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Sustainability and corrosion

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As a part of the drive to reduce carbon dioxide emissions, embodied energy figures are under consideration for construction materials. One aspect that needs to be included is the loss of embodied energy associated with corrosion and degradation throughout the life of a structure. This paper presents a review of corrosion and protection methods from the point of view of whole-life embodied carbon. This paper presents the examples that provide the lowest embodied carbon option for different environments for steel and reinforced concrete.

Keywords: climate change/corrosion/sustainability

Notation

b	metal-environment-specific time exponent
D	mass loss per unit area or penetration depth
r_{corr}	corrosion rate experienced in the first year
t	exposure time in years

1. Introduction

In assessing the sustainability of materials, embodied energy is often used. For the purposes of this work, embodied energy is defined here as the total primary energy consumed from direct and indirect processes associated with a product or service and within the boundaries of cradle to gate. This includes all activities from material extraction (quarrying/mining), manufacturing, transportation and right through to fabrication processes until the product is ready to leave the final factory gate (Circular Ecology, 2019). Figures can also be quoted in energy per kilogram of material that represents the embodied energy. To convert from energy to carbon dioxide, an understanding of how much carbon dioxide is generated for each megajoule of energy is required, and this varies depending on the production methods used. If the material is being reused, then the embodied energy is that of removing it from one place and fitting it in another. Hence reuse is favourable, provided that extensive travel and storage are not required. If a material involves a significant amount of recycled product, this may bring the embodied energy down, as a certain amount of the energy involved is already accounted for in converting raw materials into the recycled product. However, if the recycling process involves a significant transport of material and then energy usage to convert it into a useable product, then it may not. As an example, the extraction of raw materials for the manufacture of glass is relatively low energy, whereas recycling glass can involve extensive sorting and transport processes followed by grinding and remelting of the recycled material, which is relatively energy intensive (Khatib, 2009).

Once a structure has been built, corrosion may occur, leading to a reduction in capacity. This is also a waste of embodied carbon dioxide ('embodied carbon') that has been invested in producing the structure. The paper presents a review of the embodied energy expressed as carbon dioxide equivalent (CO₂e) in current corrosion prevention practices.

Unless noted otherwise, the embodied energy figures are taken from the Inventory of Carbon and Energy Database V3.0 Nov 2019 (Circular Ecology, 2019). This database provides conversion factors to obtain a mass of embodied carbon for a given mass of material.

Cradle to gate does not consider the maintenance required over the operation life. If the material produced is thermodynamically unstable, it will have a tendency to be converted over time.

2. Steel

Steel is thermodynamically unstable. Iron ore is stable; it has energy applied to it to convert it to steel. If steel is not provided with a protection system, it will corrode in the presence of moisture. When it corrodes, this embodied energy is lost to the environment and wasted. The amount of wasted energy depends on how much metal is lost, which in turn depends on the corrosion rate.

2.1 Atmospheric corrosion

BS EN ISO 9223 (BSI, 2012a) publishes corrosivity categories with corresponding rates for steel. These describe the metal lost due to corrosion, either as a mass or as a depth of penetration; however, these are first-year corrosion rates only. BS EN ISO 9224 (BSI, 2012b) provides formulae that represent a typical reduction in time. For the first 20 years, the depth of attack is described thus:

$$1. \quad D = r_{\text{corr}} t^b$$

where D = either a mass loss per unit area or penetration depth, r_{corr} = the corrosion rate experienced in the first year, t = exposure time in years and b = metal-environment-specific time exponent (0.523 for carbon steel, 0.813 for zinc).

For exposures greater than 20 years ISO 9224 (BSI, 2012b) proposes the following equation that assumes that the corrosion rate becomes linear at 20 years of exposure:

$$2. \quad D(t > 20) = r_{\text{corr}} [20^b + b(20^{b-1})(t - 20)]$$

where D = either a mass loss per unit area or penetration depth, r_{corr} = the corrosion rate experienced in the first year, t = exposure time in years and b = metal-environment-specific time exponent.

