Mechanically Activated Fly Ash For Blended Cement

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By

Chris C. Ramseyer
Assistant Professor

Roozbeh Kiamanesh
Research Assistant

Civil Engineering and Environmental Science
University of Oklahoma
Norman, Oklahoma

OKLAHOMA DEPARTMENT OF TRANSPORTATION

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The fly ash was ground for 30 and 120 minutes. The ground fly ash was used as a cementitious material in the concrete in various proportions; 20, 40, and 60% of the weight. The strength of each mix was compared with plain Portland cement concrete and the concrete samples with un-ground fly ash to determine any changes.

The results of this study show that the concrete with higher proportions of fly ash has higher workability, although the strength of the samples decreases in most cases if high volume of fly ash is used. However, the results indicate that grinding the fly ash can mechanically active the particles and not only improve the strength of the samples with high proportions of fly ash, but also increase the strength higher than traditional Portland cement concrete.

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SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units					Approximate Conversions from SI Units				
Symbol	When you know	Multiply by	To Find	Symbol	Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.40	millimeters	mm	mm	millimeters	0.0394	inches	in
ft	feet	0.3048	meters	m	m	meters	3.281	feet	ft
yd	yards	0.9144	meters	m	m	meters	1.094	yards	yd
mi	miles	1.609	kilometers	km	km	kilometers	0.6214	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	square millimeters	mm	mm^2	square millimeters	0.00155	square inches	in^2
ft^2	square feet	0.0929	square meters	m^2	m^2	square meters	10.764	square feet	ft^2
yd^2	square yards	0.8361	square meters	m^2	m^2	square meters	1.196	square yards	yd^2
ac	acres	0.4047	hectares	ha	ha	hectares	2.471	acres	ac
mi^2	square miles	2.590	square kilometers	km^2	km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.0338	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.2642	gallons	gal
ft^3	cubic feet	0.0283	cubic meters	m^3	m^3	cubic meters	35.315	cubic feet	ft^3
yd^3	cubic yards	0.7645	cubic meters	m^3	m^3	cubic meters	1.308	cubic yards	yd^3
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.0353	ounces	oz
lb	pounds	0.4536	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.1023	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	degrees Fahrenheit	(°F-32)/1.8	degrees Celsius	°C	°C	degrees Celsius	9/5+32	degrees Fahrenheit	°F
		FORCE and PRESSURE or STRESS					**FORCE and PRESSURE or STRESS**		
lbf	poundforce	4.448	Newtons	N	N	Newtons	0.2248	poundforce	lbf
lbf/in^2	poundforce per square inch	6.895	kilopascals	kPa	kPa	kilopascals	0.1450	poundforce per square inch	lbf/in^2

FEARS STRUCTURAL ENGINEERING LABORATORY

REPORT ON

MECHANICALLY ACTIVATED FLY ASH FOR BLENDED CEMENT

by

Roozbeh Kiamanesh

Chris Ramseyer PhD, P.E.
Assistant Professor,
University of Oklahoma

for

Oklahoma Department of Transportation
Oklahoma City, OK

August 2006

School of Civil Engineering and Environmental Science
University of Oklahoma
Norman, Oklahoma 73019

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Abstract

This research is designed to determine the effect of the mechanically activated fly ash on fresh concrete properties and the ultimate strength of the hardened concrete. Six types of fly ash that are locally available in the state of Oklahoma were used in this research. The activation of the fly ash was performed with a modified ball mill to increase the hydration reaction rate of the fly ash particles. Two primary variables were studied in this research; Grinding duration and the percentage of fly ash as a portion of cementitious material.

The fly ash was ground for 30 and 120 minutes. The ground fly ash was used as a cementitious material in the concrete in various proportions; 20, 40, and 60% of the weight. The strength of each mix was compared with plain Portland cement concrete and the concrete samples with un-ground fly ash to determine any changes.

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Chapter 1

Introduction

Fly ash is the non-combustion mineral portion of coal, generated in a coal combustion power plant. Before fly ash was used widely as a construction material, this waste material used as landfill or for soil stabilization. Since the 1950s, fly ash was slowly introduced to civil engineers as a valuable ingredient that can be used in concrete (Ward, 2004). ASTM has adopted the use of fly ash in concrete separately (as in ASTM C618, Class C and F), or as a component of blended cement (ASTM C595 or C1157). Fly ash can improve many desirable properties of concrete in the fresh and hardened stages. Fly ash today is used in concrete for several reasons such as improving the workability of fresh concrete, reducing of initial hydration temperature, sulfate resistance, improving the duration, and strength of hardened concrete.

Fly ash reacts with lime, the byproduct of the cement hydration, and creates additional Calcium Silicate-hydrate crystals, the component that provides strength in concrete (ACI 232). The proper replacement of cement with fly ash can improve workability and performance of fresh and hardened concrete, as well as increase the final strength. Concrete with fly ash has a lower strength at an early age than Portland cement concrete. The slow hydration reaction rate and lower strength of fly ash concrete at an early age are the main reasons that civil engineers did not use fly ash in concrete for decades, especially in time dependant projects.

Fly ash particles are extremely hot when they are collected. While fly ash is cooling down, the small particles tend to adhere to the surface of bigger particles. The rough fly ash particles have a lower reaction surface areas that reduces the hydration reaction rate of fly ash in concrete. Grinding is one of the methods that has been suggested to increase the reaction surface area of fly ash. Comparing the macroscopic pictures of un-ground and ground fly ash shows that grinding the fly ash can remove the small particles from the surface and clean the topography of the fly ash particles.

Chapter 2

Literature Review

2.1 Background

About 2000 years ago, Romans realized that the mixture of volcanic ash with lime, aggregate, and water produced the hard material that can be used as mortar and concrete (Vitruvius). Similarly, fly ash can be mixed with lime that releases from hydration of Portland cement, water, and aggregate to produce mortar and concrete.

Fly ash, also known as pulverized fuel ash, is a byproduct from the incineration of pulverized coal in furnace chambers of thermal power plants. The glassy spherical shaped “ball bearing” fly ash particles are suspended in fuel gases from the combustion air-stream exiting the power plant. The fine gray fly ash particles make up about 75-80% of the total ash formed in the combustion process. The ash collected from the bottom of the furnace is much coarser than fly ash; it is not used as a constituent of inorganic binders (Ivan, Chris Book).

Fly ash initially was used as a partial replacement of the mass or the volume of the hydraulic cement, the most expensive component of concrete, to reduce the cost. However, the results of further studies on fly ash concrete showed that the fly ash could impart beneficial properties to the concrete. The results of research in 1930’s served as a foundation to adopt the early specification, methods of testing and use of fly ash in concrete (Davis et al. 1937), and led to better understanding of the behavior of fly ash concrete.

The high temperate of the chamber, 1600°C (2900 F°), liquefies the incompressible minerals. The spherical particles of fly ash are formed upon cooling the melted material in the furnace with a predominantly glassy structure. The particles that form in lower temperatures tend to be more irregularly shaped, because of reduced amount of melted material present. About 20% of the fly ash particles are hollow, owing to entrapped gases in the molten phase. They are called cenopheres. Some of the fly ash particles contain a smaller particles inside, which are known as pleropheres (Ivan 137). In some cases tiny grains of volatile salt may sit on the surface of the fly ash particles.

