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The carbon footprint of reinforced concrete

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As legislation forces significant reductions in the operational carbon dioxide emissions of the built environment, increasing attention is focused on the embodied carbon of structural materials. As the most prevalent structural material, the embodied carbon of concrete is of paramount interest. Previous direct or indirect analyses of embodied carbon in concrete have treated it either as an elemental material with a value of single embodied carbon, or calculated embodied carbon for a limited range of reinforced concrete mix designs, or returned only values for plain concrete. In this paper, the results are presented from a preliminary study into the embodied carbon of reinforced concrete as a function of: concrete strength grade; steel strength; mix design; cement replacement; and structural form. Findings are expressed both in terms of EC_{raw} ($kgCO_2$/kg reinforced concrete) and EC_f ($kgCO_2$ per unit of structural performance). They suggest that there is a wide range of EC_{raw} (0·06−0·47) and that EC_f is minimised by using C50 concrete. Savings in EC_f achieved by adjusting mix design parameters (20–35%) generally exceed those achieved by replacing cement with pulverised fuel ash (10–25%). C50 beams of all mix designs have lower EC_f than comparable timber composite or steel beams.

Notation

- A_{st} — area of steel reinforcement in a column (mm^2, but only maximum or minimum according to Eurocode 2 considered in this paper)
- b — beam breadth
- EC_f — embodied carbon of a structural component expressed in terms of its structural performance (kg CO_2/kN per m^2 for a beam (i.e. carbon dioxide per unit length per unit moment resistance), or kg CO_2/kN per m for a column (i.e. carbon dioxide per unit length per unit axial force capacity)
- EC_{raw} — embodied carbon of a material (kg CO_2/kg of material (i.e. dimensionless))
- h — beam depth
- I_P — index reflecting whether a material has a higher ($I_P > 1$) or lower ($I_P < 1$) 'carbon footprint' than a hypothetical average material, calculated using global production figures
- l — length of beam

Introduction

Concern over the global warming impact of the built environment has manifested in recent legislation intended to reduce the operational carbon dioxide emissions (OC, sometimes referred to as Op-Carb) of buildings to zero over the coming decade (e.g. Climate Change Act, 2008; DCLG, 2009). OC is the carbon dioxide emitted as a result of heating, lighting, air conditioning and so on during the lifetime of the building, analogous to an ongoing running cost. Progress towards this ambition will lead to an increased interest in the embodied carbon dioxide (EC, sometimes referred to as Cap-Carb) of structural elements. EC is the carbon dioxide emitted as a result of materials processing and transport, construction, decommissioning and demolition, analogous to a fixed capital cost. As OC is reduced towards zero, EC becomes the greater proportion of the 'whole-life' impact. Similarly, the OC associated with infrastructure components is normally attributed to the users rather than the asset managers – consider the passage of cars over a road bridge – and thus in any case EC is generally of greater interest than OC to those concerned with the infrastructure sector of the built environment.

The main component of the EC of structural elements – beams, columns and so on – and the structures they enable is dominated by that associated with the production of the materials from which they are made (Hacker *et al.*, 2008; Harrison *et al.*, 2010). Thus the EC of structural materials has recently attracted general attention. In particular, comparisons between the EC of concrete, steel and timber (or structures made primarily thereof) purporting to present one or other of these materials as 'the greenest', have become increasingly common in both the scientific and quasi-technical literature.

The assessment of EC is complex. Attributing a value for the quantity of carbon dioxide emitted per unit of production to the major structural materials – steel, timber and concrete – is not straightforward. In principle, one should avoid such generalisations and perform a full life-cycle assessment (LCA, in accordance with ISO 14040 (ISO, 2006)) of any structural design or analysis, taking into account carbon dioxide emissions generated during all the stages of production, processing, installation, maintenance, demolition and disposal of the specific components of the particular structure under study. In practice, this is not possible at the policy, concept or tendering stages of a project (a fact that seems to be frequently overlooked by those from outside the engineering community, who zealously advocate a 'full LCA or nothing' approach to the analysis of structural materials) and so such generalisations are necessary in order that preliminary engineering decisions with respect to material specification can be made.

