COMPARATIVE-ANALYSIS ON THE EFFICACY OF CONCRETE DESIGN ON DECREASING THE CARBONATION RATE WITHIN CONCRETE

FORSMITH
BUILDING SCIENCE CONSULTANTS

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3A Architectural Engineering

May 2023

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Dear Dr. Al-Hammoud:

This report, entitled "Comparative-Analysis of the Efficacy of Concrete Design on Decreasing the Carbonation Rate within Concrete" was prepared as my 3A work term report. This technical report was prepared during my Co-op at FORSMITH Building Science Consultants, under the supervision of "*Sheldon Warman, Principal*". The intent of this investigation and subsequent report was to explore how possible variations commonly found throughout the cement and concrete industries can reduce the carbonation in new concrete structures.

The investigation focuses on exploring failures within Portland Cement based concrete. The analysis includes publicly available data that provides measurements for rate of carbonation within concrete samples. To quantitatively determine potential causes for increased rate of carbonation, various elements within concrete design were isolated as independent variables.

The investigation has successfully provided insightful information that can be used within the concrete industry, by establishing viable estimations models that can be utilized in concrete design to decrease the carbonation rate, consequently increasing structural stability and longevity of future concrete structures.

This report was written entirely by me and has not received any previous academic credit at this or any other academic institution. I would like to thank *Sheldon Warman, Principal*, and *Brad Burnham, Engineering Manager*, of FORSMITH Building Science for assisting me during the investigation and review of this report. I have received no other help with this report.

Sincerely,

Cameron Lawrence

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Summary

This investigation, titled “Comparative-Analysis of the Effect of Concrete Design on Carbonation Rate within Concrete”, studies the effects of variables within concrete design and how these modifications directly impact carbonation rates. Through this comparative-analysis, a quantitative approach was taken on publicly available data related to carbonation within Portland cement based concrete products. The analysis involved developing multiple linear regression (MLR) models to investigate how carbonation rate within concrete is minimized through altering the content of water, cement, and aggregates. The results of this investigation elicited recommendations for how concrete can be designed to minimize the risk of carbonation impacting our structures.

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Acronym	*Definition*	*Units*
COD	Coefficient of Determination, R^2	
W/C	Water to Cement Ratio	kg/kg
A/C	Aggregate to Cement Ratio	kg/kg
FA/CA	Fine to Coarse Aggregate Ratio	kg/kg
C	Cement Content	kg/m^3
FA	Fine Aggregate Content	kg/m^3
CA	Coarse Aggregate Content	kg/m^3
W	Water Content	kg/m^3
$\mathbf{R_c}$	Rate of Carbonation	mm/week
Q	Heat	J

1.0 Introduction

1.1. Carbonation

Carbonation is a commonly found chemical reaction involving atmospheric carbon dioxide (CO_2) that results in carbonate biproducts (Halsall, 1993). In concrete, Carbonation occurs through CO_2 interacting with exposed concrete surfaces. This process involves carbon dioxide reacting with calcium silicate hydrate, which is a common ingredient found within Portland cement. This can be seen in **Figure 1**. This formation of carbonates in concrete applications results in indefinite sequestration of carbon dioxide (Swedish Environmental Research Institute, 2021), which has proven to be a contentious topic regarding the carbonation of concrete.

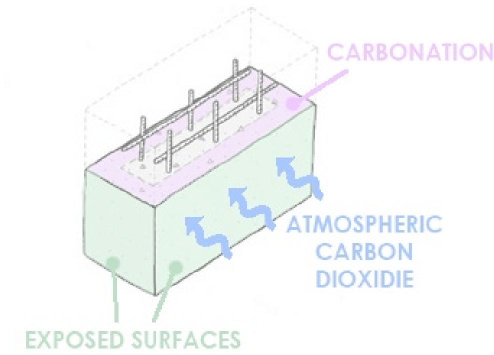

Figure 1: Carbonation on Steel Reinforced Concrete

Carbon sequestration has recently become increasingly popular as a passive form of climate control. Because the construction industry is responsible for 39% of greenhouse gas (Novak, 2020), there is a continuing necessity to develop new innovative solutions to reduce emissions. This phenomenon allows for carbon dioxide to be absorbed and held by the concrete, which assists in offsetting the emissions that occur from manufacturing concretes key component: cement. From an environmental perspective, carbon sequestration is a positive attribute of carbonation as it increases embodied carbon which reduces the carbon emissions to our environment.

