



New Jersey's Science & Technology University

## **Impact of Extended Time to Discharge on Concrete Durability and Performance**

**Submitted to**

**Ready Mixed Concrete (RMC) Research & Education Foundation  
Portland Cement Association (PCA)**

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**June 2020**

## **EXECUTIVE SUMMARY**

Every year, a substantial amount of ready mixed concrete is returned to concrete plants for disposal due to many reasons, such as excessive slump loss during transport, surplus production and trial batches. It is estimated that the amount of concrete waste is approximately 3% of total production (Obla et al., 2007), and with increasing use of concrete, the generation of such waste concrete is also expected to increase. One of the main reasons for rejecting a great number of truckloads of concrete every year is due to the strict accordance to the 90-minute time limit. This is derived from ACI 318-19, section 26.5.1.1 (d), which states, “Ready-mixed and site-mixed concrete shall be batched, mixed and delivered in accordance with requirements of ASTM C94 or ASTM C685” (2019). ASTM C94 section 12.7 states, “Discharge of concrete shall be completed within 1½ hours after the introduction of mixing water to the cement and aggregates, or the introduction of the cement to aggregates” (ASTM C94/C94M, 2018). It further states that, “This limitation may be waived” providing additional evaluation information. However, a considerable number of truckloads of concrete are still rejected owing to this time limit. As traffic and road congestion in urban environments has gotten progressively worse, this rule has unnecessarily enlarged the construction cost and become more difficult to meet. When concrete stays in the mixing truck longer than necessary, it must be disposed resulting in construction and demolition waste, increased greenhouse gas emissions, and increases costs to the suppliers and contractors.

This research was supported and funded by the Ready Mixed Concrete (RMC) Research & Education Foundation and Portland Cement Association (PCA) to investigate how extended time to discharge affects the durability and performance of the concrete load. The experimental results of this project can be utilized to identify the durability mechanisms most effected by mixing concrete for longer times than is currently allowed. The results presented herein can be used to update current specifications and guidelines that can allow the concrete suppliers and contractors to extend the concrete time to discharge up to 150 minutes.

Representative and standard concrete mixture designs were selected. The mixtures were procured, batched, and poured at a local ready-mix concrete supplier to mimic typical field construction conditions. Sample specimens to examine impact of time to discharge on strength and durability were obtained at batching and 60, 90, 120, and 150 minutes after batching. The plastic concrete properties including air content, slump, and temperature were also obtained at those intervals. Extended set retarding admixture was added as needed during mixing to maintain the workability of the concrete without altering the mixture design. Hardened concrete tests such as compressive strength, freeze-thaw, and surface resistivity were performed. The results obtained from this study indicate that the concrete time to discharge had no significant impact on the fresh properties, surface resistivity, and freeze-thaw durability up to 150 minutes. As a result of this research, the current discharge time limits and specifications are determined to be conservative and should be reexamined.

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## **CHAPTER 1: INTRODUCTION**

### **A. Background**

An estimated 3% of ready mixed concrete produced in the United States is returned to concrete plants every year, based on 2006 estimate (Obla et al., 2007). Much of this concrete is discarded as waste or washed out to reclaim the aggregates used in the system. This waste results in landfilling of hardened concrete, contaminated washout water, substantial disposal, cost, and increased greenhouse gasses due to additional transportation and production of concrete. Reducing the amount of concrete that is returned to the ready mix facility will significantly improve sustainability within the concrete industry by preventing unnecessary landfilling of material and reducing use of scarce water resources to wash aggregates reclaimed from waste concrete.

One of the main reasons concrete is rejected and then returned to a ready mix facility is because of what is known as the 90-minute rule. This rule, supported by many state highway associations and building codes, as well as the national standards governing body of the American Society for Testing and Materials (ASTM), notes that concrete must be discharged from the concrete mixing truck within 90 minutes after the mixing of the materials (cement, water, and aggregates) has begun (Prasittisopin and Trejo, 2015 and ASTM C94/C94M, 2018).

The 90-minute time limit was invoked in the original version of ASTM C94, published in 1935. It is assumed that this was inserted to protect the quality of the typical concrete mixtures produced at that time with the applicable materials and production methods. It is presumed that the intent was to ensure that excessive water was not added to a load that could negatively impact its quality.

Production methods and concrete materials used have changed considerably since 1935. It is also true that concrete was generally produced close to the project in 1935 and the average haul time has increased considerably since then – several reasons have been stated. There are a wide range of mixtures and project conditions (including weather) applicable and there is no assurance that 90 minute limit on delivery is protective of all these situations. In some ambient conditions, concrete quality (without excessive re-tempering) can be retained for periods longer than 90 minutes. In this case, acceptable quality is rejected for lack of conformance to an arbitrary time limit. There are mixtures or ambient conditions where 90 minutes is too long to retain the required quality.

If the concrete producer is informed about the expected time the mixture will be held in the mixer before it will be discharged, the producer will then have different options available to provide concrete for that delivery time stated when concrete is ordered, within some reasonable tolerance.

Regardless of the time limit, ASTM C94/C94M (2018) has provisions that permit concrete mixtures to be adjusted with water or admixtures in transit or at the job site. The primary restriction is that the quantity of water added should not exceed that established for the mixture as designed for its intended performance characteristics.

The traffic in urban environments and movement of ready-mix facilities away from city cores have increased the delivery time for concrete trucks, increasing the likelihood that concrete will be rejected then returned to the facility. Advances in concrete technology, including chemical admixtures that alter fresh concrete properties and extend setting times, may make this time limit unnecessary.

An increase to the 90-minute time to discharge limit will prevent good quality fresh concrete from being returned to ready-mix concrete facilities reducing the amount of waste material and contaminated water produced by these facilities and reducing overall operational costs. The research outlined in this report will be used to examine if extended time to discharge, up to 150 minutes, will negatively impact the long-term durability of concrete mixtures.

## **B. Project Objectives and Scope**

Workability of concrete is the ability of the concrete to flow through formwork and around rebar, and to be consolidated such that voids do not form within the bulk system and a good bond with the rebar. The most common method of measuring workability is by measuring the slump of the concrete, a test in which fresh concrete is placed in a mold and allowed to “slump” down as the mold is lifted off. One of the objectives of this research project is to determine the impact of increased time to discharge on concrete workability. Those measurements are important to be able to measure the mixtures ability to consolidate in a large open space and also to create good bonds and flow around rebar, according to ASTM Standards, at regular intervals throughout the mixing period up to 150 minutes. The results will provide a baseline for understanding how significant the impact of increased time to discharge is on concrete workability.

Air entraining admixtures are added to concrete mixtures to create small air pockets within concrete that allows for water within the system to expand without causing internal stresses, and subsequent cracking, to form in the concrete. Additional time to discharge may actually cause air entrainment to be mechanically removed out of the system by the agitation caused during mixing. Air entrainment and temperature during concrete mixing are the most effective parameters of protecting concrete from freeze-thaw deterioration that can occur in outdoor severe cold environments (Kosmatka and Wilson, 2016). Hence, the air content and concrete temperature of each concrete mixture were measured at regular intervals throughout the mixing period. Reductions in air entrainment, peak temperatures and temperature gradients over time were recorded to evaluate the impact of increased time to discharge on concrete air entrainment.

Concrete strength is an important factor to ensure the adequacy of strength that is required for design and assess the overall quality of concrete. The concrete strength specimens were sampled at various mixing length intervals up to 150 minutes and tested for 28 days, and 56 days compressive strength after casting to determine the impact of mixing duration on overall strength, as well as strength development. Compressive strength testing was performed at New Jersey Institute of Technology’s High Performance Concrete Laboratory in Colton Hall at John A. Reif Jr. Civil and Environmental Engineering Department. In addition to strength, freeze-thaw durability can be measured by exposing concrete samples to rapid and continuous cycles of freezing and thawing and continuously assessing the quality of the specimens over the duration of the test. The freeze-thaw durability testing was performed on samples casted at various intervals

during mixing up to 150 minutes. Finally, surface resistivity, which is a test method that can be used to assess a material's resistance to chloride penetration, and subsequent resistance to rebar corrosion was performed. This test method involves using a 4-point Wenner probe to quickly assess the electrical resistivity of a concrete sample. The results were correlated to chloride penetration resistance using existing protocols (Nassif, et al, 2015). The results from the discharged mixture after 60 minutes was used as the baseline for comparison with the other mixtures.

