Transportation Consortium of South-Central States

Tran-SET

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Influence of Powder Activated Carbon (PAC) in Fly Ash on the Properties of Concrete

Project No. 19CASU03

Lead University: Arkansas State University

Final Report
October 2020

Disclaimer

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16. Abstract

Class C Fly Ash (CFA) is commonly used as supplementary cementitious material (SCM) in producing concrete by ready-mix concrete contractors in Arkansas. However, CFA can be used as a partial replacement of Ordinary Portland Cement (OPC) if it meets certain ASTM requirements. It is believed that the presence of powder activated carbon (PAC) in CFA increases the demand of the air-entraining agent (AEA) to achieve specified air content, and this is a concern to transportation agencies such as the Arkansas Department of Transportation (ARDOT) and concrete producers in recent years. Thus, the main goal of this research is to assess the influence of PAC in fly ash on the properties of concrete. To achieve the goal of this study, a total of 14 mixes (12 laboratory and two plant mixes) were evaluated to determine the fresh concrete properties (e.g., air content, workability, and unit weight) as well as hard concrete properties (e.g., compressive, tensile and flexural strength, modulus of elasticity, and long-term durability). Besides the Pressure Meter method, a Super Air Meter (SAM) and a Miller 400A resistivity meter were used in this study to determine the air quality and electric resistance, respectively, of the prepared fresh concrete. Two CFAs containing the different percent of PAC (i.e., 0%, 0.25%, 0.50%, and 0.75% by the mass of CFA) were used to prepare the mixes where the dosage of AEA was selected based on the manufacture recommendation. Air content measurements of two selected hard concrete mixes were also made in the laboratory. The results showed that the PAC content had a significant effect on the air content of the fresh concrete. The air contents of plant mixes agreed with those of the laboratory mixes. The SAM test was found to be an effective test method to measure the air-void quality of fresh concrete mixes; the air content and quality measurements of fresh concrete were comparable with air voids of hard concrete. The long-term durability (alkali-silica-reactivity and scaling resistance) was found to be influenced by the PAC content as well as the source of CFA. The findings of this study can help to better understand the effect of PAC content in CFAs in producing durable concrete.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m	square meters	10.764	square feet	ft^2
m	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m	cubic meters	35.314	cubic feet	ft^3
m	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
C	Celsius	1.8C+32	Fahrenheit	^{o}F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

ACI	American Concrete Institute
AEA	Air-Entraining Agent
ARDOT	Arkansas Department of Transportation
ASCE	American Society of Civil Engineers
ASR	Alkali-Silica Reaction
ASTM	American Society for Testing and Materials
ASU	Arkansas State University
CA	Coarse Aggregate
$CaCl_2$	Calcium Chloride
CFA	Class C Fly Ash
DOT	Department of Transportation
DSU	Data System Unit
FA	Fine Aggregate
FHWA	Federal Highway Administration
FIT	Foam Index Test
FM	Fineness Modulus
LVDT	Linear Variable Differential Transformer
NaOH	Sodium Hydroxide
NCHRP	National Cooperative Highway Research Program
NMS	Nominal Maximum Size
OPC	Ordinary Portland Cement
PAC	Powder Activated Carbon
RHA	Rice Husk Hull/Husk Ash
SAM	Super Air Meter
SCM	Supplementary Cementitious Materials
SEM	Scanning Electron Microscopy
SN	SAM Number
TranSET	Transportation Consortium of South-Central States
TRB	Transportation Research Board
USDOT	United States Department of Transportation
UTM	Universal Testing Machine
%	Percent
/cwt.	Per 100 weight
°C	Degree Celsius (Unit of Temperature)
°F	Degree Fahrenheit (Unit of Temperature)
cm	Cementitious Materials
g/gm	Gram (Unit of weight)
hrs	Hours
Hz	Frequency

in.	Inch
kPa	Kilo Pascal
L	Liter
lb	Pound
min.	Minute(s)
mm	Millimeter
MPa	Mega Pascal; Unit of DMT Modulus
oz	Ounce
psi	lb/in2
µm	Micrometer
Ω	Ohm

EXECUTIVE SUMMARY

Class C Fly Ash (CFA) is routinely used by contractors as a partial replacement of Ordinary Portland Cement to produce concrete. However, transportation agencies such as the Arkansas Department of Transportation (ARDOT) are concerned about certain CFAs as they contain powder activated carbon (PAC), which may be detrimental to the long-term durability of concrete. The main objective of this study is to assess the influence of PAC in fly ash on the properties of fresh and hard concrete. Specifically, the current study focuses on the effects of different amounts of PAC in CFA-modified concrete on the air content properties, which are often related to expansions of concrete due to freeze-thaw cycles. The objectives of the current study have been accomplished through a comprehensive review of available literature in the public domain and extensive laboratory testing of CFA-containing concrete samples produced in the laboratory as well as in a ready mix plant. Fly ash samples from two sources have been used in consultation with ARDOT engineers, ready-mix contractors, project review committee (PRC) members, and fly ash suppliers. A total of 12 concrete mixes have been prepared. The Absolute Volume Method was followed to determine the mix design properties. Produced concrete samples have been produced have been tested in the laboratory to determine properties such as temperature, slump, and air-content along with the air quality. The produced hardened concrete samples have been tested for strength properties (compressive, tensile, and flexural), elastic modulus, air content, alkali-silica-reaction (ASR), and expansion properties. Data collected from the laboratory tests of laboratory and plant mixes have been analyzed and summarized to develop implementation recommendations.

This study reveals an increasing demand for the air-entraining agent (AEA) in producing durable concrete that will provide the desired air content in hard concrete. The super air meter (SAM) has been found to be an effective tool to measure the quality of air in concrete. The foaming index test (FIT) is found to be a very quick and effective tool in determining the required dosage of the air-entraining agent in PAC-contained CFA-modified concreter. Regarding the air content, the concrete samples produced in the plant were found to be comparable with those produced in the laboratory. Also, the air content obtained from SAM was found to agree with that of hard concrete. The PAC was found to have a significant influence on the air content as well as long-term durability properties such as ASR and scaling resistance.

From the fresh concrete test results, it is revealed that the slump value (workability), air content, and setting time values of the samples were increased in the case of lower percent of PAC (0% to 0.25%) or vice versa. In contrast, the unit weights and the resistivity of the samples were found to be increased due to the incorporation of a higher amount of PAC in the CFAs. Also, the FIT results showed that the optimum AEA dosages were increased with the increase of CFAs and PAC replacement levels in the mixes. Based on the hardened concrete test results, it is evident that the mechanical properties such as the compressive, tensile, and flexural strengths, and the modulus of elasticity of the concrete samples were significantly increased with the increase of the higher PAC (0.75%) the CFAs or vice-versa. The air content of hardened concrete showed that 0.5% PAC in the CFAs is desirable to satisfy the total air value recommended by the ACI.

The findings of the current study are expected to helpful for transportation agencies, ready mix plant operators, and contractors in selecting an appropriate amount of AEA to maintain the desired air content in CFA-modified hard concrete when an excessive amount of PAC is present in CFA.

1. INTRODUCTION

1.1. Problem Statement

Ready-mix concrete contractors routinely use Class C Fly Ash (CFA) as supplementary cementitious material (SCM) in producing concrete. The CFA is used as a partial replacement of Ordinary Portland Cement (OPC). Thus, the CFA must meet certain American Society for Testing and Materials, (ASTM) requirements (e.g., carbon content and loss of ignition) before it can be used in producing concrete. However, transportation agencies such as the Arkansas Department of Transportation (ARDOT) are concerned about some CFAs as they contain power activated carbon (PAC), which may create adverse impacts on the target air voids and post-construction durability of air-entrained concrete. The PAC in fly ash increases the demand of the air-entraining agent (AEA) to achieve the desired air content. A higher amount of large entrained air bubbles in fly ash-containing concrete can lead to a reduction in the volume of the entrained air bubbles over a period of time. Furthermore, the spherical shape of fly ash is reported to cause a larger rate of reduction in the volume of the entrained air bubbles as the coalescence and escape of entrained air bubbles can easily occur. The degree of coalescence of air bubbles can be reduced by careful selection of the air-entraining agent (AEA) and the mixing procedure. Alternatively, the unburned carbon can be reduced or removed by a high-temperature burnout or separated physically. To separate carbon from ash, additional steps such as the froth flotation process can be adopted. The agencies and ready-mix plant operators need a tool and/or technique so that necessary measures can be taken so that an appropriate amount of AEA can be used in the concrete mixes to obtain the desired air content. Also, special provisions can be included in the quality control/quality assurance guidelines for the ready-mix plants for using fly ash containing PAC in preparing concrete.

1.2. Background

Fly ash has been used as a supplementary cementitious material (SCM) in concrete for decades. Many pieces of research already established that fly ash improves different properties of concrete. Despite the innovation of new technologies and uses of coal combusting fly ash, the incorporation of fly ash in the concrete industry has been a high-value outlet for heavy industries such as power plants. According to the American Coal Ash Association, in 2017, about 38.1 million tons of fly ash has been produced in the US where 24 million tons of fly has been used in the concrete industry through various applications *(1)*. However, a high level of unburnt carbon in fly ash can be detrimental to the concrete. In the coal-fired power industry, PAC is used to control the level of mercury, which eventually becomes associated (0.5 to 1% PAC by weight) with fly ash *(2)*. In the production process, the mercury-laden carbon gets associated with fly ash in the ash collection system, which leads to ash containing small amounts of mercury and varying levels of activated carbon *(3-5)*. However, the activated carbon can create a significant hindrance to air-entrained concrete.

The PAC in fly ash is expected to adsorb the surface-active admixtures in concrete because of its high adsorptive capacity for organics *(6-8)*. A very low contamination level of activated carbon can cause fly ash unsuitable for use in air-entrained concrete *(6-8)*. Moreover, the PAC effects on concrete can be different due to the surface properties and adsorbed compounds. There has not been any established standard in the US to govern the use of PAC contained fly ash, which limits the ability to estimate the outcome to the concrete. Even though there are some technologies for reducing the impact of carbon content from fly ash, these technologies are most effective when the activated carbon content is high in fly ash.

The main objective of this study is to assess the influence of PAC in fly ash on the properties of concrete. This study investigates the effect of PAC on the fresh and hardened properties including the air voids and strength characteristics of concrete. Air voids characteristics were determined using a Super Air Meter (SAM), which is a modified version of ASTM C231 that uses a Type B Pressure Meter. This device is very useful to determine the real-time measurements of the size of the air bubbles as the concrete is being produced so that adjustments can be made to control the amount of the air bubbles. This ultimately helps to ensure that concrete is durable under freeze-thaw actions.

2. OBJECTIVES

The primary objective of this proposed research project is to assess the influence of PAC in fly ash on the properties of concrete. Specific objectives of this study are:

- Conduct a thorough literature review,
- Evaluate the physical properties (e.g., specific gravity, moisture content, and absorption) of ingredients used in preparing concrete samples,
- Evaluate the impacts (air voids and expansion properties) of PAC-containing fly in air-entrained concrete,
- Evaluate strength properties and air content of hard concrete,
- Suggest a tool to measure the required amount of air-entraining agent in producing concrete with the desired air content, and
- Suggest appropriate tool(s)/technique to minimize the influence of PAC in fly ash-modified concrete.

To accomplish the aforementioned objectives a set of tasks containing the evaluation of laboratory and plant mixes has been identified and executed in this study.

3. LITERATURE REVIEW

A comprehensive literature review has been conducted to gather the idea about the past and present practices related to this study. The recommendations from the past researchers were considered for designing the final experimental plan. The articles reviewed in this study include, but are not limited to, publications from the Transportation Research Board (TRB), Journals of Materials of Civil Engineering, Journal of Construction and Building Materials, and Journal of Cement and Concrete Research.

3.1. Fly Ash

Nowadays, concrete is the most widely used construction material in the world because of its durability and long-lasting performance in violent environments *(9)*. The use of supplementary cementitious material (SCM) in concrete has been increased worldwide focusing on environmental sustainability over the last few decades. Extensive research has been carried out on the possible uses of waste materials as an alternative SCM such as fly ash, slag and silica fume *(9)*, construction and demolition wastes *(10-12)*, rice husk ash *(13)*, biomass ash, and wood wastes *(14 and 15)*, blast furnace slag *(16)*, steel slag *(17)*, ceramic wastes *(18)*, glass powder *(19)*, marble powder *(20)* and other mineral powders *(21)*. These studies mainly emphasized improving the mechanical properties and enhancing the durability and sustainability of concrete by partially replacing the cement in the mixture.

The substitution of ordinary Portland cement (OPC) with SCMs in concrete can reduce carbon emissions, and therefore improve the green footprint in the concrete manufacturing processes *(22)*. Among many industrial wastes materials, several SCMs such as fly ash, ground granulated blast furnace slag, and silica fume have been chosen for the partial replacement of cement in the mixture by the industries as they have hydraulic and pozzolanic properties *(23)*.

Fly ash has been increasingly used in the concrete industry in recent years. Extensive studies have been carried out to investigate the influence of fly ash as the replacement of OPC on the fresh, mechanical, and durability properties of the concrete. The SCMs can significantly increase the properties of fresh and hardened concrete when they are used at optimum levels *(24 and 25)*. In the modern world, fly ash has been successfully and widely used in concrete production as an effective SCMs *(26-28)*. Moreover, the effective use of fly ash in concrete constructions has double advantages: (i) decrease the waste materials and their associated environmental impacts through reusing capability *(29)*, and (ii) reduce the OPC consumption amount and its associated CO_2 releases from the cement manufacturing process *(30)*. Therefore, the replacement of OPC with fly ash provides environmental and economic benefits towards achieving the goal of sustainability in the concrete industries *(24)*.

Fly ash is a by-product of the combustion of pulverized coal, which is a pozzolanic material. It makes a product similar to that formed by cement hydration when it is mixed with OPC and water, having a denser microstructure and low permeability. It improves the durability when used in concrete as a partial replacement of cement. Also, it has pozzolanic and filler effects that attributes to concrete strength *(31)*. Multiple studies have been conducted to investigate the influence of the addition of fly ash on the mechanical properties of concretes and mortars *(14-15, 32-37)*. These studies showed that a low percentage of replacement (e.g., 10%) of fly ash has a negligible effect on the mechanical and durability properties of concrete. However, these researchers observed an increment of compressive strength due to the addition of fly ash with a smaller replacement in some cases.

A group of researchers also studied the effects of biomass ash addition in concrete on elastic modulus and electrical conductivity at an early age and developed essential correlations between them *(38 and 39)*. Some studies showed that a higher amount of fly ash (e.g., 40%) can be used to achieve the desired concrete properties and lower the cost of concrete production *(40 and 41)*. Several researchers reported that the fly ash can be used as more than 50% of the total binder (cement) for normal strength concrete *(42)*, whereas the replacement level is recommended as 15-25% for high strength concrete *(43)*. However, the early strength of concrete is significantly reduced if a higher amount of fly ash is used as a pozzolanic reaction is a slower process than a hydraulic reaction *(44)*. As a result, the use of a high percentage of fly ash in concrete is needed to be carefully investigated to achieve the desired strength.

