ACCELERATED CARBONATION ASSESSMENT OF HIGH-VOLUME FLY ASH CONCRETE

by

Omkar H. Thombare, B.E.

A thesis submitted to the Graduate Council of
Texas State University in partial fulfillment
of the requirements for the degree of
Master of Science
with a Major in Technology Management
August 2019

Committee Members:

Federico Aguayo, Chair

Anthony Torres

Yoo-Jae Kim

FAIR USE AND AUTHOR'S PERMISSION STATEMENT

ACKNOWLEDGEMENTS

I would like to thank my parents, Hanumant Thombare and Vasudha Thombare for their continuous love and support. My sister, Amruta Thombare who has played an important role in shaping up my career and I would take this opportunity to convey immense thankfulness and appreciation.

I would like to express my sincere gratitude to my advisor Dr. Federico Aguayo for his support since the day I have known him. His immense knowledge, enthusiasm, motivation and patience has helped me throughout the process of research. I could not have imagined a better advisor and mentor for my thesis study.

I would also like extend my appreciation to Texas Department of Transportation (TxDOT) for their assistance and support. Finally, I would like to thank the committee: Dr. Anthony Torres and Dr. Yoo-Jae Kim for their insightful suggestions and encouragement.

TABLE OF CONTENTS

Page

ACKNOWLEDGEMENTS iv

LIST OF TABLES vii

LIST OF FIGURES viii

ABSTRACT x

CHAPTER

I. INTRODUCTION 1

Background 1
Problem Statement 2
Research Significance 3
Thesis Organization 3

II. LITERATURE REVIEW 5

Carbonation of Concrete 5
Effects of Use of SCMs on Carbonation of Concrete 6
Ground granulated blast furnace slag (GGBFS) 6
Silica fume 7
Fly ash 8
Effects of Relative Humidity on Carbonation of Fly Ash Concrete 9
Effects of Curing and Porosity on Carbonation of Fly Ash Concrete 9

III. MATERIALS AND EXPERIMENTAL METHOD 12

Materials Used 12
Mixture Proportions 14
Mixing Procedure 15
Accelerated Carbonation Setup 16
Chamber 16
De-humidifer 17

CO_2 cylinder...17
Preparation and Casting of Test Specimens..18
Carbonation Test...19
Compression Test...21

IV. RESULTS AND DISCUSSION 23
Compression Test...23
Accelerated Carbonation Test...25
Assessment based on type of fly ash...25
Assessment based on moist curing 28
Comparison based on water-cementitious materials ratio 30
Comparison based on amount of cementitious material................35
Comparison between Slag and Fly Ash...41
Correlation between Compressive Strength and Carbonation...................43

V. CONCLUSIONS AND RECOMMEDATIONS 47

APPENDIX SECTION...49

REFERENCES 76

LIST OF TABLES

Table **Page**

1. Chemical Properties of Cementitious Materials 12

2. Physical Properties of Aggregates 13

3. Concrete Mix Matrix...15

4. Carbonation Depth Comparison between Control, 30% Class C
& F Fly Ash, and 30% Slag 43

LIST OF FIGURES

Figure **Page**

1. Sieve Analysis of Fine Aggregates 13

2. Sieve Analysis of Coarse Aggregates 14

3. Accelerated Carbonation Chamber 16

4. Accelerated Carbonation Setup....................18

5. Mechanical Cutter 20

6. Carbonation Depth Recording Method 21

7. Compressive Strength of Class C Fly Ash (310 kg/m^3 and 0.50 w/cm)....................23

8. Compressive Strength of Class F Fly Ash (310 kg/m^3 and 0.50 w/cm) 24

9. Compressive Strength Comparison of Class C & F Fly Ash (340 kg/m^3 and 0.45 w/cm)....................24

10. Comparison of Class C Fly Ash Specimens with Control (1-day curing)....................26

11. Comparison of Class C Fly Ash Specimens with Control (7-days curing) 26

12. Comparison of Class F Fly Ash Specimens with Control (1-day curing) 27

13. Comparison of Class F Fly Ash Specimens with Control (7-days curing)....................27

14. Comparison between 1-day and 7-days Curing for Control 28

15. Comparison between 1-day and 7-days Curing for Class C Fly Ash 29

16. Comparison between 1-day and 7-days Curing for Class F Fly Ash....................29

17. Comparison between 0.50 and 0.45 w/cm Ratio for Control (1-day curing) 30

18. Comparison between 0.50 and 0.45 w/cm Ratio for Control (7-days curing)....................31

19. Comparison between 0.50 and 0.45 w/cm Ratio for Class C Fly Ash (1-day curing)....32

20. Comparison between 0.50 and 0.45 w/cm Ratio for Class C Fly Ash (7-days curing)....33

21. Comparison between 0.50 and 0.45 w/cm Ratio for Class F Fly Ash (1-day curing)....34

22. Comparison between 0.50 and 0.45 w/cm Ratio for Class F Fly Ash (7-days curing)....35

23. Comparison between 310, 340, and 370 kg/m^3 Cementitious Content for Control at 0.50 w/cm (1-day curing)....36

24. Comparison between 310, 340, and 370 kg/m^3 Cementitious Content for Control at 0.50 w/cm (7-days curing)....37

25. Comparison between 340 and 400 kg/m^3 Cementitious Content for Class C Fly Ash at 0.45 w/cm (1-day curing)....38

26. Comparison between 340 and 400 kg/m^3 Cementitious Content for Class C Fly Ash at 0.45 w/cm (7-days curing)....39

27. Comparison between 340 and 400 kg/m^3 Cementitious Content for Class F Fly Ash at 0.45 w/cm (1-day curing)....40

28. Comparison between 340 and 400 kg/m^3 Cementitious Content for Class F Fly Ash at 0.45 w/cm (7-days curing)....41

29. Pictorial Comparison between Control, Fly Ashes, and Slag....42

30. 2-days Compressive Strength vs 28-days Carbonation Depth....44

31. 28-days Compressive Strength vs 105-days Carbonation Depth....45

32. 90-days Compressive Strength vs 105-days Carbonation Depth....46

ABSTRACT

This investigation deals with determining the effect of 57% relative humidity and 4% CO_2 concentration on class C and class F fly ash concrete specimens under accelerated carbonation. Fly ash concrete specimens were differentiated based on the cementitious content (310, 340, 370, and 400 kg/m^3) and water-cementitious materials ratio (0.50 and 0.45). The specimens were allowed 1 and 7 days of moist curing and moved to the accelerated carbonation chamber maintained at 57% relative humidity and 4% CO_2 ingress. The specimens were tested for carbonation at an age of 28, 56, 63, 70, and 105 days. The accelerated carbonation test results indicate that with addition of supplementary cementitious materials the depth of carbonation also increases. It was evident that increase in the duration of moist curing from 1 day to 7 days had a positive effect, reducing the carbonation depth of control and fly ash concrete mixes. When both types of fly ashes were compared, class C fly ash was observed to be more resistant against carbonation than class F fly ash due to the higher calcium oxide content. Based on the compressive strength results obtained, carbonation depth appeared to decrease with increase in compressive strength, but this correlation was not significant.

Keywords: accelerated carbonation, fly ash concrete, relative humidity

I. INTRODUCTION

Background

The need for innovative infrastructures and urban housing is enormous and the burden of fulfilling these necessities is heavily reliant on the concrete industry. In order to meet these expectations, 3.7 billion tons of ordinary portland cement (OPC) is mass produced every year contributing approximately 3.0 billion tons of CO_2. These emissions add up to 7% of the total emissions from all sources indicating the enormity of the impact on environment (Malhotra & Mehta, 2008). CO_2 emissions released during the manufacturing of cement are prominently due to the calcination of limestone and usage of fuels at high temperatures required during the sintering process. Hence, the construction industry is under an immense burden to decrease these emissions of greenhouse gases, and seek alternatives to produce reliable materials having identical properties as cement (Lu, Wang, Li, Hao, & Xu, 2018). Considering the magnitude of environmental impact cement production has, there is a need to use alternative materials to replace cement partially or completely. Such materials are called supplementary cementitious materials (SCMs). Fly ash, ground granulated blast furnace slag (GGBFS), and silica fume are commonly used SCMs worldwide. A study on supplementary cementitious materials indicated that GGBFS and fly ash can potentially reduce CO_2 emissions by 22% and 14% respectively (Yang, Jung, Cho, & Tae, 2015). Lastly, a majority of the SCMs are by-product materials and hence their addition in concrete can be an efficient way of disposal.

Problem Statement

The use of SCMs in reinforced concrete such as fly ash has proved to be beneficial in mitigating the effect of alkali-silica reaction, sulfate attack, and chloride penetration. However, at the same time, the threat of carbonation in reinforced concrete can be detrimental. Fly ash is a byproduct obtained from the combustion of pulverized coal in an electrical generating station (Siddique, 2004). Fly ash is also recognized as an eco-friendly material and its usage can contribute to lowering the carbon footprint to a large extent. The partial replacement of OPC by fly ash offers greater resistance against chemical threats such as alkali-silica reaction and sulfate attack (Collepardi, Collepardi, Olagot, & Simonelli, 2004). In addition to that, it provides advantages such as better mechanical properties, lower water demand, lessen heat evolution and reduced bleeding. Durability is a key factor to assess the service life of concrete structures and fly ash assists to improve it by decreasing the permeability of concrete (Lu et al., 2018). Furthermore, during the designing phase of concrete structures, carbonation is considered to be one of the key factors for the determination of the service life. While fly ash can impart several beneficial qualities of concrete, several previous studies indicate that the addition of fly ash has a negative impact on the carbonation results. Carbonation is a serious threat to the concrete structure as the ingress and diffusion of CO_2 can corrode the reinforcement making the structure vulnerable to failure. The aim of this study is to evaluate and characterize the carbonation patterns in fly ash concrete under accelerated carbonation conditions exposed to various relative humidity conditions.

Research Significance

Carbonation of concrete is a lengthy diffusion process with chemical interaction of atmospheric CO_2 and calcium hydroxide ($Ca(OH)_2$) liberated during the hydration process (Bouzoubaâ, Bilodeau, Tamtsia, & Foo, 2010). It is important to study the carbonation because when the carbonated surface reaches the steel reinforcement inside the concrete, significant corrosion may be initiated which may ultimately reduce the service life of the structure (Stefanoni, Angst, & Elsener, 2018). In a high-quality concrete with a lower water-cementitious material ratio, typically the rate of penetration of carbon is about 0.039 inches per year (NPCA, 2015). Considering the duration required for the carbonation process, researchers adopt an accelerated carbonation method to yield the results in a short period of time. In this method, concrete specimens are subjected to carbonation at a much faster rate in a controlled environment. The rate of carbonation usually depends on several factors such as relative humidity, temperature, concentration of CO_2, porosity, and curing age of concrete. These factors are further explored in the study.

Thesis Organization

The study will further investigate the effect of 57% relative humidity on fly ash concrete specimens in an environmentally controlled accelerated carbonation chamber and access the carbonation pattern. Chapter 2 of this study covers a detailed literature review on carbonation, the effects of carbonation on concrete structure, and the factors that influence the rate of carbonation. In addition to that, a comparative study between natural and accelerated carbonation is discussed. Chapter 3 explains the types of mixtures and mixing matrices that were utilized in the present study along with detailed experimental procedures. Chapter 4 summarizes and discusses the results obtained from the tests carried out i.e. accelerated carbonation and compression test. It also converses the effects of use of SCMs in concrete on carbonation with the help of graphical representations. Finally, chapter 5 consists of the key takeaways from the research.

II. LITERATURE REVIEW

Carbonation of Concrete

Concrete structures are constructed considering primarily the compressive and tensile forces acting on the structure. Concrete is known for its resistance against the compressive forces and on the other hand, steel reinforcement is used inside concrete to negate the tensile forces. The steel reinforcement in concrete is in a highly alkaline environment (pH≈13) and a passive film of iron oxide is formed around the reinforcement which protects the steel from corrosion (Aguayo, Drimalas, & Folliard, 2015). The corrosion of reinforcing steel in concrete is considered one of the most serious problem considering the durability of the structure. It is the main reason for the degradation of concrete structures and it negatively affects its service life (Reis, Malheiro, Camões, & Ribeiro, 2015). Corrosion can occur if the moisture and oxygen penetrates the concrete and reach the steel resulting in the development of cracks, rust stains, and spalls of concrete cover (Khunthongkeaw, Tangtermsirikul, & Leelawat, 2006). When atmospheric carbon dioxide penetrates in the hardened concrete it dissolves in the pore water to form carbonation acid and further it reacts with calcium hydroxide ($Ca(OH)_2$) released during the cement hydration and produces calcium carbonate (NPCA, 2015).

$$CO_2 + H_2O \longleftrightarrow H_2CO_3$$

$$H_2CO_3 + Ca\,(OH)_2 \longrightarrow CaCO_3 + 2H_2O$$

This reaction is slow, and it deleteriously affects the passivation layer making the steel vulnerable to corrosion and this process is known as carbonation (Bouzoubaa et al., 2006). Carbonation is a vital reason for the reduction in pH value to less than 9, which can significantly weaken or could eliminate the steel protective layer. This reduction of pH is due to the carbonation reaction which consumes calcium hydroxide, and it is then partially replaced by calcium carbonate reducing its concentration. Hence, the weaker hydrogen ion concentration assists the reduction in pH value.

Effects of Use of SCMs on Carbonation of Concrete

Utilization of SCMs such as fly ash and GGBFS has been increasing around the world, particularly due to the enhanced mechanical properties and to reduce the usage of cement to decrease CO_2 emissions. These SCMs are more resistant to chemical threats such as alkali-silica reaction, sulfate attack, and chloride penetration (Collepardi et al., 2004). However, several studies have indicated that the use of SCMs have presented greater depth of carbonation when compared with the control mixture. For this study, fly ash was the primary SCM used but the effects of other SCMs on carbonation are also studied further. Since the process of carbonation takes years to get the results, the majority of researchers adopt the accelerated carbonation method to hasten the process under a controlled environment. In this study, the accelerated carbonation method was implemented due to the time constraint.

Ground granulated blast furnace slag (GGBFS)

GGBFS is known to improve the resistance of concrete to alkali-silica reaction, sulfate attack and chloride ingress. However, it possess a higher risk of carbonation at higher replacement levels as compared with fly ash and OPC concrete (Lye, Dhir, & Ghataora, 2016). The reduction in the amount of $Ca(OH)_2$ is believed to play a vital role in carbonation of GGBFS concrete as carbonation depths obtained are observed to be higher in comparison with OPC concrete. The primary reason for this reduction can be because some part of calcium hydroxide is utilized for its reaction with GGBFS (Sulapha, Wong, Wee, & Swaddiwudhipong, 2003). Also, the water required for cement production and the reactive CaO in GGBFS expresses the CO_2 buffer capacity. This is indicative of the microstructure of the mixture and shows a good correlation to the carbonation of concrete produced (Leemann & Moro, 2017).

Silica fume

An experimental study conducted by Papadakis (2000), concluded that silica fume with 10% addition replacing cement yielded the highest carbonation depth than high and low CaO content fly ashes. This indicates that the use of silica fume can be detrimental towards the passive oxide film protecting the reinforcement under controlled environment (Papadakis, 2000). However, it was noticed that the impact on the use of silica fume in concrete was very minimum as compared to ordinary Portland concrete at 0.29 w/cm ratio. Carbonation resistance was observed to weaken at higher w/cm ratios prominently at 0.7 and above (Czarnecki, Woyciechowski, & Adamczewski, 2018). Silica fume was also found very effective for resistance against carbonation in comparison with GGBFS and fly ash at 0.5 w/cm ratio and 28 days moist curing. The reason for strong resistance against carbonation is believed due to the denser pore structure which makes it difficult to penetrate the concrete made with silica fume (Sulapha et al., 2003).

Fly ash

Inclusion of fly ash in concrete reduces the calcium hydroxide content due to the pozzolanic reactions which decreases the alkalinity level required for steel protection. Also, it can reduce the pH level, consequently accelerating the carbonation which produces high risk of corrosion (Bouzoubaâ et al., 2010). Hence, researchers have found out that increase in replacement by fly ash has a negative effect on the depth of carbonation. The calcium content in fly ashes is an important indicator of how fly ash will perform in concrete. Low calcium fly ashes are produced from anthracite and bituminous coals. These fly ashes require alkali or lime to react to form cementitious hydrates which has no significant hydraulic behavior. However, high calcium fly ashes are produced from lignite and sub-bituminous coals and they react with water rapidly producing a pozzolanic and hydraulic mixture. It was also found that higher calcium oxide content fly ash can solely achieve higher mechanical strengths when used as a supplementary cementitious material (Thomas, 2007). High calcium fly ashes tend to have an advantage over the low calcium fly ashes in terms of the mechanical properties and hence it is better resistant against the threat of carbonation.

In a research conducted by Khunthongkeaw et. al. (2006), they concluded that fly ash containing higher calcium oxide (CaO) content tends to have lower carbonation depths as compared with low CaO fly ash (Khunthongkeaw et al., 2006). Another research carried out by Sanjuan and Cheyrezy confirms that the partial addition of high CaO content fly ash to the OPC offers a good resistance against carbonation (M.A. Sanjuan & Cheyrezy). Considering the claims made in the above research, calcium oxide (CaO) content in fly ash is believed to have an influence on the carbonation. However, in a research it was observed that the addition of fly ash without reducing the original cement content has a positive effect rather than the addition of fly ash to replace cement (Branca, Fratesi, Moriconi, & Simoncini, 1992). Carbonation of fly ash concrete depends upon the influence of several distinct factors and few of them are discussed further.

Effects of Relative Humidity on Carbonation of Fly Ash Concrete

Relative humidity is an important parameter to be considered while studying accelerated carbonation in a controlled environment. In case of fly ash concrete, it was observed that higher relative humidity improves the resistance against carbonation. Concrete being a porous material allows the internal water to saturate in its pores, leaving no space for CO_2 to occupy. Due to this, the ingress of CO_2 inside the concrete is limited and subsequently the resistance against carbonation is increased (Ruixia, 2010). This pattern can be validated from a study performed where specimens were allowed to moist cure for 1 day and then moved to a controlled environment (20°C and 65% RH). Carbonation was observed to decrease when relative humidity was increased from 65% to 80% and 65% to 90%. It was also observed that the significant effect of lack of moist curing time provided to the specimens was compensated by increasing the relative humidity (Thomas & Matthews, 1992).

Effects of Curing and Porosity on Carbonation of Fly Ash Concrete

Multiple researches suggest the importance of moist curing and its effect on the carbonation depths of fly ash concrete. If the concrete is adequately cured, it significantly reduces the large pores inside the concrete making it less penetrable. In a research on concrete incorporating high volumes of fly ash, the results suggested that with an increase in the moist curing period from 7 to 28 days, the carbonation depth was observed to decrease. However, the effect was not substantial when the curing period was further prolonged from 28 to 91 days (Bouzoubaa et al., 2006). Contrasting results were found in a study which indicated that 90 days curing had a positive effect against carbonation of fly ash concrete in comparison with 28 days curing (Zhao, He, Zhang, & Jiang, 2016). In an accelerated carbonation of fly ash concrete study, it was clearly evident that, the longer the specimens are allowed to moist cure before placing in the accelerated carbonation chamber, lesser will be the carbonation depth. This emphasizes the importance of moist curing conditions before exposing to the CO_2 infused environment (Atiş, 2004).

A linear relationship was found between porosity and carbonation depths indicating that the carbonation value increases as porosity increases (Atiş, 2004). It can be predicted that denser concrete mixtures would be more resistant against the threat of carbonation since lesser the porosity, slower will be the ingress of CO_2. This was supported by research done by Bouzoubaa et. al. (2010) suggesting that increase in w/cm ratio will increase the coefficient of carbonation both at 3 and 7 days of curing (Bouzoubaâ et al., 2010). Similar results were observed in a research suggesting the lower w/cm ratio mixtures offer better resistance against carbonation due to its denser pore structure (Khunthongkeaw et al., 2006). Fly ash concrete with higher w/cm ratios have higher carbonation depth due to the lack of calcium hydroxide content in the fly ash (Hussain, Bhunia, & Singh, 2017). A similar trend was observed in a research where three w/cm ratios (0.35, 0.50, and 0.65) were considered. An increase in carbonation depth was observed with an increase in w/cm ratio for specimens exposed in an accelerated carbonation chamber with a 75% relative humidity (Branca et al., 1992).