By completing all aforementioned objectives, the lengths of time to discharge, changes in workability, temperature, air content, and freeze-thaw results were correlated to understand how these various indicators may be able to be used to assess long-term durability and performance of concrete systems as well as recommend durability mechanisms and which fresh properties are most affected by extending time to discharge lengths. This work will result in helpful guidance for state highway agencies and concrete producers on the impact of employing longer time to discharge on concrete.

This research is Phase 2 of a multi-phased research project carried out by the Concrete Industry Management (CIM) program at School of Applied Engineering and Technology (SAET), New Jersey Institute of Technology (NJIT). The project has started in 2015 in an effort to evaluate the strict 90-minute time limit and propose any changes based on field and lab tests. Phase 1 was titled "Evaluation of the 90-Minute Rule as an Acceptance Criteria Considering Current Concrete Mixture Design Technology and Mixture Constituents". Phase 1 studied fresh concrete properties along with hardened concrete properties including compressive, tensile, and flexural strengths. The first phase of the research project was funded by the New Jersey Chapter of American Concrete Institute (NJACI) and the completed report was submitted on April 9, 2017 (Mahgoub and Ramanna, 2017).

The Principal Investigator, Dr. Mohamed Mahgoub has been asked by several organizations to present the finding of the first phase of this study. The Concrete and Concrete Aggregate Committee C09 of the American Society for Testing and Materials (ASTM) is in the process of balloting the 90-minute time limit research recommendations. The details of the presentations and reports are listed in the references.

## **CHAPTER 2: LITERATURE REVIEW**

Previous work has examined the impact of time to discharge on strength and workability of fresh concrete. These results have shown that increased time to discharge can lead to improved compressive strengths due to the evaporation of mixing water (Kirca et al., 2002). Improved compressive strengths are often considered positive for construction projects. However, the evaporation of water during mixing can also result in decreased workability, poor consolidation, and decreased air entrainment which can result in increased porosity and void size, and honeycombing of the concrete (Anderson and Dewar 2003). Honeycombed concrete is visually unattractive, and also can have serious impacts on concrete strength and durability. Additional time to discharge can also result in a higher-than-normal concrete temperature during placement which can result in higher levels of early-age and long-term shrinkage cracking (Prasittisopin and Trejo, 2015). These side effects of additional time spent in the concrete truck before placement can affect long-term durability by creating fast paths for aggressive agents (i.e. water and chlorides) that can induce corrosion of the steel reinforcement bars (rebar), freeze-thaw damage, and other durability concerns. Unfortunately, the impact that these durability concerns have on actual long-term performance has not been well quantified.

Vruno (2011) reported that increasing the time to discharge from 60 to 120 minutes caused a decline in the plastic and hardened air content of 1.3 % and 1.2 %, respectively. Moreover, he noted that the effect on freeze-thaw durability was negligible between 60 to 120 minutes. Trejo and Chen (2014) noted that extended time to discharge caused a reduction in compressive strengths due to loss of workability, which caused higher void contents for mixtures without air entrainment. They also reported that no reduction in hardened concrete properties was evident after long mixing durations.

Nehdi and Al-Martini (2009) investigated changes in ready mixed concrete properties during delivery under extremely hot weather conditions and reported that concrete can lose about one-third of its initial slump over short durations. Trejo and Chen (2014) reported some mixtures were difficult to cast at less than 90 minute time to discharge due to the poor workability of the concrete. However, mixtures could be cast at 180-minute discharge and no single relationship between discharge time and slump could be identified. They also reported that time to discharge had no significant effects on the mechanical properties and durability and that current mixing limits are very conservative.

Mahgoub and Ramanna (2015, 2016, and 2017) and Mahgoub and Rawlins (2018) studied how extended discharge time affects the quality of concrete. They have tested a large number of concrete batches under different weather conditions and elapsed times. The influence of current class of chemical admixtures such as extended set retarding admixture on the concrete mixture was also studied. Three different concrete mixtures produced from locally available materials were evaluated: 100% Portland Cement, 25% Fly Ash and 40% slag cement. One batch of each of the following mixtures was made with and without the use of extended set retarding admixture. The mixtures were tested twice; during hot weather and moderate conditions. The following conclusions were arrived at:

1. The use of extended set retarding admixture extended the workability of all three concrete mixtures 100% Portland Cement mixture, 25% Fly Ash mixture and 40% slag cement mixture up to 180 minutes, especially for hot weather pour. It also kept concrete temperature relatively cooler.
2. When no extended set retarding admixture was used, all three concrete mixtures were workable up to 180 minutes in moderate weather conditions (65 – 78F). This was not the case for hot weather mixtures. However, slag cement and Fly Ash concrete was workable for longer periods than 100% Portland Cement mixture in hot weather.
3. 28-day and 56-day compressive strength of concrete mixtures, per ASTM C39/C39M (2018), exceeded the target mixture design requirement of 6000 psi, even for mixtures with extended discharge period. Moderate weather pour concrete mixtures had relatively high compressive strength compared to hot weather concrete pour concrete mixtures. Also, concrete mixtures with extended set retarding admixture yielded higher compressive strength compared to mixtures without extended set retarding admixture for both hot and moderate weather pour conditions.
4. Flexural strength of concrete, per ASTM C78/C78M (2018), averaged about 11% of compressive strength even at extended time to discharge. Moderate weather pour concrete mixtures had relatively high modulus of rupture compared to hot weather concrete pour concrete mixtures. Also, concrete mixtures with extended set retarding admixture yielded higher modulus of rupture compared to control mixture without extended set retarding admixture, for both hot and moderate weather pour conditions.
5. Extended time to discharge or weather did not negatively affect the permeability of all three concrete mixtures. Mixtures with extended set retarding admixture had lower permeability compared to mixtures without it.
6. Extended time to discharge did not negatively affect shrinkage of all three concrete mixtures in both hot and moderate weather conditions. Mixtures with extended set retarding admixture experienced lower shrinkage compared to mixtures without it.
7. Excess air in concrete mixture directly correlates to reduction in compressive and flexural strength of concrete.

## **CHAPTER 3: CASTING AND TEST PROCEDURES**

### **A. Material Properties and Source**

Concrete typically consists of cement, stone (coarse aggregate), sand (fine aggregate) and water. In order to enhance concrete properties, the use of Supplementary Cementitious Materials (SCM) in concrete is a common practice in concrete industry at present time. The use of SCM in concrete also improves its mechanical and durability properties. The commonly used SCMs are class F Fly Ash, slag cement and Silica Fumes. However, Fly Ash and slag cement are used in relatively large quantities than Silica Fume. These ingredients greatly influence the setting time, workability, and placeability of concrete. Cement hydration in concrete batch begins with the addition of water to the mixture or addition of cement to aggregates that has moisture. The rate of hydration of a concrete mixture can be affected by a number of variables. These typically include cement type and chemistry, concrete mixture proportions, dosage of chemical admixtures, and mixture temperature. Thus, it would be great benefit to concrete suppliers, engineers, and inspectors in the concrete industry to have a better understanding of how elapsed time actually affects the quality of concrete, especially in light of current concrete mixture design technology and mixture constituents.

To insure a better understanding and evaluation of this research, concrete was tested at real concrete batch plants. The ready mixed concrete was supplied on site by one of ready mixed concrete providers in the state of New Jersey. Concrete was provided at two different plants: South Plainfield and Mount Holly. The concrete mixture design and properties are shown in Tables 1, 2 and 3. To ensure quality control in field testing, only ACI Field Level 1 certified personnel were allowed to perform tests such as measurement of slump, temperature, air, water content by microwave method and placing concrete for making test samples. The group would be supervised by Principal Investigator at all times. QC personnel from both the ready mixed concrete provider and admixture company would be on site the day of each pour to advise on dosing based on field conditions. If the concrete mixture didn't meet the given specifications it was discarded and started over same day or rescheduled depending on required weather conditions for the pour. Microwave water content test ensured no additional water was added to meet the given slump and air requirements over the entire discharge period. Only water reducer, extended set retarding and air entraining admixtures were used during mixing to achieve specified workability in concrete mixtures for as long as possible up to 150 minutes. An eleven cubic yard mixer was used and test loads were kept to a minimum of 5 cubic yards for each pour. The mixture design was always verified from batch tickets. Portland Cement Type 1 was conforming to ASTM C150/150M (2019), Fly Ash Class F was conforming to ASTM C618 (2019), slag cement was conforming to ASTM C989/C989M (2018), and fine and coarse aggregates were conforming to ASTM C33/C33M (2018). High Range Water Reducer, air entraining, and extended set retarding admixtures were supplied by the admixture company. Figure 1 shows the centralized batching and mixing. Dosage of admixtures was recommended by the ready mixed concrete provider and the admixture company QC personnel on-site. Nine ounces of extended set retarding admixture was used per 100 lbs of cementitious material to keep the concrete fresh for 150 minutes.