However, from an engineering standpoint, carbonation poses to be the inevitable killer for all steel-reinforced concrete structures. The relatively slow effect carbonation plays on concrete results in carbon dioxide penetrating exposed areas, embedding itself within the concrete from the surface, and migrating inwards through the concrete cover. This movement of carbon dioxide through the concrete structure eventually removes all protection to the steel reinforcement, allowing rapid corrosion of the rebar. Because a complete restoration of rebar and concrete structures is an extremely invasive and complex remedial procedure, carbonation is attributed to be the eventual demise of all steel reinforced concrete.

This dilemma between environmental control and structural engineering has caused increasing attention to the carbonation of concrete. The newfound focus on carbonation has resulted in the development of new innovative and sustainable concrete and cement manufacturers, such as CarbonCure and Solidia, and alternatives to steel reinforcements based on the innovations from fiberglass rebar manufacturers, such as TUF-BAR and MST-BAR. The concrete and cement manufacturing companies previously noted are altering the ingredients from commonly used cement products to eliminate carbon dioxide deteriorating the structures, while still offering the structural and economic advantages found in Portland cement. Whereas the fiberglass rebar manufacturers are attempting to develop alternatives to steel that cannot be corroded by carbon dioxide, by using innate materials. On small-scales, these products have been used and are within the stage of proof-of-concept, however, this technology is still extremely new and there is not enough available research to warrant an entire shift from Portland cement or steel rebar.

1.2. Manufacturing Process of Cement

To understand the issues regarding longevity of steel reinforced concrete, it is important to understand the composition of its key ingredient: Portland cement. Portland cement goes through an extensive manufacturing process, that includes lime (calcium oxide), silica (silicon dioxide), alumina (aluminum oxide), iron oxide, and sulfate (Steven H. Kosmatka, Beatrix Kerkhff, William

C. Panrese, 2002). The dry process starts with crushing the stone into small pieces, then grounding and blending the stone and other raw materials into a powder. Alternatively, the same process could be followed while introducing water in the grounding and blending, which is referred to as the wet process. Following the blending, the mixture is put into a kiln to develop clinker. After a series of chemical reactions, resulting from the introduction of excess energy, between the raw materials, the new product, clinker, contains the following compounds: Tricalcium aluminate, tetracalcium aluminoferrite, dicalcium silicate, tricalcium silicate, sodium oxide, and potassium oxide (Pennsylvania State University, 2008). Finally, the clinker is ground and blended with gypsum to create Portland cement. This process is visually represented in **Figure 2**.

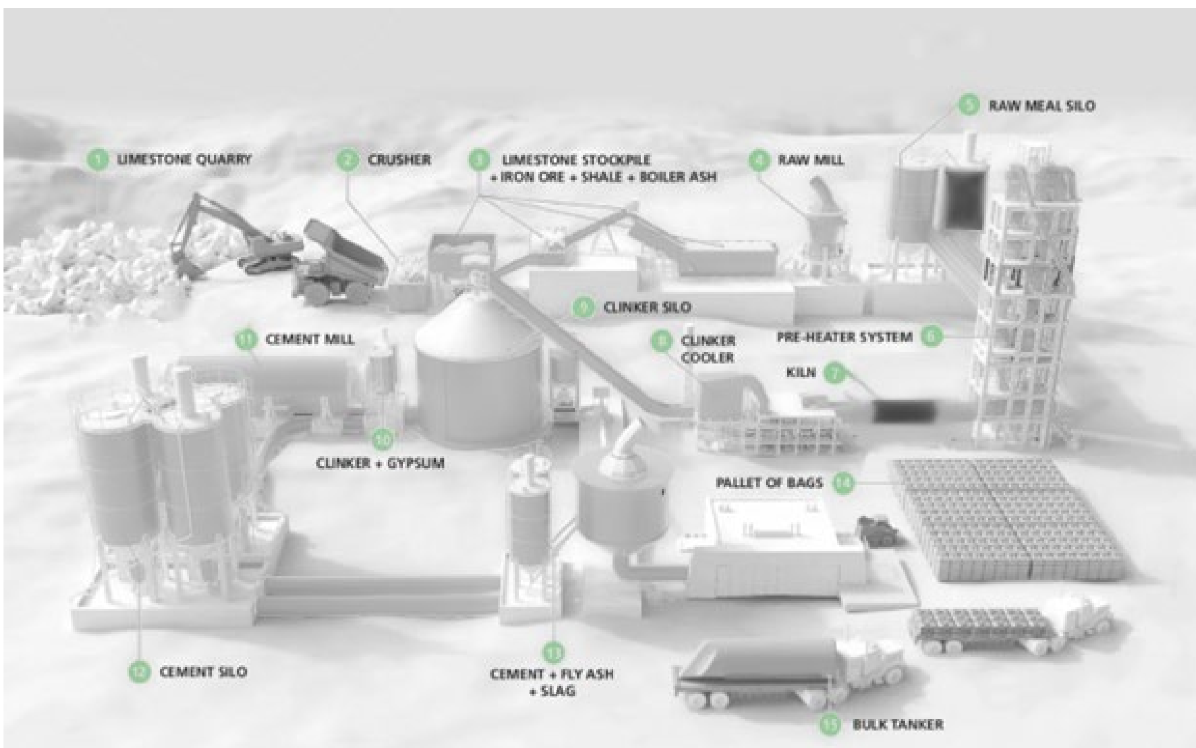

Figure 2: Cement Manufacturing Process (AfriSam, 2018)