It is vital to understand the carbonation behavior of specimens exposed to natural environments to recognize the relationship between accelerated and natural carbonation. In a study by Jia, Yan, and Aruhan (2012), they found out that the replacement of cement with SCMs and amount of cementitious materials have an influence on both natural and accelerated condition. Another important research finding was that more than half of the carbonation depth achieved in 2 years by the specimens that are naturally carbonated takes place in the first 56 days if the specimens are insufficiently cured (Jia, Aruhan, & Yan, 2012). Hence, initial curing of specimens plays a vital role against carbonation in both natural and accelerated environments. Also, it was observed that a common trend existed between natural and accelerated carbonation, i.e. with an increase in fly ash content, carbonation also increased (Bouzoubaâ et al., 2010).

III. MATERIALS AND EXPERIMENTAL METHOD

Materials Used

The cement used for this study was a Type I/II OPC which conforms to the ASTM C150 specifications (ASTM International, 2019). Fly ash and GGBFS were the two SCMs used for the tests. Two types of fly ash namely Class C and Class F fly ashes conforming to ASTM C618 were used (ASTM International, 2019). Class C fly ash consisted of higher calcium oxide (CaO) content as compared to class F fly ash. The chemical properties of the cementitious materials used are indicated in Table 1. The coarse and fine aggregates used for this research were crushed limestone rock and limestone sand respectively. The aggregate properties results are specified in Table 2 and the sieve analysis for fine and coarse aggregates are shown in Figure 1 and Figure 2.

Table 1. Chemical Properties of Cementitious Materials

Material	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**SO_3**	**Na_2O**	**K_2O**
Cement	20.8	4.4	4.3	63.62	1.1	2.9	0.11	0.67
Class C FA	41.05	17.80	3.84	20.69	3.63	1.29	1.89	0.62
Class F FA	49.40	22.02	12.64	2.99	1.04	0.79	0.75	1.52
GGBFS	32.76	6.99	0.46	48.07	10.37	0.04	0.30	0.33

Table 2. Physical Properties of Aggregates

Aggregates	**Bulk specific gravity (OD)**	**Bulk specific gravity (SSD)**	**Apparent specific gravity**	**Absorption (%)**	**Dry rodded unit weight (kg/m^3)**
Limestone Sand	2.55	2.61	2.73	2.63	1819.64
Limestone Rock	2.52	2.58	2.68	2.44	1574.89

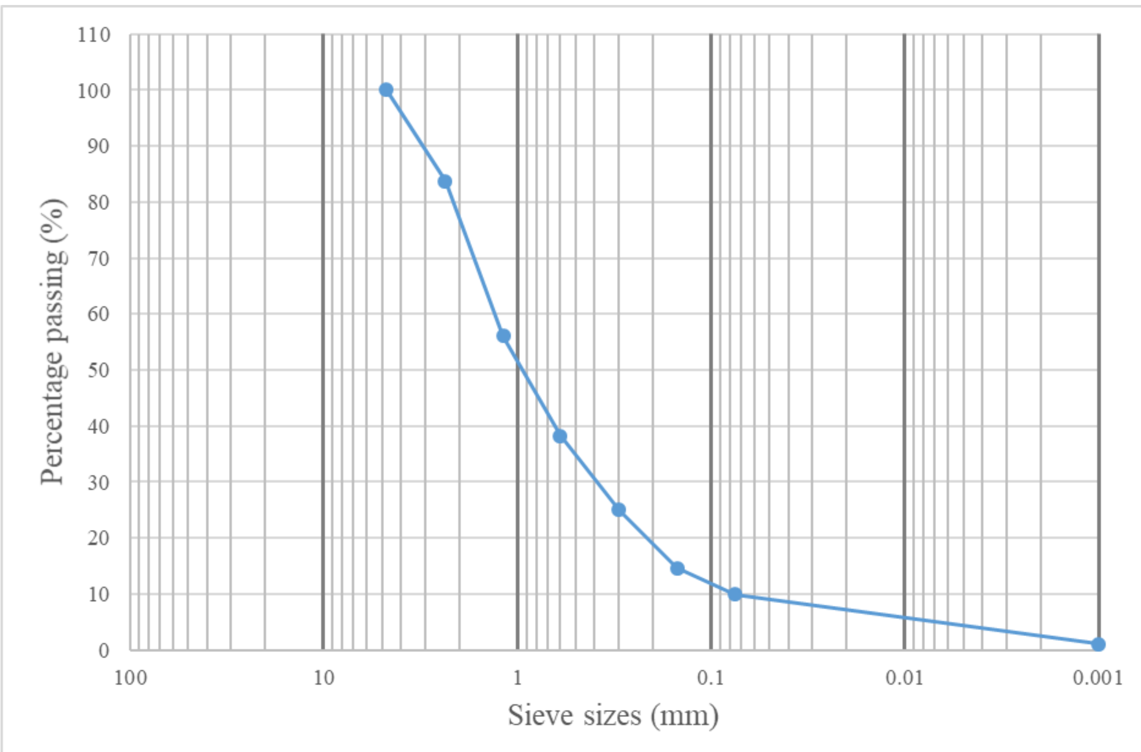


Figure 1. Sieve Analysis for Fine Aggregates

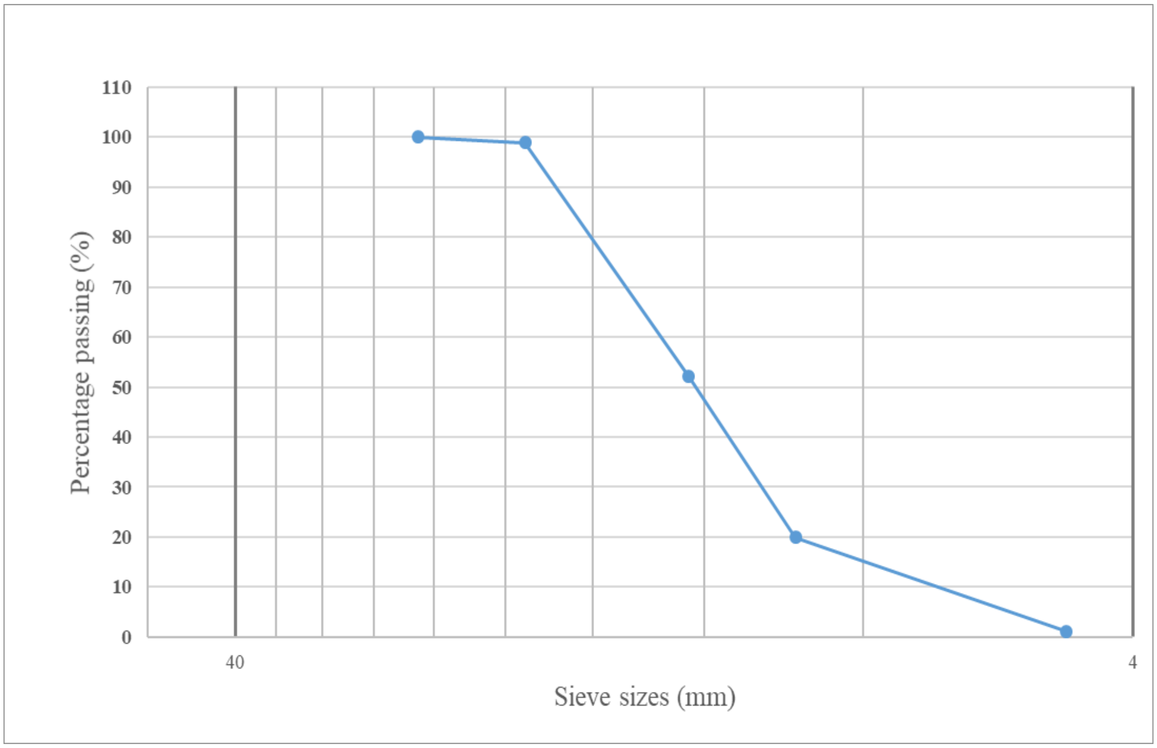


Figure 2. Sieve Analysis for Coarse Aggregates

Mixture Proportions

A total of 25 concrete mixtures were divided in two main groups based on the water-cement ratios of 0.50 and 0.45. The first series i.e. 0.5 w/c ratio were further classified in three groups based on the cement content of 310, 340, and 370 kg/m^3. Similarly, the second series with 0.45 w/c ratio were divided in two groups depending of cement content i.e. 340 and 370 kg/m^3. These series consisted of mixtures with distinct proportions of SCMs used ranging from 0% to 50% by mass of total cementitious content and are clearly specified in Table 3.

Table 3. Concrete Mix Matrix

W/C Ratio				
0.5			**0.45**	
Cementitious Content			***Cementitious Content***	
310 kg/m^3	***340 kg/m^3***	***370 kg/m^3***	***340 kg/m^3***	***400 kg/m^3***
100% OPC - Control	100% OPC - Control	100% OPC - Control	100% OPC - Control	100% OPC - Control
15% Class C Fly Ash	30% Class C Fly Ash	15% Class C Fly Ash	15% Class C Fly Ash	15% Class C Fly Ash
30% Class C Fly Ash	30% Class F Fly Ash	15% Class F Fly Ash	30% Class C Fly Ash	30% Class C Fly Ash
50% Class C Fly Ash			15% Class F Fly Ash	15% Class F Fly Ash
15% Class F Fly Ash			30% Class F Fly Ash	30% Class F Fly Ash
30% Class F Fly Ash				
50% Class F Fly Ash				
30% Slag				
50% Slag				

Mixing Procedure

Aggregates batching was done by mixing the aggregates well in the mixer for approximately five minutes to ensure uniformity. For mixing, the mixer was initially cleaned by rinsing and draining the water. Coarse aggregates were added first and were allowed to mix for three minutes, following by fine aggregates for two minutes. Approximately 70% of the total water was then added and mixed for another three minutes. Subsequently the cementitious materials were added and allowed to mix for five minutes following by the remaining water for another three minutes. The mixture was allowed to rest for another three minutes after removing from the mixer. The mixing procedure was followed in accordance with ASTM C192 (ASTM International, 2018).

Accelerated Carbonation Setup

Chamber

The carbonation chamber was large enough to accommodate 50 prisms when specimens were placed vertically. One mechanical fan was placed in the chamber to ensure air circulation. A humidity probe inside the chamber provided the information of the humidity inside the chamber. The prisms were positioned in the chamber in such a manner that a gap of at least 5 mm between prisms and chamber walls were maintained as shown in the Figure 3.

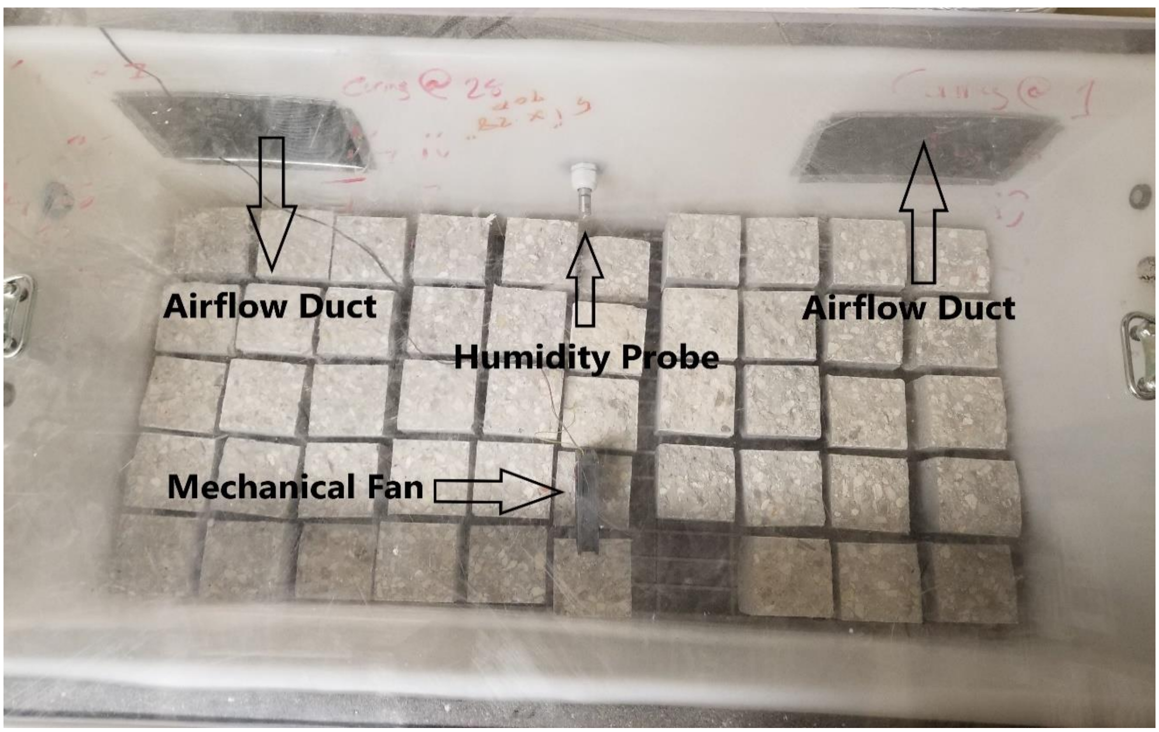


Figure 3. Accelerated Carbonation Chamber

De-humidifier

For this experiment, a Drieaz Revolution LGR Dehumidifier was used. It reduces the humidity in the enclosed environment by removing water vapor from the air. It also consists of a Humidistat mode which allows users to maintain the desired humidity level. The relative humidity level was maintained by the means of this de-humidifier placed above the carbonation chamber. The ventilation ducts were cut in such a way that the inflow and outflow of CO_2 through the system is smooth and the relative humidity is maintained. The relative humidity was controlled at 57 +/- 5%.

CO_2 cylinder

A CEA 288 CO_2 analyzer was used to monitor the carbon content inside the chamber. It consisted a digital readout with standard ranges of 0-1%, 0-10%, or 0-100%. The CO_2 level inside the chamber was adjusted to 4% with the help of a gas regulator. A digital display was placed above the carbon tank which indicated the CO_2 level and the temperature inside the carbonation chamber. Figure 4 demonstrates the entire accelerated carbonation setup.

Figure 4. Accelerated Carbonation Setup

Preparation and Casting of Test Specimens

For carbonation test, five steel molds of 0.10 x 0.10 x 0.35 m (4 x 4 x 14 inches) size was prepared per mix. Two of the five prisms were actually used for the accelerated carbonation testing. While the other three prisms were exposed to the natural environment to test for natural carbonation. However, this study focuses only on the accelerated carbonation portion. These steel molds were cleaned properly to ensure no residual concrete from previous mixes existed. Before the concrete mixture was poured in the molds, a releasing agent (WD-40) was lightly sprayed on the surface of the molds. The prisms were then cast horizontally using a vibrating table for proper compaction and were allowed to cure in the laboratory for 20 +/- 4 hours. The exposed surface of the prism was covered with partially wet polythene to avoid drying. After sufficient time of curing, the molds were stripped and one of the prisms (Day 1) was directly transferred to the carbonation chamber while the other prism (Day 7) was immediately transferred into a moist curing chamber with a temperature control of 23 +/- 2 °C. In case of compression test, twelve 4 x 8 in. cylinders were cast per mix. Standard procedure according to ASTM C31 were followed for making the specimens (ASTM International, 2019). These cylinders were allowed to cure in the laboratory for 20 +/- 4 and were then demolded. After demolding, the cylinders were transferred to the moist curing chamber and tested after desired age of curing was obtained (2, 7, 28, and 90 days).

Carbonation Test

The prisms were removed from the moist curing chamber at an age of 1 and 7 days and were allowed to air dry in a controlled environment (23 °C, 50 to 65% RH) for a minimum of 3 hours. The prisms were then vertically placed into the carbonation chamber with CO_2 level of 4.0 +/- 0.5% by volume, temperature of 23 +/- 2 °C and relative humidity (RH) of 57 +/- 5%. The ages of measuring carbonation depth were 28, 56, 63, 70, and 105 days after placing them in the carbonation chamber. For measuring the carbonation depth, a slice of approximately 50 mm thick was broken off the prism at each stage of testing with a mechanical cutting machine shown in Figure 5.

Figure 5. Mechanical Cutter

Thereafter, a solution of 0.5% phenolphthalein in 70% ethanol solution was sprayed on the freshly cut surface and allowed to air dry for 1 hour +/- 15 minutes. The carbonation front was determined by the color change i.e. from colorless to pink. The carbonation depths were measured at 5 equidistant points on each face. To locate these points the edge length was divided into 7 parts and 5 central points were used as shown in Figure 6. With the help of a ruler, the carbonation depth was determined perpendicular to the surface of the prism with a precision of 0.5 mm. This procedure was repeated on the four faces to yield 20 measurement points. The mean depth is calculated and recorded for each face and the arithmetical average is calculated for the entire specimen.

Figure 6. Carbonation Depth Recording Method

Compression Test

Compressive strength testing of concrete is a common quality control procedure to ensure that the concrete is hydrating properly, and that strength is gained at the necessary rate. In this research, it was also important to characterize and evaluate what influence the strength development plays in regards accelerated carbonation resistance for each mixture, especially those with high fly ash replacement (i.e., 50% fly ash). Concrete cylinders (4x8 in.) were cast for the evaluating the compressive strength. Cylinders were moist cured under wet-burlap for 24 hours after which they were placed in a moist curing room (100% RH at 23 +/- 3C) until they were to be tested. Compression test was performed at curing ages of 2, 7, 28, and 90 days according to ASTM C39 (ASTM International, 2018).

IV. RESULTS AND DISCUSSION

Compression Test

Control mixtures were observed to have higher initial compressive strength (2 and 7 days curing) as compared with mixes containing SCMs. From Figure 7, 8 and 9 it can be observed that Class C fly ash yielded higher strengths in comparison with class F fly ash. The strength development of class C fly ash specimens is initially slower but achieves greater strength at later ages (90 days). The optimum replacement level of class C fly ash is 30% in terms of compressive strength. While in case of class F fly ash, 15% is the maximum replacement level that yields better strength when compared with control at an age of 90 days however, high strength could be observed at later ages with continued hydration and strength development. From the results, it can be deduced that 0.45 w/cm ratio yields better strength as compared to 0.50 w/cm.

