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Preliminary investigation into the rate of carbonation of concrete blocks under normal production yard conditions

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ABSTRACT: The release of CO₂ from calcination during the manufacture of cement can be partially or fully offset by the CO₂ it naturally absorbs during its lifetime. This paper reports results from a preliminary investigation into the rate of carbonation in concrete blocks stacked in a production yard over a period of 6 months. The blocks were stacked in a normal manner under natural exposure conditions. Carbonation progress was determined by splitting the blocks and spraying the freshly exposed surface with a phenolphthalein solution at intervals over the test period. It was found that the rate of the carbonation front progression differed depending on the exposure face and the type of block. Carbonation fronts on exposed front (FF) or side faces (SF) were seen to advance at rates of well over 1 mm per week for the initial 6 months of exposure. Exposed top faces (TF) of blocks showed a slower rate of carbonation; just over 0.6 mm per week. The speed of the advance of the carbonation front into concrete slowed over time, however, it was noted that slower progression occurred during the second half of testing over the wetter winter period. Rates of carbonation and estimates of carbon sequestration were calculated using the measurements taken in the investigation. The findings suggest that carbonation should be included in the manufacturing stage of life cycle assessments for open textured concrete products such as blocks. This research identifies parameters that should be included in future testing as well as areas where the test methodology would benefit from development.

KEY WORDS: Carbonation; Concrete blocks; Carbon Dioxide Sequestering; Phenolphthalein.

1 INTRODUCTION

The release of CO₂ from calcination during the manufacture of cement can be partially or fully offset by natural sequestration of carbon dioxide over the lifetime of cementitious products [1,2,3]. The effect is also detailed in the current CEN Product Category Rules of concrete and concrete elements, which was under enquiry at the time of writing [4].

The CO₂ attributed to cementitious products in life cycle assessments should be adjusted to take account of natural sequestration in order to accurately reflect its true environmental impact. International research has shown that the amount of CO₂ absorbed by concrete can account for up to 17% of all CO₂ emitted during cement manufacture in a given year (calcination and fuel) [1]. In Ireland this effect was conservatively estimated to result in a net reduction of 75 kg of CO₂/tonne cement [3]. Failure to take account of this sequestration of CO₂ into concrete can lead to misinformed policy formulation on global and regional climate change strategies.

Carbonation (or CO₂ sequestering) is the reaction between the hydrated calcium compounds in the building element and atmospheric carbon dioxide. These chemicals dissolve in the pore water of concrete which enters through the exposed surface via the pore network. The reaction results in the precipitation of calcium carbonate in the capillary pore system and a reduction in the pH of the concrete. Concrete design usually aims to reduce the depth of carbonation due to the potential risk of corrosion when the carbonation front reaches the level of embedded steel reinforcement. Consequently, the

main focus of research into carbonation in concrete to date has been on efforts to predict and limit the depth of carbonation. Despite this, and depending on the in-service use and exposure conditions, reinforced concrete is known to absorb significant amounts of carbon dioxide which are currently unaccounted for in most estimates of environmental impact.

The rate of carbonation in dense concrete is typically modelled mathematically in the general form shown in Equation 1 [5]:

$$x = k\sqrt{t} \quad (1)$$

Where x is the depth of carbonation, k is a carbonation coefficient (or 'k-factor') dependent on material properties, t is time. Numerous variables are known to affect the rate of carbonation and are included in a wide range of different formulae which can be grouped into three main categories: factors inherent to concrete (cement, additions, w/c ratio, strength etc.), curing and moulding conditions and exposure (environmental) conditions [6].

In unreinforced concrete there is no reason to limit carbonation and there is the opportunity for designers and manufacturers to actively encourage carbonation in service. The subject of carbonation of open textured concrete products (Concrete blocks, roof tiles etc.) is considerably less well researched than dense concrete although the mechanisms are identical.

In dense concrete it is normally assumed that high levels of carbonation are attained only after recycling at the end of life, particularly in a predominantly humid Irish environment and in higher grades of concrete [3]. In more open-textured

products it could be expected that full carbonation would normally occur during the service life of the building or structure (if exposed to air). During preliminary work for this project, old blocks (of unknown age but perhaps decades old) in the storage yard were found to be fully carbonated.

This study examined whether the carbonation of blocks in a production yard prior to dispatch to customers was of a significant level to include in environmental footprints for products manufacturing phase. A full life-cycle assessment of concrete blocks would also require an examination of the carbonation of blocks in service. This longer term in-service testing fell outside the scope of this initial study.