3.2. Power Activated Carbon (PAC)

Hill et al. *(45)* characterized carbon in fly ash and its interaction with the air-entraining agents through thermal analysis and petrographic examination. They reported higher demand for air-entraining agents, and it was directly related to the presence of a higher proportion of optically isotropic and amorphous carbon. Moreover, the liquid and the vapor phase adsorption analysis indicated that the surface chemistry characteristics of the isotropic carbon caused a higher adsorption capacity for polar compounds such as air-entraining surfactants. In a related study, these researchers *(46)* investigated the performance of chemically treated fly ash for mitigating the negative impacts of activated carbon on air-entrained concrete. They stated that the presence of PAC in fly ash would have severe consequences in air-entrained concrete. Moreover, a small level of "contamination" (<0.5%) of PAC in fly ash is likely to make unusable concrete. From the test results, they highlighted the high demand for air-entraining admixture in concrete in the presence of PAC.

Kang and Sung *(47)* studied the physical and mechanical properties of concrete using waste activated carbon. These researchers stated that 3% of waste activated carbon modified concrete showed more compressive strength, flexural strength, and dynamic modulus of elasticity compared to the regular concrete. Also, they stated that the most effective contents of waste activated carbon were found to be 2% in performance and 4% in practical use. They concluded that waste activated carbon could be used for concrete material.

Liu et al. *(48)* reported some influences of the carbon on the air content of the concrete. However, they found no difficulty in entraining air in activated carbon injected fly ash concrete within the recommended amount of the air-entraining admixture. They stated that all air-entrained and PAC injected fly ash modified concretes exhibited excellent performance in compressive strength, resistance penetration, and freezing and thawing cycling tests.

Mahoutian et al. *(49)* studied the effect of PAC and AEA on the properties of fresh and hardened concrete. These researchers mostly focused on air voids of fresh concrete, compressive strength, specific surface area, spacing factor, and air voids of the hardened samples. The air voids' properties of hardened concrete were determined by using an image analysis technique on epoxy-impregnated and ink-prepared samples. They considered five different concrete mixes. Of these, four mixes contained pure fly ash and cement at a ratio of 1:4 where PAC was added from 0 to 10% by mass of the fly ash in the laboratory. The other mix had fly ash, in which PAC was injected at the power plant. They found that the effect of PAC on air void content was lower when the PAC was injected in fly ash at the power plant compared to the PAC added to the fly ash in the laboratory. However, PAC decreased the air void content and affected the specific surface area, which caused more AEA requirements to reach the required air void content. Image analysis results revealed that a 44% increase in the specific surface area was observed when 10% of PAC was added to the mix compared to the mix without PAC. It was concluded that the PAC affected the larger air voids, and the elimination of large air voids led to a higher specific surface area. They reported that more accurate and reliable air void characteristics were obtained in the case of the ink-prepared specimens compared to the epoxy impregnated specimens.

The ongoing National Cooperative Highway Research Program (NCHRP) 18-17 *(50)* study has focused on identifying the characteristics of the entrained air voids required for freeze-thaw durability of highway concrete. This study has focused on developing new or modified test methods for measuring air voids for evaluating freeze-thaw durability. The recommendations of the NCHRP 18-17 study were taken into consideration in this research.

4. METHODOLOGY

This chapter describes the selection and collection of the required material, equipment, research tools, and a brief description of the test methods employed in this study. The materials and test methods were selected based on the desired goals of this study as well as their availability and suitability in local construction projects. Fly ash samples were collected in consultation with the ARDOT engineers, the ready-mix contractors, project review committee (PRC) members, and fly ash suppliers. Fresh concrete mixes were prepared in the laboratory to determine their fresh concrete properties such as air-content and workability. Hardened concrete cylinders, beams, and mortar bars were also prepared and tested for determining their strength, long-term durability, air content, and expansion properties. The laboratory test data were then analyzed and summarized to provide implementation recommendations.

4.1. Preparation of Test Plan

As mentioned earlier, toward accomplishing the goals of the study, an extensive project plan comprised of a literature review, a study plan, a detailed test matrix, test methodologies, data collections, and data analysis and discussions has been undertaken. A project flow diagram, showing critical steps and associated tasks for the successful completion of the project, is provided in Figure 1.

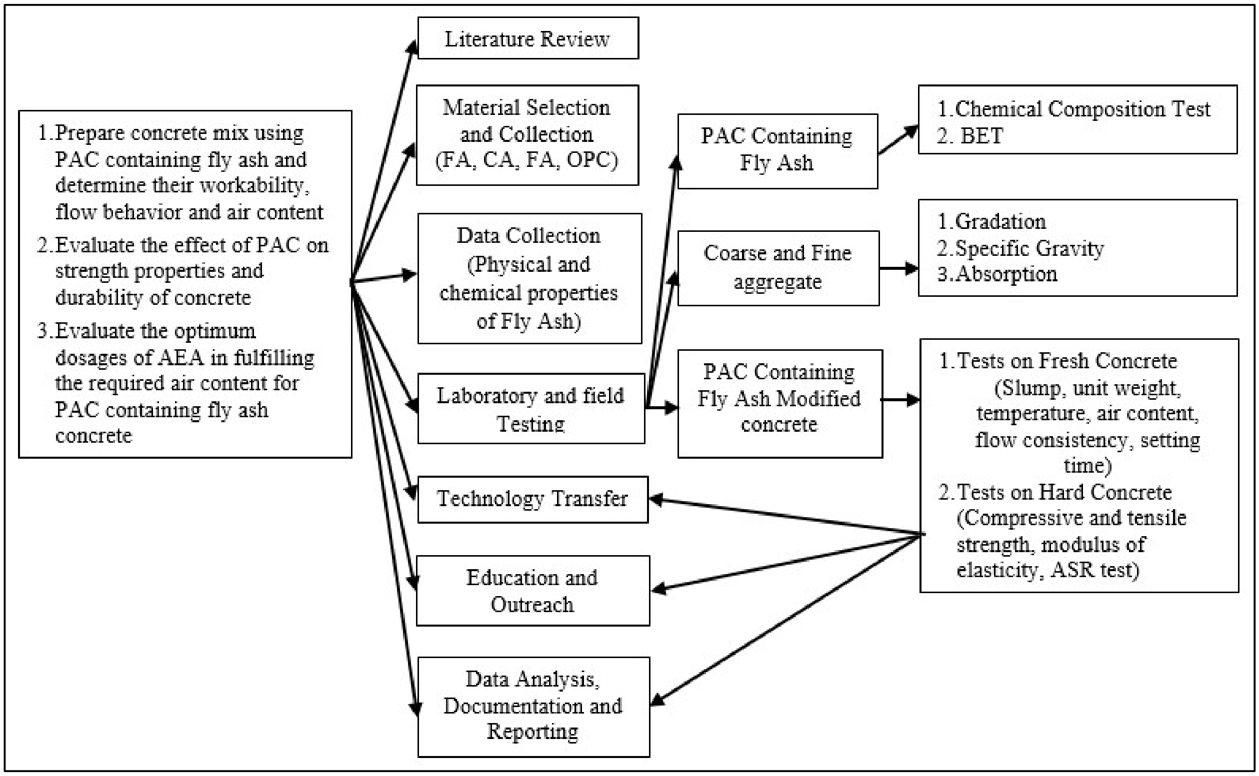


Figure 1. High-Level Project Flow Diagram.

4.2. Materials

Materials required for this project included fine aggregates (FA), coarse aggregates (CA), OPC, fly ash (Class-C), and an air-entrainment agent. A majority of these items have been collected from the plant site of the industry partner of this study, NEAR Ready Mix, located in Jonesboro, AR. Two mix designs for target compressive strength values of 3000 psi and 4000 psi have been followed. Both laboratory and plant mixes were produced based on the same mix designs. The proportions of various ingredients, water-cement ratio, admixture dosages, and fly ash percent in the mixes have been analyzed and identified to prepare the mix for laboratory testing. The CFA samples without any external injection of PAC were collected directly from fly ash plants for conducting the laboratory tests. Table 1 shows a summary of the materials used in this study along with their collection sources. As seen in Table 1, most of the raw materials were collected from NEAR Concrete's Jonesboro plant, the plant mixes were collected from its Paragould plant. However, both of the plants use the same raw ingredients and mix design in producing their concrete. During the current study, NEAR Concrete has used the same CFA and other admixtures.

Table 1. Details of Materials Used in this Study.

Material Type	Source	Origin
Coarse Aggregate (CA)	NEAR Ready Mix Concrete Plant, Jonesboro, AR	#57 Limestone, Capitol Quarries
Fine Aggregate (FA)	NEAR Ready Mix Concrete Plant, Jonesboro, AR	Concrete Sand, Hedger Aggregates
ASTM C-150 TYPE II Cement	NEAR Ready Mix Concrete, Jonesboro, AR	Buzzi Unicem
Fly Ash 1 (CFA1)	NEAR Ready Mix Concrete Plant, Jonesboro, AR; ARDOT Approved Source 1	Source 1 Plant site
Fly Ash 2 (CFA2)	ARDOT Approved Source 2	Source 2 Plant site
Air Entraining Agent (AEA)	NEAR Ready Mix Concrete Plant, Jonesboro, AR	DARAVAIR 1400, GCPAT
Powder Active Carbon (PAC)	Entergy	M & M Milling, Texarkana, AR
Plant Mixes	NEAR Ready Mix Concrete Plant, Paragould, AR	Plant site

4.3. Laboratory and Field Tests

Appropriate ASTM test methods were followed to determine the properties of CA and FA required for the mix design. Also, fresh concrete mix properties and mechanical properties of hardened concrete were estimated as per the ASTM standards. The following tests were performed in the laboratory and at the plant site.

4.3.1. Physical Properties of Fly Ash, CA and FA

The collected fly ash from Source 1 (CFA1) had amorphous calcium-aluminum silicates from 60 to 70%, crystalline silica content of less than 16%, calcium oxide of less than 25%, iron oxide of less than 7%, magnesium oxide of less than 5%, potassium oxide of less than 1%, and phosphorus pentoxide of less than 2%. The CFA1 sample's specific gravity ranged from 2.2 to 2.8, and its pH varied from 7 to 11. The intended usages of CFA1 are components of wallboard, concrete, asphalt, roofing material, bricks, cement kiln feed functional filler, and construction material for various civil engineering applications. On the other hand, the CFA from Source 2 (CFA2) had aluminosilicates from 30 to 60%, crystalline silica of less than 34%, calcium oxide from 15 to 40%, and potassium oxide of less than 12%. The CFA2 sample's specific gravity ranged from 2.3 to 2.7, and its pH varied from 10 to 12. The intended usages of CFA2 are industrial, cement replacement, and structural fill.

The ASTM C136 method was followed to perform sieve analyses of CA and FA. The fineness modulus (FM) of FA and the nominal maximum size of CA were determined from the sieve analysis. The specific gravity and absorption values of CA and FA were determined per ASTM C127 and ASTM C128, respectively.

4.3.2. Mix Design

The mix design was developed per ACI 211.1-91 (the Absolute Volume Method) to prepare the test samples. Table 2 shows the properties of the required materials for the mix design. In this study, a locally available Type-I OPC with a specific gravity of 3.15 was used. The design water-cement ratio was selected as 0.45. The slump value ranging from 50 mm 100 was considered to prepare the mix design. The required amount of CA, FA, water, and cement were determined per cubic yard of concrete based on the charts provided by ACI. The moisture correction was applied using the properties of CA and FA used in this study. The mix designs followed for 3000 psi and 4000 psi in the laboratory and plant concrete are provided in Table 2. An OPC of Type II with a specific gravity of 3.15 was used. Twenty percent of the OPC was replaced with CFA. In this study, CFA samples from two ARDOT approved sources were used. The CA used in this study had a nominal maximum size of 1 inch, a bulk specific gravity of 2.610, an absorption of 0.93%, moisture content of 0.26%, and a dry rodded unit weight of 89.33 lb/ft3 (1431 kg/m3). The FA used in these mixes had an FM of 2.9, a bulk specific gravity of 2.581, moisture content of 0.11%, and absorption of 1.00%.

Table 2. Required Materials Properties and Mix Design.

Material	**Amount needed for producing 1 yd^3 of Concrete for 3000 psi concrete**	**Amount needed for producing 1 yd^3 of Concrete for 4000 psi concrete**
Cement (lbs.)	376	451
Fly Ash (lbs.)	94	113
Coarse Aggregate	1805	1758
Fine Aggregate	1444	1424
Water (lbs.)	210	255
Air voids	5%	2%
AEA	1 oz./cwt.cm per manufacturer rec.	1 oz./cwt.cm per manufacturer rec.

4.3.3. Tests on PAC Containing Fly Ash Modified Concrete

Fourteen (14) concrete mixes containing different CFA and AEA amounts were tested in this study. The 3000 psi mix (S1-1) containing 100% OPC (no CFA and no PAC) and 5% air voids has been considered as the Control mix. The industry partner of this study, NEAR Ready Mix Concrete Plant, typically uses 20% CFA in their mixes, thus the other mixes had an 80% OPC. Among the 14 mixes, two mixes were collected from the NEAR Concrete plant located in Paragould, AR. Results from the plant mixes were compared with corresponding laboratory mixes. Three different amounts of PAC in each of the two CFAs were evaluated in the laboratory. The amounts of PAC for the laboratory mixes were included: 0.5%, the same amount of PAC used in the plant; 0.25%, which is less than the plant amount; 0.75%, which is higher than the plant dosage. The raw materials (fine and coarse aggregates) for laboratory mixes of this study were collected from the NEAR Concrete plant site. Table 3 shows the details of the different mixes evaluated in this study. A series of laboratory tests were conducted to evaluate the physical and mechanical properties of CFA modified concrete, shown in Table 4.

Table 3. Details of the Test Mixes Used in this Study.

Sample ID	Mix Type	Nomenclature	Description
S1-1 (Control)	Lab	OPC100-AEA-LAB-AV5	100% Cement with AEA Air voids (AV) 5%
S1-2	Lab	OPC100-AEA-LAB-AV2	100% Cement with AEA with AV of 2%
S1-3	Lab	OPC80-CFA1-AEA-LAB-AV2	80% OPC and 20% CFA1 containing no PAC with AV of 2%
S1-4	Plant	OPC80-CFA1-PACX-AEA-PLANT-AV2	80% OPC and 20% CFA1 containing 0.5% PAC with AV of 2%
S1-5	Lab	OPC80-CFA1-PACX-AEA-LAB-AV2	80% OPC and 20% CFA1 containing 0.5% PAC with AV of 2%
S1-6	Lab	OPC80-CFA1-AEA-LAB-AV5	80% OPC and 20% CFA1 containing no PAC with AV of 5%
S1-7	Plant	OPC80-CFA1-PACX-AEA-PLANT-AV5	80% OPC and 20% CFA1 containing 0.5% PAC with AV of 5%
S1-8	Lab	OPC80-CFA1-PACX-AEA-LAB-AV5	80% OPC and 20% CFA1 containing 0.5% PAC with AV of 5%
S1-9	Lab	OPC80-CFA1-PACY-AEA-LA - AV5	80% OPC and 20% CFA1 containing 0.25% PAC with AV of 5%
S1-10	Lab	OPC80-CFA1-PACZ-AEA-LAB-AV5	80% OPC and 20% CFA1 containing 0.75% PAC with AV of 5%
S2-6	Lab	OPC80-CFA2-AEA-LAB-AV5	80% OPC and 20% CFA2 containing no PAC with AV of 5%
S2-8	Lab	OPC80-CFA2-PAC0.50-AEA-LAB-AV5	80% OPC and 20% CFA2 containing 0. 5% PAC with AV of 5%
S2-9	Lab	OPC80-CFA2-PAC0.25-AEA-LAB-AV5	80% OPC and 20% CFA2 containing 0.25% PAC with AV of 5%
S2-10	Lab	OPC80-CFA2-PAC0.75-AEA-LAB-AV5	80% OPC and 205% CFA2 containing 0.75% PAC with AV of 5%

Table 4. Physical and Mechanical Properties of CFA-Modified Concrete.