The size of fly ash particles ranges between less than 1μm to several hundred μm. The specific surface area of the fly ash typically varies between 200 and 400 m^2/kg (Blaine) or 0.4 and 1 m^2/g (BET). Small changes in the production process of fly ash may change the fly ash properties significantly. Among those are coal combustion, environment (temperature and oxygen supply), boiler/burner configuration, and the rate of particle cooling.

Fly ash particles are collected from the exhaust gasses by mechanical or electrostatic precipitator or by bag houses. The mechanical precipitators collect and store the particles in various hoppers referring to their size distribution. However, in electrostatic precipitators the density and size of the particles tend to be disturbed due to the influence of the charge collection grids. Therefore the size, density and carbon content of the fly ash particles vary from hopper to hopper in both mechanical and electrostatic precipitators. Figure 2.1 shows a schematic of the typical electrostatic precipitator.

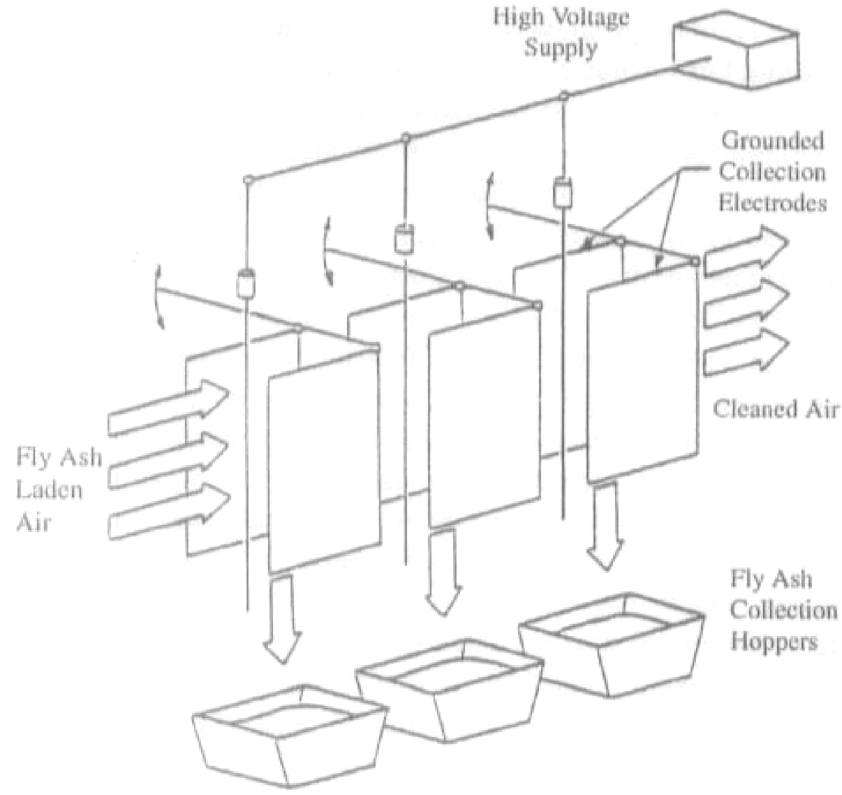


Figure 2.1 Electrostatic precipitator

The properties of fly ash may vary, depending on the composition of the inorganic fraction of the coal, the degree of pulverization, the thermal history, and the oxidation conditions. Gebler and Kovacs (Ivan) determined chemical composition of fly ash in different countries; Table 2.1 shows the ranges of fly ash component.

Calcium plays the main role in the chemical reaction of the fly ash. Therefore based on the chemical composition we can distinguish between low-calcium (ordinary) and high-calcium fly ash.

Table 2.1 Chemical composition of fly ash in different countries

Country	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO
USA	23-58	13-25	4-17	1-29	1-8
UK	43-55	22-34	6-13	1-8	1-2
Former USSR	36-63	11-40	4-17	1-32	0-5
Poland	35-50	6-36	5-12	2-35	1-4
Japan	53-63	25-28	2-6	1-7	1-2

For more than 60 years, fly ash has been used successfully in Portland cement concrete as a mineral admixture. In the last two decades, fly ash has been used as a compound of blended cement. Intergrading Portland clinker, fly ash, and calcium sulfate produce Portland-fly ash cement. Under most specifications the amount of fly ash in the cement is limited to 30-40 wt%, but typically an addition of about 15-25 wt% may be considered more practical.

The Portland clinker used for fly ash concrete should have an amount of tricalcium silicate, preferably more than 45%. Tricalcium is considered a calcium source and the hydration of this phase produce the calcium hydroxide needed for Pozzolanic reaction of the fly ash. The reaction rate of fly ash is slower than Portland cement; therefore the Portland cement is mainly responsible for the initial setting and strength development of the concrete. The strength due to fly ash hydration contributes only over a longer time period, but also affects other properties of the mix.

Fly ash may be introduced to the fresh concrete mix directly as a separate binder component instead of a constituent of cement. In this case, Portland cement, fly ash, water and aggregate are mixed in the concrete mixer to produce fly ash concrete.

2.2 Fly Ash Classification

ASTM C-618 is probably the most recognized method to classify fly ash material in the world. Base on ASTM C-618 fly ash is been classified in three major categories Class-N, C, and F. Class N is raw or calcined natural pozzolan such as some diatomaceous earths, opaline cherts, and shales; tuffs, volcanic ashes, and pumicites; and calcined clays and shales. ASTM C618 defines the specification of two classes of fly ash Class-C and F that can be used in Portland concrete. Specification categorizes fly ash by chemical composition, according to the sum of the iron, aluminum, and silicon content that is expressed in oxide form. This classification does not determine the performance of the fly ash in concrete and only represents the chemical composition of the particles.

Class-F or low-calcium fly ash is derived from anthracite or bituminous coal that normally generates more heat. It is generally poor in CaO and MgO and relatively rich in SiO_2 and Al_2O_3 in comparison with Class-C fly ash. Class-C fly ash is a high-calcium fly ash formed by burning lignite or sub-bituminous. It contains less SiO_2 and Al_2O_3 than class F fly ash, but higher amounts of lime (CaO). Part of this lime is present as in a form of free lime in the fly ash compound.

The fraction of the four major constituents of fly ash varies widely; SiO_2 (35 to 60%), Al_2O_3 (10 to 30%), Fe_2O_3 (4 to 20%), and CaO (1 to 35%). The fly ash classifies as a Class-F in respect to ASTM C-618 if the summation of the first three constituents (SiO_2, Al_2O_3, and Fe_2O_3) exceeds 70%. However, the ASTM C-618 classifies the fly ash as a Class-C if the summation only exceeds 50%. Fly ash Class-C generally contains more than 20% CaO, therefore the sum of three constituents (SiO_2, Al_2O_3, and Fe_2O_3) may be significantly lower than 70%, the minimum limit for Class-F fly ash.

ASTM C-168 specifies a limitation for the LOI of fly ash be used in concrete. Class-C fly ash usually has a LOI (Loss of Ignition) less then 1%. This number can as high as 20% for the Class-F fly ash. Most of the fly ashes used in concrete have LOI close to 6%. However, the ASTM C-618 allows LOI as high as 12% for Class-F fly ash if the performance and laboratory test results are acceptable. The Summary of ASTM C-618 is provided in Table 2.2.

Table 2.2 Summary – ASTM C-618 (A HeadWaters Company Catalog).