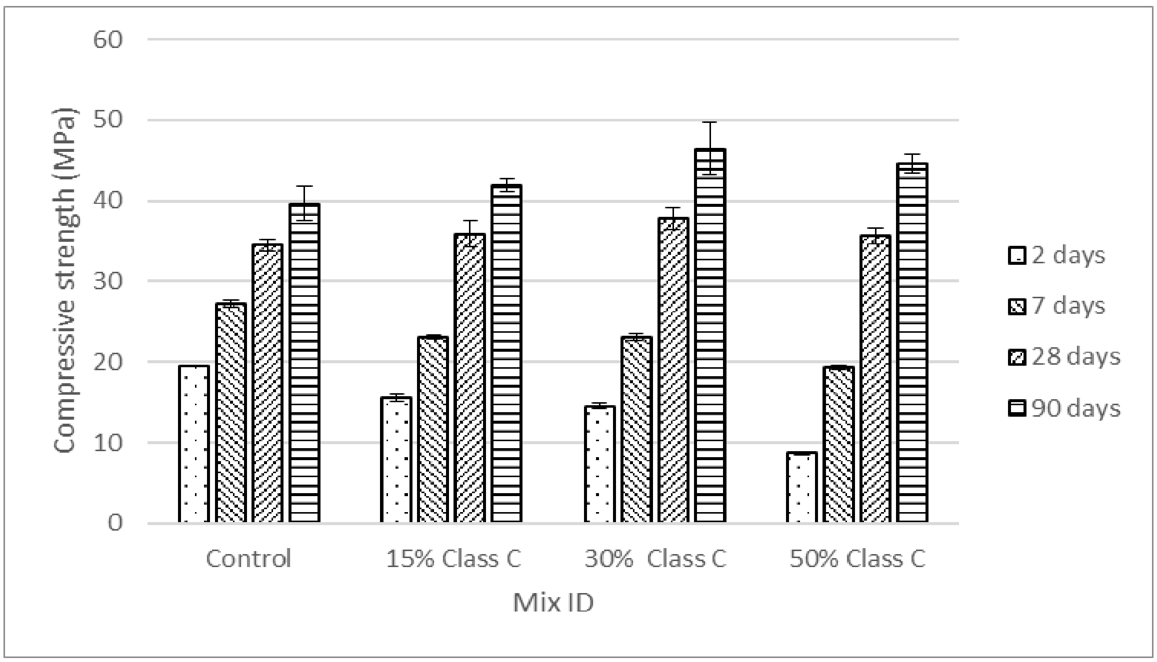


Figure 7. Compressive Strength of Class C Fly Ash (310 kg/m^3 and 0.50 w/cm)

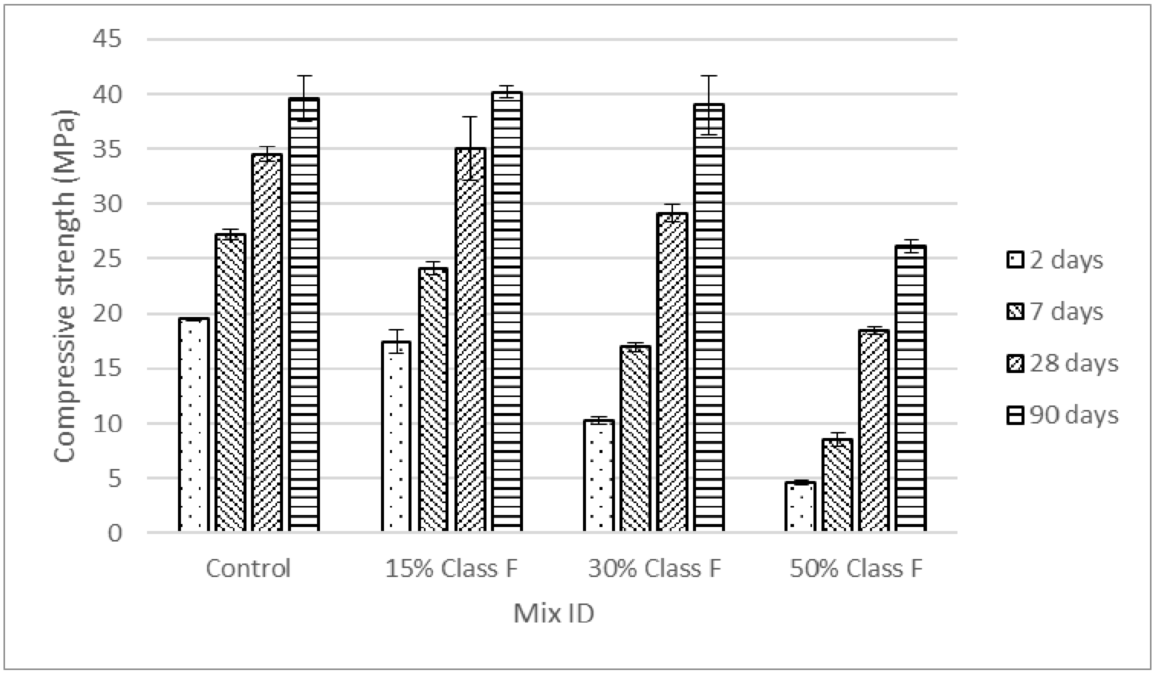


Figure 8. Compressive Strength of Class F Fly Ash (310 kg/m^3 and 0.50 w/cm)

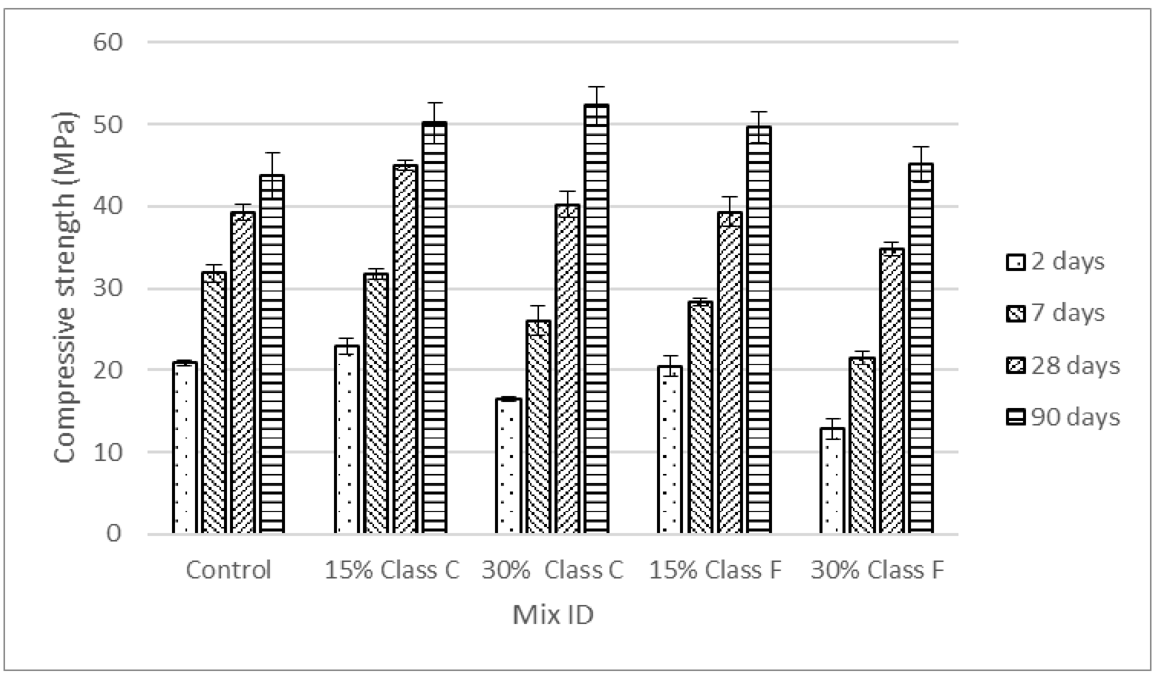


Figure 9. Compressive Strength Comparison of Class C & F Fly Ash (340 kg/m^3 and 0.45 w/cm)

Accelerated Carbonation Test

Assessment based on type of fly ash

Figure 10 and 11 demonstrates the carbonation patterns for specimens consisting class C fly ash at 0.50 w/cm ratio of moist cured for 1 and 7 days respectively. Based on the information obtained from both the graphs, the control mixture has more resistance against carbonation as compared with class C fly ash. It can be also observed that carbonation depth increases with increase in fly ash dosage. 50% class C fly ash replacement has a detrimental effect as the specimens are completely carbonated at later ages of testing. Similarly, Figure 12 and 13 signifies the effect of carbonation on class F fly ash specimens moist cured for 1 and 7 days respectively. A similar pattern can be observed as class C fly ash, indicating an increase in carbonation with increase in quantity of class F fly ash. However, the rate of CO_2 ingress in class F fly ash specimens is more rapid as compared with class C fly ash specimens.

It can be clearly inferred that class C fly ash is more resistant against carbonation as compared with class F fly ash at a given fly ash replacement percentage. This pattern was observed in majority of the cases at different cementitious content and w/cm ratios. The reason for this can be due to the higher calcium oxide (CaO) content present in the chemical composition of class C fly ash acting a buffer capacity for reducing the rate at which carbonation progress.

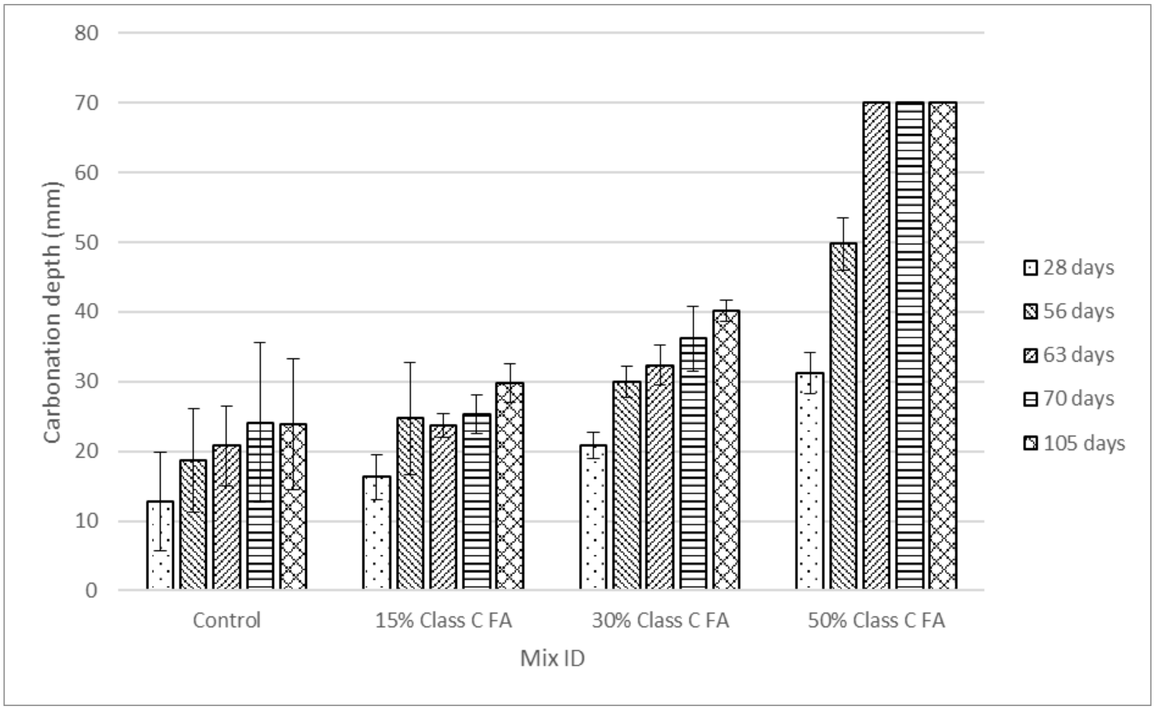


Figure 10. Comparison of Class C Fly Ash Specimens with Control (1-day curing)

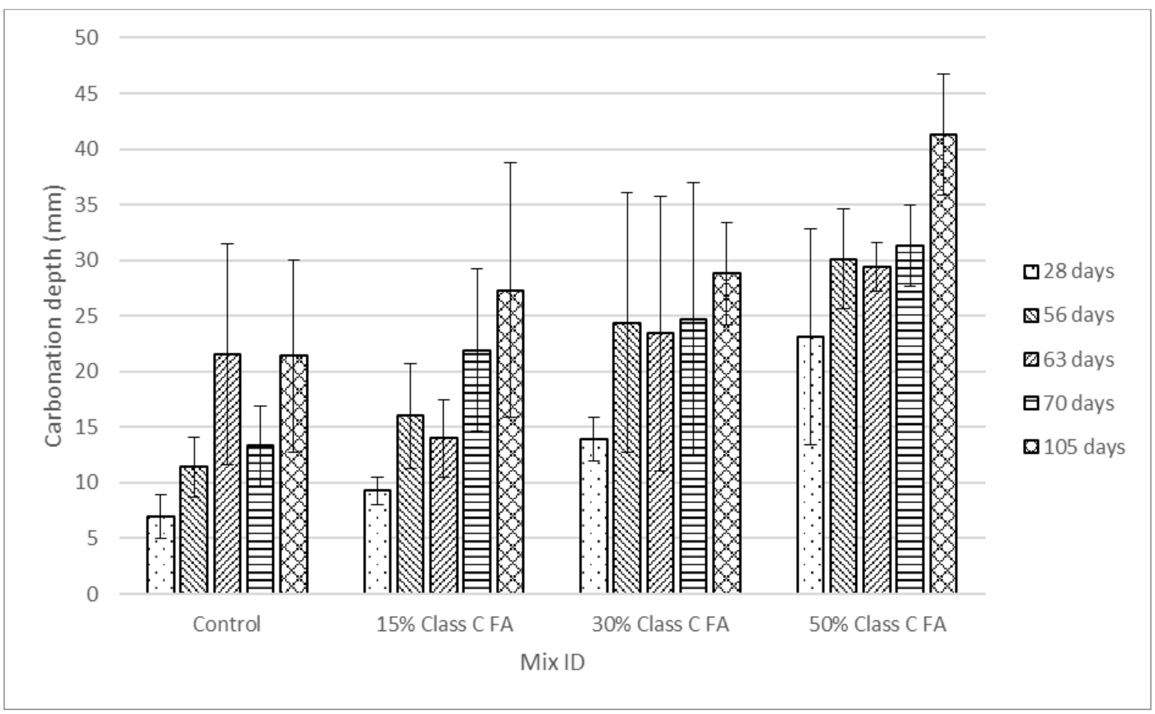


Figure 11. Comparison of Class C Fly Ash Specimens with Control (7-days curing)

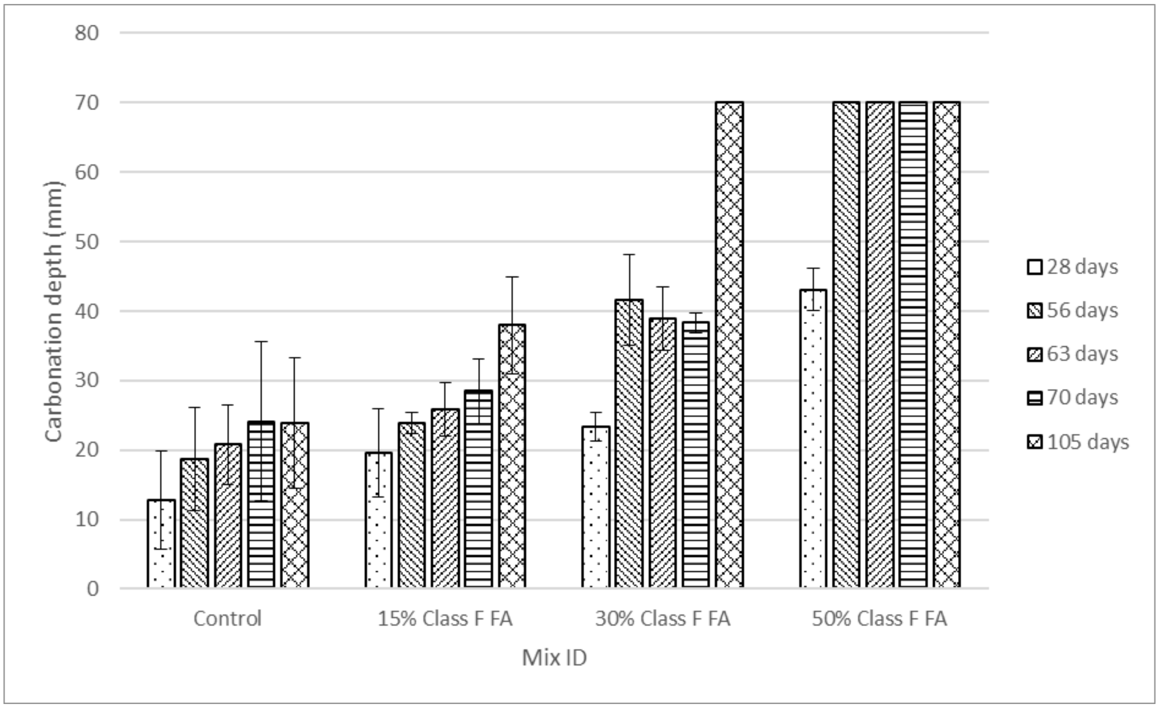


Figure 12. Comparison of Class F Fly Ash Specimens with Control (1-day curing)

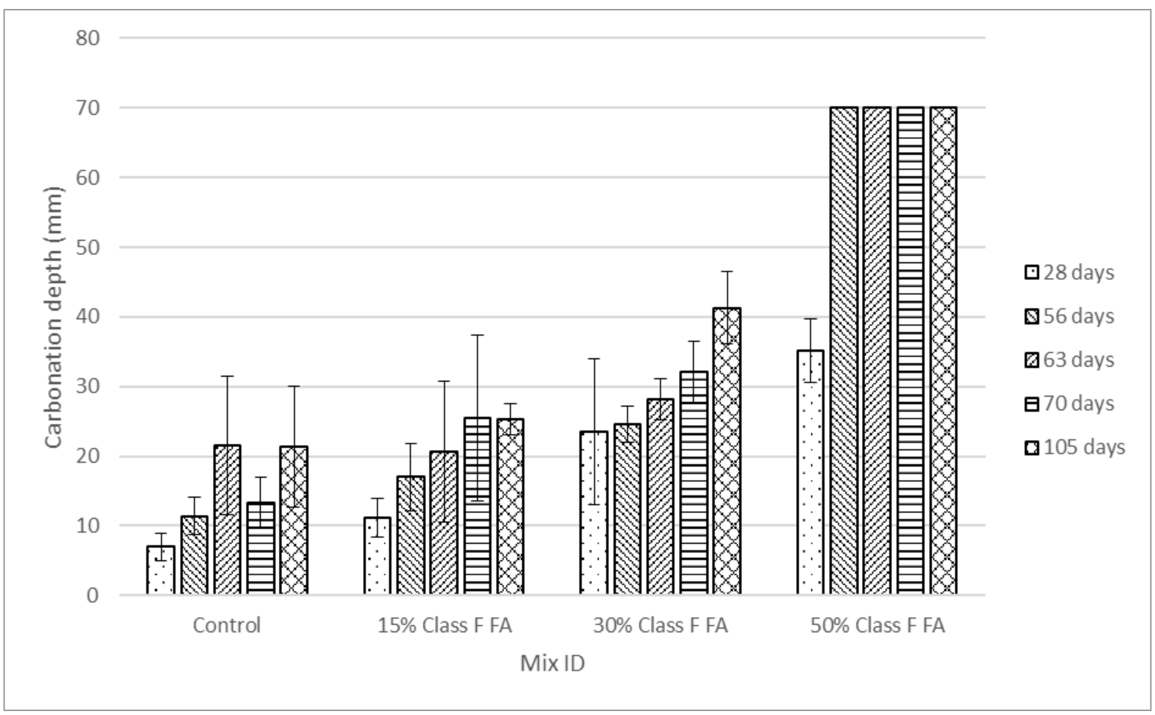


Figure 13. Comparison of Class F Fly Ash Specimens with Control (7-days curing)

Assessment based on moist curing

It was also observed that specimens with 1-day moist curing are more prone to carbonation ingress as compared with 7-day moist curing specimens. Figure 14 highlights the specimens with 0.45 w/cm ratio and 340 kg/m^3 cementitious content and it evident that longer moist curing period helps the concrete to improve resistance against carbonation. Figure 15 and 16 describes the effect of 1-day and 7-days moist curing on both class C and class F fly ash at different cementitious material concentrations.

Several such cases we tested, and it can be clearly inferred that specimens with 1-day moist curing highlights more carbonation depth as compared to specimens with 7 days of moist curing regardless of w/cm ratio or cementitious materials content.

