Alternative Cementitious Materials (ACMs) For Durable and Sustainable Transportation Infrastructures

Final Report
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Transportation Infrastructure Durability Center
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AT THE UNIVERSITY OF MAINE

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16 Abstract

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Abstract

After water, concrete is the second most consumed/produced material in the world. The cement sector is the third-largest industrial energy consumer in the world, responsible for 7% of industrial energy use, and the second industrial emitter of carbon dioxide, with about 7% of global emissions. Alternative cementitious materials offer some potential solutions as sustainable alternatives to cement. This project investigates properties of two types of concretes made with slag as one of the relatively wide available alternative cementitious materials in the state of Maine. Part I of this research is about CO_2 – activated concretes. Using 3 various curing procedures, 18 different mixtures were defined in this part of research. Workability, compressive strength, free shrinkage, bulk, and surface electrical resistivity tests were performed to study the fresh and hardened properties of these CO_2 – activated concretes. Part II of this study is about alkali – activated concretes. 13 different batches were developed and tested in this section. Compressive strength, free shrinkage, bulk, and surface electrical resistivity tests were conducted to investigate the mechanical and transport properties of the developed alkali – activated concretes. Then all 252 bulk and surface electrical resistivity tests were compared and were showed that the results are compatible. Finally, the MaineDOT method for concrete permeability evaluation was reviewed. Formation factor analysis showed that the current MaineDOT method (using surface resistivity) is not perfect and new performance-based methods based on formation factor, like AASHTO PP84-20 method, should be used.

Chapter 1: Introduction and Background

1.1 Project Motivation

Over 4 billion tons of cement were produced in 2018 (U.S. Department of the Interior 2019). After water, concrete is the second most consumed/produced material in the world. The cement sector is the third-largest industrial energy consumer in the world, responsible for 7% of industrial energy use, and the second industrial emitter of carbon dioxide, with about 7% of global emissions (International Energy Agency 2018).

Introducing any new solution in this field will be a new promising road toward sustainable development. Recent recognition of CO_2 emissions and their role in climate change has pushed the research community to find sustainable alternatives to current construction practices. Alternative Cementitious Materials (ACMs) offer some potential solutions.

Concrete produced with new-generation binding systems, otherwise known as the Alternative Cementitious Materials (ACMs), can exhibit better mechanical and durability performances compared to those produced with ordinary Portland cement (OPC). The embodied energies of ACMs are 50 to 90% lower than that of OPC depending on the production process. Some of the ACMs, including alkali-activated slag (AAS) and geopolymers, utilize more than 90% (by weight) of industrial by-products to produce concrete. Then again, other types of ACMs (e.g., CO_2 storing cement (CSC)) offer the benefit of converting CO_2 into concrete at a relatively low-cost (Ashraf et al. 2017; Ashraf and Olek 2016). The key characteristics of the concrete that are achievable with ACMs, as compared to OPC, include rapid strength gain (> 8,000 psi in 24 hours), tunable setting and rheology, relatively low cost and better resistance against elevated temperature (Ashraf et al. 2016), freeze-thaw damage (Zhang and Shao 2018) and deicer damage (Farnam et al. 2016). With all these benefits, ACMs emerged as a powerful resource to significantly enhance the sustainability and durability of concrete infrastructures. In a tech brief, FHWA suggested that ACMs represent a “game-changing” advancement and can revolutionize the construction of transportation infrastructures upon proper processing (Van Dam 2010).

However, the durability performance of ACM concrete largely depends on the selection of chemical activation route (Ke et al. 2017). Some of the ACMs can also exhibit higher autogenous and drying shrinkage compared to those of OPC depending on reaction mechanism (Ye and Radlińska 2016). Consequently, the service life performances of these materials are still not well understood. To address these challenges, this project will investigate the durability performances of ACM concrete in comparison to those of traditional OPC-concrete for cold-climatic regions (Class A and Class LP concrete in Maine (MaineDOT 2020)). Considering the wide availability of slag cement in the state of Maine, two slag-based ACMs will be used for this project, these are (i) CO_2 activated slag and (ii) alkali-activated slag. This project will also investigate the free shrinkage properties of ACM concrete. This project will emphasize the utilization of locally available materials (i.e., aggregates, cement, slag) for making ACM concrete. Such an approach, if successful, has the potential of bringing additional financial benefits to the state of Maine. The durability performances of the ACM concrete will be evaluated using relatively new method, formation factor. In addition to ACMs, volumetric stability and durability of Class A and Class LP concrete will also be considered. These concretes are often used by MaineDOT projects for infrastructural construction (MaineDOT 2020).

The durable ACM-concrete proposed here has the potential to significantly reduce the maintenance cost and extend the service life of transportation infrastructures without any notable influence on construction or production cost. In the cold climatic region, the state DOTs often spend as high as $100 million for winter maintenance and post-winter damage repair/ recovery

(The Council of State Governments 2008). The freeze-thaw cycles along with harmful deicing chemicals often lead to premature distresses of transportations infrastructures in the form of cracking, spalling, scaling as well as increased reinforcement corrosion susceptibility. The ACM-concrete will be designed to resist these forms of damages and thus, will reduce the maintenance cost. The production and maintenance cost of ACM-concretes will be lower than that of conventional concrete due to the utilization of industrial by-products. The goal of the work described in this project is to investigate the suitability of Maine’s local available aggregates, cement, and slag to improve the properties of concrete by producing CO_2 – activated and alkali – activated concretes.

1.2 Research, Objectives, and Tasks

Objectives:

(i) Developing the ACM-concrete (CO_2 - activated and alkali - activated) formulation.

(ii) Finding the most efficient time (method) for CO_2 curing of the developed slag concretes.

(iii) Finding the most efficient slag content of the developed slag concretes.

(iv) Finding the mechanical and transport properties of the developed ACM-concretes as per the AASHTO/ASTM standards.

(v) Comparing test results of bulk and surface electrical resistivity tests as two most popular methods for durability/permeability evaluation.

(vi) Verifying current MaineDOT concrete durability evaluation method (MaineDOT 2020) and recommending potential new methods for assessing durability and permeability of concrete based on formation factor analysis.

Task Plan:

Task – 1: Developing the CO_2 - activated concretes

Developing the CO_2 - activated concretes. Defining different curing procedures. Conducting corresponding slump, compressive strength, shrinkage, and bulk/surface electrical resistivity tests. Finding the most efficient time (method) for CO_2 curing and slag content for the developed slag concretes.

Task – 2: Developing the alkali - activated concretes

Developing the alkali - activated concretes. Conducting corresponding compressive strength, shrinkage, bulk/surface electrical resistivity tests. Finding the most efficient formula for the developed alkali - activated concretes.

Task – 3: Bulk and surface electrical resistivity test results comparison

A series of ASTM/ AASHTO standard bulk and surface electrical resistivity tests will be performed and the results will be compared.

Task – 4: Verifying current MaineDOT method for evaluating concrete durability

Reviewing MaineDOT concrete durability evaluation method (MaineDOT 2020) and recommending some modifications based on formation factor analysis.

1.3 Report Overview

Chapter 1 is about the motivations, background and introduction of this project. This project consists of two parts, CO_2 – activated concrete and alkali – activated concrete. Part I of research is about CO_2 – activated concrete which includes chapters 2 and 3. Chapter 2 discusses about material properties, test setups, three different curing procedures, concrete mixtures (test matrix), concrete mixing procedure, and the methods and standards that has been used for testing specimens. 18 different CO_2 – activated concrete batches have been made in this part of research. Slump, compressive strength test, shrinkage test, bulk and surface electrical resistivity tests have been conducted for all concrete specimens. Chapter 3 shows the results for all test. Results interpretation is part of chapter 3 as well.

Part II of this project is about alkali – activated concrete. Chapters 4 and 5 describe the details of this part of project. Chapter 4 is about the material properties, curing procedure, test setups, concrete mixtures (test matrix), concrete mixing procedure, and the methods and standards that has been used for testing specimens. 13 different alkali – activated concrete mixtures have been used in this part of project. Compressive strength test, shrinkage test, bulk and surface electrical resistivity tests have been conducted for all concrete specimens in this part of research. Chapter 5 explains the results of tests and discusses about them.

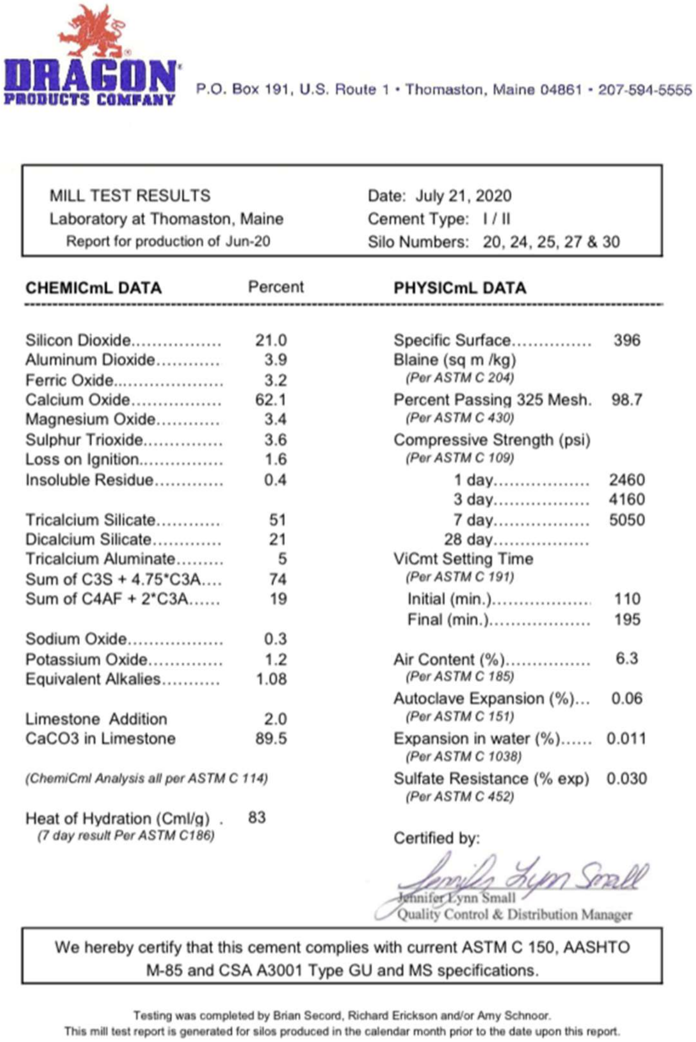
First section of chapter 6 (further discussion) is about comparing bulk and surface electrical resistivity test results. Second section is about introducing formation factor. Then formation factors for all CO2 – activated specimens will be calculated and discussed. Last chapter is chapter 7 which is about conclusions and recommendations. This report has one appendix which shows pictures of concrete specimens after completing compressive strength tests.

Part I: CO_2 - Activated Concrete

Chapter 2: CO_2 - Activated Concrete Methodology

2.1 Materials

The concrete used in this research were prepared by mixing slag, water, and cement powder to obtain mixtures with different dosages of slag. Ordinary Portland Cement (OPC), QUIKRETE Portland Type I/II , commercial grade, (fineness = 396 m^2/kg), that complies with ASTM C150/C150M 2019, Standard Specification for Portland Cement, was used in these tests. *Figure 1 shows* the mill test results of the cement.



DRAGON PRODUCTS COMPANY P.O. Box 191, U.S. Route 1 • Thomaston, Maine 04861 • 207-594-5555

MILL TEST RESULTS
Laboratory at Thomaston, Maine
Report for production of Jun-20

Date: July 21, 2020
Cement Type: I / II
Silo Numbers: 20, 24, 25, 27 & 30

CHEMICmL DATA	Percent
Silicon Dioxide	21.0
Aluminum Dioxide	3.9
Ferric Oxide	3.2
Calcium Oxide	62.1
Magnesium Oxide	3.4
Sulphur Trioxide	3.6
Loss on Ignition	1.6
Insoluble Residue	0.4
Tricalcium Silicate	51
Dicalcium Silicate	21
Tricalcium Aluminate	5
Sum of C3S + 4.75*C3A	74
Sum of C4AF + 2*C3A	19
Sodium Oxide	0.3
Potassium Oxide	1.2
Equivalent Alkalies	1.08
Limestone Addition	2.0
CaCO3 in Limestone	89.5

(ChemiCml Analysis all per ASTM C 114)

Heat of Hydration (Cml/g) . 83
(7 day result Per ASTM C186)

PHYSICmL DATA	
Specific Surface Blaine (sq m /kg) *(Per ASTM C 204)*	396
Percent Passing 325 Mesh. *(Per ASTM C 430)*	98.7
Compressive Strength (psi) *(Per ASTM C 109)*	
1 day	2460
3 day	4160
7 day	5050
28 day	
ViCmt Setting Time *(Per ASTM C 191)*	
Initial (min.)	110
Final (min.)	195
Air Content (%) *(Per ASTM C 185)*	6.3
Autoclave Expansion (%) *(Per ASTM C 151)*	0.06
Expansion in water (%) *(Per ASTM C 1038)*	0.011
Sulfate Resistance (% exp) *(Per ASTM C 452)*	0.030

Certified by:

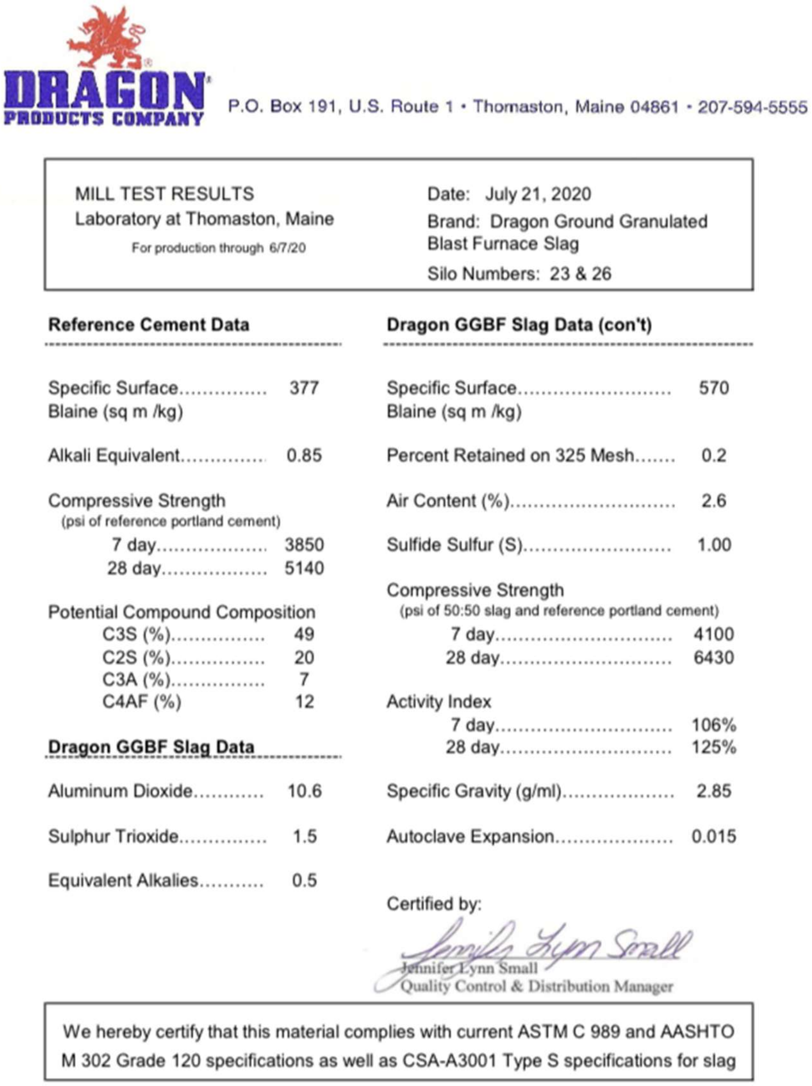
Jennifer Lynn Small
Jennifer Lynn Small
Quality Control & Distribution Manager

We hereby certify that this cement complies with current ASTM C 150, AASHTO M-85 and CSA A3001 Type GU and MS specifications.

Testing was completed by Brian Secord, Richard Erickson and/or Amy Schnoor.
This mill test report is generated for silos produced in the calendar month prior to the date upon this report.

Figure 1 OPC Type I/II Mill Test Results

Ground Granulated Blast Furnace Slag (GGBFS) Dragon slag grade 120 (fineness = 570 m^2/kg) that complies with ASTM C989/C989M 2018, Standard Specification for Slag Cement for Use in Concrete and Mortars , was used in this research. Figure *2* shows the mill test results of the slag. Both cement and slag were produced by the Dragon Products Company in Thomaston, Maine. Bulk sand, Fineness Modulus = 2.87, and fine gravels (passing 3/8", 9.5 mm) were provided by "Owen J. Folsom, INC.", Old Town, ME.



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MILL TEST RESULTS
Laboratory at Thomaston, Maine
For production through 6/7/20

Date: July 21, 2020
Brand: Dragon Ground Granulated Blast Furnace Slag
Silo Numbers: 23 & 26

Reference Cement Data

Specific Surface Blaine (sq m /kg)	377
Alkali Equivalent	0.85
Compressive Strength (psi of reference portland cement)	
7 day	3850
28 day	5140
Potential Compound Composition	
C3S (%)	49
C2S (%)	20
C3A (%)	7
C4AF (%)	12

Dragon GGBF Slag Data

Aluminum Dioxide	10.6
Sulphur Trioxide	1.5
Equivalent Alkalies	0.5

Dragon GGBF Slag Data (con't)

Specific Surface Blaine (sq m /kg)	570
Percent Retained on 325 Mesh	0.2
Air Content (%)	2.6
Sulfide Sulfur (S)	1.00
Compressive Strength (psi of 50:50 slag and reference portland cement)	
7 day	4100
28 day	6430
Activity Index	
7 day	106%
28 day	125%
Specific Gravity (g/ml)	2.85
Autoclave Expansion	0.015

Certified by:

Jennifer Lynn Small
Jennifer Lynn Small
Quality Control & Distribution Manager

We hereby certify that this material complies with current ASTM C 989 and AASHTO M 302 Grade 120 specifications as well as CSA-A3001 Type S specifications for slag

Figure 2 Slag Mill Test Results

For making concrete, 40% (by weight) river sand and 60% (by weight) gravel has been used as concrete aggregates. Binder content for all mixtures is 600 Kg/m^3 (1011 $lbs./yd^3$). Water to binder ratio (w/b) is 40% for all specimens.

2.2 CO_2 - Activated Binders (cement/slag)

In addition to cement, both parts of this research use slag as binder. First part uses carbonation (CO_2 – activation) as well. So, it is very important to know about the hydration reaction, slag pozzolanic reaction, and carbonation reaction. *Table 1* shows the well-known cement chemist notations.

Table 1 Cement Chemist Notations

Notation	Actual formula	Name
C	CaO	Calcium Oxide or Lime
S	SiO_2	Silicon Dioxide or Silica
H	H_2O	Water
A	Al_2O_3	Aluminum Oxide or Alumina
F	Fe_2O_3	Iron Oxide
$\bar{C}$	CO_2	Carbon Dioxide
$C\bar{C}$	$CaCO_3$	Calcium Carbonate
C_3S	$3\ CaO \cdot SiO_2$	Tricalcium Silicate (Alite)
C_2S	$2\ CaO \cdot SiO_2$	Dicalcium Silicate (Belite)
C_3A	$3\ CaO \cdot Al_2O_3$	Tricalcium Aluminate (Aluminate)
C_4AF	$4\ CaO \cdot Al_2O_3 \cdot Fe_2O_3$	Tetracalcium Alumino Ferrite (Ferrite)
CH	$Ca(OH)_2$ or $CaO \cdot H_2O$	Calcium Hydroxide (Portlandite)
$C - S - H$		Calcium Silicate Hydrate

CO_2 diffusion rate depends on Degree of Hydration (DOH), porosity, CO_2 concentration, RH, amounts and types of microscopic phase. Using these notations, hydration reaction, pozzolanic reaction, and CO2 – activation reaction can be written as follows (Ashraf 2016; Kashef-Haghighi and Ghoshal 2013; Morandeau et al. 2014):

Cement Hydration Reaction

$2C_3S + 6H = C_3S_2H_3 + 3CH$

$2C_2S + 4H = C_3S_2H_3 + CH$

Pozzolanic Reaction (much slower than cement hydration)

$CH + S + H = C - S - H$

$CH + A - S + H = C - A - S - H$

Carbonation of $Ca(OH)_2$

$CH + \bar{C} = C\bar{C} + H$

Carbonation of C-S-H

$C_xS_yH_z + x\bar{C} = x\ C\bar{C} + ySHt + (z-yt)H$

Carbonation of Unhydrated Cement

$C_3S + 3\bar{C} = S + 3\ C\bar{C}$

$C_2S + 2\bar{C} = S + 2\ C\bar{C}$

Figure 3 is schematic showing reaction products formed during accelerated CO2 curing from various reactive cement phases (Kashef-Haghighi and Ghoshal 2013).