Chemical		**F**	**C**	**N**
$SiO_2 + Al_2O_3 + Fe_2O_3$	min %	70	50	70
SO_3	max %	5	5	4
Moisture Content	max %	3	3	3
Loss of Ignition	max %	6	6	10
Optional Chemical				
Available Alkalies	max %	1.5	1.5	1.5
Physical				
Fineness + 325 Mesh	max %	34	34	34
Strength Activity/Cem.	min %	75	75	75
Water Requirement	max %	105	105	105
Autoclave Expansion	max %	0.8	0.8	0.8
Uniformity Requirements Density Max. Var.	max %	5	5	5
Fineness Points Var.	max %	5	5	5
Optional Physical				
Multiple Factor		225	-	-
Inc. in Dying Shrinkage	max %	0.03	0.03	0.03
Uniformity Requirements A.E. Admixture Demand	max %	20	20	20
Control of ASR Expansion, % of low alkali cement	max %	100	100	100
Sulfate Resistance				
Moderate exposure, 6 months	max %	0.10	0.10	0.10
High exposure, 6 months	max %	0.05	0.05	0.05

2.3 Chemistry of Fly Ash

The main constituents of both fly ash Class-C and F are glassy phase spheres consisting of two types: Solid and hollow (cenopheres). Between 60 to 90% of fly ash mass consists of these glassy spheres. The remaining portion of the fly ash mass is a combination of variety of different crystal (crystalline) phases. The two fractions are not entirely independent from each other. The crystalline particles can be adhered to the surface of the glassy spheres or present in a glassy particle's matrix. The combination of the two phases makes the fly ash a complex composite to be classified and characterized in specific terms.

The glassy phase is formed during rapid cooling the melt that has been created from the inorganic constituents of the original coal. The compositions of these particles are highly dependant on the composition of the pulverized coal and the temperature existing in the chamber. The Glassy phase is basically a SiO_2-Al_2O_3-(CaO)-(MgO) glass with a low degree of SiO_2 polymerization. In general, the CaO content of the glass phase makes a major difference between fly ash glass compositions. The glass phase of Class-C fly ash is rich in CaO, which causes the lower degree of SiO_2 polymerization and an increased reactivity (Mehta, 1985). Owing to its readiness to react with calcium hydroxide, the glass phase is the constituent of fly ash that is mainly responsible for its pozzolanicity.

In the presence of calcium hydroxide and water, the glass phase of fly ash presents its pozzolanic properties by forming to an amorphous C-S-(A)-H or CSH phase as a reaction product. This formation, if the reaction takes place during the concrete curing, is responsible for the concrete hardness. The chemical reaction to create CSH starts with the attack of OH^- ions to $SiO_2 - Al_2O_3$ framework and break down of the bounds between silicate and aluminate ions. A sufficient number of $Si - O - Si$ or $Si - O - Al$ bonds needs to be broken in order for free silicate and aluminate anions to be detected from the network and react with calcium hydroxide, $Ca(OH)_2$, demonized in water to yield an amorphous calcium silicate aluminate phase.

In some high calcium Class-C ash the amount of calcium hydroxide formed by hydration of calcium oxide, lime, present in the fly ash is enough for formation of amorphous calcium silicate aluminate phase. Any polar calcium component present in the ash that can be ionized and form calcium hydroxide may contribute in hardening and setting of the fly ash. In these cases, the ash possesses cementing properties even without any additional source of calcium hydroxide.

2.4 Fly Ash Physical Properties

The properties of the fresh mix, hardened concrete and the strength development of the concrete incorporated with fly ash influenced by varying of the fly ash shape, size, size distribution, and density of fly ash particle. The physical properties of one type of fly ash may vary significantly from another fly ash originating from a different source. The source of coal burned in the chamber, combustion method, and the chamber temperature can affect the physical properties of fly ash.

Generally the plants operating with similar combustion methods and coal can produce the fly ash with similar chemical and physical characteristics. The color of fly ash particles is influenced by varying the coal properties or changing the plant's operating method that can results in the hardened concrete with different colors.

2.4.1 Particle Shape

The fly ash particles size and shape characteristics are dependant on the source and uniformity of the source, the degree of pulverization before burning, the temperature level and oxygen supply of the combustion chamber, uniformity of the combustion and the type of the collection system (ACI 232, pp 9).

The majority of fly ash particles are glassy, solid or hollow and spherical in shape. Figure 2.2 and Figure 2.3 show the fly ash particles. The hollow particles are translucent to opaque, slightly too highly porous, and vary in shape from round to elongated.

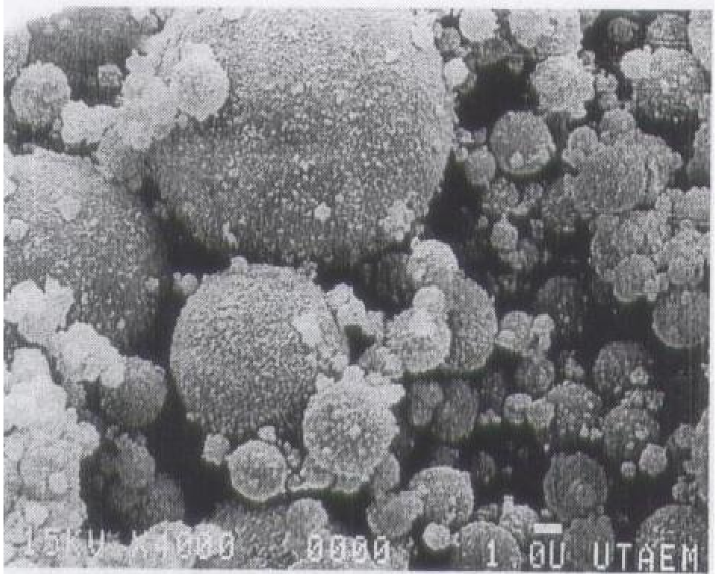


Figure 2.2 Fly ash at 4000× magnification.

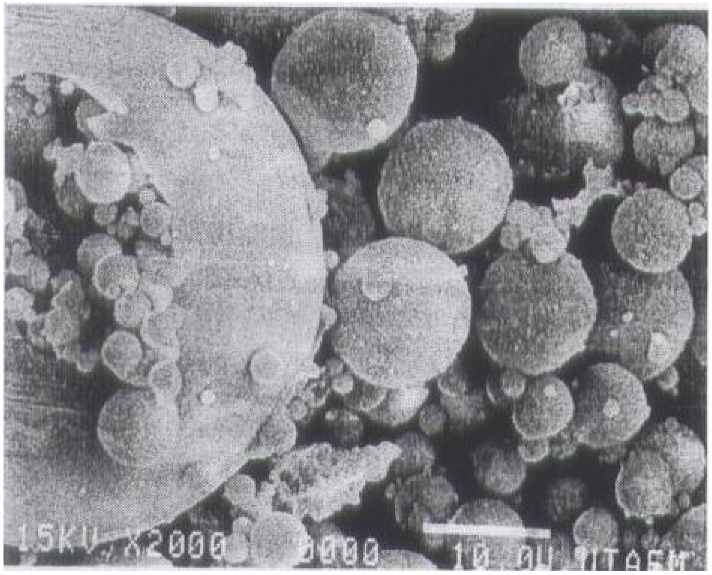


Figure 2.3 Fly ash showing plerospheres at 2000× magnification.