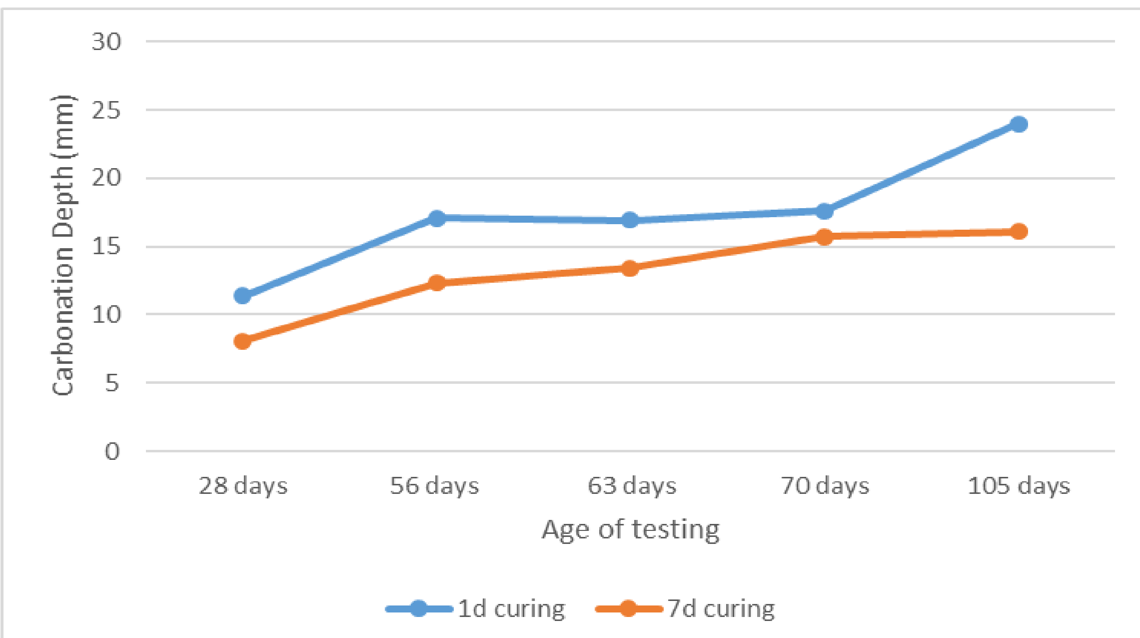


Figure 14. Comparison between 1-day and 7-days Curing for Control

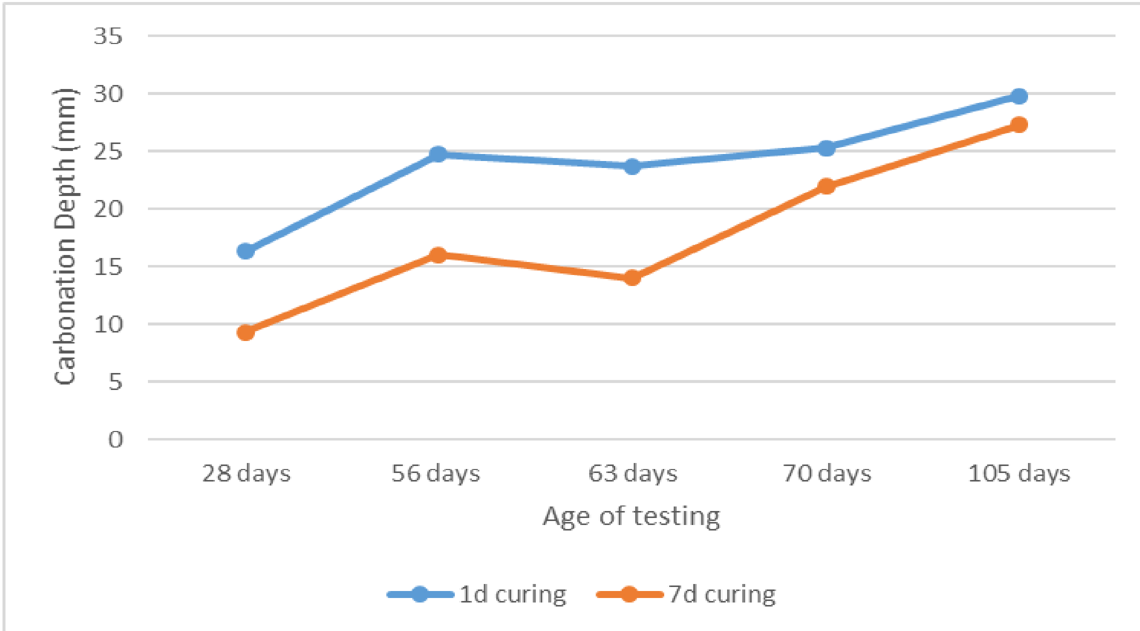


Figure 15. Comparison between 1-day and 7-days Curing for Class C Fly Ash

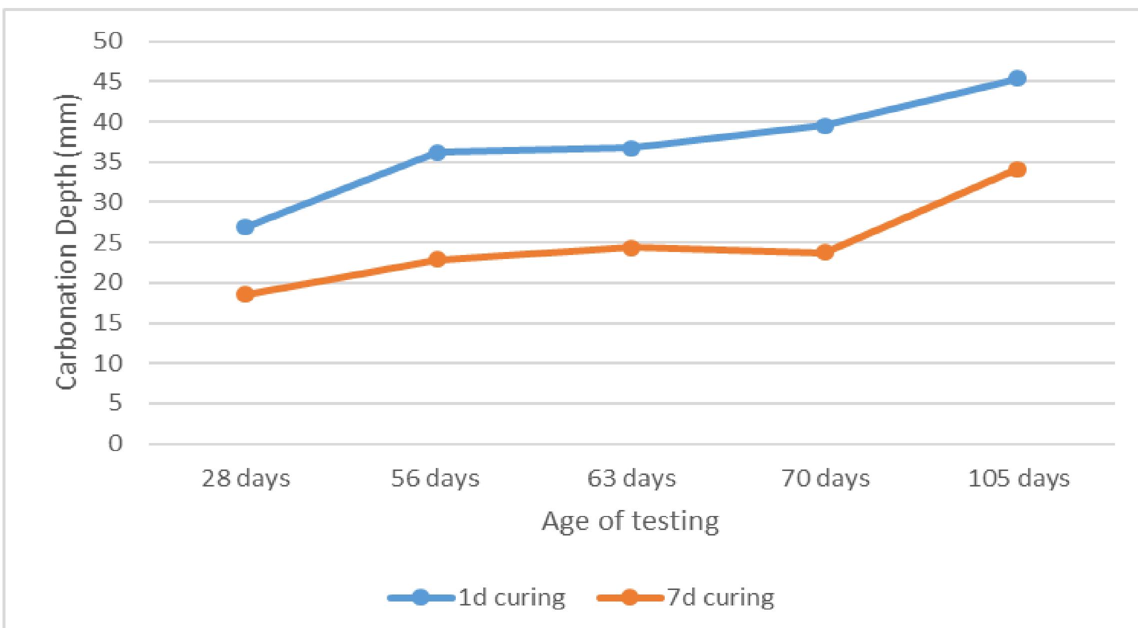


Figure 16. Comparison between 1-day and 7-days Curing for Class F Fly Ash

Comparison based on water-cementitious materials ratio

Previous studies suggested that with a decrease in water-cementitious material ratio the carbonation depth will also decrease since the concrete will be denser and less permeable. In the present study, a comparison between control mixes consisting of 0.50 and 0.45 w/cm ratio is demonstrated in Figure 17 and 18. In case of OPC control mixture, 0.5 w/cm ratio specimens indicated higher carbonation depths than 0.45 w/cm ratio specimens with 1-day and 7-days moist curing. Similarly, this trend was also observed in class C fly ash specimens. However, this pattern was not consistent throughout all days of testing. Class F fly ash specimens followed an identical trend however the difference between 0.50 and 0.45 w/cm ratio specimens was not significant.

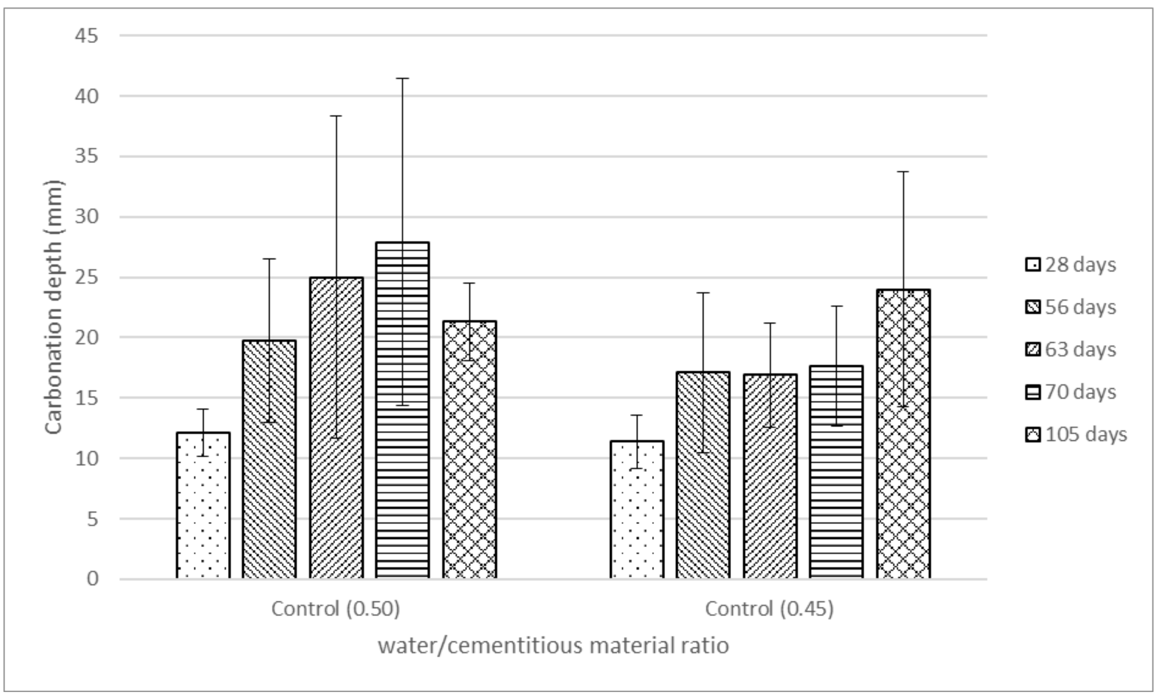


Figure 17. Comparison between 0.50 and 0.45 w/cm Ratio for Control (1-day curing)

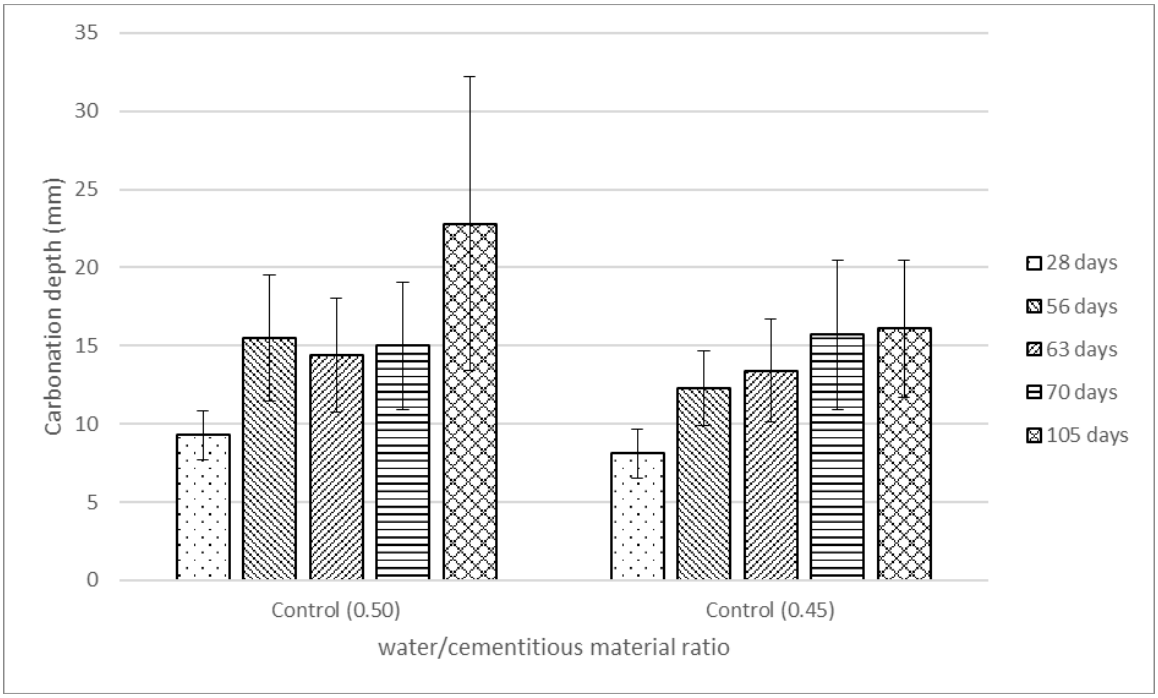


Figure 18. Comparison between 0.50 and 0.45 w/cm Ratio for Control (7-days curing)

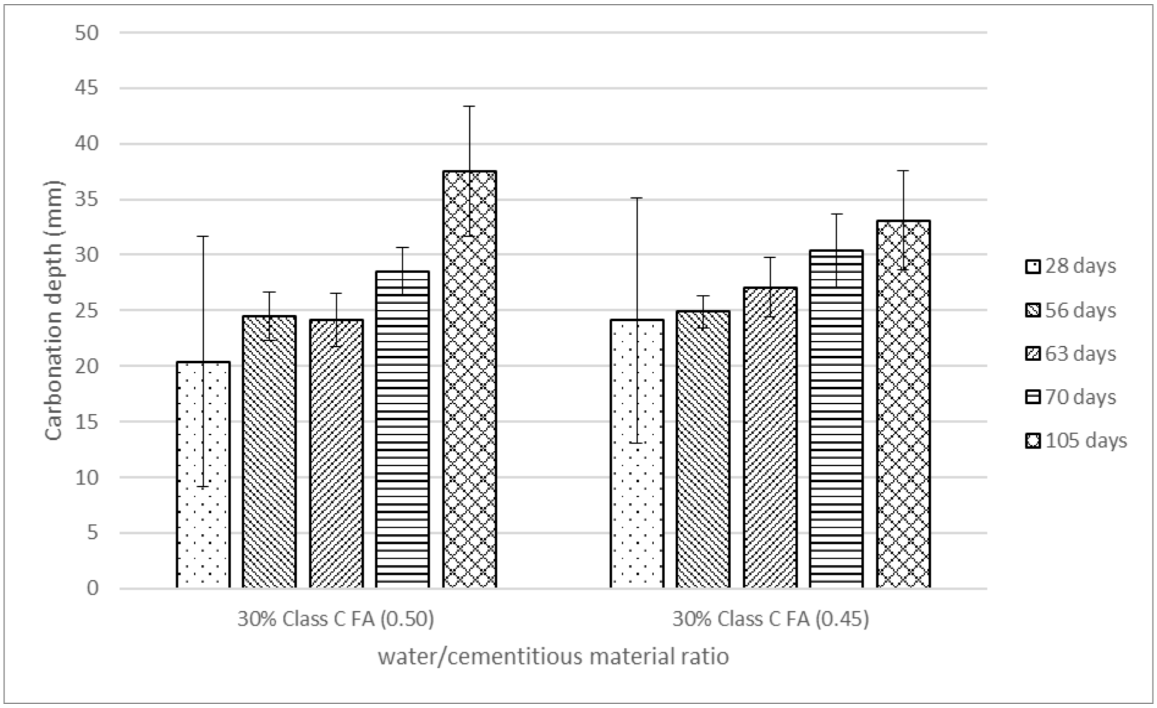


Figure 19. Comparison between 0.50 and 0.45 w/cm Ratio for Class C Fly Ash (1-day curing)

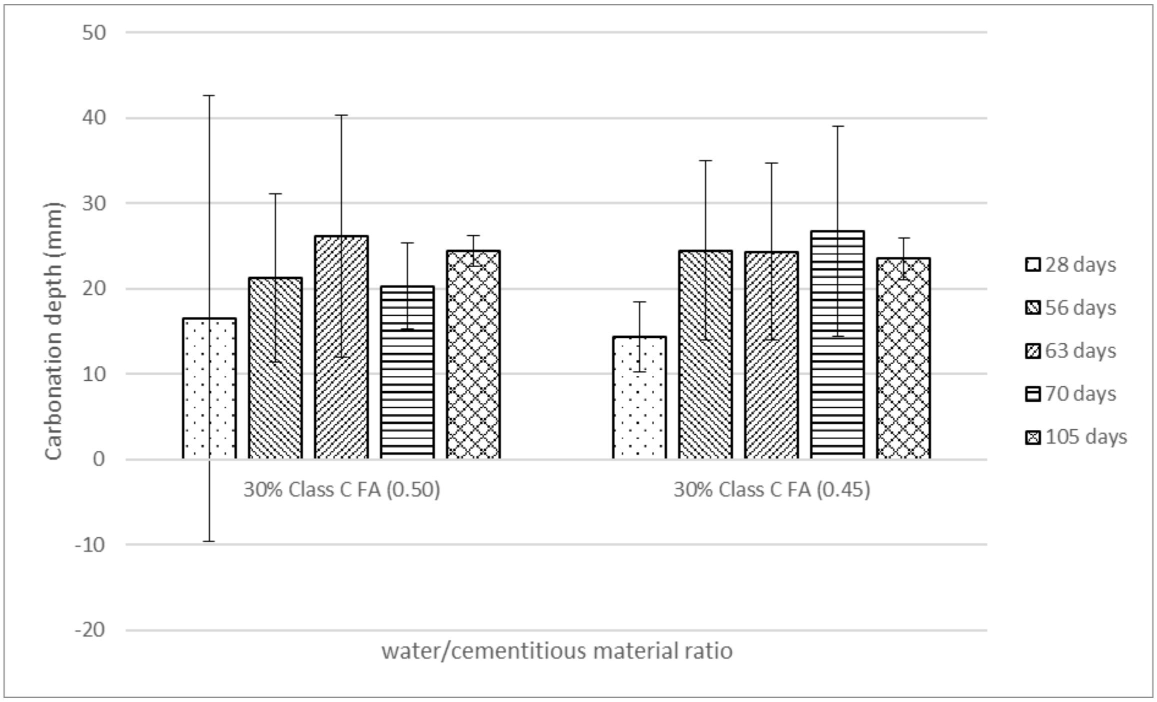


Figure 20. Comparison between 0.50 and 0.45 w/cm Ratio for Class C Fly Ash (7-days curing)

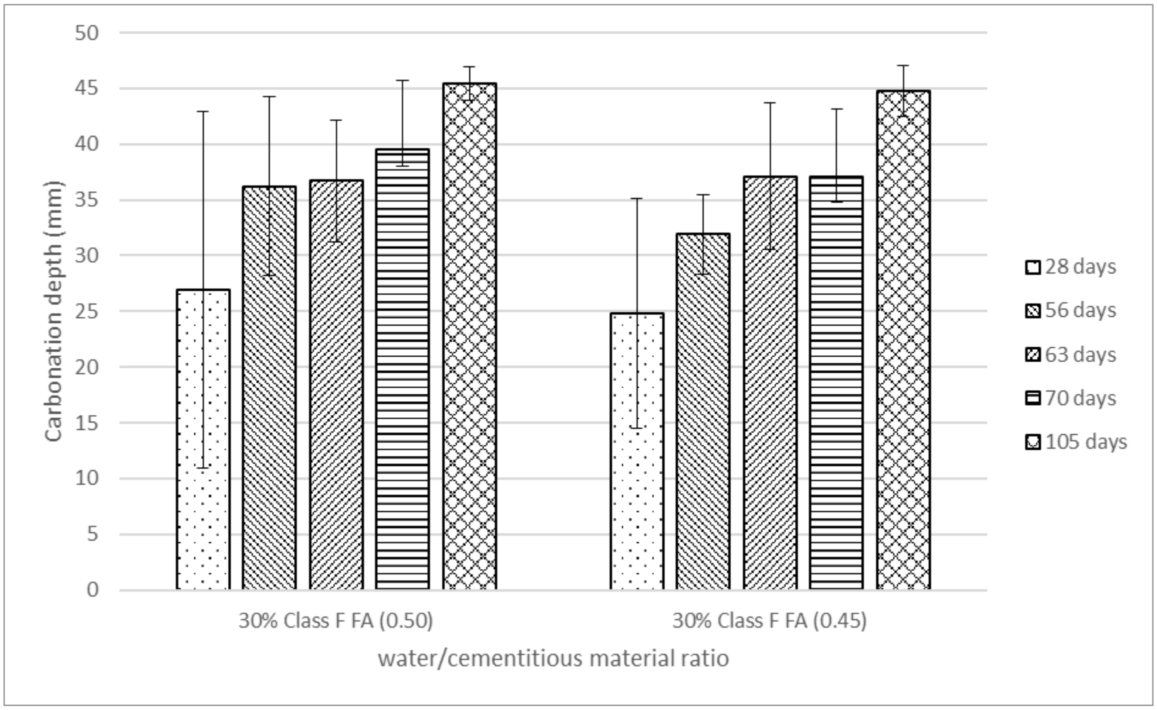


Figure 21. Comparison between 0.50 and 0.45 w/cm Ratio for Class F Fly Ash (1-day curing)

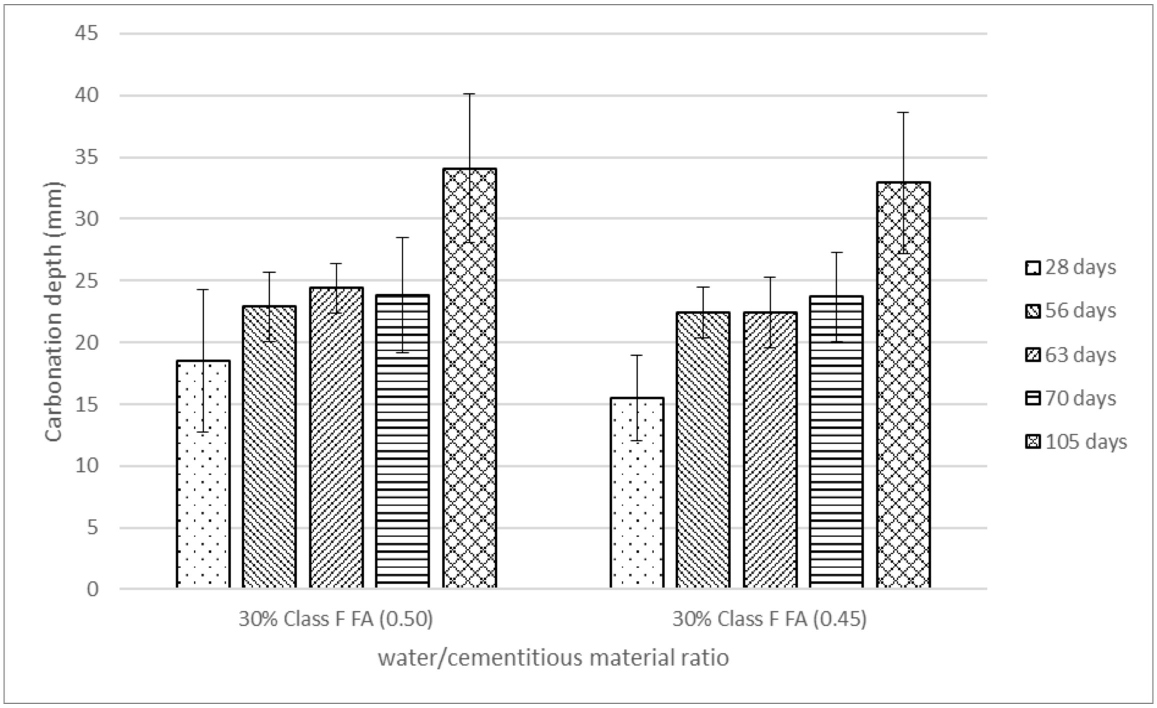


Figure 22. Comparison between 0.50 and 0.45 w/cm Ratio for Class F Fly Ash (7-days curing)

Comparison based on amount of cementitious material

A comparison between different cementitious contents was made at a given w/cm ratio and fly ash replacement. Figure 23 and 24 indicate the comparison between specimens consisting of 310, 340 and 400 kg/m^3 at 0.50 w/cm ratio with 1 and 7 days of moist curing respectively. These results indicated no significant differences between the carbonation depths. Since the difference is very small, it is difficult to establish any specific pattern from the results. However, in case of class C and class F fly ash concrete specimens a general trend can be observed that higher cementitious content specimens have more resistance against carbonation.

