MEASURING CARBONATION DEPTHS FOR ESTIMATING CO2 UPTAKE DURING THE LIFETIME OF WOOD-CEMENT PRODUCTS

SORIN PASCA & IAN D. HARTLEY

University of Northern British Columbia, 3333 University Way, Prince George, BC V2N 4Z9, Canada

ABSTRACT

Carbon Dioxide (CO_2) uptake through carbonation can have significant implications for understanding the carbon balance of wood-cement composites. This may impact CO_2 policy, product labeling and carbon footprint comparisons among various building materials. Approximately 38 kg of CO_2 can potentially be reabsorbed through carbonation from the atmosphere for each 100 kg Portland cement clinker used for fabricating cement-based materials. A phenolphthalein test was performed to assess depths of carbonation on 4 years old wood-cement samples. The results were validated by direct pH measurements on cement powder suspensions. The carbonation rate factors of the outdoor samples were lower than those of the indoor samples. Decorative wood-cement applications such as counter and table tops, floor tiles, benches or planters are slab-based structures with large surface area; therefore, they are expected to be highly carbonated during their product lifetime. An example of carbon balance for a unit of wood-cement product is suggested.

KEYWORDS:

Wood-cement; Carbonation; pH; Carbon dioxide

1. INTRODUCTION

The increase in greenhouse gas (GHG) emissions associated with both pollution and climate change, has been addressed through new ways of sustainable design that are meant to reduce the environmental impact of the buildings. The green construction approach focuses on being environmentally responsible and resource-efficient throughout the entire life-cycle of the building (Pearce et al., 2007). In terms of sustainable building products, concrete and wood are two opposing ‘concepts’ whereby concrete has a manufacturing process of producing high GHG emissions and wood has a role of carbon storage. Recently, there has been interest in engineered wood products, including products made by mixing wood and cement.

Wood-cement composites (WCC) have been developed as a hybrid material between categories of products of full-concrete versus wood-based panel products. In terms of the product attributes, the WCC are water, fire and fungal resistant and have acceptable strength characteristics, including screw and nail holding capacity. WCC products, including commercially available “cement bonded particle boards” and “wood fibre cement boards” have superior strength capabilities that make them suitable for numerous structural applications. They have been manufactured and marketed for many years around the globe. Among various WCC products, a locally produced Betlecrete has outstanding aesthetics attributes (Pasca and Hartley, 2012). It has uses for many indoor and outdoor decorative applications such as countertops, floor tiles, benches, patio elements and planters. Beetlecrete was originally developed at UNBC as a possible alternative solution for prolonging the shelf life of the beetle killed wood by incorporating smaller wood particles, thus avoiding detrimental characteristics of dead timber. It has interest from many architects, interior designers and builders.

Determining the carbon balance of products and services is a critical piece of knowledge for designing strategies for reducing CO_2 emissions. Concrete is a popular and durable building material providing foundation and core uses for numerous residential and non-residential building projects. However, using Portland cement in the product manufacturing is an extremely pollutant enterprise. On the other hand, because there are plans to increase the importance and use of wood in sustainable building, the use of WCC could contribute to this effort. By increasing the demand wood while sequestering it in a long-lasting cement-based product, WCC have an opportunity to be accepted by various certification systems for green building product. Also, with proper evaluation, information could be provided to aid designers and builders to make informed decisions regarding the environmental impacts of construction material selection and building design.

2. CARBONATION OF CONCRETE PRODUCTS

Although all concrete-based products are considered inert materials, there is a chemical process associated with the cement component in concrete that can significantly affect the carbon balance during the life-cycle of various product applications. Greenhouse gas emissions associated with manufacturing Portland cement (approximately 50 kg of CO_2 are released only through calcination of limestone for every 100 kg of produced cement) are responsible for 5% of the total global manufactured emissions into the atmosphere (Pade and Guimaraes, 2007). However, depending on product attributes and numerous environmental factors, carbon dioxide can be re-absorbed by concrete from the atmosphere through a process called *carbonation*. The carbonation process consists of a chemical reaction between the calcium hydroxides in the hydrated cement paste and the atmospheric CO_2 in the presence of water, forming calcium carbonate (Taylor, 1997).

