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Sequestration of Carbon Dioxide by Concrete Infrastructure

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Sequestration of Carbon Dioxide by Concrete Infrastructure: a Preliminary Investigation in Ireland

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Assumptions that the net contribution of cement and concrete production to greenhouse gas levels are represented by carbon dioxide (CO_2) emissions alone are inaccurate. The net contribution of CO_2 released through calcination of limestone may be over 20% less on a global scale. This is due to CO_2 uptake by concrete products in service through the naturally-occurring phenomenon of carbonation of concrete. Failure to take account of the net effect may lead to misinformed policy formulation on global and regional climate change strategies. Accurate quantification of these figures and incorporation of this concept into life-cycle assessment studies will permit a more realistic comparison to be made of the true environmental impact (CO_2 footprint) of future concrete structures.

This paper presents the methodology and findings of a preliminary investigation into the sequestration of CO_2 by concrete in Ireland. The process of concrete carbonation is well known and mathematical models of the process underpin future concrete durability design, an emerging trend in European concrete standards. Despite this, CO_2 sequestered by concrete in and after service is not generally accounted for in determinations of environmental impact. Using methodologies developed from similar work in Scandinavia, this paper details the development of initial estimates of the quantity of the CO_2 immobilised by Irish concrete in service over time, as a fraction of the CO_2 released through calcination of limestone. Possible implications of the preliminary findings and potential avenues for future research are outlined.

KEYWORDS: carbon dioxide, carbonation, concrete, Ireland, sequestration.

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Sequestration of Carbon Dioxide by Concrete

Global emissions of carbon dioxide (CO_2) generated by the manufacture of cement-based products are often quantified through summation of estimates of CO_2 released through calcination of limestone and CO_2 released through energy generation for operation of manufacturing plant. The former is predictable while the latter is variable, since it is dependent on the fuel mix used in the plant and the efficiency of the various plant processes. However even the figures popularly quoted for the CO_2 released through calcination of limestone may significantly overestimate the annual net effect. This is due to CO_2 uptake by concrete products through the naturally-occurring phenomenon of carbonation of concrete and other cementitious construction products. Failure to take account of the net effect may lead to misinformed policy formulation on global and regional climate change strategies.

Research to date into the quantity of CO_2 sequestered by concrete and other cement-based products is not well advanced. The lack of published studies has prevented incorporation of the net effect of sequestration in current life-cycle assessment (LCA) environmental determinations.

Influence of Current Design Codes on Carbonation Rate in Concrete Infrastructure

Studies of the carbonation process in concrete have identified numerous factors affecting the rate of carbonation and thereby affecting how much carbon dioxide is sequestered by the concrete during its service life. Two factors of particular significance are the permeability of the concrete and the environmental humidity in-service conditions.

One of the main factors is the diffusivity of the cement paste fraction of the concrete, which results from the type of cement used, the water to cement ratio of the mix and the degree of hydration, all of which also effect concrete strength. The curing history of a concrete is critical, with well-cured concrete having a near surface micro-structure which typically has small diameter capillary pores as well as a tortuous pore system which reduce carbonation ingress.

In open texture concrete products, such as traditional concrete blocks, the cement paste fraction is typically only a few millimetres thick (the depth of the paste fraction coating coarse aggregates). This means that full carbonation of the paste fraction is likely to be possible in a relatively short period of time.

The moisture state of the pore system at any given time plays an important part in determining the instantaneous rate of carbonation. The phenomenon requires moisture for the reaction to proceed but if the ambient humidity is very high the permeable structure of the concrete becomes saturated, which reduces the diffusion rate of carbon dioxide into the concrete. Frequently wetted surfaces of high quality concrete may have minimal carbonation depths after many years in service whereas open-textured mass concrete may fully carbonate in a short period.

Designers and specifiers of concrete infrastructure are aware of these factors. However, despite the fact that carbonation of concrete enhances strength and stability (reduced shrinkage risk), the onus on specifiers and producers has been to minimise the rate of carbonation of concrete. This is due to its potential impact on reducing the durability of reinforced concrete structures, and thereby service life, through initiation of corrosion of reinforcement.