1.3. The Chemistry of Carbonation

1.3.1. Passivation

Corrosion passivation is a methodology used to protect vulnerable materials from harmful reactions to the environment that may result in corrosion. Passivation layers can be physically applied to exterior layers of a material or may occur through a process labelled self-passivation, which is the result of a spontaneous oxidation reaction in the air. Within concrete, the passivation layer is formed due to concrete's increased alkalinity levels relative to the ambient environment and results in the formation of a layer of oxides to protect reinforcing steel (Briceño-Mena, 2020).

In acidic environments, or a pH level of less than 7, steel is known to corrode rapidly. However, in increasingly alkaline environments, the rate of steel corrosion is extremely minimal. Therefore, indicating how important an alkaline environment is to the longevity of steel. Natural passivation layers begin to form around steel in environments with an approximate pH of 12, and typical concrete pH levels range from 12-13 allowing the development of the protective coating. The self-passivation layer is crucial in moderating corrosion rates to an insignificant amount for steel embedded in concrete. Without this layer, the rate of corrosion amplifies from an average of 0.1μm/year to 100μm/year (Brian B. Hope, et al., 2001).

The complication between the passivation layer and carbonation resides in a series of chemical reactions that occur over a long duration of time. These reactions occur throughout cement manufacturing and the surface exposure of concrete products to the environment. To understand the issues that arise from carbonation and steel corrosion, it is important to understand key reactions that occur within cement and concrete products.

1.3.2. Chemical Reactions

Limestone ($CaCO_3$) is one of the main materials in Portland cement. Reaction (i) explains that once put through the kiln and introduced to increased heat, the limestone undergoes a reaction and produces calcium oxide (CaO) that remains embedded within cement and carbon dioxide (CO_2) that is released into the atmosphere. This is the fundamental reaction that explains how carbon dioxide emissions are significant within the cement industry. See reaction (i).

$$\text{(i)} \quad \mathbf{CaCO_3 + Q \rightarrow CaO + CO_2}$$

The calcium oxide (CaO) that remains within cement undergoes a reaction with water through the hydration process of cement. This reaction results in the formation of calcium hydroxide ($Ca(OH)_2$). See reaction (ii).

$$\text{(ii)} \quad \mathbf{CaO + H_2O \rightarrow Ca(OH)_2 + Q}$$

The calcium hydroxide ($Ca(OH)_2$) produced in the hydration process will then react to the ambient carbon dioxide (CO_2) within the atmosphere to create calcium carbonate ($CaCO_3$) and water (H_2O). See reaction (iii).

$$\text{(iii)} \quad \mathbf{Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O}$$

Within hardened concrete, there is a highly alkaline (pH of 13-13.8) solution that exists within imperfections, referred to as the pore solution. The water (H_2O) within the pore solution reacts with carbon dioxide (CO_2) to result in carbonic acid (H_2CO_3). See reaction (iv).

$$\text{(iv)} \quad \mathbf{H_2O + CO_2 \rightarrow H_2}\boldsymbol{CO_3}$$

The formation of carbonic acid (H_2CO_3) results in various subsequent reactions that may negatively affect the durability of steel reinforced concrete. Although carbonation affects the steel rebar, one benefit that occurs from this these reactions is that the carbonic acid (H_2CO_3) can react with existing cementitious materials to form calcium carbonate (*$CaCO_3$*) precipitate (Bill Rehm, 2012) which "inherently strengthens the concrete matrix" (Kayla Hanson, 2015). However, this highly acidic pore solution decreases the overall pH of concrete slowly to approximately 9.0. Although the concrete still serves as an alkaline environment for steel reinforcements, the pH levels are not high enough to maintain the naturally occurring self-passivation layer containing oxides on the surface of the steel, allowing for an increased rate of deterioration within the steel as can be seen in **Figure 3**.