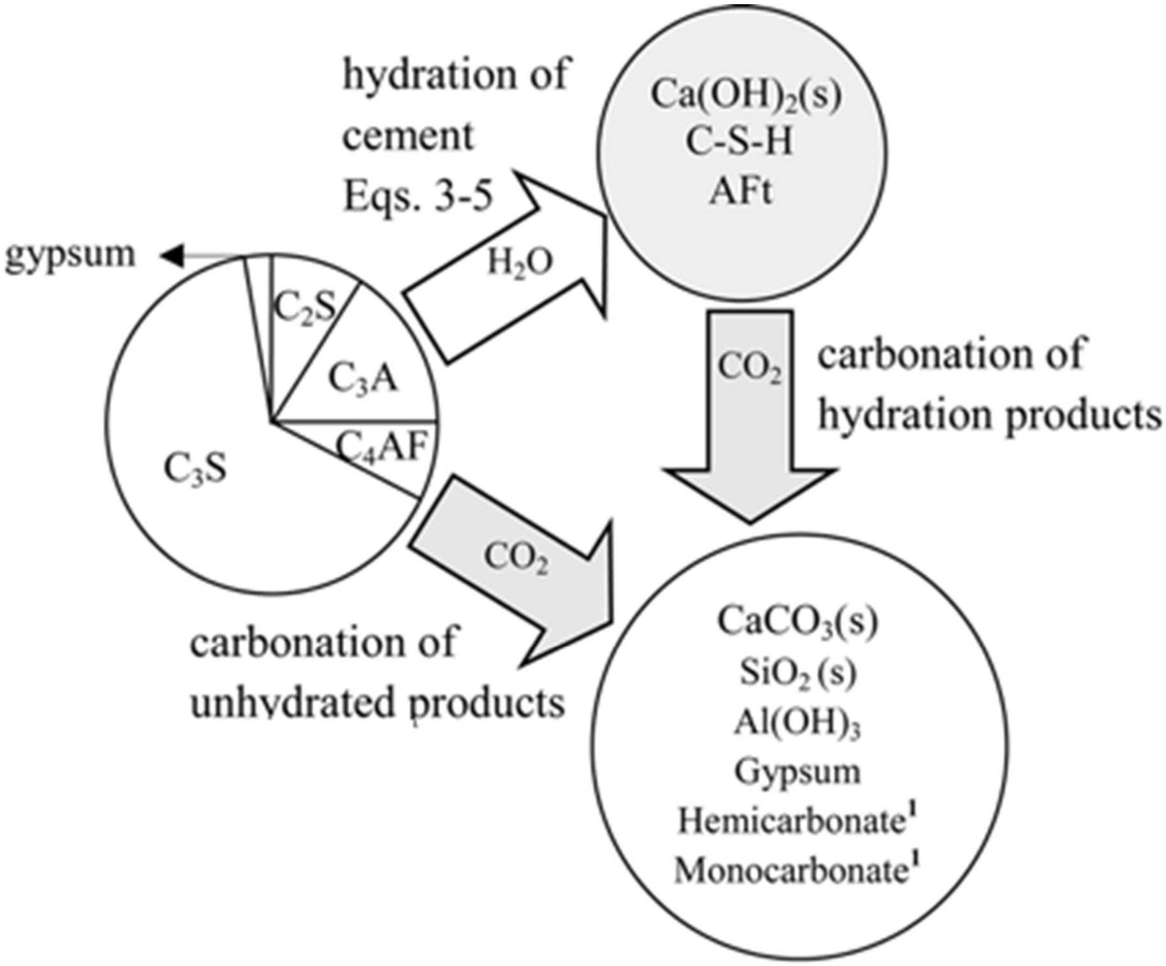

Figure 3 Schematic showing reaction products formed during accelerated CO_2 curing from various reactive cement phases

Figure *4* shows the difference between Portland cement concrete system and Portland-slag cement concrete system (Blair 2015). Following are the main differences of slag pozzolanic reaction in comparison with Portland cement concrete system:

- Pozzolanic reaction is much slower than the hydration reaction.
- Longer setting time, low initial rate of hydration, lower early strength
- Less amount of C_3S and C_3A content, less heat release, less thermal cracking

- Latent hydraulic properties, Pozzolanic reaction reduces porosity by blocking the capillary pores
- Denser micro structures resulting in lower permeability and diffusion, Increase the durability

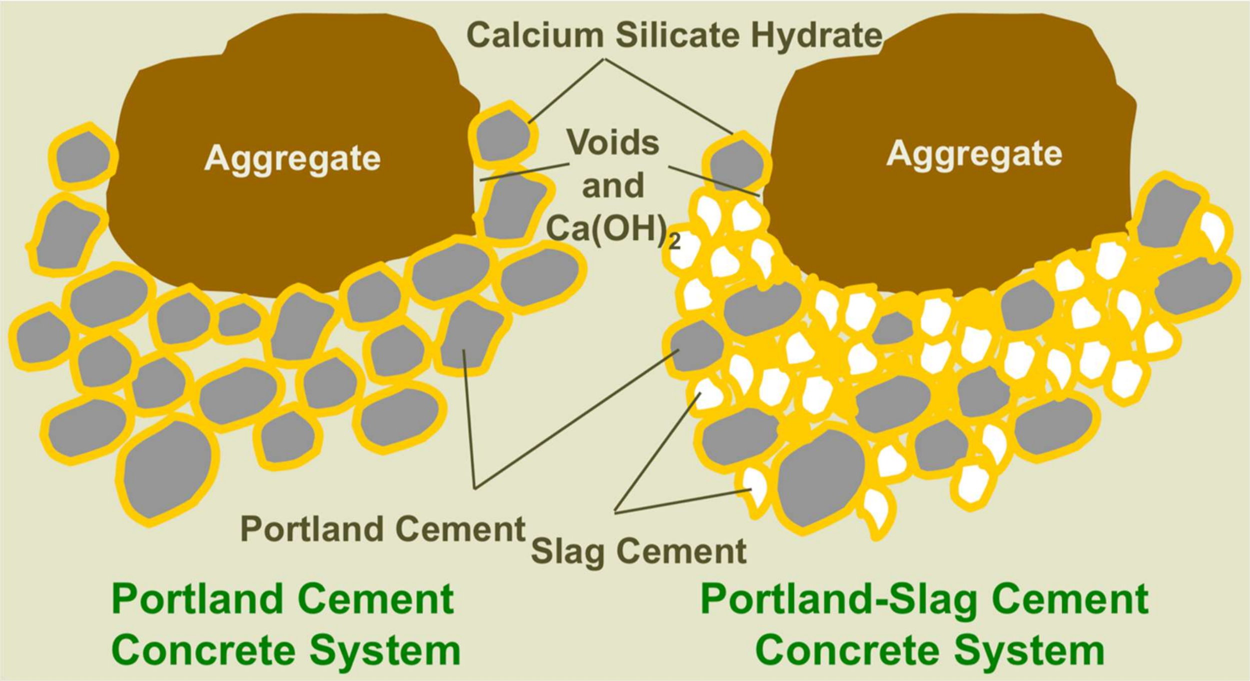

Figure 4 Portland Cement Concrete vs Portland-Slag Cement Concrete

2.3 Test Setup & Process

2.3.1 Curing Procedures

In this part of research, three different curing procedure has been used for curing concrete specimens. First curing procedure (Hydration) is regular sealed curing procedure (no CO_2 curing). It means curing sealed specimens in wet room for 28 days (Figure *5*).

Figure 5 Sealed specimens in wet room

In second procedure (Hydration + Carbonation), sealed specimens were kept in wet room for 3 days, then moved to carbonation chamber and cured with CO_2 for 4 days and finally returned to wet room and cured for remaining 21 days. *Figure 6* and Figure *7* show carbonation chamber setting. Accelerated carbonation curing test conditions are: RH = 50-60%, T = 22-25 ℃, Partial (Gauge) Pressure = 10-20 KPa.

Figure 6 Carbonation Chamber Setting

Third curing procedure (Carbonation + Hydration) means first 7 days curing in carbonation chamber and then curing in wet room for 21 days. Table *2* shows the details of these procedures.

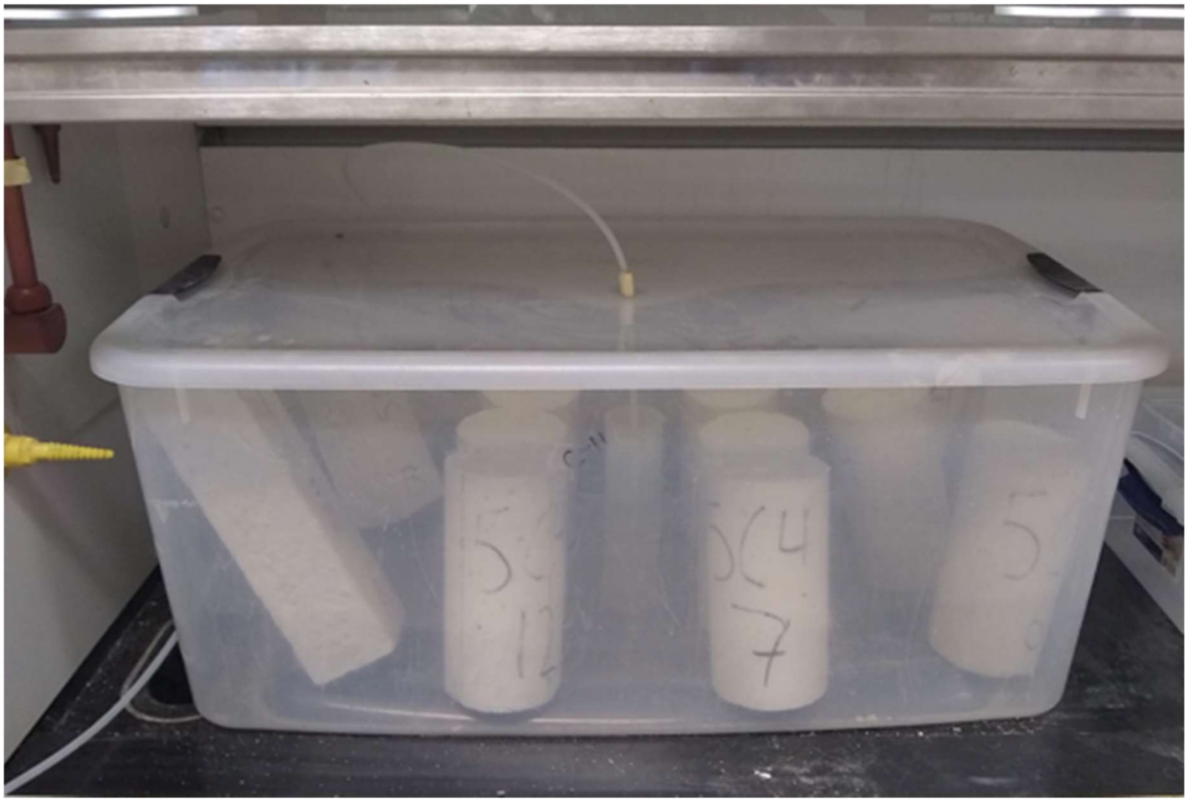

Figure 7 Carbonation Chamber

Table 2 Curing Procedures

Curing Procedure	Moist room	Carbonation Chamber	Moist room
Hydration	28 days	---	---
Hydration + Carbonation	3 days	4 days	21 days
Carbonation + Hydration	---	7 days	21 days

2.3.2 Concrete Mixtures

Based on curing procedures in *Table 2*, eighteen concrete mixtures have been defined in three groups. Group H, group C4, and group C7. For each group, six different slag contents 0, 20, 45, 65, 80, and 100% cement replacement were used.

Group H curing procedure is Hydration only (28 days in wet room). Group C4 curing procedure is Hydration + Carbonation (3 days in wet room + 4 days carbonation + 21 days in wet room). Group C7 curing procedure is Carbonation + Hydration (7 days carbonation + 21 days in wet room).

Table 3 CO_2 – Activated Concrete Test Matrix

28-day Curing Procedure	Batch Name	Cement Content (%)	Slag Content (%)	Materials
Group H **28 days in wet room**	1H	100	0	**Cement: OPC Type I/II** **Slag: Grade 120** **W/B: 0.40** **Binder Content: 600 Kg/m^3** **River Sand: 40%** **Gravel: 60%**
	2H	80	20	
	3H	55	45	
	4H	35	65	
	5h	20	80	
	6H	0	100	
Group C4 **3 days in wet room** **4 days in carbonation chamber** **21 days in wet room**	1C4	100	0	
	2C4	80	20	
	3C4	55	45	
	4C4	35	65	
	5C4	20	80	
	6C4	0	100	
Group C7 **7 days in carbonation chamber** **21 days in wet room**	1C7	100	0	
	2C7	80	20	
	3C7	55	45	
	4C7	35	65	
	5C7	20	80	
	6C7	0	100	

Total binder content for all mixtures is constant: 600 Kg/m^3 (1011 lbs./yd^3). In each group, we will have 6 different mixtures with various percentages of slag and cement contents. Slag replacement percentage changes from 0% in specimen 1 to 100% in specimen 6 in each group. Cement type I/II and slag properties can be found in Figure *1* and Figure *2* respectively.

Water to Cement ratio (w/c) is 40% for all specimens. For all mixtures, 40% (by weight) of aggregates are river sand and remaining 60% (by weight) are gravel. Table *3* shows the details of 18 mixtures that has been used in this project.

2.3.3 Concrete Specimen Preparation

Concrete mixes were prepared with the primary goal of evaluating the combined effects of slag and carbonation curing on workability, free shrinkage, compressive strength and transport properties. Concrete mixtures were prepared by mixing slag, water, sand, gravel, and cement to make batches with different slag contents.

The concrete specimens were mixed with a conventional 4 ft^3 drum mixer. Following ASTM C192/C192M 2019, Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. The following procedure was used for mixing the pastes: (1) add the coarse aggregate (gravel) before starting the mixer; (2) add 30% of mixing water; (3) start the mixer; (4) add fine aggregate (sand); (5) add cement; (6) add slag; (7) add remaining 70% of water; (8) mix for 3 minutes; (9) rest for 3 minutes (scrape during rest time); (10) mix for 2 minutes; (11) pour concrete; (12) at pan, remix with scoop. As further detailed below, slump tests were conducted immediately after completion of the mixing procedure. Concrete specimens were prepared at three different groups with constant water to cement (w/c) ratio of 0.40 and binder content of 600 Kg/m^3. By weight, 40% of aggregates are river sand and remaining 60% are gravel.

2.3.4 Concrete Slump Tests

A slump test, which was based on (ASTM C143/C143M 2020), Standard Test Method for Slump of Hydraulic-Cement Concrete, was performed for each batch directly after finishing the mixing procedure. The result is the slump in centimeters, for each batch. Figure *8* shows a typical slump test.

Figure 8 Slump Test

2.3.5 Concrete Compressive Strength Test

After mixing the concrete, nine 4 by 8 in. (101.6 by 203.2 mm) cylinder molds were used to mold 9 specimens for each batch. Molds were kept inside a wet room for 24 hours. Then specimens were demolded and cured for 28 days inside a wet room/carbonation chamber following procedures provided in Table *2*. (ASTM C39/C39M 2021), Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, was used to break the specimens and measure the compressive strengths aged for 3, 7, and 28 days. Results are the average value of compressive strengths of three specimens for each batch.

2.3.6 Concrete Free-Shrinkage Test

After mixing, two cold-rolled steel molds with dimensions of 3 by 3 by 10 in. (76.2 by 76.2 by 254 mm) were used to make the specimens. (ASTM C157/C157M 2017), Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete, was used to cast the specimens. After 24 hours of curing in a wet room, the specimens were demolded and stored in a control room with constant temperature of 25 °C and constant Relative Humidity (RH) of 50%. Length measurements were made using Dial Indicator H-3250 (Humboldt Manufacturing Inc., Raleigh, NC), a length comparator. This device meets the requirements of both (ASTM C157/C157M 2017) and (ASTM C490/C490M 2017), Standard Practice for Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete. The specimens were named and marked for the upper and lower ends to ensure that all specimens are placed in the same direction and at the same position in the length comparator device at each measurement.

The initial reading (reference) of the specimen's length was taken directly after demolding the specimens, which means after 1 day after water was added to the cement. Subsequent readings were taken at 7, 14, 21, 28, and 56 days of aging. Figure *9* and Figure *10* show a free shrinkage test and free shrinkage specimens respectively.

Figure 9 Free shrinkage test

Figure 10 Free shrinkage specimens

2.3.7 Concrete Bulk Electrical Resistivity Test

After mixing the concrete, three 4 by 8 in. (101.6 by 203.2 mm) cylinder molds were used to mold 3 specimens for each batch. Molds were kept inside wet room for 24 hours. Then specimens were demolded and for 28 days sealed cured inside wet room or unsealed cured inside carbonation chamber following procedures provided in Table *2*. These three specimens were used for both bulk and surface electrical resistivity tests.

Figure 11 Bulk electrical resistivity test setting

Giatec's RCON has been used for measuring the bulk electrical resistivity of concrete at various ages. Figure *11* shows our apparatus. Modified (ASTM C1876 2019), Standard Test Method for Bulk Electrical Resistivity or Bulk Conductivity of Concrete, was used to measure the bulk electrical resistivity of specimens aged for 1, 3, 7, 14, 21, and 28 days. Modification was in curing condition of specimens. Sealed curing condition has been used rather than simulated pore solution method mentioned in (ASTM C1876 2019). Results are the average value of bulk electrical resistivity of three specimens for each batch.

2.3.8 Concrete Surface Electrical Resistivity (4-point Wenner probe) Test

Same three specimens mentioned in previous section were used for surface electrical resistivity tests as well. Proceq's Resipod has been used for measuring the surface electrical resistivity of concrete at different ages. Figure 12 shows Resipod. (AASHTO T358 2015),

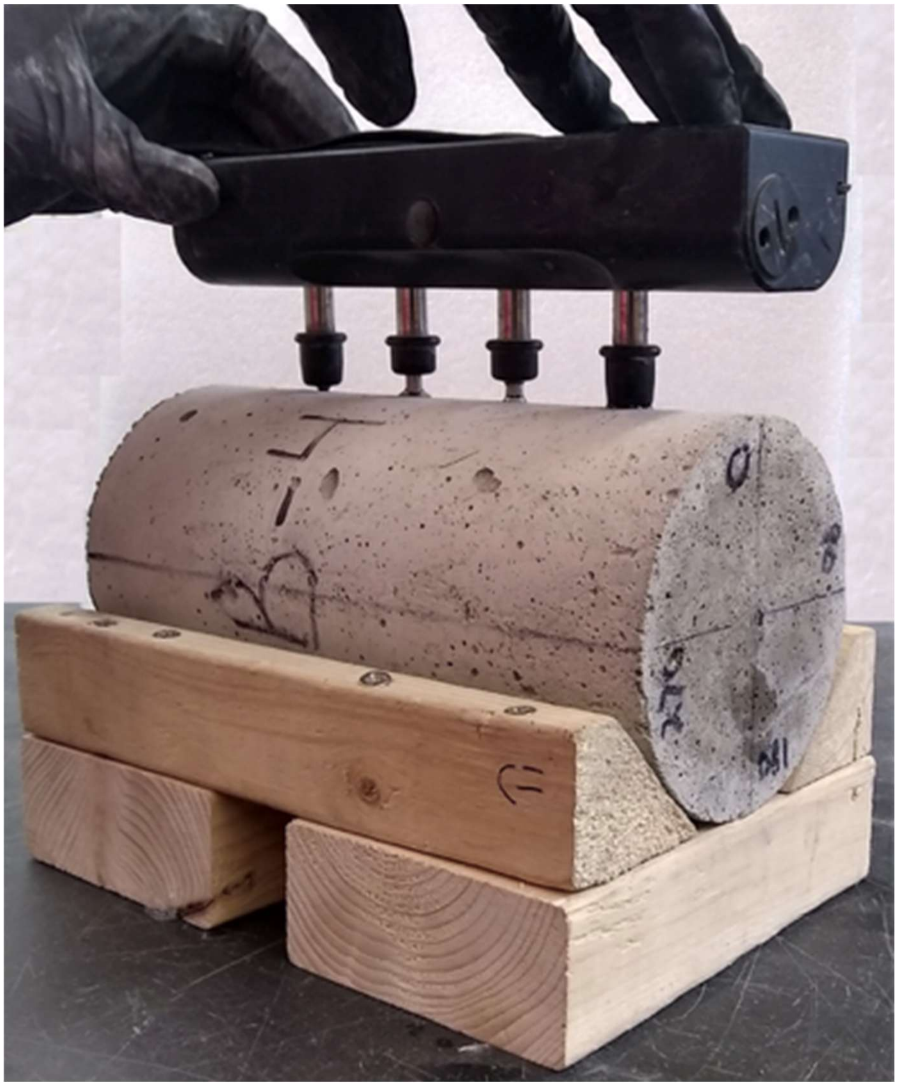

Figure 12 Surface Electrical Resistivity (4-point Wenner probe) Test

Standard Method of Test for Surface Resistivity Indication of Concrete’s Ability to Resist Chloride Ion Penetration, was used to measure the surface electrical resistivity of specimens aged for 1, 3, 7, 14, 21, and 28 days. Results are the average value of surface electrical resistivity of three specimens for each batch.

Chapter 3: CO_2 - Activated Concrete Results and Discussion

3.1 Concrete Slump Test Results

Figure 13 presents the results obtained from the concrete slump tests. This figure shows slump results for batches in Table *3* versus slag content. The plot highlights the observation that increasing slag leads to reduced workability.

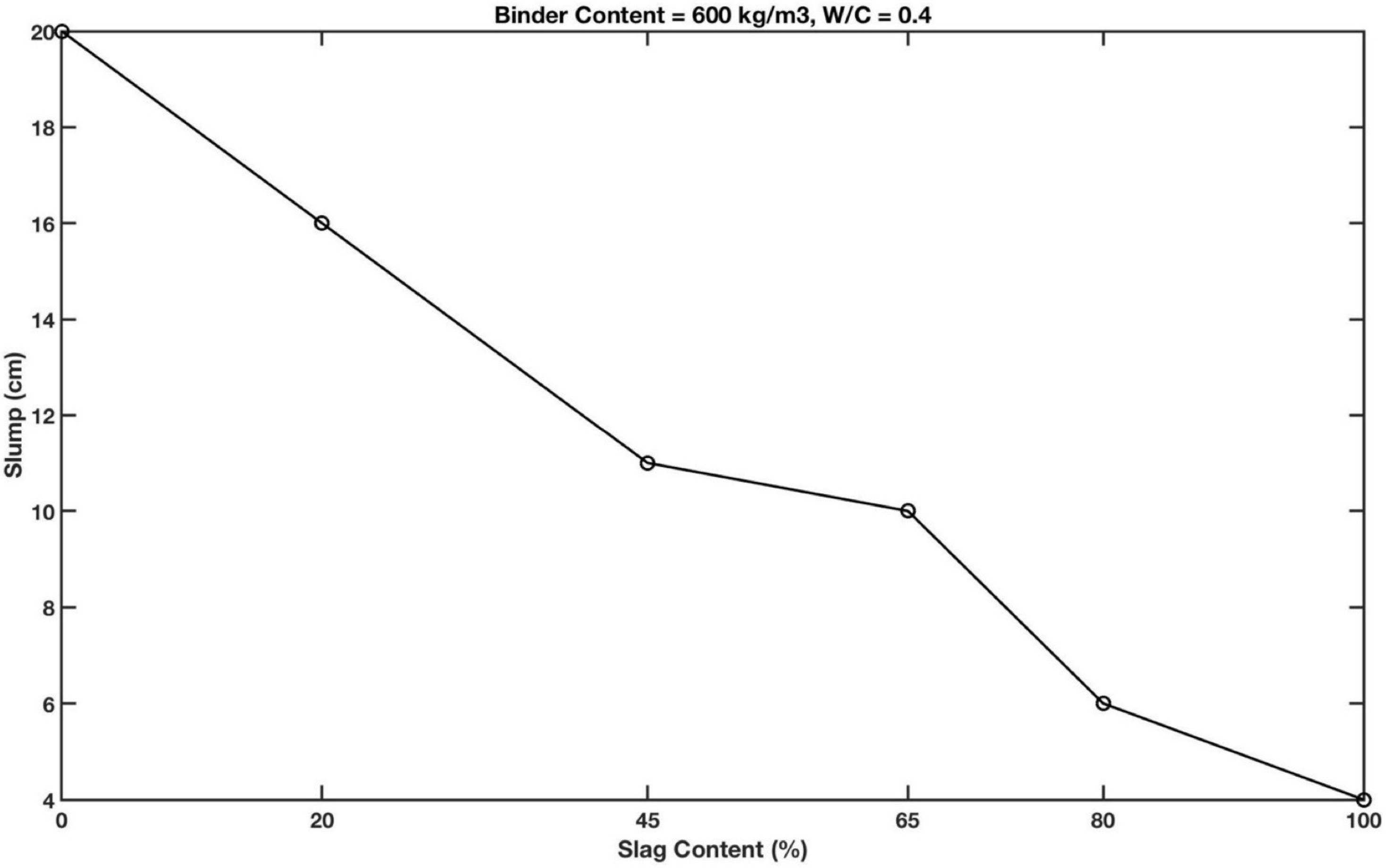

Figure 13 Concrete slump test results

3.2 Concrete Compressive Strength Test Results

Results of compressive strength tests (3, 7, and 28 days) vs slag content for concrete batches in Table *3* can be seen in Figure *14*, Figure *15*, and Figure *16*. It is clear from the plots that, in general, increasing the slag content after 65% leads to a reduction in compressive strength. However, it is also interesting to note that in groups H and C4 the best compressive strength happens in 65% slag content but for group C7, 20% slag replacement shows the best results. This shows the effect of curing procedure on compressive strength results. Also, based on Maine Department of Transportation Standard Specifications 2020 (MaineDOT 2020), concrete Class A (4000 psi) and Class LP (5000 psi) compressive strengths have been plotted for comparison