The inter-grinding of fly ash with the cement's clinker in the production procedure of Portland cement may improve the performance of hardened concrete (EPRI SC-2616-SR). Grinding breaks down the cenospheres particles, separates the particles with surface attraction, and reduces the particle size.

2.4.2 Fineness

The size of fly ash particle ranges from 1 μm (0.00004 in) to greater than 1 mm (0.04 in). The finer fly ash particles, between 5 to 30 μm, are more reactive than the courser fly ash (Malhotra and Mehta 2002). The fly ash are collected with mechanical separators are tend to be courser than the ones that are collected with modern technology (electrostatic precipitator).

The ASTM C-16 recommended that not more than 34% of the fly ash particles be retained on the 45 μm (No. 325 [0.0018 in.] sieves. The study shows that the portion of the fly ash retained on this sieve, No. 325, remain relatively constant if no major changes occur in the production of fly ash.

In 1982, Lane and Best conducted the study based on ASTM C-430 to determine the affect of the fly ash Class-F fineness on certain concrete properties such as ultimate strength, abrasion, resistance, and resistance to freezing and thawing. Their results indicate that these properties are directly a function of the portion of fly ash finer than No. 325 sieve. Lane prompted that the performance of fly ash concrete improves with increased fineness.

2.4.3 Specific Unit Weight

The fly ash specific unit weight can vary from 1.97 to 3.01; however, this number ranges from 2.19 to 2.8 for the majority of fly ashes (Luke 1961). Fine particles have higher density and some fly ash particles such as cenospheres, with air voids entrapped, are able to float on water. A study conducted by Roy, Luck, and Diamond in 1984 indicate that the fly ash particles with higher density tend to be high in iron and the fly ash with high carbon has a lower density. The fine fly ash particles, and in some cases the one with cenospheres, are permitted by ASTM for Class-C. Thus, their specific unit weight tends to be higher, in range of 2.4 to 2.8.

2.5 Effects on Properties of Fresh Concrete

Fly ash has a spherical shape. The physical shape of fly ash is the main driving force of workability benefits of using fly ash in Portland cement concrete. The ball bearing effect of fly ash particles creates the lubricating action in concrete. The other benefits of using fly ash in fresh concrete include:

2.5.1 Workability

Fly ash has lower unit weight than Portland cement. Therefore, when the same volume of cement is replaced with fly ash (assuming the w/cm is constant), the amount of paste will increase. In many cases fly ash replaced with a ratio of one or greater to increase the volume of the paste in concrete for the given water content. This higher volume of the paste provides more plasticity and cohesiveness to the concrete.

Fly ash Class-C generally has a higher proportion of fine particles smaller than 10 μm (0.0004 in.) (EPRI CS-3314). Fine fly ash particles compensate for the lack of fine aggregate in the mix, which generally improve the workability of the mix.

Brown (1980) reported that the spherical shape of fly ash particles increase the slump of the mix and permits the water in the concrete to be reduced for the given workability. A study conducted by Ravina (1984) shows that the use of fly ash in the concrete reduces the slump loss of the concrete in the hot weather condition in comparison with non-fly ash concrete.

2.5.2 Bleeding

Fly ash concrete has lower water content for the given workability and greater surface areas of the solid particles, because of finesse of fly ash particles that can reduce the bleeding in the fly ash concrete (Idorn and Henriksen 1984). Fewer bleeding channels decrease porosity and chemical attacks. Bleed streaking is reduced for architectural finishes. Improved paste to aggregate contact results in enhanced bond strengths.

2.5.3 Pumpability

The spherical shape fly ash particles serve as ball bearings in the mix and reduce the friction between the particles and between concrete and pumping line (Best and Lane 1980). Fly ash concrete is more cohesive and less prone to segregation and bleeding during pumping. Thus, pumping a fly ash concrete requires less energy and longer pumping is possible.

2.5.4 Time of Setting

Using the fly ash in concrete extends the time of setting of the concrete by reducing the cement content of the concrete. A study conducted by Jawed and Skalny (1981) showed that using the fly ash Class F delays the hydration reaction of C_3S. Fly ash

Class F usually impacts the setting time of the concrete when it is used in a concrete as a replacement with cement. Therefore, it does not change the setting time significantly when it is used as an addition to cement content. Further study on fly ash concrete by Eren, Brooks, and Celik (1995) also emphasizes the delay on hydration of C_3S due to fly ash Class C. The setting time of fly ash is a function of various factors: concrete temperature; cement's type, source, and fineness; the fly ash content, source, fineness and chemical composition (Plowman and Cabrera 1984).

The study conducted by Neville (1981) indicates that one of the key element in setting time of the concrete with Portland cement Type-I is hydration of tricalcium silicate (C_3S). The rapid raise of the concrete temperature is the indicator of the initial set and the peak of hydration temperature is approximately the final setting time. Initial and final setting time can be determine by various methods such as Vicat apparatus (BS 4550, British Standards Institution), or Test Method for Time of Setting of Hydraulic Cement by Gillmore Needles presented in ASTM C-266.

The setting time of replacement cementitious material such as fly ash or ground-granulated blast-furnace slag are generally delayed because the hydrations of those materials will not starts until sufficient amount of calcium hydroxide is liberated from hydration of the cement. Therefore, the methods base on heat of hydration and temperature rise in concrete will not be a suitable indicator of measure the setting time of the concrete.

Eren et al. (1995) tested setting time of the fly ash concrete base on the curing temperature, 6 to 80ºC. the results of this research shows that an increase in curing temperature decrease the setting time of the concrete containing fly ash replacement up to 50% of Type-I cement. Eren study on setting time of concrete containing slag shows the major contradiction with same test results conducted by Yoshida et al. (1986), probably because of the difference in chemical composition of the slag.

The effect of fly ash on the setting time of the concrete can be determined by specific testing. However, in cases that the precise results are not required, the observation may be sufficient to indicate the difference between the setting times.

2.5.5 Finishability

The setting time retardation due to the use of fly ash in concrete provides a longer time for placing and finishing. Different fly ashes may delay the setting time more in some cases and less in others. It is important that the finishing of concrete with a slow setting time be delayed. Failure to delay the finishing of the concrete with slow setting rate may cause premature finishing. Trapping the bleeding water under the surface layer, increasing the shrinkage and as a result shrinkage cracks, and surface cracking due to high evaporation are the general defects of early finishing.

There are several admixtures that can be used to decrease the setting time of the concrete. The effect of the admixture may be different from one fly ash to another. Thus, tests should be conducted to determine the special effects of each admixture on the setting time of the fly ash concrete.

Very light unburned particles in fly ash are subjected to travel upward in the high slump concrete and create an undesirable surface appearance. High content fly ash mixtures may cause thickening of the mix because of high fine particle content or high air content.

2.5.6 Air Content

In general, the dosage of air entrained admixture in the fly ash mixes needs to be adjusted to maintain the specific air content in the concrete. Some Class C fly ashes specially the one with high water-soluble alkalis, can increase the air content of the mixture (Pistilli 1983). In fact, some of the fly ashes do not affect the air content of the concrete and no change of air-entrained admixture is required. The fly ashes with high LOI are tend to have more effect on the air content the of fresh mix and a more frequent air content test is required to maintain the air content in the concrete.

Studies conducted by Meininger (1981) and Gebler and Kligger (1983) show that if the fly ash concrete requires additional air-entrained admixture, the fresh mix tends to lose most of the entrained air before it has been placed. Therefore, the air content test prior to casting is necessary to measure and adjust the air content. In the same study, Meininger (1981), indicates that after placement of the concrete, no future losses of air content were encountered. However, agitation and vibration of the placed concrete can increase the chance of losing the entrained-air.