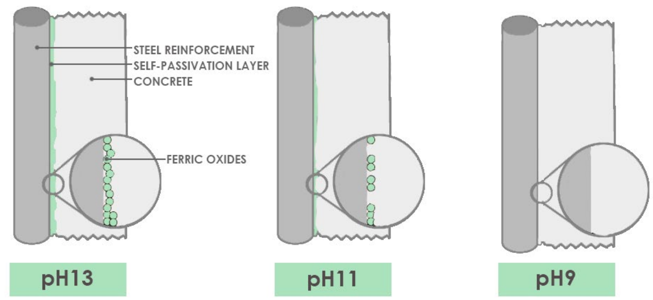

Figure 3: Self-Passivation Layer in Steel Reinforced Concrete

(Swedish Environmental Research Institute, 2021)

1.4. Scope + Objectives

Within this investigation, publicly accessible peer-reviewed articles were utilized to compile a large sample size of data that was recorded while experimenting with carbonation rates. The objective of this analysis and subsequent report was to investigate how various factors controlled within concrete design dictate the longevity of steel reinforced concrete by increasing the rate of carbonation within a sample. This investigation involved firstly analyzing measured controls separately to investigate and determine trends of carbonation in a qualitative manner. Secondly, multiple linear regression (MLR) models were developed to assess a quantifiable measurement for the impact of each variable on the rate of carbonation within concrete.

2.0 Engineering Application

This section involves a description of common controlled measures that are considered within concrete design and an explanation of the methodology used within the data collection process.

2.1. Concrete Mix Parameters and Carbonation Rate

The four components that are used in standard Portland cement-based concrete include water, cement, coarse aggregates, and fine aggregates. Although air and concrete admixtures are additionally critical when considering the parameters required to design concrete in various site-specific conditions, the investigation will be limited two the four fundamental components.

There are many factors that the mix parameters of these four components are dependent on. The water to cement ratio (W/C), aggregate to cement ratio (W/C), and the fine to coarse aggregate ratio (FA/CA) are all heavily considered values when determining the proper concrete mix for the required conditions. However, it is additionally important to note that these conditions change depending on the requirements of the concrete, based on aspects such as location, climate, available quality control, desired durability, required strength, available aggregate materials, workability, and many more. With respect to important factors regarding carbonation, the most notable may be porosity. High porosity means that liquids and gases can permeate the solids with less difficulty. Therefore, concrete with high porosity is likely susceptible to an increased level of carbon dioxide penetration, resulting in more rapid carbonation.

2.2. Methodology

To investigate the rate of carbonation within concrete, the results of studies testing various factors that are known to be corresponding to increased levels of porosity were compiled and analyzed. These factors included water to cement ratio, aggregate to cement ratio, and fine to coarse aggregate ratio.

Six experiments were compiled to produce a comparative-analysis of carbonation experiments and limit the potential for biases to have significantly modified any conclusions. To limit the impact that any uncontrolled variables may have on potential findings of the analysis, the selected studies to extract data were chosen with the most similar controlled measures. This ensures that the analysis was regulated to the highest possible extent with the available data. The six experiments tested concrete samples with a volume of 1.6 $x10^6mm^3$ to 6.4 $x10^6mm^3$. All data was collected within a temperature range of 10-40°C. All measurements within the experimented recorded the depth of carbonation at 28 days.

To measure the carbonation rate, the average rate was taken per week over the 28-day curing period. This can be seen in **Figure 4**, where the data points indicate a sample experiment where carbonation depth was recorded once per day, and the dashed line indicates the average rate of carbonation. Although the plotted sample appears to follow an exponential trend, it is estimated to be approximately linear following the 28-day curing stage because the rate of carbonation is a very slow process that is not known to accelerate over time past the curing period. The results from each of the experiments can be seen in **Appendix A**.

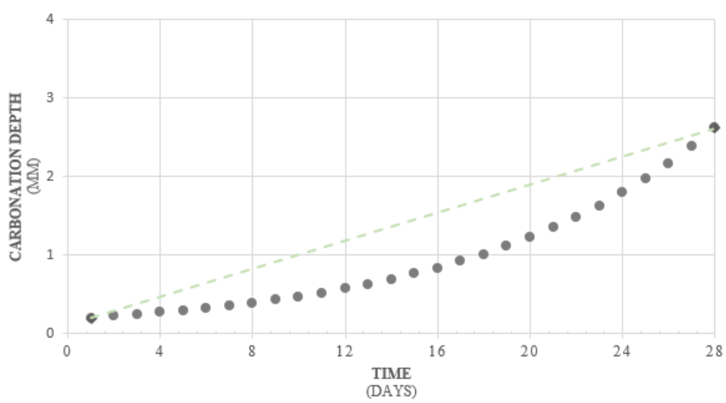

Figure 4: Average Carbonation Rate Calculation

3.0 Analysis

This section involves a qualitative and quantitative analysis of multiple controlled measures within concrete design to establish trends that exist between quantities/ratios of constituents and observed carbonation rates.