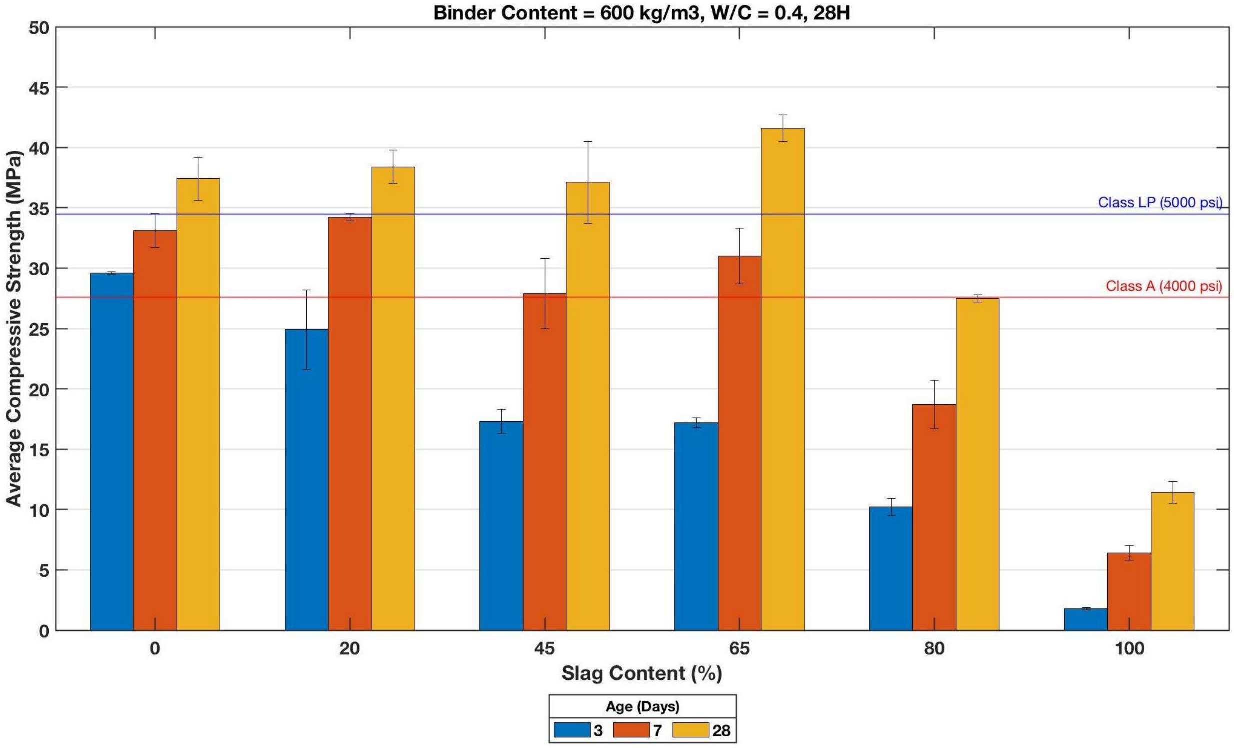

Figure 14 Concrete compressive strength results, Group H

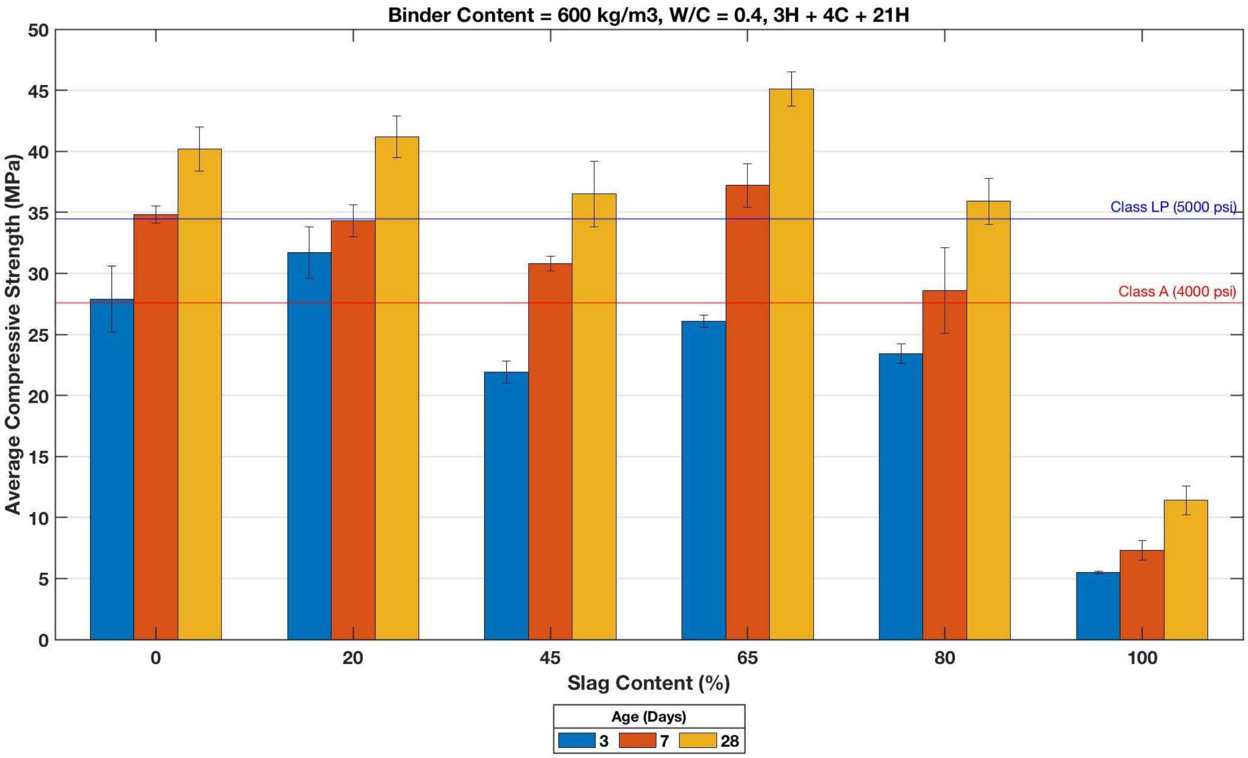

Figure 15 Concrete compressive strength results, Group C4

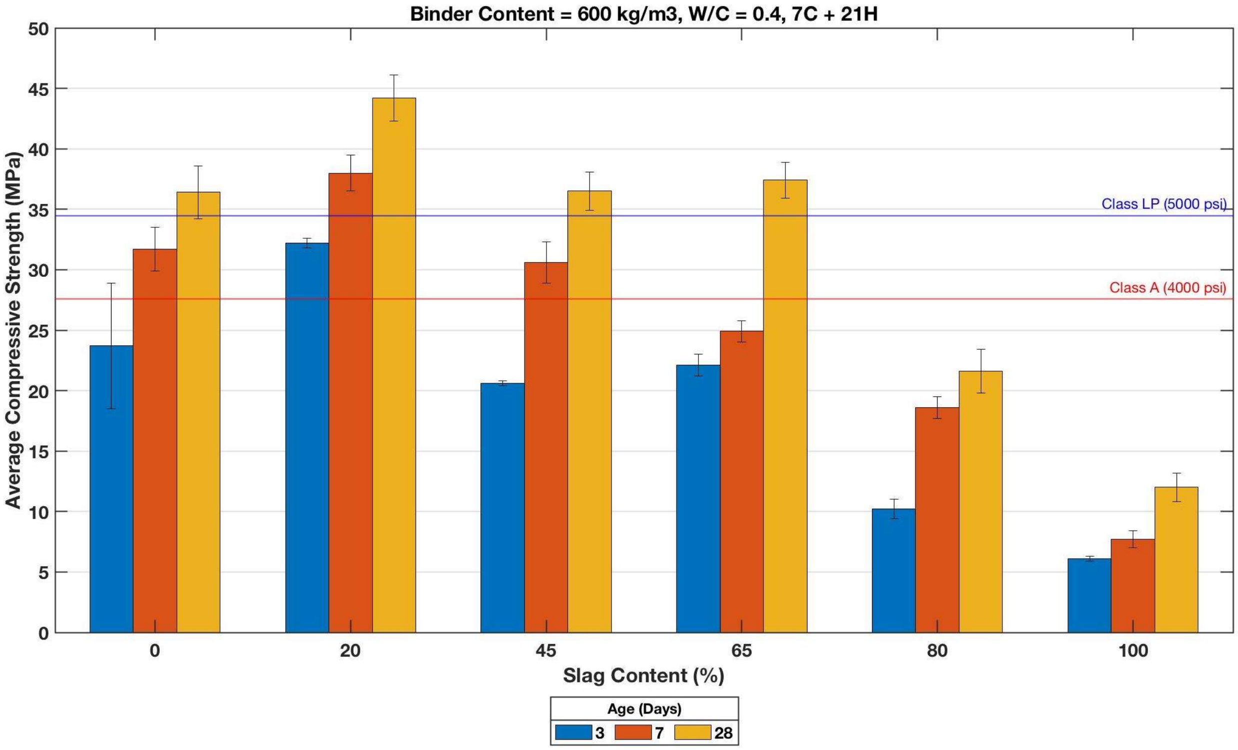

Figure 16 Concrete compressive strength results, Group C7

3.3 Concrete Free-Shrinkage Test Results

Figure *17*, Figure *18*, and Figure *19* show the results of free shrinkage versus slag content for 7, 14, 21, 28, and 56 days. The results showed that at group H (no carbonation), changing slag content doesn't affect shrinkage results dramatically. For both groups C4 and C7, free shrinkage results are very similar until 80% slag content. Results increase significantly when all cement replaced by slag (100% slag content).

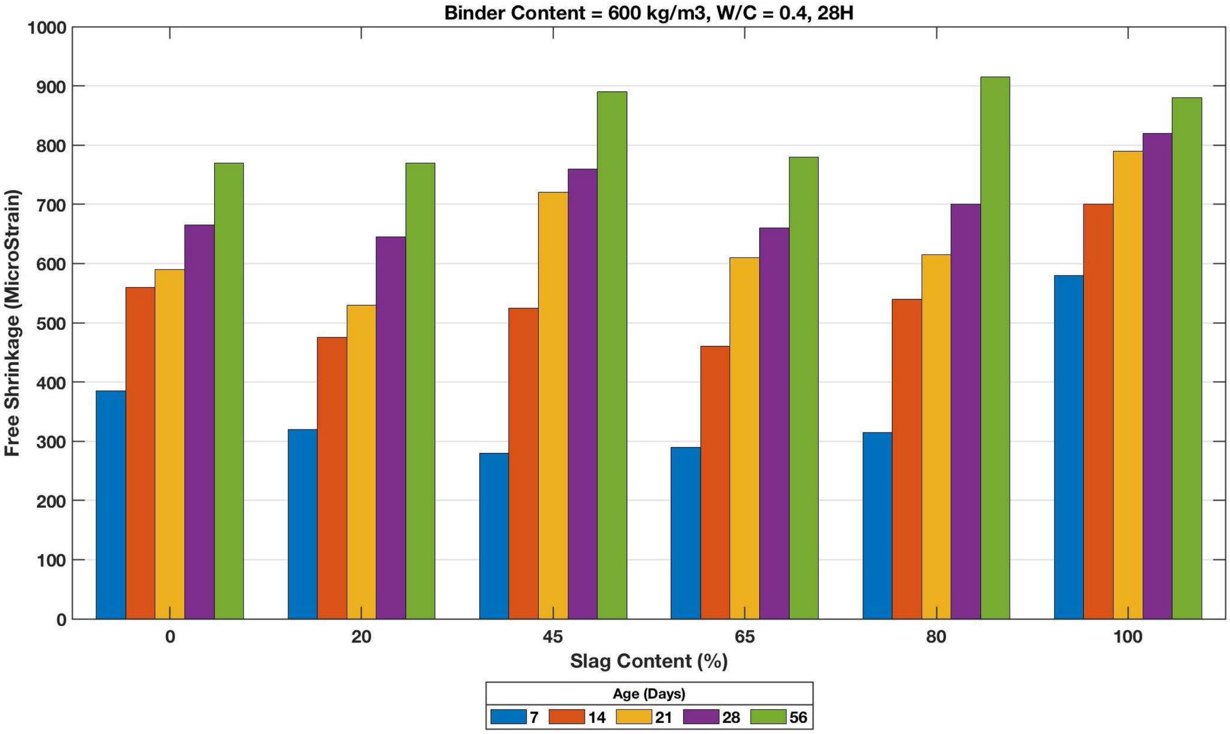

Figure 17 Concrete free shrinkage results, Group H

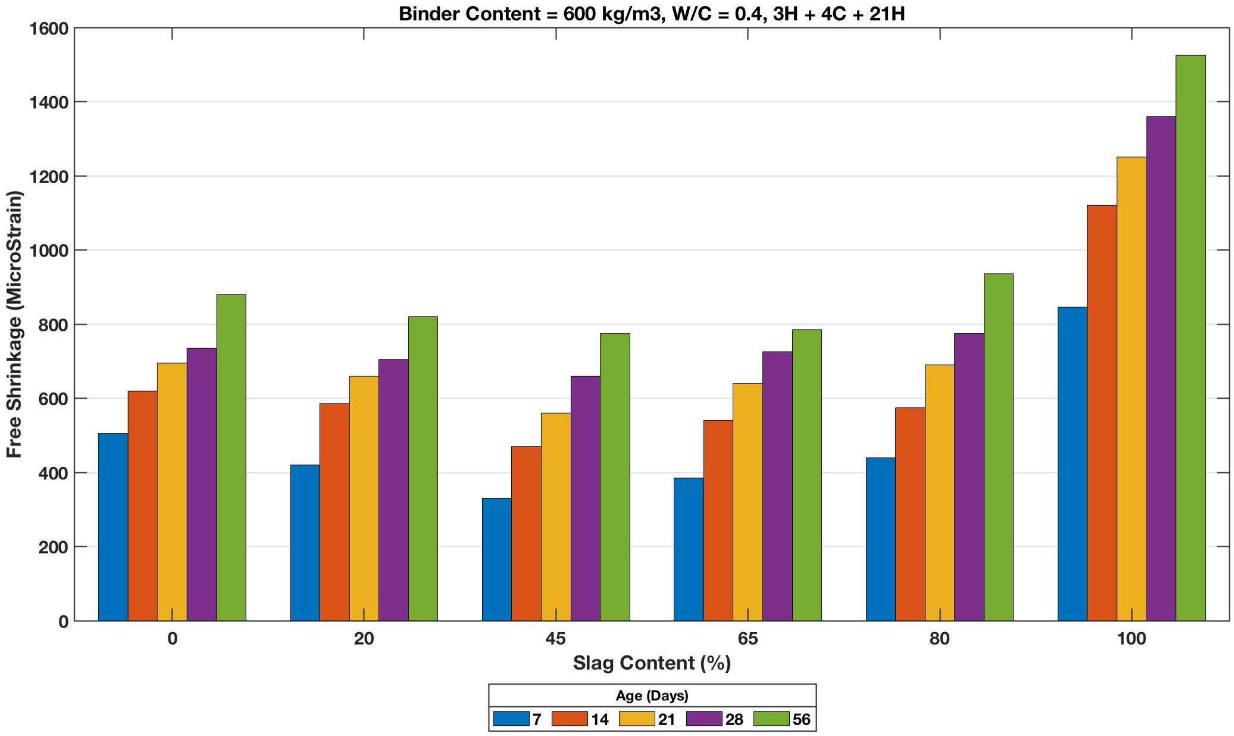

Figure 18 Concrete free shrinkage results, Group C4

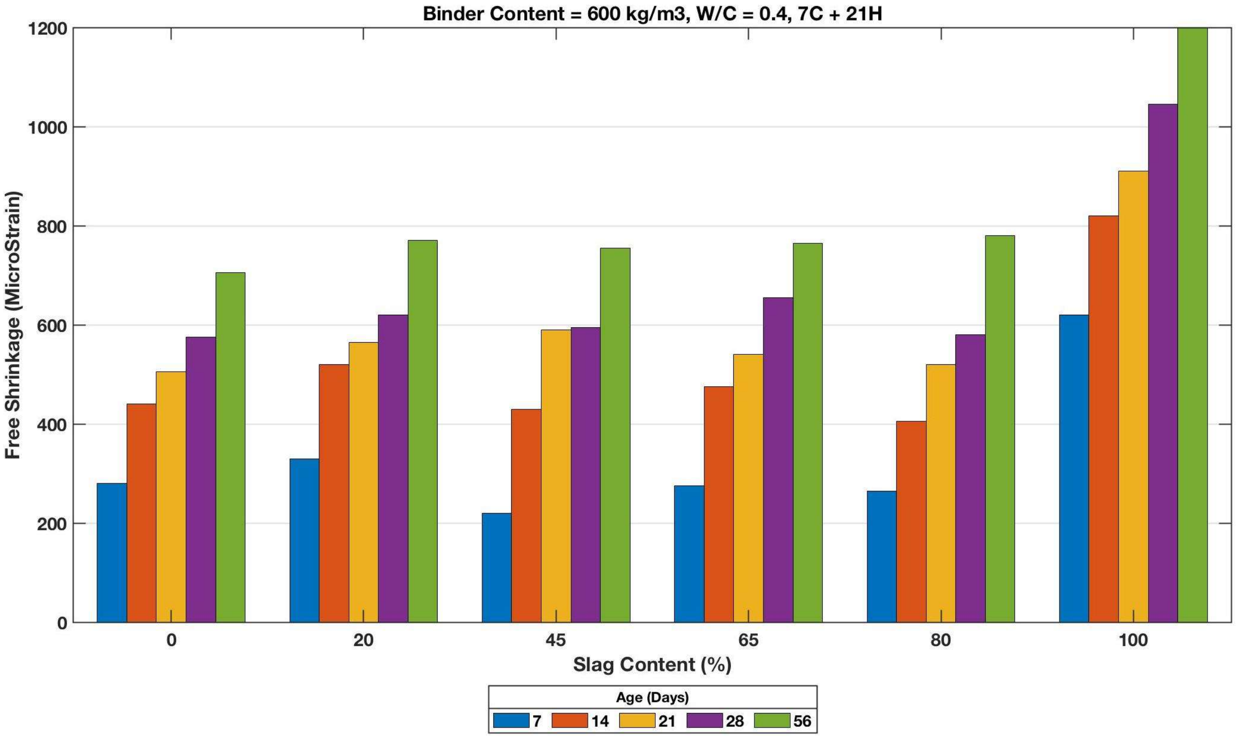

Figure 19 Concrete free shrinkage results, Group C7

3.4 Concrete Bulk Electrical Resistivity Test Results

Figure *20*, Figure *21*, and Figure *22* show the results of bulk electrical resistivity versus slag content for 1, 3, 7, 14, 21, and 28 days. The results showed that at groups H (no carbonation) and C7, increasing slag content increases the results dramatically until 80% slag. Then by removing cement (100% slag) bulk resistivity decreases. For group C4, always increasing slag content means a significant increment in bulk electrical resistivity. Bulk electrical resistivity test results have been considered as an index for permeability. It means that higher bulk electrical resistivity shows a better-quality concrete with denser microstructure and lower permeability. Results of this test shows the highest resistivity (lowest permeability) for 80% slag replacement in Group H and C7. In Group C4, 100% slag replacement shows the highest resistivity (the best (densest) microstructure).

On the other hand, compressive strength test results (see Figure *14*, Figure *16*, and Figure *15*) show that 80% and 100% slag replacement batches are the worst batches with the lowest compressive strengths (probably the highest permeability and the highest porosity). This shows that relying on raw results from bulk electrical resistivity tests is misleading. We will discuss about this issue in Chapter 6.