**Figure 1: Centralized Batching and Mixing**

## **B. Mixture Design**

Two different concrete mixtures produced from locally available materials were evaluated in the current research: 25% Fly Ash, and 40% slag cement. The mixtures were designed in conformance to ACI 211.1 (1991). The specified concrete compressive strength ( $f'_c$ ) for these mixtures was 6000 psi. No additional water is to be used in order to keep the water to cement ratio (w/c) as 0.4 per design. Eight test cylinders were cast from each sample extracted for each time interval of each mixture as shown in Table 3. The results were averaged for each time interval.

The specifications shown in Table 1 and 2 were adopted for the concrete mixture design. Extended set retarding admixture was added as needed without altering the mixture design. The dosage of admixtures was set based on manufacturer's guidelines. Table 3 shows concrete properties with respect to each time to discharge.

**Table 1: Mixture Design Specifications**

<b>Properties</b>	<b>Value</b>
f'c (28 day)	6000 psi
Air Content	6 % +/- 1.5%
Slump	5" +/- 1"
Coarse Aggregate	#57 (1 inch max)
W/C	0.4

**Table 2: Mixture Proportions**

<b>Material</b>	<b>40% slag cement</b>	<b>25% Fly Ash</b>
<b>Coarse Aggregate (lbs)</b>	1850	1850
<b>Fine Aggregate (lbs)</b>	1289	1296
<b>Cement (lbs)</b>	390	487
<b>SCM (lbs)</b>	260	163
<b>Water (lbs)</b>	258	258

**Table 3: Mixture Properties vs. Time to Discharge  
(Mixture 1, 25% Fly Ash)**

	<b>Batch Time</b>	<b>60 Mins</b>	<b>90 Mins</b>	<b>120 Mins</b>	<b>150 Mins</b>
	12:05	13:05	13:35	14:05	14:35
<b>Temperature (F)</b>	64	62	59	57	53
<b>Slump (in)</b>	7	7.5	7.5	7.25	6.5
<b>Air (%)</b>	11	7	9	5.5	8
<b>Extended Set Retarding Admixture (oz/cwt)</b>			1		1
<b>Unit Weight (lbs/ft<sup>3</sup>)</b>	146.5	146.4	145.9	149.3	144.4
<b>Average</b>	146.5				
<b>Freeze Thaw Beams</b>	2	2	2	2	2
<b>4 x 8 Cylinders</b>	8	8	8	8	8

**(Mixture 2, 40% slag cement)**

	<b>Batch Time</b>	<b>60 Mins</b>	<b>90 Mins</b>	<b>120 Mins</b>	<b>150 Mins</b>
	12:30	13:30	14:00	14:30	15:00
<b>Temperature (F)</b>	68	69	70	69	69
<b>Slump (in)</b>	7	7	6.75	6	5.25
<b>Air (%)</b>	7	4.5	6.5	5	5.5
<b>Extended Set Retarding Admixture (oz/cwt)</b>		1		0.5	0.5
<b>Unit Weight (lbs/ft<sup>3</sup>)</b>	146.4	146.0	144.6	146.0	145.2
<b>Average</b>	146.6				
<b>Freeze Thaw Beams</b>	2	2	2	2	2
<b>4 x 8 Cylinders</b>	8	8	8	8	8

### **C. Mixture Casting**

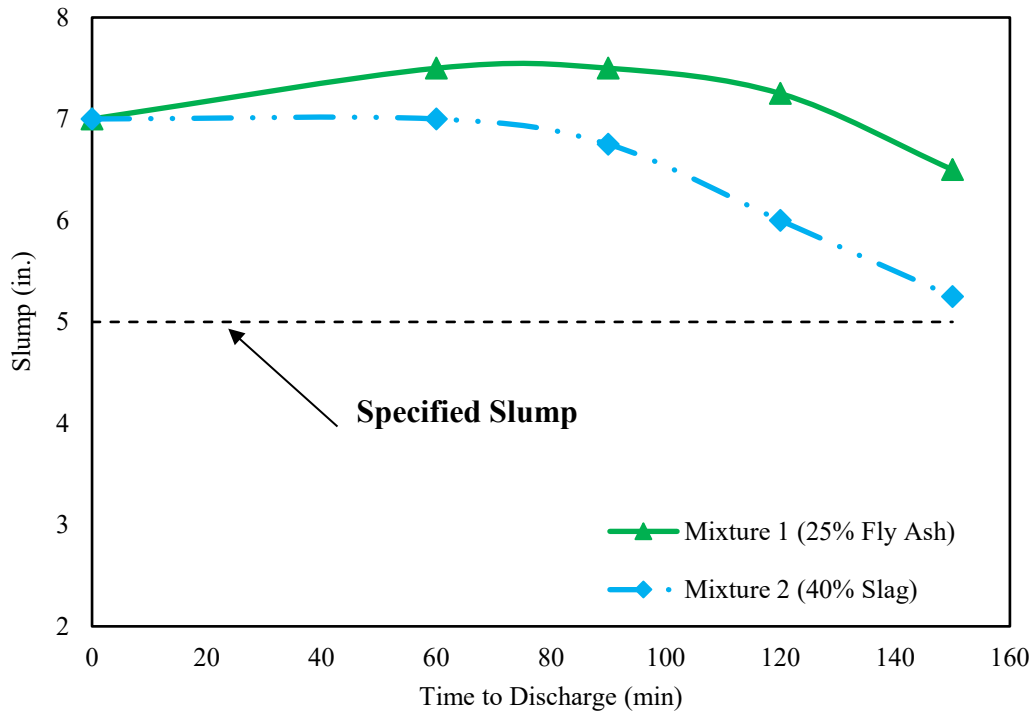
As part of research, Concrete Industry Management (CIM) ACI certified students were engaged through the casting and testing process. The engagement of the students is aimed to educate them in the practical aspect of their studies and complement the theories learned in their classes as well as provide them with the skills needed to participate in highly competitive concrete industry fields. The selected concrete mixture designs were provided in a ready mixed concrete truck. Slump, air, and temperature measurements were recorded right at each time to discharge as shown in Table 3. If the slump or air do not meet the specified requirements, the extended set retarding admixture was added to concrete mixtures. The admixtures were added directly to concrete drum with continuous and constant agitating speed. The samples were only be taken when the concrete mixture met the specified requirements at batching and 60, 90, 120, and 150 minutes after batching. At the time of the casting, the molds were prepared with form release agent.

### **D. Fresh Concrete Test Results**

Fresh properties including slump, air content, and concrete temperature, were obtained at 0, 60, 90, 120, and 150 minutes after batching. The fresh properties of the concrete were tested at different discharge increments and were maintained by adding extended set retarding admixture as needed, without altering the mixture design. The admixture dosages were based on the manufacturer's guidelines. Slump measurements were performed according to ASTM C143/C143M (2015). Figure 2 shows slump and air content test in progress. The addition of the admixtures indicates these mixtures were able retain slump for longer time to discharge above the mixtures specified slump as shown in Figure 3.

