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Towards Sustainable Concrete: Life Cycle Assessment of Carbon-Incorporated Mix Design Concrete

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ABSTRACT

The construction industry plays a significant role in global carbon emissions, with cement production being a major contributor. Exploring sustainable alternatives for concrete production is crucial to mitigating the environmental impact of the construction sector. To lessen the influence of the construction industry on the environment, it is imperative to investigate sustainable alternatives for concrete manufacturing. This study investigates the sustainability potential of carbonated water-containing concrete mix designs. Using life cycle assessment utilizing gate-to-gate system boundary, the researcher examined concrete samples' compressive, flexural, pH profiling, and thermogravimetric analysis. The researchers on one of the Brewery Inc. properties carried out the carbonation procedure. Using the data, they applied life cycle analysis to evaluate the concrete mix designs' potential for sustainability. The results indicate the possibility of improving concrete's sustainability and qualities by adding carbonated water, which offers important new information for creating greener building materials.

KEYWORDS: Life cycle analysis, carbonated concrete, sustainable concrete, green building

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INTRODUCTION

Concrete has been the most widely used building material in the civil engineering industry for many years worldwide. According to Adesina, the high consumption of concrete can be

raw materials, making it suitable for various construction applications. The large carbon dioxide (CO2) emissions of concrete are mostly due to cement manufacturing, which serves as the major binder for concrete. To produce traditional cement, also known as Portland Cement, the primary raw ingredients, namely limestone, and clay, must be heated to a temperature of about 1450 °C in a kiln. As a result, the production of 1 ton of cement releases approximately 1 ton of CO2 due to the calcination of the limestone and fuel burning. As the data reveals, cement production at cement factories results in around 8% of the world's total emissions. Concrete comprises aggregate materials, primarily rocks, sand, cement, and water.

The Life Cycle Assessment approach is one of the most popular sustainability measurement methods. A Life Cycle Assessment (LCA) systematically analyzes the effects of a given product, material, process, or other quantifiable activity on the environment. Using LCA, the industry is given clear instructions on decreasing pollution throughout a product's life cycle, protecting natural resources, improving the environment, and creating a more sustainable industry.

Life cycle assessment studies have been conducted to evaluate the environmental impact of these carbon-incorporated concrete mixes. The findings suggest that the incorporation of carbon can indeed lead to a reduction in the overall carbon footprint of concrete production and use. However, the specific benefits may vary depending on the type and amount of carbon used (Kamde et al., 2023).

To ensure the environmental sustainability of producing this new concrete, it is essential to monitor any potential carbon emissions and embodied energy consumed in its life cycle when the carbonation process of water is considered in its production and then can be compared with the environmental impacts (EI) of conventional concrete used in the Philippines. The environmental concern of excessive carbon dioxide emissions has been duly recognized worldwide.

Statement of the Problem

The general problem of the study is to evaluate and assess the gate-to-gate life cycle of two carbon-incorporated concrete mix designs.

In order to address the main problem, this experimental study intends to answer the following specific questions:

1. How is carbon-incorporated concrete described?
2. How will the type of mixing water affect the compressive strength and flexural strength of the samples?
3. How will the type of mixing water affect the pH value and CaCO3 content of the samples?

REVIEW OF RELATED LITERATURE

Several studies have investigated concrete's environmental and economic impact on natural and recycled aggregates. These studies have highlighted the potential benefits of using recycled aggregates, which can reduce the demand for virgin raw materials and the associated environmental impact. However, using recycled aggregates alone may not be sufficient to achieve the desired level of sustainability.

Incorporating carbon-based materials, such as carbon nanotubes, carbon fibers, or carbon-rich industrial by-products, into concrete mix designs has emerged as a promising strategy to further enhance the sustainability of concrete. (Kharissova et al., 2016) These carbon-incorporated concrete mixes have been shown to exhibit improved mechanical properties, durability, and even the potential for carbon capture and storage.

A new study at the University of Cordoba managed to demonstrate that concrete dosed with carbon dioxide can potentially reduce atmospheric carbon dioxide. Using carbonated water to mix and cure the concrete , and recycled aggregates, managed to capture 181% more carbon dioxide from the atmosphere than using natural aggregates and mixing with conventional water.