2 METHODOLOGY

The project sought to use a series of measurements on concrete blocks stored in a block manufacturers' yard (Figures 1a and 1b) to confirm the potential of cement-based non-reinforced construction materials to sequester atmospheric carbon dioxide (CO₂) and to understand how much of this may occur prior to their incorporation into structures or buildings.

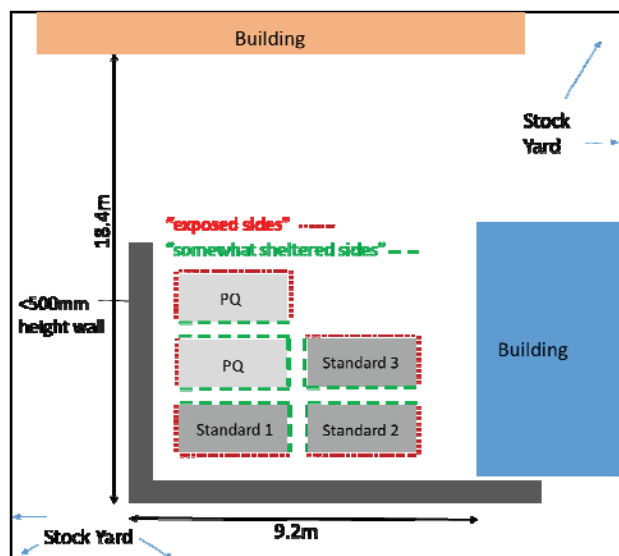


Figure 1a. Layout of stacks.



Figure 1b. Block stacks on site.

2.1 Experimental Variables

Concrete block type:

Two concrete block types were used to examine the effect of block properties on carbonation. The first type was a "standard" solid concrete block (Standard Block) and the second type was a more dense block manufactured to have

enhanced air tightness, acoustic, visual and painting properties* (PQ Block).

Block position in stack:

After manufacture it is common practice to arrange blocks in "rings" of single block height which are then placed on top of each other to make a "stack" in the yard. Five stacks in total were placed on site as shown in Figure 1a.

Figure 2 illustrates the typical block arrangement in a stack. The block position was anticipated as being a significant variable, therefore, four types of block exposure were identified:

- Top Face (TF) and Front Face (FF) of block exposed with other faces sheltered by adjacent blocks in the stack.
- TF, Side Face (SF) and FF exposed.
- FF exposed.
- FF and SF exposed.

Two type "a" blocks, one from an "exposed side" (see Figure 1a) and one from a "somewhat sheltered side", and one of each type "b", "c" and "d" were taken from each standard block stack, making 15 standard blocks sampled for each date of measurement. 5 blocks were taken from the PQ stacks. Care was taken to extract blocks from the stack without disturbing adjacent units. Units were not tested if their exposure conditions were altered by the removal of blocks from the stack previously.

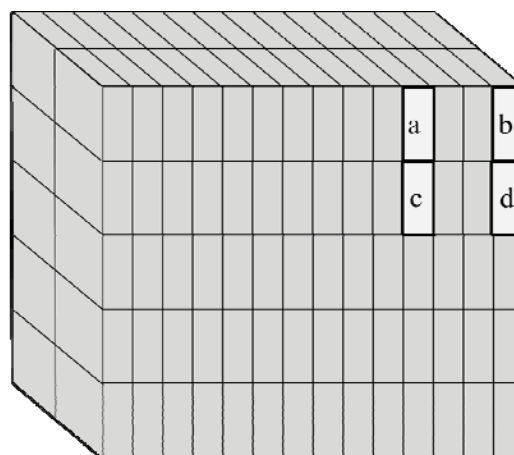


Figure 2. Stack shape showing 4 block types.

Exposure Time:

Concrete blocks are commonly retained in a production storage yard for at least 4 weeks before dispatch to site. The actual time spent in the production yard is likely to be heavily influenced by market conditions. Therefore, blocks were tested after approximately 0, 4, 8, 16 and 24 weeks after manufacture.

2.2 Tests

In dense concrete the depth of carbonation can be determined by spraying a freshly exposed surface (by splitting) of the

* Standard 7.5N Block and PQ Block (Aristocrat Range 10N) produced by Roadstone Ltd. All units 440x210x100mm.

concrete with a 1% phenolphthalein in ethanol solution [5]. The solution is made by dissolving 1gm of phenolphthalein in 90 cc of ethanol and made up to 100 cc by adding distilled water. The phenolphthalein solution is an indicator of pH with materials of lower than roughly pH 9 showing no colour change (assumed to be fully carbonated concrete –see section 1) and materials of higher pH than 9 showing pink/purple (uncarbonated concrete) [7].