For steel, while the energy and process emissions associated with production of virgin material (~35 MJ/kg and 2·8 kg CO_2/kg) are relatively well established (e.g. Hammond and Jones, 2008), the degree of recycling is highly variable; for example, the recycled content of structural steel sections is around 60%, while that for reinforcing steel is 90–100% (WRAP, 2008). As a further complication, it is often not clear whether rates are quoted at the material level (e.g. 'the average content of recycled material in steel beams is 60%') or at the product level (e.g. '60% of steel beams are made from recycled material'). It should also be remembered that recycling of steel is not 'free' in terms of energy and carbon, requiring ~9·5 MJ/kg and releasing ~0·43 kg CO_2/kg steel, respectively (Hammond and Jones, 2008).

Assigning an EC to timber is controversial. Some investigators (e.g. Labbé, 2007) insist that timber should be assigned a negative EC value, in other words that using timber somehow 'sequesters' carbon dioxide. Simple analyses purport that this arises from assuming that the growth of the timber has extracted carbon dioxide from the atmosphere and is thus 'storing' it while it is in use. This is of course only valid if the total stock of both forest wood and/or the total stock of timber in use within structures are growing significantly; if both stocks are at steady state, wood (i.e. carbon) entering the system as new growth timber is balanced by that leaving the system to decompose or be incinerated (and thus returning carbon to the atmosphere). Since neither stock is growing significantly – only 26% of world roundwood supply is from sustainable 'certified' forests, implying that the remaining 74% contributes to deforestation, and global structural timber sales have been stable or declining, not increasing (ITTO, 2011) – this popular sequestration argument is invalid.

More sophisticated investigators (e.g. Gustavsson and Sathre, 2006; Sathre and O'Connor, 2010) argue that if, over the extended life cycle of timber structural components (i.e. from new growth, through timber processing, to demolition), 70% of forestry waste, 100% of sawmill waste and 100% of demolition timber is used to replace fossil fuel in power generation, then a net 'carbon credit' of ~4 $kgCO_2$ per kg of timber can be generated. As pointed out by Purnell (2012a), this level of recycling is courageously optimistic. Furthermore, energy recovery operations (outside the sawmill) are not technically or commercially linked to timber production; as there is no direct interaction between the two processes, the carbon savings are not part of the same system and should not logically be considered within the same system boundary (in contrast to, for example, steel recycling, whose only customer is the steel industry). In any case, if the carbon credit for energy recovery is attributed to the structural material as it enters the system, then when it leaves the system at end of life it is no longer a carbon-neutral fuel – the credit cannot be double counted – and thus the major incentive to use it as fuel is removed. In the absence of this incentive, most energy producers would rather not burn wood waste because it contains toxic preservatives (e.g. arsenic, chromium) that could cause flue gas emissions to fail environmental standards (see e.g. Defra, 2010); this in turn can foment local social opposition to the use of biomass incineration (BBC, 2012); and the inclusion of biomass in electricity generation processes by way of co-firing with coal may also render the fly ash byproduct unsuitable for further use, for example in concrete (Rajamma *et al.*, 2009).

Thus other investigators (Hammond and Jones, 2008) have assigned a value for, for example, glulam timber structural composites (~12 MJ/kg, 0·7 $kgCO_2$/kg timber) based on simply analysing the energy use and emissions of forestry operations, timber processing (drying, sawmilling etc.) and transport, which requires no external justification based on assumed activities divorced in space, time and economics from the production of the material.

Calculating the EC of concrete, let alone reinforced concrete, is less controversial but rather more complex. It comprises contributions from cement, reinforcing steel, aggregate, water and admixtures (although in practice the contributions from the first two overwhelmingly dominate), which are combined in an almost infinite variety of proportions according to the design requirements of the structural component under study. While some investigators have used single values (e.g. Hacker *et al.*, 2008; Harrison *et al.*, 2010), it has been shown that the EC of reinforced concrete is in fact a strong function of structural design and loading (Purnell, 2012b), whereas that of plain concrete is critically dependent on the mix design and the compressive strength grade (Purnell and Black, 2012). Assigning a single, general value to the EC of reinforced concrete is thus likely to lead to gross over-simplifications. These could prove costly should we enter an economic environment where the cash price of carbon dioxide emissions increases substantially; some governmental commentators are suggesting that levels of up to €100/tCO_2 may be required to decarbonise the economy (Ares, 2012).