The mass of CO₂e wasted is directly related to the mass of material lost due to corrosion. For steel, a figure of 1.55 kgCO₂e (kilograms of CO₂e contained within a material)/kg has been used from the Inventory of Carbon and Energy Database V3.0 Nov 2019.

The standard method of protecting steel is the application of a coating system. Again, there are figures for the embodied energy of coatings. A generic coating contains 2.91 kgCO₂e/kg. Using a density similar to a typical two-pack epoxy of 1.62 kg/l from a commercially available product in common usage, a litre of epoxy has 4.71 kgCO₂e. One litre will cover 1 m² of steel with a thickness of 1 mm; so 1 µm of wet coating has 0.0047 kgCO₂e. This can then be further converted into a CO₂e per micron of dry film thickness. This conversion depends on the volume solids of the specific coating used. Solvented coatings generally have a greater differential between wet and dry film thicknesses. In the analysis that follows, it is assumed that the coating remains intact until the coating life expires. This is obviously not the case, as coatings get damaged and break down with time. This is considered a necessary simplification to allow this evaluation. It is also assumed that the metal corrodes evenly at the maximum rate given in ISO 9223 (BSI, 2012a) for that environment. Localised corrosion due to crevices or pitting is not included. The embodied carbon considers just the material in reapplication, and nothing is associated with the temporary works, such as grit blasting, access and power requirements on site. So it is an underestimate, but the energy and carbon associated with these items would be distributed across the total area to be coated.

Table B2 of BS EN ISO 12944 (BSI, 2019) Part 5 provides an example of the minimum dry film thickness for a range of coating types to provide high durability (15–25 year life). It ranges from 160 µm, for C2 environments coated with alkyds, to 300 µm, for C5 coated with epoxies. The embodied energy figures are not for specific formulations but are based on typical values from the Inventory of Carbon and Energy Database V3.0. Table 1 presents the embodied carbon wasted when 1 m² of steel corrodes for 15 years and the embodied carbon wasted by applying a coating to prevent this degradation.

Table 1. Embodied carbon in coated steel

Corrosivity category	Steel corrosion rate: µm/year	Mass lost: (kg/ year)/m ²	Mass lost in 15 years: kg/m ²	Energy wastage: kgCO ₂ e/m ²	Energy in coating: kgCO ₂ e/m ² (epoxy)	Energy in coating: kgCO ₂ e/m ² (alkyd)
C1	1.30	0.01014	0.042	0.06	Not required	Not required
C2	25	0.195	0.803	1.25	0.666	0.887
C3	50	0.390	1.607	2.49	0.998	1.109
C4	80	0.624	2.571	3.98	1.331	1.442
C5	200	1.560	6.427	9.96	1.664	Not recommended

kgCO₂e, kilograms of CO₂e contained within a material

It can be clearly seen that painting steel has a lower embodied energy than that which is wasted due to corrosion during a 15-year period. It is a significant benefit to the environment in any corrosivity category more aggressive than C1. The CO₂e wasted in steel corrosion over 15 years in a C1 environment is equivalent to a coating thickness of approximately 11 µm. It would be likely that a coating would not result in saving CO₂e. Epoxies generally involve less embodied carbon than alkyds based on the mass of coating used. Note that the CO₂e figures are not specific for specific formulations. The CO₂e saved by coating with an epoxy rather than letting the steel corrode ranges between approximately 0.58 and 8.30 kg.

There are also figures for the embodied carbon of zinc (3.09 kgCO₂e/kg), so the same process can be repeated for both galvanised steel and coated galvanised steel. The thickness of hot-dip galvanising depends on the element being galvanised, and so two figures are included, 45 and 85 µm. From Equation 1, zinc corrodes 9.02 times the first-year corrosion rate over 15 years. The embodied carbon figures are presented in Table 2, including the figures associated with the embodied CO₂e of coatings. Note that the recommended coating thicknesses are not the same as that of steel that is not galvanised.