Property	Designation	Description
Temperature	ASTM C 1064	The temperature of fresh concrete mixes
Unit Weight	ASTM C 138	Unit weight of fresh concrete mixes
Setting Time	ASTM C 408	Setting time of fresh concrete mixes
Slump Test (Workability)	ASTM C 143	Slump cones will be used to determine the workability of fresh concrete mixes
Air Content	ASTM 231	Pressure Method: air content of freshly mixed concrete Super Air Meter: air void spacing and air volume of fresh concrete
Foam Index	GCPAT 2019	relative levels of Air Entraining Agent (AEA) needed during concrete mixing
Compressive Strength	ASTM C 109	The effect of curing on the compressive strength of hardened concrete
Tensile Strength	ASTM C 496	Splitting tensile strength of hardened concrete (28 days)
Flexural Strength	ASTM C 293	Flexural strength of hardened concrete (28 days)
Modulus of Elasticity	ASTM C 469	Modulus of elasticity of hardened concrete (28 days)
Alkali-Silica Reaction (ASR)	ASTM 1557	Expansion properties of mortar
Air Content of Hardened Concrete	ASTM C 457	Scanning Electron Microscope: Air Content of hardened concrete
Scaling Resistance	ASTM C 672	The effect of mixture proportioning, surface treatment, curing, or other variables on resistance to scaling
Electrical Resistivity	Four Point (Wenner Probe) method	Electrical resistivity of fresh concrete mixes

4.3.4. Properties of Fresh Concrete

The properties of the fresh concrete mix such as the slump, unit weight, and air content were determined by following ASTM methods. The slump, unit weight, and air content of the concrete mix were estimated per ASTM C143, ASTM C138, and ASTM C231, respectively.

Firstly, the temperature of fresh concrete mixes was also measured using a thermometer, as shown in Figure 2(a). The slump test was conducted to estimate the workability of the fresh concrete mixes. In the slump test, a 300-mm long slump cone with a 100-mm diameter at the top and a 200-mm diameter at the bottom was used to measure the workability of concrete, shown in Figure 2(b). In this test, fresh concrete was poured into the slump cone at three layers. Each layer was tamped by 25 times using a tamping rod of 16 mm diameter. Later, the slump cone was lifted vertically upward and the slump value was measured with the help of a measuring tape.

A 0.25 ft^3 cylindrical mold was used to measure the unit weight of the concrete as shown in Figure 2(c). Afterward, using the same mold, the air content of the concrete mix was estimated by following the pressure method (Type B Meter) as shown in Figure 2 (d).

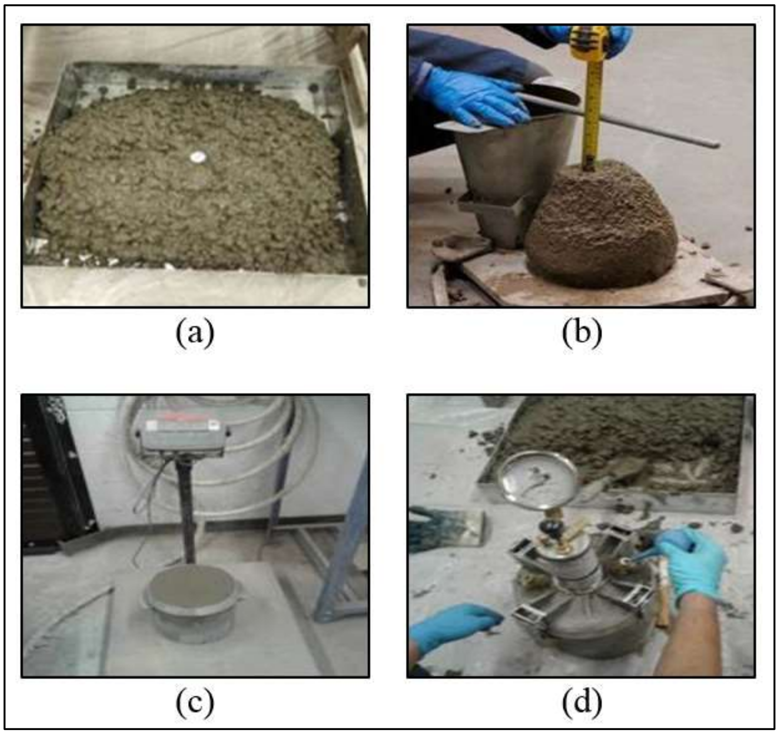


Figure 2. Fresh Concrete Mix Tests: (a) Temperature, (b) Slump (Workability), (c) Unit weight, and (d) Air Content.

4.3.5. Foam Index Test

The AEA dosage level of 1 oz./cwt.cm, chosen to be used in the mixes, was verified by conducting the Foam Index test (FIT). The FIT is a rapid method to determine the relative levels of AEA needed for concrete containing fly ash and/or OPC that affect air entrainment in concrete (GCPAT, 2019). The FIT procedure followed in this study are: i) firstly, about 20 g of cementitious material (e.g., 20 g OPC, or 16 g OPC+ 4 g CFA) was placed in a 125 ml glass jar, ii) later, 50 ml of water were added to the jar; it was then capped and shaken for 1 minute, iii) then, diluted AEA solution (50 ml AEA: 50 ml water) was added in small increments of 2 to 5 drops at a time. After each addition, the jar was shaken vigorously for 15 seconds. The stability of the foam was observed, and iv) The minimum amount of diluted AEA needed to produce a stable foam (bubbles exist over the entire surface) for 45 seconds is the Foam Index of the cement mixture. Figure 3 shows several major steps involved in the FIT.


(a) (b) (c)

Figure 3. (a)-(c): Foam Index Test in the Laboratory.

4.3.6. Super Air Meter (SAM) Test

A Super Air Meter (SAM), a modified version of a typical pressure meter (ASTM 231), was used to determine the air-void quality in the fresh concrete mixes, as shown in Figure 4. The SAM test measures the SAM number (in psi) and air volume in 10 minutes. Based on the manual, the primary modification is that two sequential pressurizations are applied to the concrete. At first, the deformation of the concrete is examined at 14.5, 30, and 45 psi; later the pressure is released, and again, the same pressure steps were used to measure the deformation. Thus, the differences between the first and second pressure steps were used to calculate the SAM number, which is reported to correlate well with the average spacing between air voids in the concrete mixes as well as the long-term durability of hard concrete due to freeze-thaw effects per ASTM 457. Based on the specification and ACI 201 Concrete Durability Committee, a SAM number of 0.20 psi or below indicates a satisfactory air void size distribution.

Figure 4. SAM Tests of Fresh Concrete Mixes.

4.3.7. Electrical Resistivity Tests

A Miller 400A analog resistivity meter, as shown in Figure 5, was used to determine the electrical resistivity of the fresh concrete mixes in this study. The advantage of using this meter is that the resistance measurements taken by the Miller 400A are unaffected by any stray interference signals (having frequencies other than 97Hz) that may be present in the mixes during the measurement. Another advantage is that it has a wide range of resistance measurements from 0.01Ohm (0.01Ω) to 1.1 MOhm (1.1MΩ), which can be achieved by employing a set of 8 range settings and a system of internal "standard" resistors.

The following steps were undertaken to measure the resistivity of the mixes in the lab: i) the test leads were connected and the electrodes (pins) were set up for the 4-electrode applications; ii) as the approximate resistance of the mix was unknown, the range selector switch (labeled "Ohms Multiply By") was moved to the 100K setting, and the "Balance Dial" knob positioned at "10"; iii) the "Null Sensitivity" switch was pulled down to the "Low" position and noted that the null indicating meter needle moves to the right, indicating too high a resistance setting; iv) while holding the "Null Sensitivity" switch in the "Low" position, stepped down through the resistance ranges (10K, 1K, 100Ω, etc.) until the needle moved to the left of the null position (left of the center position) and then stepped back up one range; v) the position of the "Balance Dial" adjusted until the needle was positioned at the null (center) location on the meter; vi) the "Balance Dial" setting and the range setting (setting on the switch labeled "Ohms Multiply By") were recorded; vii) the resistance value was obtained by multiplying these two values found in the earlier step; viii) finally, the resistance value was used to calculates the resistivity using Equation 1 as follows:

$$\rho\ (\Omega.\text{cm})=2\ \pi * S * R \qquad [1]$$

where, R is the resistance value in ohms as determined using the MILLER400A, ρ is the resistivity in ohm.cm, π is the constant 3.1416, and S is the electrode separation in cm.

Figure 5. Schematic Set-up of Electrical Resistivity in the Laboratory.

4.3.8. Time of Setting of Concrete Mixtures by Penetration Resistance

A universal penetrometer was used to determine the time of the setting of concrete mixes with a slump greater than zero. In this test, the penetration resistance measurements were taken on mortar sieved (Sieve No. 4) from the concrete mixture. The weight of the test plunger itself used in this test was 47.5gm and additional weight of 50gm was added before the needle penetration. This test procedure is suitable when tests of the mortar fraction will provide the information required. The time was recorded at zero penetration depth of the needle into the concrete mix. Figure 6 shows the laboratory test set-up for the setting time test of the concrete mix.

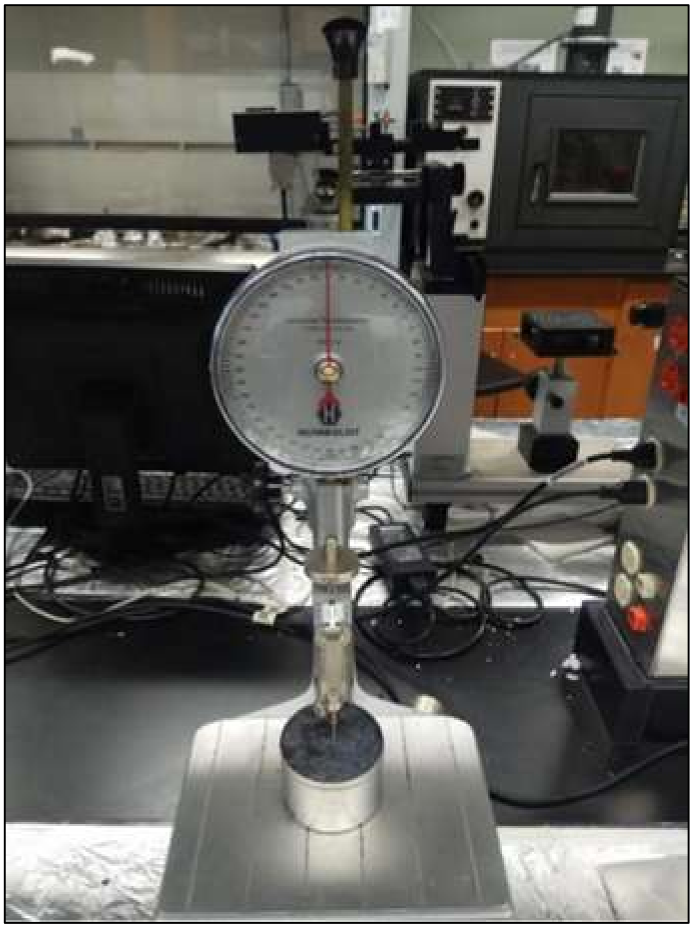


Figure 6. Schematic Set-up of Setting Time test using the Universal Penetrometer.

4.3.9. Curing of the Test Samples

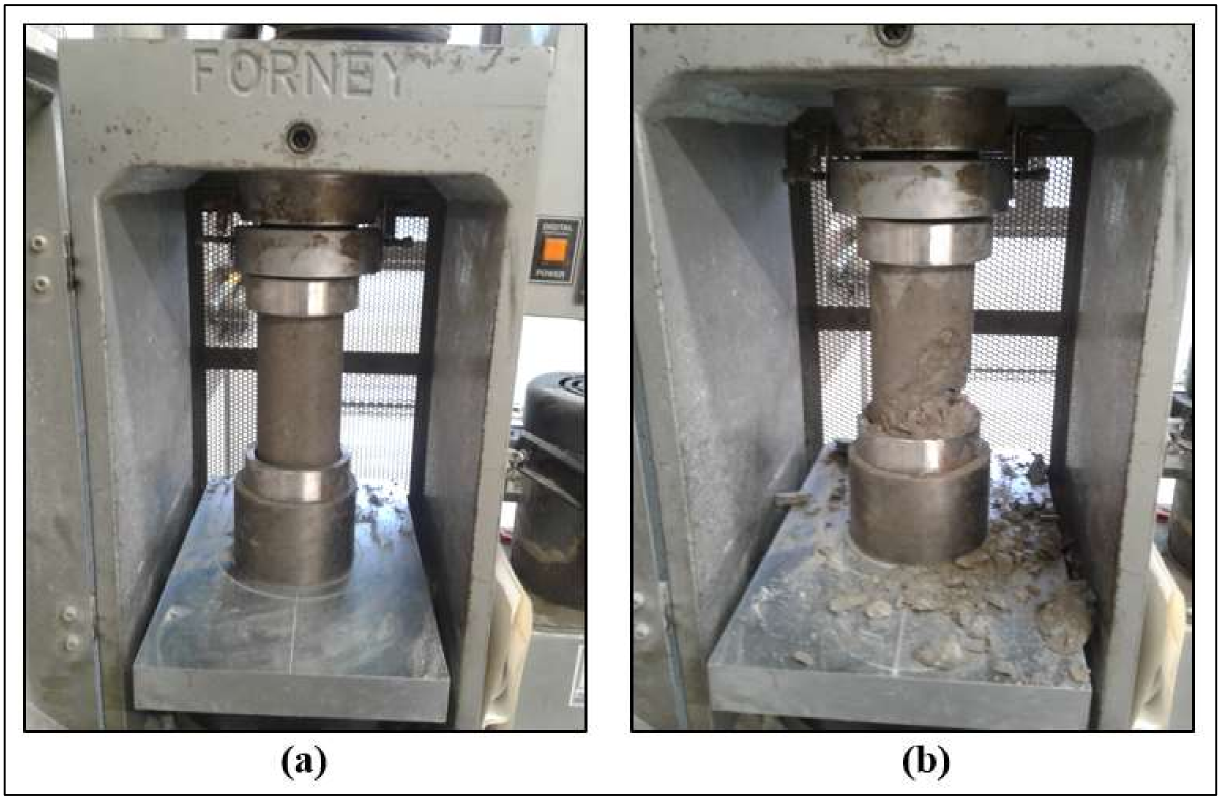
The fresh concrete mix was used to cast the cylinders of a size of 100-mm diameter and 200-mm height using the plastic cylindrical molds, and the beams of 525-mm in length with a cross-section of 150-mm by 150-mm using the steel beam molds. After 24 hours (hrs.) of casting, cylinders and beams were demolded and placed in a water bath for curing at a room temperature of 23ºC. The curing of the test samples was done as per ASTM C31. The tap water was used for curing the test samples. The test samples were kept in the water bath until the age of the testing, as shown in Figure 7.