Following spraying with phenolphthalein solution the depth of the carbonation (the uncoloured layer), as shown in Figure 3, from the external surface is measured to the nearest 0.5mm at different positions, and the average taken.

The feasibility of using this standard dense concrete carbonation test method for open textured material (cement blocks) was unknown at the outset of the project, however, the method produced clearly defined colour changes indicating carbonation depth during early stage testing. The method was therefore deemed an appropriate one to use for the duration of the test series.



Figure 3. Measuring depth of carbonation.

2.3 Testing Methodology

Samples were marked on exposed surfaces and transported to the test laboratory where they were split as shown in Figure 3 using an Avery Denison 100kN capacity 7123 traverse unit with the single point flexure setup. Break 1 split the block in half along the long face, and Break 2 split the FF in half producing two quarter blocks.

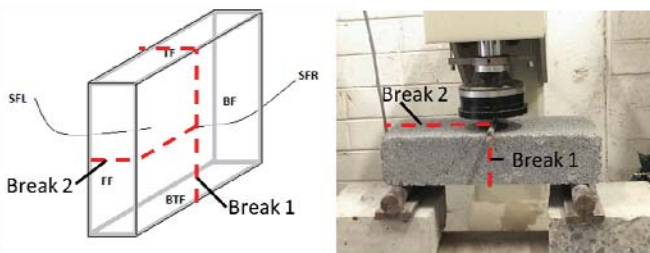


Figure 4. Splitting of the concrete blocks.

The freshly broken surfaces were immediately cleared of any dust and loose material before being sprayed, photographed and the depth of clear colour measured using a measuring tape or ruler as shown in Figure 3. It should be noted that findings from this study are deduced using these cut positions as a snapshot of carbonation within the block. The determination of interactions between exposure sides, for example at the exposed corner in block type “b”, is not possible using this method.

Average monthly meteorological data [6] for the test period was obtained from the Met Éireann Casement Aerodrome

station (Figure 5), which is roughly 3km away from the block exposure site.

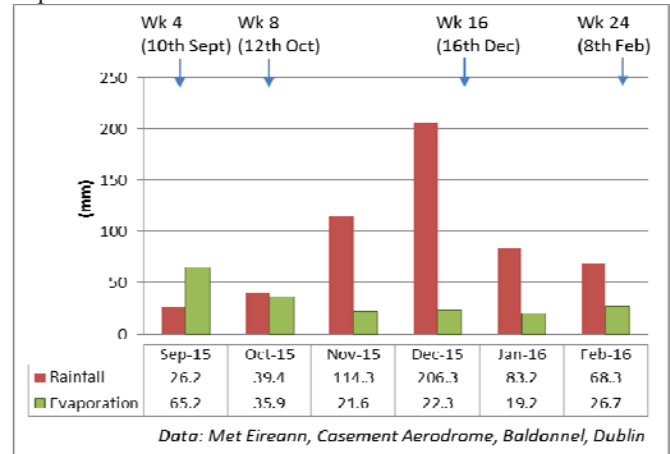


Figure 5. Rainfall and evaporation data for test period

3 RESULTS

When the substrate has a pH of below 9 the phenolphthalein indicator remains clear and it is assumed that the concrete is fully carbonated. On a substrate with a pH above 9 the indicator turns purple and the concrete is deemed uncarbonated (Phenolphthalein indicator turns purple).

3.1 Block type

The greatest carbonation depth was recorded on the exposed FF for both block types examined in this study. Figure 5 shows the average depths of carbonation on the FF of all Standard (15 blocks) and PQ Block (5 blocks) types over the test period. At 24 weeks the depth of ingress was on average 79% lower on the PQ blocks. This effect was particularly evident in the first 4 to 8 weeks of exposure whereby carbonation progressed much more rapidly in Standard Block types (Figure 6).