Construction is an environmentally demanding industry that usually requires mass consumption and disposal. This means that as time passes, the consumption of construction materials, especially concrete, may result in excessive carbon emissions to the environment. It is stated that concrete is made by combining a "binder," which is usually cement and water, with aggregates to make concrete, which is then cast or poured into the shape of its final form, such as slabs, flooring, and so on (Duxson & Provis, 2008).

According to Yang, Yu, Dong, and Zhao et al. (2019), the cement industry, which creates the second-most common construction material, has been expanding quickly until being compelled in the late 1990s to lessen its environmental burdens, like carbon dioxide. There are four alternative technologies to reduce CO2 in the cement industry, according to Nazari & Sanjayan (2016). However, the researchers only concentrate on one of them, "Adding a chemical absorption process that would capture CO2," as it is the only one that can be done with the researchers' resources. One way to accelerate concrete's carbon dioxide uptake is through carbonation and using carbon-incorporated concrete.

Carbonation is often assumed to be related to the diffusion of a gas through a porous material, in this case, concrete. The diffusion of this gas, carbon dioxide, through the concrete depends on the properties, moisture state, and nature of the concrete. However, this mechanism does not account for the movement of dissolved carbon dioxide. As these properties vary, the rate of carbonation will vary. However, it is generally accepted that the relationship will be of the form $x = A\sqrt{t}$, where x = depth of carbonation at time t and carbonation rate (Andersson et al., 2019).

The carbonation reaction increased the content of calcium carbonate, CaCO3, and a reduction of calcium hydroxide, Ca (OH)2, from the concrete surface to the inside. Thus, carbonated products alter the pH of the concrete pore solution; CaCO3 reduces the pH value, and Ca (OH)2 increases the pH value (Liu et al. 2018).

In the research of Dias, Silvestre, and Kurda et al. (2022), they compared natural and recycled aggregates using LCA. They only focus on the A1-A3 (cradle-to-gate) method and analyze data using CML Baseline, Cumulative Energy Demand, Eco-Indicator, Mat France, and IMPACT 2002+. As a result, coarse natural crushed aggregates have the highest impacts when it comes to global warming potential and energy use. In contrast, coarse natural rolled aggregates have the lowest, and recycled aggregates have lower impacts than natural aggregates.

These days, LCA is crucial in quantifying these effects on the environment. The LCA can generate environmental impacts by entering all the materials and energy used during each process stage. According to Chua (2021), using LCA provides the industry with a clear direction to reduce pollution throughout a product's life cycle, preserve natural resources, improve the environment, and create a more sustainable industry in the near future.

Kwasny, Basheer and Russell (2014), discovered that the initial hydration rate of carbonated pastes increased compared to the non-carbonated mixes, but the later hydration rate was drastically reduced. They studied CO2 sequestration in cement-based materials during the carbonated water mixing process. Compared to the control mix, higher temperatures were observed when cement was mixed with carbonated water in a gaseous CO2 environment. The study's thermogravimetric (TG) analysis, X-ray diffractometry

(XRD), and Fourier transform infrared spectroscopy (FTIR) results showed that the carbonated pastes' CaCO3 and Ca(OH)2 contents increased and decreased considerably, respectively.

The findings of the previous research done by Silva, Nogueira, Bogas, and Rodrigues in 2021 showed different results from those of Morales et al.'s investigation in 2022. In the study by Silva et al. (2016), four cement pastes were created by mixing water with various CO2 levels. The pH of the mixture was measured to assess the effect of CO2 on the mixture's loss of alkalinity. To evaluate the impact on the hydration processes as well as the level of carbonation, the compressive strength, X-ray diffraction (XRD), and Scanning electron images (SEM) were also carried out. Due to the quicker hydration processes and greater concentration of calcite or calcium carbonate, the test findings seem to support the increased compressive strength for carbonated samples at an early age of 3 days. The decreased compressive strength of the carbonated samples at later ages (7, 14, and 28 days) may be explained by the carbonated water's lower pH level. The study further implies that reducing pH due to CO2 compromises performance at longer ages.

