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Is carbon dioxide pricing a driver in concrete mix design?

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The global cement industry is responsible for 7% of anthropogenic carbon dioxide emissions and, as such, has a vital role to play in the transition to a low carbon dioxide economy. In recent years, this has been achieved by technological advances and increased use of supplementary cementitious materials, but the authors have recently shown that there are other means of achieving comparable carbon dioxide savings, for example, by reducing workability. However, price remains a considerable barrier to the widespread implementation of low carbon dioxide concrete. Using the same model for concrete mix design as was used to determine embodied carbon dioxide (ECD), variations in the cost of the components of concrete have now been considered. Considering 24 different mix designs, each spanning a range of characteristic strengths from 20 to 100 MPa, measures to reduce the carbon dioxide footprint were also found to reduce the material cost of the concrete. As such, it may be considered that the construction industry is already encouraged to reduce its 'carbon footprint'. However, the concept of the carbon footprint was then considered in a more nuanced fashion, considering the ECD per unit strength. On such a basis, the cheapest mixes did not have the lowest ECD. Therefore, the impact of levying a charge on the carbon footprint was considered. To ensure low carbon dioxide concrete is also the cheapest, carbon dioxide emissions would have to be priced approximately one to two orders of magnitude higher than current market value. This would become the dominant factor in construction, with serious consequences for the industry. Furthermore, such charges may pose ethical problems, being viewed as a 'licence to pollute' and therefore undermining society's efforts to reduce the carbon dioxide emissions of the construction industry.

Introduction

On 26 May 2013, the Mauna Loa observatory in Hawaii, USA, recorded a weekly average atmospheric carbon dioxide (CO_2) level of 400·03 ppm (ESRL, 2015). This was the first time in the history of humankind that the concentration of carbon dioxide passed the 400 ppm threshold. Shortly after this event, Christiana Figueres, Executive Secretary of the United Nations Framework Convention on Climate Change, stated that current efforts to mitigate the effects of climate change were insufficient to ensure that global warming was kept to less than 2°C above pre-industrial levels (UNNC, 2013). This has since been confirmed by publication of the International Panel on Climate Change Working Group I Assessment Report, which stated that 'Warming of the climate system is unequivocal, human influence on the climate system is clear, and limiting climate change will require substantial and sustained reductions of greenhouse gas emissions' (IPCC, 2014).

In assessing the potential for reducing the carbon dioxide emissions of the global economy, various 'costs' have been placed on carbon dioxide emissions, and a range of measures have been implemented to try and drive behaviour. Probably the most widely known of these is the – sometimes derided – European Union emissions trading scheme (EU-ETS), which has adopted a 'cap and trade' principle. However, despite allowances within the current third phase being 21% lower than in the first phase (2005–2007), the European economic downturn led to an oversupply of carbon dioxide allowances and the price of such allowances plummeted, with prices of around £4/t during 2013. This has recently risen (Carr and Vitelli, 2014), but is still considerably lower than had been anticipated when the scheme was first introduced. Recognising the fact that EU-ETS allowance prices did not provide an incentive to reduce carbon dioxide emissions, and driven by a need to fulfil obligations under the 2008 Climate Change Act, the UK government recently announced a 'carbon price floor' (CPF) as part of the 2012 Finance Act (Finance Act, 2012). This tax on fossil fuel burning for power generation will be levied to ensure a minimum price for carbon dioxide emissions. The initial price was £4·94/t of carbon dioxide, rising to £9·55/t in 2014/5 and £18·08/t in 2015/6 (Finance Act, 2012). In addition to these initiatives, there are plans for similar carbon dioxide markets in China and a number of other countries. Meanwhile, in a move that passed many by at the time, the US government increased its 'social cost of carbon' (SCC) from \$23.80 to \$38 per ton from 2015 (US Government, 2013). Whilst not a direct tax, it is intended that the SCC will help to drive more environmentally friendly policies, by providing a consistent, quantitative assessment of the impact of climate change. Opposition to many of these proposals has been vocal (e.g. Ares, 2014; Gosden, 2013), with demands for the UK government to rescind, or not increase, the CPF, and the Australian government abolishing plans for a carbon dioxide market in 2014. Conversely, Moore and Diaz (2015) proposed a SCC of \$220/ton (~£156/t) to account for both climate change and its associated impact on economic growth.