(a) (b)

Figure 7. (a)-(b): Curing of the Concrete Cylinders and Beam Samples.

4.3.10. Compressive Strength Tests

The fresh concrete mixes were used to cast the cylinders (size of 150 mm X 300 mm) using the plastic cylindrical molds for the compressive strength test. The test samples were removed from the water bath and applied load with a compression machine as per the ASTM C39-04a method. The compressive strength was measured at 7, 14, 21, and 28 days. For each testing condition, two samples were tested and the average of the two test results was reported. Figure 8 shows a typical compressive strength test setup in the laboratory.



(a) (b)

Figure 8. (a) Before and (b) After the Compressive Strength Test.

4.3.11. Tensile Strength Tests

The splitting tensile strength was conducted on the cylindrical samples (size of 100 mm X 200 mm) as per the ASTM C496 method. The samples used in this test were water-cured (by ponding) for 28 days. A typical laboratory setup of the splitting tensile strength test is shown in Figure 9. In this test, two samples were tested for each test condition and the average value was reported.

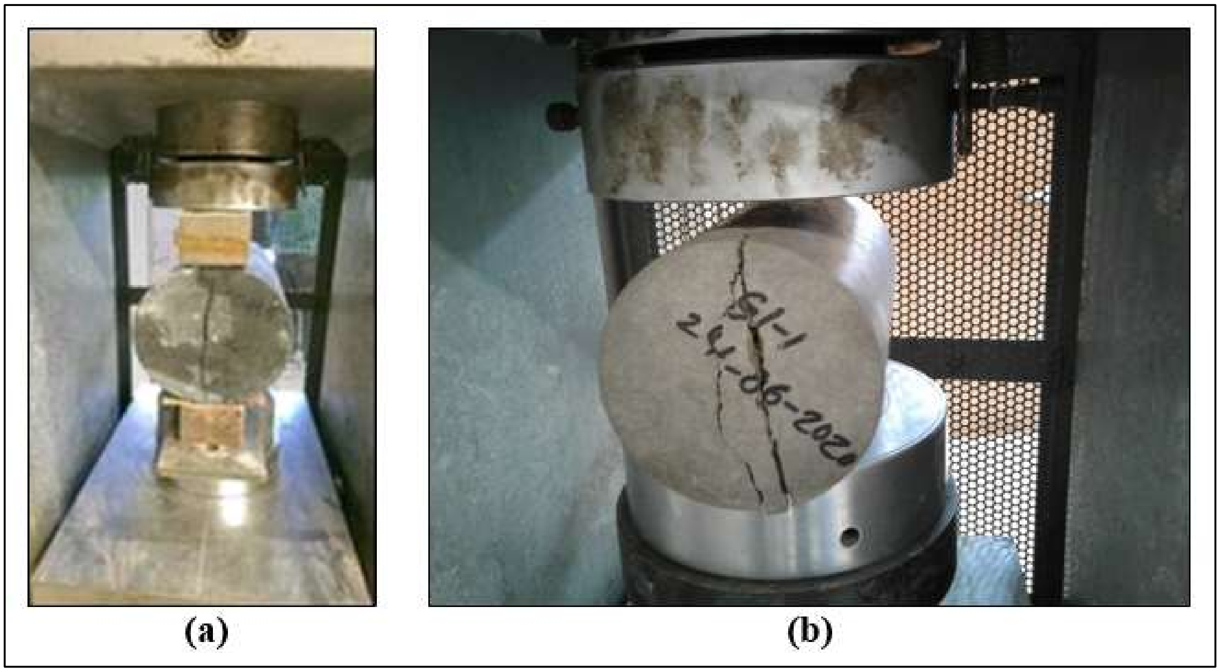


Figure 9. (a) Before and (b) After the Splitting Tensile Strength Test in the Laboratory.

4.3.12. Flexural Strength Tests

The flexural strength of the hardened concrete beams was conducted as per the ASTM C293 method. In this test, the concrete beams having a size of 525 mm long with a cross-section of 150 mm X 150 mm were cast and tested in the laboratory. One beam sample was prepared for each mix type and tested for 28 days of the curing. In this study, the flexural strength of the beam was determined using the two-point loading method. A typical setup of this test is shown in Figure 10.

Figure 10. (a) Before and (b) After the Flexural Strength Test Set Up in the Laboratory.

4.3.13. Modulus of Elasticity Tests

The modulus of elasticity values of hardened concrete samples (size of 100 mm X 200 mm) were calculated according to the ASTM C469 method. To determine the modulus of elasticity, a load of no more than 40% of the 28-day failure compressive load was applied to the cylindrical sample. A companion sample was used for the determination of the 40% of the failure load during the modulus of elasticity test. In this test, strain gauges and a strain indicator device were used to obtain the longitudinal strain, as shown in Figure 11. The average of measurements of two-strain gauge mounted at the mid-height of the cylinder was recorded for estimating the strains at different stages of the loading.

Figure 11. Schematic Set-up of Modulus of Elasticity Tests in the Laboratory.

4.3.14. Alkali-Silica Reaction (ASR) Tests

In this study, the alkali-silica reaction (ASR) tests were conducted to determine the expansion of concrete in the presence of alkaline water and reactive aggregate. In this test, the mortar bars of 285mm X 25 mm X 25 mm were cast and evaluated in the laboratory. The mortar bars were prepared with the cementitious material and the aggregate with a ratio of 1:2.25, and with a water to cement ratio of 0.47. The mortar bars were mixed as per the ASTM C 305 method and molded within 2 mins. and 15 s. During the preparation of the mortar bars, the molds were filled in two equal layers and each layer was compacted with a tamper until a homogenous mix is obtained. Two samples for each test condition were prepared and kept in the moist room for 24 hrs. The mortar bars were then demolded and placed in water at 80°C for another 24 hrs. The mortar bars were then removed from the water and the initial reading was taken. The mortar bars were then placed in 1N NaOH solution for the next 14 days and intermediate readings were recorded at 4, 8, 12, and 14 days, respectively to estimate the expansion. The readings were taken with a linear variable differential transformer (LVDT) sensor of an ELE Data System Unit (DSU) as shown in Figure 12.

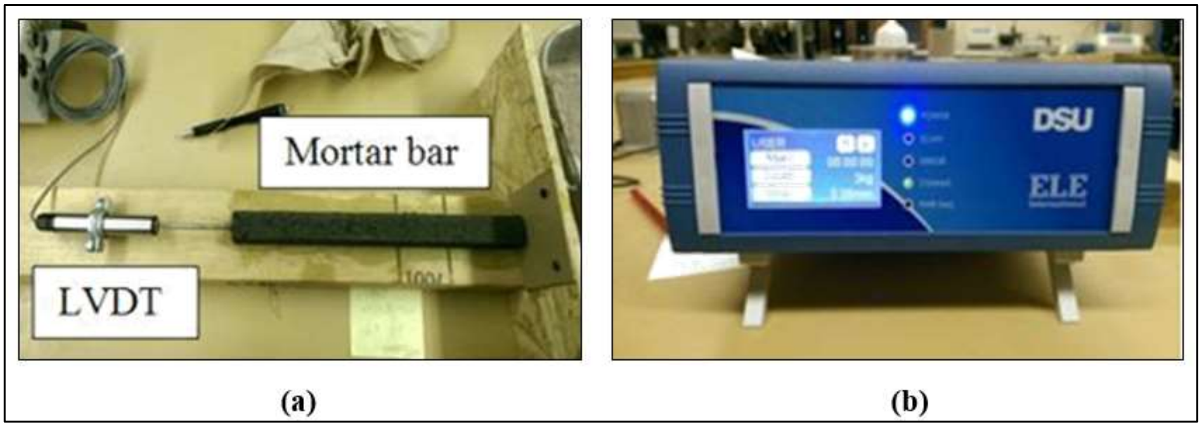


Figure 12. (a) Mortar Bar and LVDT Set-up, and (b) Data Storage Unit.

4.3.15. Scaling Resistance Tests

The scaling resistance was conducted to evaluate the effect of a deicing chemical of PAC-modified concrete. The concrete mortar bars prepared for this test had a dimension of 285mm X 25 mm X 25 mm as per the ASTM C305 method, as shown in Figure 13. Afterward, the mortar bars were submerged in a solution containing 40 g of anhydrous calcium chloride per liter of water. Later, the freezing and thawing cycle procedures were followed as per the ASTM C672 method. In this test, the mortar bars were placed in a freezing environment of -12ºC for 16 hrs. Then, the mortar bars were removed from the freezer and placed in the laboratory at an air temperature of 23 ± 2ºC with a relative humidity of 55%. After drying in the air for 8 hrs, the mortar bars were experienced one freezing-thawing cycle. This cycle was repeated daily and continued for 10 cycles. As per the ASTM C672 method, mortar bars were visually examined and surface conditions were rated from 0 to 5 indicating "0" and "5" for "no scaling" and "severe scaling" respectively, at the end of the 10th cycle of freezing-thawing.

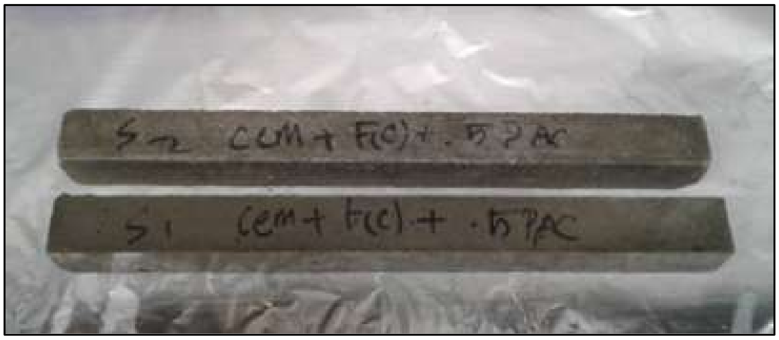


Figure 13. Mortar Bars Prepared for the Scaling Resistance Tests.

4.3.16. Air Content Analysis of Hardened Concrete

To determine the air content of hardened concrete, "ASTM C457 (Rapid Air 457): Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened

Concrete (Method C)" was followed. Two 100 mm X 200 mm concrete cylinders [(one cylinder for each of 4000 psi (S1-4) and 3000 psi (S1-7)], shown in Figure 14, were tested in this study. In this method, the cylinders were cut perpendicular to the surface and prepared as polished sections for air void analysis. This test was performed by a technician at a commercial laboratory (Ash Grove Technical Center) located at Overland Park, KS.

Figure 14. Samples Used for Determining the Air Content of Hardened Concrete.

5. ANALYSIS AND FINDINGS

In this section, the findings of different test results are discussed. Several tests were conducted to evaluate selected workability and performance properties of modified concrete. The foam index test results are illustrated in this section. This section discusses the air void quality measurement results of the freshly mixed concrete using the SAM. The electrical resistivity values of the concrete mixes are also presented in this section. Additionally, the properties of fresh concrete, mechanical properties such as compressive, tensile, flexural strength, and modulus of elasticity of hardened concrete, and results from ASR and deicing chemical tests are discussed in this section. Moreover, air content analysis of the hardened concrete is presented.

5.1. Mix Design Properties

The CA and FA collected from the local plant were used in this study and tested to determine the required mix design properties such as specific gravity, absorption, fineness modulus (FM), and nominal maximum size (NMS). Both CA and FA were graded with the ASTM standard sieves as per the ASTM C136 method. The FM of FA was found to be 2.9, indicating coarse sand. The NMS of CA was determined as 25 mm. The specific gravity and absorption values of the CA and FA were determined according to ASTM C127 and ASTM C128, respectively. The bulk specific gravity values of the CA and FA were found to be 2.610 and 2.581, respectively. The absorption of the CA and FA were determined as 0.93% and 1.06%, respectively. In this study, Type I OPC having a specific gravity of 3.15 was used to prepare the test specimens.

5.2. Fresh Concrete Properties

Table 5 shows the properties of fresh concrete mixes determined in the laboratory and plant. The control mix (S1-1) had a slump value of 3.5 inches (88 mm). The S1-2 and S1-3 mixes showed lower slump values than the control mix and were found to be 3 inches (75 mm), and 3.25 inches (81 mm), respectively. Concrete mixes of S1-8 and S2-8 with 20% fly ash containing 0.5% PAC showed slump values of 5 inches (125 mm) and 4.25 inches (106 mm), respectively, indicating good workable mixes. The slump values of the 20% CFA1 containing 0% PAC and 0.25% PAC-modified concrete mixes (e.g., S1-6 and S1-9) were found as 4.75 inches (119 mm) and 3.75 inches (94 mm), respectively, whereas the slump values of 6 inches (150 mm) and 4 inches (100 mm), respectively were found for similar CFA2 mixes. However, both CFA1 and CFA2 containing 0.75% PAC showed the slump values of 3.0 inches (75 mm) and 3.0 inches (75 mm) for S1-10 and S2-10 mixes, indicating low workable mixes. Thus, it can be said that the addition PAC in zero or lower percentage in the CFA increased the workability of the mixes which further decreased with the higher PAC amount. Moreover, the slump values of plant mixes, namely, S1-4 and S1-7 were found to be 5.5 inches (138 mm), and 4 inches (20 mm), respectively, indicating good workable mixes. The slump values determined in the case of plant concrete mixes were found to agree with the similar mixes fabricated in the laboratory.

In this study, the air contents of the fresh concrete mixes were evaluated as per ASTM C231 and are summarized in Table 5. As seen in Table 5, the control mix had an air content of 4.7%. It was found that all CFA1-modified concrete mixes had lower air contents than the control mix except the S1-6 mix which contained no PAC in the CFA. Likewise, the air contents of CFA2-modified mixes were found to be higher than corresponding CFA1-modified mixes as well as the control mix. An increase of the PAC content in CFAs reduced the air contents of the mixes. For example, the air contents for 20% CFAs containing 0.25% PAC were 4.6% and 7.2%, respectively, for S1-

9 and S2-9 mixes. On the other hand, the air content of 3.0% and 3.2% were found in the case of 0.75% PAC containing S1-10 and S2-10 mixes, respectively. It was also observed that the air contents of the CFA2-modified mixes were slightly higher compared to their corresponding CFA1-modified mixes.