Beyond the product evaluation for carbonation alone, it has been reported by others (Gajda, 2001; Galan et al., 2010) that the effect of demolition and subsequent crushing of concrete structures, increased the rate of carbonation (Lagerblad, 2005; Engelsen et al., 2005; Pommer and Pade, 2005). This aspect seemed to be neglected by previous models for computing CO_2 uptake through product carbonation and consequently, the CO_2 emissions related to concrete industry might have been overestimated. Knowing that the CO_2 can be re-absorbed into the concrete-based product alone and after demolition, there may be a significant impact on CO_2 policies, product labeling and carbon footprint comparisons among various building materials.

Concrete carbonation depends on the availability of the atmospheric CO_2 within the hardened cement paste. It is useful to determine the depth of the carbonation in concrete structures. The carbonation penetration is given by the formula:

$$D = K\sqrt{t} \tag{1}$$

where, D is the depth of carbonation (mm), K is the carbonation rate factor (mm year$^{-1/2}$), and t is the service life (year). The carbonation rate factor, K, depends on the product's physical characteristics such as porosity, and its environmental conditions, such as temperature and humidity. Consequently, the quality of concrete, the surface area exposed to environmental conditions and the physical location and application of the concrete structure are all attributes contributing to the carbonation process. The rate of carbonation, and consequently, the penetration in concrete is a slow process; it is of the order of years and decades.

Carbonation process can potentially have significant implications for the life cycle assessment and the carbon balance of WCC. It is expected that the rate of carbonation for both primary and secondary life of the wood-cement structures is higher than those for ordinary concrete. The natural high porosity of the WCC material is a factor that may enhance carbonation rates of WCC. Although wood is dried to low moisture content during the manufacturing of the WCC product, the hygroscopic nature of it may be a key factor for increased rates of carbonation -- moisture will be re-absorbed by the wood and this moisture increase in the product is a requirement for the initial stages of the chemical process of carbonation. There is no information available on the rate factors for wood-cement materials and the studies outlined above are limited in scope. The percentage of the overall carbonation of WCC products could be high because of the relative small physical size (thickness) of the material in applications such as boards, slabs and tiles and because of the fact that wood-cement products can be easily crushed into small fragments after demolition.

3. MATERIALS AND METHOD

In order to measure the depth of carbonation of WCC, a standard phenolphthalein[1] test will be conducted on samples of WCC. The carbonation rate factor can then be determined from Equation 1 and used for estimating total carbonation during the service life of WCC products. The WCC samples used in this study were prepared for other past research at UNBC (Choi et al., 2011). The blocks of material are four years old and made of beetle killed wood (*Pinus Contorta*) at a cement/wood/water ratio of 3.75/1/2.4 (on a mass basis). The wood shavings were initially ground with a powerful grinder. The particles passing through the 16-size mesh and retained by the 32-size mesh were used for making the WCC material. As the WCC product could be used for indoor applications as well as outdoor applications, it will be part of this study to determine if the rates of carbonation are different for indoor and outdoor wood-cement products. Three samples were selected from each group. The indoor samples were kept in a lab environment at a temperature of 21°C and a relative humidity of 35%. The outdoor samples were exposed to weather conditions characteristic to a very cold climate in northern British Columbia. They were covered in snow for almost 5 months every year.

A phenolphthalein solution 1% (alcoholic) was sprayed on a freshly broken section profile of each sample. Initially, the samples were cut with a saw but the results were inconclusive because during the cutting process the cement dust from different layers throughout the sample was mixed and randomly spread over the entire cut section. However, good results were obtained when the samples were broken using a chisel and a hammer. The phenolphthalein turns pink on pH values of 10 and higher of the non-carbonated cement and remains colorless at a pH under 10 which is an indication of the cement paste carbonation. The depth of carbonation was measured in five points equally spaced along the exposed sides of the sample and the average was recorded. Measurements from the bottom side

---

[1] Chemical formula: $C_{20}H_{14}O_4$

were avoided if there was a clear indication of a disproportioned penetration depth through the respective side because of reduced exposure to the atmosphere.