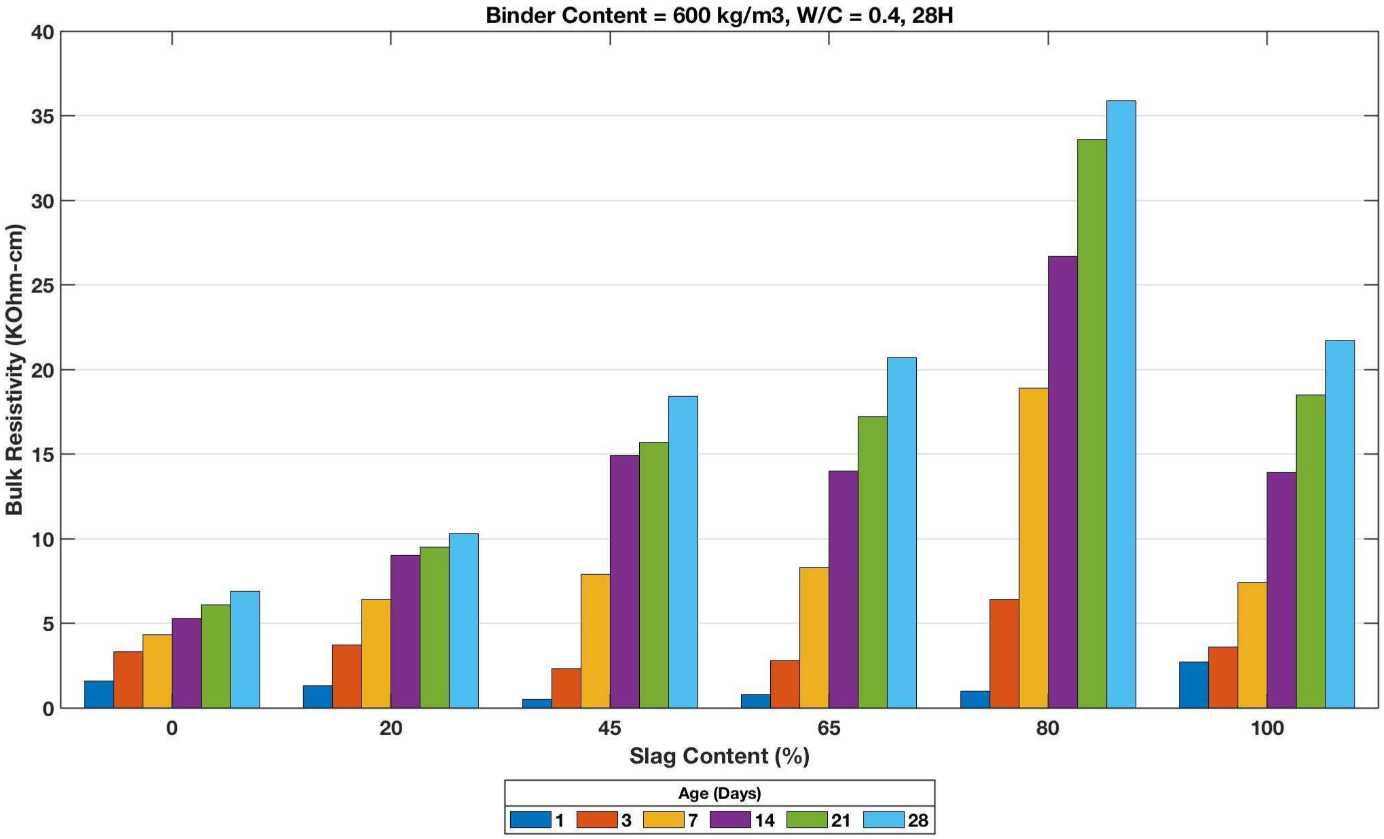

Figure 20 Concrete Bulk Electrical Resistivity Test Results, Group H

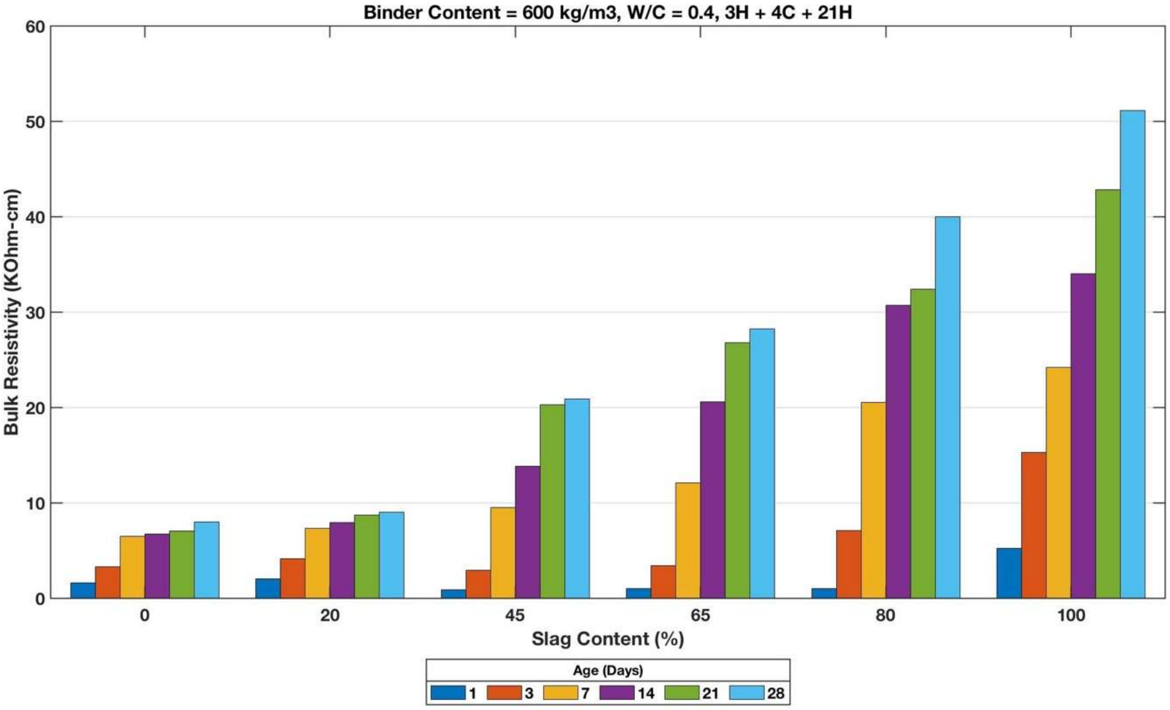

Figure 21 Concrete Bulk Electrical Resistivity Test Results, Group C4

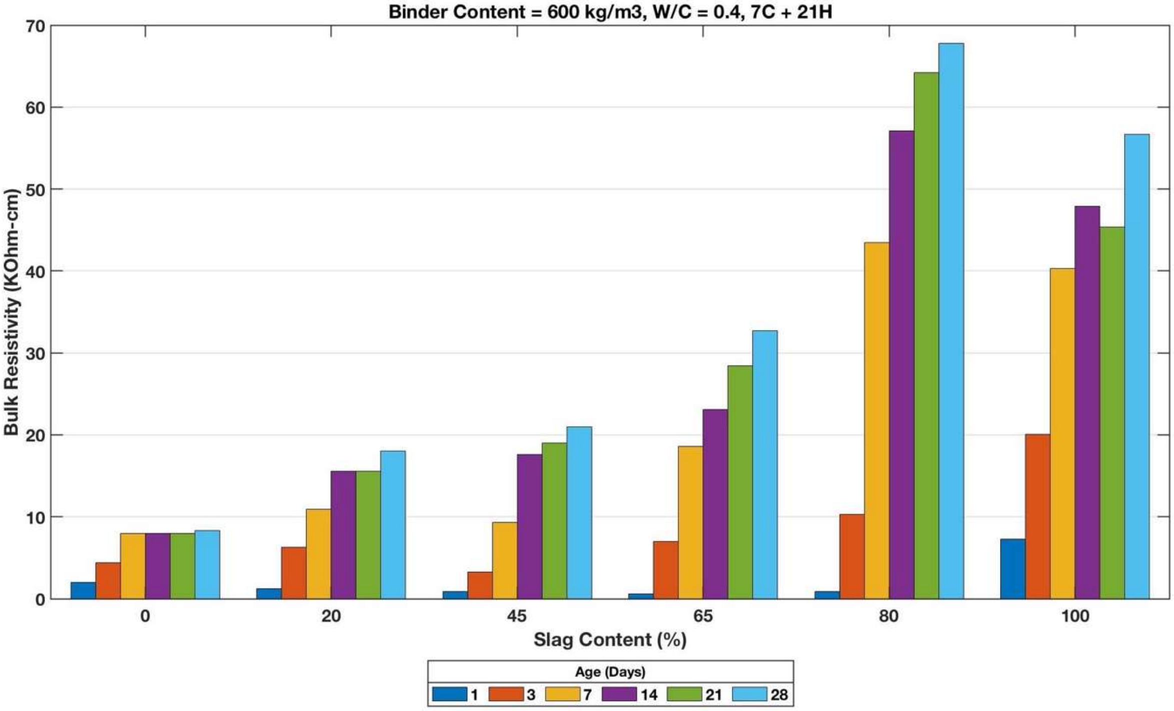

Figure 22 Concrete Bulk Electrical Resistivity Test Results, Group C7

3.5 Concrete Surface Electrical Resistivity (4-point Wenner probe) Test Results

Figure *23*, Figure *24*, and Figure *25* show the results of surface electrical resistivity (4-point Wenner probe) versus slag content for 1, 3, 7, 14, 21, and 28 days. The results showed that at groups H (no carbonation) and C7, increasing slag content increases the results significantly until 80% slag. Then at 100% slag, surface resistivity decreases. For group C4, always increasing slag content means a significant increment in surface electrical resistivity. Also, based on Maine Department of Transportation Standard Specifications 2020 (MaineDOT 2020), concrete Class A (14 KOhm-cm) and Class LP (17 KOhm-cm) required permeability, indicated by surface resistivity have been plotted for comparison.

Surface electrical resistivity test results have been used as an index for permeability. Concrete with higher surface electrical resistivity means higher quality concrete with denser microstructure and lower permeability. Results show the highest resistivity (lowest permeability) for 80% slag replacement in Group H and C7. For Group C4, 100% slag replacement shows the highest resistivity (the best (densest) microstructure).

On the other hand, compressive strength test results (see Figure *14*, Figure *16*, and Figure *15*) show that 80% and 100% slag replacement batches are the worst batches with the lowest compressive strengths (probably the highest permeability and the highest porosity). This shows that interpreting the results based on raw results from surface electrical resistivity tests is very confusing. We will discuss about this issue in Chapter 6.

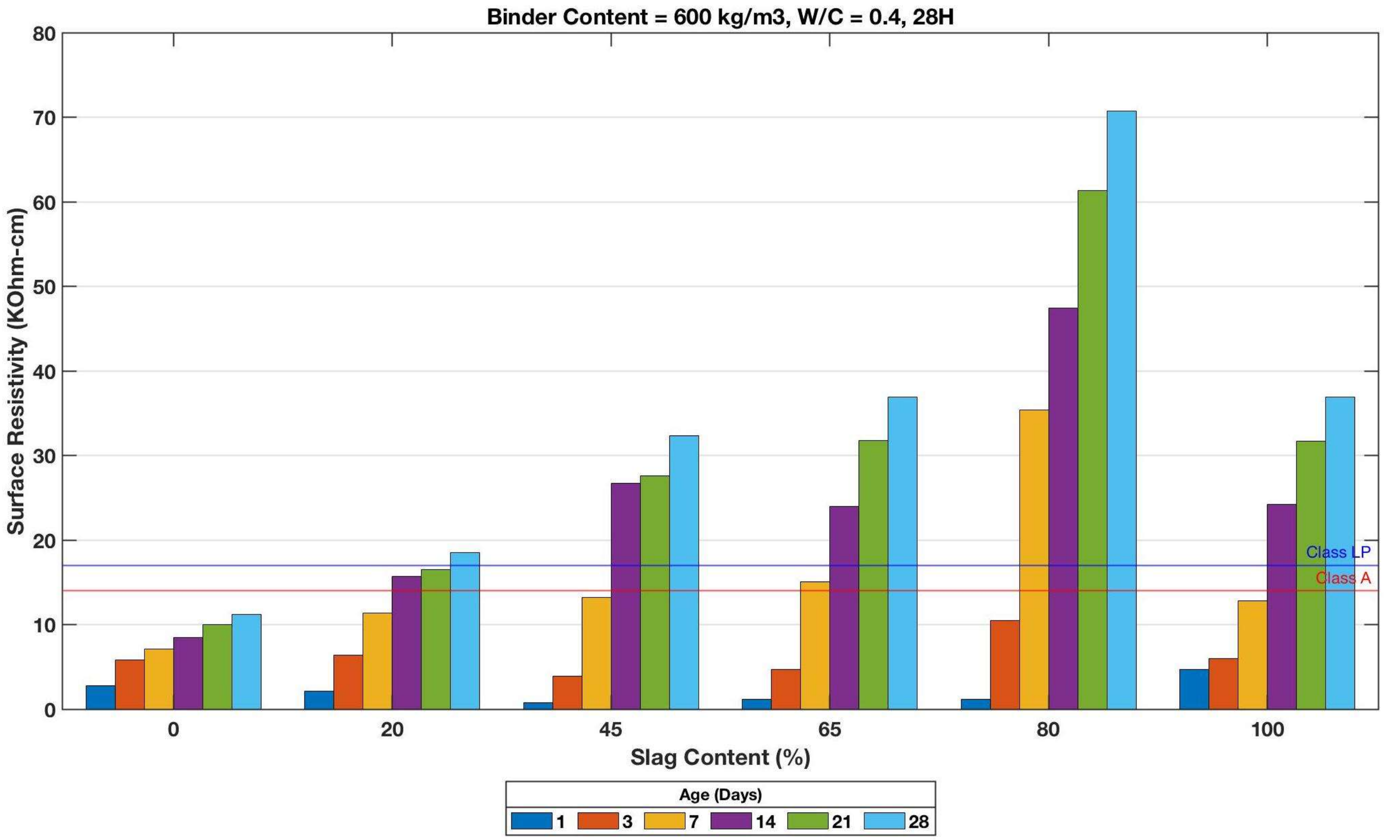

Figure 23 Surface Electrical Resistivity (4-point Wenner probe) Test Results, Group H

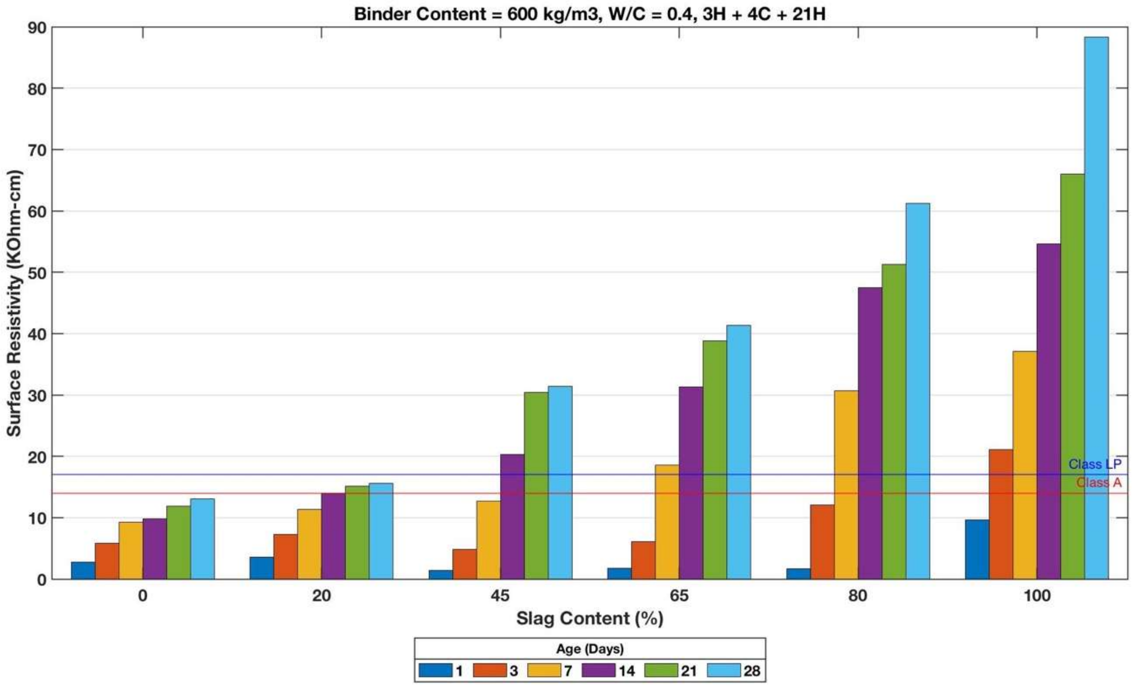

Figure 24 Surface Electrical Resistivity (4-point Wenner probe) Test Results, Group C4

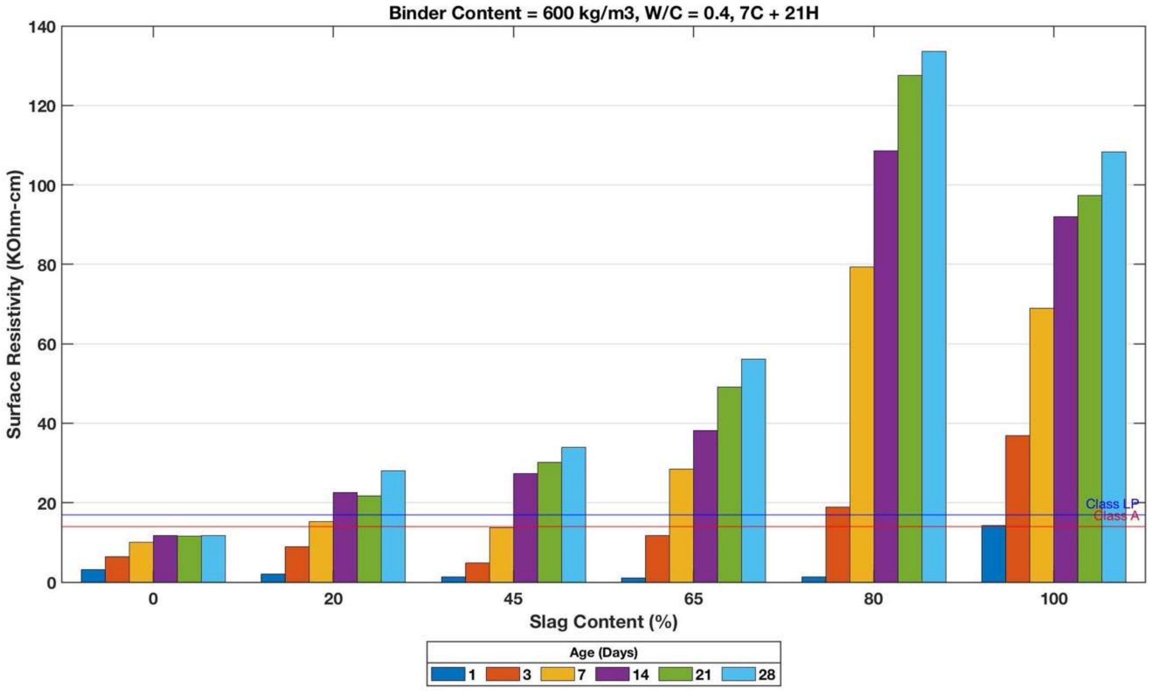

Figure 25 Surface Electrical Resistivity (4-point Wenner probe) Test Results, Group C7

Part II: Alkali - Activated Concrete

Chapter 4: Alkali - Activated Concrete Methodology

4.1 Materials

The concrete used in this part of research were prepared by mixing slag, water, Sodium Hydroxide pellets (NaOH, CAS Registry Number: 1310-73-2), and liquid sodium silicate, water glass, (Na_2SiO_3, CAS Registry Number: 1344-09-8) to obtain mixtures with different percentage of Na_2O and Silica Modulus (SiO_2 / Na_2O ratio). For making concrete, 40% (by weight) river sand and 60% (by weight) gravel has been used as concrete aggregates. Binder content for all mixtures is 375 Kg/m^3 (632 lbs./yd^3). Water to binder ratio (w/b) is 40% for all specimens.

Mill test results of Ground Granulated Blast Furnace Slag (GGBFS) Dragon slag grade 120 (fineness = 570 m^2/kg) have been shown in *Figure 2*. Bulk sand, Fineness Modulus = 2.87, and fine gravels (passing 3/8", 9.5 mm) were provided by "Owen J. Folsom, INC.", Old Town, ME.

Alkali activators of this concrete are NaOH and Na_2SiO_3. Sodium Hydroxide pellets (NaOH) were from "ACROS" with purity of 98.5% and density of 2.13 g/cm^3. Liquid sodium silicate, (Na_2SiO_3) were 4 Liter Aqua Solutions form "VWR". 29.3% of this product was SiO_2, 9.1% was Na_2O, and remaining 61.6% was H_2O.

4.2 Test Setup & Process

4.2.1 Curing Procedures

For alkali-activated concrete, sealed curing procedure has been used for curing concrete specimens. It means keeping sealed specimens in wet room until test day. See Figure *5*.

4.2.2 Concrete Mixtures

Based on literature review and previous research (Choi and Lee 2019; Pacheco-Torgal et al. 2008a; b; Provis 2018; Wang et al. 1994; Yusuf et al. 2015), one reference batch (A0) with cement binder only (no slag, no alkali – activators) and 12 alkali – activated concrete mixtures with slag binder only (no cement) have been defined in three groups (3%, 4%, and 5% Na_2O). For each group, 4 different silica moduli (SiO_2 / Na_2O ratio) were used (0.8, 1, 1.25, and 1.5)

Total binder content for all mixtures is constant: 375 Kg/m^3 (632 lbs./yd^3). Cement type I/II and slag properties can be found in Figure *1* and Figure *2* respectively. Water to binder ratio (w/b) is 40% for all specimens. For all mixtures, 40% (by weight) of aggregates are river sand and remaining 60% (by weight) are gravel. Table *4* shows the details of 13 mixtures that has been used in this part of project.

Table 4 Alkali – Activated Concrete Test Matrix

	Batch Name	**Silica Modulus (SiO2 / Na2O)**	**Na_2O (%)**	**Materials**
Reference	A0	0	0	**Binder = Cement only (OPC Type I/II)**
3% Na_2O	A1	0.8	3	**Binder = Slag only (Grade 120)** **W/B: 0.40** **Binder Content: 375 Kg/m^3** **River Sand: 40%** **Gravel: 60%**
	A2	1	3	
	A3	1.25	3	
	A4	1.5	3	
4% Na_2O	A5	0.8	4	
	A6	1	4	
	A7	1.25	4	
	A8	1.5	4	
5% Na_2O	A9	0.8	5	
	A10	1	5	
	A11	1.25	5	
	A12	1.5	5	

4.2.3 Concrete Specimen Preparation

Concrete mixes were prepared with the primary goal of evaluating the combined effects of changes in silica modulus and Na_2O percentage on free shrinkage, compressive strength and transport properties. Concrete mixtures were prepared by mixing slag, water, sand, gravel, NaOH solution (NaOH pellets + water), and liquid Na_2SiO_3 to make batches with different dosages of alkali - activators.

NaOH reaction with water is exothermic, where heat will be released. So, NaOH pellets should be mixed with water one day before concrete preparation. The molarity (M) of NaOH solution (NaOH pellets + water) in this research was 10 M (mol/liter). At mixing day, room temperature already prepared NaOH solution were mixed with liquid Na_2SiO_3 to make the final mixing solution.

The concrete specimens were mixed with a conventional 4 ft^3 drum mixer. Following ASTM C192/C192M 2019, Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. The following procedure was used for mixing the pastes: (1) add the coarse aggregate (gravel) before starting the mixer; (2) add 30% of mixing solution; (3) start the mixer; (4) add fine aggregate (sand); (5) add slag; (6) add remaining 70% of solution; (7) mix for 3 minutes; (8) rest for 3 minutes (scrape during rest time); (9) mix for 3 minutes; (10) pour concrete; (11) at pan, remix with scoop. Concrete specimens were prepared with constant water to cement (w/c) ratio of 0.40 and binder content of 375 Kg/m^3. By weight, 40% of aggregates are river sand and remaining 60% are gravel.

4.2.4 Concrete Compressive Strength Test

After mixing the concrete, nine 4 by 8 in. (101.6 by 203.2 mm) cylinder molds were used to mold 12 specimens for each batch. Molds were kept inside a wet room for 24 hours. Then specimens were demolded, sealed and cured for 28 days inside a wet room. (ASTM C39/C39M 2021), Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, was used to break the specimens and measure the compressive strengths aged for 1, 3, 7, and 28 days.

Results are the average value of compressive strengths of three specimens for each batch. *Figure 26* shows a typical test.

Figure 26 Compressive Strength Test

4.2.5 Concrete Free-Shrinkage Test

After mixing, two cold-rolled steel molds with dimensions of 3 by 3 by 10 in. (76.2 by 76.2 by 254 mm) were used to make the specimens. (ASTM C157/C157M 2017), Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete, was used to cast the specimens. After 24 hours of curing in a wet room, the specimens were demolded and stored in a control room with constant temperature of 25 °C and constant Relative Humidity (RH) of 50%. Length measurements were made using Dial Indicator H-3250 (Humboldt Manufacturing Inc., Raleigh, NC), a length comparator. This device meets the requirements of both (ASTM

C157/C157M 2017) and (ASTM C490/C490M 2017), Standard Practice for Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete. The specimens were named and marked for the upper and lower ends to ensure that all specimens are placed in the same direction and at the same position in the length comparator device at each measurement.