Carbonation lowers the pH of the concrete which has the effect of reducing the corrosion protection that concrete offers embedded reinforcement. A 'front' of carbonation progresses inwards from the exposed face of a concrete element at a rate dependent on the factors referred to. If a 'front' of carbonation reaches the level of the reinforcement then, given certain conditions, corrosion of the reinforcement is possible. Current design codes therefore manage the risk of carbonation-initiated reinforcement corrosion through prioritisation of ensuring that the 'front' is unlikely to reach the depth of embedded reinforcement during the design life of a structure.

This risk management approach underpinning the philosophy of current design codes aims to minimise the rate of carbonation and has, understandably, discouraged consideration of reinforced concrete infrastructure as a potential asset for carbon dioxide sequestration. Optimal use of infrastructure as a carbon sink therefore must target unreinforced concrete (for example in the residential sector of countries where low-rise units dominate the market) and the uncarbonated fraction of reinforced concrete at the end of its service life.

In respect of the low-rise residential sector, open textured products such as some concrete blocks, roof tiles etc. may fully carbonate during the service life. Dense impermeable reinforced concrete, which in-service has only developed a shallow surface region of carbonated concrete, has a large mass of uncarbonated concrete. This uncarbonated concrete has the capacity to immobilise CO_2 if it is crushed at the end of its life, stockpiled and exposed to atmospheric or elevated CO_2 concentrations.

Mathematical Modelling of Carbonation Rate

The rate of carbonation is typically modelled mathematically in the form of Equation 1:

$$x = k\,t^{n} \qquad (1)$$

where:
x is the depth of carbonation, k is a carbonation coefficient (or 'k-factor') dependent on material properties, t is time and the coefficient n is related to environmental conditions in service.

Models of the carbonation coefficient (k) vary in complexity. Table 1 presents the models which were initially considered in the study.

Models of relevance to this study (Table 1) were limited to consideration of those involving readily estimated retrospective parameters which characterise typical concretes, such as water/cement ratio or compressive strength, representative of a given construction period.

Selection of a model which is most applicable to sequestration studies in a particular region requires calibration with in-service carbonation depth data from that region in circumstances where readily-available data or reliable estimates can be made on parameters in the model. This was available in Ireland from a previous study by Richardson (1988).

Methods

Overview

The research examined the potential scale of CO_2 sequestration in the context of concrete infrastructure in service in a defined geographical region with a temperate European climate. The area selected was the island of Ireland. Sequestration was estimated through determination of the best-fit model for the rate of carbonation in Irish environmental conditions; adoption of an assumed rate of CO_2 release through calcination (mass of CO_2 per ton of clinker) and an estimate of cement usage by sector in Ireland. This allowed estimation of CO_2 currently being immobilised by cement-based products in Ireland per annum relative to CO_2 released from limestone calcination, for cement clinker production, per annum.

Selection of Best-Fit Carbonation Model for Ireland

Following a preliminary review of carbonation rate trends, modelled by the formulae in Table 1, a subset of four formulae were selected for closer study. The initial large set of models were calibrated against in-service data under a variety of assumptions so that theoretically calculated values could be determined to see if a realistic range of in-service values for Ireland was apparent. This comparison allowed the selection for further study of the smaller subset of models that could best predict the carbonation of concrete in Ireland with an acceptable degree of accuracy for this preliminary study. It should be noted that the majority of these models were derived

Table 1

Mathematical models of carbonation rate considered in this study, which are fully referenced in a review by Richardson (2002), supplemented by models of Lagerblad (2005), Andersson *et al* (2013) and Silva *et al* (2014), referenced in this paper