The results were validated by direct pH measurements on cement powder suspensions, using distilled water as a solvent. The use of power suspensions was proposed as an alternative to the standard pH measurement method on extracted pore solution from concrete samples (Rasanen and Pentalla, 2004; Grubb et al., 2007). The pH determination can be useful when testing carbonation of dyed material and the color change of the phenolphthalein is not visible. The pH values can also represent a good indication of the degree of carbonation. The sample preparation consisted in breaking the WCC blocks in small pieces using a chisel, followed by collecting material from both carbonated and non-carbonated zones. For the reasons already described above, the use of saws or drilling tolls was avoided. The standard sample preparation technique for ordinary concrete recommends sanding a small portion of the area of interest and collecting the generated dust. However, by sanding a wood-cement material there will be impossible to separate the wood dust from the cement dust. The wood pH is rather acidic and therefore, wood addition to the powder suspension can significantly alter the pH value of the solution. In this study, pieces of materials were put in plastic bags and crushed with a hammer to the dust fraction, then screened through the 32-size mesh in order to separate the wood component. Samples of 2 grams of cement powder diluted with 4 ml of distilled water were manually mixed for 3 minutes. The pH was repeatedly measured after 1, 5, 15 and 60 minutes, using a digital pH meter. A last measurement was conducted after 6 hours.

4. RESULTS AND DISCUSSION

Phenolphthalein color change as an indication of the carbonation of the indoor WCC samples is shown in Figure 1. The not-carbonated zone is relatively visible although differentiation between carbonated and non-carbonated zones may be difficult in some areas. The non-carbonated zones of the outdoor samples (Figure 2) are definitely more visible. The phenolphthalein's changed color is more vivid and the transition to the carbonated zone is more evident. The average carbonation depth for the indoor samples is 12.1 mm while for the outdoor samples it is 8.3 mm (Table 1). The temperature is an important factor affecting the rates of carbonation. It was documented by Liang et al. (2000) that indoor climate or exposure in warmer regions would lead to faster carbonation on concrete structures, given all other parameters remained constant. It would be expected that the carbonation penetration to be even higher if the indoor relative humidity was higher. The cold climate was definitely a strong impeding factor for carbonation of the outdoor samples even under higher moistures level. One sample kept outdoors presented a relatively narrow penetration depth, of only 6.4 mm. A possible explanation could be the fact that the respective sample was extracted from a stepping stone which was coated with a water-based wood stain. A surface treatment or cover correction factor of 0.7 was suggested by Lagerblad (2005) for ordinary concrete.

Figure 1. Carbonation of 4 years old indoor WCC samples

Table 1. Carbonation characteristics of 4 years old wood-cement samples

	D (mm)	K (mm year$^{-1/2}$)	pH carbonated zone	pH non-carbonated zone
Indoors	12.1 *(1.19)*	6.1	9.83 *(0.18)*	12.29 *(0.11)*
Outdoors	8.3 *(1.64)*	4.2	9.74 *(0.08)*	12.76 *(0.07)*

Note: Standard deviations appear in parenthesis as a result of three replications

The calculated rate of carbonation factor (K) for the indoor samples was 6.1, which corresponded to the carbonation rate factor calculated for ordinary concrete kept indoors and in the 25-35 MPa strength class (Lagerbald, 2005). For the outdoor samples, the carbonation rate factor was 4.2, equivalent to concrete in the <15 MPa strength class and exposed to relatively similar environmental conditions in the Scandinavian countries.