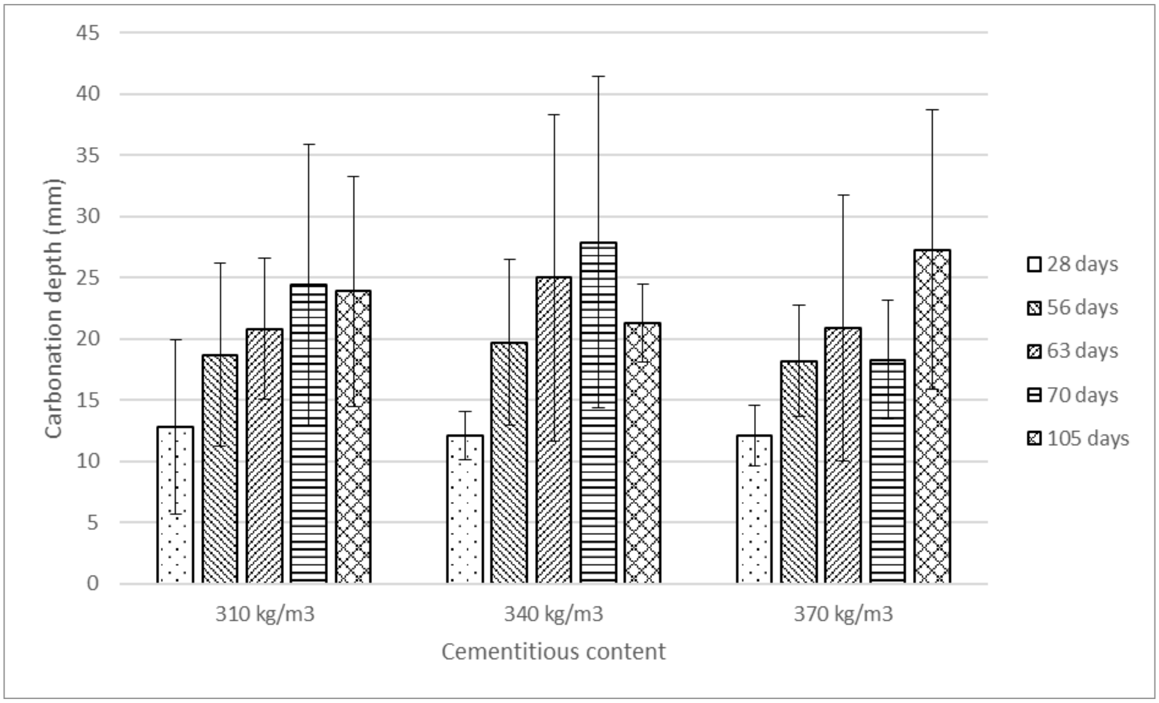


Figure 23. Comparison between 310, 340, and 370 kg/m^3 Cementitious Content for Control at 0.50 w/cm (1-day curing)

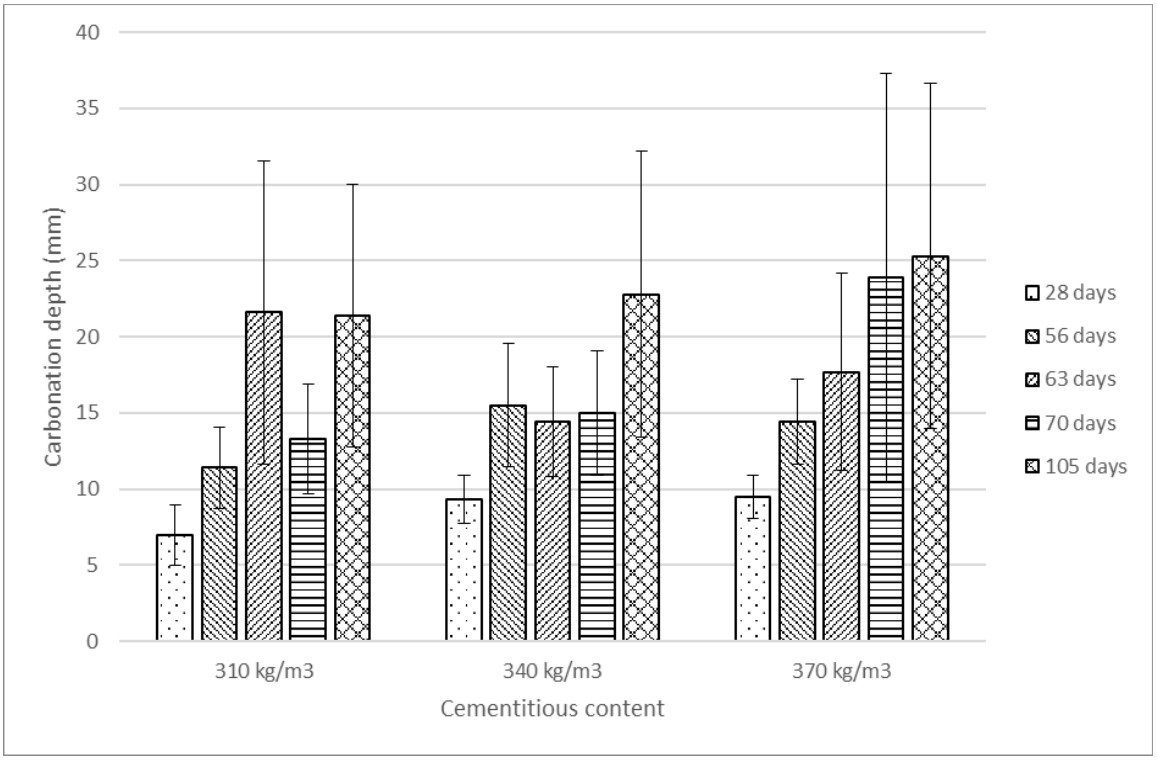


Figure 24. Comparison between 310, 340, and 370 kg/m^3 Cementitious Content for Control at 0.50 w/cm (7-days curing)

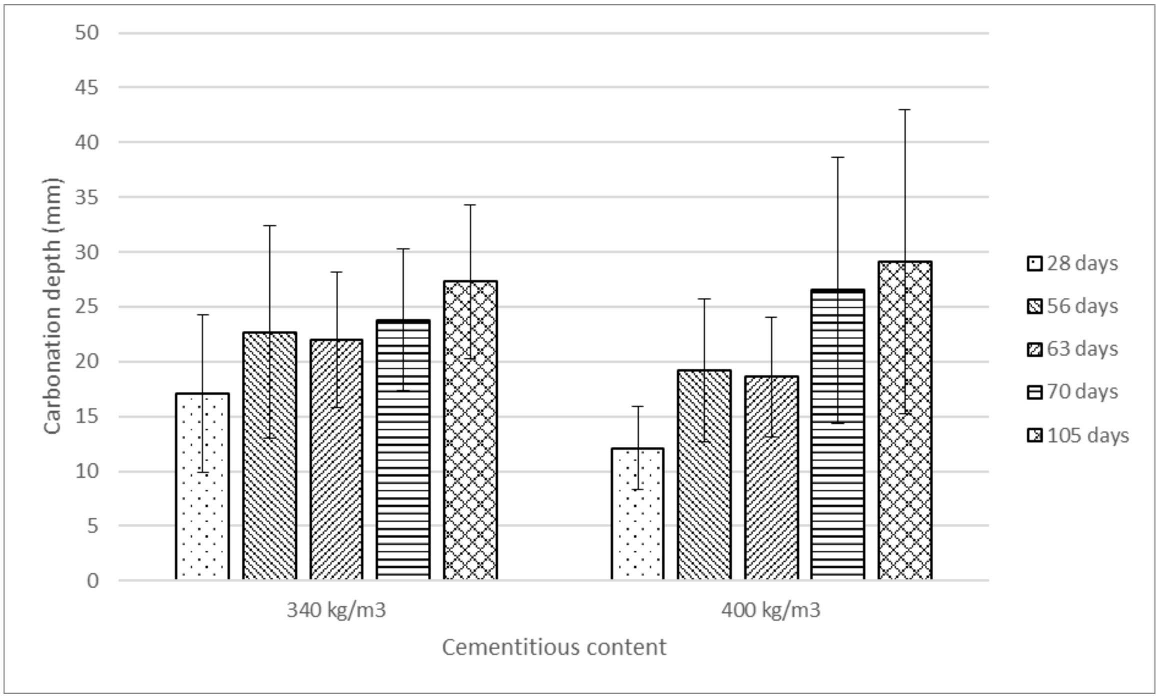


Figure 25. Comparison between 340 and 400 kg/m^3 Cementitious Content for Class C Fly Ash at 0.45 w/cm (1-day curing)

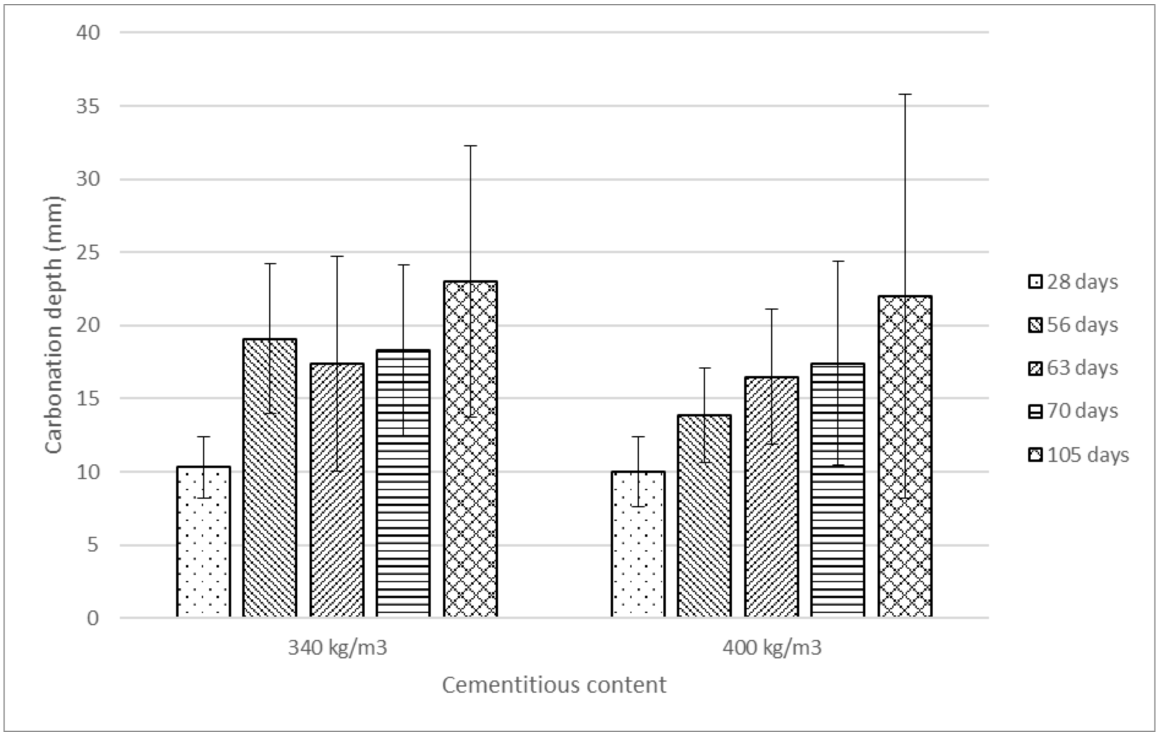


Figure 26. Comparison between 340 and 400 kg/m^3 Cementitious Content for Class C Fly Ash at 0.45 w/cm (7-days curing)

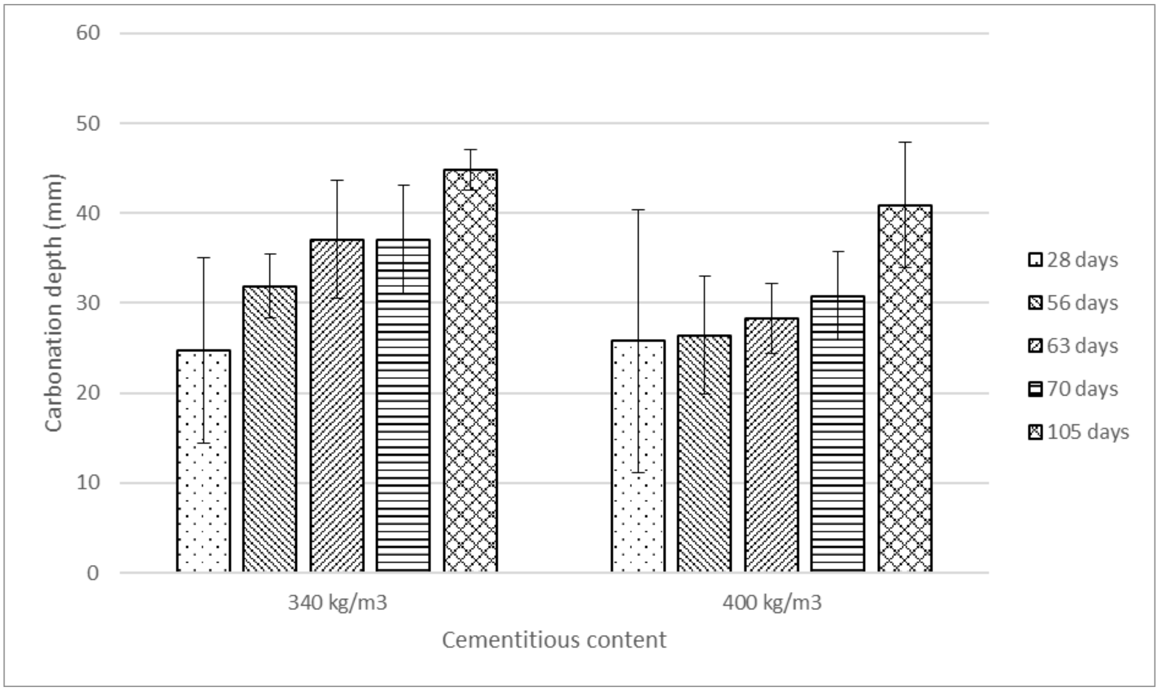


Figure 27. Comparison between 340 and 400 kg/m^3 Cementitious Content for Class F Fly Ash at 0.5 w/cm (1-day curing)

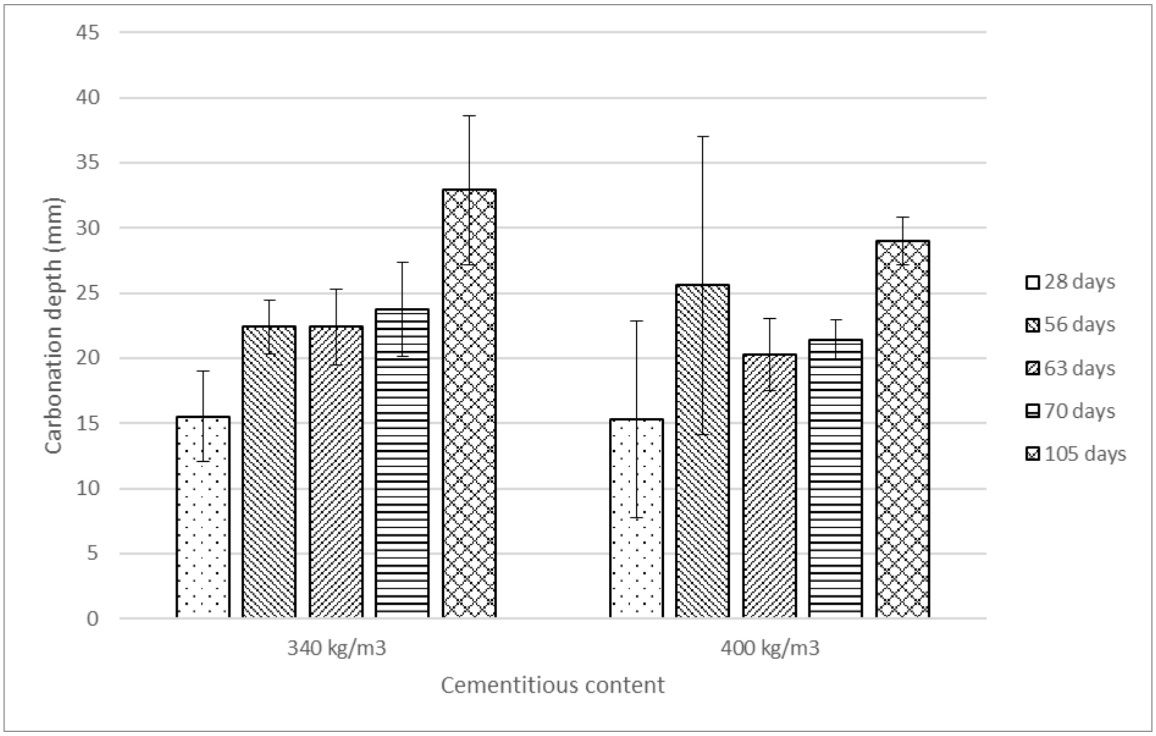
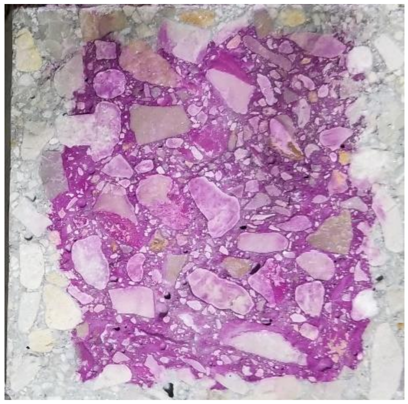


Figure 28. Comparison between 340 and 370 kg/m^3 Cementitious Content for Class F Fly Ash at 0.5 w/cm (7-days curing)

Comparison between Slag and Fly Ash

Lastly, GGBFS was also briefly tested for carbonation with replacement levels of 30 and 50% for cementitious content of 310 kg/m^3 and 0.5 w/cm ratio. It was observed that GGBFS offered more resistance against carbonation at given replacement levels as compared with both types of fly ash at the given replacement levels as represented below in Figure 29.



a. 310 kg/m^3, 0.5 w/cm, Control

b. 310 kg/m^3, 0.5 w/cm, 30% Class C fly ash

c. 310 kg/m^3, 0.5 w/cm, 30% Class F fly ash

d. 310 kg/m^3, 0.5 w/cm, 30% Slag

Figure 29. Pictorial and Results Comparison between Control, Fly Ashes, and Slag

Table 4. Carbonation Depth Comparison between Control, 30% Class C & F Fly Ash, and 30% Slag

	Control		30% Class C		30% Class F		30% Slag	
	1 d (mm)	***7 d (mm)***	***1 d (mm)***	***7 d (mm)***	***1 d (mm)***	***7 d (mm)***	***1 d (mm)***	***7 d (mm)***
28 d	12.8	7.0	20.8	13.9	23.3	23.5	18.8	10.8
56 d	18.7	11.4	30	24.4	41.6	24.6	21.6	16.4
63 d	20.8	21.6	32.3	23.4	38.9	28.2	25.4	16.2
70 d	24.1	13.3	36.2	24.7	38.3	32.1	23.3	18.2
105 d	23.9	21.4	40.1	28.8	70	41.3	26.3	17.1

Correlation between Compressive Strength and Carbonation

Several previous studies have established a correlation between compressive strength and depth of carbonation. Researchers claim that with an increase in compressive strength, the depth of carbonation decreases. A comparison between 2 days compressive strength and 28 days carbonation is demonstrated in Figure 30. It demonstrates a correlation between carbonation and compressive strength, and it can be inferred that with increase in compressive strength, carbonation decreases. However, no such correlation can be observed, and it cannot be said that greater compressive strength specimens offer better resistance against carbonation. Further, the correlation between 28-days compressive strength verses 105-days carbonation depths and 90-days compressive strength verses 105-days carbonation depths are shown in Figure 31 and 32 respectively. It can be concluded that this correlation gets weaker and weaker as the curing time for compression and carbonation increases.