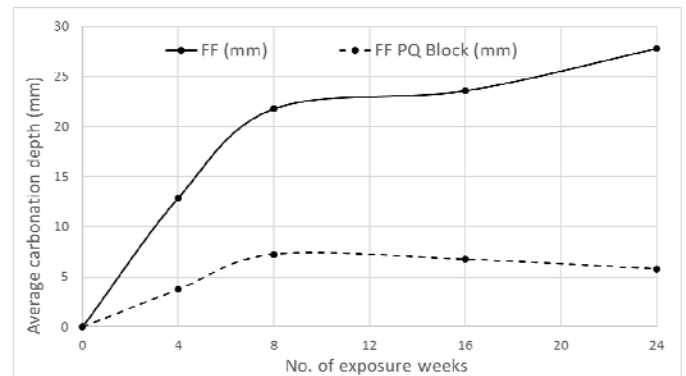


Figure 6. Depth of carbonation on Front Faces of Normal and PQ blocks.

Given that all blocks were exposed to the same weather conditions (Figure 5), it can be concluded that the difference in carbonation behavior between Standard and PQ blocks was due to their differing compositions and structure. The reason for this differential is very likely to be related to the reduced air permeability of PQ Blocks, which are designed to be more suitable for airtight buildings.

3.2 Block Stack Exposure

Standard Block stacks 1, 2 and 3 had one “exposed side” and one “somewhat sheltered side”, sheltered by neighbouring stacks (< 300mm adjacent) as defined in Figure 1a and photographed in Figure 1b. The “exposed sides” as indicated in Figure 1a generally experienced higher levels of carbonation as shown in Figure 7, which uses the example of “a” type block FF’s carbonation depth as recorded in week 16 to highlight this observation.

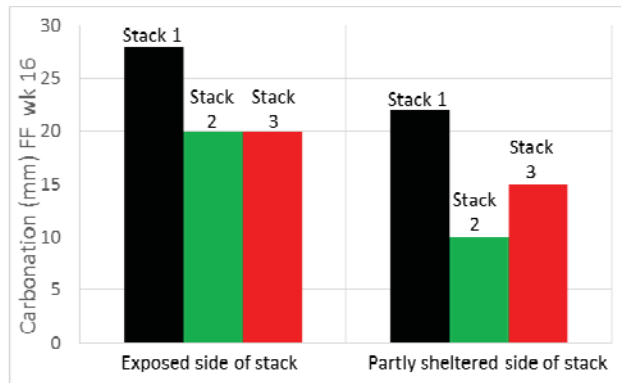


Figure 7. Comparison of “exposed sides” and “somewhat sheltered sides” week 16 data.

The general trend that more exposed sides of the stack experienced higher depths of carbonation was identified. However, no definitive pattern emerged and the degree of shelter offered by neighbouring objects and buildings was not taken into account when comparing sides. For future testing, more rigid measurement of sheltering combined with prevailing wind conditions and weather monitoring would be required to clearly define any relationship between sheltering and carbonation.

3.3 Pattern

Initial weeks showed a clearly defined line between coloured and uncoloured parts of blocks when sprayed with phenolphthalein solution. The findings for weeks 16 and 24 tended to have scattered mixes of coloured and uncoloured portions as well as more clearly defined lines. A comparison is shown in Figure 8 whereby (i) and (ii) show clearer borders between coloured and uncoloured portions, while later tests show less clear boundaries (iii) and (iv).

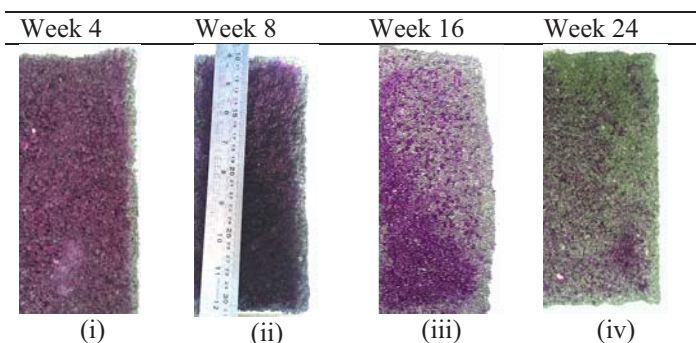


Figure 8. Comparison of ingress patterns in “b” blocks from the same stack in week 4, week 8, week 16 and week 24.

For the purposes of this study “scattered” areas were deemed to be uncarbonated concrete and measured accordingly. Particularly heavy rainfall was experienced during the months of November to January, which encompassed all post-week 8 readings (Figure 5) and is thought to be a possible reason for the dispersed pattern.

3.4 Exposure Faces

Although the highest carbonation was recorded on FFs (in both Standard and PQ Blocks) other exposed faces also showed varying significant depths of carbonation.