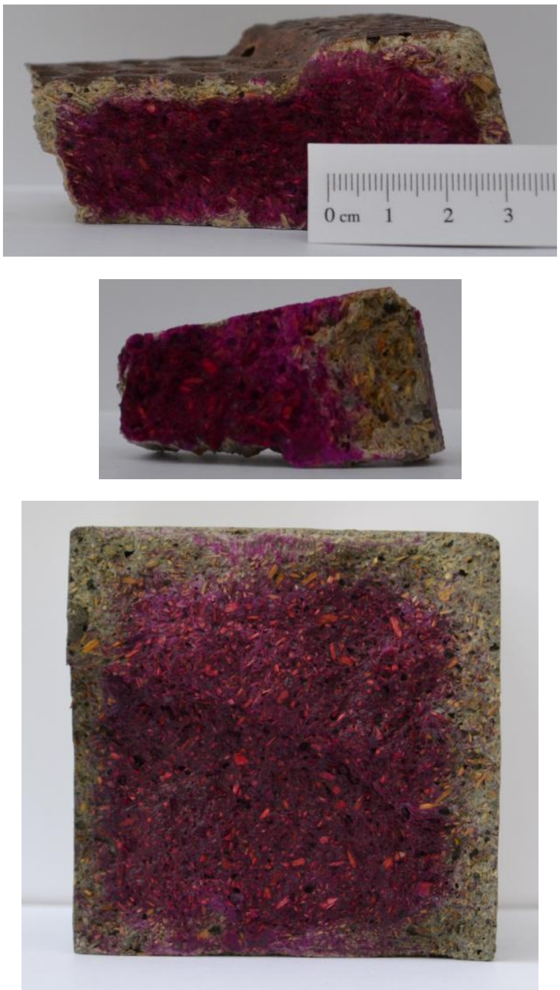

Figure 2. Carbonation of 4 years old outdoor WCC sample

The pH values measured 1 hour after preparing the powder suspensions showed no significant difference between the indoor (pH=9.83) and outdoor (pH=9.74) samples in the carbonated zone. However, there is a statistically significant difference (p=0.017) between the pH mean in the non-carbonated zone of the indoor samples (pH=12.29) and the pH mean in the non-carbonated zone of the outdoor samples (pH=12.76). As expected, the indoor samples are more susceptible to carbonation than those exposed to a cold climate. Also, most of the indoor samples showed no clear demarcation between the carbonated and non-carbonated zone, therefore it would have been possible that the non-carbonated samples to be tainted by small amounts of carbonated material. The pH values recorded after 15 minutes do not differ significantly from those measured after 1 hour, therefore 15 minutes of extraction time can guarantee good results for measuring pH of WCC. This finding can be used in further research for increasing the efficiency in conducting the test. However, all the determinations after 6 hours showed lower pH values (although, not statistically significant). Traces of wood into the powder samples could affect the overall pH of WCC because wood is acidic and its fully separation from the cement component during sample preparation might not have been successful. More research is needed for better understanding and overcoming the challenges related to sample preparation and for developing a reliable method for determining the pH of the wood-cement material.