Formula	Comments
$x = A\sqrt[n]{t}$ (Alekseev & Rozental, 1976)	A = coefficient n = 1.92 w/c ratio 0.6 n = 2.54 w/c ratio 0.7
$x = k\,\gamma\sqrt{t}$ Andersson *et. al* (2013)	k = k-value based on strength and exposure condition γ = degree of carbonation depending on exposure condition
$x=\left(\frac{582w}{\sqrt{sosf}}+1.12w-1.47\right)\sqrt{t}$ (Commission Carbonatation, 1972)	w = water / cement ratio s = loss on ignition o_{sf} = 'specific surface'
$x=R\left(\frac{4.6\,w-1.76}{\sqrt{7.2}}\right)\sqrt{t}$ (Kishitani, 1960)	w = water / cement ratio ≤ 0.6 $R = r_c r_a r_s$ factors associated with cement type, aggregate type and surface active agent
$x = \sqrt{\frac{2\,D\,\Delta c}{c_0\,\rho}}\sqrt{t}$ (Kondo, Daimon, Akiba, 1969)	D = diffusion coefficient Δc = concentration difference c_0 = amount of reactant per unit weight ρ =density
$x = k_1 k_2 k_3\sqrt{t}$ Lagerblad (2005)	k_1 =default k-value based on strength (four categories) and exposure condition (5 categories) k_2 =correction factor (0.7 to 1.0) depending on surface treatment and cover k_3 =correction factor (1.05 to 1.30) depending on secondary cementitious binder type and fraction
$x = \frac{ak^{0.4}}{c^{0.5}}\,t_i^n$ (Parrott, 1994)	a = coefficient (assume 64) k = air permeability c = CaO content n = 0.5 for indoor exposure but less if concrete exposed to wetting
$x = (n_1\,n_2\,n_3\,n_4\,n_5\,k_{av})\sqrt{t}$ (Richardson, 1988)	n_1 =2, carbonation front parameter n_2 = 0.6 for exposure to rain, 1.0 for sheltered and internal n_3 = concrete quality parameter n_4 = 0.3 for float-finished horizontal surfaces, otherwise unity n_5 = CO_2 concentration parameter (e.g. 1.0 rural, 2.0 internal) k_{av} = correlation factor
$If RH \leq 70\%, x = (0.556c - 3.602X - 0.148f_c + 18.734)\sqrt{t}$ and $If\ RH\ \geq 70\%, x = (3.355c - 0.019C - 0.042f_c + 10.83)\sqrt{t}$ Silva et al (2014)	c = CO_2 content X = Integer related to Exposure 'XC' Class f_c = compressive strength at 28 days C = clinker content
$x = a\left(\frac{w}{\sqrt{N_T}} - b\right)\sqrt{t}$ (Smolczyk, 1969)	w = water / cement ratio N = compressive strength at T days T = age of specimen
$x=(1.187w-0.493)\sqrt{t}$ (Tsukayama, Abe, Nagataki, 1980)	w = water / cement ratio

from modelling rates of carbonation under controlled laboratory conditions. Therefore significant divergence from in-service values was expected. Nevertheless trends were identified such that four models were deemed worthy of further screening, through comparison of theoretical rates with actual in-service carbonation rates determined from tests on concrete from 120 locations in Ireland (Richardson, 1988). The four models selected for further study, including two from the same author, were calibrated against data of carbonation depths determined from structures in service.

Following this evaluation, a single model was chosen, allowing conservative carbonation co-efficients (*k*-factors) to be determined for moderate humidity conditions (less than 70%). These were then scaled for different exposure conditions (indoor, exposed to rain, sheltered from rain) to allow for the effect of increased humidity on reduction of carbonation rate.

Carbon dioxide release from calcination

Calcination of one mole of limestone ($CaCO_3$) releases one mole of CaO (56.08g/mole) and one mole of CO_2 (44.01g/mole). The mass of CO_2 released per ton of clinker (*EFclinker*) is therefore represented by Equation 2.

$$EF_{clinker} = P\,\frac{44.01}{56.08} \qquad (2)$$

where

P is the percentage of CaO per ton of clinker. The value of *P* is a variable dependent on the manufacturing plant and can vary over time.

The Intergovernmental Panel on Climate Change (2000) have adopted a figure of 64.6% for *P. Figures derived from records at cement plants in Ireland indicated an average percentage of 64.25%. The international figure of 64.6% was therefore deemed suitably conservative for this study. B*ased on this value the calcined CO_2 released per ton of clinker was determined to be 504 kg CO_2 per ton of clinker produced.