Running counter to the need to reduce carbon dioxide emissions, there is global demand for improved living standards and infrastructure development. While Portland cement may now often be blended with supplementary cementitious materials (SCMs), it is still the material of choice for such development, with 3·24 billion tonnes of clinker produced in 2014 (USGS, 2015). As a result of cement's popularity, the global cement industry is responsible for 1·9 Gt of carbon dioxide, or 6·7% of anthropogenic emissions (Allwood and Cullen, 2011). Consequently, just small improvements in reducing the carbon dioxide footprint per unit mass can have a large impact on global carbon dioxide emissions, and so the cement and concrete industries have a valuable role to play in the transition to a low carbon dioxide economy.

In recent years there has been considerable improvement in the technology of cement production. The gradual transition from wet to dry processes, along with more widespread use of pre-calciners and other heat recovery systems, has led to marked reductions in the embodied carbon dioxide (ECD, defined as the mass of carbon dioxide released due to production of a given mass of material) of cement clinker associated with process energy consumption. Current ECD figures for European CEM I cement manufacture are 884 kg CO_2/t (EC, 2014). As energy use in European cement manufacture approaches maximum efficiency (Allwood and Cullen, 2011) and improves greatly across the world, without significant changes in the composition of the clinker there is little scope for further reductions in ECD (i.e. emissions associated with the chemistry of the process), hence the continual drive towards increased use of SCMs such as pulverised-fuel ash (PFA) and ground granulated blast-furnace slag (GGBS). Current replacement levels in the UK are just over 13%, and there is potential to increase this further, with a target of 30% by 2050 (MPA, 2013).

However, at this point, it is perhaps important to note that while great strides have been made in reducing the 'carbon footprint' of cement production, we should be more nuanced and consider the structural material, concrete, rather than cement. We should also consider the function that the concrete is designed to provide (Purnell, 2013) (i.e. resistance to compressive stress) as the variable against which we are trying to minimise 'per unit' carbon dioxide emissions (rather than mass of cement and/or concrete). For example, with careful and judicious concrete mix design it has recently been shown that considerable savings in the ECD of concrete's structural function (i.e. the provision of compressive strength) can be achieved even without using 'low carbon' binders (Purnell and Black, 2012). When this is recognised, we can then make sure that the potential to make additional carbon dioxide savings afforded by the use of low carbon binders in the design of concrete structures can be fully exploited.

However, any drive towards reducing the carbon footprint of construction cannot ignore financial considerations. The use of lower carbon dioxide concrete mixes must still be economically viable and, just as different mix designs can lead to wildly differing ECD values, the same could be envisaged for materials prices. Changes in ECD and material cost as a function of mix design are compared in this paper, and an attempt is made to consider how material costs may vary, should a charge be levied on the carbon dioxide emissions associated with the constituent materials of concrete. It is recognised that the prices of concrete's constituent materials can vary dramatically depending on location, quantities required, transportation costs and so on. However, these prices will not vary by orders of magnitude and so were used as indicators.

Methodology

A total of 96 theoretical 'virtual' concrete mixes were designed according to the method of Teychenne *et al.* (1997), as previously reported when considering ECD (Purnell and Black, 2012). Then, 24 mix designs were considered, each spanning 16 predicted mean compressive strengths at 28 d standard curing of cube specimens (target mean strength). For each of the target mean strengths, the mix design variables considered were

- workability: 0–10, 10–30, 30–60 and 60–180 mm slump
- SCM content: 0, 20 or 40% replacement with PFA
- use of water-reducing admixture (polycarboxylate ether): yes or no.

