

# CONSIDERING SUSTAINABLE DEVELOPMENT DECISION IMPACTS IN LIFE CYCLE ANALYSES AND TESTING METHODOLOGIES FOR CONCRETE TRANSPORTATION MATERIALS

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## ABSTRACT

As sustainable development principles are adopted for the transportation industry and decisions are made concerning novel material alternatives, care must be taken that the testing methods and the life cycle analyses performed are adapted to rapidly changing material and environmental conditions. Of particular importance are considerations for novel concrete applications and the current focus on producing concrete-based infrastructure with a lower carbon footprint. The carbon footprint of the infrastructure must include not only the cradle to gate analyses, but also the fate and transport of carbon during the operational life and disposal of these materials and associated impacts of the material characteristics. As the absorption of carbon dioxide by concrete is encouraged, its material characteristics such as pH change. These changes will need to be considered with respect to the use of alternative reinforcing materials, comprehensive life cycle assessments, and potential modifications to material testing methodologies.

**Keywords:** concrete, carbon footprint, life cycle analysis, testing methods, reinforcement.

## 1 INTRODUCTION

Life cycle assessment or analysis (LCA) is being used as a tool for the evaluation, design, and management of urban infrastructure materials, structures, and systems. Concrete is the most used building material in Japan and in the world, and is particularly important in the transportation industry [1]. Life cycle analyses performed on concrete usage in transportation systems must be adaptable to the material modifications made as sustainability decisions effect alterations in the makeup of concrete and also encourage the development of novel or modified concrete applications. In addition, durability metrics and associated testing criteria may need to be modified to include these changing material characteristics.

Concrete is a very complex and dynamic material. It is primarily produced from a mixture of cementitious materials, water, aggregates and specialty admixtures (chemical additives) to encourage more favorable performance in a variety of ways. When placed, a concrete structure might also include reinforcing materials such as reinforcing steel or fiber reinforced polymers (FRP). The primary cementitious material used in concrete is

Portland cement, but a significant amount of the Portland cement is frequently replaced with supplementary cementitious materials (SCMs) such as fly ash or slag, byproducts from the coal and steel industries respectively. These SCMs are chosen for many sustainability reasons, such as increasing the recycled content, lowering the energy footprint of the product or improving the economics.

After placement, the chemical composition of concrete changes with time and these changes are influenced by both its internal composition and the environmental conditions under which the concrete is aging. These changes in the chemical composition of concrete affect the fate and transport of other chemicals important in environmental life cycle analyses. Some examples are the carbon dioxide cycle which will be furthered analyzed herein and the acid rain neutralization capacities of concrete structures [2,3].

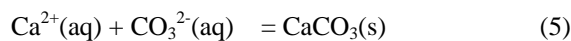
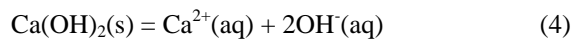
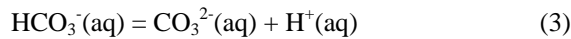
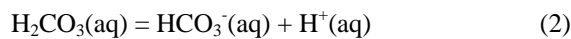
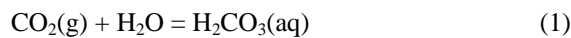
Concrete is considered to have a large anthropogenic carbon footprint, particularly due to its main cementitious ingredient, Portland cement. Traditionally, the production of one tonne of Portland cement emits from 0.8 to 1.1 tonnes of carbon dioxide. These emissions result from both energy usage and the chemical reaction in the

manufacturing process. Typically the carbon dioxide emissions are split approximately half and half due to energy use and chemical reaction in the production of cement [4].

Large amounts of energy are used in the manufacture of Portland cement, and the carbon footprint of this manufacturing process will be dependent on the carbon footprint of the associated fuels used in the kilns. There are efforts to decrease the carbon footprint of cement by using alternative fuels in its production.