3.1. Water to Cement Ratio

Figure 5 demonstrates how the rate of carbonation changes by plotting a multiple line graph to measure the average rate of carbonation after 28 days with varying water to cement and aggregate to cement ratios.

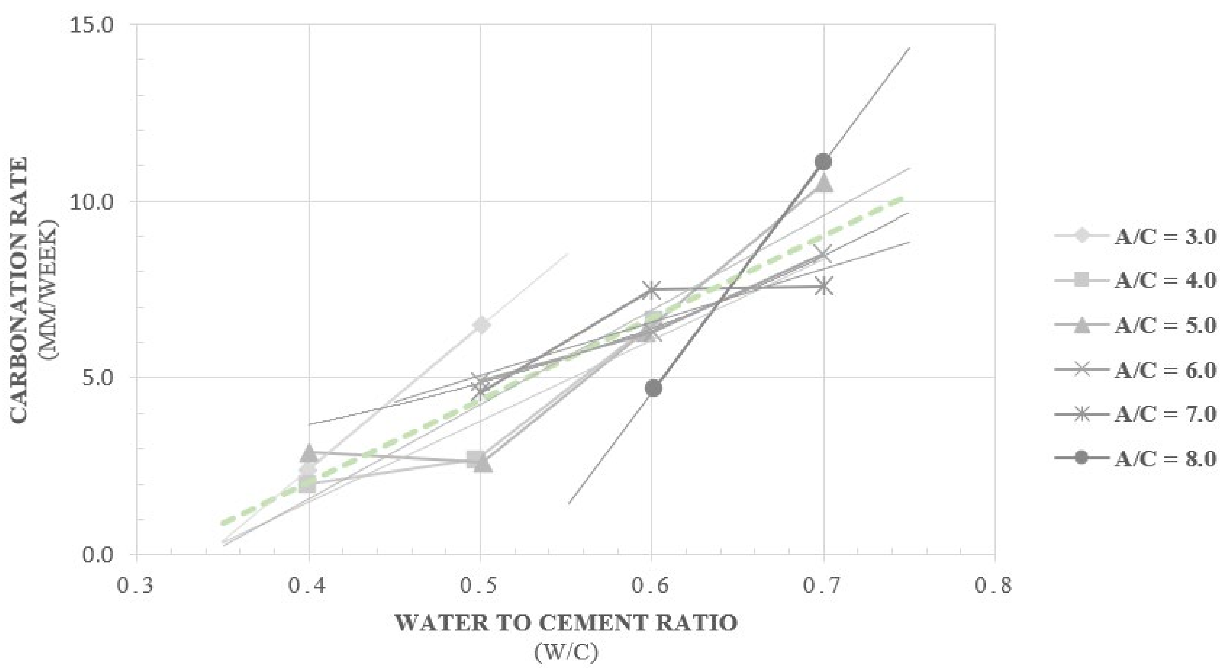

Figure 5: Effect of Water to Cement Ratio (W/C) on Carbonation Rate

The green dashed line indicated in **Figure 5** shows the general trend for rate of carbonation based on the water to cement ratio of concrete. This seems to align with current literature as an investigative paper from researchers at Hiroshima University studies the effect on water increasing water content and carbonation, concluding that an increased quantity of water promotes carbon dioxide transport within the medium. Although there does seem to be a marginal effect on the carbonation rate in regard to the aggregate to cement ratio by comparing the increasing slope intensity between the data for aggregate to cement ratio from 3.0 and 8.0, there does not appear to be a strong correlation that exists.

3.2. Aggregate to Cement Ratio

Figure 6 demonstrates how the rate of carbonation changes by plotting a multiple line graph to measure the average rate of carbonation after 28 days with varying aggregate to cement and water to cement ratios.2