The initial reading (reference) of the specimen's length was taken 7 day after water was added to the cement. Subsequent readings were taken at 14, 21, and 28 days of aging. Figure *9* and Figure *10* show a free shrinkage test and free shrinkage specimens respectively.

4.2.6 Concrete Bulk Electrical Resistivity Test

After mixing the concrete, three 4 by 8 in. (101.6 by 203.2 mm) cylinder molds were used to mold 3 specimens for each batch. Molds were kept inside wet room for 24 hours. Then specimens were demolded and for 28 days sealed cured inside wet room. These three specimens were used for both bulk and surface electrical resistivity tests.

Giatec's RCON has been used for measuring the bulk electrical resistivity of concrete at various ages. Figure *11* shows our apparatus. Modified (ASTM C1876 2019), Standard Test Method for Bulk Electrical Resistivity or Bulk Conductivity of Concrete, was used to measure the bulk electrical resistivity of specimens aged for 1, 3, 7, 14, 21, and 28 days. Modification was in curing condition of specimens. Sealed curing condition has been used rather than simulated pore solution method mentioned in (ASTM C1876 2019). Results are the average value of bulk electrical resistivity of three specimens for each batch.

4.2.7 Concrete Surface Electrical Resistivity (4-point Wenner probe) Test

Same three specimens mentioned in previous section were used for surface electrical resistivity tests as well. Proceq's Resipod has been used for measuring the surface electrical resistivity of concrete at different ages. Figure 12 shows Resipod. (AASHTO T358 2015), Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration, was used to measure the surface electrical resistivity of specimens aged for 1, 3, 7, 14, 21, and 28 days. Results are the average value of surface electrical resistivity of three specimens for each batch.

Chapter 5: Alkali - Activated Concrete Results and Discussion

5.1 Concrete Compressive Strength Test Results

Results of compressive strength tests (1, 3, 7, and 28 days) vs Na_2O percentage and Silica Modulus for concrete batches in Table *4* can be seen in Figure *27*. Based on Maine Department of Transportation Standard Specifications 2020 (MaineDOT 2020), concrete Class A (4000 psi) and Class LP (5000 psi) compressive strengths have been plotted for comparison. It is clear from the plots that, in general, compressive strengths are very high. After 7 days, all batches satisfy MaineDOT Class A concrete requirements (4000 psi). Actually, in many of them Class A criteria (4000 psi) will be satisfied after 3 days. In some batches (4% and 5% Na_2O) you will obtain it in first day. It means the structure is ready to use in one day. Regarding MaineDOT class LP concrete, all batches satisfy Class LP compressive strength (5000 psi) after 28 days. Many of them reach to this number after 7 days. Some of them meet this criterion after 3 days. One batch will have it in one day. As can be seen in this plot, there are no results for last batch A12 (5% Na_2O, Silica Modulus = 1.5). Because of very low workability, we couldn’t cast that mixture.

Increasing the silica modulus usually leads to an increment in compressive strength. However, it seems that there is an optimum value for silica modulus that gives the best results. For 3% Na_2O, it happens in silica modulus of 1.5 but for 4% and 5% Na_2O, silica modulus of 1.25 gives the best results.

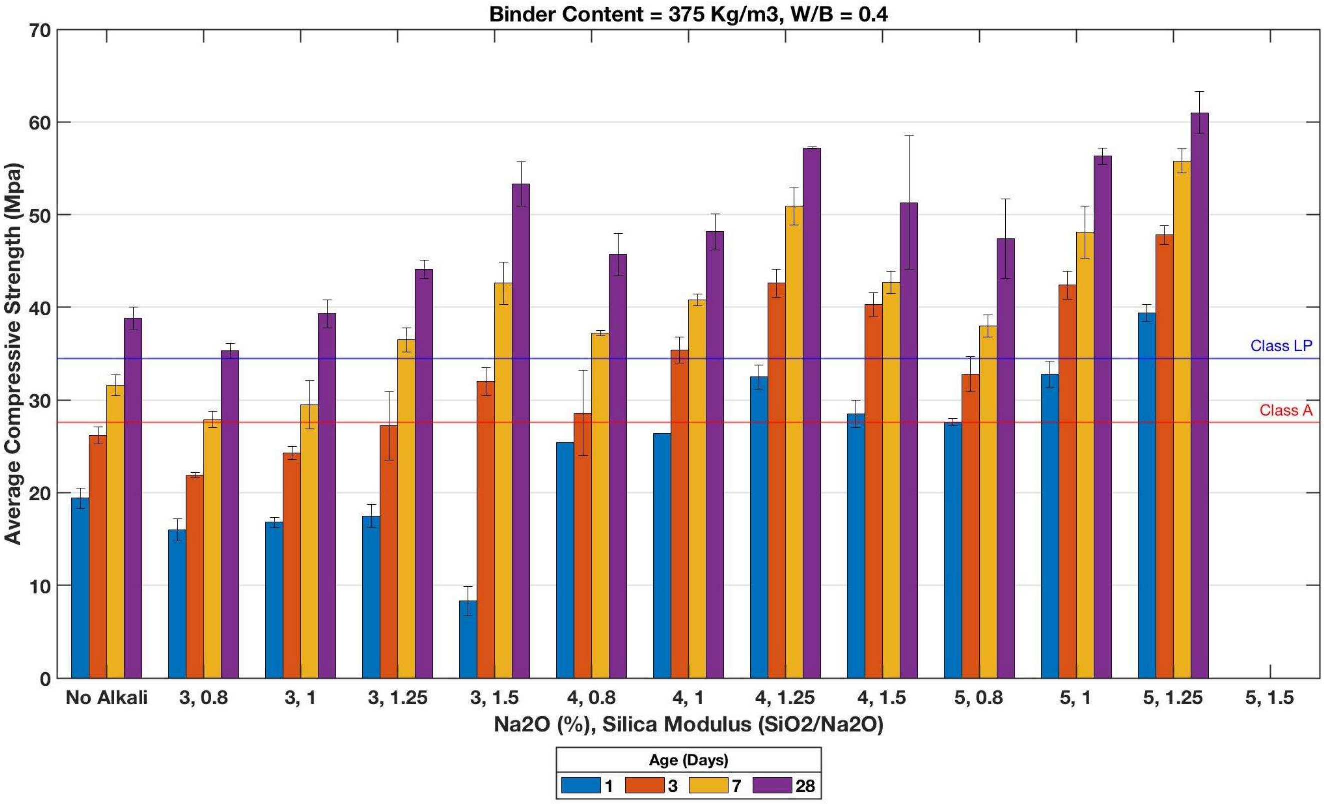

Figure 27 Compressive Strength Test Results for Alkali – Activated Concretes

5.2 Concrete Free-Shrinkage Test Results

Figure *28* shows the results of free shrinkage versus Na_2O percentage and Silica Modulus (see Table *4*) for 7, 14, 21, and 28 days. As can be seen in this plot, there are no results for last batch A12 (5% Na_2O, Silica Modulus = 1.5). Because of very low workability, we couldn't cast that mixture.

The results showed that, generally increasing the silica modulus leads to an increment in free shrinkage. However, it seems that there is an optimum value for Na_2O dosage that gives the best results (least free shrinkage). Results shows that 4% Na_2O gives the minimum free shrinkage results.

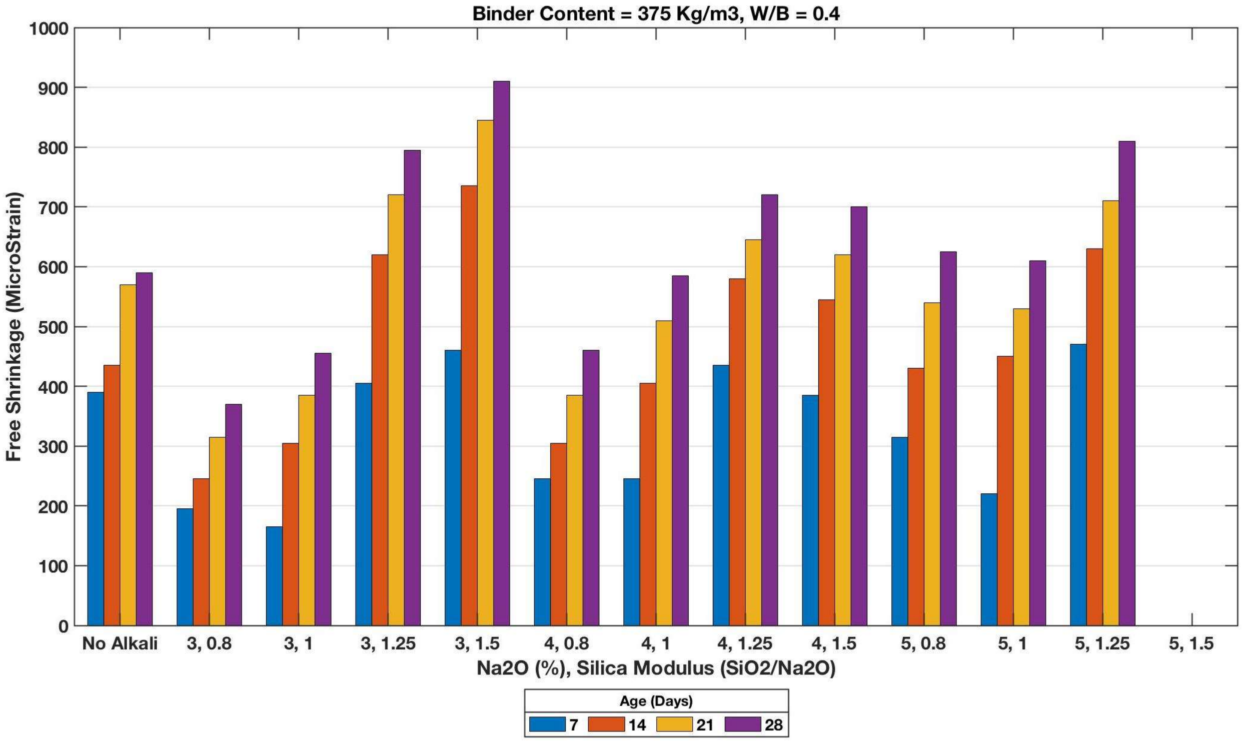

Figure 28 Free-Shrinkage Test Results for Alkali – Activated Concretes

5.3 Concrete Bulk Electrical Resistivity Test Results

Figure *29* shows the results of bulk electrical resistivity versus Na_2O percentage and Silica Modulus (see Table *4*) for 1, 3, 7, 14, 21, and 28 days. We missed some measurements because the test device was broken at those specific days. The results show that the highest bulk electrical resistivity happens at higher silica modulus (1.25 and 1.5) at 3% Na_2O.

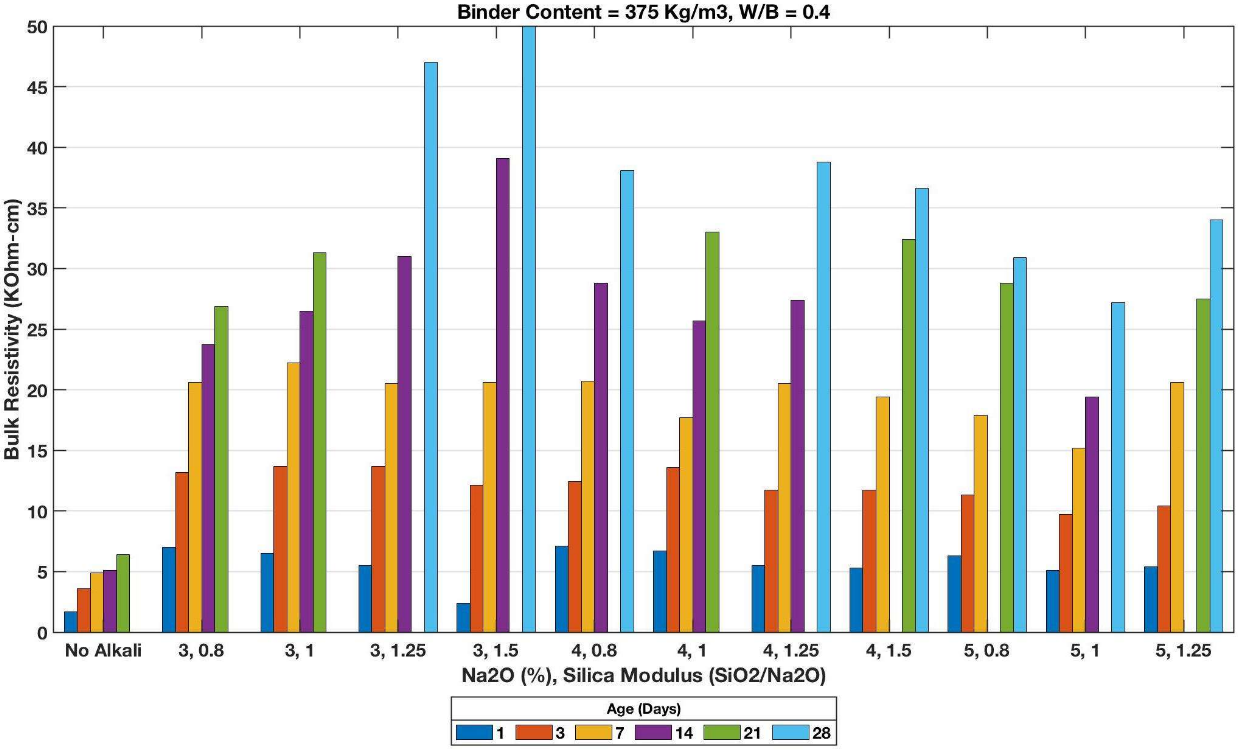

Figure 29 Bulk Electrical Resistivity Test Results for Alkali – Activated Concretes

Bulk electrical resistivity test results have been used as an index for permeability. Concrete with higher bulk electrical resistivity means higher quality concrete with denser microstructure and lower permeability. Results show the highest resistivity (the lowest permeability = the best quality) for 3% Na_2O.

On the other hand, compressive strength test results (see Figure *27*) shows that batches with 4% and 5% Na_2O are the best. This contradiction shows that interpreting the results based on raw results from bulk electrical resistivity tests is very confusing. We will discuss about this issue in Chapter 6.

5.4 Concrete Surface Electrical Resistivity (4-point Wenner probe) Test Results

Figure *30* shows the results of surface electrical resistivity (4-point Wenner probe) versus Na_2O percentage and Silica Modulus (see Table *4*) for 1, 3, 7, 14, 21, and 28 days. As can be seen in this plot, there are no results for last batch A12 (5% Na_2O, Silica Modulus = 1.5). Because of very low workability, we couldn't cast that mixture. Based on Maine Department of Transportation Standard Specifications 2020 (MaineDOT 2020), concrete Class A (14 KOhm-cm) and Class LP (17 KOhm-cm) required permeability, indicated by surface resistivity have been plotted for comparison.

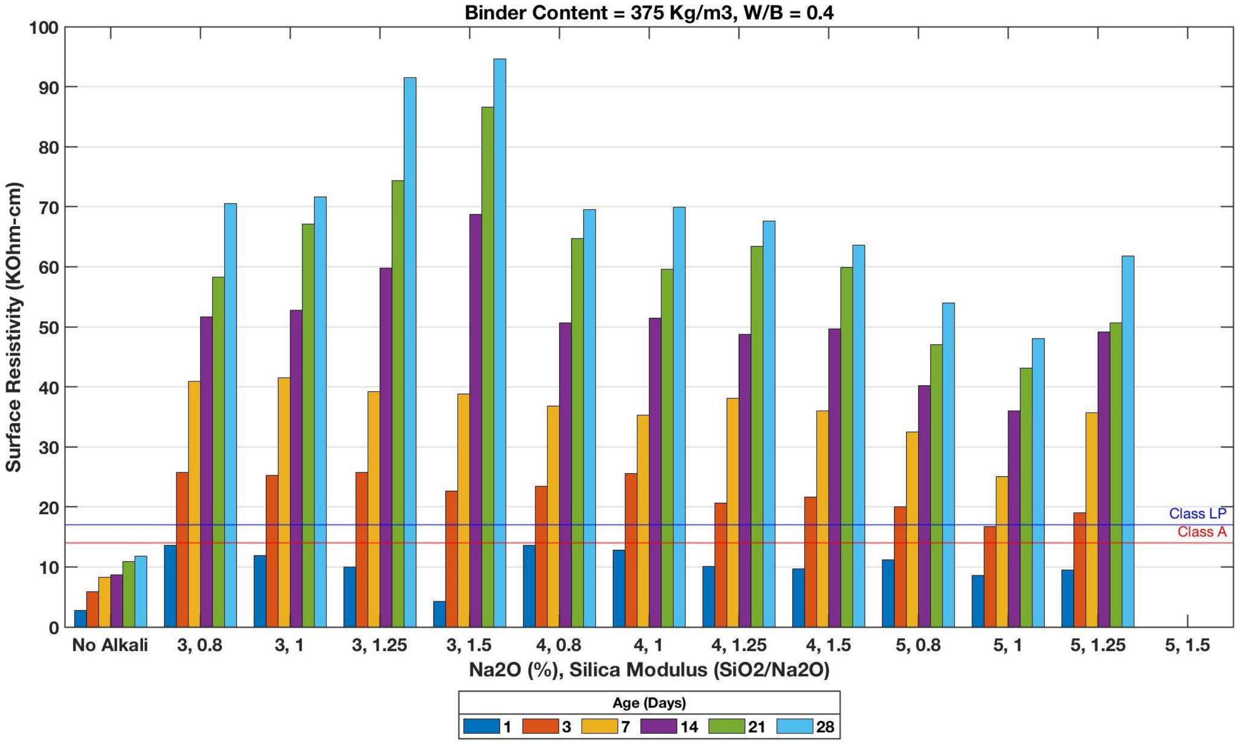

Figure 30 Surface Electrical Resistivity Test Results for Alkali – Activated Concretes

Surface electrical resistivity test results have been considered as an index for permeability. Concrete with higher surface electrical resistivity means higher quality concrete with denser microstructure and lower permeability. The results show that the highest surface electrical resistivity (the lowest permeability with the best (densest) microstructure) happens at higher silica modulus (1.25 and 1.5) at 3% Na_2O.

On the other hand, compressive strength test results (see Figure *27*) shows that batches with 4% and 5% Na_2O are the best. This shows that explianing the results based on raw results from surface electrical resistivity tests could be misleading. We will discuss about this issue in Chapter 6.

Chapter 6: Further Discussion

6.1 Comparing Bulk and Surface Electrical Resistivity Test Results

Both bulk and surface electrical resistivity measure the electrical resistivity of the concrete specimens (Layssi et al. 2015). Comparing the results from these two tests could be interesting. Question is this: do we really need to do both tests? Or doing one of them is enough? And the results will be the same at the end of the day?

For answering this question, we compared the results of these two tests for CO_2 – Activated Concretes (Part I: Groups H, C4, and C7). Before comparing the results, based on recommendations from (Spragg et al. 2013), surface electrical resistivity test results should be modified for finding the corresponding bulk electrical resistivity.

Our specimens were 4 by 8 in. cylinders. Proceq's Resipod with 1.5 in. probe spacing (see Figure 12) has been used for measuring surface electrical resistivity. So, parameters mentioned in (Spragg et al. 2013) will be:

d (diameter of specimen) = 4 inches

L (length of specimen) = 8 inches

a (uniform electrode spacing) = 1.5 inches

$d/a = 2.67 < 4 \Rightarrow$ OK and $L/a = 5.33 > 5 \Rightarrow$ OK

$\Rightarrow$ k (geometry correction factor) = $2\pi a / 1.92$

From Proceq's Resipod manual (PROCEQ 2017), it can be found that device's k is $2\pi a$. It means $2\pi a$ is already included in measurements and modifying the surface electrical resistivity results means dividing the original results by 1.92 (modification factor for this geometry). In other words, by this geometry (diameter, d, and length, L, of concrete specimen and electrode spacing, a, of Resipod), dividing measured surface resistivity (measured by Proceq's Resipod) by 1.92 (modification factor for this geometry) shows the corresponding bulk electrical resistivity.

Modified surface electrical resistivities vs measured bulk electrical resistivities have been plotted for each group separately (See *Figure 31*, Figure 32, and Figure 33). Plot of this comparison for all specimens (252 test results from groups H, C4, and C7) can be seen in Figure 34. Coefficients of determination (R^2) for all fittings are higher than 0.99 which shows that bulk resistivity can be estimated with a very high accuracy by measuring surface resistivity and vice versa. It means conducting one of these two tests is enough and second test results can be estimated by modifying the results of the first one.