Comparing structural materials

The nature of the construction industry, where structural solutions are often classified and promoted primarily according to their main functional materials ('concrete structures', 'steel structures' or 'timber structures') inevitably leads to the temptation of comparing the carbon footprint of structural materials. A number of approaches are possible.

In trade and quasi-technical literature, a narrative, non-analytical approach is favoured; statements such as

- 'the steel industry is winning the sustainability argument over concrete' (by a major steel supplier)
- 'Replacing 1 m^3 of concrete or red brick with the same volume of timber can save around 1 tonne of carbon dioxide' (by a governmental organisation concerned with forestry)
- or, 'Comparing lightweight timber homes with medium weight and heavyweight masonry and concrete homes . . . the latter has the lowest CO_2 emissions' (by a cement and concrete trade body).

are commonplace. These often have little basis in credible analysis and should be regarded as marketing blurb.

A 'top-down' analysis from global consumption and emissions statistics is also possible. For example, anthropogenic production of all substances has been estimated at 60×10^{12} kg (60 Gt) per annum (2005 figures from Krausmann *et al.*, 2009). If fossil fuels, non-harvested crops (grazed biomass, fodder crops) and globally significant waste streams (crop residues, mine tailings) are excluded, then the total quantity of virgin 'products' produced annually by mankind (i.e. earth's resource consumed to manufacture tangible items made from functional, structural and/or edible materials) is 34 Gt; the global carbon dioxide emissions for the same period were 30 Gt (Boden *et al.*, 2010). The production of the major structural materials – reinforced concrete, steel and timber – accounts for a significant proportion of these quantities. By comparing the proportions both of global production and of global carbon dioxide emissions attributable to each material, a simple index I_P can be constructed that reflects whether the carbon footprint of each is higher ($I_P > 1$) or lower ($I_P < 1$) than the hypothetical 'average' material (Table 1). It can be seen that by this simple ecometric measure, the manufacture of concrete is significantly less carbon dioxide intensive than other materials.

However, such an analysis, while informative in terms of the overall carbon dioxide emissions picture, has little use in a structural engineering sense, since it takes no account of the relative utility of each material. Similarly, 'bottom-up' calculations that return values for EC of structural materials per unit mass or volume are ipso facto of limited use for preliminary structural design; 1 kg of concrete does not do the same job as 1 kg of timber or 1 kg of steel. Thus, in order that analyses remain comparable, it is important to define a 'functional unit' that allows comparison of like with like. For example, a column is designed to resist compressive load and supply a given height clearance; thus the correct functional unit to compare columns would be '$kgCO_2$ per unit load capacity per unit height' ($kgCO_2$/(kN m)). A beam must provide a resistance to bending moment over a prescribed span, and thus should be compared on the basis of '$kgCO_2$ per unit bending moment capacity per unit span' ($kgCO_2/(kN\ m^2)$) (Purnell, 2012b).

Previous work has analysed either the EC of plain concrete as a function of strength grade and mix design, or the EC of reinforced concrete as a function of structural form. In this paper,

Material	Production/GT	As % of total products (A)	CO_2 emitted during production/GT	As % of total CO_2 (B)	$I_P = B \div A$
Concrete (RC + plain)[a]	19	57	2·7	9	0·16 ± 0·04
Steel[b]	0·98	3	2·3	8	2·7 ± 1·1
Timber[c]	2·1	6	5·4	18	2·9 ± 1·5