As can be seen, for all environments below C5 corrosivity, the CO₂e wasted due to coating degradation is more than the CO₂e wasted due to corrosion of the galvanising, regardless of the thickness of galvanising.

Table 2. Embodied carbon in coated galvanised steel

	Zinc corrosion rate: µm/year	Mass lost: (kg/ year)/m ²	Mass lost in 15 years: kg/m ²	kgCO ₂ e/m ² wastage for 45 µm	kgCO ₂ e/m ² wastage for 85 µm	CO ₂ e in coating: kgCO ₂ e/m ²
C1	0.1	0.001	0.006	0.020	0.020	—
C2	0.7	0.005	0.045	0.140	0.140	0.444
C3	2.1	0.015	0.136	0.421	0.421	0.666
C4	4.2	0.030	0.273	0.843	0.843	0.887
C5	8.4	0.060	0.546	8.175*	1.686	1.109

*Denotes that galvanising has been fully depleted and steel corrosion has commenced

kgCO₂e, kilograms of CO₂e contained within a material; —, not applicable

For a C2 environment, $45\text{ }\mu\text{m}$ of galvanising would provide 133 years before consumption. For a C3 environment, $45\text{ }\mu\text{m}$ of zinc provides 41 years before steel corrodes. To achieve 100 years, either a corrosion allowance is required for 59 years' worth of corrosion or coatings are needed. This would be $483\text{ }\mu\text{m}$ of steel corrosion ($5.84\text{ kgCO}_2\text{e}$). If a coating with a 15-year durability is applied once, this extends the life of the galvanising by at least 15 years, so the corrosion of steel is reduced by 15 years. The effects of repeated coating are presented in Figure 1. With no coating, the embodied carbon being wasted is initially that which is associated with the corrosion of zinc, in accordance with Equation 1. Once the zinc is depleted, the energy wasted is that which is associated with the corrosion of steel in accordance with Equation 1. For coated options, the coating life is assumed to be 15 years, after which the structure is either recoated or corrosion commences. Each coating exercise adds the embodied energy associated with the coating used. This is repeated to achieve a 100-year assumed design life.

In this case, the most carbon dioxide efficient approach is to coat the structure four times, with an embodied carbon of $3.60\text{ kgCO}_2\text{e/m}^2$. The residual life is then made up of the corrosion of the galvanising.

As an alternative, $85\text{ }\mu\text{m}$ could be applied. This would give 82 years before steel corrosion and so would only need to be recoated once to provide the most carbon dioxide efficient approach at 2.9 kg , as illustrated in Figure 2.

In a C3 environment, the use of coated galvanised steel, with the thickest galvanising possible, produces the lowest embodied carbon.

A similar approach can be taken for a C4 environment. Forty-five microns of galvanising with no coating produces the responses shown in Figure 3.

The lowest CO_2e option is also chosen to repeatedly coat the structure until the galvanising provides the corrosion resistance

Figure 1. Carbon wasted due to corrosion in a C3 environment with $45\text{ }\mu\text{m}$ galvanising

Figure 2. Carbon wasted due to corrosion in a C3 environment with $85\text{ }\mu\text{m}$ galvanising

Figure 3. Carbon wasted due to corrosion in a C4 environment with $45\text{ }\mu\text{m}$ galvanising

required for the structure's lifespan. In this case, with $45\text{ }\mu\text{m}$ galvanising, recoating needs to take place six times.

For $85\text{ }\mu\text{m}$ galvanising, shown in Figure 4, minimising embodied carbon required six recoats, although there is only a marginal gain (approximately 11 g) between the fifth and sixth coating.

Based on Figure 4, the largest waste of CO_2e occurs when the structural steel is allowed to corrode.