The cement also contributes to the release of carbon dioxide to the atmosphere due to the chemical reactions in its manufacturing process. The primary component of cement is calcium oxide (CaO) which is made by the dissociation (calcination) of calcium carbonate from limestone (CaCO<sub>3</sub>) in the kiln with the associated release of carbon dioxide. Additional strategies to decrease the carbon footprint of concrete might include replacing a portion of the Portland cement with SCMs, or accelerating the re-absorption (sequestering) of carbon dioxide into concrete during its life cycle [4].

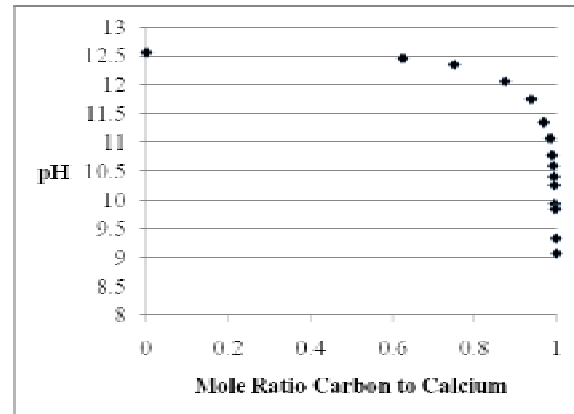
It has been recognized for decades that concrete has the capacity to reabsorb carbon dioxide [5]. It is a very complex process and dependent on many variables such as the concrete mix design, extent of carbon absorption, humidity, temperature, surface area exposure and ambient carbon dioxide concentrations. When concrete is produced, water is added to the cement and a hydrated cement paste is formed. One of the products which might form over time is calcium hydroxide (Ca(OH)<sub>2</sub>). In addition there are many other calcium bearing solid phases in concrete which change with time. The carbon absorption process associated with the calcium hydroxide phase can simplistically be summarized by the following series of equations (although it can also be modeled as a solid to solid reaction exchange with solid calcium oxide reacting directly with gaseous carbon dioxide to form calcite):



Where (g) represents a gaseous phase, (aq) represents an aqueous phase and (s) represents a solid phase [6].

The equilibria in Equations 1 through 5 are associated with the hydroxide and hydrogen ions.

Therefore, carbon absorption in concrete will not only change its solid composition, but it will also change the pH in its pores. This can result in many material and environmental impacts. Figure 1 depicts measurements in an aqueous solution in equilibrium with various combinations of calcium hydroxide and calcium carbonate solids based on percent by mole of carbon to calcium. As can be seen, significantly higher proportions of calcium carbonate relative to calcium hydroxide result in a drop in pH.



**Figure 1:** pH of CaCO<sub>3</sub>-Ca(OH)<sub>2</sub> Aqueous Suspension as a Function of Carbon to Calcium Mole Ratio

How will these chemical changes influence strength, durability or compatibility with reinforcing materials? As carbon sequestration considerations and technologies are included in sustainable development decisions for concrete structures, they must also be included in the analysis of affected technologies and associated life cycle analyses.

The development of FRP usage in concrete for transportation infrastructure needs to be considered simultaneously with preferred sustainability metrics and developing life cycle assessments. This paper addresses three overlapping issues important in this integrated approach.

- The use of FRP in novel concrete applications where traditional reinforcement may not be appropriate such as in pervious concrete.
- The incorporation of modified carbon footprint information into life cycle assessments for the infrastructure. This should include both a base-lined carbon footprint which includes the fate and transport of carbon in the full life cycle of traditional concrete production and use, and also the modifications to the footprint as novel sustainability approaches are embraced to lower the carbon footprint in transportation

infrastructure.

- Many testing methods for concrete which are based on traditional concrete chemistry might need to be adapted to a modified chemistry as the carbon content and other supplementary material percentages change in concrete structures to address complementary sustainability issues.

## 2 THE USE OF FRP IN NOVEL CONCRETE APPLICATIONS

The sustainability movement has increased the momentum for developing novel materials or innovative designs that are environmentally friendly while still maintaining serviceability and addressing social and economic aspects of development. Two examples in the concrete industry are pervious concrete and concrete with a lower chemical carbon dioxide footprint.