Gebler and Kligger's study shows that fly ash concrete can lose between 40 to 100% of its entrapped air in less than 90 minutes. Gaynor, 1980, listed the factors that a loss of air depends on: properties and proportion of fly ash, cement type and its fineness, length of the mixing or agitation time, and the type of air-entrained admixture.

2.6 Effects on Properties of Hardened Concrete

The most important issue with regard to the use of fly ash in concrete is its performance in hardened concrete. If fly ash mixes and cures properly, fly ash concrete performs equal to or better than ordinary concrete in all-important categories. It should be noted that to enhance the performance of fly ash concrete, longer curing periods are required. Ordinary concrete achieves most of its strength on the first 28 days. The slow reaction of fly ash delays this curing time to about 56 days. Regardless of slow curing of fly ash concrete, using fly ash in non-time critical applications is beneficial. In this section the hardened concrete performance improvements due to use of fly ash will be explained in detail.

2.6.1 Compressive Strength and Rate of Strength Gaining

The early age strength, final strength and the strength gaining of the fly ash concrete is a function of several factors such as; Type of cement, chemical composition and characteristics of the fly ash particles used in concrete (EPRI CS-3314). In general, the fly ash concretes contain fly ash Class-F has lower strength in early age (Abdun-Nur 1961) and using by using admixtures such as water reducer, accelerator, activator the strength equivalent to strength of Portland cement concrete can be achieve in early age (Shi and Qian 2000).

After the hydration reaction of hydraulic cement slows in early age and the concrete does not gain any significant strength because of this reaction. However, the Pozzplanic activity of fly ash remains steady as long as the concrete kept moist. Therefore the concretes contain fly ash with the same strength in early age, 7 days, tend to have higher strength at later age than concrete without fly ash (Berry and Malhotra 1980).

In general, fly ash Class-C has higher rate of hydration reaction that results in higher strength in early age. Fly ash class-C typically gives reasonable strength to the concrete at 28 days. Several studies such as Cook (1981) and Pitt and Demiral (1983) indicate that Class-C fly ash has the same effect on the strength of the concrete with the same binder mass bases. On the other hand some Class-C fly ashes does not perform as reactive as Hydraulic cement and in some cases perform lower than Class-F fly ash.

Tan and Pu (1998) studied the effect of finely ground fly ash and finely ground granulated blast furnace slag on the compressive strength if the concrete. His results show a significant increase in the strength of the samples with 20% of replacement of binder with ground fly ash 6021 (cm^2/gr) or slag 5923 (cm^2/gr). He reveals that the combination of fly ash and slag, 10% each, results in the higher final strength.

Jaturapitakkul (2002) et al. study the strength of the concrete contain course fly ash particles, 90-100 μm, with various portion and compare its results with strength of the concrete with ground fly ash, 3.8 μm. This study show that grinding the fly ash give higher strength to the samples containing ground fly ash replacement between 15% and 50%. The best strength found in this research was from the samples with 25% of fly ash. The samples contain less that 20% of fly ash gained no benefit from usage of ground fly ash and had the same compressive strength as PCC at the curing age of 60 days.

2.6.2 Modulus of Elasticity

Study conducted by Lane and Best (1982) shows that the fly ash concrete has lower compression strength and modulus of elasticity in early age and slightly higher at later age than the similar concrete without fly ash. Fly ash has lower impact on the modulus of elasticity that compression strength of the concrete. Figure x.x shows the different between modulus of elasticity of the concretes with and with out fly ash. Further study conducted by Cain (1979) reports that aggregate characteristic and size distribution will have grater impact on the modulus of elasticity than use of fly ash.

2.6.3 Creep

The rate and magnitude of creep strain in concrete is depend on several parameters, including curing and surrounding temperature, ambient moisture, strength of concrete, modulus of elasticity, aggregate content, the age of the concrete when load is applied. The increase of the creep strain of the concrete due to usage of fly ash is limited to the concretes that have lower strength due to slow strength gaining of fly ash. The fly ash concrete samples tend to have higher creep strain in the early age in comparison with the concrete with the same binder volume mix, due to lower strength of the concrete in the early age (Lane and Best 1982). Same study, Lane and Best 1982, indicates that the fly ash concretes have almost same creep strain as the concretes without fly ash if the compression strength of the samples the equal.

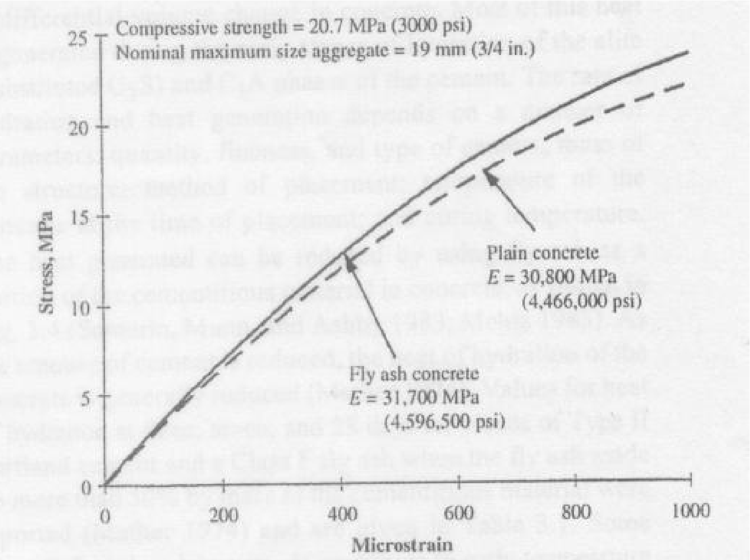


Figure 2.4 Stress-strain relationship at 90 days (Tennessee Valley Authority 1981).

2.6.4 Bond

The concrete bond with reinforcement steel bars is the function of numerous parameters such as the surface area of the steel, the location of reinforcement, and the density of the concrete. Using the fly ash in the concrete usually reduces the density and bleeding and increases the paste volume in the mix. Thus, using the fly ash in concrete can increase the contact surface area of the mix with the concrete and creates stronger bonds. However, the most important factor to determine the development length of reinforcement in concrete is the concrete strength. Therefore, the development length of the reinforcement in fly ash concrete should be at least equal to that in concrete without fly ash.

2.6.5 Impact Resistance

The impact resistance property of the concrete is highly related to the ultimate compression strength of the mortar and hardness of aggregates. The usage of fly ash in concrete only improves the impact resistance of the concrete if the fly ash increases the compression strength of the concrete.

2.6.6 Abrasion Resistance

Compressive strength, curing condition, finishing, and aggregate properties are the major factors that control the abrasion resistance of concrete (ACI 201.2R; ACI 210R). Concretes with equal compressive strength and curing conditions perform the same abrasion resistance regardless of the use of fly ash in the mix or not.

2.6.7 Temperature Rise

The hydration reaction of the cement with water generates heat, which indicates the rate of strength gaining of concrete. The majority of the heat generated in concrete is the result of the hydration of alite (C_3S) and C_3A component of the cement. The rate of generation of heat of hydration is dependent on a number of factors such as quantity, fineness, and type of cement; mass of the structure; method of placement; temperature of the concrete at the time of placement; and curing temperature. Figure 2.5 (Samarin, Munn, and Ashby 1983; Mehta 1983) shows the mixes with lower fly ash content have a higher heat of hydration peak in an earlier time.