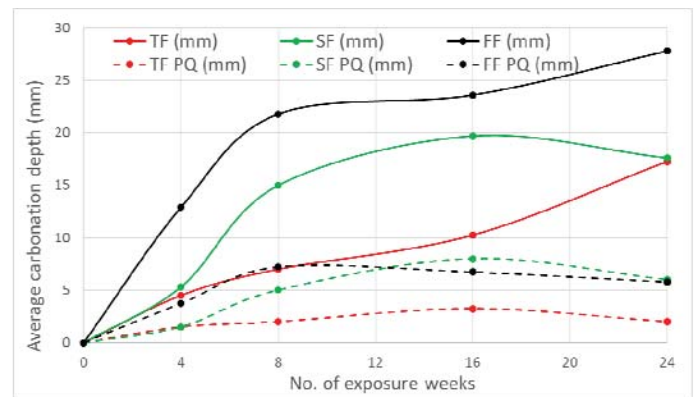


Figure 9. Relationship between exposed face position and carbonation front ingress by week.

Figure 9 displays that carbonation was significantly higher on FFs (all 15 blocks had exposed FF) compared to other exposed faces for Standard Blocks. Standard deviations increased as the weeks progressed, advancing from 1.9mm for week 4 recordings to 22.7mm for week 24. Generally, TFs showed the lowest carbonation depths (9 blocks had exposed TF) and a lower standard deviation of 1.2mm in week 4. The cause of this lower carbonation rate was not immediately evident. In week 24 the TF average increased steeply to the same depth of ingress as the SF average (6 blocks had exposed SF). Individual block values for TFs ranged between 10mm and 15mm, however, one “b” type corner block showed 40mm carbonation depth, which considerably increased the average. Removing this anomaly would reduce the average TF value to 12mm in week 24 which would maintain the identified trend. However, due to the low number of blocks used for the study no carbonation depth results were omitted from the data set.

In PQ blocks the differential between exposure faces was less pronounced. Similar to Standard Blocks, TFs of PQ blocks also exhibited the lowest level of carbonation.

Figure 9 shows the SF of Standard Blocks (and to a lesser extent PQ blocks) having an unexpected reduction in carbonation at week 24. Carbonation is an irreversible process and these measurements appear to show the degree of specimen to specimen variation in the results rather than a real effect as standard deviations increased from 0.5mm in week 4 to 12.7mm in week 24.

There is evidence that some degree of carbonation also occurred on internal faces of the blocks tested. Figure 10 provides an example of a “c” type block after 24 weeks of exposure. Only the FF is externally exposed, all other faces were sheltered by adjacent blocks in the stack, however, a

scattered purple and clear pattern was seen to ingress from the surface on those covered sides. Carbonation on the internal faces of blocks were not the focus of this testing series, however, all blocks were photographed at time of test which allows general observations to be made. All internal faces tended to show some carbonation, though the depths varied from 0-10mm in week 24. It is thought that the variation may have been due to the gap widths between adjacent blocks in the same stack.

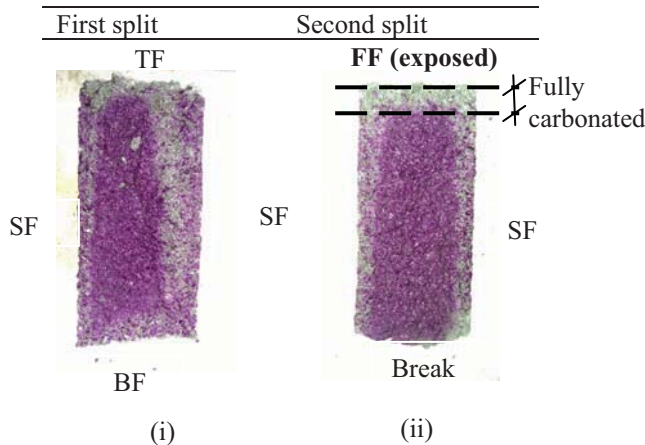


Figure 10. Example of “c” type Standard Block. (i) Break 1: all faces shown are internal. (ii) Break 2: only the FF is external.

3.5 Rate of carbonation

The general trend of rapid initial carbonation, which slows over time, was observed and displayed in Figure 11. The exception to this trend is noted for TF data point in week 24 as discussed in section 3.4. In normal dense concrete this can be explained by the time - carbonation depth relationship (Equation 1). This, however, may not completely explain the apparent fall off in carbonation rates in open textured blocks such as those examined for this study. Figure 5 clearly shows that the initial 8 weeks (taken Sept-Oct) were reasonably dry with the following weeks substantially wetter and with lower evaporation rates (Nov-Feb). It is speculated that this influenced carbonation rates significantly.