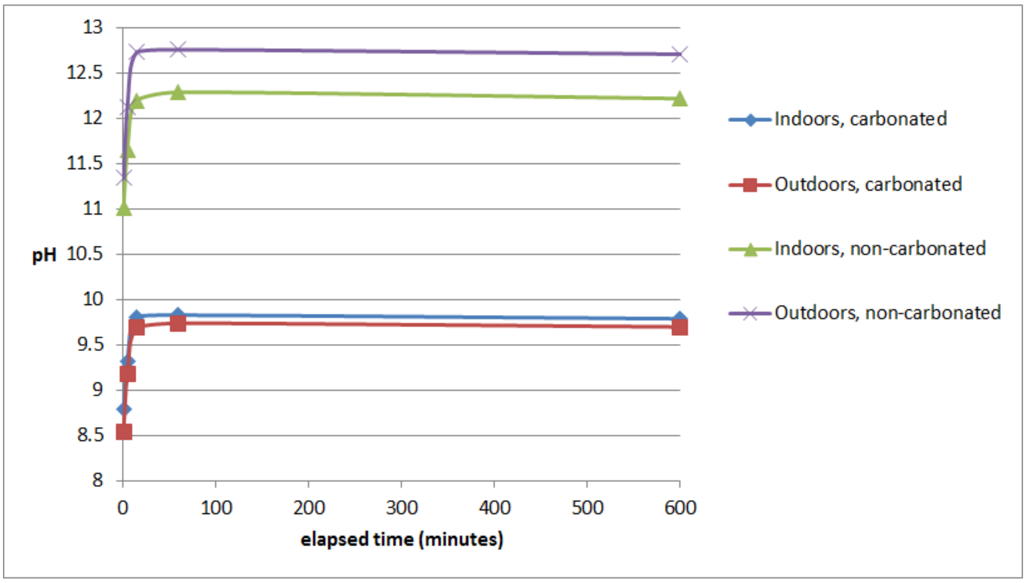

Figure 3. Effect of extraction time on the pH of WCC powder suspensions

5. EXAMPLE OF CALCULATING THE CO_2 BALANCE OF THE WOOD-CEMENT PRODUCT

Estimates of the carbonation depths for WCC material used in applications having various service life spans are presented in Table 2. Conversely, it can be predicted that a 4 cm thick countertop slab, as an indoor application, will be fully carbonated in 11 years, assuming carbonation penetrates at equal rates on both sides of the slab and none of the sides are coated or sealed. On the other hand, a proposed WCC road block (Jersey barrier) application will be carbonated within 30% of its volume after 50 years of exposure to a northern climate, resulting in a penetration depth of 3 cm around its exposed sides. Special designs on cement-based applications can enhance the rates of carbonation. For example, a perforated profile would allow exposure to a larger surface and consequently, an increased volume of carbonated material. Crushing the structures after the end of life will also contribute to achieving the goal of full carbonation of the wood-cement material during the entire life cycle of the product.

Table 2. Predicted carbonation depths for indoor and outdoor WCC products during service life

	10 years	25 years	50 years	100 years
	Carbonation depth (mm)			
Indoors	19.2	30.5	43.1	61.0
Outdoors	13.3	21.0	29.7	42.0

Lagerblad (2005) suggested the following equation for calculating the CO_2 uptake in carbonated concrete, based on the assumption that 75% of the calcium oxide (CaO) component in the original cement will be carbonated and the clinker to cement ratio is 100%:

$$CO_2 \text{ uptake} = 0.75 \text{ x } PC \text{ x } CaO \text{ x } MCO_2/MCaO \text{ (kg)} \qquad (2)$$

where 75% of CaO in original cement is carbonated, PC is the amount of Portland cement (kg), CaO is the percentage of CaO in cement (65%) and M is the molar weights. The depth of carbonation and the exposed surface area can be used to calculate the total volume of the carbonated WWC and consequently, to determine the amount of Portland cement originally used in making the product. 38% of that can represent the CO_2 amount reabsorbed from the atmosphere into a fully carbonated product.

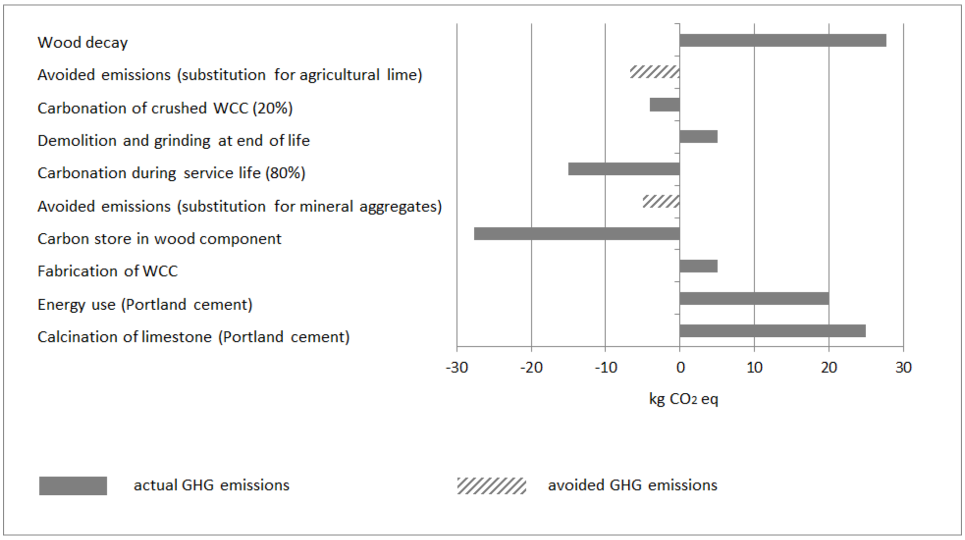

Figure 4. The carbon balance for a unit of WCC (countertop slab)