Aside from these factors, mix designs were calculated assuming the use of CEM I 52·5, uncrushed aggregate, and 20 mm maximum aggregate size. This gave a total of 24 ($4 \times 3 \times 2$) mix families, each then designed for 16 strengths (i.e. 384 data points).

Using these 384 mix designs it was then possible to examine the variation of both ECD and price with concrete mix design. While ECD values for each component were relatively easy to find and verify (Table 1), as noted earlier, constituent prices can vary dramatically. However, indicative prices were obtained and considered to be a reasonable approximation.

Constituent	Cost: £/t	ECD: kg CO_2/t
CEM I 52·5	95	884
PFA	45	27
Coarse aggregate	20	3·2
Fine aggregate	16	2·3
Water	0·0025	0·56
Water-reducing admixture (SP)	1·5 £/l	$5{\cdot}2 \times 10^{-3}$ kg CO_2/l

Table 1. Cost and ECD data for various concrete constituents

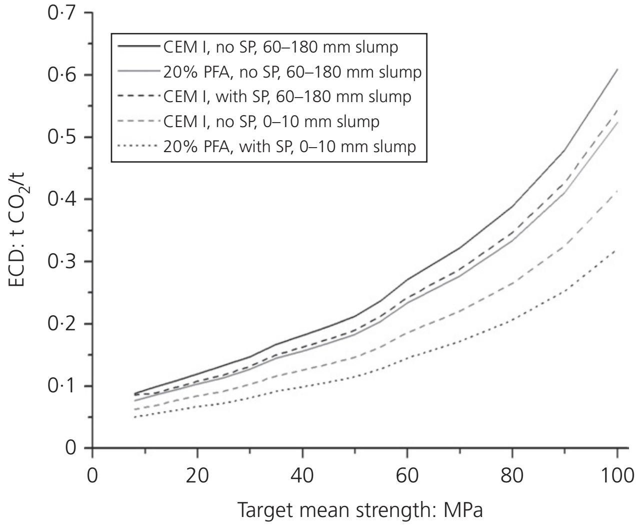

Figure 1. Variation in ECD as a function of compressive strength and mix design

When trying to determine how carbon dioxide pricing would affect the price of concrete constituent materials, it was assumed that any 'carbon price' was passed on entirely by the producer to the consumer; for example, a price of £10/t of carbon dioxide would increase the price of one tonne of cement by £8·84, PFA by 27p and coarse aggregate by 3·2p. This ignores price elasticity, assuming that consumers would be willing to shoulder the full cost of any price increase. Furthermore, by making this assumption, the impact of carbon dioxide pricing upon constituent prices was then assessed firstly by calculating a 'carbon-free price' (i.e. subtracting £5/t carbon dioxide from the price of CEM I). Hypothetical carbon prices could then be levied on just the CEM I or on all constituents as required.

It should be stressed that this approach was very much an estimate. It assumed fixed prices for each of the components, when these may well vary depending on a number of factors. Equally, no attempt was made to consider labour costs, ease of workmanship or any other non-material factors. For example, it is recognised that reduced workability will necessitate increased compaction and hence increased carbon dioxide emissions but, for a first approximation such as this, such factors were ignored. Similarly, this approach did not consider the impact on durability of any of these mixes; it simply used compressive strength as a measure of performance.