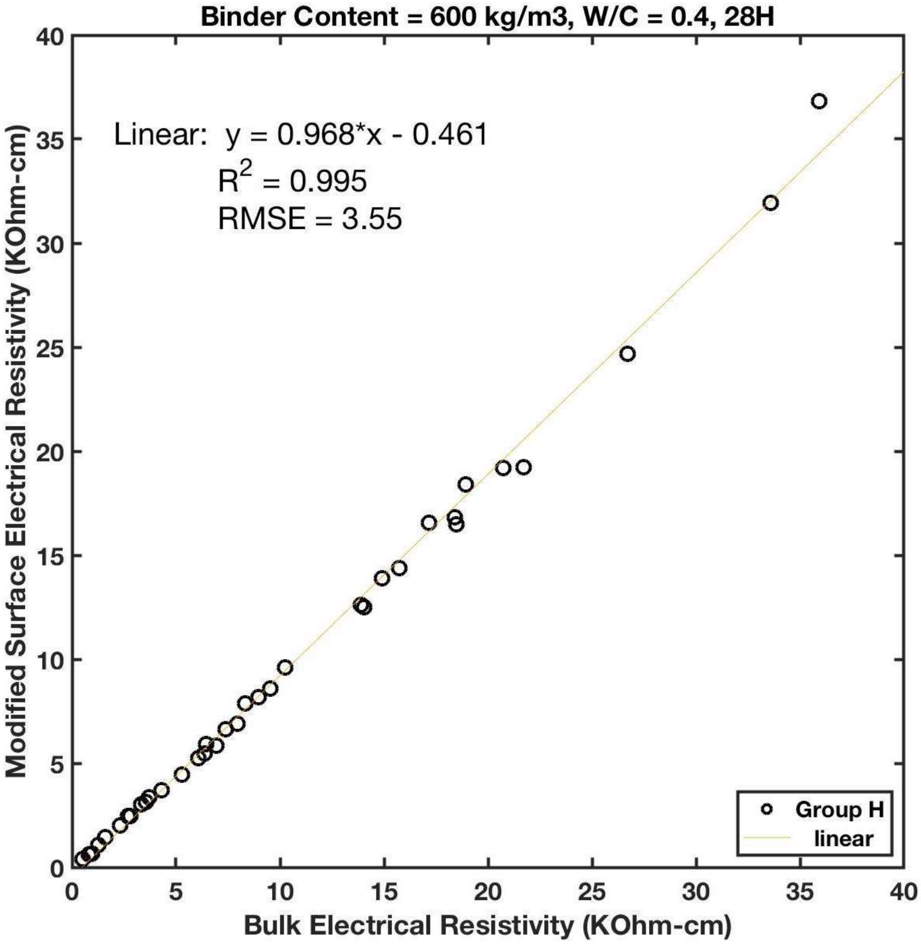

Figure 31 Bulk vs Modified Surface Electrical Resistivity Test Results, Group H

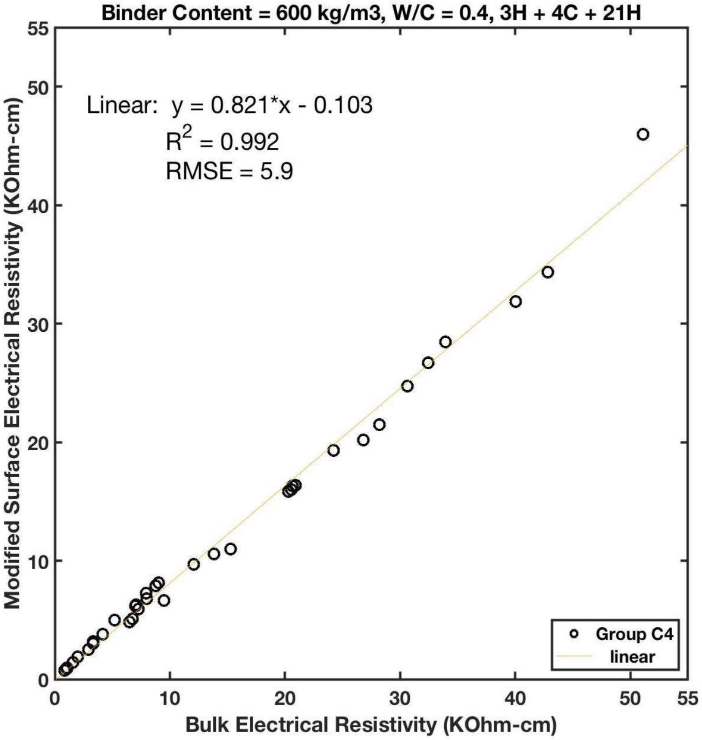

Figure 32 Bulk vs Modified Surface Electrical Resistivity Test Results, Group C4

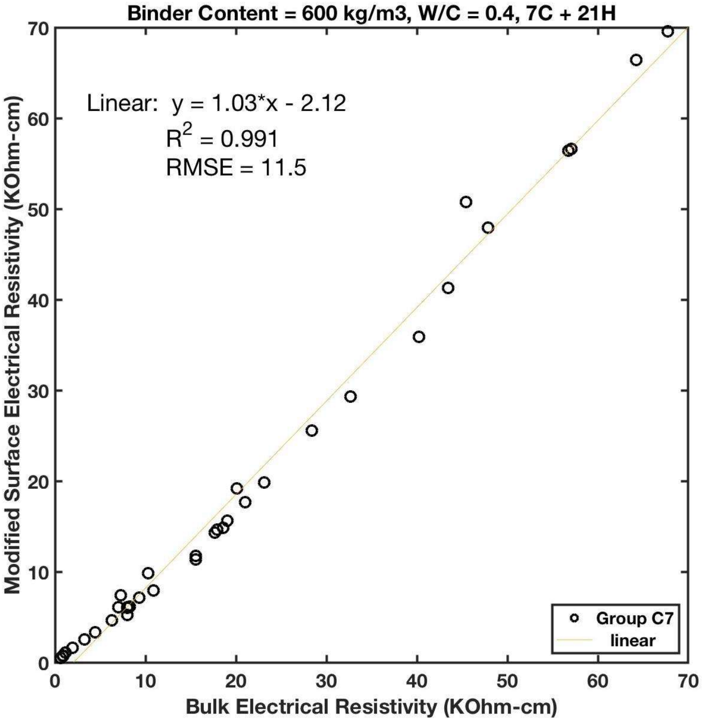

Figure 33 Bulk vs Modified Surface Electrical Resistivity Test Results, Group C7

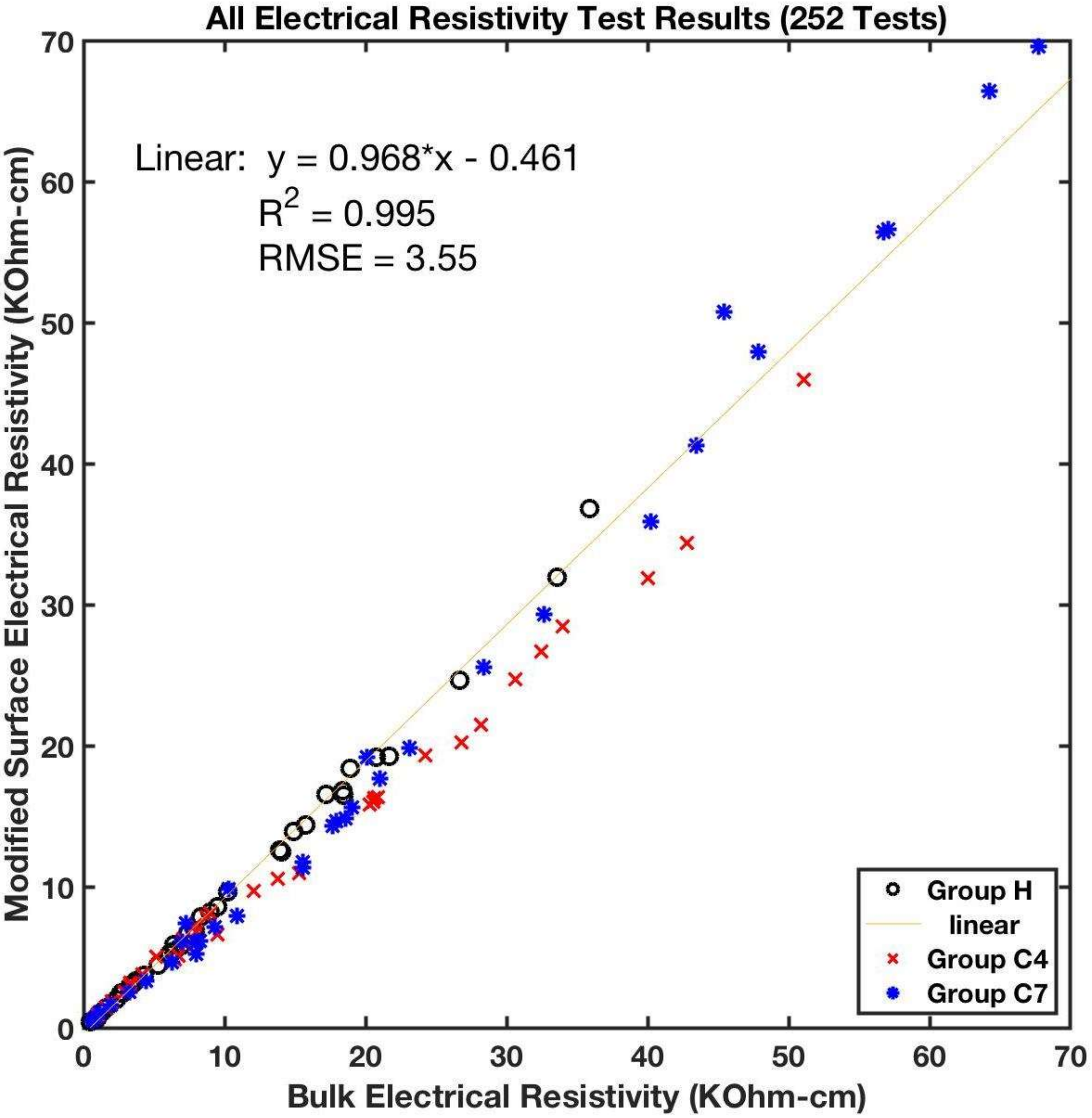

Figure 34 Bulk vs Modified Surface Electrical Resistivity Test Results, All Groups H, C4, C7

6.2 Formation Factor

Discussions in sections 3.4, 3.5, 5.3, and 5.4 showed that relying on bulk/surface electrical resistivity test results as an index for permeability/durability of concrete and its microstructure could be misleading. The main reason of this confusion comes from the quantities that we are measuring in electrical resistivity tests.

It is well known that concrete is a porous material. The porosity in concrete comes from a system of interconnected nano and microscopic pores. Concrete resistivity consists of the pore microstructure resistivity (volume and connectivity of the pores) plus the pore solution resistivity (higher concentration of ions in the pore solution means lower resistivity) *(Tanesi et al. 2019).*

Figure 35 (Tanesi et al. 2019) shows that how electrical resistivity test could be misleading. It shows two saturated concretes with the same resistivity. It means bulk/surface electrical resistivity test results will classify these two concretes the same with the same durability (which is wrong). Checking microstructure of concrete A shows poorer microstructure (less durable). It means pore microstructure resistivity of concrete A is lower than concrete B and it should be classified as concrete with lower durability.

This confusion happens because of the misleading effect of pore solution resistivity. Higher pore solution resistivity (lower pore solution conductivity) in concrete A increases the total resistivity (microstructure resistivity + pore solution resistivity) in concrete A and makes it equal with concrete B in bulk/surface electrical resistivity tests. In other words, direct comparison of bulk/surface electrical resistivity test result for two concretes with different pore solution resistivity is not correct and leads to a wrong conclusion.

Bulk/surface electrical resistivity tests can not capture the misleading effects of pore solution resistivity. A new parameter should be considered for assessing durability/permeability of concrete. This new parameter is Formation Factor.

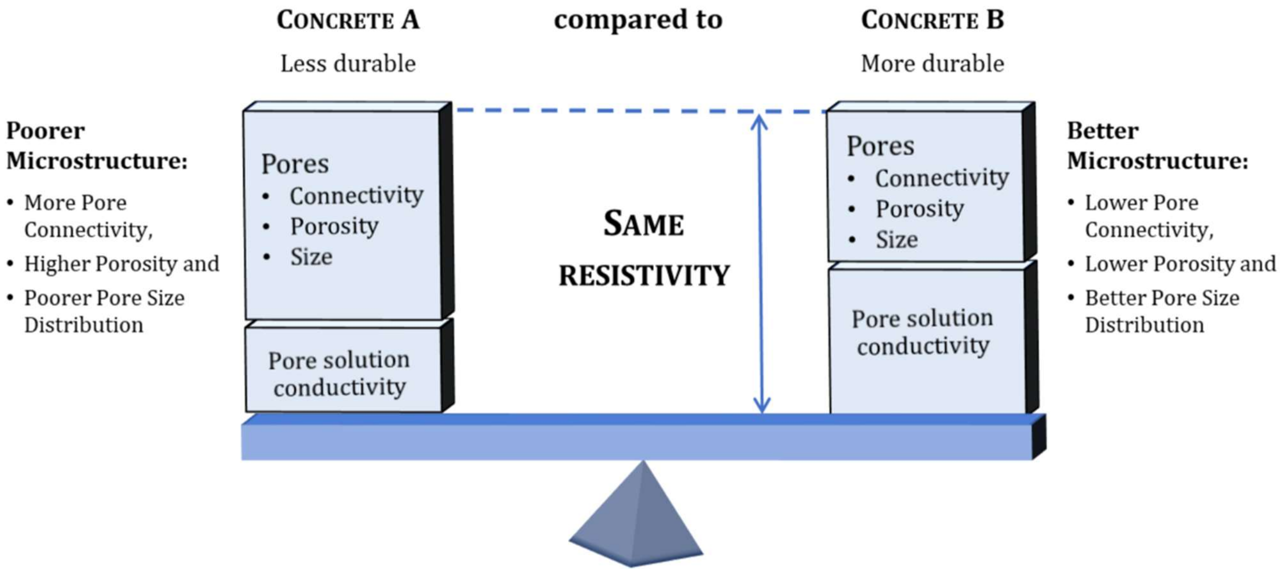

Figure 35 Two saturated concretes with the same resistivity but different potential durability resulting from different pore structures

Formation Factor (F) provides an indication of the total pore volume and how the pores are interconnected among each other (connectivity). Formation factor is a fundamental property that is inversely related to the porosity of the concrete and the connectivity of the pores (Weiss et al. 2016).

$$F = \frac{\rho}{\rho_0} = \frac{1}{\varphi . \beta}$$

F = Formation factor
ρ = Concrete resistivity (bulk or surface)
ρ_0 = Pore solution resistivity
φ = Concrete porosity
β = Concrete pore connectivity

Equation 1 Formation Factor

Formation Factor definition clearly shows that (confusing) effect of pore solution resistivity has been removed by normalizing bulk/surface electrical resistivity (ρ) of a concrete with respect to pore solution resistivity (ρ_0) of that concrete.

Finding Formation Factor needs both bulk/surface electrical resistivity (ρ) and pore solution resistivity (ρ_0) of concrete. Bulk/surface electrical resistivity (ρ) is already known and measured in previous sections. In this research, NIST method (Bentz 2007; Snyder et al. 2003) has been used for pore solution resistivity (ρ_0) estimation. For using NIST method, degree of hydration (DOH) of the system should be estimated. For DOH estimation, DOH model mentioned in (Feng et al. 2004) has been used. Figure *36* shows the estimated degree of hydrations. Slower rate of hydration by increasing slag content is clear in this figure.

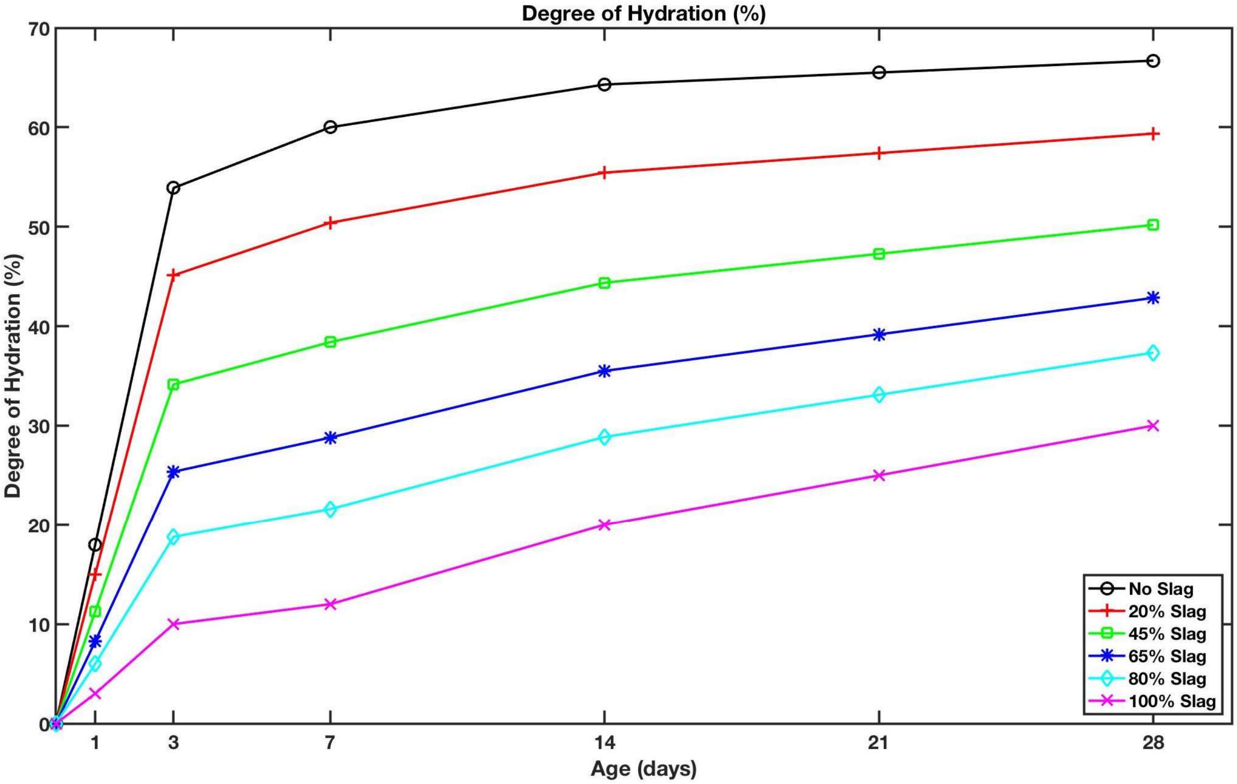

Figure 36 Estimated Degree of Hydration at different ages for different slag replacements in Groups H, C4, and C7

Figure *37* shows the estimated pore solution resistivities at different ages for different slag replacements in Groups H, C4, and C7 (see Table *3*) using NIST method (Bentz 2007; Snyder et al. 2003). It can be seen that pore solution resistivity is high at early ages (because of lower concentration of ions at early ages) and then will be constant at higher ages (because of constant concentration of ions at higher ages). Also, it is clear that pore solution resistivity is increasing by increasing slag content. In theory, it goes to infinity at 100% slag mixture. Because of this special condition, we couldn't calculate the Formation Factor for batches with 100% slag binder.

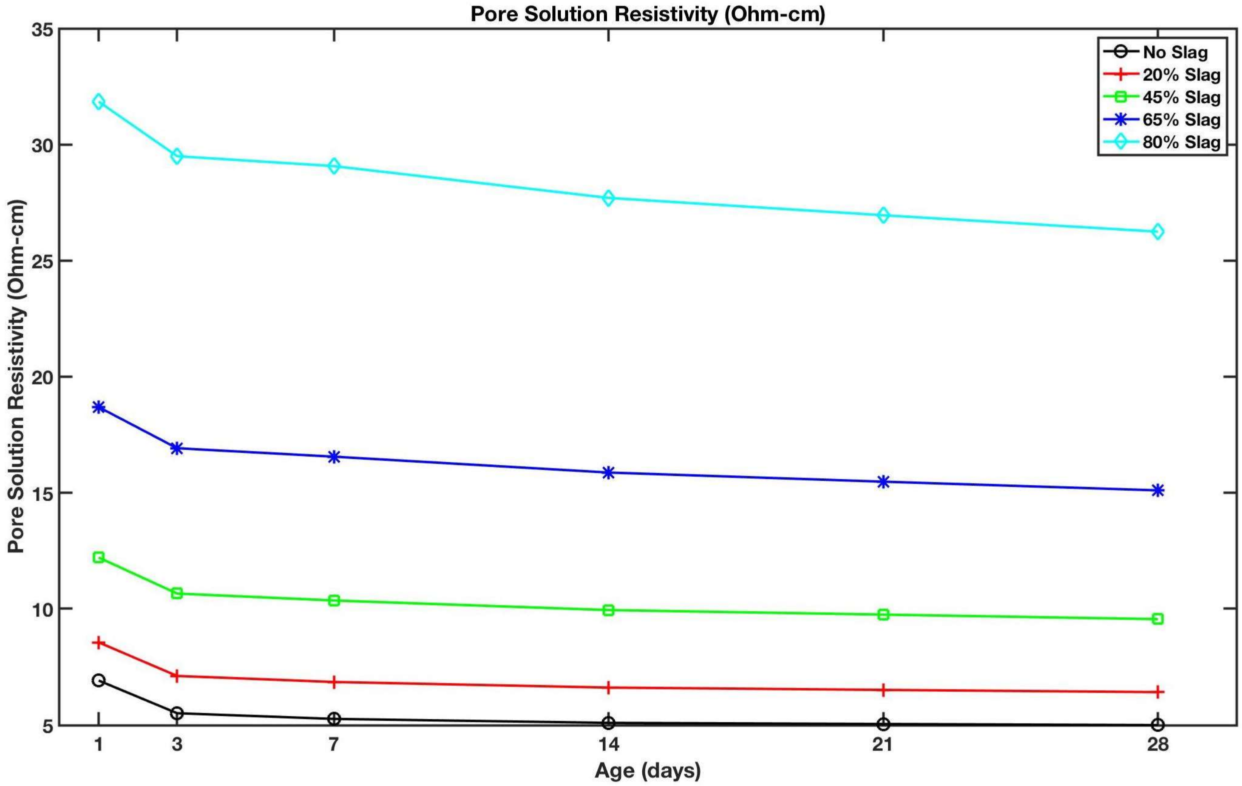

Figure 37 Estimated pore solution resistivity (using NIST method) at different ages for different slag replacements in Groups H, C4, and C7

Now, all bulk/surface electrical resistivities (ρ) and pore solution resistivities (ρ_0) for all Groups (H, C4, and C7) are known. Next step is finding Formation Factors based on Equation *1*. AASHTO PP84-20, Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures, (AASHTO 2020) , defines chloride penetrability ranges as follows:

1. Low chloride penetrability ⇒ Formation Factor (91 days) > 1000
2. Moderate chloride penetrability ⇒ 500 < Formation Factor (91 days) < 1000
3. High chloride penetrability ⇒ Formation Factor (91 days) < 500

Figure *38*, Figure *39*, and Figure *40* show formation factors for specimens in Groups H, C4, and C7. Green (formation factor = 1000) and red (formation factor = 500) lines show AASHTO PP84-20 limits for low and high chloride penetrability respectively.