[a] Production figures for concrete matrix (19·2 Gt) were derived from an average of the 'cement related minerals' figures reported by Krausmann *et al.* (2009) and a calculation based on the cement content of a typical concrete mix design (C25/30) and US Geological Survey figures for cement production (see Van Oss, 2012). Production figures for rebar (0·17 Gt) assumed that 15% of steel production is rebar (Hugas, 2007), steel figures derived as for footnote[b] below. Total concrete figure = concrete matrix + rebar. Carbon dioxide emissions figure is the sum of the figures for cement manufacture (2·3 Gt, e.g. Akashi *et al.* cited in Rubenstein (2010)) and the 15% of steel-related carbon dioxide emissions (see below). This will overestimate the rebar-related emissions, as the recycled content of rebar is significantly higher than that of other structural steel.
[b] Production figures for non-rebar steel derived as 85% of total steel production (1·15 Gt, see WSA (2011) and Hugas (2007)). Emissions figures derived from 85% of total steel emissions (2·6 Gt, 2004) given by the Carbon Trust (2011) and scaled linearly with growth in global carbon dioxide emissions to provide 2005 figures (2·7 Gt). Note that this includes the production of recycled steel; arguably, only virgin steel production (0·81 Gt) should be included (since only this involves direct geological resource depletion according to the methodology of Krausmann *et al.*, 2009).
[c] Figures for timber production and emissions are diverse, divergent and difficult to obtain. Production figures are an average of the Krausmann *et al.* (2009) figure for wood (2·2 Gt) and the Eliasch (2008) figure of 3·5 Gm^3 assuming an average density of 600 kg/m^3. Emissions figures for wood were the sum of forestry emissions (17% of global carbon dioxide emissions = 5·1 Gt according to the Intergovernmental Panel on Climate Change (IPCC) cited in Eliasch, 2008) and an estimate of non-biomass derived processing energy (drying, sawmill, transport etc.) of 72 kg CO_2/m^3 timber (total 0·25 Gt, Puettmann *et al.* (2010)).

Table 1. Production and carbon dioxide emissions for the major structural materials (2005 figures). Error bands in I_P are estimates based on expert judgement

the variation of EC per unit of structural performance for reinforced concrete components is analysed as a function of concrete compressive strength grade, reinforcement steel strength and concrete mix design for beams, short columns and slender columns, complementing these previous analyses.

Methodology

A range of reinforced concrete beam and short column designs was produced according to a consistent optimisation procedure based on Eurocode 2 (BS EN 1992, BSI (2004)) and then analysed for EC, based on the methodology previously described by Purnell (2012b: 'Supporting information'). Three mix design families (M0, M1, M2) were used (Table 2) for 13 strength grades between C16 and C90 (characteristic compressive cylinder strengths of between 16 and 90 MPa), giving 39 different mix recipes for analysis, after the method of Purnell and Black (2012). M0 represents a normal, utility concrete; M2 and M1 represent concretes more closely optimised for low EC (according to Purnell and Black (2012), with and without partial replacement of cement by pulverised fuel ash (PFA), respectively. In designing the sections, two steel strengths were used; 400 MPa (labelled 'low' on graphs) and 600 MPa ('high'), that is the upper and lower bounds permitted by Eurocode 2. For the columns, designs employing both minimum ('Min') and maximum ('Max') steel areas A_{st} permitted in Eurocode 2 were analysed.

Embodied carbon was calculated in two ways

- as 'EC_{raw}', the simple 'cradle to gate' mass of carbon dioxide emitted per unit mass of reinforced concrete (considering all major emissions during mining, processing, transport to site and so on, but not post-installation operations, e.g. demolition; these are generally not significant)
- as 'EC_f', expressed in terms of functional units, that is normalised with respect to the relevant structural parameters as described above (for more details, see Purnell (2012b)).

This latter term is of primary interest as it allows comparisons and optima to be identified.

The values used for the EC of the various components were as those used by Purnell and Black (2012) (in units of $kgCO_2/kg$): cement = 0·83; PFA = 0·01; aggregate = 0·005; superplasticiser = 0·01; and water = 0·001. The value used for reinforcing steel was 0·68, corresponding to a 90% recycled fraction as used by Purnell (2012b). Note that the EC values for the reinforced concrete were overwhelmingly dominated (>95%) by the EC of the cement and the steel.

Mix	Aggregate	Slump: mm	PFA: % binder	Superplasticiser?
M0	Uncrushed	60–180	0	No
M1	Crushed	10–30	0	Yes
M2	Crushed	10–30	40	Yes

Table 2. Mix design families for concrete. PFA, pulverised fuel ash

Results and discussion

Figure 1 shows EC_{raw} (Figure 1(a)) and EC_f (Figure 1(b)) for a simply supported reinforced concrete beam. Curves were calculated for a wide range of beam sizes and aspect ratios and all curves showed the same principal features and relationships between families; thus only the curves for a single beam (12·0 × 1·0 × 0·4 m) are reported here.