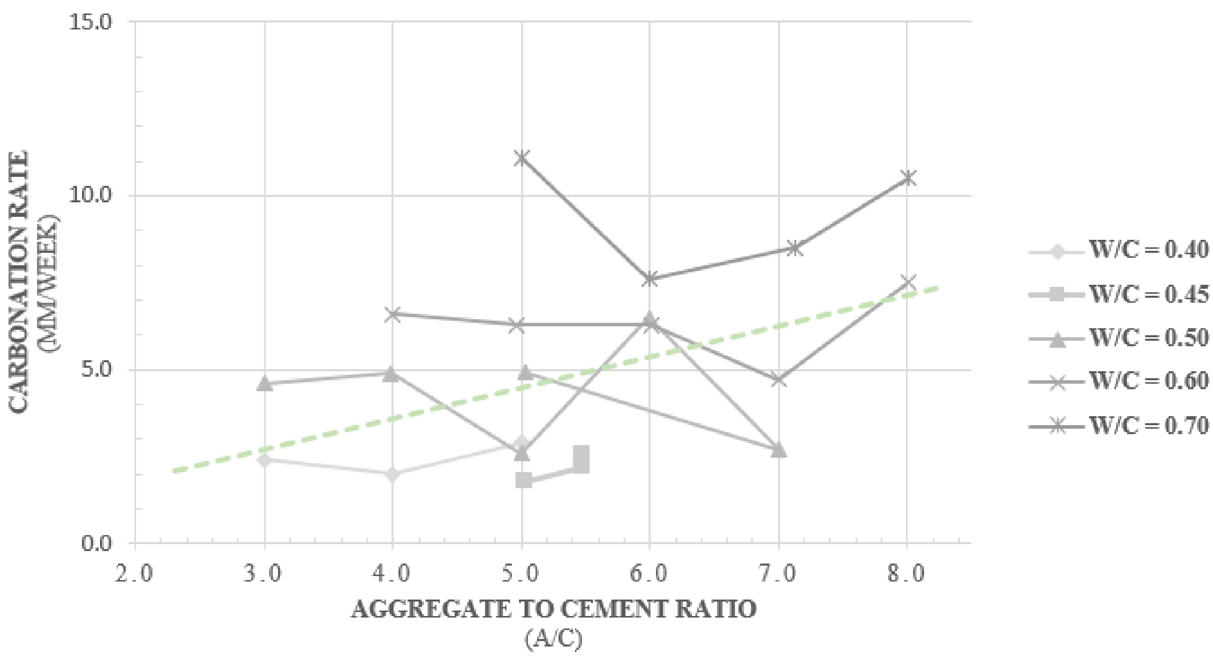

Figure 6: Effect of Aggregate to Cement Ratio (A/C) on Carbonation Rate

By analyzing the trend in **Figure 6**, it can be seen that similarly to water to cement ratio, aggregate to cement ratio does have a positive trend such that increasing aggregate to cement ratio will increase the rate of carbonation to a minimal extent, further supporting the findings in **Figure 5**. However, the trend is much less definitive than with water to cement ratio and appears to be substantially more random. This observation is supported by a study published from Zhengzhou University (Jianguo Chen, 2022) studying the effect of increased aggregate content and size will increase porosity.

3.3. Multiple Linear Regression Models

Multiple Linear Regression (MLR) models will be used to test the efficiency of various concrete mix constituents on the rate of carbonation when integrated into one function. A MLR function is a linear function that involves multiple first order independent variables. To incorporate multiple factors into a linear function, the following equation will be modified to include the proper number of variables for a given model.

$$y = m_1 x_1 + m_2 x_2 + \cdots + m_n x_n + b$$

Where y is the dependent (responsive) variable, x_n is the n^{th} independent (explanatory) variables, m_n is the coefficient (multiplier) for the n^{th} variable, and b is the y-intercept. The MLR analysis will involve two separate characteristic models with unique explanatory variables. Below are the MLR models, associated variables, and MLR function, where the rate of carbonation (**R_c**) indicates the responsive variable, **β** indicates the explanatory variable multiplier and **α** indicates the y-axis intercepts.

1) **Concrete Mix Parameter Ratios**
    i) Water to Cement Ratio (W/C)
    ii) Aggregate to Cement Ratio (A/C)
    iii) Fine to Coarse Aggregate Ratio (FA/CA)

$$R_c = \beta_{W/C}(W/C) + \beta_{A/C}(A/C) + \beta_{FA/CA}(FA/CA) + \alpha_1$$

2) Concrete Mix Parameter Quantities

i) Cement Content (C)

ii) Fine Aggregate Content (FA)

iii) Coarse Aggregate Content (CA)

iv) Water Content (W)

$$R_c = \beta_C(C) + \beta_{FA}(FA) + \beta_{CA}(CA) + \beta_W(W) + \alpha_2$$

The MLR models were developed and verified using a Multiple Linear Regression analysis program from "**stats.blue**" (Stats.Blue, 2018) and "**Statistics Kingdom**" (Statistics Kingdom, 2017). A simple linear regression (SLR) model was developed for the concrete mix parameter ratios and quantities, to quantify each of the explanatory variables and the degree of responsibility it has with regard to carbonation rate. Following this, empirical models were developed based on the MLR functions above to provide an accurate estimation. With a sample size of about 30, it is not necessary to test for normality within the data. Hence why it is assumed that this data that includes 62 experimental data points will be sufficiently large enough for a theoretical normal distribution and will not be tested for normality.