Future investigation, Mather 1974, indicates that the higher portion generally reduces the heat of hydration in concrete. Mather chose Portland cement type-II and a Class-F fly ash. He measured the heat of hydration of five different mixes with more than 50% fly ash at three, seven, and 28 days. The results of this study are given in Table 2.3. However, other studies (Dunstan 1984) show fly ash Class-C can contribute in temperature rise of concrete in early age. Specific tests should be conducted to measure the heat of hydration of the mix if the curing temperature is a major concern.

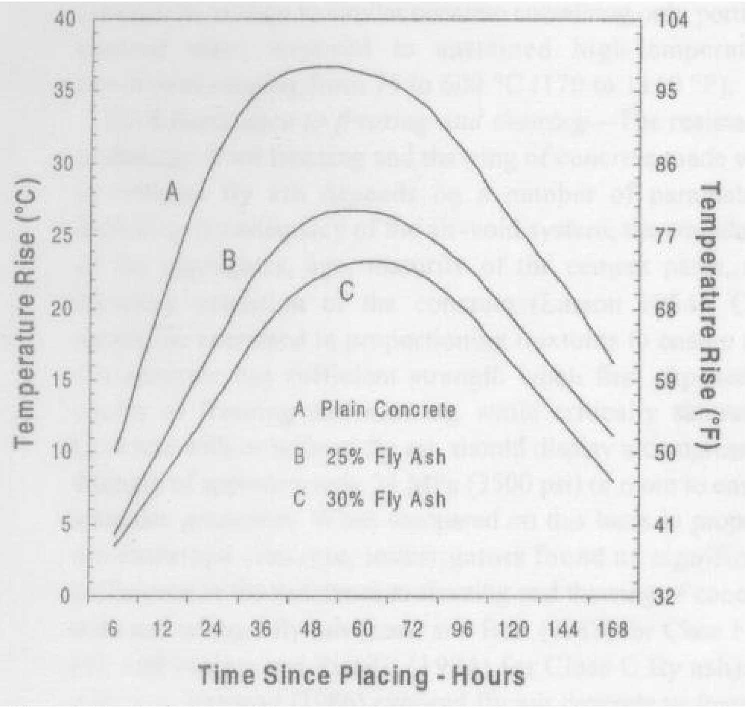


Figure 2.5 Variation of temperature with time at the center on 15 m3 block concrete blocks(Samarin, Munn, and Ashby 1983)

Table 2.3 Heat of hydration of Portland cement/fly ash blends (Mather 1974)

Fly ash % of cementitious material	Calories per gram		
	3 days	7 days	28 days
0	61	75	91
52	31	42	61
57	37	43	56
65	35	42	53
68	31	40	49
71	29	36	48

2.6.8 Resistance to High Temperature

A study conducted by Carette, Painter, and Malhotra (1982) shows that the use of fly ash in the mix does not change the mechanical properties of concrete when it is exposed to and sustained at a high temperature. This study specifies that the fly ash concrete has similar resistance to high temperature as the concrete without fly ash when it was exposed to temperature ranges from 75 to 600 ºC (170 to 1110 ºF).

2.6.9 Resistance to Freezing and Thawing

The resistance of the concrete to freezing and thawing is governed largely by the numbers of factors, including the air content, the sandiness of the aggregates, age, maturity of the cement paste, and moisture content of the concrete (Larson 1964). It is important that concrete reach its ultimate strength before it exercise the first freezing and thawing cycle.

The results of studies (Lane and Best 1982) on fly ash Class-F and (Majko and Pistilli 1984) on fly ash Class-C show no significant advantage on resisting freezing and thawing by using fly ash in concrete in comparison with similar concrete without fly ash. In 1986, Halstead performed the same study on early age fly ash concrete; he reported no considerable degradation of performance when compared to control concrete.

2.6.10 Permeability and Corrosion Protection

The permeability of the concrete is governed by several factors such as the amount of cementitious material, water content, aggregate size distribution, consolidation, and curing condition. The study conducted by Powers, Copeland, and Mann (1959) shows that the degree of hydration required to reduce the capillary continuity is the function of the water to cement (w/c) ratio and time.

Calcium hydroxide, $Ca(OH)_2$, the by product of cement hydration, is water soluble and may leach out of concrete and leave the voids for entering the water to the hardened concrete. The hydration of the fly ash with these Pozzplanic particles produces C-S-H, which fills the voids and ultimately reduces the permeability of the hardened concrete.

2.6.11 Sulfate Resistance

The effect of fly ash Class-F on the sulfate resistance of the concrete is better understood when compared to fly ash Class-C. In general, fly ash Class-F improves the sulfate resistance of the mixture. Many researchers believe this improvement is because of the chemical reaction between fly ash and free calcium hydroxide that exists in the cement that forms additional C-S-H in the concrete. This C-S-H tends to block the void volumes that used to be filled with calcium hydroxide, thus reducing the permeability of the concrete and ingress of sulfate solution. It is not simple to draw the same conclusion on the effect of fly ash Class-C on the sulfate resistance of the concrete. Mather (1982) believes that use of 30% fly ash with the cements with high C_3A decreases the sulfate resistance of the concrete. However, the results from other studies conducted by Tikalsky, Carrasquillo, and Snow (1992); and Dunstan (1976) show that concretes with high calcium and fly ash content have higher resistance to sulfate attack. A further study, Tikalsky and Carrasquillo (1993), reported the concretes with a higher volume of calcium and fly ash have greater susceptibility to sulfate deterioration.

In general, deterioration due to sulfate attack in the concrete is the result of a chemical reaction that produces products with a higher volume than the original material. This expansion cause internal pressure and generates cracks on the surface of the concrete. Sulfates can ingress to the concrete from various sources such as sulfate rich ground water or sulfate bearing soils and react with C_3A in the concrete. The damage due to sulfate attack can be minimized by reducing the amount of the C_3A in the concrete. Dikeou (1975) and Pierce (1982) reported that certain fly ashes improve the susceptibility of the concrete due to sulfate attack regardless of environmental condition and type of the cement used in the mixture. However, fly ash has a greater effect on the susceptibility due to sulfate attack on certain types of cements. The following list indicates the descending order of resistance to sulfate attack due to the use of fly ash Class-F:

(a) Type V plus fly ash – most resistant to sulfate
(b) Type II plus fly ash
(c) Type V

(d) Type II

(e) Type I plus fly ash

(f) Type I – least resistant

The factors that affect sulfate resistance of the concrete with fly ash are the same for non fly ash concrete, which includes curing conditions, exposure, and w/cm. However, certain properties of fly ash such as class, amount, and the physical and chemical characteristics can influence the sulfate susceptibility of the concrete.

Dunstan (1980) introduced a new parameter, $\check{R}$, called the sulfate resistance factor, and developed later by Pierce (1982) to the form of:

$$\Re = \frac{CaO\%_{(in..the.Mix)} - 5\%}{Fe_2O_{3(in.Fly.Ash)}}$$

Note: the values are based on bulk chemical analysis.