For a C5 environment, the results shown in Figure 5 are obtained. In effect, the approach needed is to keep recoating the steel, in which case the presence of galvanising does not minimise the embodied carbon and, therefore, could be omitted. In practical terms, the coating will not all fail at once and galvanising will improve the coating resistance to undercutting at defects. This would be of benefit, although additional thickness may not necessarily be a significant benefit.

One obvious approach would be to use a corrosion-resistant steel. Generic stainless steel typically has an embodied CO_2e three times that of structural steel but will obviously not lose this CO_2e

Figure 4. Carbon wasted due to corrosion in a C4 environment with 85 µm galvanising

Figure 5. Carbon wasted due to corrosion in a C5 environment with 45 µm galvanising

by corroding. It is worth noting that most grades of stainless steel will corrode in the presence of chlorides, and many are not resistant to crevice corrosion. Based on these figures and those calculated for CO₂e wasted in the C3 or C4 environment above, the use of structural stainless steel uses more embodied CO₂e than coated structural steel where the member thicknesses are over 0.13 mm in a C3 environment or 0.26 mm in a C4 environment.

2.2 Buried or submerged steel

For buried or submerged steel, inspection and recoating are more complex than atmospherically exposed steel as the structure cannot be easily accessed. The approach to managing corrosion is either to use corrosion allowances, coatings, cathodic protection or a combination of these. Corrosion allowances can often be employed because the stresses involved in manufacture and installation exceed those required in service, and so the material is naturally thicker than required. Coatings prevent the steel from being exposed to the environment but they degrade with time and are vulnerable to damage. Cathodic protection applies a voltage that relocates the corrosion processes so that the steel does not

corrode. Combined coatings and cathodic protection reduces the size of the cathodic protection system required, and allows for coating damage to be tolerated.

BS EN 1993-5 (BSI, 2007) provides corrosion rates or amounts of section loss for buried steel. These are reproduced in Table 3 for a range of different lifespans. The section loss can be converted to CO₂e wasted, and the figures are shown in Table 4.

While it would not be possible to reapply a coating, in many cases, it could be applied prior to installation. Table C6 in BS EN 12944 (BSI, 2019) Part 5 has a maximum application thickness of 600 µm to provide very high durability (>25 years). Assuming a similar

Table 3. BS EN 1993 corrosion allowances (buried steel)

Environment	Duration of exposure				
	5 years: mm	25 years: mm	50 years: mm	75 years: mm	100 years: mm
Undisturbed soils	0.06	0.30	0.60	0.90	1.20
Polluted natural soils and industrial sites	0.15	0.75	1.50	2.25	3.00
Aggressive natural soils	0.20	1.00	1.75	2.50	3.25
Non-compacted and non-aggressive fills	0.18	0.07	1.20	1.70	2.20
Non-compacted and aggressive fills	0.50	2.00	3.25	4.50	5.75

Table 4. CO₂e values of corrosion allowances in BS EN 1993-5 (BSI, 2007)

Environment	Duration of exposure				
	kgCO ₂ e/ m ² after 5 years	kgCO ₂ e/ m ² after 25 years	kgCO ₂ e/ m ² after 50 years	kgCO ₂ e/ m ² after 75 years	kgCO ₂ e/ m ² after 100 years
Undisturbed soils	0.7	3.6	7.3	11	15
Polluted natural soils and industrial sites	1.8	9.1	18	27	36
Aggressive natural soils	2.4	12	21	30	39
Non-compacted and non-aggressive fills	2.2	8.5	15	21	27
Non-compacted and aggressive fills	6.0	24	39	54	70

kgCO₂e, kilograms of CO₂e contained within a material

embodied CO₂e to the epoxy coating used above this would equate to 3.3 kgCO₂e/m². This is lower than the CO₂e wasted for any of the environments over any increment of 25 years. Note that for a 100-year lifespan, the coating means that the steel is only exposed for 75 years, so the coating should be compared with the difference between a 75- and 100-year exposure.