METHODOLOGY

Materials and Methods

Ordinary Portland Cement was used in this study for concrete since it is the most widely used cement in the world because of its price point and abundance. For the carbonated water, the researchers incorporated the carbon into the water to use it as a mixing agent in producing concrete that will serve as an experimental sample. The carbonation process was conducted in one of the firms located in Pasig City and was delivered to Sta. Cruz, Guiguinto Bulacan. Coarse Aggregates range from 3/8 "to 1 ½", wherein the Fine Aggregates are less than 3/8" as the standard ratio of Aggregates according to ASTM C33.

The professional personnel and Construction Materials Testing Services facility did the Batching and Mixing procedures. To achieve the same relative proportions of concrete ingredients as intended by the mix design, weight batching of cement, sand, and gravel was performed. The researchers used the cylindrical mold, as shown in the testing facility of Construction Materials Testing Services. The chosen curing period for the samples is 7 days, 14 days, and 28 days. The curing was done wherein the samples were fully submerged in conventional water, as presented in Figure below.

Mixing Ratio

The researchers followed the conventional mixing ratio in the Philippines, which is 1:2:3, and 0.5 for the water-cement ratio.

Testing Procedures

The compressive strength of cylindrical concrete specimens was measured according to the American Society for Testing and Materials (ASTM) C39 standard. Only the concrete with a unit weight more significant than 50 lbs./ft3 (800 kg/m3) will be subjected to testing. The outcomes of this test procedure serve as the foundation for concrete quality control. According to ASTM, for flexural strength, the specimen must be three times its depth in length, 150 mm wide, and 150 mm deep. Molded specimens were covered on top and stored for 24 hours in a temperature-controlled area. Both tests were conducted on the 7th, 14th, and 28th day of curing of the specimens and conducted with the assistance of personnel at the facility Construction Materials Testing Services.

The cylindrical samples were stored in the carbonation chamber for seven days; powdered samples were taken at the samples' 0-5 mm depth. These powdered samples were allocated for thermogravimetric analysis (TGA) to quantify the amount of calcium hydroxide and calcium carbonate present within the powdered samples, the compounds most closely associated with carbonation. These compounds were quantified and plotted. The TGA of concrete was conducted in the Advanced Device and Materials Testing Laboratory (ADMATEL) located at Bicutan, Taguig City.

Life Cycle Assessment

The purpose of the LCA in this study is to calculate how much embodied energy and CO2 emissions of carbon-incorporated concrete were emitted. The system boundaries of this study are gate-to-gate, which covers the quantification of embodied energy and CO2 emissions associated with concrete production. By observing the ISO 14044 (LCA) standard, the software open LCA was used to perform the LCA of the concrete mixture designs. The open LCA allows for the fast calculation of results with the largest data set available for LCA. The database used for the impact analysis was Eco invent.

The researchers described the input data for the Life Cycle Inventory (LCI), which converts the data inputs into its corresponding outputs that are equivalent to environmental impacts. The inventory for production of 1 kg of clinker and 1 kg of Ordinary Portland Cement.

Impact Category	Reference Unit
Climate Change (GWP100)	kgCo2-Eq

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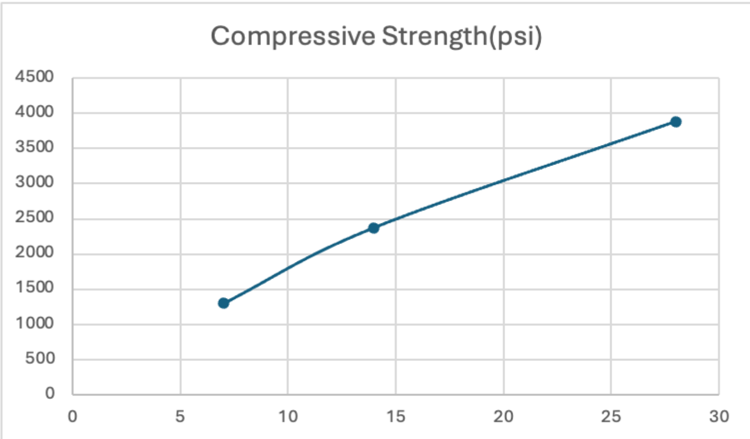
Freshwater EcoToxicity (FETPinf)	kg 1, 4-DCB-Eq
Human Toxicity (HTPinf)	kg 1, 4-DCB-Eq
Marine EcoToxicity (METPinf)	kg 1, 4-DCB-Eq
Marine Eutrophication (MEP)	Kg N- Eq
Particulate Matter Formulation (PMFP)	Kg PM10- Eq
Energy Use	MJ/kg

