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Embodied carbon dioxide in concrete: variation with common mix design parameters

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Abstract

The transition towards a low-carbon infrastructure requires an understanding of the embodied carbon (eCO_2) associated with concrete. However, much current work on eCO_2 underestimates the complexity of its relationship with concrete mix design. This paper demonstrates how eCO_2 of concrete is not a simple function of strength. Rather, for a given strength, considerable eCO_2 savings can be made by careful attention to basic mix design. Replacement of cement with PFA (pulverised fuel ash) can achieve considerable savings; additionally, using a concrete of lower workability, employing a superplasticiser, using crushed rather than rounded aggregate and using a higher strength of cement can have comparably significant effects. The analysis is presented in terms of embodied carbon per unit strength; this shows that there is an optimum strength for all concretes (with regard to minimising eCO_2 per unit of structural performance) of between 50 and 70 MPa.

1. Introduction

Carbon dioxide emissions attributed to construction in the UK amount to almost 52 Mt per year [1], accounting for 9.6% of the UK's 'carbon footprint' [2]. Legislation binds the UK Government to an 80% reduction in CO_2 emissions by 2050, and hence their reduction is a government priority [3]. Since operational CO_2 (oCO_2), defined as those emissions associated with the energy used in heating, lighting, air-conditioning, IT services, maintenance etc [4], makes the greatest contribution to emissions, current guidelines rightly concentrate exclusively on reducing these emissions.

Yet the embodied CO_2 (eCO_2) emissions – those associated with the construction and disposal phase of the lifecycle – are a significant proportion of the total lifecycle emissions. Sturgis and Roberts [4] quote figures of 30% for housing, 20% for a supermarket, 45% for an office and 60% for a warehouse. This proportion will approach unity as low-carbon operational paradigms – better insulation, low-energy lighting, fabric energy storage etc. – are introduced, pushing towards the target of reducing oCO_2 to zero by 2019 [5]. Furthermore, for infrastructure, operational emissions are either negligible (e.g. for a dam) or attributed to users (e.g. exhaust emissions from vehicles using a bridge). Thus it is important that we begin to understand the eCO_2 associated with construction.

Most analyses of eCO_2 in construction conclude that it is dominated by the emissions associated with the industrial production of materials [e.g. 6]. Concrete is the most predominant construction material, with global production approaching 20×10^{12} kg per annum, significantly more than all other construction materials combined; and increasing at several percentage points annually as large developing nations upgrade and install infrastructure [7]. Thus, formulating policy for reducing the overall carbon emissions of the built environment will require that the eCO_2 of concrete is known with some degree of confidence, and that approaches to maximise the efficiency of concrete use are developed.

In contrast to many other major structural materials, concrete is a complex composite. Its wide palette of engineering properties – compressive strength, workability, permeability, chemical resistance etc – is under the nominal control of the structural designer, rather than the materials supplier. Each of these properties can vary dramatically depending on mix recipe; in most cases there are many mix recipes that will result in a concrete which fulfils the designer's requirements. This multiplicity offers the structural designer an effectively infinite range of concretes, each of which will have its own eCO_2 value. Any notion that concrete has a single, easily defined eCO_2 is clearly deficient.

Despite this, many commentators have published eCO_2 values for concrete, either as individual values or a small range depending on certain properties (mainly compressive strength grade and the use of supplementary cementitious materials). Hammond and Jones [8] give a general value of 0.107 and a monotonic relationship between eCO_2 (0.061 – 0.188) and characteristic cube strength (8 – 50 MPa) for CEM I and CEM II concretes (see below). However, they do advise against the indiscriminate use of these values. Meanwhile, Hacker [9] uses a value of 0.200 with no strength discrimination, whilst Harrison [10] uses 0.13 for plain concrete and 0.24 for "2% reinforced"; the additional CO_2 attributable to the steel. Among those reporting on a volumetric basis, Flower & Sanjayan [11] use values of 0.225 - 0.322

kg/m^3 for normal and blended cement concretes, corresponding to eCO_2 ~ 0.09 – 0.12. However, none of these studies give systematic details of mix designs (i.e. relative proportions of constituent materials).