Results and discussion

As discussed by Purnell and Black (2012), Figure 1 illustrates that there is not a single value for the ECD of concrete. Rather, ECD is a function of compressive strength, with higher strength concretes having a greater carbon footprint. However, there can be considerable variation for a given compressive strength, indicating that mix design can play an important role in minimising the ECD of construction activities. With all else equal, use of a superplasticiser (SP) reduces the ECD by about 10%. This is due to the admixture reducing the water content of the mix, therefore reducing the cement content, while maintaining the water/binder ratio. Switching from CEM I to a 20% PFA blend reduces the ECD by about 14%, due to the lower ECD of PFA compared with Portland cement. Finally, switching from a very wet to a very dry mix can reduce the ECD by about 30%, again due to the reduced water content allowing a reduced cement content (note, as mentioned earlier, this approach ignores the additional emissions associated with increased compaction of a stiffer concrete mix). Combining all three factors offers a potential carbon dioxide saving of just over 45%, compared with the baseline CEM I mix with a workability of 60–180 mm without the use of a water-reducing admixture.

Figure 1 shows that the increase in ECD is not linear with regard to compressive strength. This offers the potential for optimisation based upon the concrete's function (i.e. resistance to compressive stress). Thus, calculating the ECD per unit strength (Figure 2) reveals a minimum at 50 MPa. This offers the potential for optimisation beyond straightforward mix design.

Moving from ECD to the monetary cost of the components of concrete, Figure 3 and Figure 4 show, as a function of compressive strength, the cost per tonne of concrete and the cost per tonne per unit strength, respectively. As with ECD, there is a non-linear increase in cost with respect to strength (i.e. stronger concrete is more expensive). Similarly, the factors that reduce the carbon footprint of concrete (i.e. the use of a water-reducing admixture, use of PFA and preparation of a less workable mix) also help to reduce the cost of concrete. As with ECD, it is again possible to determine the effect of changing mix design on the cost of one tonne of concrete. With all else equal, the use of a SP reduces the cost only by about 1·7%. Switching from CEM I to a 20% PFA blend reduces the cost by about 3·5%, while switching from a very wet to a very dry mix can reduce the cost by 14·7%. These data are summarised in Table 2.

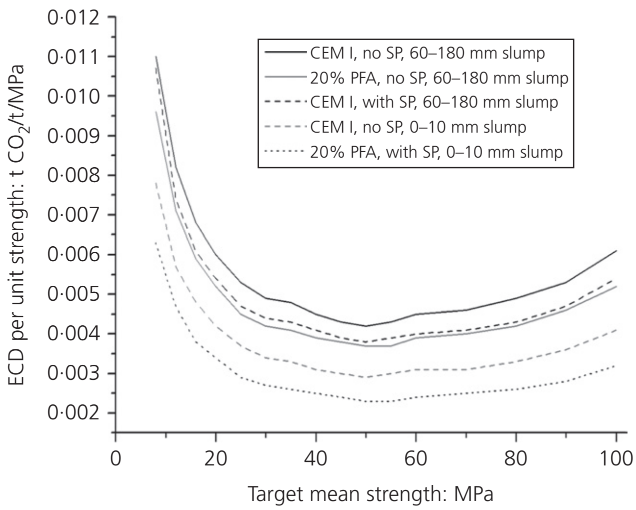

Figure 2. Variation in ECD per unit strength as a function of compressive strength and mix design

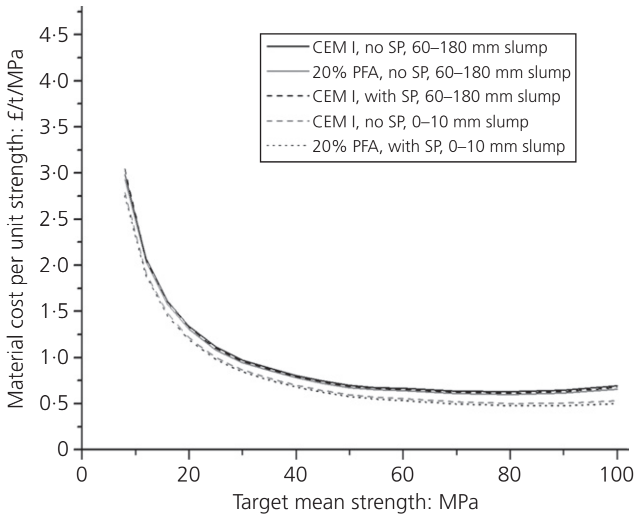

Figure 4. Variation in cost of components of concrete per unit strength as a function of compressive strength and mix design, assuming current prices