The dominant cement type in Ireland, during the 40-year period of the study was CEM I. Ireland transitioned from a market where CEM I was predominantly used, until 2006, to a market where 80% of cement was CEM II/A over the years 2006 to 2010. This factor is incorporated in the data generated in this study, with an appropriately lower calcined CO_2 value per ton of cement used for the relevant period. Assuming a clinker content of 95% in CEM I, a value of 479 kg calcined CO_2 per ton of CEM I cement was adopted in this study for production up to 2006. Assuming a clinker content of 85% for CEM II/A, a value of 428 kg calcined CO_2 per ton of cement was assumed for CEM II/A from 2006.

Estimate of Cement Usage by Sector in Ireland

An estimate the total amount of cement used in on the island of Ireland over the last 40 years was determined through historical records and trends. This period represents a key period in Ireland's economic development and thereby is representative of the majority of existing concrete-based infrastructure. Cement usage from 1972 to 1979 was estimated from historical data on sales trends in the records of Irish Cement Limited. Data from the years 1980 to 2011 was determined from the International Cement Review (2011) biennial report. This data set includes imported cements and excludes cement and clinker exports. While the limitations of this method is acknowledged, it is considered adequate for the purposes of giving an estimate of the quantity of calcined CO_2 which was produced from cements used during the period in the region defined by the island of Ireland.

Sectoral breakdown was determined from financial output data derived from Government statistics published by the Department of the Environment in various years and later by DKM Economic Consultants (Construction Industry Review and Outlook Series). The sectors were classified as

'Residential', 'Civil Works' and 'Other/Commercial'. The 'residential' category is predominantly made up of low-rise housing units for the majority of the period under investigation. The 'civil works' category incorporates infrastructure works including roads, airports, ports, harbours and water services. The 'other/commercial' category primarily encompasses cement usage in commercial developments and the agriculture industry.

Results

Carbonation Coefficients (k)

A comparison of actual and predicted values for the four selected models are illustrated in Figures 1 for structures in service in Ireland in external environments, sheltered from rain. The comparison involves use of a multiple of the splitting strength value, rather than compressive strength, which partly accounts for the degree of scatter. Following inspection it was decided to adopt the model of Silva *et al* (2014), relative humidities of less than 70%, as the core prediction tool to conservatively represent Irish conditions. Additional relative modification factors for Irish conditions were adopted based on Richardson (1988) as follows: 1.0 'internal environments', 0.5 'external sheltered from rain' and 0.3 'external exposed to rain', based on the relative combined impact of factors n2 and n5 in the Richardson model outlined in Table 1.

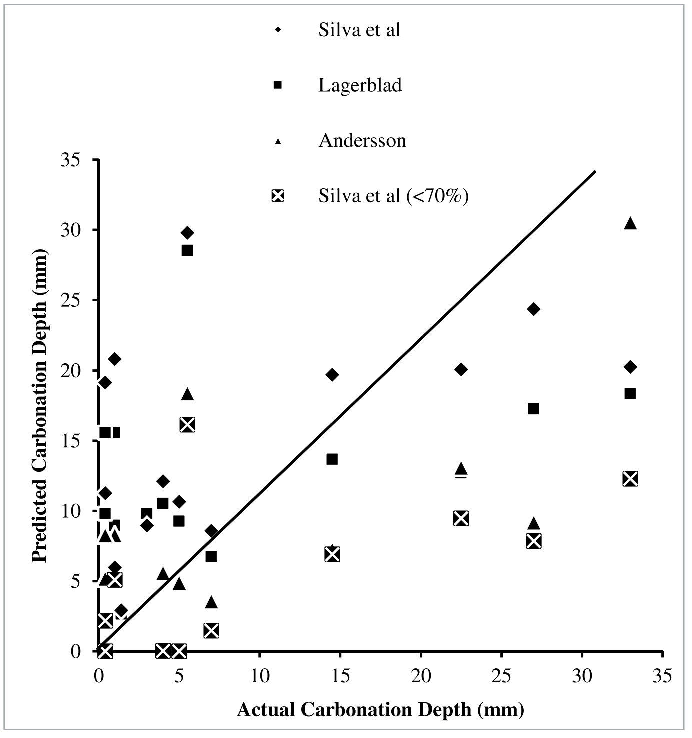

Fig. 1
Comparison of predicted and actual values of carbonation depth in Irish external environments, sheltered from rain

Construction Sector Outputs 1972 to 2011

Estimated Irish cement sales per annum over the last four decades are illustrated in Figure 2.