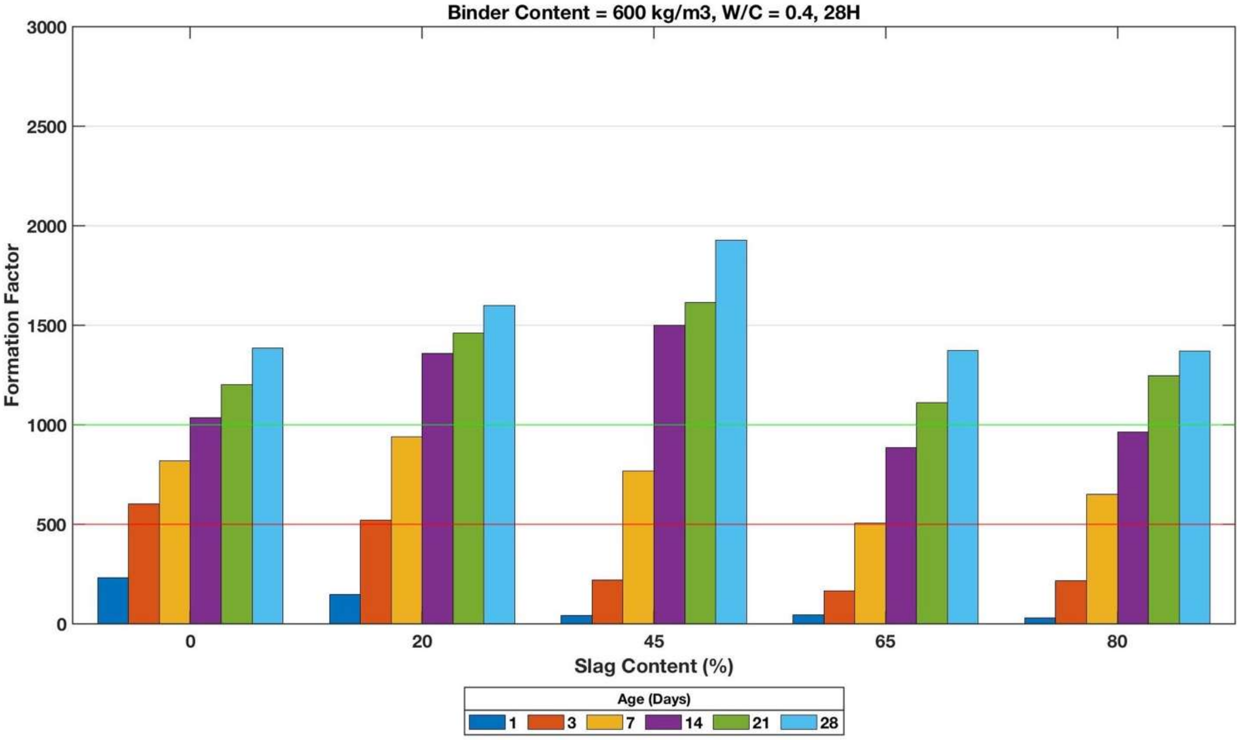

Figure 38 Formation Factor for Group H specimens

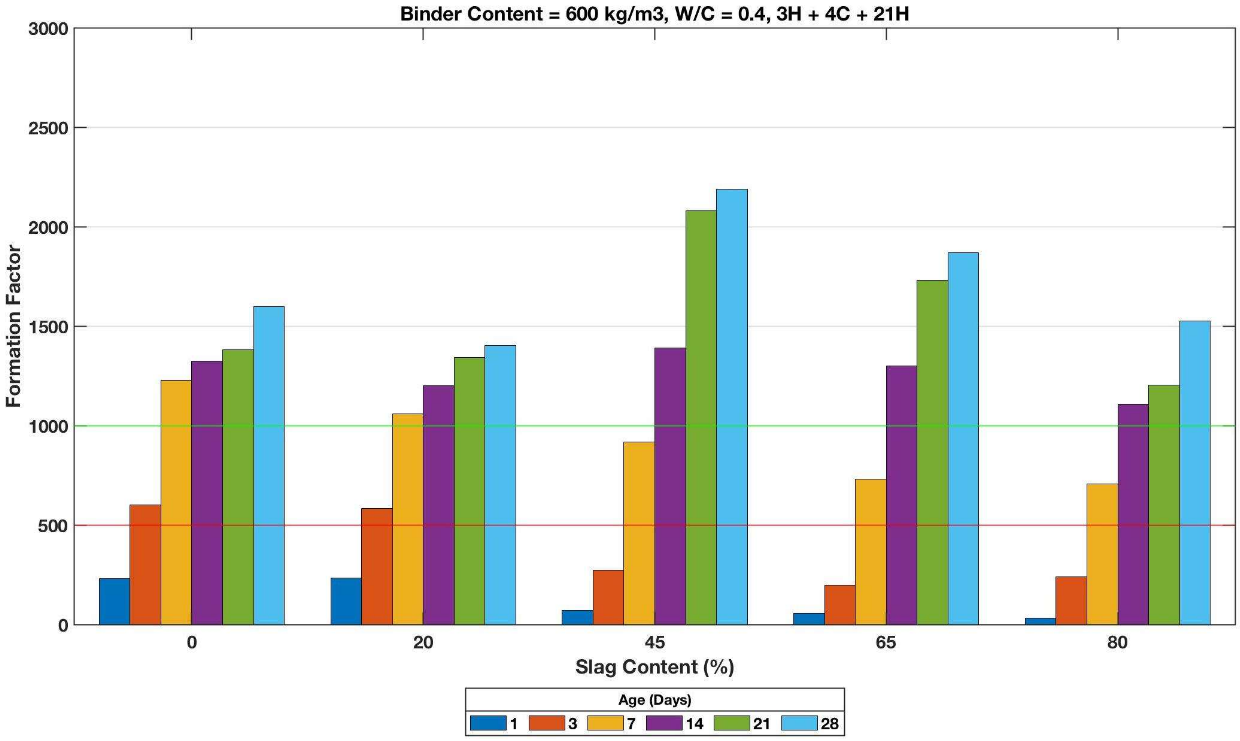

Figure 39 Formation Factor for Group C4 specimens

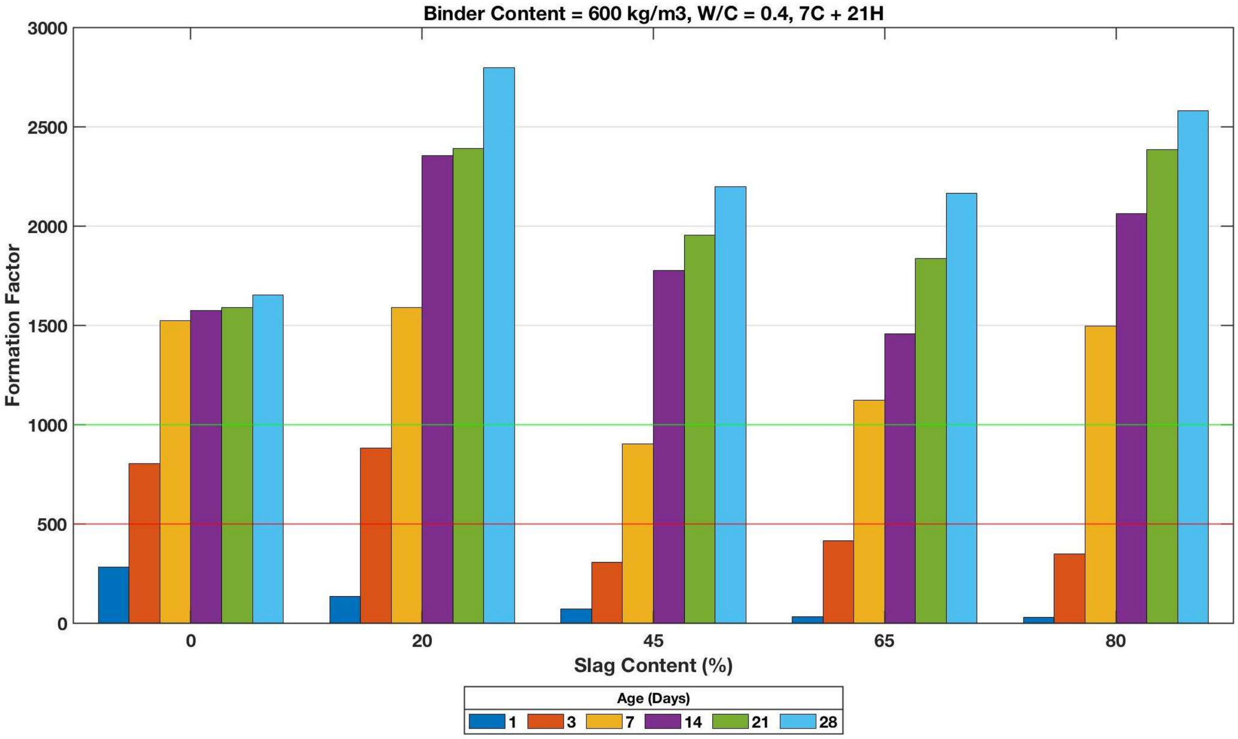

Figure 40 Formation Factor for Group C7 specimens

It can be seen that at group H (Figure *38*), all batches satisfy moderate chloride penetrability limit (500 < Formation Factor < 1000) after 7 days. Also, all of them meet low chloride penetrability criteria (Formation Factor > 1000) after 21 days. 45% slag replacement shows the best quality (highest formation factor) in this group.

At group C4 (Figure *39*), all batches satisfy moderate chloride penetrability limit (500 < Formation Factor < 1000) after 7 days. Also, all of them meet low chloride penetrability criteria (Formation Factor > 1000) after 14 days. Again, 45% slag replacement shows the best quality (highest formation factor) in this group.

At group C7 (Figure *40*), all batches satisfy moderate chloride penetrability limit (500 < Formation Factor < 1000) after 7 days. At day 7, almost, all of them (except 45% slag replacement) meet low chloride penetrability criteria (Formation Factor > 1000) as well. 20% slag replacement shows the best quality (highest formation factor) in this group. Group C7 specimens show the best results (the highest formation factors) comparing groups H and C4 specimens.

Comparing Formation Factor figures (Figure *38*, Figure *39*, and Figure *40*) with corresponding bulk electrical resistivity figures (Figure *20*, Figure *21*, and Figure *22*) and surface electrical resistivity figures (Figure *23*, Figure *24*, and Figure *25*) clearly shows the misleading effects of pore solution resistivity.

Bulk/surface electrical resistivity results (Figure *20*, Figure *21*, and Figure *22*) and (Figure *23*, Figure *24*, and Figure *25*) show the highest resistivity (lowest permeability) for 80% slag replacement in Group H and C7. For Group C4, 100% slag replacement shows the highest resistivity (the best (densest) microstructure). As mentioned in sections 3.4 and 3.5, compressive strength test results (Figure *14*, Figure *16*, and Figure *15*) show that 80% and 100% slag replacement batches are the worst batches with the lowest compressive strengths (probably the highest permeability and the highest porosity). This shows that interpreting the results based on raw results from surface electrical resistivity tests is very confusing.

Comparing formation factor results (Figure 38, Figure 39, and Figure 40) as an index for chloride penetrability (durability) with corresponding compressive strength test results (Figure 14, Figure 16, and Figure 15) makes more sense. At group H, both formation factor and compressive strength figures show 20%, 45%, and 65% slag replacements as the best batches. For group C4, both show 45% and 65% the best batches. At group C7, 20% slag replacement shows the best results for both test results.

These comparisons and discussion show that current MaineDOT method for permeability (durability) evaluation based on Maine Department of Transportation Standard Specifications (MaineDOT 2020) which uses surface resistivity as an index for permeability is not correct (because of misleading effect of pore solution resistivity). The correct method for assessing concrete durability is using formation factor and its corresponding chloride penetrability ranges based on AASHTO PP84-20, Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures, (AASHTO 2020).

Chapter 7: Conclusions and Recommendations

Part I: CO_2 – Activated Concrete

- Higher slag content means lower workability (Figure *13*)
- Slag improved compressive strength at a later age (Figure *14*, Figure *16*, and Figure *15*)

Observations and Trends (28 days)

Group C7: Injecting CO_2 after demolding (day 1) is more effective at lower slag content (20%):

- Relatively low enough formation factor (135)/DOH/porosity at time of CO_2 addition (day 1) increases rate of CO_2 diffusion (Figure *40*)
- There is high enough cement content (80%) for producing enough hydration products (CH and C-S-H) which are necessary for carbonation reaction.
- Because of less pozzolanic reaction at early age, there is less competition between CO_2 and slag for consuming CH.

Group C4: Injecting CO_2 after 3 days is more effective at higher slag contents (45% and 65%):

- Relatively low enough formation factor (273,198)/DOH/porosity at time of CO_2 addition (day 3) increases rate of CO_2 diffusion (Figure *39*)
- Formation Factor for lower slag content (20%) is relatively high (583) which reduces rate of CO_2 diffusion (Figure *39*)

Finding the best time for adding CO_2

Injecting CO_2 at early age (after demolding) is more effective:

- Earlier ⇒ lower Degree of Hydration ⇒ more free water available for carbonation
- Earlier ⇒ lower Formation Factor/Degree of Hydration/Porosity ⇒ higher diffusion rate of CO_2
- Earlier ⇒ less pozzolanic reaction ⇒ less competition for Ca(OH)2 consumption

Overall Best Results (28 days)

- Injecting CO_2 after demolding with 20% (2C7 batch) slag ⇒ the best compressive strength (almost 20% increase), Figure *16*
- Injecting CO_2 after demolding with 20% (2C7 batch) slag ⇒ the best Formation Factor (almost100% increase), Figure *40*

Comparing CO_2 injection after 3 days and full hydration curing, Group C4 and H

- Trends for curing with CO_2 after day 3 and full hydration curing are very similar
- Curing with CO_2 improves the results but not as much as adding CO_2 at day 1
- 65% slag (4H & 4C4) ⇒ the best compressive strength (Figure *14* and Figure *15*)
- 45% slag (3H & 3C4) ⇒ the best Formation Factor (Figure *38* and Figure *39*)

Improvements due to 3 days CO_2 curing (28 days), Group C4

- Injecting CO_2 after day 3 with 65% slag (4C4) ⇒ improves compressive strength up to 20% (Figure *15*)
- Injecting CO_2 after day 3 with 45% slag (3C4) ⇒ increases Formation Factor up to 60% (Figure *39*)

Shrinkage Results (Figure *17*, Figure *18*, and Figure *19*)

- No big change in free shrinkage results except in 100% slag with carbonation curing
- It depends on paste volume (AASHTO 2020) which is almost constant (43-45%) for all mixtures

Remaining Questions/Issues

- Studying developments and reactions in microstructural level
- Confirmation of pores solution resistivity estimation using NIST Model

- Adding admixtures and studying the effects of different admixtures on fresh and hardened properties of CO_2 – Activated concretes

Part II: Alkali – Activated Concrete

Compressive Strength Results (Figure *27*)

- Compressive strength results are as high as 60 MPa (8700 psi) ⇒ up to 60% increase
- Almost all batches reach MaineDOT Class A concrete strength (4000 psi) after 3 days
- Some mixtures reach Class A concrete compressive strength (4000 psi) after day 1
- Almost all batches reach MaineDOT Class LP concrete strength (5000 psi) after 7 days
- Best results happen at higher silica modulus (1.25 and 1.5)

Free Shrinkage Results (*Figure 28*)

- Mixtures with lower silica modulus (0.8 and 1) show better (lower) free shrinkage results
- Batches with 4% Na_2O show relatively better shrinkage results
  - **Bulk and Surface Electrical Resistivity Test Results (**Figure *29* and Figure *30***)**
- Almost all batches reach MaineDOT Class A and Class LP concrete (MaineDOT 2020) required electrical resistivities (14 and 17 KOhm-cm) after 3 days
- Batches with 3% Na_2O show the highest electrical resistivities

Remaining Questions/Issues

- Studying developments and reactions in microstructural level
- Adding admixtures and studying the effects of different admixtures on fresh and hardened properties of Alkali – Activated concretes

Bulk vs Surface Electrical Resistivity (*Figure 31*, Figure 33, Figure 32, and *Figure 34*)

- 252 test results show bulk resistivity can be estimated with a very high accuracy by measuring surface resistivity and vice versa. It means conducting one of these two tests is enough and second test results can be estimated by modifying the results of the first one.

MaineDOT Method for Permeability Evaluation of Concrete

- Current MaineDOT method for concrete permeability (durability) evaluation based on Maine Department of Transportation Standard Specifications (MaineDOT 2020) which uses surface resistivity as an index for permeability is not perfect.
- The correct method for assessing concrete durability is using formation factor and its corresponding chloride penetrability ranges based on AASHTO PP84-20, Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures, (AASHTO 2020).

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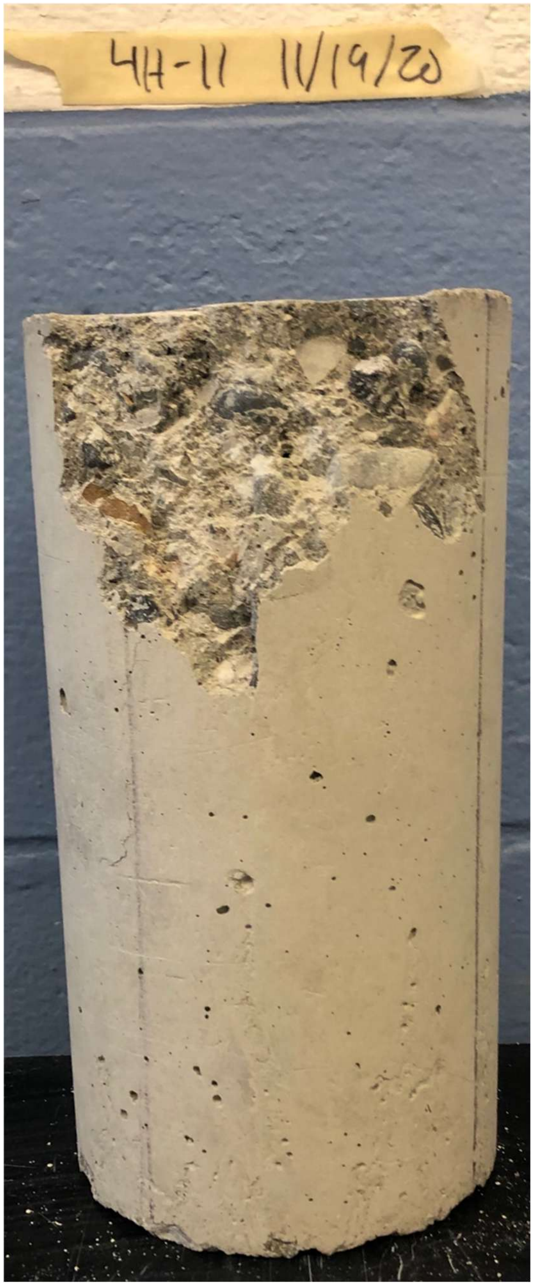
Appendix 1 (Compressive Strength Test Pictures)

Group H Specimens, 28H (*Table 3*)

3H – 56 days



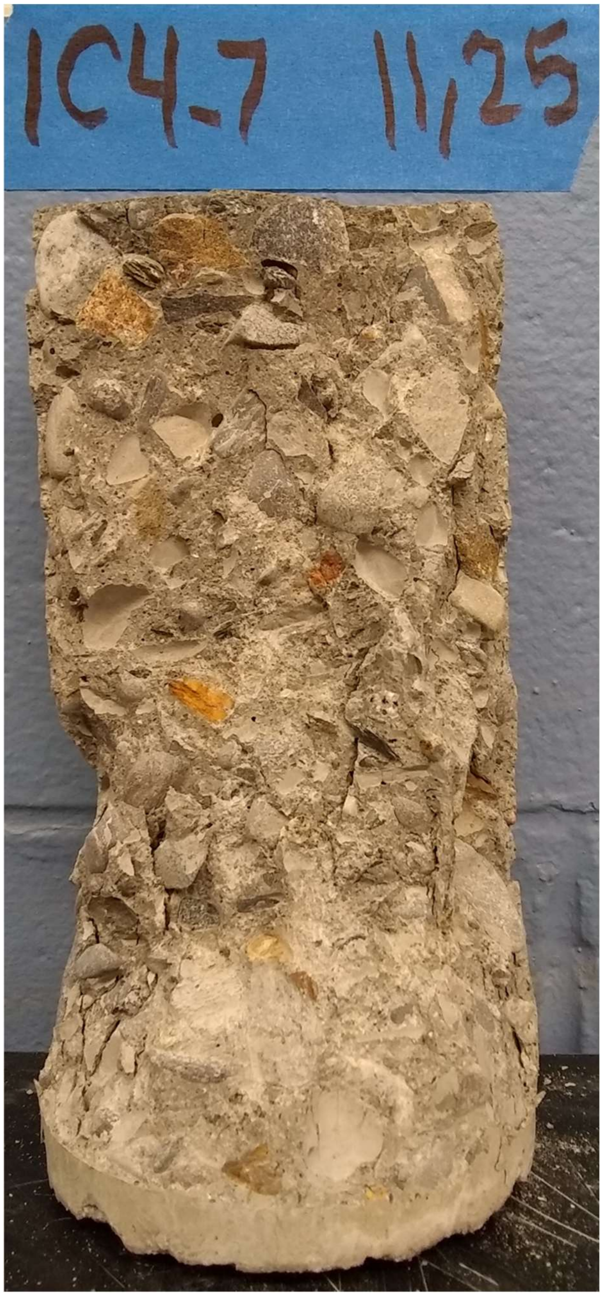
4H – 56 days

Group H Specimens, 28H (*Table 3*)

5H – 56 days

6H – 56 days

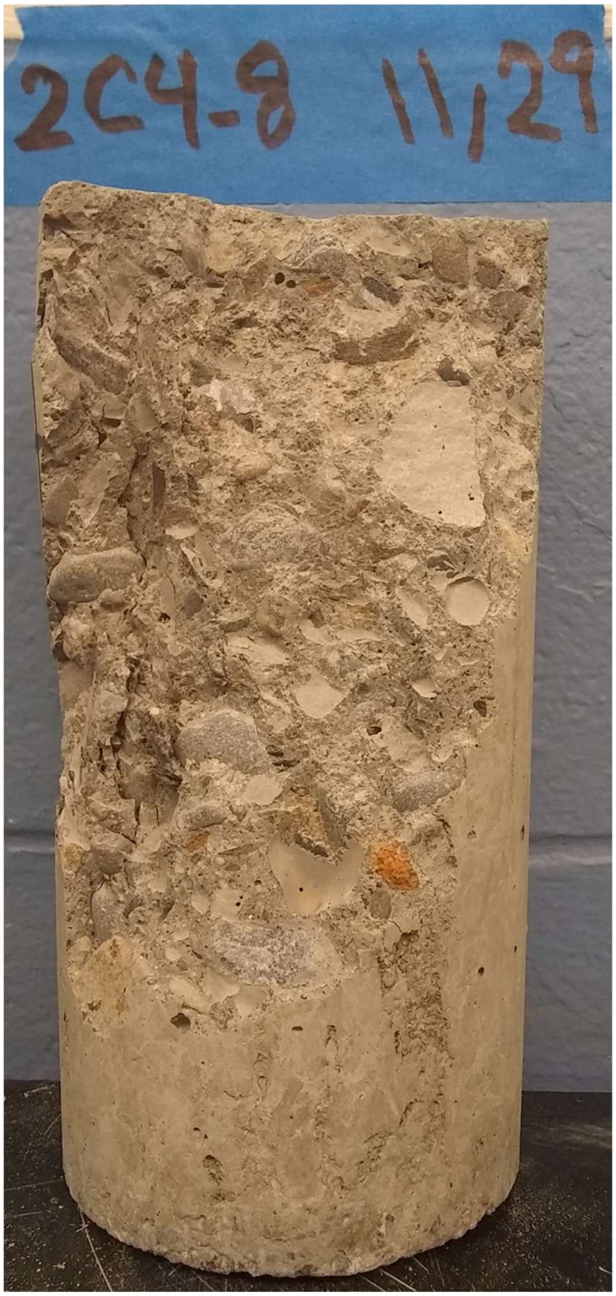
Group C4 Specimens, 3H + 4C + 21H (*Table 3*)