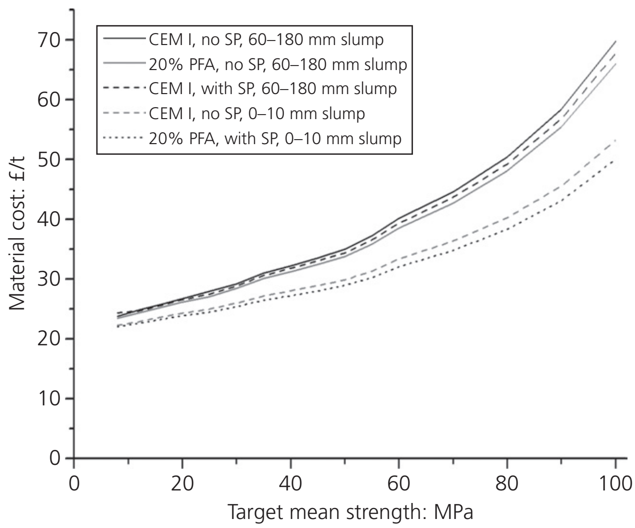

Figure 3. Variation in cost of components of concrete as a function of compressive strength and mix design, assuming current prices

Thus, while the factors that result in a low carbon dioxide concrete also result in reductions in material costs, the extent of the impacts differ. The carbon dioxide savings can be considerable, but the cost savings are much more modest. Use of PFA leads to a considerable reduction in ECD since it is an industrial by-product with emissions associated with the primary product, electricity. However, since there is a market for PFA, its price is not trivial. Conversely, SP use also considerably reduces ECD. However, it is a relatively expensive component and so does not lead to such a great cost reduction. Finally, moving from a wet to a dry mix effectively replaces cement clinker with coarse and fine aggregate, giving considerable carbon dioxide savings, but more modest cost savings.

With a carbon price of £5/t assumed in these calculations (based on typical 2013 prices), the similarity between Figures 1 and 2 implies that the financial incentives are already in place for delivering low carbon dioxide concrete. However, comparing Figure 1 and Figure 3, the increase in cost with increasing strength is not quite as marked as the corresponding increase in ECD. These differences have implications when considering the optimum strength of concrete. While the optimum strength in terms of ECD per unit strength is about 50 MPa, the minimum cost per unit strength lies between 80 and 90 MPa (Figures 2 and 4). At these higher strengths, the ECD per unit strength is some 20–25% above its minimum value. The effects of changes in the price of carbon dioxide were therefore investigated further – firstly to investigate the impact of various carbon dioxide pricing scenarios and secondly to find the carbon price required to ensure that the lowest cost per unit strength was at 50 MPa.

As mentioned previously, a number of figures are available for carbon price. The EU-ETS price is inherent within the prices used in the calculations above, where a value of £5/t of carbon dioxide was assumed. However, from 2015, the UK CPF was set at £18·08/t carbon dioxide (Ares, 2014) and, in the USA, the SCC was set at $38/ton ($41.89/t).

Although it has been implemented just for the power generation sector, its intention as a means to drive investment in low carbon dioxide technologies (Ares, 2014) made the UK CPF a convenient starting point to consider the impact of carbon dioxide pricing on the costs of the various components of concrete. Imposition of a carbon price of £18·08 still kept the minimum cost per unit strength at 80 MPa (i.e. the CPF does not overtly encourage the adoption of the lowest carbon

		Carbon price				
		£5 EU-ETS	£18·08 UK CPF	$38[a] US SCC	€100[a]	£160
Cost: £/t		35·00	37·69	39·54	51·70	66·96
Carbon-dioxide saving measure	Carbon-dioxide saving: %	Cost saving: %				
Use of SP	10	1·7	2·4	2·8	4·7	6·1
Use of 20% PFA	14	3·5	4·3	4·8	7·2	8·9
Use of a drier mix	30	14·7	15·9	16·7	20·5	23·3

[a]$38 = £24·52, €100 = £86

Table 2. Cost of concrete (50 MPa, CEM I, no SP, 60–180 mm slump) at various carbon prices, plus the cost savings of adopting various carbon dioxide saving measures

concrete). However, it did give a greater cost saving to the carbon dioxide saving measures described above – that is, use of a SP (2·4%), use of 20% PFA (4·3%) and adoption of a drier mix (15·9%) – but led to an increase in the cost of the baseline mix (CEM I, no SP, 60–180 mm slump) by 7·7%.

Performing similar calculations assuming the US SCC, the minimum cost per unit strength remained at 80 MPa, but the cost of the standard mix rose by 13%. However, the differential between the baseline mix and the three carbon dioxide saving measures increased, as shown in Table 2.

From these results, it is clear that low carbon dioxide concrete may already be the most cost-efficient and that carbon dioxide pricing, as currently enshrined in UK or US policy to achieve further carbon dioxide savings, is inefficient. However, looking beyond this, we can envisage higher carbon prices as the need to reduce carbon dioxide emissions becomes more urgent. Some governmental commentators have suggested that a carbon price of up to €100/t carbon dioxide may be required to drive a reduction in emissions (Ares, 2014). Factoring these costs into the model led to the minimum cost per unit strength shifting from 80 MPa to 60 MPa, with a price increase of 53·5%. At these strengths, the ECD of concrete is only about 6% greater than the optimum (i.e. at 50 MPa).

It was not until the carbon price approached £160/t that the lowest cost per unit strength coincided with the lowest ECD, at 50 MPa. This figure is comparable to that proposed recently by Moore and Diaz (2015) of a SCC of £156/t ($220/ton). However, Figure 5 and Figure 6 show the variation, with respect to compressive strength, of cost of concrete components and cost per unit strength, respectively. Even when applying a carbon price of £160/t, the minimum was not as pronounced as that for ECD, yet it brought about a 91% increase in the cost of the baseline mix. Adoption of the three carbon dioxide saving measures investigated would reduce the ECD by 38·1% (the three effects are not simply summative), bringing the price to £45·41/t, still a 30% increase over the current cost of the components of the baseline mix.

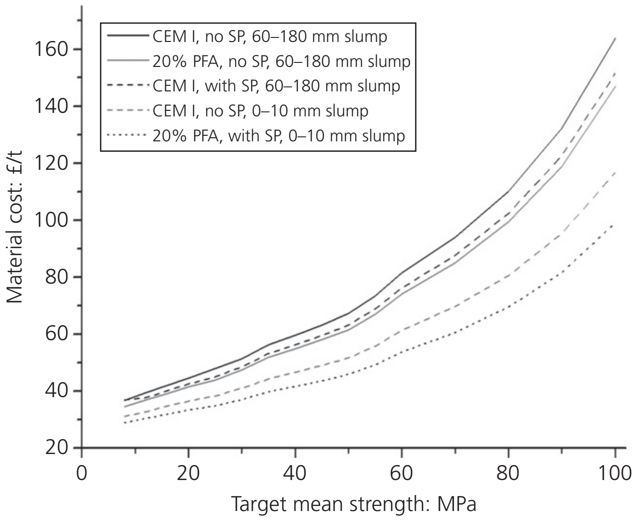

Figure 5. Variation in cost of components of concrete as a function of compressive strength and mix design, assuming a price of £160/t carbon dioxide

To put these figures into perspective, in his report on the economics of climate change, Lord Stern suggested that economies needed to spend 1% of their gross domestic product (GDP) on adaptation measures to avoid the worst ravages of climate change (Stern, 2007). This figure was subsequently revised to 2% in 2008. With UK per capita GDP at £24 869 in 2013, 2% equates to £497·38. If this sum were to be levied as a tax on carbon dioxide emissions, then with UK per capita carbon