As expected, EC_{raw} rises with concrete strength grade owing to the increased cement content of the concrete and the concomitant increase in steel area required to preserve ductile failure

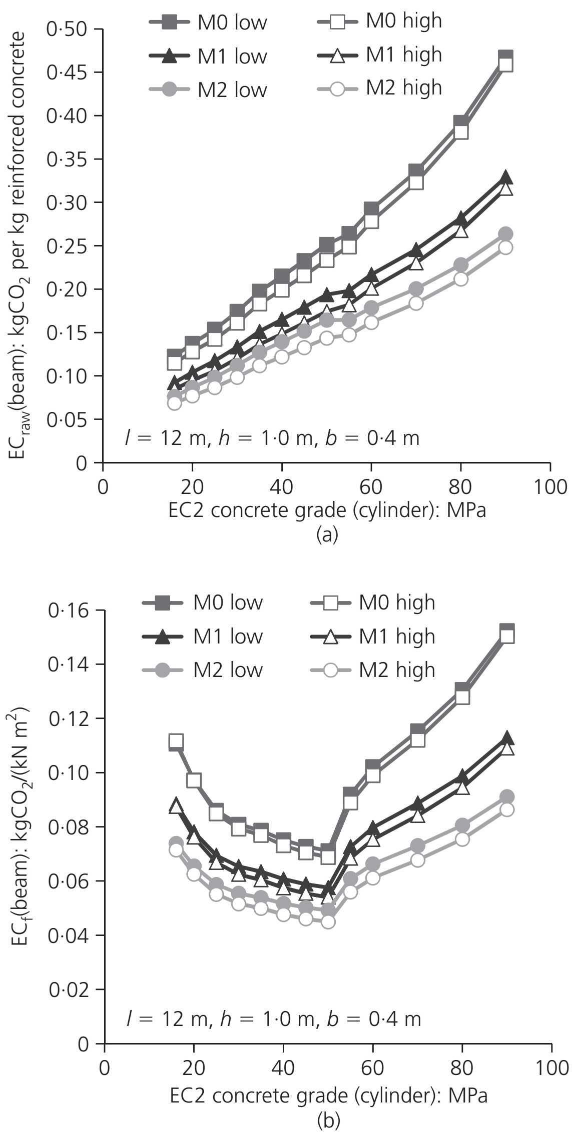

Figure 1. EC plotted against concrete strength grade for beams: (a) EC_{raw}; (b) EC_f. EC, embodied carbon dioxide

characteristics. However, the envelope of EC_{raw} values ($0{\cdot}07 \leqslant EC_{raw} \leqslant 0{\cdot}52$) is rather wider than that normally quoted. The EC savings gained by moving from M0 to M1 – adjusting 'normal' mix design parameters such as slump value or use of plasticiser – are generally greater than those obtained by replacing cement with PFA (M1 to M2). The difference between using high and low-strength steel with respect to EC_{raw} appears to be negligible.

Of more interest is the variation of EC_f since this will control the overall EC of structural components. Here, it can be seen that the differences between mix families and so on are similar to those for EC_{raw}. However, there is a clear minimum in all curves at a concrete strength grade of C50, at which the EC per unit of structural performance is optimised. Below 50 MPa, the savings in EC gained by the lower cement content are outweighed by the carbon cost of having to use more concrete (and, to a lesser extent, more steel).

However, the optimum is much sharper than that previously reported (Purnell and Black, 2012) for unreinforced concrete (in which the material savings gained by use of high-strength concrete are outweighed by the higher cement content required). This is due to provisions within Eurocode 2 (BS EN 1992, BSI (2004)) (see paragraphs 3.7.1-3; 7.4.2-2; 5.5) that, for concrete strengths greater than 50 MPa, limit both the depth of the neutral axis and the size of the stress block used in analysis, and also introduce a strength factor of <1; these combine to require greater steel areas and less efficient sections for high-strength concrete. The EC_f saving in using (for the same mix family) C50 concrete compared with low or high-strength alternatives is 40–50%.