Further studies conducted by Mehta (1986) and Tikalsky, Carrasquillo and Snow (1992) shows that the $\check{R}$ factor is not a good indicator or the sulfate resistance. They reported that the concrete sulfate resistance is the factor of reactive alumina content and the presence of the expansive phase in the fly ash, and $\check{R}$ factor does not influence only by the amount of Fe_2O_3 as it mentioned in Dunstan study. Based on ASTM C-618 fly ash with less than 15% of CaO may improve the susceptibility of the concrete due to sulfate attack. However, any fly ash with more CaO should be tested for sulfate expansion using ASTM C-1012 or USBR Test 4908.

2.6.12 Drying Shrinkage

The drying shrinkage of the concrete is the function of several parameters such as fraction volume of the paste, water content, cement content, type of the cement, and type and size distribution of the aggregate. Because the lower specific unit weight of the fly ash, addition of fly ash into the mix increases the volume of the paste that may increase the drying shrinkage if the water content remains the same. However, by reduction of the water content, the drying shrinkage of the concrete should be about the same as concrete without fly ash. A study conducted by Davis et al. (1937) shows no significant variation of drying shrinkage of the concretes with less than 20% fly ash and non-fly ash concrete. Other studies, Dunstan (1984) and Symons and Fleming (1980), recorded slightly lower drying shrinkage for the samples with a higher fly ash content.

2.6.13 Efflorescence

Efflorescence is the results of traveling free calcium hydroxide, lime or $Ca(OH)_2$, and other salts to the surface of the concrete. The $Ca(OH)_2$ reacts with the CO_2 in the air and forms $CaCO_3$, the main source of discoloration of the concrete. The use of fly ash can effectively reduce the efflorescence by reducing the permeability and amount of free lime that exists in the concrete.

2.6.14 Deicing Scaling

Scaling of the concrete due to deicing chemicals occurs when immature or non-air-entrained concrete pavements are exposed to a large quantity of deicing chemicals in a freezing and thawing environment. Concrete pavements containing fly ash should be air entrained and reach certain maturity or strength before being exposed to deicing chemicals as mature concretes tend to have more durability against deicing chemicals.

Results of several studies performed on different types of fly ashes shows the concretes that contain more than 40% fly ash, as a percentage of the total mass, are more susceptible to scaling (Gebler and Klieger 1986; Ernzen and Carrasuillo 1992; Johnston 1994).

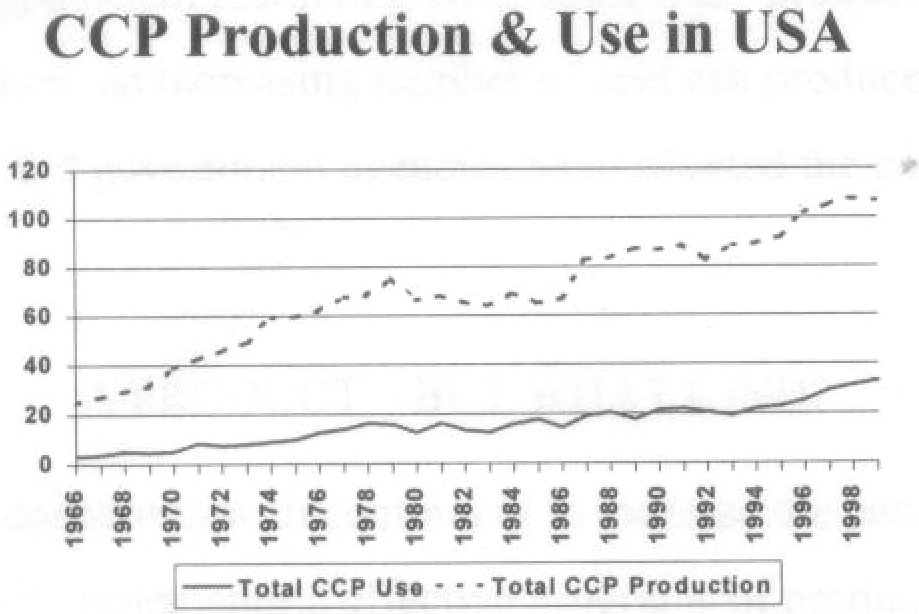
2.7 Environmental Sound

Concrete is the most common building material in the world (4.) Portland cement concrete is being used almost two times more than any other structural material. The production of cement consumes an extreme amount of energy and requires enormous amounts of raw materials. Production of one ton of Portland cement requires two tons of raw material and 4000 (MJ) of electrical energy. It is common to burn high dense plastics such as disposed tires, in cement production facilities to supply the heat required. Study shows that producing one ton of cement, releases one Kg carbon dioxide (CO_2) and 3 Kg nitrogen oxide (NO). The carbon dioxide produced and released from cement facilities in the world accounts for 7-8% of the CO_2 released into the air annually.

Decreasing the worldwide demand of Portland cement by replacing a portion of cement with waste fly ash recycled from coal plants is an easy and efficient way to control the CO_2 emissions. The US produces 60 million tons of fly ash per year, and the world produces 600 million tons of fly ash (Alden, 2003). If this suitable substitute is used properly for concrete, then it can have significant environmental benefits in both reducing the production of cement which has a high environmental cost, and relatively reduce CO_2 emissions, and in addition recycling the coal power plants byproducts.

2.8 Economy

Most of the electricity consumed in the United State is generated in coal power stations. Although the numbers of nuclear power plants are increasing quickly, coal power plants are going to stay the number one source of electricity in America. A study conducted by the American Coal Ash Association (DATE) showed a steady increase in the demand of coal combustion products such as fly ash, bottom ash, boiler slag, and flue gas desulphurization. Between the various types of coal combustion products, fly ash has highest price value and demand. However, the utilization growth of fly ash is not as fast as the production rate of fly ash (Ward, 2004). Thus, a significant amount of fly ash is disposed of each year without being use properly. Figure 2.6 shows the gap between the production and use of coal combustion products (ACAA, date).



SOURCE: American Coal Ash Association

Figure 2.6 CCP production and use

Currently, less than 35% of all fly ash produced is recycled to be used in Portland cement concrete or for soil stabilization. The other portion, roughly 42 million tons, is disposed of in landfills. This amount of fly ash is approximately equal to 80% of the cement produced in a country. By using the disposed fly ash, four-lane highway, with 600 lb/yd3 binder could be built round the whole perimeter of the United States.

By comparing the expensive and energetic process of producing Portland cement, with the enormous amount of available land fill fly ash, this will demonstrate the economical benefits of using fly ash in concrete. Replacing fifty percent of cement with fly ash can reduce the cost of concrete up to 25 percent.

Chapter 3

Testing Program

3.1 Introduction

The laboratory-testing program was implemented to achieve five objectives: (1) to investigate the strength variation of fly ash concrete due to variation of fly ash portions, (2) to identify the affect of grinding and grinding duration of fly ash on the strength of the concrete, (3) to explore the affect of changes of mixture properties such as w/c ratio and binder content on the mixtures with ground and un-ground fly ash, (2) to monitor the changes in performance of the concrete by changing fly ash source in respect to changes of parameters mentioned before ; and (5) to evaluate and define the material properties of the most promising materials. Besides the compressive test, a split tensile test was performed to monitor the changes in the tensile strength of the concrete. The slump test and air content were other standard tests that were performed to verify the workability and performance of fresh concrete. Table 3. 1 lists the tests with the corresponding ASTM standard designations.