### 2.1 Pervious Concrete

Pervious concrete is a novel paving material which is not only porous like traditional concrete, but is also permeable to water, allowing water to flow through the material. It is being developed as a structural surface for pedestrians and vehicles which also allows stormwater to infiltrate into the ground below. This addresses many environmental concerns of development including stormwater runoff quantity control, stormwater runoff quality control, and maintenance of groundwater levels [7]. Pervious concrete pavement is considered to be a Low Impact Development (LID) practice.

Pervious concrete is made with cementitious materials such as Portland cement, aggregate, water and assorted chemical admixtures, similar to traditional concrete. However, the water to cementitious material ratio is typically lower than most traditional pavement mix designs and the aggregates are usually narrowly graded so that the concrete can be placed with an expansive void structure. Many of the voids are interconnected, allowing stormwater to flow through the pavement to the subbase or soils below [8].

Pervious concrete is also being considered for many other applications. It is being used for slabs in greenhouses or manure drying operations where water flow through the floor to collection facilities below may be a benefit [9]. It may also be used for retaining walls to address hydrostatic pressure concerns in soils and for other vertical and horizontal applications which might benefit from its unique void structure. One additional example is as an overlay on highways to aid in the removal of water from the pavement surface for safety and acoustic purposes [10].

Many pervious concrete structures, similar to traditional concrete pavement, slab and wall applications, might benefit from structural reinforcement. However, traditional steel reinforcement may not be effective in these applications, as carbon absorption in pervious concrete might lower the pH and allow corrosion processes to progress. Therefore there is a need for alternative reinforcing options as the use of pervious concrete expands.

### 2.2 Concretes with a Lower Chemical-Reaction Based Carbon Dioxide Footprint

Researchers have been investigating accelerated carbon dioxide sequestering in certain concrete applications in response to the interest in reducing their carbon footprint. Conversely, there are also studies which are exploring alternative concrete mixes which use less calcium carbonate as the raw material for the cementitious portion of the concrete mix.

One study at McGill University investigated the ability of six common cementitious materials to bind carbon dioxide while cured under conditions with very high levels of carbon dioxide [11]. Gartner and Quillin have studied cement mixes rich in calcium sulfur aluminates and belite-calcium sulfoaluminate-ferrite which use less calcium carbonate in their manufacture [12]. There are increasing applications of concrete with much higher levels of SCMs, both in response to the desire for a higher recycle content and to potentially lower the carbon dioxide footprint with respect to the chemical reactions involved [13, 14].

In summary, the mix characteristics and curing conditions for many concrete applications are expected to change in response to these concerns about the carbon footprint of concrete. Therefore, there might be increased opportunities for alternative reinforcing materials to be used which are not as affected by the resulting pH or other chemical characteristics within the concrete pores of these modified concrete mixes. These alternative reinforcing materials should be evaluated not only for their strength and durability characteristics, but also with respect to their contribution to the decreased carbon footprint of a concrete structure when used with lower carbon-footprint concretes.

## 3 MODIFIED LIFE CYCLE ASSESSMENTS OF THE CARBON FOOTPRINT

The carbon footprint of concrete is not fully known and constantly changing. In response, there are efforts to develop standards for the environmental management of concrete and concrete structures within the ISO framework and which can be utilized in conjunction with the LCA standards

also being developed on an international scale [1]. However, currently there is little knowledge of the fate and transport of carbon dioxide into a concrete structure during production and subsequent use and final recycling or disposal of the material.

The carbon footprint may also be constantly changing, not just in response to modified raw materials and chemicals used in its manufacture as mentioned in Section 2.2 and the incorporation of the uptake of carbon dioxide during the life of a structure by many of the sequestration reactions as described in Section 1, but also as the energy intensity of the industry is modified in response to the sustainability movement and economic demands. For instance, a common practice in the United States is to use hazardous waste for a portion of the cement manufacturing fuel source, reducing the consumption of fossil fuels. In addition many renewable fuel sources are being explored and implemented.