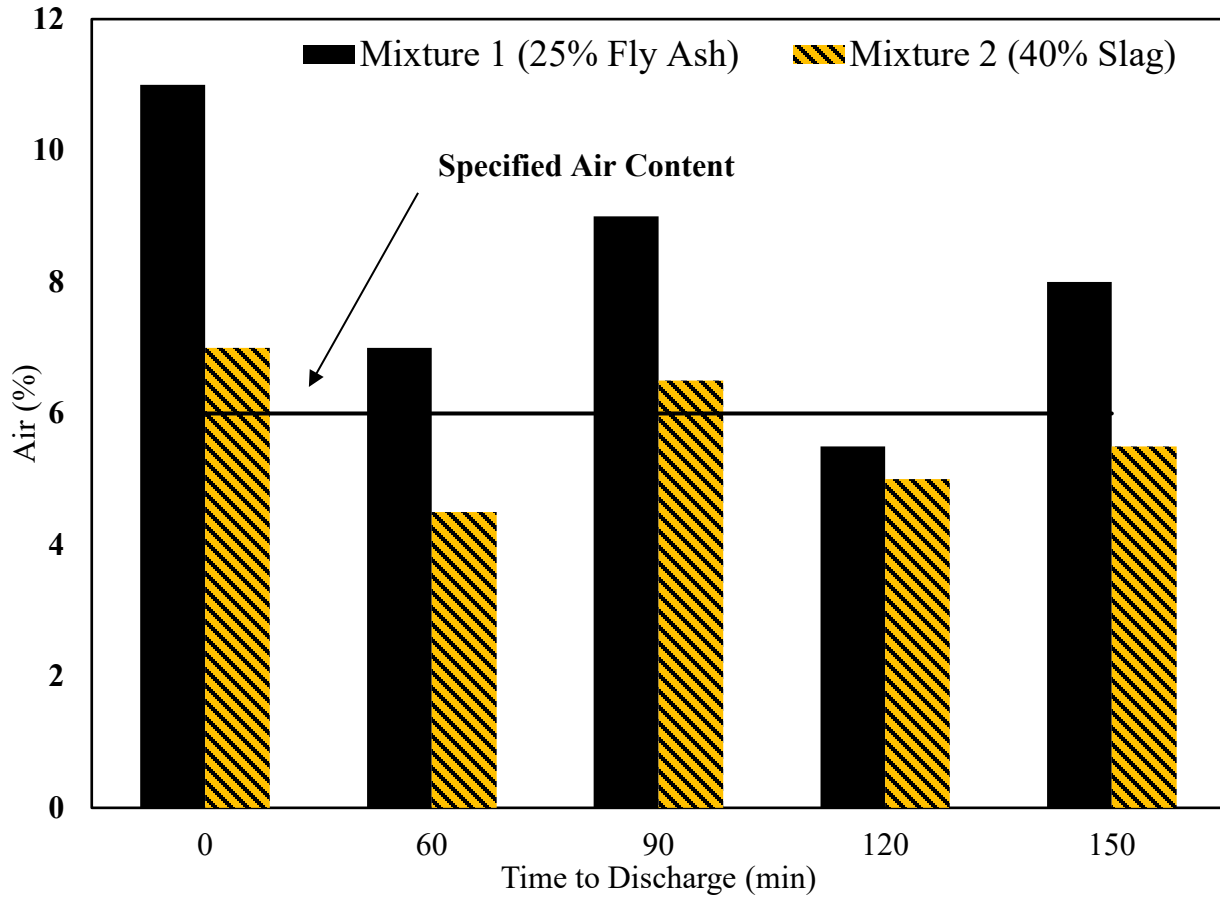


**Figure 2: Slump and Air Content Test in Progress**



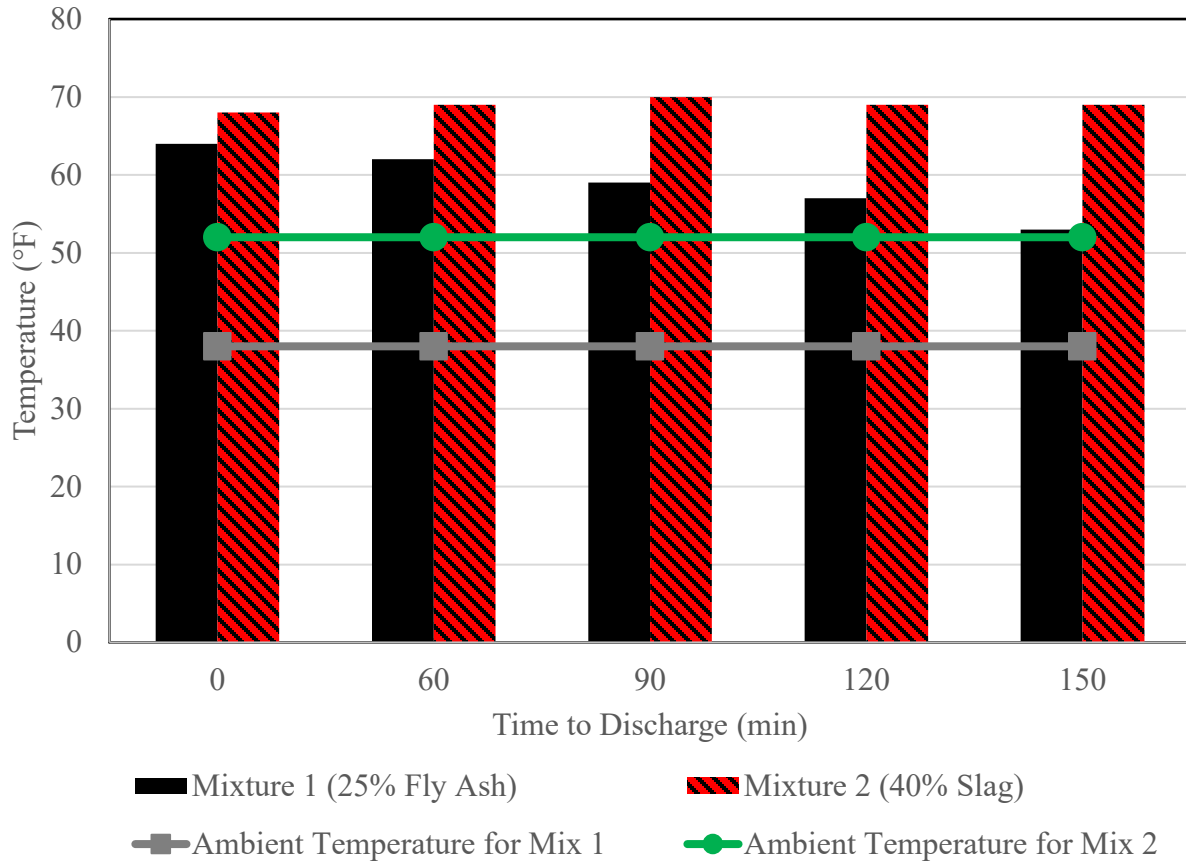
**Figure 3: Slump vs. Time to Discharge**

Air content was measured according to ASTM C231/C231M (2017). The air content in the mixtures ranged between 11% and 5.5% for Mixture 1 (25% Fly Ash) and ranged between 7% and 4.5% for Mixture 2 (40% slag cement) as presented in Figure 4.



**Figure 4: Air Content vs. Time to Discharge**

The ambient temperature was recorded as 38°F and 52°F for Mixture 1 (25% Fly Ash) and Mixture 2 (40% slag cement), respectively. The concrete mixtures were tested in cold and moderate weather scenarios to study the concrete performance at aforementioned time lapses. For this research, cold weather was considered when ambient temperature is below 40°F, as defined by ACI 306R-16 (2017). The maximum recorded concrete temperature was 64°F and 70°F for Mixture 1 and Mixture 2, respectively as indicated in Figure 5. The largest changes in the concrete temperature were recorded to be 11°F and 2°F for Mixture 1 and Mixture 2, respectively.



**Figure 5: Temperature vs. Time to Discharge**

### **E. Hardened Concrete Test Results**

The samples were transported, de-molded with proper care to keep the samples undisturbed, then cured. The curing room was maintained at 100% Relative Humidity and  $73F \pm 3F$  temperature throughout the curing process. The samples were prepared and cured in accordance to ASTM C31/C31 (2019). The hardened concrete properties such as compressive strength, freeze-thaw, and surface resistivity were obtained at various mixing length intervals up to 150 minutes. The samples were cast into standard 4 inch diameter and 8 inch height plastic cylinder molds. They were cast according to ASTM C31/C31M (2019) and the concrete compressive strength was performed in accordance to ASTM C39/C39M (2018).

On the day of field pour, all concrete molds were form released and prepared. Some molds had the metal studs screwed in place. Additional set of calibrated equipment such as air meter and digital thermometer were placed in service. ACI Field Level I personnel were briefed on the number of specimens to be made and the test interval. Sample would be taken right before the time to discharge interval to measure slump, air, temperature and water content by microwave method. If the slump or air did not meet the requirement, then the concrete mixture would be modified by adding extended set retarding admixture, remixed and sampled again as shown in Table 3.