The typical average use of cement in Ireland was found to be 1.8 Mt per annum, except for a period of unprecedented demand in the early 2000's ('Celtic Tiger Economy') when demand tripled. The effect of the period of elevated economic growth (colloquially referred to as 'The Celtic Tiger Economy' period) on cement sales is starkly illustrated in Figure 2.

The sectoral split of end use of cement over the period studied is illustrated in Figure 3. This reveals a dominance of residential unit output (50%) over both civil works (20%) and 'other/commercial' (30%).

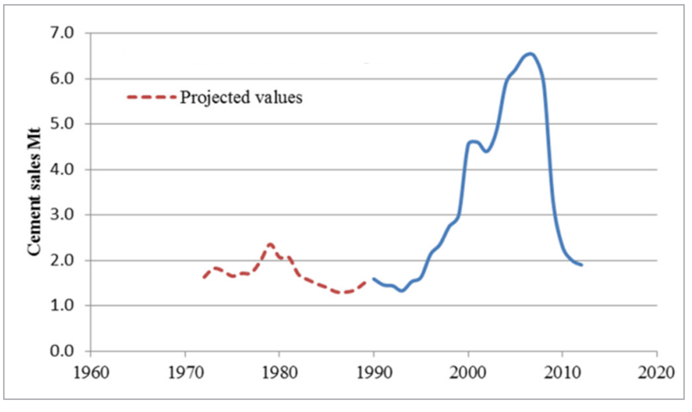

Fig. 2
Estimated Irish cement sales per annum over the last four decades based on historical data (projected values) and data from International Cement Review (2011)

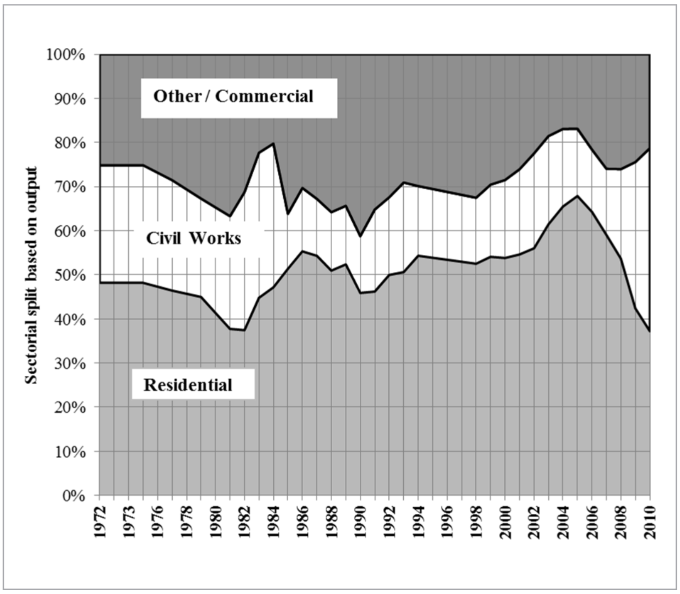

Fig. 3
Relative construction sector outputs per annum, Republic of Ireland, over four decades derived from Government statistics published by the Department of the Environment and later by DKM Economic Consultants. Data for 1972-1974 estimated using 1975 data

Surface Exposure and Cement Content by Sector

Each market sector was examined with regard to typical surface exposures in-service and concrete strengths used. Effort was made to assume values which best represented the period 1972–2010.

Residential housing

Residential housing in Ireland for the period 1972–2010 was assumed to be represented by a single-storey dwelling of 90 m^2 footprint and a total volume of concrete of 64.7 m^3. This first estimate is undoubtedly a simplification, given that four or five storey apartments became more common for a limited period in urban centres from approximately 2000 until the economy slowed in 2007. The form of the assumed 'typical' single storey house is shown in Figure 4, with its major cementitious components detailed and itemized in Table 2.

Carbonation through internal walls was assumed to proceed at 30% of the normal rate due to decorative coatings. The foundations were assumed not to carbonate over the life of the structure due to the saturated environment and lack of access to atmospheric CO_2.