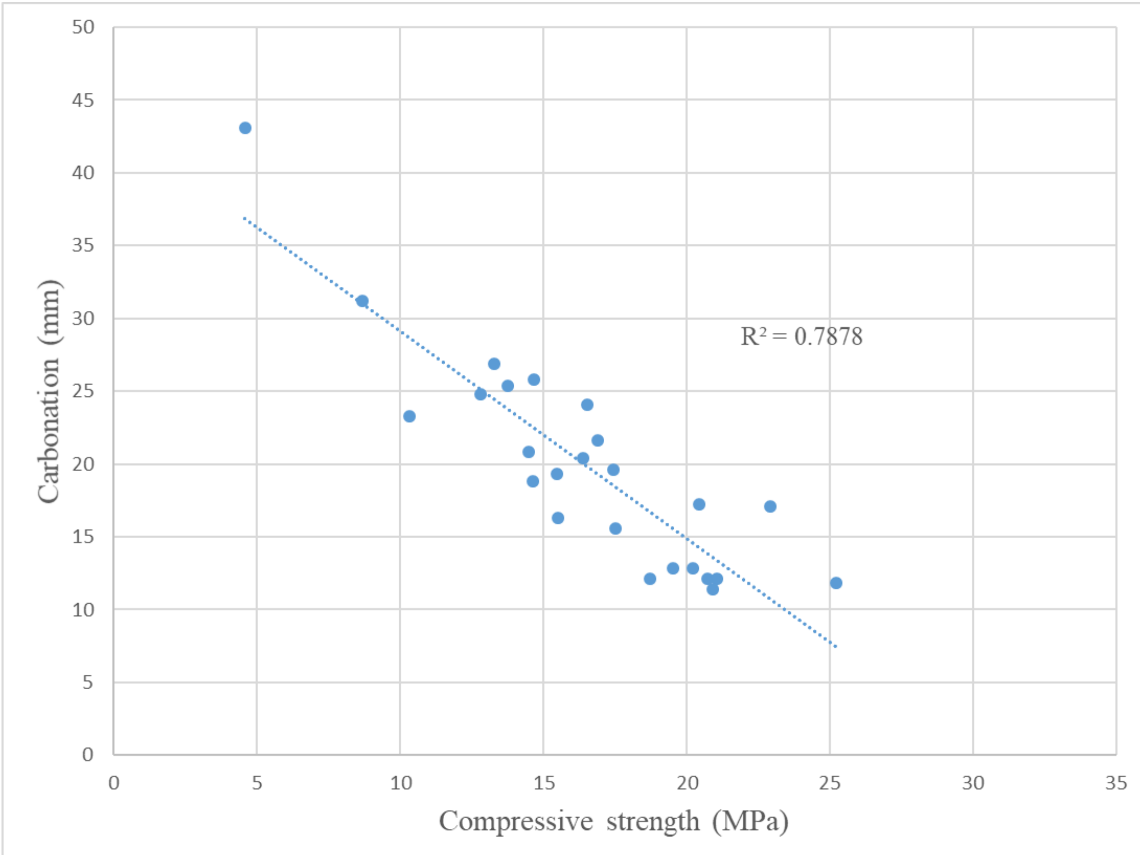


Figure 30. 2-days Compressive Strength vs 28-days Carbonation Depth

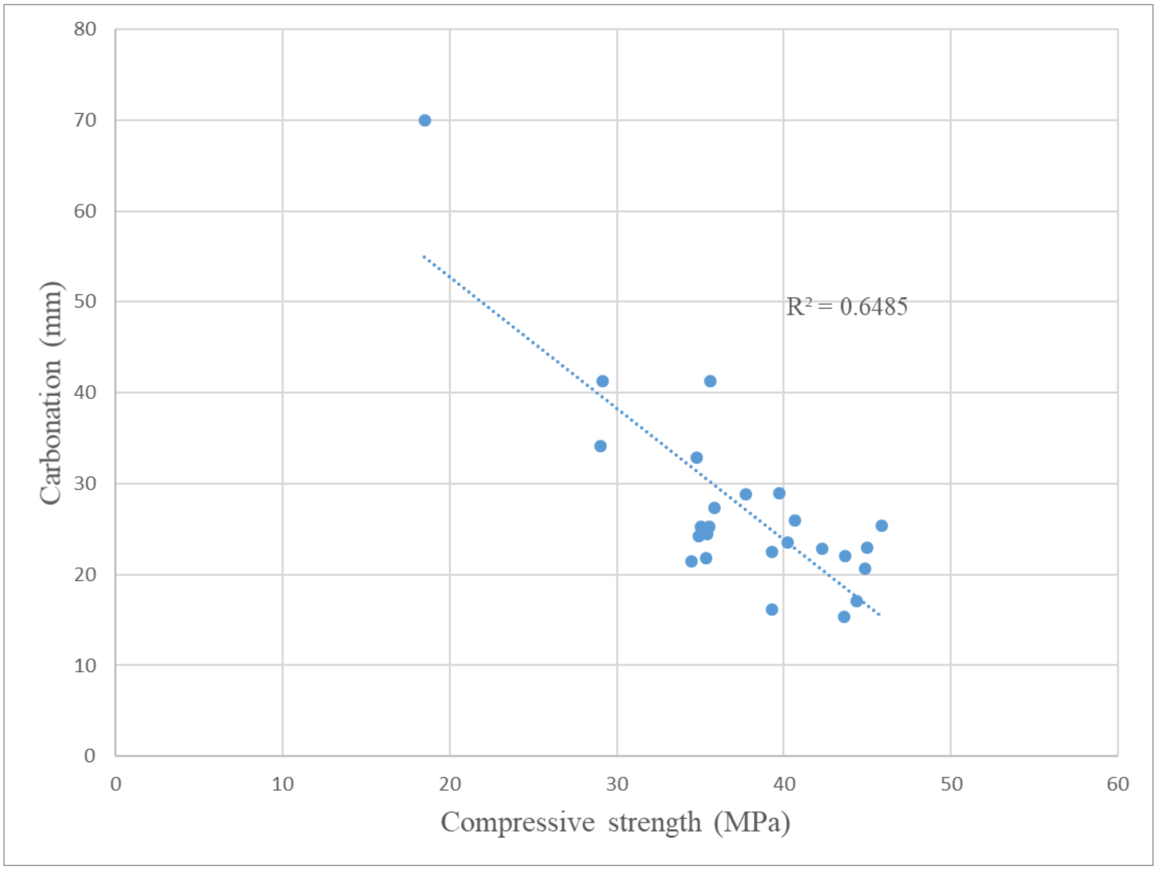


Figure 31. 28-days Compressive Strength vs 105-days Carbonation Depth

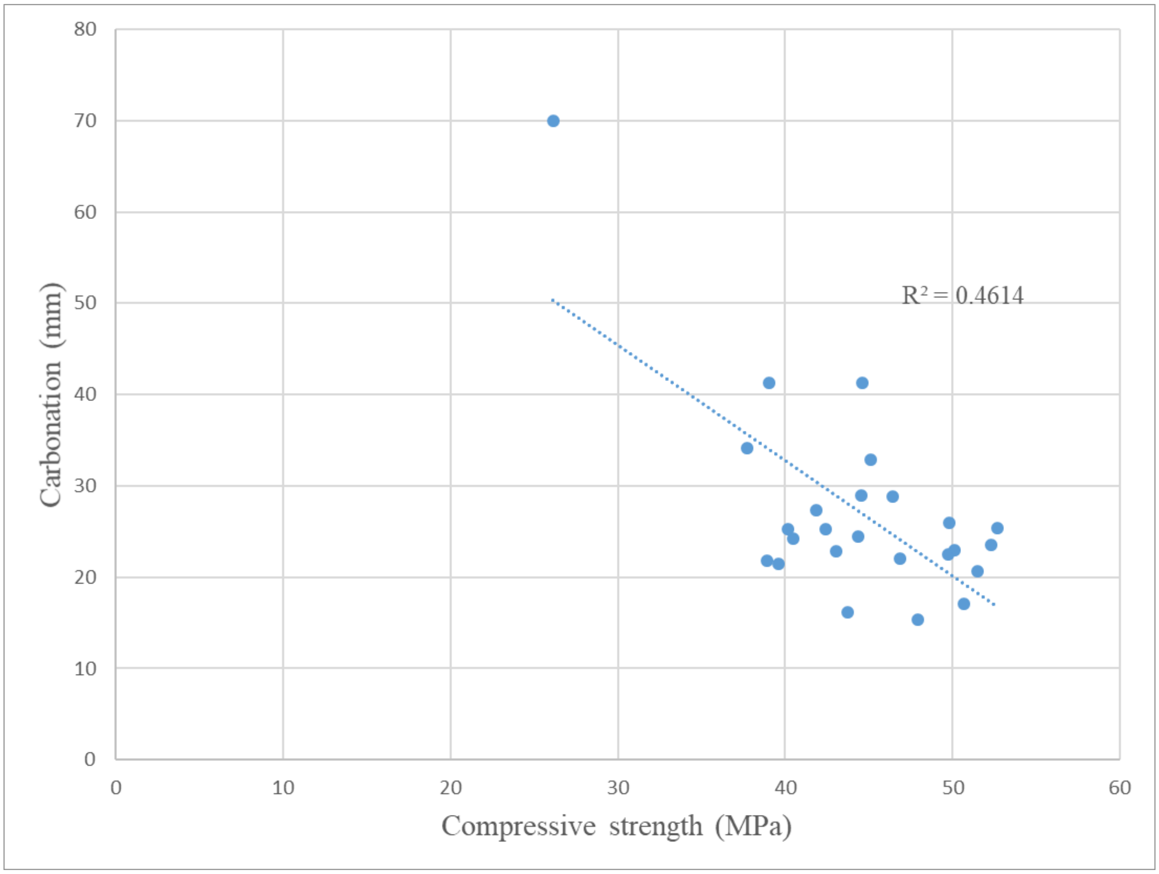


Figure 32. 90-days Compressive Strength vs 105-days Carbonation Depth

V. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn from the present study.

1. Regardless of the type of fly ash used, the depth of accelerated carbonation increased with an increase in fly ash content. Class C fly ash was more resistant against the threat of carbonation as compared to class F fly ash.
2. GGBFS offers greater resistance against carbonation at a given replacement percentage as compared with both types of fly ash. Additionally, it also yields greater compressive strengths (7, 28, and 90 d) as compared to class C, class F fly ash and control mix.
3. The depth of accelerated carbonation decreased as the moist curing period increased from 1 to 7 days.
4. Accelerated carbonation was decreased with a decrease in water-cementitious material ratio from 0.5 to 0.45 in case of control mixes. However, no clear pattern was observed in case of fly ash concrete mixes.
5. Cementitious content did not seem to affect the carbonation severely and no fixed pattern can be determined from the results for control mixes. In case of class C and class F fly ashes, increase in cementitious content seemed to have a positive effect against carbonation.
6. Better compressive strength results were obtained with mixtures containing SCMs at 0.45 w/cm ratio as compared to 0.5 w/cm ratio at a given cementitious content.

The following future recommendations are proposed.

1. Accelerated carbonation results can be compared with natural carbonation and a model can be established to relate the two methods.
2. Future studies can explore the results at different relative humidity and at different CO_2 concentrations.
3. GGBFS resistance against carbonation was observed to be better as compared to fly ash in this study. A detailed investigation with GGBFS used as a SCM can be useful information.
4. Effect of moist curing was clearly evident in this study. Future researchers can investigate this effect at extended moist curing periods along with different w/cm ratios.

APPENDIX SECTION

Carbonation Results

310 kg/m3, Control, 0.5 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
	10.5	40.5	38.5	43.5	57.5		7	13	29	16	21
	10.5	14.5	17.5	17	25		6.5	10.5	17	14	16
Face 1	8	15.5	16	15.5	22	**Face 1**	7.5	8	15	12.5	20
	9.5	12.5	14.5	16.5	20		8	7	17.5	11	17
	40	33	27	31.5	NA		8.5	11.5	34	17	25
	12.5	25	24	23.5	NA		11.5	14	38.5	19.5	43
	17	15	17.5	17	20.5		5.5	10	19.5	19	15
Face 2	8	15.5	23	17.5	24.5	**Face 2**	6	9	14.5	18.5	14.5
	10	12.5	21.5	22	21.5		8.5	11.5	11	11.5	17
	13	26	22	56	23		4.5	10	19.5	11	20
	9	21	19	45.5	20		5.5	9	29.5	10	25
	11	11	18	20.5	18.5		8	15	13	12.5	17.5
Face 3	6	9.5	17.5	20.5	18	**Face 3**	5	11	11	9	18
	7	19	14	17	16.5		4	10.5	17.5	7	20
	16.5	20	30.5	18.5	35		8	16.5	41	16.5	22.5
	18	19.5	22	20.5	24.5		7	10.5	18	16	45
	14.5	12.5	15.5	14	17		3	13	17	8	13.5
Face 4	9.5	13	17	15	19	**Face 4**	9.5	15	14.5	11.5	12.5
	10	18.5	19	20.5	24		8	7.5	12.5	11	15
	16	19.5	22	35.5	NA		8	15	42	14.5	30

310 kg/m3, 15% Class C, 0.5 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
Face 1	11	NA	NA	NA	NA	**Face 1**	11	20	14	39.5	44
	15	22	25.5	26	27		11.5	20.5	15.5	17.5	24
	13.5	22	22.5	21.5	23.5		10.5	17	13	24.5	17.5
	14.5	20.5	23	24	31		9.5	15.5	10	21.5	23.5
	26	NA	NA	NA	NA		9	18.5	24.5	33	NA
Face 2	14.5	NA	NA	NA	NA	**Face 2**	9.5	31	18.5	17.5	NA
	14.5	23	23	24	33		8	14	15	17	31
	19	22.5	24.5	24.5	29		8.5	14.5	9.5	17	21.5
	16.5	26	21.5	21	32.5		9	15	11	16.5	25
	18.5	NA	NA	NA	NA		10	17	13	19	58.5
Face 3	15.5	NA	NA	NA	NA	**Face 3**	9	12	12	NA	NA
	13	26	23	28	33		8.5	11.5	11	17	25
	19.5	17.5	21.5	29	28		7	9.5	10	18	22
	17	19.5	23	29.5	31.5		8.5	10.5	11.5	15.5	21
	19	NA	NA	NA	NA		11.5	13	16.5	35	42
Face 4	15.5	51.5	NA	NA	NA	**Face 4**	11	15.5	17.5	33	NA
	12.5	22	26	23.5	31.5		8	13.5	13	18	20
	15	24.5	27	24	27.5		8.5	13.5	16	16	15
	17	23.5	23.5	28	29.5		8	16.5	12.5	17	20
	18.5	NA	NA	NA	NA		9	21.5	15	23.5	NA

310 kg/m3, 30% Class C, 0.5 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
Face 1	NA	NA	NA	NA	NA	**Face 1**	17	20.5	NA	NA	NA
	21.5	27	34	45.5	NA		11.5	19	18	24	24
	20	25.5	27	30	42		12	17	16.5	18	20
	22.5	31.5	30.5	40.5	NA		11.5	16	22.5	18.5	30
	NA	NA	NA	NA	NA		16	NA	NA	NA	NA
Face 2	NA	NA	NA	NA	NA	**Face 2**	15.5	27	64.5	NA	NA
	18.5	33.5	29.5	38	NA		15	18	18.5	21	29
	17.5	31.5	31	33	41.5		15	21	20	22	28.5
	18.5	30.5	33	31.5	40		10.5	22	21.5	20.5	30
	NA	NA	NA	NA	NA		11	38	NA	68.5	NA
Face 3	NA	NA	NA	NA	NA	**Face 3**	13	NA	NA	NA	NA
	22	31	35.5	NA	NA		14.5	21	14.5	21	40
	21	29	31	34.5	39		14	18	22	19.5	28
	24	28	38	38.5	NA		14	17.5	19.5	19	30
	NA	NA	NA	NA	NA		17	60.5	NA	NA	NA
Face 4	NA	NA	NA	NA	NA	**Face 4**	14.5	27.5	NA	25.5	NA
	19.5	31.5	34.5	39	NA		17	17.5	19.5	23	25
	21	31.5	30.5	30	38		14	17.5	17	22	31.5
	23	29	33.5	38	NA		12	16	17.5	23.5	30
	NA	NA	NA	NA	NA		13	46	35.5	NA	NA

310 kg/m3, 50% Class C, 0.5 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
Face 1	NA	NA	NA	NA	NA	**Face 1**	NA	NA	NA	NA	NA
	35.5	NA	NA	NA	NA		18	25	30	28	NA
	26	53.5	NA	NA	NA		15.5	23	25.5	26.5	30
	29.5	NA	NA	NA	NA		20.5	26	28	32.5	45
	NA	NA	NA	NA	NA		NA	NA	NA	NA	NA
Face 2	NA	NA	NA	NA	NA	**Face 2**	43	NA	NA	NA	NA
	31	NA	NA	NA	NA		20.5	30	27.5	30	45
	28.5	NA	NA	NA	NA		17.5	27.5	29.5	32.5	40
	32	NA	NA	NA	NA		18.5	37.5	30.5	35.5	45
	NA	NA	NA	NA	NA		NA	NA	NA	NA	NA
Face 3	NA	NA	NA	NA	NA	**Face 3**	NA	NA	NA	NA	NA
	33.5	NA	NA	NA	NA		21	36	31	40	40
	27.5	46	NA	NA	NA		19.5	29	26.5	32	35
	34	NA	NA	NA	NA		21	33.5	32.5	32.5	NA
	NA	NA	NA	NA	NA		51.5	NA	NA	NA	NA
Face 4	NA	NA	NA	NA	NA	**Face 4**	NA	NA	NA	NA	NA
	34	NA	NA	NA	NA		21.5	34	33	30	50
	29	NA	NA	NA	NA		18	26.5	28.5	28.5	42.5
	33.5	NA	NA	NA	NA		18.5	33.5	30.5	27	40
	NA	NA	NA	NA	NA		22.5	NA	NA	NA	NA

310 kg/m3, 15% Class F, 0.5 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
	31.5	NA	NA	NA	NA		11.5	25.5	38	59	NA
	17.5	25.5	27.5	32	50		8.5	15.5	16	18	27.5
Face 1	14	24	27	29	35	**Face 1**	9.5	14	14.5	16	23
	16.5	26	32	30.5	50		9.5	17.5	15	17.5	22
	29	NA	NA	NA	NA		15.5	18	47	41	NA
	23.5	NA	NA	NA	NA		14.5	28.5	28	37	NA
	15.5	24.5	32	31	40		9.5	10.5	18	21.5	23
Face 2	14	25	23	25.5	30	**Face 2**	14	26.5	15.5	15.5	24
	15	22	23.5	36	28		15	16	17.5	18	30
	21	NA	NA	NA	NA		9	19	20	18.5	NA
	33	NA	NA	NA	NA		14	22	44.5	41	NA
	13	26.5	20.5	36.5	33.5		15.5	13.5	17.5	18.5	28
Face 3	14.5	23.5	21.5	26.5	32.5	**Face 3**	9.5	14	16	15	27
	15.5	21.5	29	23.5	40		12.5	14	14	17	25
	24	NA	NA	NA	NA		9.5	16.5	10	22	NA
	20.5	NA	NA	NA	NA		5	13	15	42	NA
	15	23.5	24	23	45		10.5	14	14.5	18.5	25
Face 4	14.5	22.5	22	21.5	34	**Face 4**	8.5	13.5	17	20.5	24.5
	15	22.5	28.5	27	38		11	14	17	19.5	25
	29.5	NA	NA	NA	NA		11.5	14.5	19.5	32	NA