2.3 Corrosion rates in freshwater/marine environments

BS EN 1993-5 (BSI, 2007) also provides corrosion rates or amounts of section loss for immersed steel. These are reproduced in Table 5 for a range of different environments and lifespans.

These can be converted to CO₂e wasted, and the figures are shown in Table 6.

As with buried steel, this could be coated prior to installation, with an associated embodied carbon of 3.30 kgCO₂e. This is lower than

Table 5. Recommended value for the loss of thickness (mm) due to corrosion for piles and sheet piles in freshwater or in seawater

Required design working life	5 years	25 years	50 years	75 years	100 years
Common freshwater (river, ship canal, ...) in the zone of high attack (water line)	0.15	0.55	0.90	1.15	1.40
Very polluted freshwater (sewage, industrial effluent, ...) in the zone of high attack (water line)	0.30	1.30	2.30	3.30	4.30
Seawater in temperate climate in the zone of high attack (low-water and splash zones)	0.55	1.90	3.75	5.60	7.50
Seawater in temperate climate in the zone of permanent immersion or in the intertidal zone	0.25	0.90	1.75	2.60	3.50

Table 6. CO₂e values of corrosion allowances in BS EN 1993-5 (immersed)

Required design working life	5 years	25 years	50 years	75 years	100 years
Common freshwater (river, ship canal, ...) in the zone of high attack (water line)	1.8	6.6	11	14	17
Very polluted freshwater (sewage, industrial effluent, ...) in the zone of high attack (water line)	3.6	16	28	40	52
Seawater in temperate climate in the zone of high attack (low-water and splash zones)	6.6	23	45	68	91
Seawater in temperate climate in the zone of permanent immersion or in the intertidal zone	3.0	11	21	31	42

the CO₂e wasted for any of the environments over any increment of 25 years in most cases. The only exception is the long lifespans in common freshwater. Again, for a 100-year lifespan, the coating means that the steel is only exposed for 75 years, so the coating should be compared with the difference between a 75- and 100-year exposure.

2.4 Cathodic protection of steel

When steel is buried or immersed, it is possible to employ cathodic protection (CP). There are two distinct approaches, either using a metal that will corrode in place of the steel (galvanic CP), or an external power supply (impressed current CP). BS EN ISO 15589-1 (BSI, 2017) reports the typical current densities for the protection of bare steel or cast iron fall within the range 0.1–1 A/m². In a galvanic system, the mass of anode lost corresponds to the amount of current required for protection. The capacity of anode materials is quoted in BS EN 12496 (BSI, 2010) in terms of ampere hours per kilogram of anode. Zinc has a capacity of approximately 780 A h/kg, aluminium has a capacity of 2500 A h/kg. The embodied carbon corresponds to the mass lost, with zinc and aluminium having embodied energy figures of 3.09 and 6.67 kgCO₂e/kg, respectively. Table 7 illustrates the embodied carbon wasted to protect 1 m² of uncoated steel for 25 years at a current density of 0.1 A/m², requiring a total of 2.5 A years. Note that a full CP design is more complex than these simple examples may indicate.

The most CO₂e the steel wastes is 24 kg. It is quite clear that the use of galvanic CP employs materials with higher embodied carbon to prevent corrosion of a material having lower embodied carbon. From a sustainability point of view, it is significantly more efficient to use a thicker section and allow the steel to corrode.

Impressed current CP will typically employ anodes that do not corrode and an external power supply. The energy required for protection is applied voltage × current × time. The required voltage depends on the resistance of the overall circuit, which is a function of the anode dimensions and resistivity of the soil, plus the cabling. There is an additional CO₂e requirement embodied in the power supply and cabling. The anode does incur a CO₂e, but this is not wasted as the anode is not significantly consumed. A bigger anode will give a lower anode resistance and hence a lower drive voltage, but will obviously require more anode material. Assuming a drive voltage of 8 V, to provide the same amount of current, the energy used is 175 kW/h over 25 years. The current government conversion to CO₂e in the UK is 0.2556 kgCO₂e/(kW h) (BEIS, 2019), while 17 kW/h is equivalent to 44 kgCO₂e.