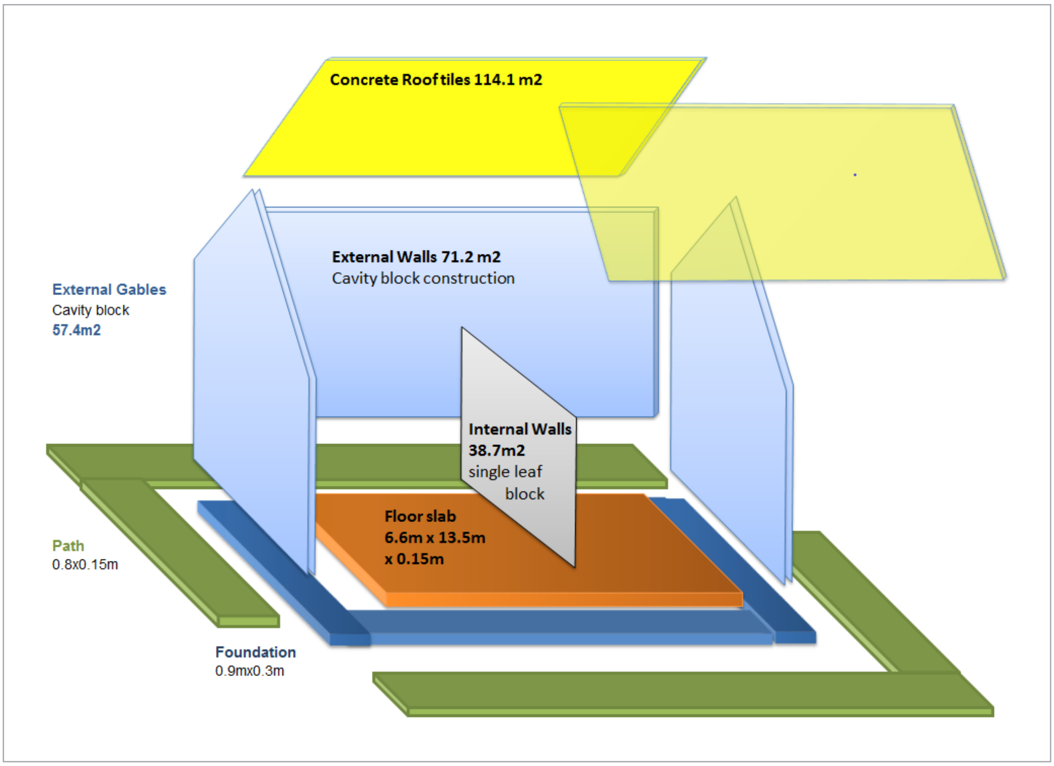

Fig. 4
Cementitious components of the assumed model Irish residential unit

Element	Description	Assumed cement content per 1 m^3 of concrete (kg)	Surface area available for CO_2 ingress (m^2)
Path	800 mm wide by 150 mm deep, C12/15 concrete	220	34.7 (upper face only)
Floor slab	150 mm deep, C20/25 concrete	280	89.1 (upper face only)
Internal walls	100 mm thick, 5N block	106	77.4 (both faces)
External cavity wall, outer leaf	100 mm thick, 5N block	106	128.6 (external face of outer leaf)
			128.6 (internal cavity face of outer leaf)
External cavity wall, inner leaf	100 mm thick, 5N block	106	128.6 (external face of inner leaf)
			128.6 (internal cavity face of inner leaf)
Roof tiles	50 mm thick	300	114.1 (upper face)

Table 2
Relevant components of the residential unit

Civil Engineering and Commercial

The figures used in this study to represent the surface area available for CO_2 ingress for structures in 'Civil Works' (bridges) and 'Other/Commercial' developments were adopted from Anderson *et. al* (2013).

In respect of commercial properties it was assumed that reduced ability to carbonate should be allowed for in the case of indoor concrete elements covered by finishes such as plasterboard, linoleum, parquet or laminate flooring. An assumed value of 30% carbonation rate was adopted in this preliminary study. Concrete surfaces covered with tiles were assumed to have no carbonation.

The assumed values for Ireland are presented in Table 3 and Table 4 for 'civil works' and 'other/commercial' developments respectively. The volume of concrete per bridge was assumed to be 277 m^3.