Table 3. 1 Primary Objective Tests to be Performed

Primary Objective	
TEST	**ASTM Number**
Compressive Strength	C39
Splitting Tensile	C496
Slump	C143
Temperature	C138
Unit Weight	C1064
Air Content	C231

3.2 Mixture Design Matrix

The main objective of this research is to define the changes in properties of fresh and hardened concrete due to different proportions of ground fly ash used in concrete. Two grinding durations, 30 and 120 minutes, were selected base on primary testing as a bench mark to monitor the changes of concrete properties due to varying the grinding duration. Studying the changes in concrete properties due to changes of fly ash content was the other target of this research. Thus, 20, 40 and in some cases 60 percent of Portland cement were replaced with fly ash. These values were selected to cover the samples with broad range of fly ash content. The samples were compared in respect to different fly ash content and grinding duration to detect the change of concrete properties when altering these parameters. To simplify the comparison between the samples concrete with 100% Portland cement was used as a base line. This base line provides an easy method to follow the strength gain of the samples and determine its difference with the strength of traditional Portland cement concrete. Table 3. 2 illustrates the matrix used for each mixture design.

Table 3. 2 Mixture Design Matrix

Percent Replacement	Grinding Time (min)		
0*	**0**		
20	**0**	**30**	**120**
40	**0**	**30**	**120**
60	**0**	**30**	**120**

---

* PCC or 100% Portland cement concrete

Six type of fly ash that were locally available and widely used by the Oklahoma Department of Transportation (ODOT) were tested in this research. These fly ashes were collected from different DeLose® batch plant in 50 gallons drums and stored in an enclosed and dry environment prior to consumption. The types of fly ash used in this research are listed below.

Red Rock fly ash
Oologah fly ash
Muskogee fly ash
Boral fly ash
Amarillo fly ash
Pampa fly ash

Concrete properties are sensitive to several parameters such as *w/c* ratio and binder content. The behavior of concrete in both fresh and hardened stages may change significantly by varying any of these parameters. It should be noted that fly ash is a cementitious material that reacts with lime and contributes in the hydration process of concrete. It should be expect that changes of binder content and *w/c* ratio would have the same affect on fly ash concrete regardless of the fly ash content or grinding duration of the fly ash. To investigate this hypothesis three mix designs with various *w/c* ratio and binder content were selected. The specific properties of each mix design are provided in detail in the next section.

3.3 Base Mix Design

Two mix designs commonly used by ODOT with constant *w/c* ratio but different binder content were selected. The proportioning of these two mix designs, ODOT-4000 and ODOT-7000, are provided in Table 3.3 and Table 3. 4. The third mix was adopted from the ODOT-4000 by changing the *w/c* ratio from 0.35 to 0.39 and keeping the binder content constant, that enables the researcher to monitor the properties of the concrete use to only changes of *w/c* ratio. The proportioning of this mix design is shown in Table 3.5. These mix design are respectively name mix-A, B, and C in this document.

Table 3.3 The ODOT Concrete Mix Design (Mix-A).

Material	**Weight**
Cementations Materials	600.0 lb/yd^3
Sand	1543.3 lb/yd^3
Stone	1772.6 lb/yd^3
HRWR	50 oz.
w/c	0.35

Table 3. 4 The ODOT Concrete Mix Design (Mix-B).

Material	**Weight**
Cementations Materials	850 lb/yd^3
Sand	1052 lb/yd^3
Stone	1690 lb/yd^3
HRWR	50 oz.
w/c	0.35

Table 3.5 Modified Concrete Mix Design (Mix-C)

Material	Weight
Cementations Materials	600 lb/yd^3
Sand	1475 lb/yd^3
Stone	1772 lb/yd^3
HRWR	50 oz.
w/c	0.39

The constituent materials used consist of:

Portland Cement (ASTM Type I) (From Holcim Midlothian, TX)

Dover River Sand (From Dover, OK)

#67 gravel (From Richards Spurs, OK)

Tap Water

WRA (ADVA 500) (From W.R. Grace)

Fly Ash (AASHTO Class C) (as listed before)

To determine the effect of each individual parameter on the final strength of the concrete it was essential to keep all the other parameters such as water content and dosage of superplastisizer constant for all the mixtures through out the research. Changes in workability and slump were expected.

3.4 Instrumentation and Test Procedures

3.4.1 Slump

The slump test is the simplest and most common test used to determine the workability. This test can be performed in the site or the laboratory. The slump cone is filled with 3 layers of fresh concrete, each layer tamped with the proper rod 20 times to remove voids, and the concrete is leveled off to the top of the cone after the third layer.

On removing the cone, the slump is measured. The test was performed in accordance with ASTM C 143 (ASTM 1995).

3.4.2 Temperature

Temperature significantly affects the rate of the chemical reaction in fresh concrete. A different rate of chemical reaction also would mean a different rate of hydration of cement in the fresh mix. Concrete temperature is important since this research is investigating the physical properties of concrete during early age. It is essential to measure the temperature of the freshly mixed concrete in order to keep this constant and under control. The temperature of the water used in batching was adjusted to keep the initial batch temperature within a small range. The test was performed in accordance with ASTM C 138 (ASTM 1995).

3.4.3 Unit Weight

This test determines the density of freshly mixed concrete in pound per cubic foot (pcf). This is to ensure the quality of the design mix. The measured unit weight was checked against the theoretical unit weight. The test was performed per ASTM C 138 (ASTM 1995).

The formula for calculating unit weight is as below:

$$\gamma_{concrete} = \frac{W_{concrete}}{V_{measure}}$$

where: $\gamma_{concrete}$ = unit weight of concrete (lb/ ft^3)

$W_{concrete}$ = net weight of concrete (lb)

$V_{measure}$ = volume of measure (ft^3)

3.4.4 Air Content

This test measures the amount of air unintentionally entrapped in the concrete mix during the mixing process. A properly batched mix usually consists of approximately two percent of entrapped air content. The air content of fresh concrete is measured based on the pressure-to-volume relationship of Boyles Law. Pressure is applied to the sample to compress the entrained air in the pores. This test was performed in accordance with ASTM C 231 (ASTM 1995).

3.4.5 Compressive Strength test

Fresh concrete was cast in cylinder molds with 4 inch diameters and 8 inches of height. They were then cured in the environmental chamber where the temperature and humidity were kept at 73.4 ºF and 50% respectively. The cylinders were de-molded after 24 hours and tested for compressive strength at 1, 7, 14, 28 and 56 days. The compressive strength is often regarded as the direct measurement of the general quality of concrete. The cylindrical samples were placed in a hydraulic loading machine and loaded to failure. The ultimate loads were recorded by the built-in data acquisition system. The compressive stresses were calculated by dividing the ultimate load by the horizontal cross-sectional area, 12.56 in^2, of the specimen. The test was performed in accordance with ASTM C39 (ASTM 1995).

3.4.6 Splitting Tensile Test

This ASTM test method determines of tensile strength of cylindrical concrete specimens. A compressive force is applied along the length of a cylindrical specimen. This loading induces tensile stresses on the plane containing the applied load. Tensile failure occurs rather than compressive failure. Plywood strips were used so that the load was applied uniformly along the length of the cylinder. The maximum load was divided by longitudinal cross-section area of the cylindrical specimen to obtain the splitting tensile strength. The test was performed in accordance with ASTM C496 (ASTM 1995).

The splitting tensile strength is calculated by the empirical formula as below:

$$T = \frac{2 \times P}{\pi \times L \times D}$$

Where

T = