine coastal (Corcoran et al., 2014; Turner et al., 2019; Furukuma, 2021; De-la-Torre et al., 2022; Ellrich and Ehlers, 2022; Furukuma et al., 2022; Santos et al., 2022; Goswami and Bhadury, 2023) and freshwater habitats (Arturo and Corcoran, 2022). Therefore, information on plastic forms in terrestrial habitats is very limited. However, since plastiglomerate has been related to campfires and waste incineration fires on sandy beaches and rocky shores (Corcoran et al., 2014; De-la-Torre et al., 2022; Furukuma et al., 2022; Santos et al., 2022) and experimental research showed that melted plastic adheres to rock (Luo et al., 2023), we suggest to examine terrestrial habitats for plastiglomerate that may form during regional (e.g., bush or forest fires; Goswami and Bhadury, 2023) and local fires caused by, for example, accidents or vandalism (Fig. S16). Also, since rusty metal remains are frequently recovered from the seafloor off Helgoland during explosive ordinance disposal operations (THB, 2022; NDR, 2023) and we very recently detected plastimetal$_8$ in the shallow Augustamole subtidal zone on 7 April 2023 (Fig. S17, Table S2), it would be interesting to examine whether plastimetal occurs in benthic offshore habitats because information on plastic forms in such habitats is still missing.

Concerning coastal clean-ups, we note that most plastimetals (71.4 %) contained relatively thin rusty metal rods (1.5–4.3 cm in width; Table S2), presumably as such protruding and pointed structures, that may also lead to injuries in animals and human, facilitate plastic fiber entanglement (Fig. S8). Thus, we recommend to remove such rusty metal rods during coastal clean-ups to prevent injuries and plastimetal formation.

Plastic (PE and PP) equipment is widely used in oyster aquaculture (Wootton et al., 2022; Hingant et al., 2023) and reef restoration (Comba et al., 2022; Walters et al., 2022). Aquaculture oysters often contain microplastics (PE and PP) resulting from aquaculture equipment (Phuong et al., 2018; Wootton et al., 2022) and sustainable alternatives to plastic equipment are currently under investigation (Comba et al., 2022; Walters et al., 2022). Plastic fibers typically stem from synthetic mesh, nets and ropes (Szulc et al., 2015; Welden and Cowie, 2017; Ehlers et al., 2021; Wootton et al., 2022) that are common in marine habitats (O'Hanlon et al., 2019; Ostle et al., 2019; Int-Veen et al., 2021; Fig. S6, S8). Therefore, we recommend avoiding the use of such plastic equipment to limit plastisessile formation. This is crucial for the numerous oyster reef restoration projects worldwide (e.g., zu Ermgassen et al., 2021; Smith et al., 2023) because spatially complex oyster reefs (Troost, 2010; Reise et al., 2017) may promote plastic fiber (or mesh) entanglement and subsequent overgrowth by conspecific oysters (Section 4.2). In fact, oyster shells can persist in the marine environment for thousands of years (Fan et al., 2011; Sander et al., 2021) and may, thereby, conserve overgrown plastics (by shielding them from ultraviolet radiation and mechanical abrasion; Sun et al., 2022) in the geological record.