Figure 2 shows EC_{raw} (Figure 2(a)) and EC_f (Figure 2(b)) for a simply supported short column. The curves for high and low-strength steel were almost identical and so only those for the former are reported. Note that curves for maximum and minimum steel contents are, however, both reported. There appears to be some benefit in using maximum rather than minimum steel areas for columns – the increase in EC caused by the increased steel content is outweighed by the structural efficiency – but this effect becomes smaller as the concrete grade and/or mix family approaches the optimum with respect to EC_f. Otherwise, the overall outlook for both EC measures is very similar to those reported for beams, suggesting that the general findings are applicable to a wide range of structural elements.

Figure 3 compares the percentage savings in EC_f obtained by replacing M0 with M1, or M1 with M2. It can be seen that the saving is a strong function of concrete strength grade, steel strength and A_{st}. Replacing M0 with M1 can save between 20 and 40%. Replacing M1 with M2 (i.e. using PFA to replace 40% of cement) saves between 10 and 25%, which is generally less than the saving gained by adjusting normal mix design variables reported above, and not 40% as is frequently assumed, owing to the contribution of the steel and the secondary effects on mix design described by Purnell and Black (2012). The combined effect (i.e. replacing M0 with M2) for a given strength class ranged from 28 to 55%.

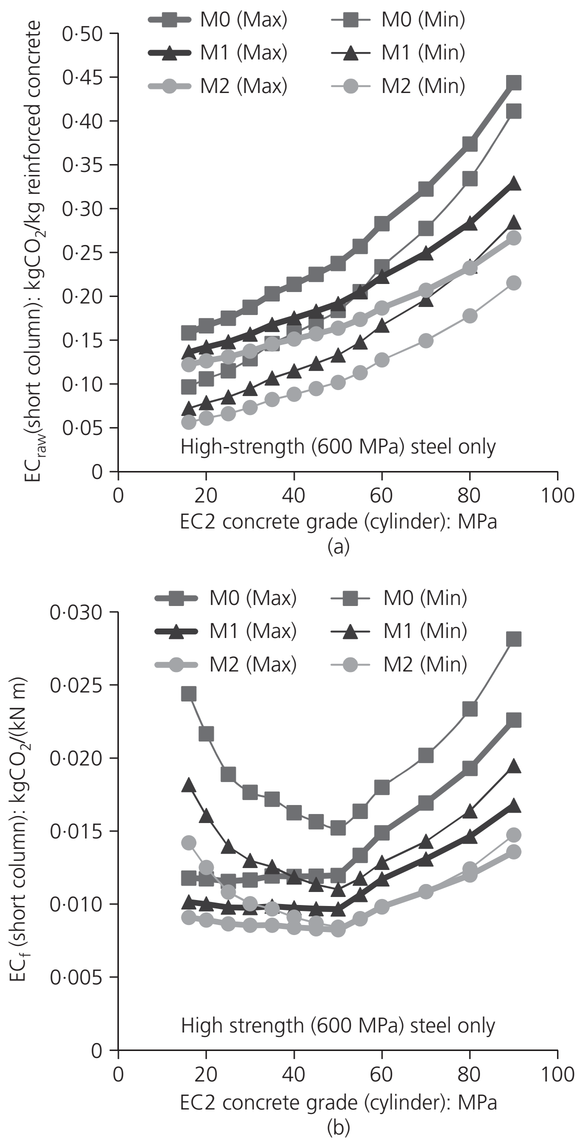

Figure 2. EC plotted against concrete strength grade for short columns: (a) EC_{raw}; (b) EC_f. EC, embodied carbon dioxide

Since it is clear that C50 is the optimum concrete grade, it is instructive to compare EC_f of structural components made thereof (for the three mix families M0, M1 and M2) with comparable standard structural sections of other materials. Figure 4 compares C50 reinforced concrete beams with standard steel universal beam (assuming a 60% recycled content (WRAP, 2008) and glulam timber composite sections (over an 8 m simply supported span) for a range of section sizes. The difference between high and low-strength steel was negligible and thus only high-strength steel is shown.