Table 1 displays a list of each characteristic model with their associated variables and the coefficient of determination (COD) based on a simple linear regression (SLR) model calculation.

Table 1: Coefficient of Determination of Characteristic Model Variable and Carbonation Rate

Characteristic Model	Variable	COD, $\mathbf{R^2}$
Ratios	W/C	0.737
	A/C	0.177
	FA/CA	0.232
Quantities	W	0.253
	C	0.062
	CA	0.211
	FA	0.035

Using the information in **Table 1**, for each characteristic model a multiple linear regression calculation was done, introducing a single variable for each calculation. These variables were introduced in a decreasing order of coefficient of determination so that any observable improvement would start with the most impactful variable. By introducing these variables incrementally, we can measure the percentage of the model that can be explained and also quantify the improvement of the same model when including new variables. The results can be seen in **Table 2**.

Table 2: Multiple Linear Regression Models for Characteristic Models and Carbonation Rate

Characteristic Model	Variable	COD, $\mathbf{R^2}$	Percent Explained	Improvement
Ratios	W/C	0.737	73.7%	+0.0%
	W/C + FA/CA	0.825	82.5%	+8.8%
	W/C + FA/CA + A/C	0.828	82.8	+0.3%
Quantities	W	0.253	25.3%	+0.0%
	W + CA	0.522	52.2%	+26.9%
	W + CA + C	0.812	81.2%	+29.0%
	W + CA + C + FA	0.814	81.4	+0.2%

Based on the MLR model development in **Table 2**, the explanatory variable multipliers, $\boldsymbol{\beta}$, and the y-axis intercepts, $\boldsymbol{\alpha}$, were calculated. These values are shown in **Table 3**.

Table 3: Multiple Linear Regression (MLR) Model Values

Characteristic Model	Variable	Explanatory Variable Multiplier, $\boldsymbol{\beta}$	COD, $\mathbf{R^2}$	Y-Intercept, $\boldsymbol{\alpha}$
Ratios			0.828	-0.795
	W/C	23.757		
	A/C	-0.137		
	FA/CA	-11.865		
Quantities			0.814	1.268
	W	0.068		
	C	-0.030		
	CA	0.050		
	FA	-0.007		

The values in **Table 3** provide the required information to develop the empirical prediction models for the carbonation rate of concrete. **Table 4** presents these models and the percentage of the dependent variable (rate of carbonation) that the equations can accurately explain.

Table 4: Carbonation Rate Predictive Models

Characteristic Model	Equation	Percent Explained
Ratios	$R_c = 23.757(W/C) - 0.137(A/C) - 11.865(FA/CA) - 0.795$	82.8%
Quantities	$R_c = 0.068(W) - 0.030(C) - 0.007(FA) + 0.050(CA) + +1.268$	81.4%

3.4. Results

Based on the findings in sections 3.1, 3.2, and 3.3 of the investigations analysis, multiple observations can be drawn regarding the constituents within concrete design and their implications on carbonation rates. Modern literature has documented that an increase in porosity will enable increased carbon permeability within the concrete and consequently induce carbonation.

Based on the qualitative assessment of ratio of ingredients used in concrete, it was found that the most impactful parameter to control was water to cement ratio. The porosity was least heavily affected by the aggregate to cement ratio, although visually there was still evidence of a minimal amount of correlation, it was evidently much less conclusive and less responsible for increased carbonation rates compared to the other characteristic variables for the ratio model.

The quantitative analysis through the use of single and multiple linear regression models produced informative results that substantiated the claims made throughout this report indicating what parameters bear the most critical impact to increased carbonation rates within concrete. A general observation was that the absolute mass content of each ingredient (water, concrete, fine aggregates, and coarse aggregates) did not have nearly as much of an impact as the ratios between them. Therefore, to develop a model that accurately predicts the rate of carbonation using mass content, it is important to factor in water content, coarse aggregate content, and cement content to achieve a value of 81.2% for an explanation rate, whereas the fine aggregate content is responsible for a minimal (+0.2%) improvement. However, using ratios as a characteristic model for the MLR analysis demonstrated that water to cement ratio was responsible for explaining 73.7% of the relationship for carbonation rate, and introducing fine to coarse aggregate ratio had the next most substantial impact (+8.8%). The results are indicative of proving increased porosity will increase carbonation rate, altering these ratios will directly impact the permeability of the mixture.

4.0 Conclusion

In conclusion, the importance of this investigation and subsequent report is to analyze how variations in mix parameters of Portland cement-based concrete can directly influence the rate of carbonation in concrete. Throughout this report, the fundamental knowledge of carbonation was explored: including the chemistry, the causation, and the implications to steel reinforced concrete structures.