The purpose of this paper is to demonstrate how changing some of the independent mix design variables that have the greatest effect on a concrete mix – cement grade, crushed vs uncrushed aggregate, use of superplasticisers, use of PFA (pulverised fuel ash, also known as fly ash) and workability (i.e. slump) – affects eCO_2 in traditional concrete mixes. It will also introduce a 'normalised' eCO_2 value to account for the trade-off between higher cement content (and thus increased eCO_2 per unit of material) and higher strength (and thus use of less material and decreased eCO_2 per component), and by extension the concept of a functional unit for correct analysis of the eCO_2 of structural elements. This goes some way towards aligning the treatment of such problems from an engineering perspective with formal life cycle analysis methods (e.g. ISO 14040).

2. Methodology

In summary, we calculated the eCO_2 and predicted mean compressive strength at 28 days standard curing of cube specimens (target mean strength) for 512 theoretical, 'virtual' concrete mixes, as a function of the most important mix design variables. These model mixes were derived from a widely accepted and validated mix design method used throughout UK academia and industry. Whilst it was clearly not feasible to manufacture and test over 500 mixes in a preliminary study of this nature, a number of real trial mixes were prepared, cured and tested for compressive strength in the lab to check the validity of the model.

The BRE mix design method [12] was used as the basis for this work by transferring the graphical method therein to a spreadsheet in order that the entire range of theoretical mix designs could be explored. The five design variables having the greatest effect on the concrete mix specification were varied from their maximum to their minimum values, i.e.:

- CEM I Cement strength class: 52.5 or 42.5 MPa
- Addition of PFA: 0% or 40% replacement of cement
- Use of super-plasticiser (1% by mass of binder content as liquid additive): no or yes
- Aggregate type: uncrushed or crushed
- Slump value: low (L, 0 – 10 mm) or high (H, 60 – 180 mm).

All other mix design factors (aggregate size, grading etc) were kept constant as they have minimal effect on strength for normal concrete mixes. This approach gave $2^5 = 32$ mix families, as described in table 1. For each mix family, individual mixes were designed for 16 target mean compressive cube strengths between 17 and 120 MPa (approximately corresponding to the 16 characteristic strength classes between C8/10 and C100/115 specified in Eurocode 2 [13]; assuming a standard deviation in compressive strength of 4 MPa), giving a total of 512 virtual mix designs (i.e. 32 mix families × 16 strength classes).

The embodied carbon dioxide (on a mass basis i.e. kg CO_2 per kg of concrete and thus a dimensionless quantity) for each virtual mix was calculated according to the contribution from each of its constituents, using the values given in table 2 [8, 11, 14, 15]. These values are considered by the authors to be the most authoritative available in the open literature. Note that the eCO_2 value for the concrete is overwhelmingly dominated (>95% in most cases) by that associated with the cement content.

To validate the strength predictions of the model, eight real trial mixes for mean compressive cube strengths of between 27 and 70 MPa were manufactured in triplicate. A plot of predicted virtual strength vs. measured real strength at 28 days was obtained and the resultant calibration curve was linear with slope of 1.04 and a correlation coefficient of >0.95 i.e. the model tended to slightly, but not significantly, underestimate strength.

3. Results & Discussion.

Figure 1a shows eCO_2 vs. target mean strength for all 32 concrete mix families. This represents the entire envelope of data generated by the mix design model; each curve corresponds to a single mix family. The figure is intended merely to show general trends and thus for clarity, only the maximal (mix family 18) and minimal (mix family 15) curves are labelled. As expected, eCO_2 rises with concrete strength, owing to the higher cement contents required of such mixes to preserve workability and compaction. However, for a given concrete strength, eCO_2 varies by a factor of ~3; thus, any notion that eCO_2 is a simple monotonic function of strength is clearly overly simplistic and explains the scatter encountered by Habert [16]. The eCO_2 of the concrete mixes where the binder is a blend of CEM I and PFA (dashed lines in Figure 1) is typically lower than the eCO_2 of concrete mixes with only CEM I (solid lines in Figure 1). However, this is not always the case. It is possible to have a PFA-CEM I concrete with a higher eCO_2 than a CEM I concrete of the same strength; i.e. there is some overlap between the sets of dashed and solid lines in Figure 1. Thus the commonly held view that a concrete made with a blended cement binder will automatically and necessarily have a lower carbon footprint than a traditional concrete is also erroneous.