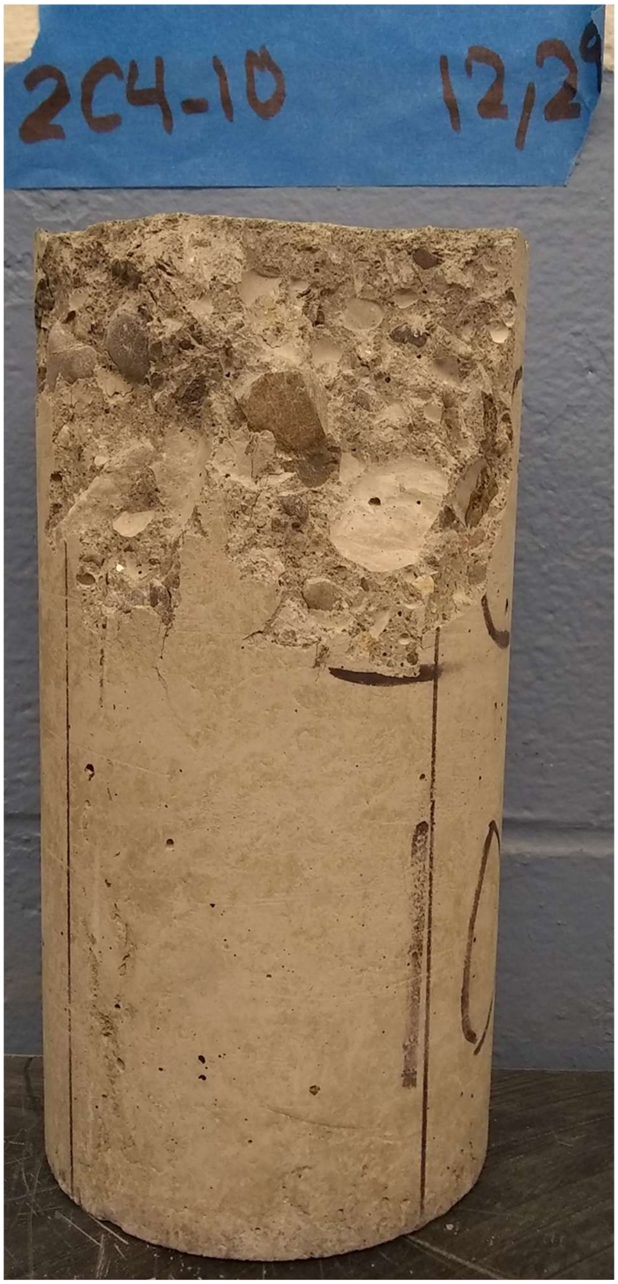
1C4 – 28 days

1C4 – 56 days

Group C4 Specimens, 3H + 4C + 21H (*Table 3*)



2C4 – 28 days



2C4 – 56 days

Group C4 Specimens, 3H + 4C + 21H (*Table 3*)

4C4 – 28 days

4C4 – 56 days

Group C4 Specimens, 3H + 4C + 21H (*Table 3*)

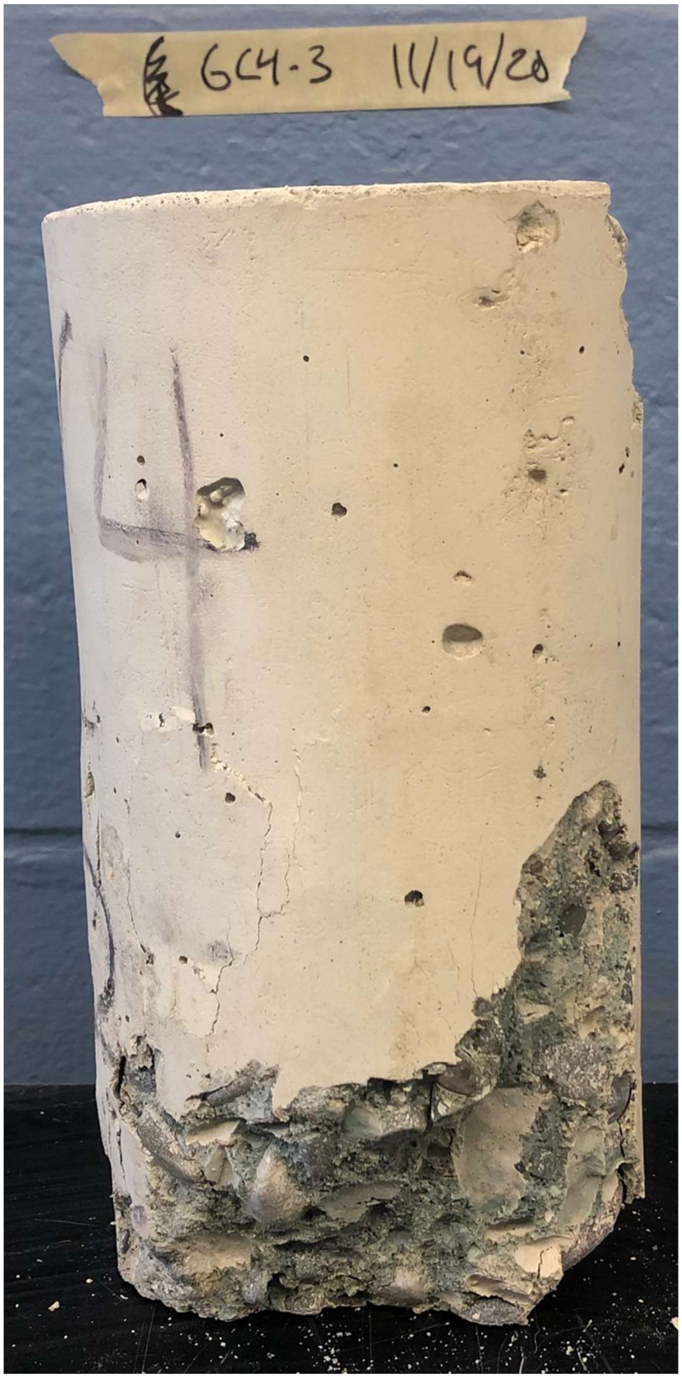
5C4 – 7 days

5C4 – 28 days

Group C4 Specimens, 3H + 4C + 21H (*Table 3*)

5C4 – 56 days

Group C4 Specimens, 3H + 4C + 21H (*Table 3*)

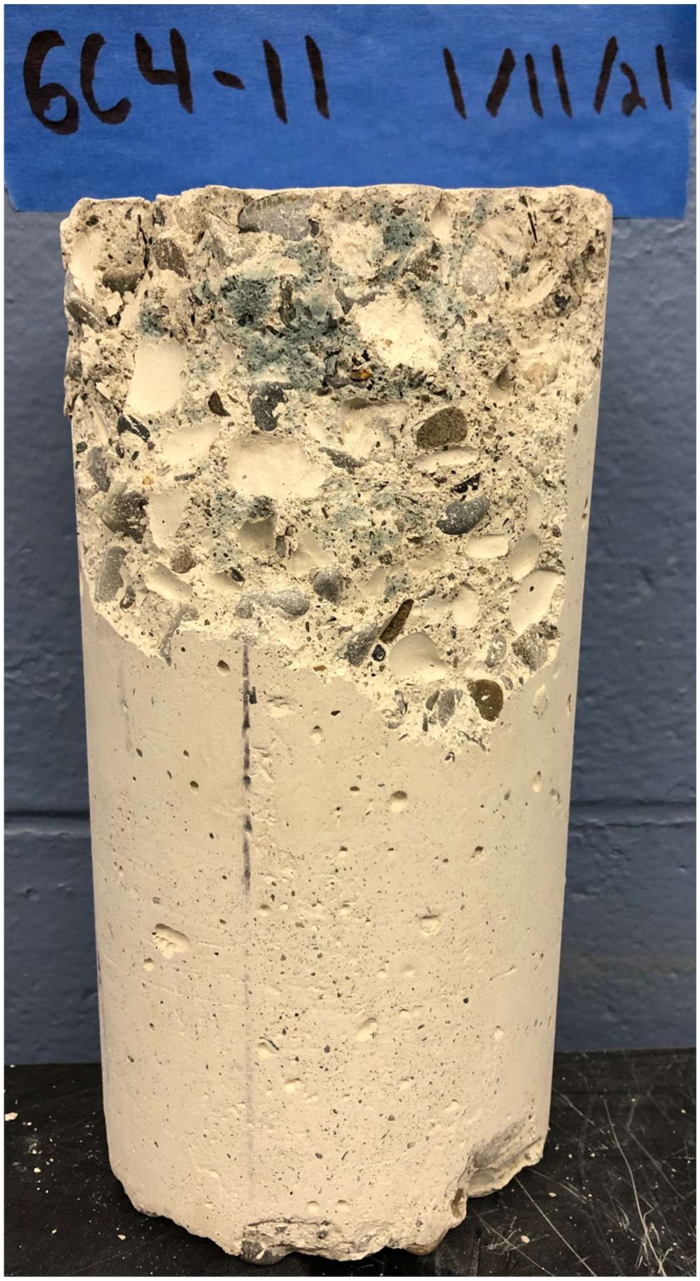


6C4 – 3 days

6C4 – 7 days

Group C4 Specimens, 3H + 4C + 21H (*Table 3*)

6C4 – 28 days



6C4 – 56 days

Group C7 Specimens, 7C + 21H (*Table 3*)

1C7 – 56 days

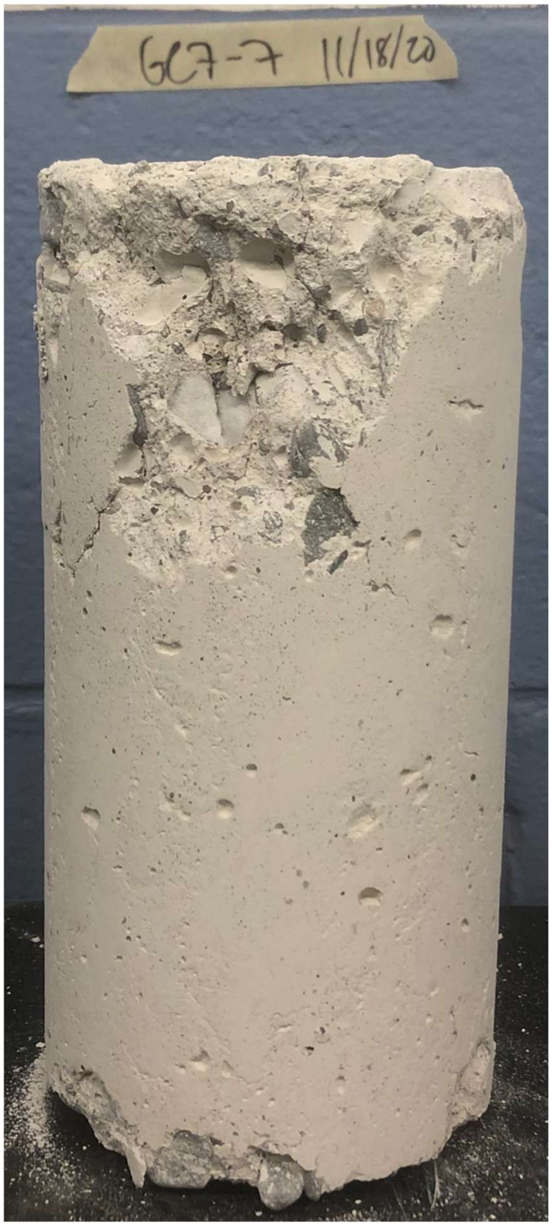
3C7 – 56 days

Group C7 Specimens, 7C + 21H (*Table 3*)

4C7 – 56 days

5C7 – 56 days

Group C7 Specimens, 7C + 21H (*Table 3*)



6C7 – 28 days

6C7 – 56 days

Alkali-Activated Specimens (Table 4)

A1 – 28 days

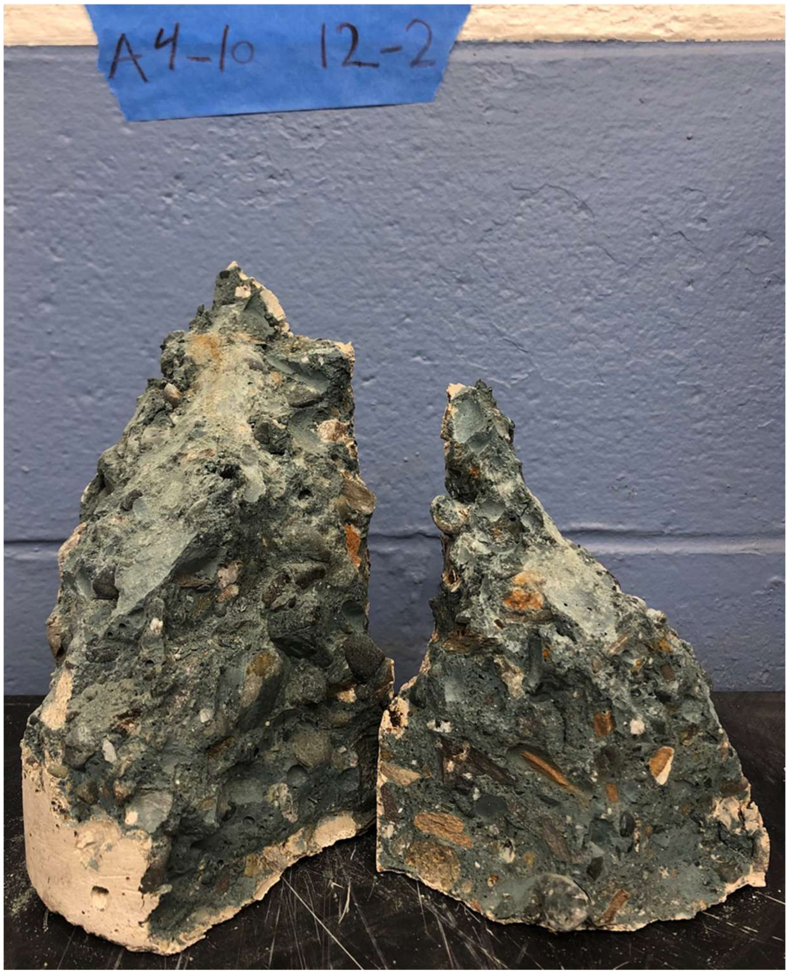
A2 – 28 days

Alkali-Activated Specimens (Table 4)

A3 – 28 days

Alkali-Activated Specimens (Table 4)

A4 – 7 days

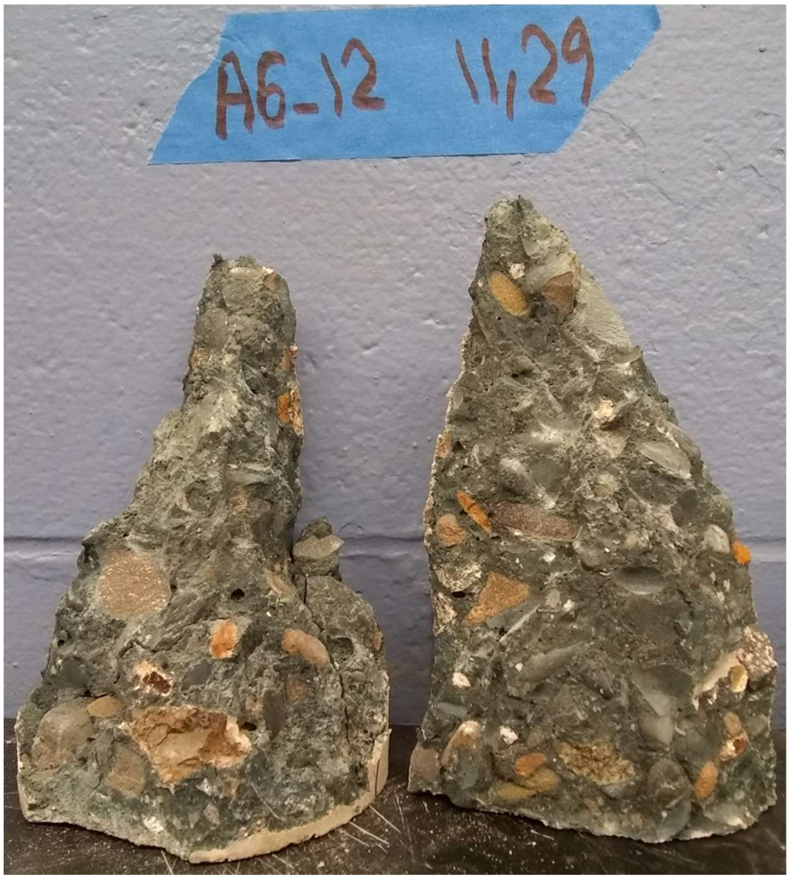


A4 – 28 days

Alkali-Activated Specimens (Table 4)

A5 – 3 days

Alkali-Activated Specimens (Table 4)



A6 – 28 days

A6 – 28 days

Alkali-Activated Specimens (Table 4)

A8 – 7 days

A8 – 28 days

Alkali-Activated Specimens (Table 4)

A9 – 1 days

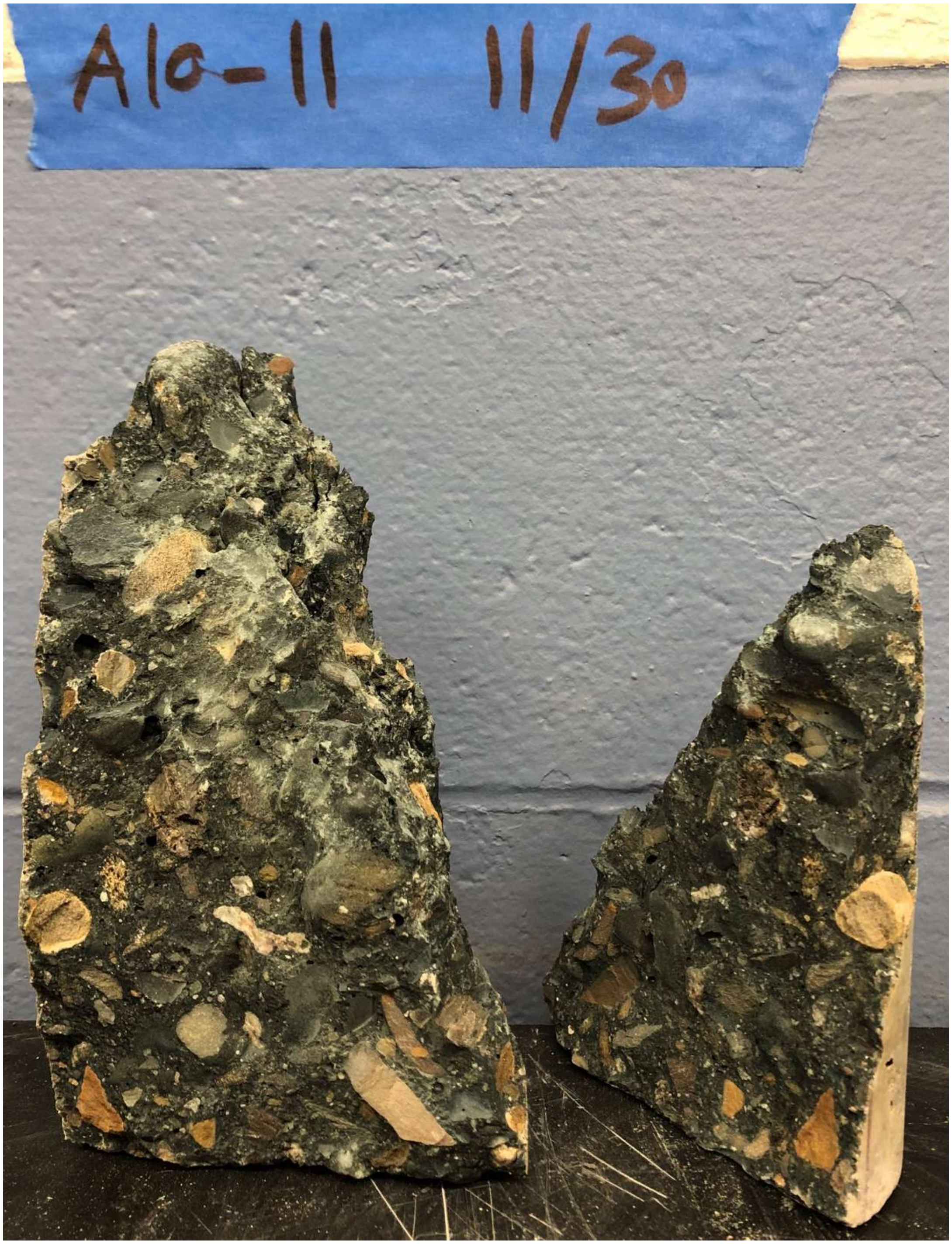
A9 – 3 days

Alkali-Activated Specimens (Table 4)

A9 – 7 days

A9 – 28 days

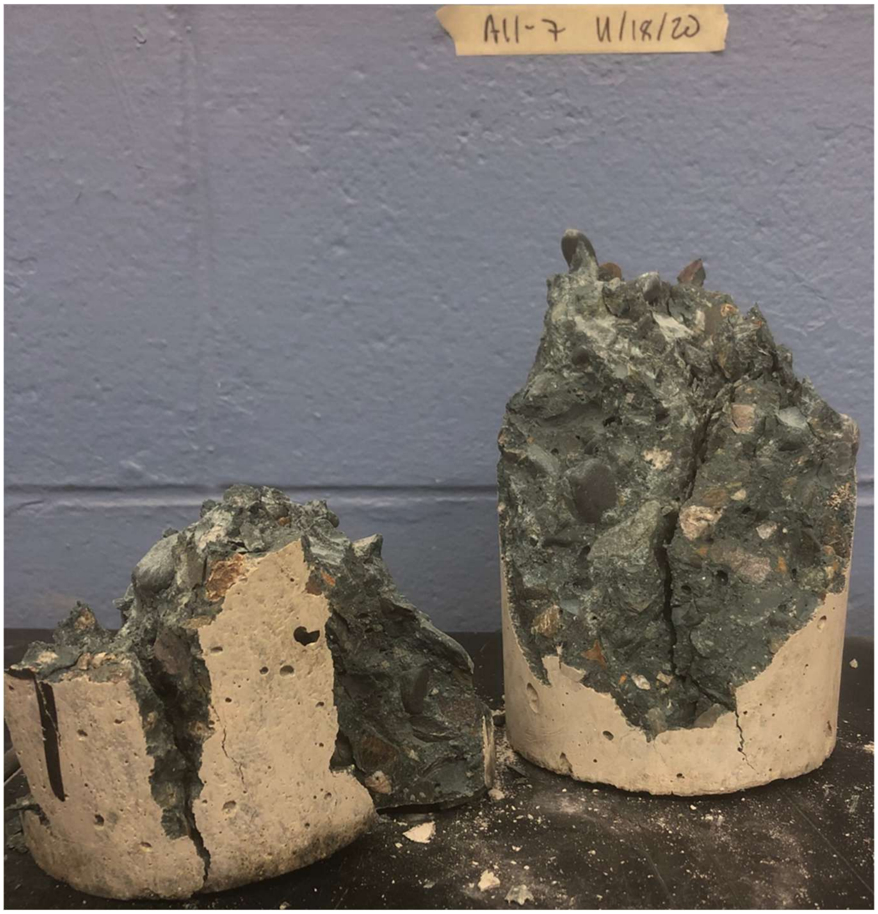
Alkali-Activated Specimens (Table 4)



A10 – 28 days

Alkali-Activated Specimens (Table 4)

A11 – 3 days



A11 – 7 days

Alkali-Activated Specimens (Table 4)

A11 – 28 days

TIDC

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