The unit weights of all modified concrete mixes were measured as per ASTM C138, and the results are presented in Table 5. It is seen that the unit weight of the control mix (S1-1) was found to be 2402 kg/m3. The unit weight of S1-2 was 2429 kg/m3, which is slightly higher than the control mix as this mix was designed for the 2% air void that exhibits more dense mixes. In the case of S1-3, when pure fly ash of 20% replacement of cement was used, the unit weight reduced to 2269 kg/m3, which is less than either control or S1-2 mix. This reduction of unit weight could be due to the incorporation of 20% CFA as a replacement of cement, which provides less weight with lower density compared to the OPC. However, the unit weight was found to be increased with a lower rate with the increase of PAC content in the CFAs. For instance, the unit weight of CFA1 and CFA2 containing 0.25% PAC mixes were 2353 kg/m3 and 2255 kg/m3 for S1-9 and S2-9 while the values of unit weight were 2395 kg/m3 and 2380 kg/m3 for 0.5% PAC contained mixes of S1-8 and S2-8, respectively. The 0.75% PAC contained mixes of S1-10 and S2-10 exhibited a further increment in unit weights of 2426 kg/m3 and 2421 kg/m3, respectively which are somewhat higher than the unit weight of the control mix. Moreover, it can be said that the incorporation of CFAs in concrete reduced the unit weight of the concrete mix since CFAs are lighter than the cement. Also, the presence of a higher PAC amount in CFAs occupied more voids in the mix and thus increased the unit weight of the mix to some extent.

Table 5. Properties of Fresh Concrete Mixes.

Sample ID	Mix Type	Temperature (°C)	ASTM C231 Air (%)	Slump (in.)	Unit Weight (kg/m^3)
S1-1 (Control)	Lab	72	4.7	3.5	2402
S1-2	Lab	74	2.5	3.0	2429
S1-3	Lab	74	3.1	3.25	2269
S1-4	Plant	93	7.5	5.5	2280
S1-5	Lab	74	1.3	4.0	2416
S1-6	Lab	74	5.8	4.75	2259
S1-7	Plant	89	1.5	4.0	2425
S1-8	Lab	73	4.5	5.0	2395
S1-9	Lab	68	4.6	3.75	2353
S1-10	Lab	69	3.0	3.0	2426
S2-6	Lab	74	5.0	6.0	2283
S2-8	Lab	69	5.1	4.25	2380
S2-9	Lab	70	7.2	4.0	2255
S2-10	Lab	71	3.2	3.0	2421

5.3. Foam Index

The Foam Index Test (FIT) was conducted followed by the test method introduced by the GCPAT, and the results are presented in Table 6. As mentioned in Section 4.3, different replacement levels such as 0%, 5%, 10%, 15%, 20%, 25%, 30%, 35% and 40% of CFA were chosen with cement to conduct the FITs. A beaker of 300 ml capacity was used to conduct this test. An amount of 50 ml water was used and dilution of AEA/water was 50 ml/ml. The initial mixing period was 60 s, which was then followed by a shaking of 15 s and a rest period of 45 s.

From Table 6, it is evident that the optimum AEA dosages to obtain the permanent foam were increased with the increase of CFA amount in the cement. The control mix consisted of 0% CFA (100% cement) showed the required AEA dosage of 1.53 ounce (oz.) per 100-pounds (lbs.) of cementitious materials (oz./100 lb-cm). The optimum AEA dosages for 20% and 40% CFA mixes were determined as 3.26 oz./100 lb-cm, and 4.60 oz./100 lb-cm, respectively. Therefore, it is seen that the AEA dosages were increased by over two times for 20% CFA and three times for 40% CFA containing mix. Based on the FIT results, it is found that the optimum AEA dosage is higher in the laboratory measurements compared to the manufacturer recommendation (e.g., 1 oz./100 lb-cm) used in plant mixes.

Table 6. Foam Index Test (FIT) Results.

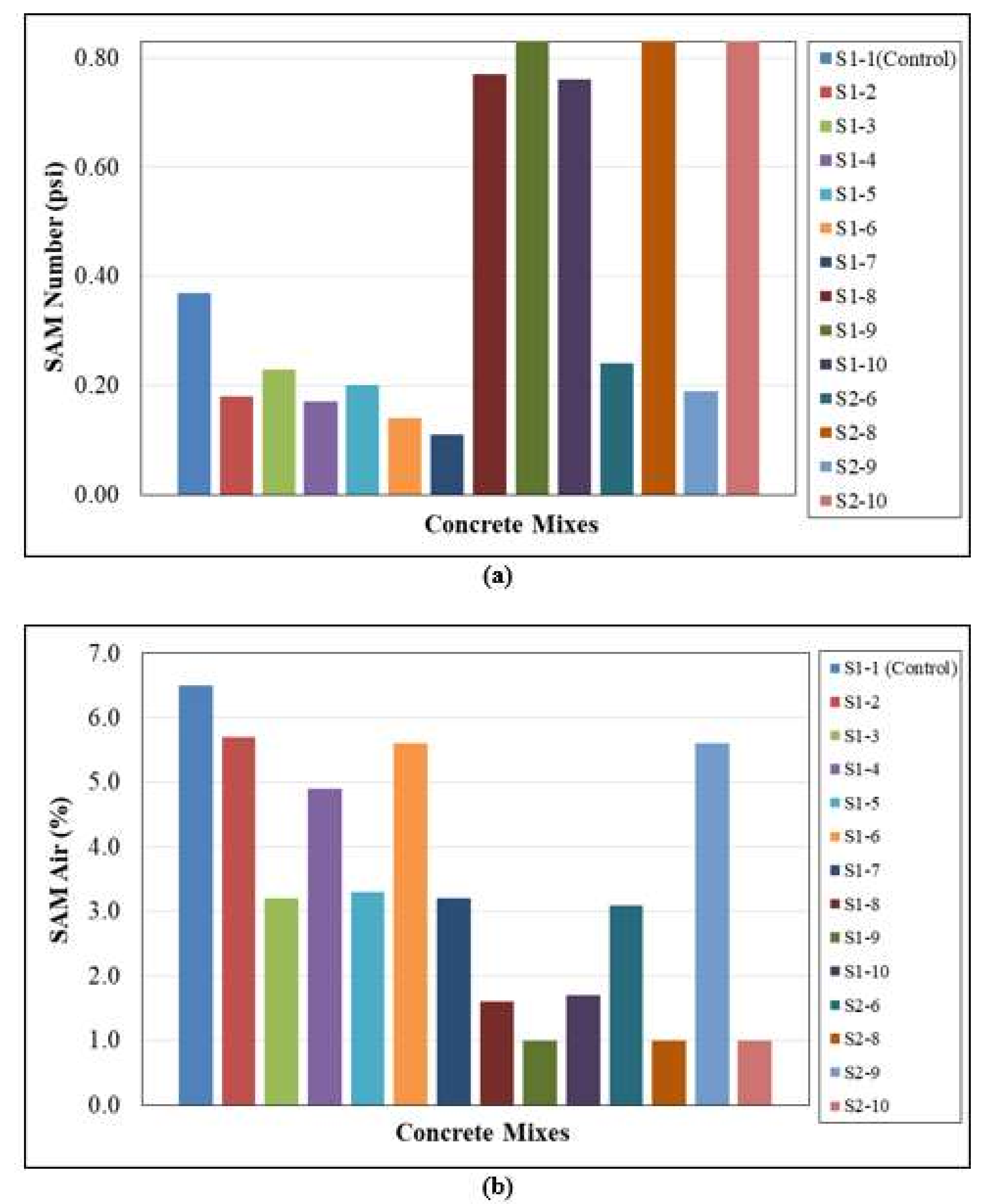
Fly Ash (g)	Cement (g)	Fly Ash/Cement (%)	Required drop	ml AEA/Drop (1ml = 20 drops)	Required AEA Dosage (oz./100 lb-cm)
0	20	0	8	0.005	1.53
1	19	5	10	0.005	1.92
2	18	10	12	0.005	2.30
3	17	15	13	0.005	2.49
4	16	20	17	0.005	3.26
5	15	25	18	0.005	3.45
6	14	30	20	0.005	3.83
7	13	35	21	0.005	4.03
8	12	40	24	0.005	4.60

5.4. Super Air Meter (SAM)

The air-void quality in the fresh concrete mixes was determined by conducting the Super Air Meter (SAM) tests. The SAM tests of different modified mixes are shown in Table 7. As described in the earlier section, the SAM number (SN) (psi) and total air volume (%) were determined in the laboratory from the SAM tests. The graphical presentations of air content and SN for various modified mixes are shown in Figure 15.

Table 7. SAM Test Results of the Fresh Concrete Mixes.

Sample ID	Mix Type	SAM Air (%)	SAM No. SN(psi)	Meet Freeze-Thaw Requirement (SN≤0.20)?
S1-1 (Control)	Lab	6.5	0.37	No
S1-2	Lab	5.7	0.18	Yes
S1-3	Lab	3.2	0.23	Maybe
S1-4	Plant	4.9	0.17	Yes
S1-5	Lab	3.3	0.2	Yes
S1-6	Lab	5.6	0.14	Yes
S1-7	Plant	3.2	0.11	Yes
S1-8	Lab	1.6	0.77	No
S1-9	Lab	1.0	≥ 0.83	No
S1-10	Lab	1.7	0.76	No
S2-6	Lab	3.1	0.24	Maybe
S2-8	Lab	1.0	≥ 0.83	No
S2-9	Lab	5.6	0.19	Yes
S2-10	Lab	1.0	≥ 0.83	No



(a)

(b)

Figure 15. SAM Test to determine Air-Void Quality of Fresh Concrete (a): Comparison of SAM Number (psi) and (b): Comparison of SAM Air (%).

As seen in Table 7 and Figure 15, it is seen that the control mix (S1-1) had the air content and the SN of 6.5% and 0.37 psi. The control mix exceeded the maximum limit of SN equal to 0.20 psi or less. In the case of plant mixes, 0.5% PAC contained in 20% CFAs, the air content, and the SN were found as 4.9% and 0.17 psi for S1-4 mix, and 3.2% and 0.11 psi for S1-7 mix, respectively. Therefore, both S1-4 and S1-7 mixes had lower values of SN to satisfy the air-void size distribution criteria. In the case of laboratory measurements, the air content and SN were determined as 3.3% and 0.2 psi for S1-5 mix while these values were found as 1.6% and 0.77 psi for S1-8 mix. Thus, it is seen that both air content and SN values were found be to lower than their corresponding mix prepared in the plant. It is found that the incorporation of CFAs in the mix with a reasonable percentage of PAC content is desirable to fulfill the total air volume in the mix as well as the freeze-thaw requirement. However, the presence of the excess amount of PAC in the CFA could make the mix unsuitable for the fulfillment of the durability requirement by reducing the air voids at an alarming rate, as shown in Figure 15. For instance, the S1-10 mix contained 0.75% PAC in CFA1 and showed an air content of 1.7% and SN of higher than 0.83, indicating the mix will not satisfy the ACI durability criteria. A similar trend was also observed in the case of CFA2-modified mixes. The increment of air content and reduction of SN is possible if the rate of AEA dosage is increased in the mixes.

5.5. Electrical Resistivity

The electrical resistance values of the concrete mixes were estimated based on the four-electrode applications of the Miller 400A analog resistivity meter. At first, the resistance of the concrete mixes was estimated, and later, the resistivity and conductivity of the corresponding mixes were calculated using the specified formula, shown in Table 8.

As shown in Table 8, the control mix (S1-1) had a resistivity value of 16.76 Ω.m. It is seen that the electrical resistivity values were increased in the case of S1-2 and S1-3 mixes compared to the control mix and were found to be 18.35 Ω.m and 17.56 Ω.m, respectively. It is noticed that the plant mix, namely, S1-4 and S1-5 have a similar percentage of PAC in CFA (0.5%) and the same value of resistivity of 15.16 Ω.m was found in both mixes. The resistivity values of S1-7, S2-6, and S2-9 mixes were found as 16.76 Ω.m, which is equal to the resistivity value of the control mix. In the case of CFA1-modified concrete mixes, it is seen that the addition of fly ash without or a lower amount of PAC increased the concrete mix's resistivity values. For example, the S1-6 mix contained 0% of PAC showed a resistivity value of 17.56 Ω.m, where the S1-9 mix had a resistivity value of 18.35 Ω.m, indicating a lower conductivity in the mix. However, the resistivity value was decreased with further increment of PAC content in the CFAs. It is found that S1-8 and S1-10 mix had resistivity values of 14.36 Ω.m and 6.46 Ω.m, respectively. Among all CFA1- and CFA2-modified mixes, it is observed that 0.75% PAC containing mixes had the least resistivity value, indicating the higher conductivity of the mixes. Therefore, the increment of PAC percent in the CFAs may increase the corrosion rate of concrete.

Table 8. Electrical Resistivity of Fresh Concrete Mixes.

Sample ID	Mix Type	Resistance (Ω)	Resistivity (Ω.m)	Conductivity (S/m)
S1-1 (Control)	Lab	21	16.76	0.060
S1-2	Lab	23	18.35	0.054
S1-3	Lab	22	17.56	0.057
S1-4	Plant	19	15.16	0.066
S1-5	Lab	19	15.16	0.066
S1-6	Lab	22	17.56	0.057
S1-7	Plant	21	16.76	0.060
S1-8	Lab	18	14.36	0.070
S1-9	Lab	23	18.35	0.054
S1-10	Lab	8.1	6.46	0.155
S2-6	Lab	21	16.76	0.060
S2-8	Lab	22	17.56	0.057
S2-9	Lab	21	16.76	0.060
S2-10	Lab	4.1	3.27	0.306

5.6. Time of Setting of Concrete Mixtures

The time of setting of concrete mixtures was determined using a universal penetrometer penetration in this study. The time required for zero depth of penetration into the concrete surface is used to define the time of setting of the concrete mixes. Figure 16 shows the penetration resistance values of different types of CFAs-modified mixes.

From Figure 16, it is observed that the setting time of the control mix (S1-1) mix was found to be 420 mins. The setting time was found to be increased for most of all types of CFA-modified mixes, indicating the less stability of the mixes. The rate of increment is similar to the incorporation of CFAs in the mixes. In contrast, the S1-2 and S1-3 mixes showed a smaller reduction in setting time indicating higher stability of the mix within less time compared to the control mix. Surprisingly, it is seen that both S1-10 and S2-10 mixes had the maximum reduction rate of setting time among all types of mixes. The required time for the setting of S1-10 and S2-10 mixes were determined as 330 mins. and 300 mins., respectively. The presence of the high PAC content (0.75%) in CFAs could be one of the possible reasons to expedite the setting time compared to the other mixes evaluated in this study.