The carbon balance of a 2’ x 8’ x 2” countertop slab made of Beetlecrete is shown in Figure 4. The emissions in this diagram represent approximations and they are not the result of any inventory analysis. However, this model shows GHG emissions associated with the entire life-cycle of the WCC product: extraction and processing raw materials, manufacturing, primary use and secondary use at the end of life through recycling and reusing. The slab has an approximate volume of 0.075 m^3 and it requires 50 kg of Portland cement and 15 kg of wood particles (oven dried) for its fabrication. 25 kg of CO_2 (emissions resulted from calcination of limestone) and 20 kg of CO_2 (emissions resulted from burning fossil fuels during the manufacturing process) are process emissions associated with manufacturing 50 kg of Portland cement. A total of 19 kg of CO_2 can be reabsorbed through fully carbonation during service life and after demolition. The carbon balance also includes avoid emissions from product substitution. Using the wood as a substitute for mineral aggregates in ordinary concrete can avoid emissions generated through extracting, processing and transportation mineral aggregates, while recycling the carbonated WCC material as amendment for acidic soils can avoid extra emissions potentially generated by processing agricultural lime (approximately 6.7 kg CO_2 emissions per 50 kg of agricultural lime, crushed and transported to the delivery site (West and McBride, 2005)). The wood component is carbon neutral, although in short term, sequestering wood into a long lasting WCC product can contribute to the goal of reducing GHG emissions. Emissions associated with fabricating the product and crushing the structures at the end of life complete the carbon balance.

6. CONCLUSION

The amount of re-absorbed CO_2 into the fully carbonated wood-cement structures can be as high as 38% of the Portland cement component, on a mass basis, that is, 38 kg of CO_2 can be re-absorbed through carbonation for every 100 kg of Portland cement originally used in WCC products. It means that almost half of the CO_2 initially released during cement manufacturing can be chemically bound again through carbonation of the WCC structures during the service life and especially, after demolition.

The rates of carbonation for the outdoor WCC exposed in a cold climate are rather small, but the possibility of crushing the WCC products at the end of life to the dust fraction can guarantee fully carbonation. The pH determinations may bring additional information on the degree of carbonation which can be used for better evaluating the CO_2 uptake during primary life of WCC products. However, the method for measuring the pH of WCC powder suspensions needs to be improved, especially with respect to sample preparation, powder/solvent ratio and extraction time.

REFERENCES

Choi, S., Ng, A., Park, S-J. 2011. “Purchase decision: Sustainability of mountain pine beetle wood concrete products”. *Forest Products Journal* 61 (4):333-339.

Engelsen, C.J., Mehus, J., Pade, C., Saether, D.H. 2005. “Carbon dioxide uptake in demolished and crushed concrete”. *Norwegian Building Research Institute* Project Report 395-2005.

Galan, I., Andrade, C., Mora, P., Sanjuan, A. 2010. “Sequestration of CO2 by concrete carbonation”. *Environmental Science & Technology* 44 (8):3181-3186.

Gajda, J. 2001. “Absorption of atmospheric carbon dioxide by Portland cement”. *Serial no. 2255a* PCA, R&D:Chicago, IL

Grubb, J.A., Limaye, H.S., Kakade, A.M. 2007. “Testing pH of Concrete”. *Concrete International* April:78-83.

Lagerblad, B. 2005. “Carbon dioxide uptake during concrete life cycle - State of the art”. *Swedish Cement and Concrete Research Institute* NI-Project 03016.

Liang, M.T., Qu, W-J., Liao, Y.S. 2000. “A study of carbonation in concrete structures at existing cracks”. *Journal of Chinese Institute of Engineers* 23(2):143-153.

Pade, C., Guimaraes, M. 2007. “The CO2 uptake of concrete in a 100 year perspective”. *Cement and Concrete Research* 37:1348-1356.

Pasca, S, Hartley, I.D. “Beetlecrete – An attractive solution to mountain pine beetle epidemic” – IIBCC - 2012, Canberra, Australia

Pearce, A.R., DuBose, J.R., Bosch, S.J. 2007. “Green Building Policy Options for the Public Sector”. *Journal of Green Building* 2 (1):156-174.

Pommer, K., Pade, C. 2005. “Uptake of carbon dioxide in the life cycle inventory of concrete”. *Nordic Innovation Centre Project* NI-project 03018.

Rasanen, V., Penttala, V. 2004. “The pH measurement of concrete and smoothing mortar using a concrete powder suspension”. *Cement and Concrete Research* 34:813-820.

Taylor, H.F.W. 1997. “Cement Chemistry – 2nd Edition”. Thomas Telford Publishing, London, 1997.

West, T.O., McBride, A.C. 2005. “The contribution of agricultural lime to carbon dioxide emissions in the United States: dissolution, transport, and net emissions”. *Agriculture, Ecosystem and Environment* 108:145-154.