Table 7. CO₂e values for anode mass required for 25-year life at 0.1 A/m²

Anode material	Embodied kgCO ₂ e for 2.5 A years: kg
Aluminium	58
Zinc	91

kgCO₂e, kilograms of CO₂e contained within a material

The energy value appears to be a significant saving, but the current needs to be outputted by an anode, which is typically titanium, and the system will need power supplies and external control systems. Titanium has an embodied CO₂e of between 20 and 42 kg CO₂e/kg. An anode rated at 2.5 A for use in soil weighs 180 g, and so the anode has an embodied carbon of 3.6–7.5 kgCO₂e. Note that this could protect 25 m², so the CO₂e per square metre is 0.15–0.30 kgCO₂e. There would be additional carbon dioxide associated with cabinets and cables, but the figure likely to be most significant is any computer control system. Figures for embodied carbon of these items are not readily available. If the system is computer controlled, there are published figures for embodied energy of items such as memory chips. A 2 GB memory card in 2009 was reported to contain 2700 MJ of embodied energy (De Decker, 2009). Direct conversion depends on a number of assumptions, but using UK electricity equivalent figures, this would be approximately 190 kgCO₂e. This is a significant mass, but a computer-based system would be used to protect a large area of steel, so again, its effect would be reduced if assessed on a per-square-metre-of-steel basis and is likely to be less than 1 kgCO₂e/m². While a computer-controlled system may sound attractive, consideration should be given as to whether the additional functionality is actually of benefit, given the cost of embodied carbon associated with it.

3. Concrete

Ordinary Portland cement (OPC) is universally recognised as a significant contributor to carbon dioxide emissions on a cradle-to-gate basis, and so concrete is often considered to be poor. In making reinforced concrete structures, it should not be forgotten that reinforced concrete contains steel and aggregate and that it is common to use cement replacements. These materials are typically industrial by-products. Typically, in the UK, the most common materials were pulverised fuel ash (PFA), from coal-fired power stations, or ground granulated blast-furnace slags (GGBSs) from steel manufacturers, but as these industries have reduced production, the by-products needed are often now imported. Taking a 254 mm × 254 mm × 107 kg/m steel universal column, it is considered similar to a 450 × 450 mm reinforced concrete column. The embodied carbon in the steel column, at 1.55 kgCO₂e/kg is 165 kgCO₂e/m. For the concrete equivalent, the mass of concrete per metre of column is approximately 485 kg. The embodied energy of an OPC mix is 0.138 kgCO₂e/kg, giving 67 kgCO₂e per metre of column. If 30% PFA is used, this is reduced to 46 kgCO₂e per metre of column, and for 70% GGBS, this is reduced further to 25 kgCO₂e per metre of column. Steel reinforcement is required. Assuming four No. 12 mm dia. bars, with 8 mm dia. links at 225 mm centres, this adds a further 10 kgCO₂e per linear metre, which is a significant contribution to the CO₂e. The total kgCO₂e per metre of a concrete column is therefore approximately 77 kgCO₂e/m for an OPC mix, which is reduced to 35 kgCO₂e/m when the column is made using cement replacements. The uncoated steel equivalent contains significantly more CO₂e than the reinforced concrete column.

When concrete is made, the material is generally thermodynamically stable. It may deteriorate in the presence of sulfates, acids or

aggressive carbon dioxide, but in standard buried or atmospherically exposed environments, over the typical lifetime of a structure, it is inert. It also provides corrosion protection to the steel, and so, from gate to grave, it has no additional CO₂e.