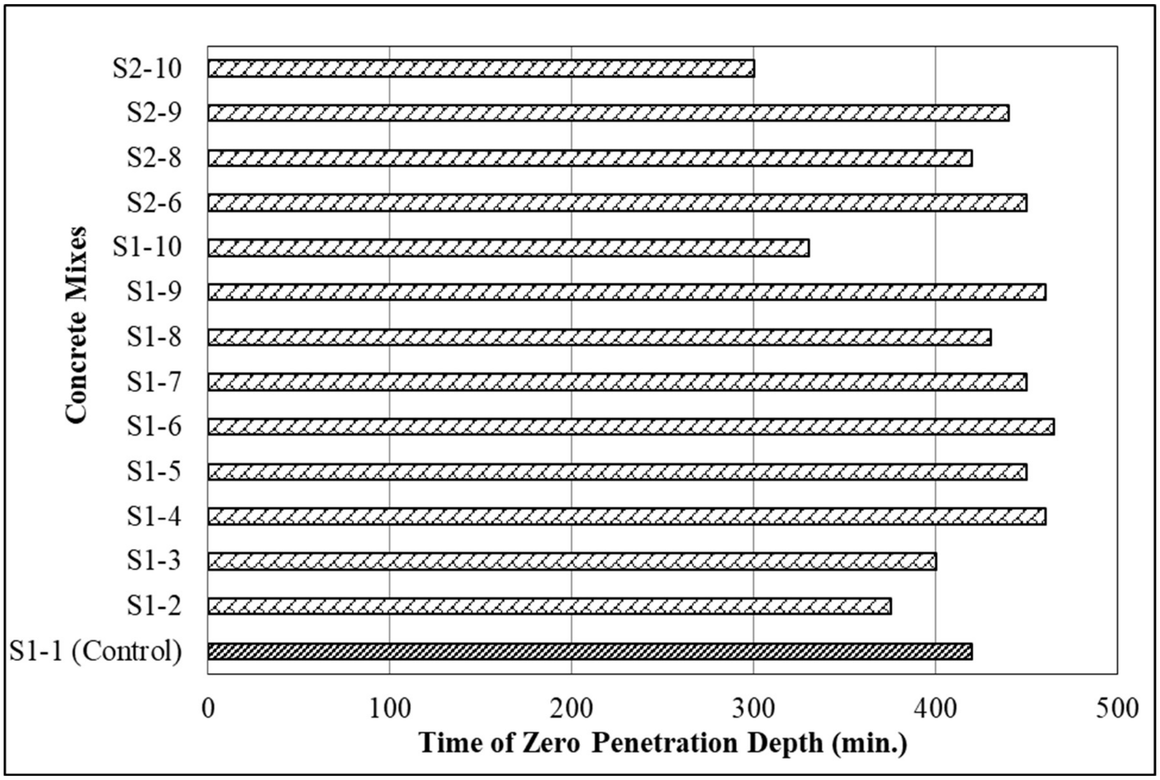


Figure 16. Setting Time (min.) of the Concrete Mixes.

5.7. Compressive Strength

Among all of the mechanical strength properties, the compressive strength is commonly used to determine the quality of any concrete. All unmodified and modified concrete cylinders were cured up to 28 days to determine the effects of curing on its compressive strength of concrete. In this study, a total of fourteen different types of concrete mixes were prepared and two concrete cylinders (100-mm diameter and 200-mm height) were cast from each type of mixes. Afterward, the concrete cylinders were tested to observe the curing effects at 7, 14, 21, and 28 days. The compressive strength data of concrete are shown in Figure 17.

It was observed that most of the CFAs-modified mixes evaluated in this study gained a lower compressive strength at the early ages of curing. The presence of PAC content can play a major in reducing the strength development in concrete at 7 and 14 days. However, some concrete mixes had lower compressive strength at the early curing period and later sharply increased at 21 days and continued to increase further till 28 days of curing. It is also seen that both S1-2 and S1-5 mixes showed a higher rate of strength development during all curing days and found that S1-5 had the highest rate of increment in compressive strength.

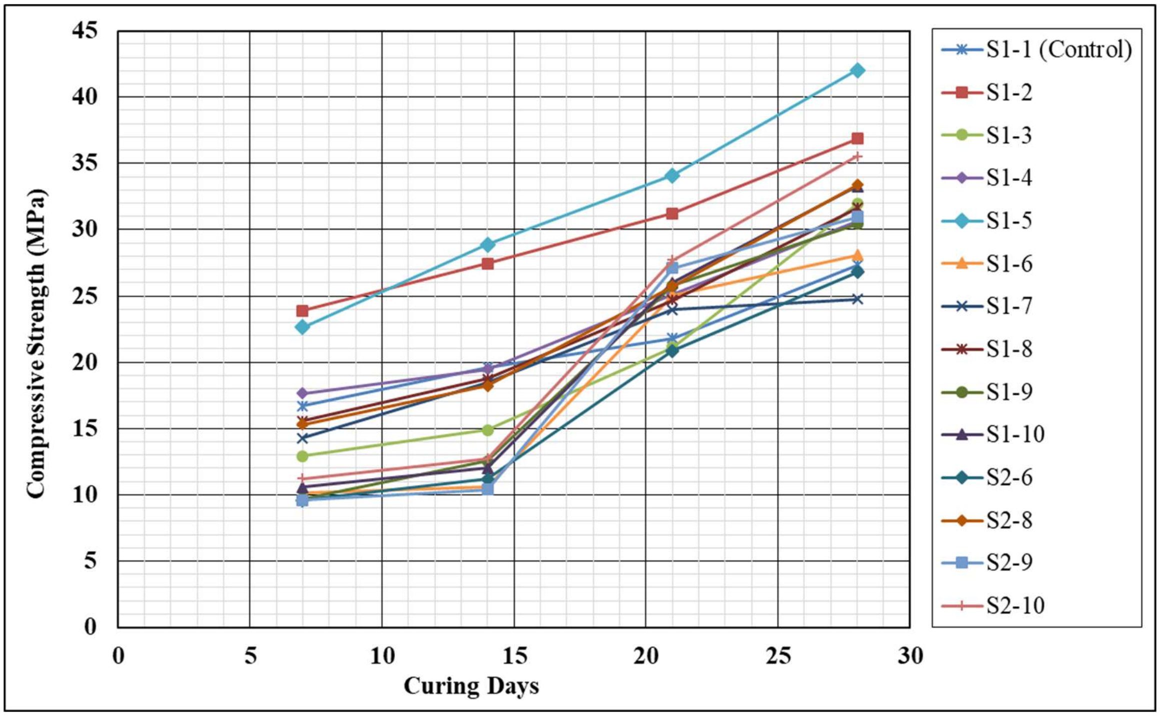


Figure 17. Effect of Curing on Compressive Strength of Modified Concrete.

The compressive strengths of all concrete mixes at 28 days are shown in Figure 18. The control mix (S1-1) exhibited a compressive strength of 27.3 MPa (3966 psi) at 28 days of curing. It is seen that the average compressive strength at 28 curing days increased most of all concrete mixes. On the other hand, the plant mix (S1-7) and the laboratory mix (S2-6) showed a little bit lower compressive strength than the control mix and were found to be 24.7 MPa (3589 psi) and 26.8 MPa (3885 psi), respectively. The incorporation of CFA1 with the increment of PAC content in the mixes exhibited a higher compressive strength at 28 curing days. For example, the compressive strength of 0%, 0.25%, 0.5% and 0.75% PAC-containing mixes were determined as 28.1 MPa (4072 psi), 30.4 MPa (4413 psi), 31.6 MPa (4589 psi), and 33.3 MPa (4824 psi), respectively. Moreover, a similar increasing trend was also observed in the case of CFA2-modified concrete. Among all mixes, S1-5 showed the highest level of strength development at 28 curing days and was found to be 42.1 MPa (6100 psi). Therefore, it is evident that concrete mixes containing different percentages of PAC in CFAs increased the overall strength at 28 curing days even though the rate of strength development was lower in the early curing time.

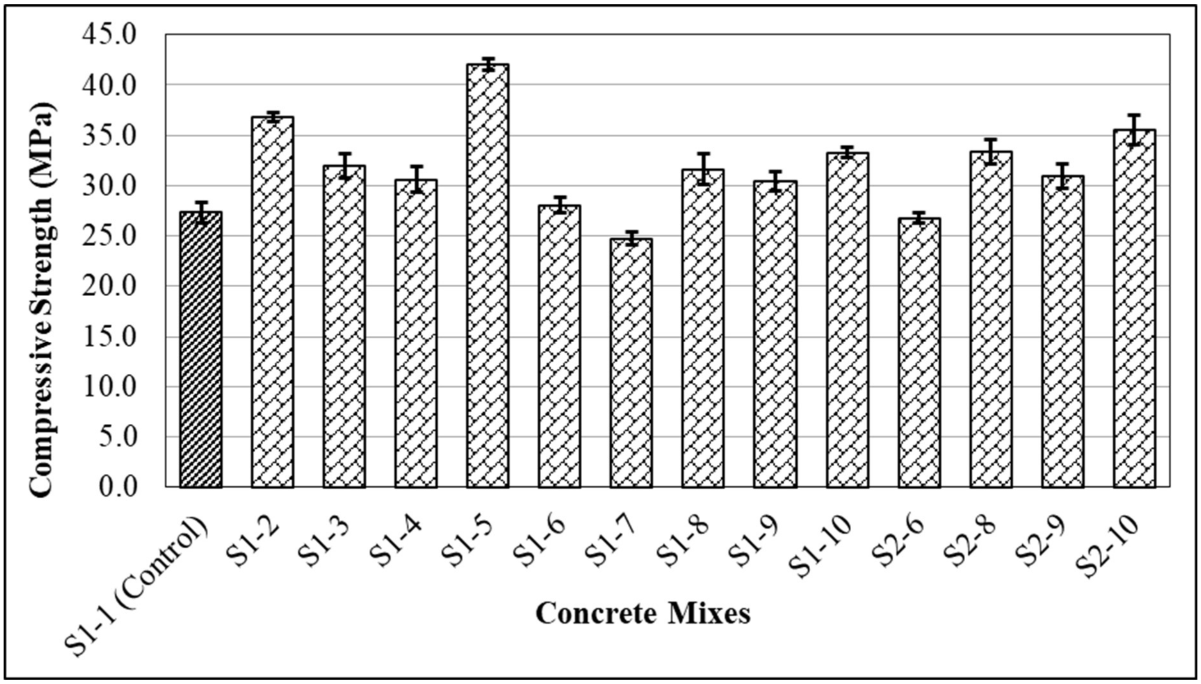


Figure 18. Comparison of Compressive Strengths of Modified Concrete.

5.8. Tensile Strength

The splitting tensile strengths of control and different types of modified concretes were determined as shown in Figure 19. Two concrete cylinders of 100 mm in diameter and 200 mm in height were tested for each mix type to estimate the tensile strength at 28 days of curing.

From Figure 19, it was observed that the S1-2 mix had a higher tensile strength of 3.03 MPa (440 psi) where S1-3 showed a reduction in tensile strength of 2.45 MPa (356 psi) compared to the control mix (S1-1). In the case of CFA1-modified mixes, the tensile strengths were determined as 2.45 MPa (356 psi), 2.65 MPa (384 psi), 2.74 MPa (398 psi), and 3.05 MPa (442 psi) for the mixes contained with 0% PAC (S1-6), 0.25% PAC (S1-9), 0.50% PAC (S1-8), and 0.75% PAC (S1-10), respectively. A similar increasing pattern was observed in the CFA2-modified mixes where S2-6 showed a smaller increment in tensile strength where 0.75% PAC contained CFA2 exhibited the highest level of increment 3.32 MPa (482 psi). The tensile strength of the control mix (S1-1) was found to be 2.47 MPa (359 psi). In the case of plant mix samples, it is also observed that the S1-4 mix exhibited a higher tensile strength of 2.60 MPa (377 psi), whereas a lower value of 2.09 MPa (303 psi) was found for the S1-7 mix compared to the control mix. A general trend is that the tensile strength is about 10% of the compressive strength, as suggested by the ACI.

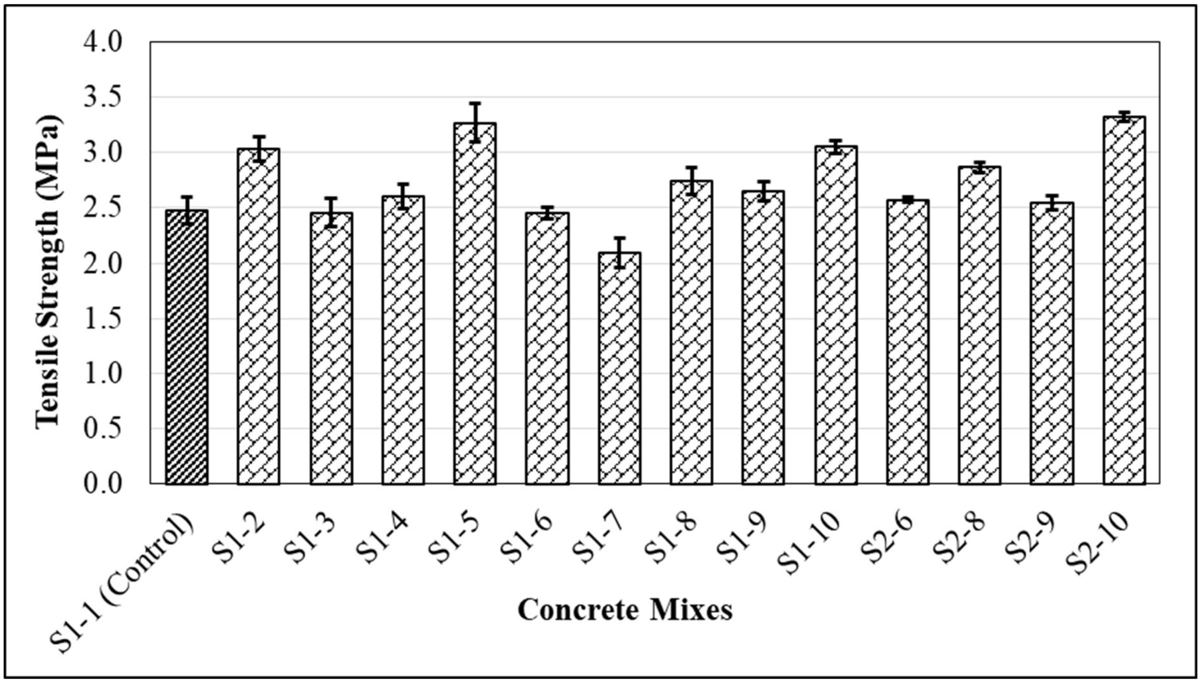


Figure 19. Comparison of Splitting Tensile Strengths of Modified Concrete.

5.9. Flexural Strength

The flexural strength test determines the bending resistance of the concrete beam samples. Figure 20 shows the flexural strength test data of different types of concrete mix evaluated in this study.

As seen in Figure 20, the flexural strength value of 3.26 MPa (472 psi) was found for the control mix (S1-1). The S1-2 mix designed for 2% air voids, containing neither CFA nor PAC content, exhibited a higher value of the flexural strength of 3.78 MPa (548 psi). The flexural strength values of S1-3 and S1-5 mixes were found to be 3.52 MPa (511 psi) and 4.04 MPa (586 psi), respectively which are higher than the control mix. Therefore, it can be said the incorporation of CFA in the mixes increased the flexural strength of the concrete samples. A similar increment of the flexural strength also evident in the case of plant mix sample (e.g., S1-4) and found as 3.45 MPa (500 psi).