The LCI results were then divided into impact categories and given common unit characteristics for comparison for Life Cycle Impact Assessment (LCIA). Six
Environmental impacts related to the product's carbon footprint and embodied energy were addressed, particularly climate change, human toxicity, marine ecotoxicity, marine eutrophication, particulate matter formation, and freshwater ecotoxicity. The LCIA used for this study was ReCiPe (RIVM, Radboud University, CML, and PRé Consultants) midpoint analysis, a process-oriented analysis.

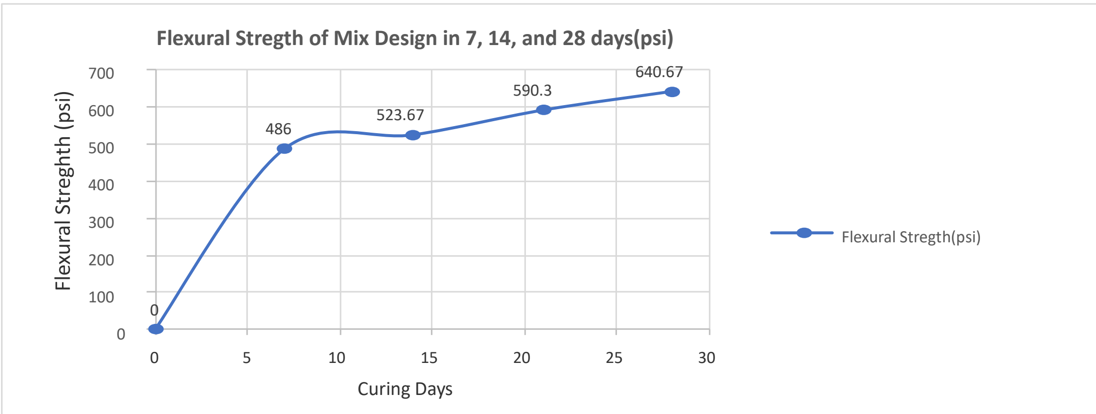
RESULTS

Table 1. Graph of Average Compressive Strength at the Curing Age of 7, 14, and 28 days



From the figure, the effect of the type of mixing water on concrete's compressive strength was observed. carbon-incorporated concrete shows an increase in compressive strength as the curing age increases.

Table 2. Based on the graph, the concrete mix designs maintained a consistent increase in flexural strength as the curing ages increased.



According to Ariawan et al. (2018), the flexural strength of Portland Cement Concrete slabs, which falls within a certain range of 4.14-5.17 MPa, determines the strength of the slabs. With this, it can be concluded that the carbon-incorporated concrete mix design is capable of satisfying the flexural strength requirements since the value is still within the acceptable range

Carbon Dioxide (CO2) Uptake of Concrete Samples Using Thermal Gravimetric Analysis

The thermal gravimetric analysis (TGA) was used to quantify the species developed in six (6) concrete samples, particularly $Ca(OH)_2$ and $CaCO_3$. In addition, the CO_2 uptake of the hardened control and experimental concrete specimens was also determined by TGA. Table 4.10 shows the analysis results for all the mixes with 28 days of curing age. To determine the average rate of carbon dioxide sequestration (grams/time), the mean values of the three obtained values for both the control and experimental groups are calculated. The six samples tested using TGA are new concrete samples, meaning they are not yet subjected to carbon dioxide sequestration.

Table 3. Results obtained in the Thermogravimetric Analysis CarbonIncorporated Mix Design test.