The steel can start to corrode if the concrete either carbonates or gets contaminated with chlorides. Carbonation is a process that is sometimes used to suggest that concrete can be used as a storage of carbon dioxide. Atmospheric carbon dioxide is absorbed, but this results in a reduction of the pH of the concrete. Unfortunately, the reason that steel does not corrode in concrete is its high pH, and so once carbonation depths reach the steel, it will start to corrode. The rate of carbonation is a function of the external environment and mix design. Dry concrete can carbonate quickly, but without moisture, the steel will not corrode. External UK concrete generally carbonates slowly due to the moisture levels in the environment. Carbonation-induced corrosion of external concrete structures in the UK is generally confined to those with extremely low-cover (<20 mm) or poor-quality concrete. Typically, wherever the steel is in a carbonated environment, in the presence of moisture, it will corrode. For chloride-induced corrosion to occur, a critical amount of chloride needs to penetrate the concrete to the depth of the steel. Unlike carbonation-induced corrosion, the corrosion sites do not occur everywhere within a chloride-contaminated zone. This means that if repairs are undertaken without due regard for the presence of chlorides, corrosion will initiate in unrepaired areas after the initial repair.

When steel corrodes in concrete, typically, the corrosion product is expansive and causes spalling at even a relatively small amount of section loss. Repairs involve identifying the cause (chlorides, carbonation or a combination of the two) and then either removing all the contaminated or carbonated concrete and reinstating or repairing the damage and addressing the contamination. In the case of carbonated concrete, corrosion will typically occur wherever the contamination is, so the removal and reinstatement of loose material do not leave significant possible future corrosion. It does, however, require the replacement of the original concrete with a repair material, and this needs to be compared with the embodied energy of a method that could prevent this degradation.

The typical prevention method for carbonated concrete would be the use of an anti-carbonation coating. Representative figures for the embodied carbon of anti-carbonation coatings are not available, but they are likely to be similar to the steel coatings discussed above. Five hundred microns of epoxy would equate to approximately 2.7 kgCO₂e, and by preventing carbonation, it prevents the removal and reinstatement of a 100 mm thick layer of concrete, assuming that breaking out behind the bar is required. The repair concrete is likely to have more polymer than the original, so it is likely to be more carbon dioxide intensive. For this reason, it is practical to use the embodied CO₂e for OPC concrete rather than anything where the carbon dioxide has been reduced.

This volume of standard concrete has a value of 33 kgCO₂e, and so, if there is a risk of carbonation, repeated applications of anti-carbonation coatings with an embodied carbon of 2.7 kgCO₂e are likely to be the lowest embodied carbon option. One key difference between coating steel and coating concrete is that steel will start to corrode once the coating fails, whereas concrete will start to carbonate, and then in time, the reinforcement will start to corrode. It is therefore not necessary to instantly repair failed coatings on concrete to prevent corrosion.

It is not unusual for chloride contamination to be significant by the time repairs are undertaken, and so the removal of all the concrete is required. As an alternative, CP can be employed, and chloride-contaminated but structurally sound concrete can remain in place. This saves significant embodied carbon due to the reduced amount of material removal and reinstatement. It is commonly considered that for chloride-contaminated concrete, approximately 10% of the concrete will have been spalled by the time of repair, adding 3.3 kgCO₂e as a repair material. A common approach is to use a specially coated titanium mesh in a sprayed concrete overlay. If a mesh and overlay system is used, there will be an additional 300 g of titanium mesh (10 kgCO₂e), and 25 mm of sprayed concrete overlay (8 kgCO₂e), giving a total additional CO₂e per square metre of 21.3 kg, compared with 33 kg to replace 100 mm of concrete. As with anti-carbonation coatings, chloride ingress could be prevented with coatings with an embodied carbon value of 2.7 kgCO₂e, which would significantly lower CO₂e than would allowing corrosion to take place.