Moreover, in the case of CFA1-modified concrete mixes, 0% PAC (S1-6), 0.25% PAC (S1-9), 0.50% PAC (S1-8), and 0.75% PAC (S1-10) had the flexural strength values of 3.30 MPa (479 psi), 3.43 MPa (498 psi), 3.50 MPa (508 psi), and 3.59 MPa (521 psi), respectively. A similar increasing trend was also observed in the case of CFA2-modified mixes. Based on test results, it is seen that the highest level of PAC percent (0.75%) is required to get the maximum flexural strength of the concrete beam subjected to the bending resistance.

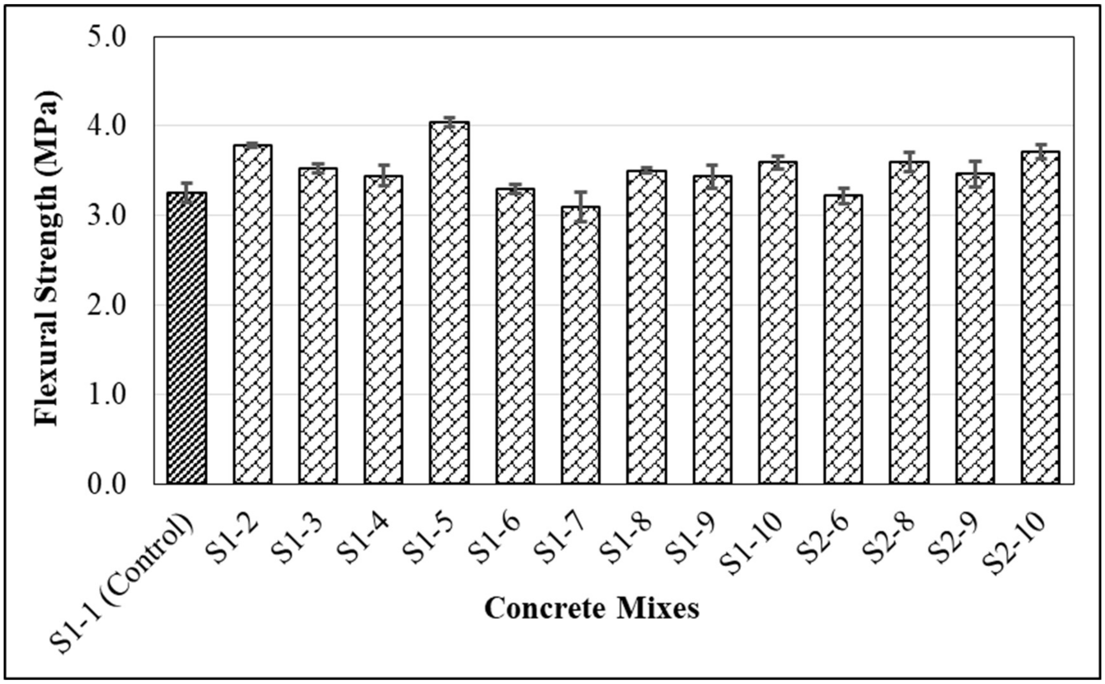


Figure 20. Comparison of Flexural Strengths of Modified Concrete.

5.10. Modulus of Elasticity

The modulus of elasticity values of the CFAs-modified concrete cylinder samples were determined as shown in Table 9. Afterward, the elastic moduli were compared with the estimated value using the ACI formula, presented in Table 9.

As seen in Table 9, the control sample (S1-1) showed the modulus of elasticity of 3.72x10^4 MPa. It was found that the S1-2 and S1-3 mixes had the modulus of elasticity of 4.21x10^4 MPa and 4.05x10^4 MPa, respectively, indicating a higher value than the control sample. Among all tested samples, the S1-5 sample exhibited the highest increment in the modulus of elasticity and was found to be 5.01x10^4 MPa. On the other hand, the highest reduction in the elastic modulus was seen in the case of the S1-7 sample and was found to be 2.97x10^4 MPa. Therefore, it is evident that the modulus of elasticity of the modified concrete increased with the increase of compressive strength as well as the CFAs and vice versa. However, the rate of increment in modulus of elasticity was not uniform and varied with the amount of total PAC content in the CFAs present in the mixes. It was observed that CFA1 and CFA2-modified samples had an increasing rate in modulus of elasticity values determined in the laboratory.

Moreover, the ACI formula was used to estimate the modulus value of all modified concrete to compare with the laboratory test results. As seen in Table 9, the estimated modulus values were found to be less than the corresponding sample's laboratory measurements regardless of the sample type. Like the laboratory-based elastic modulus values, a similar trend was observed in the case of the ACI formula-based determination.

Table 9. Modulus of Elasticity of Modified Concrete.

Sample ID	Mix Type	Measured in the Laboratory (MPa)	Estimated from ACI formula: $E_c=4700\sqrt{f'_c}$ (MPa)
S1-1 (Control)	Lab	3.72×10^4	2.46×10^4
S1-2	Lab	4.21×10^4	2.85×10^4
S1-3	Lab	4.05×10^4	2.66×10^4
S1-4	Plant	3.94×10^4	2.60×10^4
S1-5	Lab	5.01×10^4	3.05×10^4
S1-6	Lab	3.65×10^4	2.49×10^4
S1-7	Plant	2.97×10^4	2.34×10^4
S1-8	Lab	4.01×10^4	2.64×10^4
S1-9	Lab	3.82×10^4	2.59×10^4
S1-10	Lab	4.11×10^4	2.71×10^4
S2-6	Lab	3.13×10^4	2.43×10^4
S2-8	Lab	4.12×10^4	2.72×10^4
S2-9	Lab	3.90×10^4	2.61×10^4
S2-10	Lab	4.17×10^4	2.80×10^4

5.11. Alkali-Silica Reaction (ASR)

The ASR test results predicted the behavior of concrete subjected to an adverse weather condition like the presence of alkaline water in the surrounding soil of the concrete structures. Further, the ASR is a swelling reaction that occurs over time in concrete between the highly alkaline cement paste and the reactive non-crystalline (amorphous) silica found in many common aggregates in presence of water. The ASR test results of CFA-modified mortar bars evaluated in this study are shown in Table 10.

As seen in Table 10, in general, CFA2-modified mortar bars showed a lower expansion compared to the corresponding expansion values of CFA1-modified mortar bars. In the case of CFA1-modified mortar bars, the expansion was found to lower at a lesser extent than the control bar (100% cement). However, there was no improvement for the 0.5% PAC modified mortar bar (S1-8) and showed the same expansion of the control bar (e.g., 0.04%) after 16 days of curing. In the case of CFA2-modified mortar bars, the expansion of the modified mortar bars containing a lower percentage of PAC amount (0%) had the least expansion among all mortar bars. It was also observed that the PAC content in the CFAs increases the expansion rate of the mortar bars. For example, an increment of PAC content slightly increased the expansion rate of all CFA2-modified mortar bars compared to that of the mortar bar containing no PAC. It is also evident that both CFA1 and CFA2-modified mortar bars exhibited expansion lower than the ASTM C1567 recommended limit of 0.10% at 16 days. Therefore, it can be said that all concrete samples have a low-risk of deleterious expansion under the field condition.

Table 10. ASR Expansion (%) at Various Curing Days of CFAs-Modified Mortar Bars.

Sample ID	Mix Type	4 Days	8 Days	12 Days	16 Days
S1-1 (Control)	Lab	0.015	0.020	0.035	0.040
S1-6	Lab	0.025	0.025	0.030	0.030
S1-8	Lab	0.010	0.035	0.040	0.040
S1-9	Lab	0.030	0.035	0.035	0.035
S1-10	Lab	0.005	0.035	0.035	0.035
S2-6	Lab	0.000	0.010	0.020	0.020
S2-8	Lab	0.025	0.025	0.030	0.030
S2-9	Lab	0.000	0.020	0.025	0.025
S2-10	Lab	0.030	0.030	0.035	0.035

5.12. Scaling Resistance

The scaling resistance test was intended to continue for 10 cycles of freezing and thawing. At the end of each cycle, the mortar bars were removed from the deicing chemical (calcium chloride) solutions and visually inspected for the surface damage rating. The scaling test results of all tested mortar bars are shown in Table 11. A total of 10 freezing-thawing cycles were planned for each set of mortar bars but discontinued if a visual rating of “5” was assigned. A scaling resistance of “5” prior to 10 cycles of freezing-thawing cycle indicates that the mortar bars disintegrated in the solution and the testing discontinued. Scaling resistance data suggest that the effect of deicing chemicals is higher on the PAC-modified mortar bars.

Table 11. Effect of Deicing Chemicals on Modified Mortar Bars.

Sample ID	Mix Type	Surface Damage Rating*	No. of Freezing-Thawing Cycle
S1-1	Lab	4	10
S1-6	Lab	5	5
S1-8	Lab	3	10
S1-9	Lab	5	8
S1-10	Lab	3	10
S2-6	Lab	5	5
S2-8	Lab	3	10
S2-9	Lab	5	10
S2-10	Lab	0	10

*Note: “0” means “no scaling”; “3” means “moderate scaling (some coarse aggregate visible)” and “5” means “Severe Scaling (coarse aggregate visible over the entire surface).

From Table 11, it is seen that the effect of deicing chemicals is severe in the case of mortar bars containing 0% or low PAC content. The increase of PAC percentage in the CFA had less surface damage compared to the control sample after subjecting to the freeing-thawing cycles. For instance, both S1-6 and S2-6 mortar bars showed a surface damage rating of "5," which indicates severe scaling only after 5 cycles of freezing and thawing. The control mortar bar had a damage rating of "4" after 10 freezing-thawing cycles. On the other hand, in the case of S1-10 (CFA1-modified 0.75% PAC containing mortar bar), the damage rating was found to be "3" after 10 cycles while S2-10 (CFA1-modified 0.75% PAC containing mortar bar) has a zero (0) rating. A similar trend is also observed for CFA-modified mortar bars containing 0.5% PAC. For example, both S1-8 and S2-8 had the same damage rating of "3" after 10 cycles of freezing-thawing, indicating a moderate scaling. Figure 21 represents the surface conditions of some of the tested mortar bars evaluated in this study. Scaling resistance test data presented in this study should be used with cautions as there was a significant variation of sample curing procedures, which require 14 days of air curing before applying freeze-thaw cycles. Due to limited time, only one day of air curing was done in this study, thus presented scaling resistance data is highly conservative.

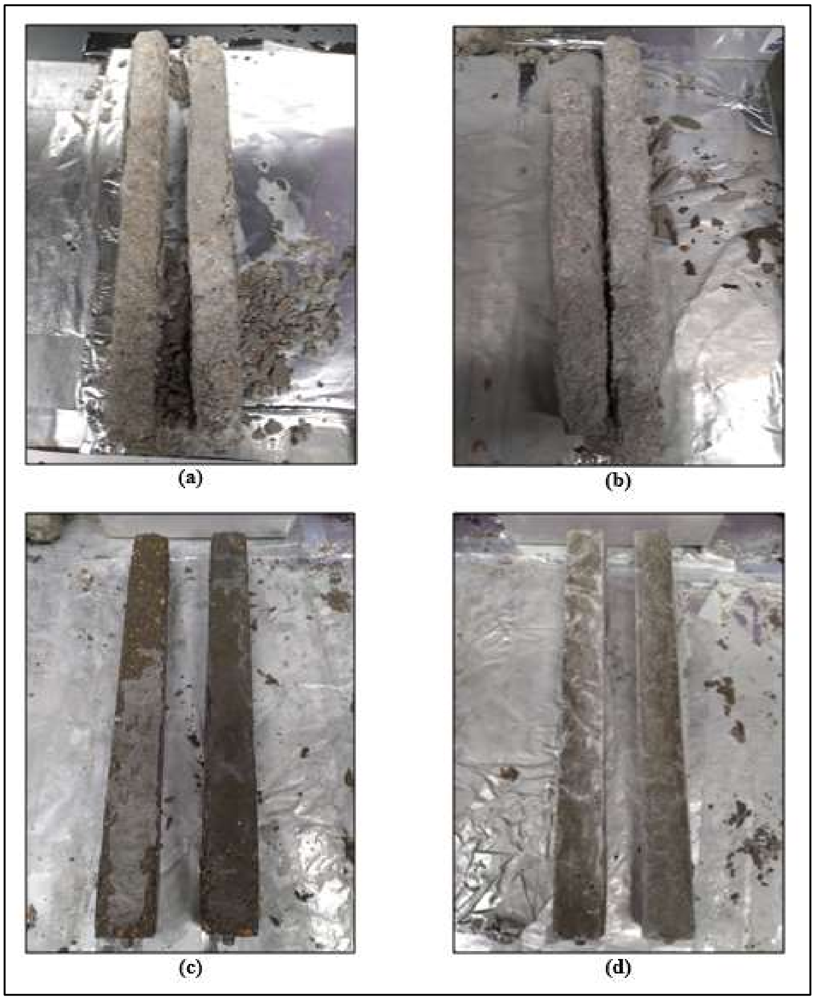


Figure 21. Scaling Test Results of Mortar Bar Samples: (a) S1-6, (b) S2-6, (c) S1-10, and (d) S2-10.