Test samples at specified intervals would only be taken when the concrete mixture met the specified workability requirements. Sampling was discontinued after 150 minutes or when the mixture was no longer workable despite addition of extended set retarding admixture as determined by QC personnel and NJIT Team. The test samples were tagged for identification, covered in plastic sheet and left for curing overnight and transported to curing room after 24 hours. Proper care was taken during transportation and demolding process to keep the samples in best possible condition. Figure 6 shows the sample preparation at the ready mixed concrete plants.



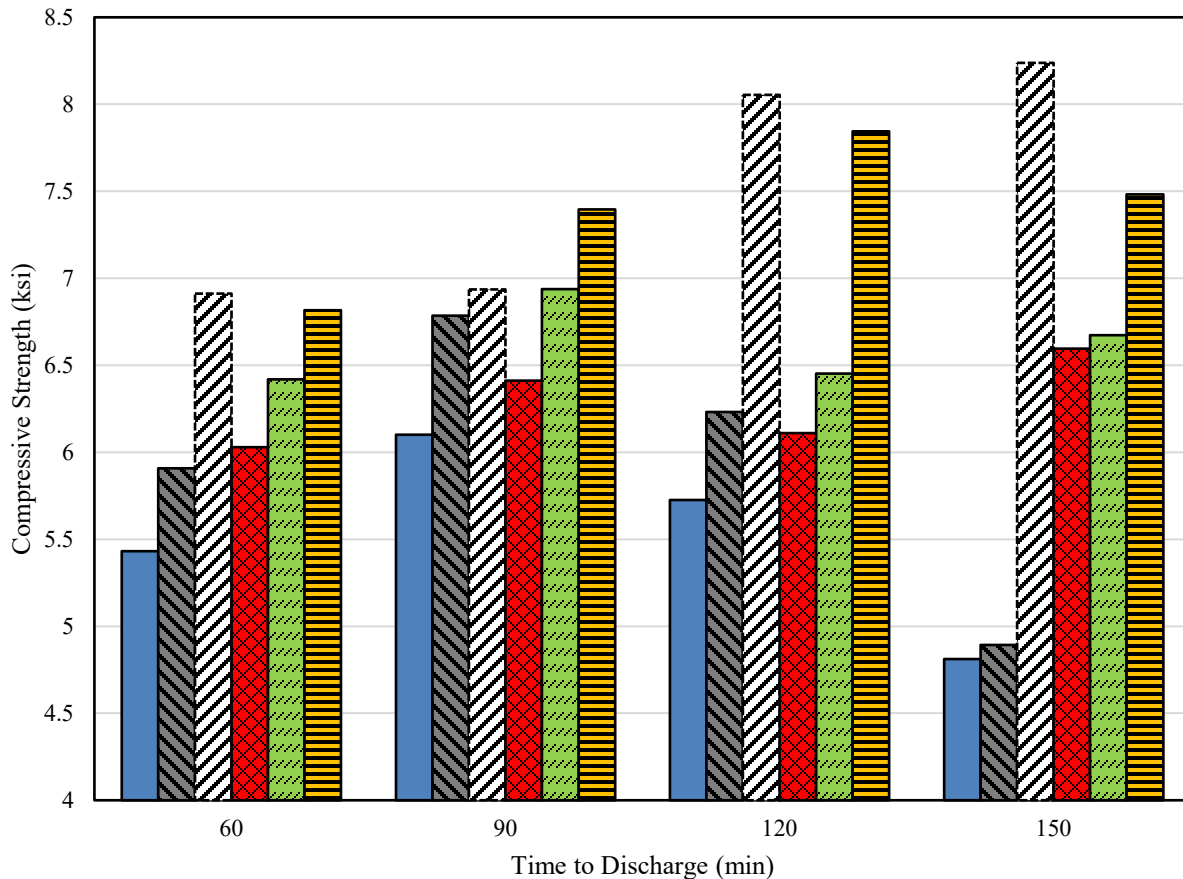
**Figure 6: Concrete Molds for Sampling**

## **F. Compressive Strength Testing**

The Compression test was carried out at NJIT's High Performance Concrete laboratory located in Colton Hall, Department of Civil and Environmental Engineering. Test mark II system, which is capable of applying 400,000 lbs of load with digital load and stress indicator, was used to test the 4x8 inch cylinders. The cylinders were weighed prior to testing. The surface would be

sulphur capped if necessary as determined by ACI Strength Testing certified lab personnel. The test was performed in strict accordance with ASTM C39/C39M (2018).

Compressive strength was determined for both mixtures at 28 and 56 days and more than 150 days to confirm the mixture design strength. The results are shown in Figure 7. It is clear from the figure that the 28-day and 56-day compressive strength of concrete mixtures met the target design requirement of 6000 psi for most of samples. There were three anomalous samples (out of 24 samples) that showed a relative drop in compressive strength at extended discharge intervals. These three points were related to Mixture 2, 25% Fly Ash, 28 day (120 and 150 minutes) and Mixture 2, 25% Fly Ash, 56 day (150 minutes).



- Mixture 1-28 Days-Strength    ■ Mixture 1-56 Days-Strength
- ▨ Mixture 1-168 Days-Strength    ■ Mixture 2-28 Days-Strength
- ▨ Mixture 2-56 Days-Strength    ■ Mixture 2-154 Days-Strength

**Figure 7: Compressive Strength vs. Time to Discharge**

## G. Surface Resistivity Testing

The Surface Resistivity (SR) Test is a rapid Non-Destructive Testing (NDT), used to assess the concrete permeability in lieu of typical accelerated chloride permeability testing. The test provides a direct indication of chloride diffusion rate and potential of reinforcement corrosion. The testing was conducted using Proceq Resipod fully integrated 4-point Wenner probe Resistivity Meter in conformance to AASHTO T 358-19 (2019) as shown in Figure 8. The device produces a current and measures the electrical resistivity of concrete between the two inner probes using the following equation:

$$\rho = 2\pi a \frac{V}{I}$$

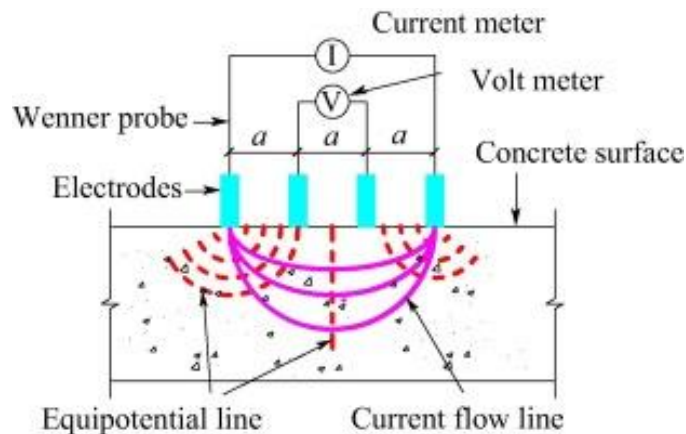
Where:

$\rho$  = Resistivity (k $\Omega$ cm).

$a$  = Probe Spacing (mm).

$V$  = Voltage (V).

$I$  = Current (amp).