Element	Concrete Strength Class*	Assumed cement content (kg/m^3)	Surface area available for CO_2 ingress per bridge (m^2)
External -Exposed	C32/40	360	43.8
External -Sheltered	C32/40	360	422.0
Ground Slab -coarse fill only	C32/40	360	170.8

*Strength Class C32/40 is a typical strength class permitted for use in Ireland under the national annex to European Standard EN206-1

Table 3
Relevant components 'Civil Works' infrastructure

Table 4
Relevant components 'Other/Commercial' infrastructure

Element	Concrete Strength Class	Assumed cement content per 1 m^3 of concrete (kg)	Surface area available for CO_2 ingress per gross floor area (m^2)
External -Exposed	C30/37	320	0.06 per GFA
Ground Slab -coarse fill only	C30/37	320	0.01 per GFA
Ground Slab - sand and gravel fill.	C30/37	320	0.32 per GFA
Indoor - Bare	C30/37	320	0.82 per GFA
Indoor - Painted	C30/37	320	0.61* per GFA
Indoor - Lino	C30/37	320	0.64* per GFA
Indoor - Parquet	C30/37	320	0.03* per GFA

* Indicates one third carbonation rate assumed compared to 'bare'

Preliminary Estimate of CO_2 Sequestration

For each year since 1972 the amount of cement sold (and hence the annual amount of calcined CO_2 produced) was calculated for each market sector. The annual percentage carbonation of concrete for each market division and the annual amount of sequestered CO_2 for each market segment was calculated for 100 years.

The model allowed for variation in the amount of calcined CO_2/t cement from year to year which was caused by the shift to CEM II/A cements. Additionally a conservative modification factor of 0.9 was applied to estimates of sequestered CO_2 in residential sectors from the year 2000 to 2008, allowing for an increase in the building of multi-storey apartment blocks rather than detached houses.

Approximately 780,000t of CO_2 was calcined during cement production in Ireland in 1972. Concrete made in Ireland in 1972 is estimated to have absorbed over 98,000 t of this calcined CO_2 by the end of 2013.

Initial (conservative) estimates from this study indicate that, on average, the rate of sequestration is of the order of 75 kg of CO_2/t of cement sequestered over a 100 year service life, which is approximately 16% of total calcined CO_2.

Discussion

CO_2 Sequestration

The finding of a preliminary estimate that 75 kg of CO_2/t of cement are sequestered over a 100 year service life (approximately 16% of total calcined CO_2 per tonne of cement produced) is less than the results of the study by Anderson *et. al.* (2013). They postulated that the figure could be approximately 125 kg CO_2 per tonne of cement sequestered over 100 years of normal exposure in service. The difference can be explained by the consistently conservative assumptions made in this first study of Irish conditions, in the absence of detailed information. The wet Irish climate, which may be expected to generally reduce the rate of carbonation of exposed concrete may also account for some of the difference between Irish and Swedish geographical regions. Nevertheless it may be speculated that further research, to determine more accurate values of the relevant parameters, will narrow the gap between these preliminary estimates.

Significant differences were found in CO_2 sequestration across different Irish market sectors. Civil engineering infrastructure applications tended to have a significantly lower total carbonation over time due to the relatively high concrete strength classes (implying low permeability) and lower surface to volume ratio of concrete elements. On the other hand residential construction had a much higher total carbonation due to higher surface to volume of elements as well as the use of open texture concrete products which readily carbonate. The mix of markets was seen to vary the overall national CO_2 100 year sequestration rate (in respect of percentage of calcined CO_2). The average value of 16.3% over the 40-year period studied included lows of 12.3% in 2010 a high of 17.8% in 1986. Irrespective of the annual variations, it may be noted that all of these figures are of a significant magnitude.

Open texture concrete blocks and concrete roof tiles which have been a large feature of Irish residential construction over the past decades are responsible for a significant proportion of sequestered CO_2 identified in this study. This may provide pointers for fruitful research into more sustainable building units.

Implications and Future Opportunities

The quantity of carbon dioxide sequestered by concrete in service in Ireland has been found to be significant and the findings of the study imply that a substantial correction to current assumptions in life cycle assessment methodologies is warranted.