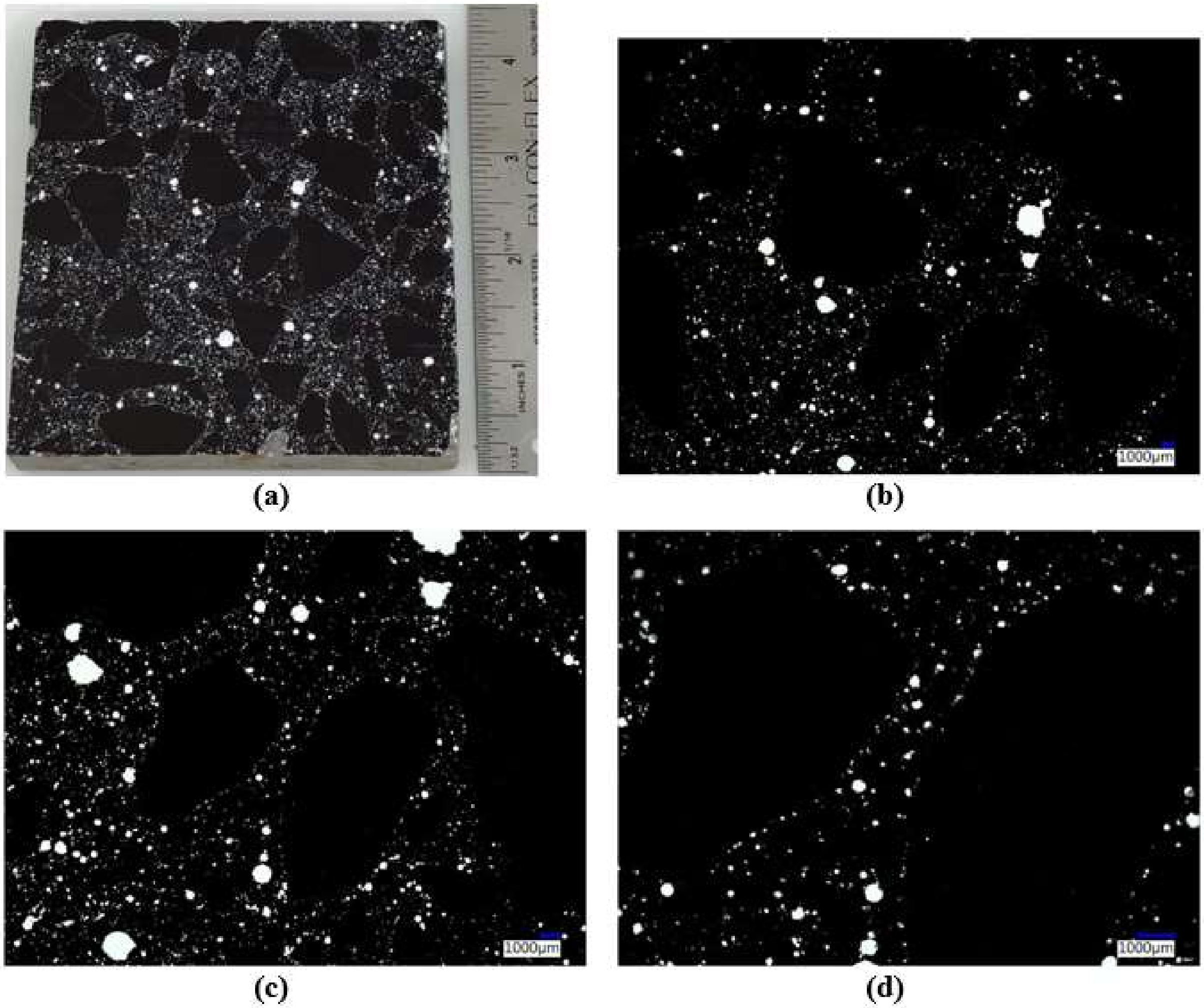
From Table 11, it is seen that the effect of deicing chemicals is severe in the case of mortar bars containing 0% or low PAC content. The increase of PAC percentage in the CFA had less surface damage compared to the control sample after subjecting to the freeing-thawing cycles. For instance, both S1-6 and S2-6 mortar bars showed a surface damage rating of "5," which indicates severe scaling only after 5 cycles of freezing and thawing. The control mortar bar had a damage rating of “4” after 10 freezing-thawing cycles. On the other hand, in the case of S1-10 (CFA1-modified 0.75% PAC containing mortar bar), the damage rating was found to be “3” after 10 cycles while S2-10 (CFA1-modified 0.75% PAC containing mortar bar) has a zero (0) rating. A similar trend is also observed for CFA-modified mortar bars containing 0.5% PAC. For example, both S1-8 and S2-8 had the same damage rating of “3” after 10 cycles of freezing-thawing, indicating a moderate scaling.

5.13. Air Content of Hardened Concrete

As mentioned in Chapter 4, the air content of the hardened concrete samples was determined as per the ASTM C457 (Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete) test method. In this study, two plant-mix samples (e.g., S1-4 and S1-7) were used to determine the air content at 28-days of curing.

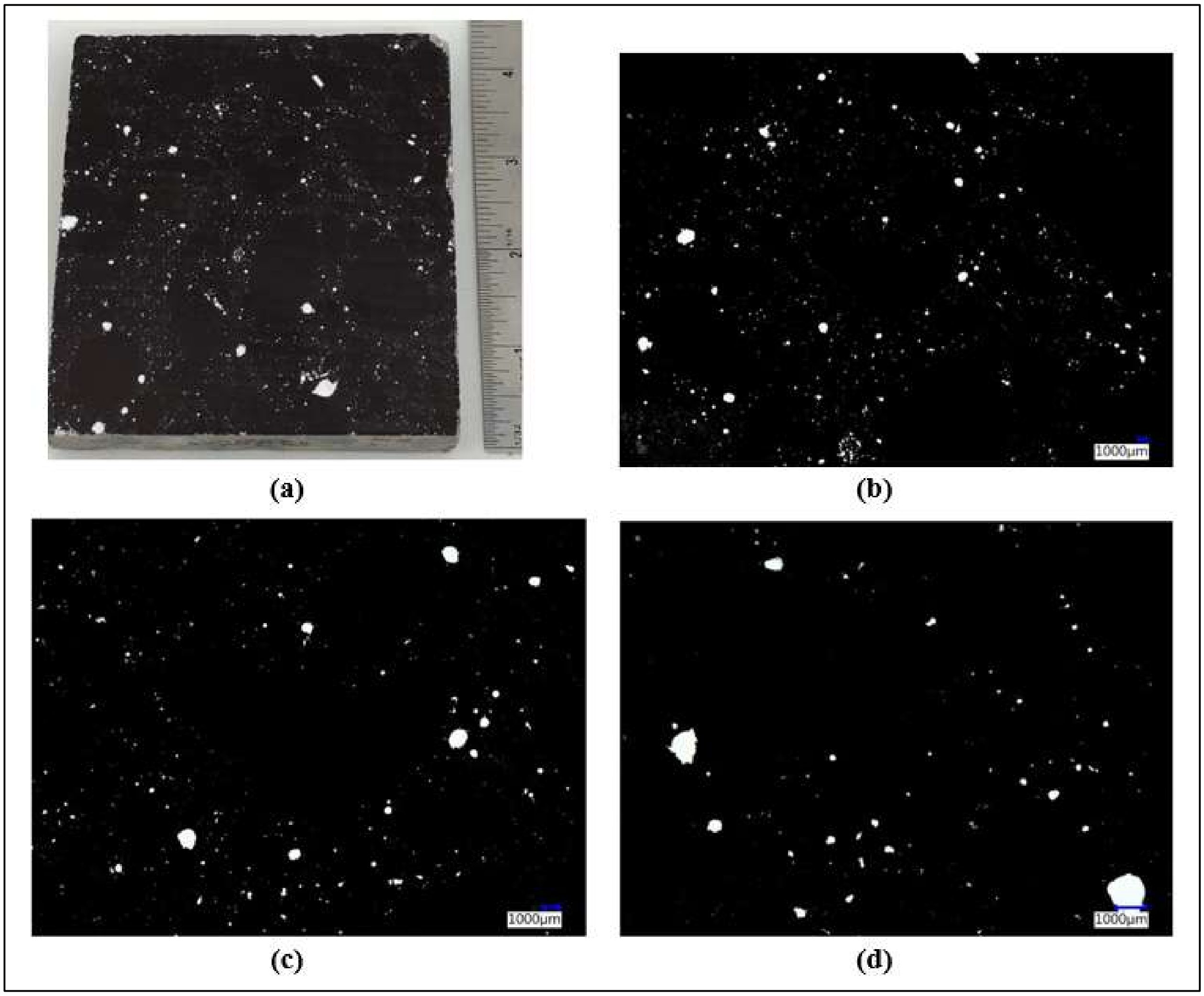
Figure 22 shows the analysis of the air content of the S1-4 hardened concrete sample with a design compressive strength of 4,000 psi (air content of 2%). As shown in Figure 22, a polished section of the S1-4 sample after enhancement for air void analysis where the white areas are voids and black areas are paste and aggregates. Figure 23 shows the air content analysis of the S1-7 hardened concrete sample with a design compressive strength of 3,000 psi (air content = 5%). Figure 23 represents a polished section after enhancement of the S1-7 sample for the air void analysis where the white areas indicate the voids and black areas mean the paste and aggregates.

The summary of the air content test results is presented in Table 12. As seen in Table 12, the air contents were found to be 7.8% and 2.4% for the S1-4 and S1-7 concrete samples, respectively. From a practical application point of view, the air content of the S1-4 sample had slightly higher air voids than the ACI recommended air value ranging from 4.5% to 7.5%. But, S-7 had a design air content of 5%. On the other hand, the S1-7 sample showed a significantly lower air content than the ACI requirement, indicating its negative effect on the long term durability of the concrete. However, the design air content of S1-4 was 2%, indicating a special mix and the manufacturer confirmed that it was intended for a private construction job where the concrete will not be exposed to high freezing and thawing. A similar trend was also found in the case of air content test results of fresh concrete samples determined from the SAM and ASTM C231 (Pressure Method) test methods. While following the SAM method, the air contents of the S1-4 and S1-7 samples were found to be 4.9%, and 3.2% respectively. On the other hand, based on ASTM 231, the air contents of S1-4 and S1-7 samples were determined as 7.5% and 1.5%, respectively. It can be noted that both of these samples had a 0.5% PAC in the CFA1 sample used in preparing the concrete.



(a) (b) (c) (d)

Figure 22. S1-4 Sample Used for Determining the Air Content of Hardened Concrete (4000 psi): (a) Photograph of polished slab, (b) 5X photomicrograph, (c) 10X photomicrograph, and (d) 20X photomicrograph.



(a) (b)

(c) (d)

Figure 23. S1-7 Sample Used for Determining the Air Content of Hardened Concrete (3000 psi): (a) Photograph of polished slab, (b) 5X photomicrograph, (c) 10X photomicrograph, and (d) 20X photomicrograph.

Table 12. Air Content Analysis of Hardened Concretes.

Sample ID	**Mix Type**	**Design Air Content (%)**	**ASTM C231 Air Content (%)**	**SAM Air Content (%)**	**ASTM C457 Air Content (%)**	**ASTM C457 Specific Surface (in^2/in^3)**	**ASTM C457 Spacing Factor (in)**
S1-4	Plant	5.0	7.5	4.9	7.8	788	0.004
S1-7	Plant	2	1.5	3.2	2.4	658	0.010
ACI Recommendation	--	N/A	N/A	N/A	4.5 to 7.5 (6.0 ± 1.5)	>600	<0.008

6. CONCLUSIONS

The main objective of this study was to assess the influence of PAC in fly ash on the properties of concrete. To fulfill the objective of this project, a total of fourteen mixes were prepared and evaluated in the laboratory and on the plant site. The physical properties of fly ash, coarse aggregates (CA), and fine aggregates (FA) were determined in the laboratory or obtained from the suppliers. The required amounts of CA, FA water, and cement were determined per cubic yard of concrete based on the charts provided by the ACI specifications (the Absolute Volume Method). A Type II Ordinary Portland Cement (OPC) was used in the mixes. The air-entraining agent (AEA) dosages used in the mixes were based on the manufacturer's recommendation and the results of the foam index test (FIT) method. In the mix design, the slump value was considered to be varied between 50 mm and 100 mm. Two mix designs for target design strength values of 3000 psi (5% air) and 4000 psi (2% air) were considered in the plant mixes of this study. The same mix designs were followed during the mixing and batching processes in the laboratory. In this study, two CFAs containing the various percentages (0%, 0.25%, 0.50%, and 0.75%) of powdered active carbon (PAC) were used to prepare the mixes and evaluated to find their effects on concrete properties. All mixes had a CFA content of 20% (by the mass of the total cementitious materials). The fly ash used in the plant mixes and their corresponding laboratory mixes had a PAC content of 0.5% (by the mass of fly ash). While using 0.25% and 0.75% PAC in the laboratory mixes, a manual blending process was followed.

To achieve the goal of this study, a series of laboratory tests on fresh and hardened concrete were conducted and test data were analyzed to draw conclusions and recommendations. For fresh concrete mixes, the properties determined in the laboratory included the air content, slump value (workability), and unit weight. Additionally, a Super Air Meter (SAM), and Miller 400A resistivity meter were used in this study to determine the fresh concrete mixes. Moreover, the mechanical properties of hardened concrete such as the compressive strength, tensile strength, flexural strength, and modulus of elasticity were determined. The long-term durability of the prepared concrete samples was determined by performing alkali-silica-reactivity and scaling tests of mortar bars. Furthermore, the air contents of selected hard concrete samples were determined by following ASTM C457. Based on the test results, the following conclusions can be drawn:

1. A higher amount of PAC (0.75%) in CFA reduced the workability (slump value) of concrete compared to the 0.5% PAC (typical) samples.
2. The air contents of the mixes were significantly affected by the incorporation of PAC in the CFA-modified concrete. The air content test results suggested that the CFA containing no PAC had higher air content, whereas a lower air content was observed in the case of higher PAC content.
3. The FIT test can be followed to determine the dosage level of the air-entraining-agent (AEA). Based on the FIT results, it is evident that the required AEA dosages were increased with the addition of CFAs and PAC content as well to generate the permanent foam in the mixes. It is observed that the optimum AEA dosage obtained in the laboratory is always higher compared to the corresponding plant mixes produced as per the AEA manufacturer's recommendation.
4. The SAM was found to be useful in determining the air-voids quality in the fresh concrete. The SAM test results suggested that that the incorporation of CFAs with a certain percentage of PAC is desirable to satisfy the freeze-thaw requirement (ACI durability criteria). This test
5. The electrical resistivity test results showed that 0.75% PAC containing CFAs-modified concrete had the least resistivity value, thus, indicating the higher conductivity of the mixes.

As a result, the corrosion rate of concrete produced with higher PAC percent in the CFAs will increase and reduce concrete durability.

6. The results showed that the setting time was increased due to the incorporation of CFAs with 0.5% PAC in the mixes compared to regular concrete. However, the presence of a higher PAC (0.75%) amount in CFA exhibited a significant reduction of the setting time in the concrete.
7. The compressive strength test results showed that the concrete containing different percentage of PAC in CFAs had a lower rate of strength development in the early days of curing, however, the overall strength at 28 curing days is increased compared to the control sample.
8. The tensile strength test results showed that the CFAs-modified concrete containing a higher percent of PAC (0.75%) had a significant increment in tensile strength while the lower rate of increase in tensile strength was observed in the case of a lower percent of PAC containing CFAs-modified concrete. The tensile strength was about 10% of the compressive strength of the tested concrete samples.
9. Based on the flexural strengths test data, it was observed that 0.75% PAC contained CFAs-modified concretes showed the increment in flexural strengths whereas the concrete contained 0% PAC in CFAs had a minimal effect on flexural strengths compared to regular concrete.
10. The modulus of elasticity results revealed that the modulus of elasticity of CFAs-modified concretes was increased with the increase of CFA and with a higher PAC amount than regular concrete. The rate of increment in modulus of elasticity was found to be similar to the increasing rate of compressive strengths of the concretes and vice versa. Moreover, the modulus values of all concrete estimated using the ACI formula were found higher than the laboratory-based measurements.
11. The ASR tests suggest that an increment of PAC in the CFA is expected to increase the expansion of concrete in the field. However, all test CFAs modified mortar bars exhibited lower expansions than the ASTM C1567 recommended value.
12. The scaling test resistance data suggest that the mortar bars containing a higher amount of PAC (0.75) in the CFAs had a lower effect of deicing chemicals on modified mortar bars compared to the control samples.
13. The air content analysis of hardened concrete samples (plant mixes) showed a similar trend with the air content test (e.g., SAM test and ASTM C231) results of fresh concrete samples prepared in the laboratory and at the plant site.

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