The investigation provides valuable insight as to how carbonation occurs and can be accelerated through various design decisions that occur within the cement and concrete manufacturing process. As discussed in section 3.4, the results indicated that the most important factor that would induce higher rates of carbonation was water to cement ratio, as it had the most direct impact on porosity, allowing the permeation of carbon dioxide. However, the average rate of carbonation can be determined based on the quantities / ratios of the concrete mix parameters. This conclusion demonstrates a reliable method to estimate and control the rate of carbonation depending on the needs of the concrete application.

An engineer knows that there are many properties of concrete that are considered ideal: workability, strength, durability, water resistance, etc… However, a successful engineer knows that perfect concrete does not exist, and it is not feasible to create the ultimate concrete mixture by maximizing every ideal property. This indicates that concrete design is contextual for each application, and different properties need to be prioritized to varying extents based on the project requirements. Reducing carbonation rates has not quite become mainstream and relatively few structures have a proactive design to combat this, whereas almost all carbonation reducing measures taken today have taken a reactive approach after extensive damage has occurred. Based on this analysis, it is recommended that decreasing carbonation rates through the mix parameters of water, cement, fine aggregates, and coarse aggregates be examined as a primary design consideration in steel reinforced concrete, which can be effectively estimated to an accuracy of approximately 82-83%.

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APPENDIX A: Average Carbonation Rate of Concrete Samples

W/C	A/C	FA/CA	C	FA	CA	W	R_c
kg/kg	kg/kg	kg/kg	kg/m^3	kg/m^3	kg/m^3	kg/m^3	mm/week
0.40	3.0	0.5	563	563	1125	225	**2.4**
0.50	3.0	0.5	533	533	1066	267	**6.5**
0.40	4.0	0.5	468	624	1248	187	**2.0**
0.50	4.0	0.5	448	595	1190	223	**2.7**
0.60	4.0	0.5	429	572	1145	258	**6.6**
0.40	5.0	0.5	400	667	1333	160	**2.9**
0.50	5.0	0.5	387	645	1290	194	**2.6**
0.60	5.0	0.5	374	619	1238	223	**6.3**
0.70	5.0	0.5	360	600	1200	252	**10.5**
0.50	6.0	0.5	340	679	1359	170	**4.9**
0.60	6.0	0.5	328	657	1314	197	**6.3**
0.70	6.0	0.5	319	637	1274	223	**8.5**
0.50	7.0	0.5	302	705	1410	151	**4.6**
0.60	7.0	0.5	295	688	1377	177	**7.5**
0.70	7.0	0.5	287	669	1377	201	**7.6**
0.60	8.0	0.5	266	710	1419	160	**4.7**
0.70	8.0	0.5	260	694	1388	182	**11.1**
0.90	9.4	0.8	195	785	1045	178	**1.7**
0.90	9.4	0.8	195	785	1045	178	**3.3**
0.90	9.4	0.8	195	785	1045	178	**5.6**
0.60	6.8	0.7	270	780	1050	172	**1.2**
0.60	6.8	0.7	270	780	1050	172	**2.4**
0.60	6.8	0.7	270	780	1050	172	**4.4**
0.50	5.0	0.7	350	710	1052	162	**0.3**
0.50	5.0	0.7	350	710	1052	162	**1.7**
0.50	5.0	0.7	350	710	1052	162	**3.0**
0.35	3.7	0.5	450	557	1088	157	**3.6**
0.50	4.5	0.6	394	655	1125	197	**4.9**
0.65	6.1	0.7	304	734	1114	197	**6.3**
0.65	8.2	0.7	230	769	1107	150	**3.9**
0.55	7.0	0.7	265	737	1105	147	**3.2**
0.45	5.5	0.6	325	680	1102	145	**2.6**
0.65	8.2	0.7	230	769	1107	150	**2.7**
0.55	7.0	0.7	265	737	1105	147	**2.5**
0.45	5.5	0.6	325	680	1102	145	**2.2**
0.91	9.4	0.8	195	785	1045	178	**2.3**
0.64	6.8	0.7	270	780	1050	172	**2.0**
0.46	5.0	0.7	350	710	1052	162	**1.8**

NOTE: *This table includes publicly available data from the following sources.*

(Tarek Uddin Mohammed, Md Mezbah Uddin Masud, 2019)

(P.A.M. Basheer, D.P. Russell, G.I.B. Rankin, 1999)

(Jianxin Peng, Huang Tag, Jianren Zhang, Steve C.S. Cai, 2018)

(Peng Liu, Ying Chen, Zhiwu Yu, Rongling Zhang, 2019)

(Hussain Shaik, Shamsher Bahadur Singh, 2016)

(Peng Liu, Zhiwu Yu, Ying Chen, 2020)