Failure to take account of the net effect of concrete carbonation may lead to misinformed policy formulation on global and regional climate change strategies. This may lead to inappropriate restrictions on the rate of development of the infrastructure required to enhance the quality of life and economic development of countries, especially in the developing world. There is a need to determine estimates of uptake on a regional and even global scale which examine the different cement types, climates and end uses for cement in different countries.

Clearly there are significant implications for the carbon footprint of cementitious materials. The lifecycle inventory of concrete products should be more appropriately calculated bearing in mind the various degrees of carbonation in concrete units during their service life.

An opportunity arises for processing end of use concrete to maximise CO_2 sequestration. This study identifies that potentially over 80% of the original calcined CO_2 in cement is potentially available for carbonation at the end of life (in excess of 400 kg CO_2/t cement). Unlike in-service carbonation, end of life carbonation is not expected to occur in an economical timeframe without intervention, given the nature of the high humidity external environment in climates such as Ireland's. The intervention would probably involve the development of an industrial process to treat reclaimed exposed dense concrete from civil engineering applications. While the details of the process, its efficiency and cost in both financial and energy terms have yet to be estimated, the significant potential benefits of developing an end-of-life sequestration process are clearly considerable.

Limitations of Study

The figures generated in this study use assumptions which have been deliberately and consistently chosen to be conservative. It is expected that future research work in this area will address the main limitations on accurate data for the initial estimates presented in this study.

It is assumed that the value of each market split is directly related to the quantity of cement used in each. In Ireland where concrete road pavements are not common this may not hold. The effect of the assumption is conservative as it potentially overstates the amount of cement used in civil works (concrete in service in Civil Engineering applications is calculated to have less carbonation than other sectors).

The application of market splits which are based on the Republic of Ireland sales to total cement sales based on an all-island basis is a limitation of the study. Obtaining a cement sales estimate for the Republic of Ireland (alternatively but less likely, split between sectors encompassing the whole island) over the period is likely to lead to a refinement of the model accuracy.

The representation of concrete use in different sectors should be developed to better represent the Irish built environment. The current model is based on a mixture of Swedish figures for the physical dimensions in the case of Civil and Other/Commercial sectors while the Irish residential model requires development to include the mix of residential types which became prevalent in the past 10 years. The assumptions regarding the spread of concrete strength classes in different applications would benefit from study to confirm their suitability.

The carbonation models used are likely to give an overly conservative estimate of the carbonation rate of open textured concrete, such as concrete blocks. Assumptions such as much reduced carbonation through internal covered surfaces would benefit from a survey of actual performance to obtain a better estimate of sequestered CO_2. In addition, a better understanding of carbonation of open textured concrete products such as concrete blocks, roof tiles and permeable paving would benefit the model. The carbonation model selected in this study was verified from data of in-service carbonation depths in Ireland and therefore any limitations, while acknowledged, are confined and unlikely to affect general conclusions of the study.

Against these limitations the approach adopted has an inherent strength, in that it cannot grossly overestimate the amount of potentially sequestered CO_2. The total amount of potentially sequestered CO_2 in each year is conservatively calculated using historic sales estimates and a known quantity of calcined CO_2 per tonne. This provides a defined upper boundary to the study output.

Conservative assumptions have been made throughout this preliminary investigation and further studies which may lead to refinements of the model are likely to result in increased values of the estimated sequestered CO_2 in Irish concrete practice.

Conclusions

The amount of CO_2 calculated to be naturally sequestered (without intervention) by concrete in Ireland over a 100 year service life is calculated to be at least 75 kg per tonne of cement produced. This is a conservative estimate based on currently available data.

The end use of cement is seen to affect the CO_2 uptake of concrete products significantly. This has a direct effect on life cycle inventories for concrete products. The role of open-textured concrete products, such as unreinforced units, is particularly noteworthy.

There is a significant potential for end-of-life processing of concrete to sequester CO_2, particularly from high specification dense concrete won from significant infrastructure elements.

The conservatively estimated quantity of CO_2 currently being sequestered is significant. The amount of CO_2 attributed to cement manufacture should therefore be adjusted to take account of natural sequestration of carbon dioxide by concrete and more accurately reflect its relative environmental impact.

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