As presented in Figure 1, the observation that eCO_2 increases with compressive strength is not surprising, and has been reported elsewhere [8, 11]. However, it is not realistic to consider the eCO_2 of concrete solely in terms of its mass. It is clear that to resist a given compressive load, using a higher strength concrete will result in the use of a lower mass of concrete. Rather, the concrete should be considered in terms of its structural performance; thus the simple eCO_2 plot in Figure 1a is of limited value. Therefore, Figure 1b normalises eCO_2 with respect to compressive strength.

The embodied CO_2 of concrete is dominated by the contribution from the cement and so rises approximately linearly with cement content. Yet the relationship between strength and cement content is non-linear and dominated by the well-known (and also non-linear) interaction with water:binder ratio [see e.g. 17] . Consequently, as clearly demonstrated in Figure 1b, there is an optimum concrete strength with regard to minimising eCO_2 per unit of structural performance, at around 60 MPa. For weaker concretes, the reduction in eCO_2 associated with lower cement content is outweighed by the need to use more concrete for any given structural component. For stronger concretes, the reduction in material use afforded by the increased strength is outweighed by the increased cement content required to achieve that strength. Using the optimum strength concrete will result in eCO_2 reductions of up to 40% for any given mix family. Fortunately the minima are quite broad, which allows the designer to retain considerable flexibility in mix design without a large carbon penalty.

In addition to the data presented in Figures 1a and 1b, it was also possible to use the raw data to extract the effect of the individual mix design variables (there is negligible interaction) and assess their relative importance. As expected, an important factor was moving from 100% CEM I binder to 40% replacement by PFA, producing a reduction in eCO_2 (for a given concrete strength) of 35 ± 1%. Note that this is contrary to the simple expectation that replacing 40% of the PFA reduces eCO_2 by ~40%. For a given target 28 day strength, adding PFA requires that the water/binder mass ratio (w/b) be reduced to compensate for the lower reactivity of the PFA (a k value of 0.3 has been assumed, [12]). Even though PFA is ~30% less dense than cement and thus replacing cement with PFA tends to increase binder volume, the net effect is that in order to keep the paste (i.e. cement + PFA + water) fraction of the concrete constant, the total binder mass content must be increased by ~13% and thus the cement content is only reduced by ~35%, not 40%.

The specification of workability had a surprisingly large effect on eCO_2. Moving from a slump class of 60-180 mm to 0-10 mm decreased eCO_2 by 35 ± 1% i.e. was as significant a factor as the use of PFA. Increasing the workability of a normal concrete mix (all other factors remaining the same) requires that the water content of the mix be increased. In order that the w/b ratio remains constant, preserving strength, the binder content must again be increased correspondingly.

Use of a superplasticiser was found to reduce overall eCO_2 by 26 ± 1%, since a given workability could be achieved at reduced water content and thus to keep the w/b ratio constant the binder content could be reduced correspondingly. This saving could be achieved because the eCO_2 imparted by the superplasticiser itself was negligible.

Changing the aggregate type from uncrushed to crushed, or the cement strength class from 42.5 to 52.5 MPa, both had a relatively small effect on eCO_2 (savings of 9 ± 1% and 7 ± 1% respectively). Therefore, to more clearly visualise the impact of the key variables on eCO_2, the data are re-plotted in Figure 2, with the curves for cement strength class 42.5 and/or uncrushed aggregate having been removed. Additionally, the curve focuses on the strength range from 20 to 80 MPa, since this is the region in which extensive laboratory experience suggests we can be confident in the model.

Overlaid in Figure 2 are eCO_2 and normalised eCO_2 values for selected mix designs from the literature spanning >20 years [18-20]. The mix designs arrived at via traditional means [18, 19], fall into the envelope predicted by the model. The designs supposedly optimised for ‘ecological effects’ using a neural network model however [20], would appear to be rather expensive in terms of eCO_2. The two monotonic relationships presented by Hammond [8] are also overlaid. They are almost coincident with the upper bound curves for both normal (mix 4) and PFA (mix 12) concretes.

Conclusions

This work has shown that it is an oversimplification to consider the embodied carbon of concrete either as a fixed value or as a direct function of compressive strength. It is clear that carbon savings may be achieved by carefully considering the mix recipe in detail. Replacement of cement clinker with PFA can achieve considerable savings, as is often reported, but using a concrete of lower workability, employing a superplasticiser, using crushed rather than rounded aggregate and/or using a higher strength of cement can have comparably significant effects. Furthermore, analysing eCO_2 normalised for compressive strength as a function of mix design clearly indicates that there is an optimum strength, typically about 60 MPa, at which the eCO_2 per unit of structural performance is minimised.