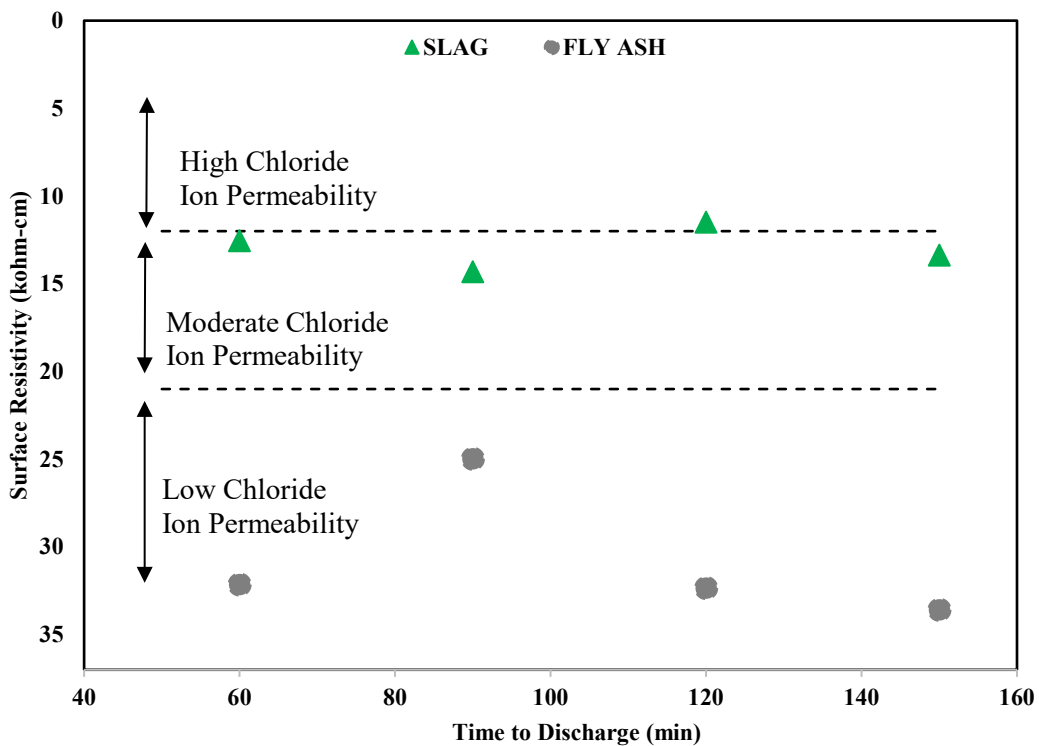


**Figure 8: Schematic of the Wenner electrical resistivity test of concrete (Yu et al., 2017)**

Two samples of each mixture for each time to discharge were used to confirm the consistency of results. The samples were cured in the laboratory steam room for 146 and 132 days for Mixture 1 and 2, respectively. The measurements were taken at zero-degree angles and repeated in 45-degree increments around the surface of each cylinder. Nine readings were recorded per sample at Saturated Surface Dry (SSD) condition. The final results are shown in Figure 9 and compared to the averaged of the readings and evaluated using Surface Resistivity Limits which are presented in Table 4 (Rabie, 2015). The values presented in Table 4 are used to understand the penetrability of chloride and anticipated service life of the concrete. As shown in Figure 9, there is no significant change in concrete permeability with time to discharge.

**Table 4: Surface Resistivity Limits for 4 in. x 8 in. Cylinder**

Chloride Ion Penetrability	Upper Limit (kohm-cm)	Lower Limit (kohm-cm)
High	0	12
Moderate	12	21
Low	21	37
Very Low	37	254
Negligible	254	1000

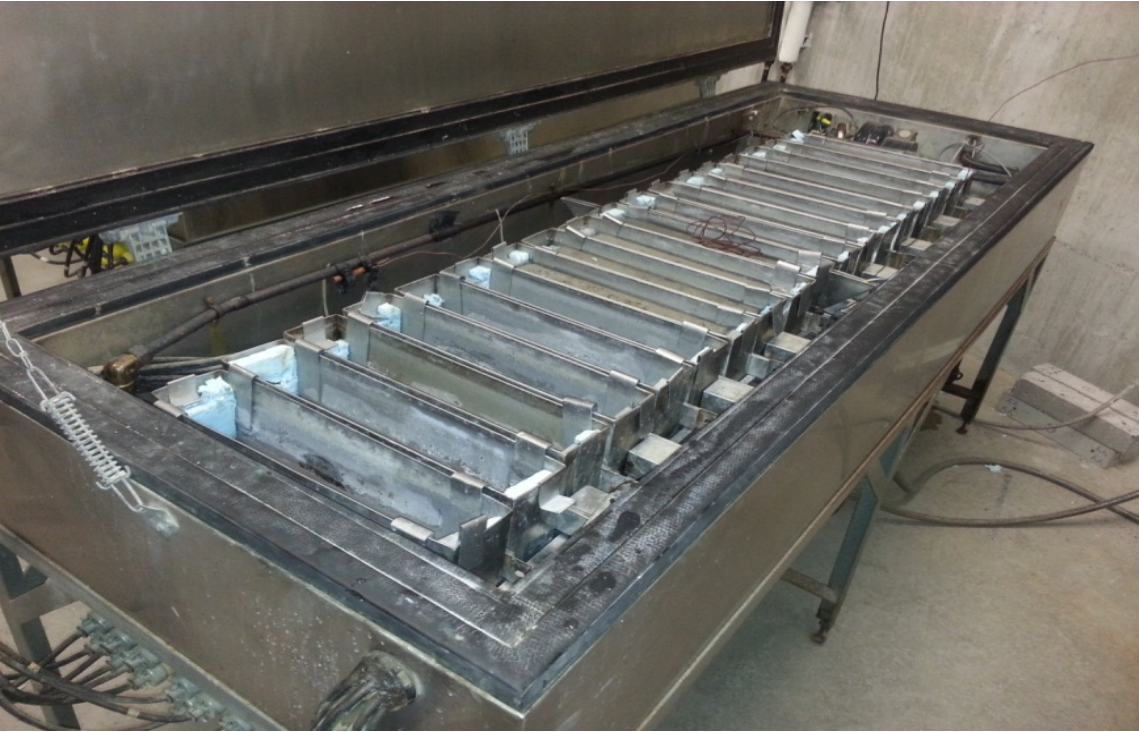


**Figure 9: Surface Resistivity vs. Time to Discharge**

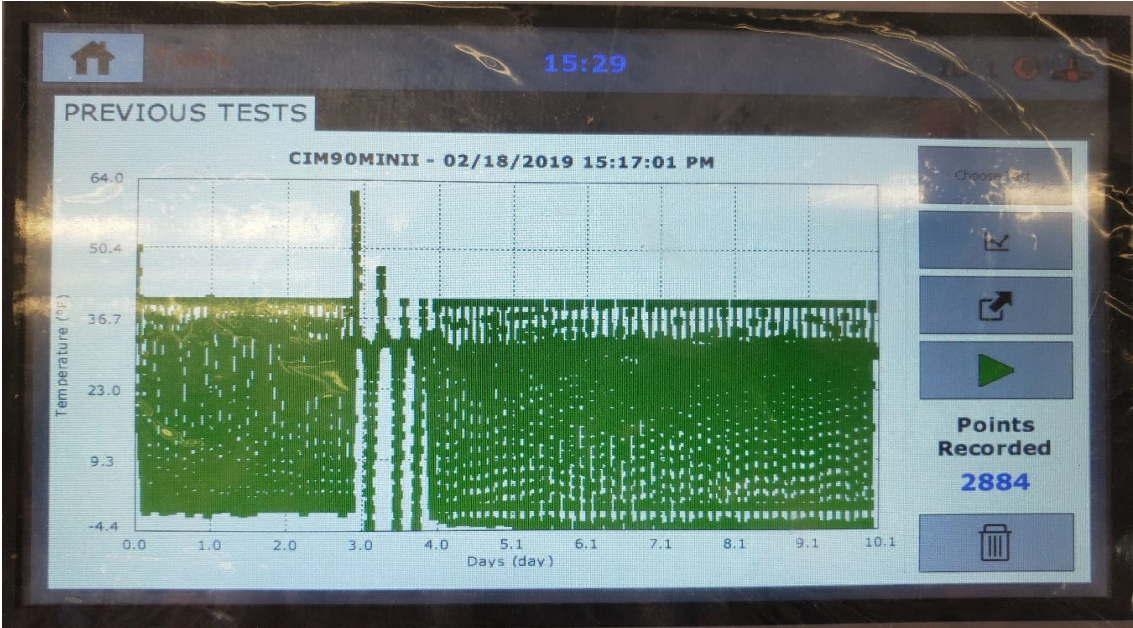
### H. Freeze-Thaw Testing

A freeze-thaw cabinet was used for the freeze-thaw resistance testing at the concrete laboratory. A picture of the machine is shown in Figure 10. This freeze-thaw machine is used to measure the resistance of concrete to deterioration caused by repeated cycles of freezing and thawing. It is designed to test up to eighteen specimens simultaneously, with one being a control. The cabinet is equipped with a data acquisition system that is connected to a seven-inch, waterproof screen that provides at-a-glance monitoring of testing functions, in a real-time graphical display, without the use of a computer, as shown in Figure 11.

The samples for the freeze-thaw durability testing were cast in 3-inch-wide x 4-inch-high x 16-inch-long containers as shown in Figure 12. The freeze-thaw test was performed according to ASTM C666/C666 (2015) in order to assess the influence of various “times to discharge” on the freeze-thaw durability of concrete.