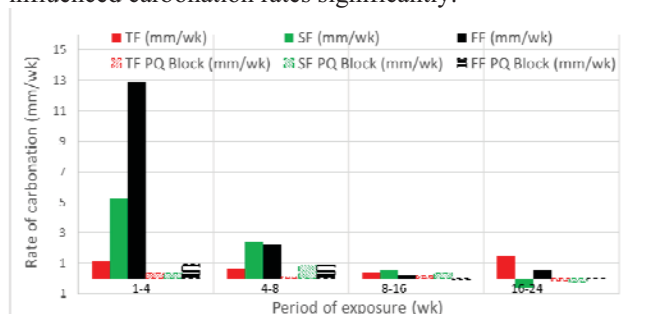


Figure 11. Relationship between exposed face position and rate of carbonation front progression in mm per week.

The “negative” rate of carbonation recorded in Figure 11 illustrates specimen to specimen variation (introduced in section 3.4) as carbonation of concrete is not process that can be reversed.

3.6 Estimate of sequestered carbon

Using the carbonation measurements recorded in this investigation (plotted in Figure 9) an estimate of the sequestered carbon in an average Standard Block can be made.

Table 1 – Percentage of blocks carbonated

block type	exposed faces	week 4	week 8
		% of block carbonated	% of block carbonated
type (a)	FF, TF	3.7	6.1
type (b)	FF, TF, SF	9.0	21.1
type (c)	FF	2.8	4.7
type (d)	FF,SF	8.1	19.7

Each tonne of CEM II/A cement is estimated to result in roughly 428kg of calcined CO₂ (not total CO₂) [3]. The exact quantity of cement in each block is considered commercially sensitive information and not publicly available. The estimate that one standard 440x215x100mm block typically contains 1kg of cement was used to estimate the quantity of sequestered carbon dioxide.

Using the results in table 1 for type “d” blocks it can be estimated that each type “d” block has immobilised 0.031kg of CO₂ by week 4 and 0.076 kg by week 8 (assuming a degree of carbonation of 0.9 [1]).

The limitations of this calculation are explicitly acknowledged. The rate of carbonation was found to be highly variable, with weather in particular being an influencing factor. The carbonation depths used in the calculation relate only to measurements in this initial study and cannot be generalised to represent typical or expected performance.

4 DISCUSSION AND CONCLUSION

This study has found that significant amounts of carbonation in concrete blocks can occur in an Irish production storage yard in relatively short periods. Peak rates of carbonation of up to 13 mm/week over 4 weeks were recorded in this study on exposed faces.

The study found that the positioning of block stacks and the position of individual blocks in a stack influenced the amount of carbonation that occurred. The results also show that weather and rainfall could have a very significant effect on the rate of carbonation. A notable finding from this initial study is the lack of information on the general nature of the rate of carbonation of open textured concrete products. A straightforward laboratory study is recommended to assist in providing the required insight into the general nature of carbonation of open textured blocks.

In life cycle analysis the impact of materials is divided into different life stages, therefore, this study relates only to the manufacture stage. The results of the study indicate that action by a manufacturer (e.g. covering or uncovering stacks during storage, adjusting the spacing of stacks) could be used to maximise recarbonation during storage and hence reduce the environmental footprint of their product.

Measurements from this study were used to estimate the amount of carbonation (carbon sequestration) occurring in a normal block in a particular location in the block stack. The estimates indicate that significant quantities of calcinated CO₂ arising from cement used in standard blocks was reabsorbed in the first 8 weeks of storage. This suggests that there is potentially a significant reduction in environmental impact of concrete blocks if carbonation is taken into account in lifecycle analysis. It is clear from this work that the recarbonation of standard open textured concrete should be considered in the manufacturing or product stage of life cycle assessments. Significantly less carbonation was seen to occur in more closed textured concrete blocks (PQ Blocks).

The test series was effective in highlighting variables that would benefit from more extensive monitoring and/or controlling in any future research on this topic. This includes the degree of stack sheltering, the measurement of gaps between blocks in each stack as well as a more detailed investigation of the degree of carbonation within the portion of blocks which indicated in a “scattered” weak indication of carbonation. Inter-specimen variation was evident in the results and should be kept in mind when designing further investigations.

Research into carbonation of open textured concrete products should also be extended to include carbonation in-service. The aim of such research would be to confirm that carbon sequestration continues after installation in most construction types.

ACKNOWLEDGEMENTS

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