The installation of the titanium mesh could be included in the original construction and could be energised if required. This would require fewer anodes, probably of the order of 100 g/m² (3 kgCO₂e), and unlike a coating, these would not be needed to be reapplied, which means that the CP installed during construction is likely to be the lowest embodied carbon option, if there is a risk of chloride-induced corrosion. There would be an ongoing energy consumption associated with the operation of a system. This depends on the operating voltage and current being passed. One square metre of concrete typically requires 2 mA/m² to prevent corrosion, rising to 10 mA/m² to reverse active corrosion. The operating voltage would be expected to be between 2 and 8 V, giving an annual energy requirement between 0.035 kW/h and 0.7 kW/h, or 0.01–0.18 kgCO₂e per annum. Considering a 100-year life, installing CP to reinforced concrete during construction would add 4 kgCO₂e/m². Considerations with regard to computer-controlled systems are similar to those with the protection of buried or immersed steel.

4. Conclusions

Based on embodied CO₂e calculations, the following can be stated.

Atmospherically exposed steel

- In a C1 environment, coatings do not reduce CO₂e over the life of the structure.

- In a C2 environment, 45 µm of galvanising results in the lowest lifetime waste of CO₂e.
- In a C3 environment, 85 µm of galvanising and recoating once results in the lowest lifetime waste of CO₂e.
- In a C4 environment, 85 µm of galvanising and recoating five times results in the lowest lifetime waste of CO₂e.
- In a C5 environment, 85 µm of galvanising and repeatedly recoating every 15 years produces the lowest lifetime waste of CO₂e.
- Stainless steels generally use more CO₂e than any of the above options.

Buried/submerged steel

- An initial coating prior to installation reduces the lifetime waste of CO₂e in all cases apart from a long-term immersion in fresh water.
- CP uses more CO₂e than a corrosion allowance.
- Impressed current CP systems have lower CO₂e than galvanic CP systems; computer control systems should not be overspecified.

Reinforced concrete

- In an example column, reinforced concrete has lower CO₂e than an equivalent steel column before coating.
- If there is a risk of carbonation-induced corrosion, coating and recoating the concrete wastes less CO₂e than allowing the corrosion to take place and then undertaking concrete repair.
- If chloride-induced corrosion has taken place, impressed current CP wastes less CO₂e than concrete replacement.
- If there is a risk of chloride-induced corrosion, coating the concrete wastes less CO₂e than allowing the corrosion to take place. The inclusion of an impressed current CP system at the time of construction wastes the smallest amount of CO₂e.

REFERENCES

- BEIS (Department for Business, Energy & Industrial Strategy) (2019) *Greenhouse Gas Reporting: Conversion Factors 2019*. BEIS, London, UK. See <https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019> (accessed 19/11/2021).
- BSI (2007) BS EN 1993-5: Eurocode 3. Design of steel structures – Part 5: Piling. BSI, London, UK.
- BSI (2010) BS EN 12496: Galvanic anodes for cathodic protection in seawater and saline mud. BSI, London, UK.
- BSI (2012a) BS EN ISO 9223: Corrosion of metals and alloys. Corrosivity of atmospheres. Classification, determination and estimation. BSI, London, UK.
- BSI (2012b) BS EN ISO 9224: Corrosion of metals and alloys. Corrosivity of atmospheres. Guiding values for the corrosivity categories. BSI, London, UK.
- BSI (2017) BS EN ISO 15589-1: Petroleum, petrochemical and natural gas industries. Cathodic protection of pipeline systems. On-land pipelines. BSI, London, UK.
- BSI (2019) BS EN ISO 12944-5: Paints and varnishes. Corrosion protection of steel structures by protective paint systems. Protective paint systems. BSI, London, UK.

Circular Ecology (2019) *Embodied Carbon - The ICE Database*. Circular Ecology, Bristol, UK. See www.circularecology.com/embodied-carbon-footprint-database.html (accessed 19/11/2021).

De Decker K (2019) The monster footprint of digital technology. *Low-Tech Magazine*, 16 June. See <https://www.lowtechmagazine.com/>

2009/06/embodied-energy-of-digital-technology.html (accessed 19/11/2021).

Khatib JM (ed.) (2009) *Sustainability of Construction Materials*. Woodhead Publishing, Cambridge, UK.

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