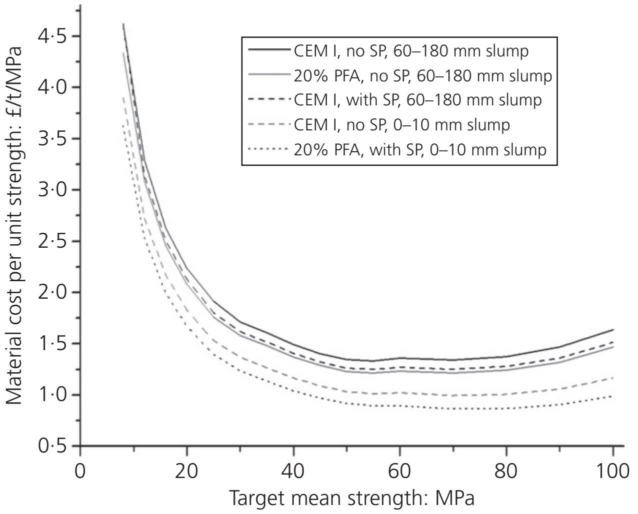

Figure 6. Variation in cost of concrete components per unit strength as a function of compressive strength and mix design, assuming a price of £160/t carbon dioxide

dioxide emissions at 7·68 t/year, the figure would be £64·76/t of carbon dioxide. Levying such a tax would add about 35% to the cost of the baseline concrete mix and 28% to the cost of the lowest carbon dioxide mix. As a result, the cost of the lowest carbon dioxide mix would be approximately 37% less than the baseline mix. This could help to encourage more efficient use of materials.

For most major infrastructure projects, materials (and thus concrete) costs are a small percentage of project costs. Exact 'project by project' figures are scarce owing to commercial issues, but UK government analysis of the construction sector suggests that the gross value added of the contracting and services industries (£77 billion) is around six times that of the products industry (£13 billion) (DBIS, 2013); in other words, design and construction costs far outweigh material costs. This encourages inefficient design, as there is a much greater incentive to reduce design and implementation costs by using over-simplified structural component designs with excessive factors of safety than there is to reduce the consumption of materials. Increased materials costs would help drive more materials-efficient design, lower material consumption and thus lower carbon dioxide emissions (since the ECD of the materials is generally the greatest proportion of the ECD of a construction project, or indeed most other consumer products (Allwood and Cullen, 2011)).

Conclusions

With the aim of investigating the carbon price required to encourage adoption of low carbon dioxide concrete, the cost of the components of optimum concrete mix designs has been considered both in terms of the cost of the constituents required to make one tonne of concrete and the cost per unit compressive strength.

The current costs of the constituent materials of concrete already encourage the use of carbon dioxide saving measures (the use of PFA and superplasticiser and the adoption of drier mixes). However, the financial incentives are weak and may easily be outweighed by factors outside the scope of the current study (e.g. transportation, labour or other construction costs).

The adoption of more nuanced mix designs, ensuring the lowest cost per unit strength, would require a 40-fold increase in the price of carbon dioxide over current figures. Such a figure would be far in excess of any figure based on the recommendations of the Stern report (Stern, 2007) and would lead to considerable increases in the cost of construction. Furthermore, while such carbon prices would discourage wastefulness, an outcome that carbon dioxide markets may not always encourage (Skopek, 2010), there is a risk that such charges may be seen as a 'mechanism to buy our way out of the more fundamental changes in habits, attitudes and ways of life that may be required to address the climate problem' (Sandel, 2012). Therefore, carbon dioxide pricing could be used to drive efficient material use by encouraging engineers to consider optimisation of their material use, but it may also be considered an ultimately inefficient tool by itself to drive the adoption of low carbon dioxide concrete.

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