Sample	Temperature (°C)				Chemical Species				
	105-400	400-480	480-640	640-1000	H2O (cement) (%)	Ca(OH)2 (%)	CaCO3 (%)	Mass Loss (%)	Rate of CO2 sequestration (g/t)
E1	0.5200	0.28715	0.25604	3.73263	0.52004	0.28715	3.98867	0.64357	643.57
E2	0.9313	0.23953	0.32995	4.09424	0.93133	0.23953	4.42419	1.07909	1079.09
E3	0.938	0.2281	0.4252	4.5541	0.9384	0.2281	4.9793	1.6342	1634.28
	5	4	4	4	5	4	8	8	

The lower pH values of carbon-incorporated concrete were consistent with the analysis results, which showed increased calcium carbonate [$CaCO_3$] content and lower calcium hydroxide [$Ca(OH)_2$] content. With this information, it can be concluded that using carbonated water significantly improves the concrete's ability to capture Carbon Dioxide [CO_2].

LIFE CYCLE ASSESSMENT

Life Cycle Assessment This section discusses the results of the life cycle impact assessment of 1-kilogram production of a conventional and carbon-incorporated concrete mix design using the ReCiPe Midpoint method. The findings of this evaluation are discussed in this section. The effect categories include climate change, freshwater ecotoxicity, human toxicity, marine ecotoxicity, eutrophication, particulate matter formation, and energy use. Each category's impact score was displayed in a bar graph, and the percentage difference between the concrete mix design was also computed using the formula % change = $\boldsymbol{new\ value - old\ value\ old\ value * 100}$%. Higher score values indicate that the concrete produced greater environmental impacts than lower values.

Impact Category	Reference Unit	Carbon-Incorporated Concrete Mix
Climate Change (GWP100)	kgCo2-Eq	.8383085332
Freshwater EcoToxicity (FETPinf)	kg 1, 4-DCB-Eq	6.9876357648

Human Toxicity (HTPinf)	kg 1, 4-DCB-Eq	0.0203835925
Marine EcoToxicity (METPinf)	kg 1, 4-DCB-Eq	0.0003578649
Marine Eutrophication (MEP)	Kg N- Eq	0.000331501
Particulate Matter Formulation (PMFP)	Kg PM10- Eq	1.991089280
Energy Use	MJ/kg	6.0876200000

The table shows that The LCIA of the concrete mixture designs revealed that the environmental impacts of conventional concrete and carbon-incorporated concrete mix design are similar in terms of Climate Change, Human Toxicity, Marine Eutrophication, and Particulate Matter Formation. On the other hand, carbon-incorporated concrete has a higher environmental impact. Moreover, the carbon-incorporated concrete mix design showed a higher energy consumption due to the energy used for the production process of carbonated water.

CONCLUSION

The study mainly compared the Life Cycle Assessment of carbon-incorporated mix design from all the tests performed and data.

The carbon-incorporated concrete mixture design with a mixing ratio of 1:2:3 (1 part of cement, 2 parts of sand, and 3 parts of coarse aggregates) passed to the compressive strength and flexural strength standards for pavement use.

(i) The carbon-incorporated mix design has a significantly lower pH value, particularly on the 0-5 mm depth and 25-30 mm depth. The reduction in the pH of the concrete was due to the direct exposure to CO2 and implies that the carbonation process takes place in the depths. Thus, the carbonation process happens from the surface to the inside of the concrete. (iii) In terms of CO2 sequestration, carbon-incorporated concrete has a faster rate, which is double that of conventional concrete. From the LCA of the production process, the carbonincorporated concrete has a similar CO2 production emission of 0.8383085332 kg CO2, Equivalent to 1 kg of the concrete production process. Thus, a carbon-incorporated mix design is more environmentally suitable to use for lessening carbon emissions, considering the performance and environmental sustainability in terms of CO2 emissions.

RECOMMENDATIONS

The researchers recommend trying cement-water ratios other than 1:2:3 (1 part of cement, 2 parts of sand, and 3 parts of coarse aggregates) and incorporating carbon through carbonated water.

(i) To have varying replacement of water such as 75%, 50%, and 25% carbonated water for testing its performance and environmental impact, especially in lessening the embodied energy of the concrete production.

(ii) The system boundaries, such as cradle-to-gate and CSI specifications, were also recommended to be explored in the LCA.

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