Cradle to gate analyses of concrete may also need to be modified for novel applications such as pervious concrete. The functional unit of a pervious concrete placement has different material mix ratios than similar traditional concrete placements. Amponsah analyzed these two alternative pavements for greenhouse gas emission and energy use for a representative unit of pavement for a specific portion of their life cycles. These analyses were based on a modified EIO-LCA (Economic Input Output – Life Cycle Assessment) methodology [15]. Several environmental impact factors were quantified for pervious concrete and compared to traditional pavement analyses using EIO-LCA previously published by Horvath and Hendrickson [16]. Similar modifications to established LCA tools may need to be adopted for full life cycle assessments of the carbon footprint of pervious concrete and other novel concrete applications.

There are also many other novel ways to reduce the carbon footprint of concrete. In Japan, a study analyzed the geographic distribution of ready-mix concrete plants in order to reduce transportation related and other energy costs of concrete production [17].

Probably the most uncertain aspects of understanding the carbon footprint of concrete are in determining the amount of carbon dioxide initially held in a concrete sample and the quantities slowly sequestered over time. Assuming that using the carbon dioxide emitted in the manufacturing of cement as a good measure of the chemical portion of carbon footprint of concrete may not be sufficient for life cycle analyses. During and after production concrete has the potential to sequester carbon dioxide to form calcite and other species.

In the past half century, there have been substantial research efforts into the *carbonation* of

concrete, where *carbonation* typically refers to the amount of calcite formed within a certain depth of a concrete structure to alter the pH at that depth sufficiently to affect reinforcing steel. This is typically tested with a phenolphthalein technique by which a specimen is soaked in a phenolphthalein solution and the depth of the color change is noted [18]. These studies mainly focused on this higher level of carbon dioxide uptake considered potentially detrimental to reinforcing steel. There have also been substantial efforts at using more advanced techniques to determine the level of calcite formation at various depths in concrete [19, 20].

However, there may be substantial quantities of carbon dioxide species sequestered in concrete which have not been diligently studied. With recent concerns over greenhouse gas emissions and cycles, there is a need to more accurately determine the carbon footprint of concrete. This includes further analyzing other carbonate species and other calcite composition levels within concrete, both for traditional mixes and for novel and modified applications.

Some classic studies indicated that there was substantially more carbon dioxide held in traditional concrete specimens than could be determined by calcite analyses [21, 22]. Recent efforts have reconfirmed these results [6]. Other studies have shown that there are partially *carbonated* regions in concrete ahead of the typically researched carbonation front [20]. There are also carbon absorption opportunities for end-of-life applications and disposal of concrete structures, particularly when crushed with enhanced surface area exposure to carbon dioxide sources such as with recycled concrete aggregates (RCA) [23].

Together, these studies emphasize the importance of future research into the carbon footprint of concrete when first placed, and over both its primary life and secondary uses in order to more accurately perform associated life cycle analyses. There is currently a lack of information into both the amount of time needed to reach various carbon absorption levels and the final percent carbonation possible in concrete based on the stoichiometry of the calcination reaction [24, 25].

In addition to the incorporation of these natural carbon sequestration estimates in determining future carbon footprints of various concrete applications, life cycle assessment must also incorporate accelerated carbon absorption technologies. These are developing in response to the desire for a lowered carbon footprint in concrete and also for other environmental reasons such as the treatment of wastes by stabilization or solidification [11, 26].