**Figure 10: Freeze-Thaw Cabinet**



**Figure 11: Freeze-thaw Output Data**



**Figure 12: Freeze-thaw Samples**

Figure 13 shows a representative sample of freeze-thaw testing after 343 cycles, without any signs of deterioration.

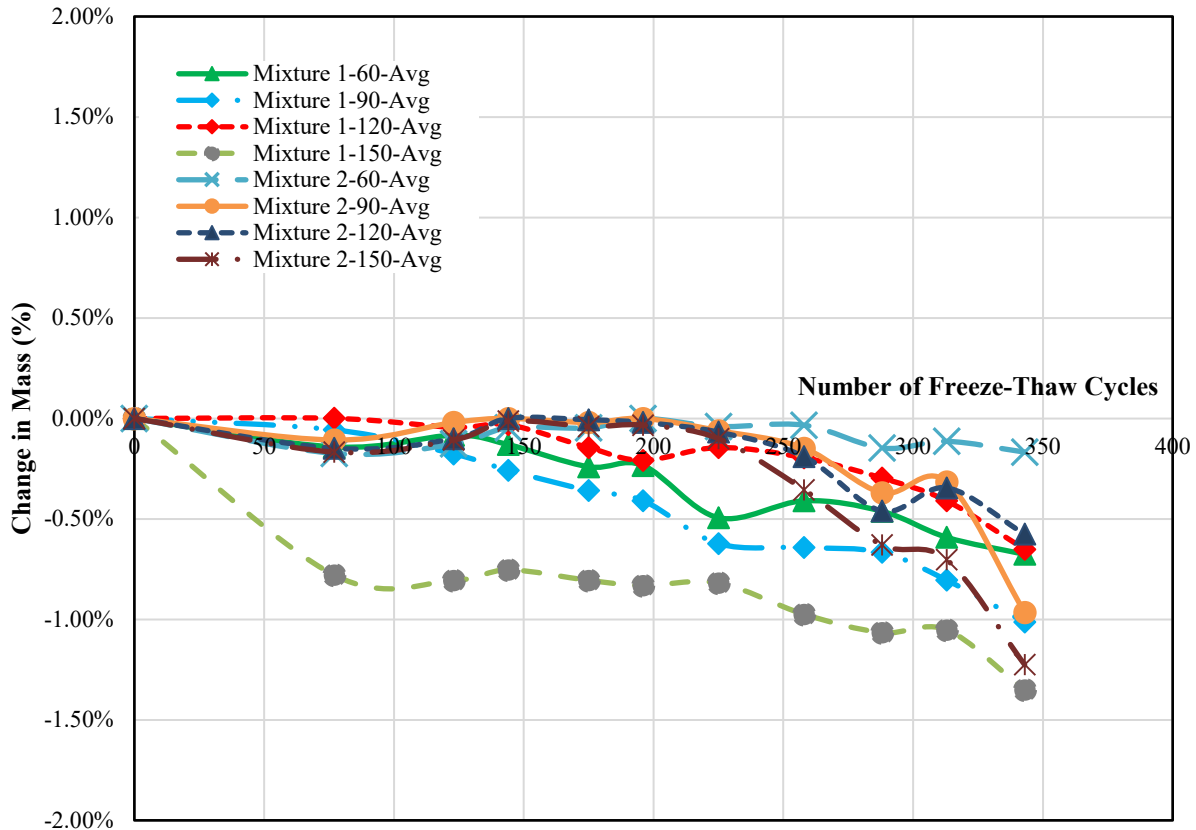


**Figure 13: Sample after 50 freeze-thaw cycles**

The 28-day-moist cured samples were exposed to more than 300 freeze-thaw cycles. The results of the mass losses as a function of the freeze-thaw cycles are shown in Figure 14. In general, none of the samples failed before the 300 freeze-thaw cycles. The results indicate that there were trivial mass losses for both concrete mixtures after approximately 300 freeze-thaw cycles. Ideally, the samples should not experience change in mass. However, the samples exhibited a minor increase or decrease in mass due to the variation in humidity and temperature. This change is attributed to wetting and/or drying of the samples.

It can be noted from Figure 14 that the concrete samples containing 25% Fly Ash have experienced more mass losses (approximately 1% maximum for the 150-minute average samples)

compared to the concrete samples containing 40% slag cement (approximately 0.70% maximum 150-minute average samples). These mass losses are not considered significant after more than 300 freeze-thaw cycles. It can also be noted from the figure that the mass losses corresponding to the 150-Minute time to discharge are approximately the same as the ones obtained from the 90-minute time to discharge for most of the samples. It can be safe to conclude that the time to discharge has insignificant effect on the losses due to the freeze-thaw action.



**Figure 14: Change in Mass vs. Freeze-Thaw Cycles**

The results of the Relative Dynamic Modulus of Elasticity (RDM) versus the number of the freeze-thaw cycles for the two tested concrete mixtures subjected to the various “times to discharge” are shown in Figure 15. The RDM values varied decreased slightly. The obtained values were in the range of  $100.00\% \pm 2.11\%$ . This indicates that all the tested concrete samples have high resistance to freeze-thaw action.

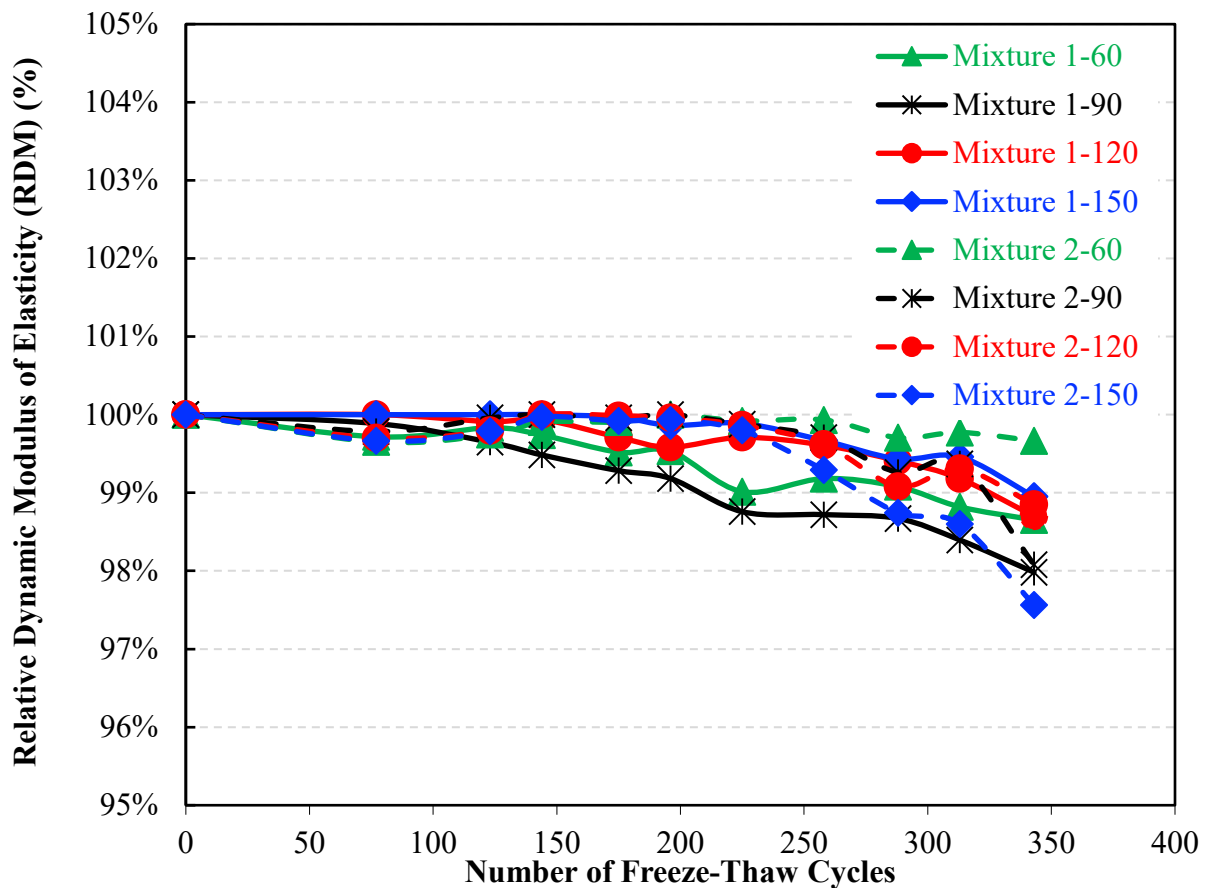


Figure 15: Relative Dynamic Modulus of Elasticity (RDM) up to 343 Cycles

The Durability Factor (DF) was also calculated for the tested samples using the following equation:

$$DF = \frac{P_n N}{M}$$

where:

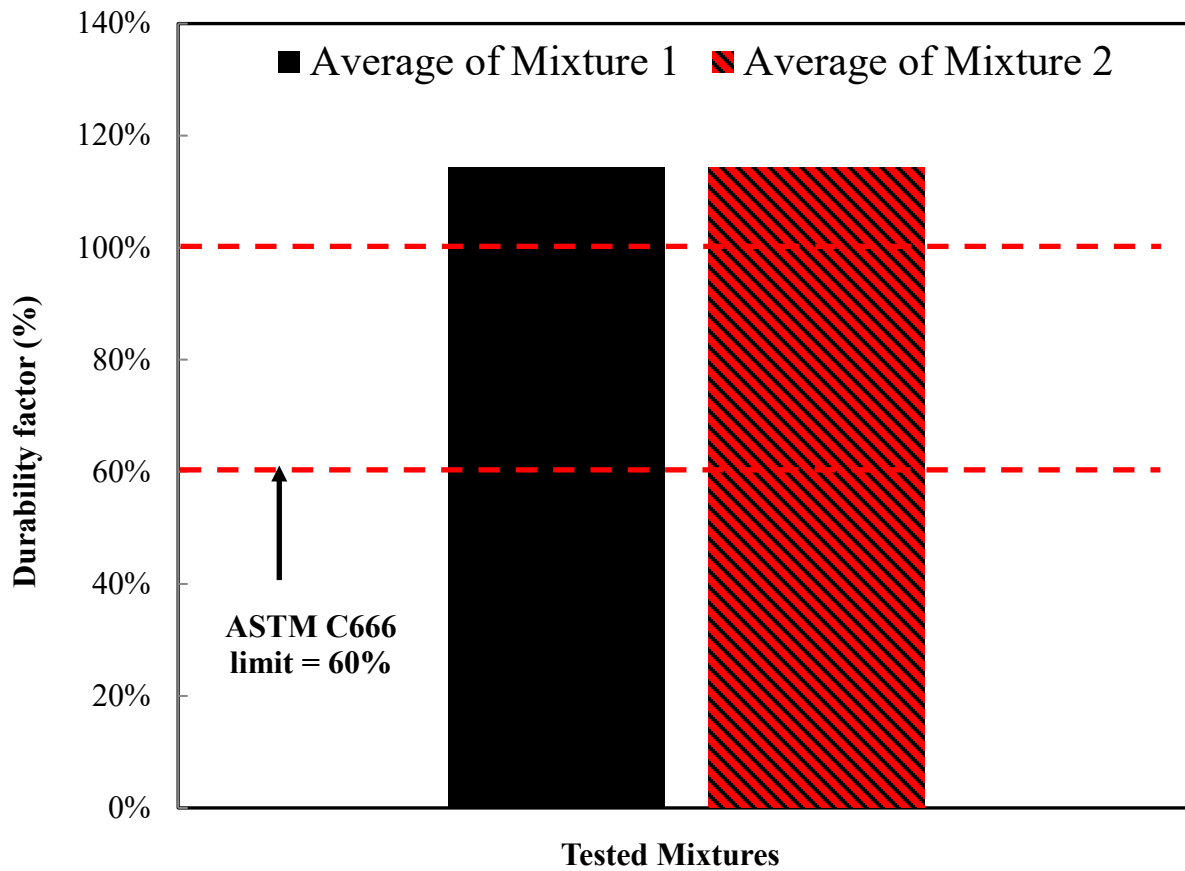
DF = durability factor of the test specimen.

$P_n$  = relative dynamic modulus of elasticity at N cycles, %.

N = number of cycles at which  $P_n$  is calculated.

M = specified number of cycles at which the exposure is to be terminated.

Typically,  $DF > 60\%$  indicates that the mixtures has good freeze-thaw resistance as per ASTM C666/C666M (2015). Both mixtures 1 and 2 were tested to 343 cycles without exhibiting any failure, which yielded DF values of 114% as shown in Figure 16. This can be attributed to the air content of concrete, which varied between 5.5% and 8% as shown in Table 3. It was maintained at different “times to discharge” and thereby there was no impact on freeze thaw durability. The durability factor was very close to the average values shown in the figure for all “times to discharge” of each mixture.



**Figure 16: Freeze-thaw Durability Factor after 343 Cycles**

## **CHAPTER 4: CONCLUSIONS**

This research project mainly investigated the behavior of hardened properties of ready mixed concrete that was discharged at different intervals: 60, 90, 120, and 150 minutes. In this study, workability was retained at extended time to discharge through the use of extended set retarding admixture. These conclusions are valid as long as no water is added with extended time to discharge. This phase of the study was conducted at an ambient temperature of 38°F and 52°F when the concrete temperature of the two mixtures evaluated stayed between 53°F and 70°F. Based on the data acquired in the light of the types of mixtures and conditions evaluated, the following conclusions were arrived at:

1. It was observed that the use of extended set retarding admixture maintained the concrete slump and air content of the mixtures.
2. The 28-day, 56-day and approximately 150-day compressive strength of concrete mixtures exceeded the target mixture design requirement of 6000 psi, for 21 samples out of 24 samples. The maximum drop in the compressive strength of the three (3) samples was 13%. Concrete strength, while not a direct measure of concrete durability, can be used to assess the overall quality of concrete.
3. The surface resistivity results indicated that there is no influence, due to a time to discharge of up to 150 minutes, on the Surface Resistivity and potential of reinforcement corrosion.
4. The freeze-thaw results indicated that discharge time has a minor influence on the freeze-thaw durability. The durability factors of the two mixtures were recorded to be 114% after 343 cycles as per ASTM C666/C666M (2015).

In conclusion, the 90-minute term does not fully recognize the variations in the mixtures and the surrounding conditions, and consequently is not significantly protective for the quality of concrete, as is intended.

The quality of concrete can be maintained for a time that exceeds the ASTM C94 time limit when the specific conditions are known, and appropriate steps are taken to retain the quality of concrete for the known time limit to discharge.

In the light of the mixtures types and conditions highlighted in this study, the results demonstrated that time to discharge up to 150 minutes had no significant impact on the hardened concrete's three main properties: compressive strength, surface resistivity, and freeze-thaw durability. As a result of this research along with other supporting studies, the time to discharge limits (90 minutes) and specifications are determined to be conservative and should be reexamined, and that the present advancement and capability of chemical admixtures can comfortably alter that time to discharge.

The proposed revision to ASTM C94 is to establish an appropriate time limit to discharge between the purchaser and the producer based on predetermined project-specific conditions. The purchaser is better aware of travel restrictions and placement methods that will impact the discharge period. This clearer understanding at the time concrete is ordered allows the producer to

take necessary steps for the anticipated time to discharge without compromising the quality of the concrete.

The ultimate goal is to prevent the addition of excess water to concrete to achieve the required slump for placement before it is discharged, thereby ensuring the required concrete quality as specified in the contract or design specifications.

## **ACKNOWLEDGEMENT**

The Concrete Industry Management (CIM) program of School of Applied Engineering and Technology (SAET), at New Jersey Institute of Technology (NJIT) would like to thank the following companies, associations and individuals for their contributions and assistance towards this research:

- For their continued financial support:
  - Ready Mixed Concrete (RMC) Research & Education Foundation
  - Portland Cement Association (PCA)
  
- Provision of materials and facilities to execute the mixing of concrete:
  - Silvi Group of companies
  - SIKA Admixtures
  
- For providing the manpower, skills necessary to accomplish testing and finalizing this report:
  - Concrete Industry Management (CIM) students and Research Assistant, Mohab Hussein
  
- For their assistance with guiding the students in the Civil and Environmental Engineering concrete laboratory at NJIT:
  - Nasser Channaoui
  - Stephen George

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