4.7. Plastic form as umbrella term

There is currently no umbrella term for the plastic forms characterized so far. Therefore, the terms plastiglomerate (Corcoran and Jazvac, 2020), new plastic formation (De-la-Torre et al., 2021; Furukuma, 2021), novel plastic form (Furukuma et al., 2022), plastic rock (Rangel-Buitrago et al., 2022), plastic debris form (Ellrich and Ehlers, 2022; Santos et al., 2022), plastic litter variant (Chowdhury et al., 2023) and plastic form (Ellrich et al., 2023; Landrigan et al., 2023; this study) have been used when summarizing plastic forms. This variety may, to some degree, be caused by the two facts that scientists from different disciplines, including ecology, geology and pollution research, study these plastic forms and that this interdisciplinary research field is still emerging. However, most of these terms are inappropriate as umbrella terms. Since plastiglomerate was defined as plastic melted together with (in)organic material (Corcoran et al., 2014), it cannot be used as umbrella term covering other plastic forms such as pyroplastic that consists of just melted plastic (Turner et al., 2019) or plasticrusts which derive from plastic being abraded on intertidal rocks by water motion (Ellrich et al., 2023). Novel plastic form (and new plastic formation) is inappropriate as umbrella term because a novel plastic form is considered old once a newer plastic form is discovered. Plastic rock is also inappropriate since plastic forms (e.g., pyroplastic, plastimetal) do not necessarily contain rock (Turner et al., 2019; this study). Plastic debris form cannot cover intact plastic items embedded in beachrock (Irabien et al., 2015; Fernandino et al., 2020) or tar (Gregory, 1983; Wilber, 1987; Turner and Holmes, 2011; Domínguez-Hernández et al., 2022). Similarly, plastic litter variant does not cover pre-production plastic raw material (i.e., plastic nibs, nurdles, spherules or pellets) often embedded in tar (Gregory, 1983; Wilber, 1987; Turner and Holmes, 2011; Domínguez-Hernández et al., 2022). In fact, plastic form appears as the most appropriate umbrella term because it refers only to the plastic and its form: Molten plastic matrix (Corcoran et al., 2014), molten plastic (Turner et al., 2019), plastic encrusting rock (Gestoso et al., 2019), plastic enclosed in beachrock (Fernandino et al., 2020), plastic with a molten rock-like appearance (Santos et al., 2022), plastic embedded in tar (e.g., Wilber, 1987; Domínguez-Hernández et al., 2022), plastic hardened in concrete, plastic rusted with metal, and plastic attached to benthic substrates by sessile invertebrates (this study), which clearly differentiates these plastic forms from each other and from regular plastic (Landrigan et al., 2023). Therefore, we propose plastic forms as umbrella term for summarizing plastic forms.

4.8. Summary

We discovered, introduced, characterized and discussed three new plastic forms on Helgoland that we termed plasticoncrete (plastic hardened in concrete), plastimetal (plastic rusted with metal) and plastisessiles (plastic attached to benthic substrates by sessile invertebrates). These non-floating plastic forms contained plastic (PE, PP) fibers that typically float in seawater which indicated that the formation of plasticoncrete, plastimetal and plastisessiles influences the fate of such plastic fibers in the environment. Plasticoncrete and plastimetal are the first plastic forms entirely consisting of man-made materials. The plastisessiles revealed that plastic forms can result from biological interactions between plastic fibers and sessile invertebrates. Our field experiment found that coastal waves and onshore winds are environmental drivers of plasticoncrete deposition in coastal sediments. We provided first records of plasticoncrete in terrestrial habitats on Mallorca which show that plasticoncrete is neither a local phenomenon nor limited to intertidal habitats. We contributed first records of plastimetal in intertidal habitats on Hikoshima which revealed that plastimetal can also result from plastic mesh entangling metal. We suggested future research on plastic forms in terrestrial and offshore habitats, recommended measures to limit the formation of plastimetal and plastisessiles, and proposed the umbrella term ‘plastic forms’. Thereby, our study contributes to the growing fundamental knowledge of plastic forms that is essential to recognize, record, communicate and understand these emerging pollutants in the environment.

4.9. Conclusions

Based on the omnipresence of plastics in the environment, our findings on Helgoland, Mallorca and Hikoshima, and the facts that concrete, metal and oyster shells can persist in marine environments for hundreds to thousands of years, we conclude that geochemical interactions between concrete, metal, oysters and plastic can lead to the formation of plastic forms that may, just as the continued usage of plastic containing concrete building materials, contribute to the worldwide conservation of plastic in the sedimentary and geological record.

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CRediT authorship contribution statement

Julius A. Ellrich: Conceptualization, Investigation, Methodology, Formal analysis, Writing – original draft, Visualization, Data curation. **Sonja M. Ehlers:** Conceptualization, Investigation, Methodology, Formal analysis, Writing – review & editing, Visualization, Data curation. **Shunji Furukuma:** Investigation, Methodology, Formal analysis, Writing – review & editing, Visualization, Data curation. **Bernadette Pogoda:** Resources, Writing – review & editing. **Jochen H.E. Koop:** Resources, Writing – review & editing.

Data availability

All data are included in the Supplementary material files.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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