#### 4 MODIFICATIONS TO TRADITIONAL CONCRETE TESTING METHODOLOGIES

## WHICH INCORPORATE SUSTAINABILITY-INDUCED ANOMALIES

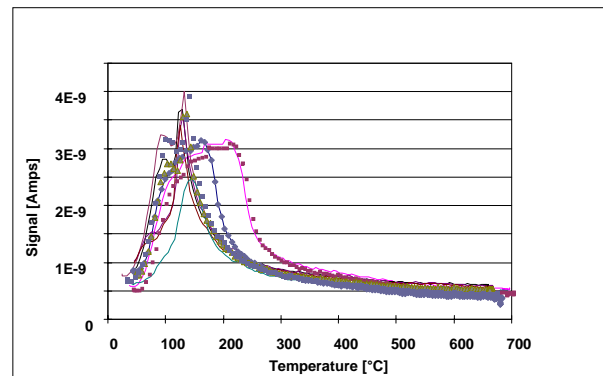
Technological advances in concrete design and innovative applications are exploding in this rapidly developing world, particularly in response to the sustainability movement. There are currently a suite of international and national standards related to testing methods for various characteristics and acceptance measures for concrete structures. These methods should be re-analyzed for applicability when applied to these novel technologies and their new material characteristics. For instance, standard concrete porosity tests cannot be directly applied to pervious concrete as the absorbed water will flow out during the transfer to the scale. Therefore modified methods are being proposed [27].

This paper addresses a different change which may impact the effectiveness of various traditional testing methods, i.e. the different chemical make-up in concretes modified for reduced carbon footprints. Many future concretes will be aged with increased access to carbon dioxide and therefore will have enhanced levels of carbon dioxide absorption. As noted in Section 1, this may also result in other changes in the material characteristics such as a lower pH and higher density. Studies indicate that carbonation might reduce the porosity of concrete and therefore increase its compressive strength and elastic modulus, but decrease its ductility over time [28]. An additional change in early age concrete is related to the calcium hydroxide composition novel to new concrete applications with higher levels of surface area exposed to ambient air such as in pervious concrete. This is further described herein.

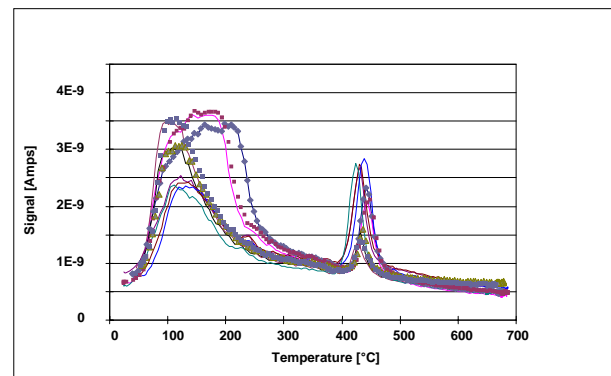
Traditionally, concrete within a structure is expected to develop significant ( 20 – 25 %) levels of calcium hydroxide within the cement paste matrix, in addition to many other hydroxides [29]. However, recent research on cement samples which were aged under conditions with large surface areas exposed to ambient air as compared to samples with these surface areas covered resulted in a unique chemical structure [30]. A significant portion of these exposed cement samples did not have calcium hydroxide forming in the cement paste for the early age samples analyzed, while the covered samples formed calcium hydroxide in most of the samples over the same aging period.

The specimens used in the calcium hydroxide study were analyzed with a Thermal Programmed Desorption (TPD) methodology where the aged hydrated cement pastes were heated to temperatures exceeding the decomposition temperature of calcium hydroxide and the released gases analyzed with amperage signals in a mass spectrometer. Figures 2 and 3 depict typical results for the open and the covered specimens respectively. The left sets of peaks in both figures portray water desorption in the

cement paste. The right set of peaks in Figure 3 is representative of calcium hydroxide decomposition to calcium oxide and water in a temperature range between approximately 450 to 500 °C [30].



**Figure 2:** Water Desorption Curves while Heating Typical Cement Samples Previously Aged ‘Open’ to Ambient Air (Analyzed with TPD) [30]



**Figure 3:** Water Desorption Curves while Heating Typical Cement Samples Previously Aged ‘Covered’ (Analyzed with TPD) [30]

Chen et al. have also noted that calcium hydroxide is not abundant in carbonated traditional and blended (those with varying amounts of SCMs) cements [2]. The degree of hydration under various conditions and with various blends can affect the microstructure of concrete, which can subsequently have an impact on other material characteristics.

Many current research practices include a curing period on concrete specimens prior to testing that is intended to mimic the conditions under which typical structural concrete components might age. One common practice is to cure representative specimens in a water bath for an extended time period prior to the analyses [31].