It can be seen that, where Eurocode 2 permits a section to be designed according to limits therein on span:depth ratio, the optimised reinforced concrete beams outperform both steel and timber in terms of cradle-to-gate embodied carbon per unit of

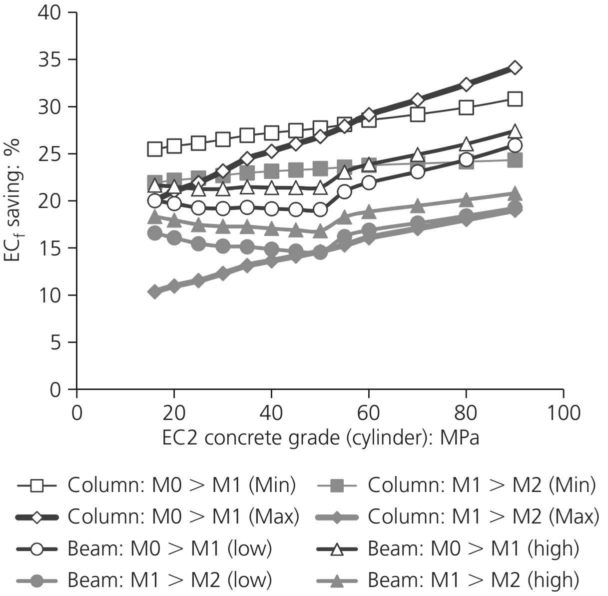

Figure 3. Savings in EC_f achievable by adjusting mix design or cement replacement with PFA. EC, embodied carbon dioxide; PFA, pulverised fly ash

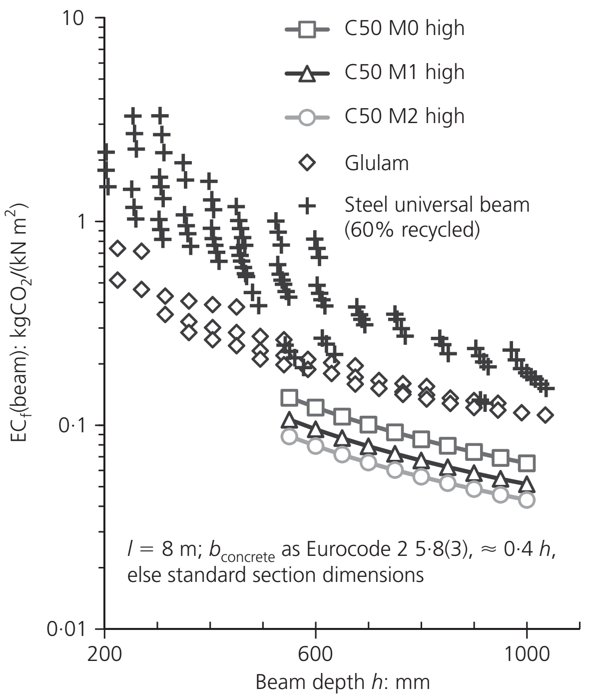

Figure 4. EC_f plotted against beam section depth for various structural materials. Standard sections were used in analysis for timber and steel beams, that is breadth b was a non-monotonic function of the total section depth h. For reinforced concrete sections, the b:h relationship was as specified in Eurocode 2 section 5·8(3) (BSI, 2004), which for most cases of large beams gives $b = 0{\cdot}4\ h$. For detailed methodology, see Purnell (2012b). EC, embodied carbon dioxide

structural performance, regardless of the mix family used. Reinforced concrete remains optimal with regard to EC_f for a wide range of structural situations, except for very lightly loaded sections (such as those used in low-density residential construction), where timber becomes competitive (Purnell, 2012a, 2012b).

Conclusions

The EC_{raw} of reinforced concrete varies over a wide range (0·07–0·52) depending on mix design, compressive strength grade, structural form and load capacity, and thus any notion that there is a single EC value for reinforced concrete is fallacious. There is a clear optimum with regard to EC per unit of structural performance (EC_f) that occurs at a concrete grade of C50; using C50 concrete can potentially halve EC_f. The reduction of EC_f achievable by adjusting normal mix design parameters for a given concrete grade is ~20–35%; that achievable by replacing 40% of cement with PFA is ~10–25%; and that achievable by combining both approaches ~25–50% (the variation in all being a function of structural form). Reinforced concrete beams designed with optimised strength concrete present significantly lower EC_f values than comparable steel or timber composite beams over the entire range of permissible concrete section sizes in large-scale construction.

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