310 kg/m3, 30% Class F, 0.5 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
Face 1	NA	NA	NA	NA	NA	**Face 1**	57.5	NA	NA	NA	NA
	24.5	NA	NA	NA	NA		20	24	32	34.5	NA
	22.5	33.5	38	39	NA		14.5	20.5	26.5	34	40
	24	51.5	NA	NA	NA		15	24.5	30.5	34	NA
	NA	NA	NA	NA	NA		24.5	NA	NA	NA	NA
Face 2	NA	NA	NA	NA	NA	**Face 2**	24	NA	NA	NA	NA
	24	NA	NA	NA	NA		15.5	25	31.5	37	NA
	20.5	46.5	35.5	36	NA		16	25.5	28	28	37.5
	21	NA	NA	NA	NA		19.5	22.5	31	40	NA
	NA	NA	NA	NA	NA		31.5	NA	NA	NA	NA
Face 3	NA	NA	NA	NA	NA	**Face 3**	26	NA	NA	NA	NA
	24.5	48.5	NA	NA	NA		17	23.5	23.5	37.5	NA
	22.5	34.5	46.5	40	NA		16.5	21.5	26	29.5	50
	28	NA	NA	NA	NA		14.5	29.5	29.5	27	NA
	NA	NA	NA	NA	NA		28.5	NA	NA	NA	NA
Face 4	NA	NA	NA	NA	NA	**Face 4**	34.5	NA	NA	NA	NA
	24	NA	NA	NA	NA		16	26.5	30.5	28	NA
	20.5	38	35.5	38	NA		21	24	23.5	26.5	37.5
	24	39	NA	NA	NA		19	28.5	26	29	NA
	NA	NA	NA	NA	NA		39.5	NA	NA	NA	NA

310 kg/m3, 50% Class F, 0.5 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
Face 1	NA	NA	NA	NA	NA	**Face 1**	NA	NA	NA	NA	NA
	NA	NA	NA	NA	NA		39.5	NA	NA	NA	NA
	47	NA	NA	NA	NA		32	NA	NA	NA	NA
	NA	NA	NA	NA	NA		37.5	NA	NA	NA	NA
	NA	NA	NA	NA	NA		NA	NA	NA	NA	NA
Face 2	NA	NA	NA	NA	NA	**Face 2**	NA	NA	NA	NA	NA
	NA	NA	NA	NA	NA		40	NA	NA	NA	NA
	41	NA	NA	NA	NA		29.5	NA	NA	NA	NA
	NA	NA	NA	NA	NA		36	NA	NA	NA	NA
	NA	NA	NA	NA	NA		NA	NA	NA	NA	NA
Face 3	NA	NA	NA	NA	NA	**Face 3**	NA	NA	NA	NA	NA
	NA	NA	NA	NA	NA		44.5	NA	NA	NA	NA
	39.5	NA	NA	NA	NA		31	NA	NA	NA	NA
	NA	NA	NA	NA	NA		31.5	NA	NA	NA	NA
	NA	NA	NA	NA	NA		NA	NA	NA	NA	NA
Face 4	NA	NA	NA	NA	NA	**Face 4**	NA	NA	NA	NA	NA
	NA	NA	NA	NA	NA		32.5	NA	NA	NA	NA
	45	NA	NA	NA	NA		29.5	NA	NA	NA	NA
	NA	NA	NA	NA	NA		38	NA	NA	NA	NA
	NA	NA	NA	NA	NA		NA	NA	NA	NA	NA

310 kg/m3, 30% Slag, 0.5 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
Face 1	27	NA	NA	NA	NA	**Face 1**	10	16	17	45	NA
	12.5	23	30.5	25	25		12	16.5	16	14.5	15
	9.5	18	22.5	27	20		13.5	18	16	18.5	15
	17.5	17.5	24	21.5	30		17	16	13	13	16.5
	31.5	NA	NA	NA	NA		11	19.5	31	21.5	NA
Face 2	21	NA	NA	NA	NA	**Face 2**	13	23	31.5	47	NA
	14.5	19	25	20.5	35		12	15	17	15	20
	11	18.5	30.5	21	29.5		10.5	16	19.5	16	15
	17	21	24	26	27.5		12	13	12	14.5	17.5
	18.5	NA	NA	NA	NA		8.5	14.5	11	10	25
Face 3	18	NA	NA	NA	NA	**Face 3**	12	27.5	12.5	15	NA
	17.5	21.5	28	25.5	22.5		8.5	14.5	16	13	20
	17	24.5	27	24.5	24		8.5	13	14	10.5	9.5
	18	27.5	22	25	30		10	16	16.5	15	5.5
	22.5	NA	NA	NA	NA		10.5	15.5	10.5	12	NA
Face 4	20.5	NA	NA	NA	NA	**Face 4**	9.5	19	13	14.5	20
	24	24.5	24	23.5	25		11	15.5	15	15	20
	18	22.5	21.5	19.5	25		8	13	12	16.5	25
	17	22	25.5	21	22.5		8.5	14	13.5	17	15
	23	NA	NA	NA	NA		10.5	11.5	16	20	NA

310 kg/m3, 50% Slag, 0.5 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
	41	63.5	NA	NA	NA		11	15	20	26	30
	20.5	24.5	30	28	60		11.5	12.5	16	17	21
Face 1	19	26	27	24.5	30	**Face 1**	11	17.5	18	17.5	20
	19.5	28	24	35	50		13.5	14	17.5	17.5	17.5
	50.5	62.5	NA	NA	NA		12	28.5	27.5	28.5	30
	NA	NA	NA	NA	NA		15.5	26	29	19.5	21
	20	22	28.5	34	40		11.5	8	9	17.5	15
Face 2	16	20	18	28	35	**Face 2**	7.5	10	14.5	14	20
	19.5	17	20	24	35		3	16.5	9.5	14	20
	33.5	NA	NA	NA	NA		13	27	16	11.5	30
	43.5	29.5	NA	NA	NA		14.5	36.5	13	14.5	32
	16	22	20.5	25.5	35		10.5	16	11	13	14
Face 3	19	28	20	27	27.5	**Face 3**	10	12	13	16.5	15
	17.5	21	27	25	20		15.5	13.5	13.5	13.5	16
	46.5	38	NA	NA	NA		10.5	26	13	25	12
	23.5	NA	NA	NA	NA		9.5	23.5	15	22.5	20
	17.5	21.5	18	28	30		9	14.5	15.5	18	15
Face 4	15.5	25	20	26	40	**Face 4**	9	11.5	17	18.5	20
	18.5	21	26.5	30.5	35		7.5	9	16.5	22.5	15
	NA	NA	NA	NA	NA		9	17.5	25	27	30

340 kg/m3, Control, 0.5 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
	13	24.5	41	58	NA		8.5	11	18.5	23	40
	11.5	14.5	17	17.5	15		10	14	8	13	15
Face 1	11	17	16.5	17	18.5	**Face 1**	7	12.5	12.5	10.5	15
	14	14.5	18	17	21.5		8	13	12.5	10.5	15
	16.5	36.5	25.5	41	NA		7.5	18.5	22	21	30
	16.5	31.5	27.5	44	NA		11	23	19.5	24	30
	10.5	19.5	20.5	19.5	25		8.5	12.5	11.5	12	16
Face 2	12	17	24	21	20	**Face 2**	8	14	15.5	13.5	13.5
	10	16	18	17	22.5		8	14	12	16.5	15.5
	11.5	24	22	36	NA		12	18.5	11	13.5	20
	13.5	23	71	59	NA		9	22	14.5	15	40
	13	13	18	20.5	25		8	12	15	10.5	16
Face 3	11.5	18	17	15.5	23	**Face 3**	10.5	12.5	14	15.5	14.5
	11	13.5	15.5	17.5	25		10.5	10	9.5	10.5	20
	12	28	46	40.5	NA		8.5	21	15	13.5	35
	8.5	21	28.5	25.5	NA		12.5	23	18	11.5	40
	11	12.5	19.5	20	22		11.5	14	12.5	15.5	18
Face 4	11.5	12	11.5	20	21.5	**Face 4**	9.5	11.5	12	15	15
	13	12	17.5	19	16		9	15	14	13.5	19.5
	10.5	25.5	24.5	33	NA		7.5	17.5	20.5	21	28

340 kg/m3, 30% Class C, 0.5 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
Face 1	38	NA	NA	NA	NA	**Face 1**	8.5	23	NA	NA	NA
	18.5	27	26	29	41		9	15.5	18.5	17.5	23
	19	25.5	25	27.5	34		10	14.5	18	20	23.5
	18	26	27.5	31	47.5		9.5	18	16	14.5	29.5
	61.5	NA	NA	NA	NA		13	19	32	25	NA
Face 2	NA	NA	NA	NA	NA	**Face 2**	12	24	26	32.5	NA
	19.5	24.5	27	29.5	46		11	17	16	19	25.5
	20	29	25	28.5	29		130	19	20	18	25
	15	24	27.5	28.5	34		12	19.5	20	17.5	22
	12	NA	NA	NA	NA		12.5	38	28.5	NA	NA
Face 3	14.5	NA	NA	NA	NA	**Face 3**	8	58.5	63.5	NA	NA
	16	26	22	27	34		11	16.5	15.5	21.5	23.5
	17	21	20.5	25	30.5		6.5	13.5	17.5	28	24.5
	14.5	22	21.5	33	44.5		9.5	15.5	18	16.5	23
	15.5	NA	NA	NA	NA		13.5	22	24	NA	NA
Face 4	17	NA	NA	NA	NA	**Face 4**	12.5	19.5	55	NA	NA
	15.5	23	22	30	39.5		10.5	17	18.5	13.5	25
	16	23.5	22.5	25	33.5		10.5	18.5	18.5	18	24.5
	19	23	23	28	36		9	18.5	20	18.5	24
	NA	NA	NA	NA	NA		11.5	19	53	25	NA

340 kg/m3, 30% Class F, 0.5 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
	72.5	NA	NA	NA	NA		22	NA	NA	NA	NA
	21	61	46	NA	NA		12	19	23	18.5	30.5
Face 1	20	28.5	31	34.5	47.5	**Face 1**	14	20	25	16.5	27.5
	18	35.5	35	41	NA		14	20.5	25.5	17	34
	NA	NA	NA	NA	NA		39	NA	NA	NA	NA
	NA	NA	NA	NA	NA		21	NA	NA	NA	NA
	20	34.5	38	55	NA		18.5	22	26.5	28	37
Face 2	22	30.5	32	33	43.5	**Face 2**	17.5	25	26	32	29
	20.5	34	41	41	NA		14.5	26	25	30	37.5
	61	NA	NA	NA	NA		17.5	NA	NA	NA	NA
	NA	NA	NA	NA	NA		19.5	NA	NA	NA	NA
	22	33	38	NA	NA		25.5	28.5	25.5	25.5	44
Face 3	23	30.5	33	33	44.5	**Face 3**	14	24.5	20	22.5	29.5
	16.5	35	34	43	NA		18.5	24	23	23	37
	NA	NA	NA	NA	NA		18.5	NA	NA	NA	NA
	28	NA	NA	NA	NA		19	NA	NA	NA	NA
	17.5	36.5	33.5	40.5	NA		17	24	27	25.5	46
Face 4	20	40	31	34.5	46	**Face 4**	15.5	19.5	21.5	22.5	27
	21.5	35	48	39.5	NA		12.5	21.5	24.5	24	30
	NA	NA	NA	NA	NA		19.5	NA	NA	NA	NA

370 kg/m3, Control, 0.5 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
Face 1	9.5	24.5	20	17	40.5	**Face 1**	9.5	18	26	36.5	31
	9	17	15.5	16.5	22		11	11.5	15	16	16
	9.5	16.5	15	17.5	16.5		8.5	16.5	14.5	16.5	17.5
	12	15.5	15.5	17.5	18.5		9	16	12	12.5	14
	12	24.5	24.5	36.5	NA		7	17.5	15.5	25.5	49
Face 2	12.5	32	33	NA	49	**Face 2**	13.5	12.5	18	42	32
	13.5	14	15	22	23.5		10	12	13	20	21
	12	23.5	17	17.5	26		8	14	14	18.5	17.5
	13	16	18	22	21.5		8.5	8	12.5	16.5	17
	12	17	20.5	19	51.5		7.5	11	21	26.5	47
Face 3	12	14	63.5	NA	NA	**Face 3**	10	14	17	58.5	37.5
	12.5	14.5	15	17.5	21.5		9.5	13	11	8	15.5
	11	15.5	17	14.5	18		8	14	11.5	14.5	13
	8.5	14.5	17	16.5	16.5		9.5	15	14.5	13	17
	15.5	18	22.5	15	35		9.5	13.5	37	21	35
Face 4	19	15	25	16	37	**Face 4**	11	13.5	28.5	22.5	27.5
	14.5	17	18	16	20		9	14.5	21	17	20
	9.5	16	13	15	16		10.5	15	12.5	17	17.5
	10	17	12.5	17	18		9.5	19	16.5	21.5	17
	14.5	22	20	16.5	41		10.5	20	22	55	43

370 kg/m3, 15% Class C, 0.5 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
Face 1	19	NA	NA	NA	NA	**Face 1**	15	32.5	21	50	NA
	13	18	23.5	20	26		10.5	13	17	17	19.5
	15.5	17.5	20	21	26		14.5	17.5	16.5	21	19
	12	14	23	21	23.5		14	18	18.5	18.5	22
	15	51.5	NA	NA	NA		10.5	28	34	30	NA
Face 2	17.5	NA	NA	NA	NA	**Face 2**	14	38	43	NA	57
	13	21	19.5	21	26.5		10	13	18	17	24.5
	14	18	20.5	20	25		9.5	13	16.5	16.5	22
	15	18	23.5	25.5	25.5		13	13.5	16	20.5	23
	14.5	NA	NA	NA	NA		16	22.5	32.5	27.5	NA
Face 3	14	35	NA	NA	NA	**Face 3**	11	21	29	45	NA
	17	23	20.5	25	26.5		10.5	14.5	17	15	22
	14	19	20	18	24.5		8.5	16	10	14.5	21
	17.5	17	23.5	26.5	24		10	12.5	14	25	21
	15.5	NA	NA	NA	NA		9.5	25	30	30	NA
Face 4	18.5	NA	NA	NA	NA	**Face 4**	13.5	27.5	36.5	50	NA
	13	22	27	25	30.5		14	16.5	17.5	17	20.5
	16	21	20.5	25.5	29		12.5	15	15	18.5	20
	15	20.5	23	27	30.5		15	15.5	14.5	18	20.5
	23.5	NA	NA	NA	NA		12	19	20.5	NA	26.5

370 kg/m3, 15% Class F, 0.5 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
Face 1	59.5	NA	NA	NA	NA	**Face 1**	12	32	69.5	45	NA
	16	22	27.5	28	32		12.5	17.5	22	18	23
	16	25.5	22.5	26	27.5		11	18.5	20	17.5	22
	15.5	24	29	27	46.5		14	17	19.5	20	23
	41.5	NA	NA	NA	NA		16	42	45	33.5	NA
Face 2	22	NA	NA	NA	NA	**Face 2**	16.5	35	27	NA	NA
	17.5	26	29	27.5	43		12	18.5	20	20	24.5
	16	20.5	28	24.5	32.5		12.5	17	18	25	24
	14	21	25	25	34.5		8	16.5	20	16.5	20.5
	17.5	46	NA	NA	NA		8	25.5	26.5	23.5	NA
Face 3	18	NA	NA	NA	NA	**Face 3**	12	25	46.5	56	NA
	12	20.5	25.5	27	35		14	15	13	25	17
	13.5	17	19.5	22	28		10	14	12	15	19
	14	21	22	27.5	30.5		10.5	16	18	21	19.5
	19.5	NA	NA	NA	NA		15.5	29.5	19	25	NA
Face 4	21	48.5	NA	NA	NA	**Face 4**	16	38	37.5	27	NA
	13.5	20.5	20.5	27.5	28.5		11.5	15.5	20	28	21
	23	23	25.5	22.5	28.5		6.5	15	18.5	15	24.5
	18	23	26	22	31.5		8.5	17	22	25	23.5
	44	NA	NA	NA	NA		12.5	32	67	NA	NA

340 kg/m3, Control, 0.45 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
Face 1	11	32	17	21.5	43	**Face 1**	6	11	15.5	16	18
	12	14.5	12	15.5	19		7.5	15	11.5	10	13.5
	14	11.5	14	13	17.5		7	10	12	12	12.5
	7.5	14	14	13.5	15.5		10.5	14	13.5	8.5	12
	12	28	20	33.5	33		10	13.5	19	20	14.5
Face 2	13	25.5	21	22.5	31.5	**Face 2**	8	11	22	27	14
	10.5	12	16	15.5	16		7	11	9	16	14.5
	9	11	15.5	11	17.5		6.5	12	8	14.5	15.5
	7	9.5	14	15	17		7	13.5	8.5	13.5	10.5
	8	15	18	21	31		8	12	14.5	18	21.5
Face 3	12.5	15.5	18.5	20	34.5	**Face 3**	7	18.5	14.5	25	24
	10	11	16	20	18		6	11.5	14.5	15	14
	10	14.5	13	13.5	15.5		8.5	6	12.5	8.5	11.5
	12	14.5	13.5	14.5	18		9.5	13.5	12	16	14.5
	14.5	21.5	31	17	24.5		9.5	10	14	19	23.5
Face 4	14	30.5	23.5	15.5	46.5	**Face 4**	8.5	12	14	18	26
	11	15	14	14	15		7	13	11	17.5	13
	14.5	13	14.5	16	14		8.5	14.5	13	10	12.5
	13	14	14	16.5	19.5		8	13	12.5	13.5	17
	12.5	18.5	18	23	34		12	11.5	17	15	19

340 kg/m3, 15% Class C, 0.45 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
	44.5	56	NA	NA	NA		11	16	32.5	32	48
	16.5	20.5	23.5	23.5	31.5		8.5	23	16.5	16.5	21.5
Face 1	17	18.5	21.5	21.5	28	**Face 1**	9	24.5	18	25	19
	17	23.5	18	25	31		16.5	23.5	15	20	20.5
	16.5	37	33.5	42	NA		12	30	16.5	28.5	29
	16	NA	NA	NA	NA		8.5	NA	32.5	27.5	45
	14	18	20	21.5	25		9	13	16	16.5	16
Face 2	14	16	21.5	20	25.5	**Face 2**	8	15	15.5	18	13
	13	13.5	17	25	20		10	17	8.5	13.5	17.5
	11	28	20	25	47.5		10.5	21.5	15	20	28
	13	25	40	22.5	NA		10	25	15	20	28.5
	13.5	24.5	17.5	17.5	23.5		10.5	17	10	10	18
Face 3	13	17	18	16	21.5	**Face 3**	7.5	12.5	5	10	14.5
	13	15.5	23	15.5	18.5		10.5	18	15.5	13.5	13
	22	20	NA	NA	NA		9	24.5	21.5	15	23
	21	21	NA	35	NA		8.5	17	25	15	28
	13	15.5	18	21.5	25		12	12.5	10	15	17.5
Face 4	12	19	20	24	28	**Face 4**	9	13.5	13.5	15	16.5
	17	20	18.5	25	29.5		14	15	15.5	15	18
	25.5	NA	NA	NA	NA		11.5	25	30	20	25

340 kg/m3, 30% Class C, 0.45 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
Face 1	33	NA	NA	NA	NA	**Face 1**	28	NA	45	40	NA
	18	24.5	27	35.5	41		12.5	20	21.5	22	23
	18.5	25	29	28.5	29.5		12	20.5	23	18	20.5
	20	24	28.5	27	36		10.5	29	16.5	17	22
	30.5	NA	NA	NA	NA		18	40	42.5	50	NA
Face 2	41	NA	NA	NA	NA	**Face 2**	18	NA	NA	35	NA
	18.5	25.5	25	35	38		15	18	22	25	23
	20.5	24.5	28	30	29.5		11.5	13.5	22	16	22
	22	23	27.5	28.5	34		11	17	14.5	15	23
	28	NA	NA	NA	NA		16.5	45	22.5	22.5	NA
Face 3	NA	NA	NA	NA	NA	**Face 3**	13	50	40	30	NA
	16.5	23	30	32	38		13.5	20	14	17	23
	18	23	22.5	27.5	27		11	17	15	15	27
	22.5	26	25	32.5	28		12	15	20	18	25
	13.5	NA	NA	NA	NA		15.5	21.5	27	40	NA
Face 4	61	NA	NA	NA	NA	**Face 4**	15	NA	42.5	33	NA
	16.5	27	31.5	27	30		14	14.5	15	20	29
	17.5	27.5	22.5	26.5	30		9.5	23	15	20	20.5
	14.5	26	28.5	35	36.5		11.5	24.5	20	20.5	24
	27.5	NA	NA	NA	NA		19.5	28	NA	60	NA