Table 1 gives a list of some representative ASTM test methods, specifications and practices related to the testing of concrete specimens. ASTM C 39/C 39M – 05 and ASTM C 1609/C 1609M – 07 are common methods for determining compressive

strengths and flexural performance respectively of concrete specimens. Both of these test methods refer to either ASTM C 31/C 31M – 08a or ASTM C 192/C 192M – 07 for the standard practice of final curing of the prepared samples. ASTM C 617 – 98 (2003) is an alternative for cylinder curing when freshly molded specimens are capped with neat cement. These standard final curing practices maintain a high moisture level, usually in a water tank, in water saturated with calcium hydroxide, in a moist room or appropriately wrapped. ASTM C 511 – 06 gives specifications for many of the available high moisture curing facilities [32].

**Table 1:** List of Example ASTM Standards Used in Testing Concrete Specimens [32]

ASTM Number	Title
C 39/C 39M - 05	Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
C 1609/C 1609M - 07	Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading)
C 31/C 31M – 08a	Standard Practice for making and Curing Concrete Test Specimens in the Field
C 192/C 192M - 07	Standard Practice for making and Curing Concrete Test Specimens in the Laboratory
C 617 – 98 (2003)	Standard Practice for Capping Cylindrical Concrete Specimens
C 511 - 06	Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes
C 873/C 873M - 04	Standard Test Method for Compressive Strength of Concrete Cylinders Cast in Place in Cylindrical Molds
C 330 - 05	Standard Specification for Lightweight Aggregates for Structural Concrete

However, with the onset of novel sustainable development designs and material modifications resulting from decreased carbon footprints, there will be future concrete applications and mixes for which testing sample preparation may need to be modified. The samples may not necessarily be cured under these high moisture conditions (usually greater than 95 % relative humidity). These variations might lead

to modifications of the standard test methods or alternative methods. Examples of alternatives to the standard final curing practices already exist in many standards. ASTM C 873/C 873M – 04 provides an alternative for curing a cylinder cast in place to provide curing conditions similar to the actual slab. ASTM C 330 – 05 provides for a modified final curing for lightweight concrete under conditions with a relative humidity of approximately 32% [32]. It is anticipated that similar alternative standards or modifications to existing standards will be developed for testing of concrete specimens modified for novel sustainable uses or with different chemical characteristics.

If futuristic concrete blends and applications have enhanced carbonate exposure and decreased hydroxide formations, then material testing procedures for strength and compatibility with reinforcing materials should include applicable modifications to the curing process. In response to the dynamic nature of technological enhancements due to sustainability goals and life cycle assessment impact considerations, the very nature by which researchers and practitioners test for other sustainability metrics must also change.

## 5 SUMMARY

Concrete is a very dynamic material. It is also a very versatile material which can be made from a myriad of raw and recycled materials. Sustainable development will effect even more variations in the components of concrete and its applications. These variations will need to be considered in comprehensive life cycle assessments of concrete structures for both environmental impacts/benefits and durability considerations. The full suite of possible changes will promote increased research into their effects, will result in even more novel technological innovations and will necessitate modifications to testing methodologies to include application and material variations. The environmental impacts that are affected and the other life cycle considerations are too numerous to include herein. Therefore, only the three issues included in this research paper are summarized as follows.

- Many of the future concrete mixes and applications will not be amendable to more traditional reinforcing technologies such as reinforcing steel. Therefore alternative technologies such as the use of FRPs will need to be considered.
- An environmental life cycle assessment of concrete needs to include its entire life due to the variability in mix designs and its dynamic chemical make-up. This is particularly important when determining the

carbon footprint of concrete as concrete can be produced with varying levels of carbon dioxide and has the potential for carbon dioxide sequestering during its primary life and also during alternative secondary applications.

- As sustainable development principles promote alternative mix designs and novel concrete applications, the standardized tests used to determine life cycle factors such as durability and strength may need to be appropriately modified to include the associated chemical and environmental changes. Of specific note is the potential change in calcium hydroxide composition in novel concrete applications and the resulting change in pH. This might alter the conditions under which testing specimens should be cured.

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