The absolute values presented here should emphatically not be taken as a definitive guide to the eCO_2 of concrete. Rather, they serve to highlight that considerable CO_2 savings can be achieved by adjusting everyday parameters without recourse to e.g. exotic cements.

Figure captions.

Figure 1: variation of eCO_2 (a) and eCO_2 per unit strength (b) for 32 mix families. Solid lines represent concrete with a CEM I binder. Dashed lines represent concrete with a 60% CEM I – 40% PFA binder.

Figure 2: detail of selected mixes from Figure 1, with selected data points from literature overlaid [8, 18-20]. Closed symbols indicate CEM I mixes; open symbols indicate 30 to 50% cement replacement by PFA. NB. Curves for mixes 12 & 3, and 16 & 7 overlap

Table captions

Table 1: Mix design families

Table 2: eCO_2 values for major concrete constituents.

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Purnell, Black – “Embodied … parameters” – Table 1

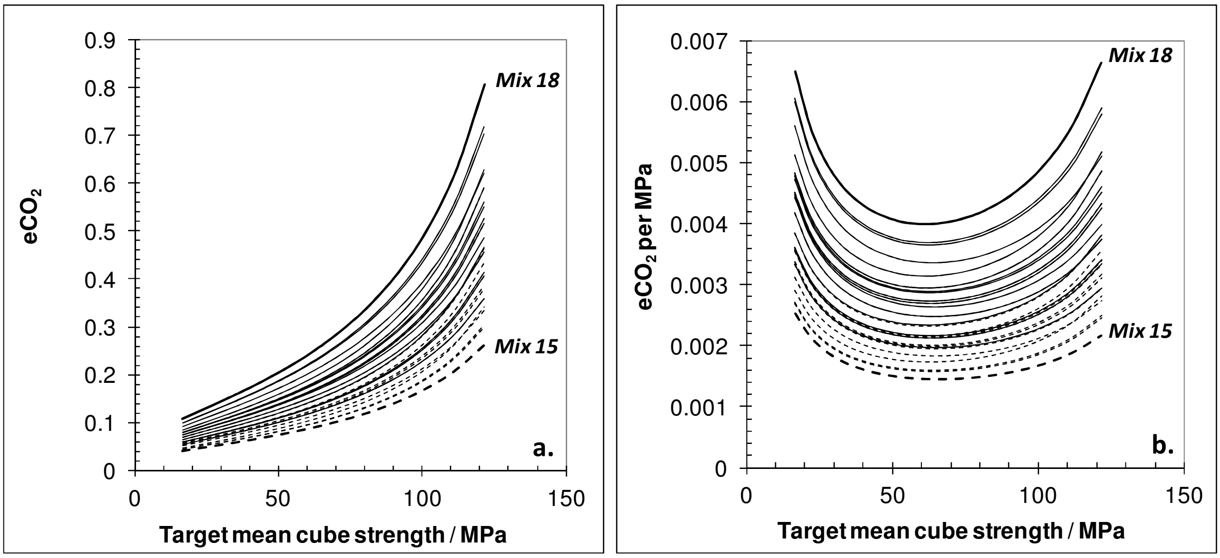
Mix family	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
CEM1 Cement class	52.5 MPa															
PFA content	0%								40% replacement of CEM1							
Superplasticiser	No				Yes				No				Yes			
Aggregate type	Uncrushed		Crushed		Uncrushed		Crushed		Uncrushed		Crushed		Uncrushed		Crushed	
Slump	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H

Mix family	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**
CEM1 Cement class	42.5 MPa															
PFA content	0%								40% replacement of CEM1							
Superplasticiser	No				Yes				No				Yes			
Aggregate type	Uncrushed		Crushed		Uncrushed		Crushed		Uncrushed		Crushed		Uncrushed		Crushed	
Slump	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H

Purnell, Black – “Embodied … parameters” – Table 2

Constituent	**eCO2**	**Reference**
Cement	0.93	8, 14
PFA	0.01	8
Aggregate	0.005	8
Superplasticiser	0.01	11
Water	0.001	15

Purnell, Black – “Embodied … parameters” – Figure 1



Purnell, Black – “Embodied … parameters” – Figure 2