340 kg/m3, 15% Class F, 0.45 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
Face 1	26	63	NA	60	NA	**Face 1**	9.5	25	25.5	40	NA
	16	20.5	24	18	26		9	12.5	13.5	15.5	17
	16	21.5	22.5	16.5	24		13	13.5	14	13	17
	12	23	20	20	25.5		12	14	16.5	15	18
	15.5	28	45	NA	NA		13	25	21	30	NA
Face 2	17.5	NA	NA	45	NA	**Face 2**	10	23	25	20	28
	16.5	18	23.5	16.5	26		12	18	15	15	18
	14	16.5	16	17.5	24.5		10.5	15.5	13	20	18.5
	11	21.5	22.5	20	29		10.5	16	24.5	16	20.5
	22	20	24	50	NA		11	20	17.5	25	NA
Face 3	24.5	52	50	NA	NA	**Face 3**	10.5	23	15	23.5	NA
	12	16.5	14.5	20	24		11.5	11	12.5	15	19
	13.5	18	16	15	22.5		13	17.5	13.5	12.5	20
	12.5	18	17.5	20	30		9	13	12.5	15	19.5
	22.5	15.5	NA	37.5	NA		9.5	18	22	20	NA
Face 4	20.5	NA	45	45	NA	**Face 4**	8.5	17.5	20	27	56.5
	17	16.5	20	23.5	27		9	16	23.5	17.5	18
	18	17	20	20	22		11	15.5	15	16.5	18.5
	15	22	20.5	22.5	25		10	17	20	20	19.5
	22	NA	NA	30	NA		10.5	18	18.5	20	30

340 kg/m3, 30% Class F, 0.45 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
	47.5	NA	NA	NA	NA		25.5	NA	NA	NA	NA
	22	36	45	45	NA		14.5	23.5	30	30	47
Face 1	19	28	32	33.5	44.5	**Face 1**	13	20	22.5	25	28
	21.5	35	41.5	40	NA		11.5	25	22	25	31.5
	NA	NA	NA	NA	NA		15.5	NA	NA	NA	NA
	NA	NA	NA	NA	NA		16.5	NA	NA	NA	NA
	22	37.5	45	50	NA		17	20	23.5	22.5	33
Face 2	21	30.5	30	33.5	45	**Face 2**	15	21.5	21.5	23	24
	20.5	32	37.5	35	NA		15	23.5	23	30	34
	NA	NA	NA	NA	NA		9	NA	NA	NA	NA
	NA	NA	NA	NA	NA		17.5	NA	NA	NA	NA
	21	35	45	35	NA		15	25	19	20	36
Face 3	21.5	27	25	28.5	41.5	**Face 3**	14	21.5	20	18.5	29
	22.5	28.5	35.5	40	NA		12	21	21.5	25	34.5
	52	NA	NA	NA	NA		15	NA	NA	NA	NA
	NA	NA	NA	NA	NA		13.5	NA	NA	NA	NA
	19	30.5	40	36.5	NA		15	26	20	20	35.5
Face 4	18	27.5	28.5	28.5	48	**Face 4**	17.5	21.5	20	20	26
	19.5	35	40	40	NA		16	20	25.5	25	36
	NA	NA	NA	NA	NA		22	NA	NA	NA	NA

400 kg/m3, Control, 0.45 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
Face 1	10.5	24	27.5	20	44.5	**Face 1**	8.5	15	12.5	18	19.5
	11	12	18	17.5	18		9	9.5	10	12.5	15
	11.5	12.5	14	16	16		9	15.5	13	10	14.5
	14.5	14	15	15	17		8	14.5	15	12.5	15
	11.5	40.5	25.5	17.5	37		6	8	10	22.5	25
Face 2	13	22	20	20	37.5	**Face 2**	9	15	15	20	21
	12.5	19	13.5	14.5	19.5		6.5	10.5	8	19.5	14
	13	14	17	13.5	14.5		8	8.5	13.5	10	13
	8	12	20	22.5	15.5		7	17	13	8.5	11
	13	13.5	20	16	20		7.5	7.5	17	12	15.5
Face 3	7.5	14	26.5	20	36	**Face 3**	7.5	13.5	18	15	15.5
	11.5	13	12	13.5	13		9	14	11.5	14.5	11.5
	13	11	10.5	12	15.5		9	12.5	12.5	8	12
	11	14	12.5	12.5	16.5		8	11	20	15	11.5
	12	18	13	20	16		7	11.5	10	20	14
Face 4	14.5	14.5	15	22.5	17.5	**Face 4**	7	8	20	17.5	14
	11.5	15	13	12.5	19.5		9	10.5	13.5	7.5	11
	12	12	12	13	23.5		10	8	16	10	14.5
	12	11.5	13.5	18	16.5		8	10	10	13.5	16
	12.5	16.5	25	17.5	24		9	11.5	12.5	15	24.5

400 kg/m3, 15% Class C, 0.45 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
Face 1	17.5	14	40	25	43.5	**Face 1**	14.5	17	26.5	30	77
	10	15.5	17.5	15.5	21		9.5	15	12.5	13.5	16.5
	12.5	15	18.5	17.5	19.5		12	13.5	13.5	12	16.5
	9	20.5	19	20	26		13.5	12	10	15	16
	22	34.5	20	50	65		7	18	20	40	37
Face 2	17.5	36	19.5	53	56	**Face 2**	9.5	23.5	20	16	26
	11.5	16	17.5	20	25		9	12.5	12.5	17	19.5
	9.5	15	15	16.5	24.5		7.5	14.5	13.5	10	15
	8	13.5	15	23	18		8	13.5	17.5	15.5	14
	5	17	21.5	25	44		9.5	11	20.5	15	18
Face 3	12	20	22	50	37	**Face 3**	7.5	13.5	27.5	15	18
	7.5	13	13	20	21.5		9.5	12	13.5	20	17
	13	15.5	16.5	20	18.5		7	11.5	12.5	19	17
	12.5	18	16.5	16	19		13	8	13.5	10	17
	12	27.5	15.5	35	26		9.5	12.5	14	17.5	12.5
Face 4	11.5	24	14	43	23	**Face 4**	10	11.5	17.5	23.5	12
	11	16	15	17	13		10.5	10.5	15	14	19.5
	12.5	15.5	16.5	16	16		14	15	20	10	22
	11	14	18.5	22	22		7	15.5	13.5	15.5	21.5
	16.5	22.5	21	25	43.5		12	16.5	17	20	28

400 kg/m3, 30% Class C, 0.45 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
	26.5	NA	NA	NA	NA		13.5	26	25	30	69.5
	15	22	23	23.5	28		10.5	16	15	16	23.5
Face 1	14.5	21.5	22	18	26	**Face 1**	10.5	24.5	17.5	15	22
	19.5	22	23	17.5	26.5		9.5	19	16.5	17	26.5
	22	NA	NA	NA	NA		13	28	27	40	NA
	33.5	38	NA	NA	NA		16.5	27	20	40	NA
	17	23.5	21.5	26.5	26		15	19.5	15	20	22
Face 2	19	23	21	21	25	**Face 2**	10.5	19	13.5	16.5	22
	15.5	24	20	20	31		12	22	15	22.5	23.5
	15.5	62	25.5	NA	NA		8	23	20	30	NA
	18.5	NA	NA	NA	NA		11.5	NA	35	45	NA
	15.5	23	22	22.5	28		11	16.5	20	18.5	20
Face 3	16	21.5	22	18	25.5	**Face 3**	10	17.5	17.5	13.5	23.5
	13.5	17.5	25	25	30		11.5	14.5	20	14	19.5
	31	NA	NA	NA	NA		14	16	20	45	23.5
	18.5	34	NA	NA	NA		11.5	18	45	20	NA
	16	16.5	25	25	30		9	20	18	18	18
Face 4	18	23	27.5	26	25.5	**Face 4**	10.5	16.5	20	17.5	20.5
	18.5	23	25	23.5	34		14	18	16	15	22
	23	38	NA	NA	NA		15	27.5	20	45	NA

400 kg/m3, 15% Class F, 0.45 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
Face 1	15.5	55.5	NA	35	NA	**Face 1**	11	22.5	20.5	20	53
	12	12	20	20	24.5		9	17	17	15.5	18
	10.5	16.5	19.5	18.5	25		7	16	15	15	22
	13.5	17	18.5	20	24.5		9	15	15	13.5	22.5
	14.5	26	41	30	NA		12.5	20	31	25	49
Face 2	14	27	NA	NA	NA	**Face 2**	11.5	22	27	30	39.5
	13	18	21	18.5	21		8.5	11	15	15	20
	11	17.5	17	21.5	22		9.5	11.5	10	13.5	17.5
	13	17	17	16.5	22		8	11	16.5	12	20
	9	17	22.5	15	58		7	20	15	12	28
Face 3	12	27	35	20	NA	**Face 3**	7.5	30	20	15	47
	13	16	12	16.5	23		6.5	10.5	12	14.5	15.5
	11.5	14	15	15	20		7	13	15	10.5	18.5
	10	13.5	20	18.5	18.5		11	14.5	10	10	17.5
	11.5	18.5	21	25	NA		14	20	15	15	25
Face 4	11.5	23	22	40	22	**Face 4**	10	21	15	15	27
	20.5	13.5	20.5	10.5	22		9.5	16.5	15	10	14
	14	19	19	20	22.5		9.5	18.5	13.5	13.5	16
	11	20	19	15	21		11	13.5	16.5	15	23
	15.5	25.5	36	NA	NA		13	18.5	13.5	15	26

400 kg/m3, 30% Class F, 0.45 w/cm											
1-Day Curing						7-Days Curing					
	Day 28	**Day 56**	**Day 63**	**Day 70**	**Day 105**		**Day 28**	**Day 56**	**Day 63**	**Day 70**	**Day 105**
	(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**		**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
	62	NA	NA	NA	NA		47	61	NA	NA	NA
	20	26.5	32.5	33.5	40		14	23.5	25	23.5	32
Face 1	16.5	25	27	26.5	36	**Face 1**	13	19	17.5	20	30.5
	16.5	27	35	42.5	54		11.5	20.5	20	23.5	28
	48	NA	NA	NA	NA		15.5	NA	NA	NA	NA
	NA	NA	NA	NA	NA		15	NA	NA	NA	NA
	20	26	33	32.5	40		16	24.5	18	23	30
Face 2	16	20	25	27	34	**Face 2**	12.5	21	20	22	31
	18.5	21.5	26	26.5	35		14	22	22.5	20	26.5
	17	36	NA	NA	NA		12	21.5	NA	NA	NA
	NA	NA	NA	NA	NA		13	NA	NA	NA	NA
	11.5	25.5	33	28.5	37.5		16	17	20	21.5	30
Face 3	16	20	23	23.5	35.5	**Face 3**	14	20	20	23.5	27
	21.5	22	26.5	30	41.5		10.5	15	18.5	20	30.5
	24	NA	NA	NA	NA		14	36.5	NA	NA	NA
	58.5	45.5	NA	NA	NA		10	32	NA	NA	NA
	15	27	24.5	30	56.5		11	15.5	18	20	26
Face 4	26.5	22.5	25.5	35.5	38	**Face 4**	12	20	26.5	20	28
	23	24.5	29	34	43		18.5	22	18	20	28
	33.5	NA	NA	NA	NA		17	43.5	NA	NA	NA

Compressive Strength Results

Mix ID	Cement (Kg/m3)	Fly Ash (Kg/m3)	w/cm ratio	Compressive strength (MPa)			
				2 d	*7 d*	*28 d*	*90 d*
310							
Control	310	0	0.5	19.52	27.22	34.50	39.60
15% Class C	263.5	46.5	0.5	15.49	23.13	35.82	41.85
30% Class C	217	93	0.5	14.49	23.08	37.71	46.45
50% Class C	155	155	0.5	8.69	19.31	35.61	44.60
15% Class F	263.5	46.5	0.5	17.44	24.18	35.05	40.19
30% Class F	217	93	0.5	10.31	16.93	29.16	39.03
50% Class F	155	155	0.5	4.59	8.50	18.50	26.14
30% Slag	217	93	0.5	14.64	31.06	44.36	50.65
50% Slag	155	155	0.5	13.75	31.41	44.85	51.48
340							
Control	340	0	0.5	21.07	32.15	42.29	43.06
30% Class C	238	102	0.5	16.38	25.89	35.38	44.37
30% Class F	238	102	0.5	13.27	19.21	29.02	37.75
370							
Control	370	0	0.5	18.71	26.54	35.54	42.39
15% Class C	314.5	55.5	0.5	17.53	24.22	34.91	40.51
15% Class F	314.5	55.5	0.5	16.91	23.03	35.36	38.89
340							
Control	340	0	0.45	20.92	31.89	39.29	43.75
15% Class C	289	51	0.45	22.93	31.70	44.99	50.13
30% Class C	238	102	0.45	16.52	26.06	40.20	52.28
15% Class F	289	51	0.45	20.45	28.26	39.30	49.73
30% Class F	238	102	0.45	12.82	21.50	34.76	45.11
400							
Control	400	0	0.45	25.21	33.99	43.59	47.93
15% Class C	340	60	0.45	20.74	30.50	43.65	46.87
30% Class C	280	120	0.45	15.47	28.39	45.84	52.66
15% Class F	340	60	0.45	20.23	30.49	40.69	49.83
30% Class F	280	120	0.45	14.68	25.11	39.74	44.52

Fresh Properties Results

Mix ID	Cement	Fly Ash	w/cm ratio	Fresh Properties		
	(Kg/m3)	(Kg/m3)		Slump	Air Content	Unit Weight
				(mm)	*(%)*	*(kg/m3)*
310						
Control	310	0	0.5	69.85	3.5	2345.11
15% Class C	263.5	46.5	0.5	76.20	3.0	2350.23
30% Class C	217	93	0.5	76.20	2.0	2410.46
50% Class C	155	155	0.5	107.95	2.5	2369.46
15% Class F	263.5	46.5	0.5	50.80	2.3	2392.52
30% Class F	217	93	0.5	76.20	1.9	2375.86
50% Class F	155	155	0.5	95.25	1.8	2387.40
30% Slag	217	93	0.5	57.15	2.6	2391.24
50% Slag	155	155	0.5	38.10	2.0	2372.02
340						
Control	340	0	0.5	101.60	2.1	2368.18
30% Class C	238	102	0.5	158.75	2.4	2318.20
30% Class F	238	102	0.5	190.50	2.4	2325.89
370						
Control	370	0	0.5	215.90	3.1	2318.20
15% Class C	314.5	55.5	0.5	190.50	2.4	2309.23
15% Class F	314.5	55.5	0.5	209.55	2.6	2337.42
340						
Control	340	0	0.45	69.85	2.1	2411.75
15% Class C	289	51	0.45	31.75	2.0	2416.87
30% Class C	238	102	0.45	69.85	2.1	2415.59
15% Class F	289	51	0.45	44.45	1.9	2404.06
30% Class F	238	102	0.45	76.20	2.2	2404.06
400						
Control	400	0	0.45	120.65	2.5	2380.99
15% Class C	340	60	0.45	139.70	2.4	2369.46
30% Class C	280	120	0.45	177.80	2.2	2369.46
15% Class F	340	60	0.45	133.35	1.4	2406.62
30% Class F	280	120	0.45	146.05	1.3	2424.56

REFERENCES

Aguayo, F. M., Drimalas, T., & Folliard, K. J. (2015). Natural Carbonation Of Concrete. *Special Publication*, *305*, 2.1-2.12.

ASTM International. (2018). ASTM C192/C192M-18 Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. Retrieved from https://doi-org.libproxy.txstate.edu/10.1520/C0192_C0192M-18

ASTM International. (2019). *ASTM C150/C150M-19a Standard Specification for Portland Cement*. Retrieved from https://doi-org.libproxy.txstate.edu/10.1520/C0150_C0150M-19A

ASTM International. (2019). ASTM C618-19 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. Retrieved from https://doi-org.libproxy.txstate.edu/10.1520/C0618-19

ASTM International. ASTM C31/C31M-19 Standard Practice for Making and Curing Concrete Test Specimens in the Field. West Conshohocken, PA; ASTM International, 2019. doi: https://doi-org.libproxy.txstate.edu/10.1520/C0031_C0031M-19

ASTM International. ASTM C39/C39M-18 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. West Conshohocken, PA; ASTM International, 2018. doi: https://doi-org.libproxy.txstate.edu/10.1520/C0039_C0039M-18

Atiş, C. D. (2004). Carbonation-porosity-strength model for fly ash concrete. *Journal of Materials in Civil Engineering, 16*(1), 91-94.

Bouzoubaâ, N., Bilodeau, A., Tamtsia, B., & Foo, S. (2010). Carbonation of fly ash concrete: laboratory and field data. *Canadian Journal of Civil Engineering, 37*(12), 1535-1549.

Bouzoubaa, N., Tamtsia, B., Zhang, M., Chevrier, R., Bilodeau, A., & Malhotra, V. (2006). Carbonation of concrete incorporating high volumes of fly ash. *Special Publication, 234*, 283-304.

Branca, C., Fratesi, R., Moriconi, G., & Simoncini, S. (1992). Influence of fly ash on concrete carbonation and rebar corrosion. *Special Publication, 132*, 245-256.

Collepardi, M., Collepardi, S., Olagot, J. O., & Simonelli, F. (2004). *The influence of slag and fly ash on the carbonation of concrete.* Paper presented at the Proc. of 8th CANMET/ACI Int. Conf. on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, held May.

Czarnecki, L., Woyciechowski, P., & Adamczewski, G. (2018). Risk of concrete carbonation with mineral industrial by-products. *KSCE Journal of Civil Engineering, 22*(2), 755-764.

Hussain, S., Bhunia, D., & Singh, S. B. (2017). Comparative study of accelerated carbonation of plain cement and fly-ash concrete. *Journal of Building Engineering, 10*, 26-31. doi:https://doi.org/10.1016/j.jobe.2017.02.001

Jia, Y., Aruhan, B., & Yan, P. (2012). Natural and accelerated carbonation of concrete containing fly ash and GGBS after different initial curing period. *Magazine of Concrete Research, 64*(2), 143-150. doi:10.1680/macr.10.00134

Khunthongkeaw, J., Tangtermsirikul, S., & Leelawat, T. (2006). A study on carbonation depth prediction for fly ash concrete. *Construction and building materials, 20*(9), 744-753.

Leemann, A., & Moro, F. (2017). Carbonation of concrete: the role of CO 2 concentration, relative humidity and CO 2 buffer capacity. *Materials and Structures, 50*(1), 30.

Lu, C.-f., Wang, W., Li, Q.-t., Hao, M., & Xu, Y. (2018). Effects of micro-environmental climate on the carbonation depth and the pH value in fly ash concrete. *Journal of Cleaner Production, 181*, 309-317.

Lye, C.-Q., Dhir, R. K., & Ghataora, G. S. (2016). Carbonation resistance of GGBS concrete. *Magazine of Concrete Research, 68*(18), 936-969.

M.A. Sanjuan, C. A., & Cheyrezy, M. Comparison Beween Accelerated and Natural Carbonation Results in Different Concretes. *Special Publication, 207*. doi:10.14359/12395

Malhotra, V. M., & Mehta, P. K. (2008). *High-performance, high-volume fly ash concrete for building sustainable and durable structures*. Ottawa, Canada: Supplementary Cementing Materials for Sustainable Development.

NPCA. (2015). Understanding Carbonation - NPCA. *Precast Inc. Magazine*. Retrieved from https://precast.org/2015/07/understanding-carbonation/#

Papadakis, V. G. (2000). Effect of supplementary cementing materials on concrete resistance against carbonation and chloride ingress. *Cement and Concrete Research, 30*(2), 291-299.

Reis, R., Malheiro, R., Camões, A., & Ribeiro, M. (2015). *Carbonation resistance of high volume fly ash concrete.* Paper presented at the Key Engineering Materials.

Ruixia, H. (2010). A study on carbonation for low calcium fly ash concrete under different temperature and relative humidity. *The Electronic Journal of Geotechnical Engineering, 15*, 1871-1877.

Siddique, R. (2004). Performance characteristics of high-volume Class F fly ash concrete. *Cement and Concrete Research, 34*(3), 487-493.

Stefanoni, M., Angst, U., & Elsener, B. (2018). Corrosion rate of carbon steel in carbonated concrete–A critical review. *Cement and Concrete Research, 103*, 35-48.

Sulapha, P., Wong, S., Wee, T., & Swaddiwudhipong, S. (2003). Carbonation of concrete containing mineral admixtures. *Journal of Materials in Civil Engineering, 15*(2), 134-143.

Thomas, M. (2007). *Optimizing the use of fly ash in concrete* (Vol. 5420): Portland Cement Association Skokie, IL.

Thomas, M., & Matthews, J. (1992). Carbonation of fly ash concrete. *Magazine of Concrete Research, 44*(160), 217-228.

Yang, K.-H., Jung, Y.-B., Cho, M.-S., & Tae, S.-H. (2015). Effect of supplementary cementitious materials on reduction of CO2 emissions from concrete. *Journal of Cleaner Production, 103*, 774-783.

Zhao, Q., He, X., Zhang, J., & Jiang, J. (2016). Long-age wet curing effect on performance of carbonation resistance of fly ash concrete. *Construction and building materials, 127*, 577-587. doi:https://doi.org/10.1016/j.conbuildmat.2016.10.065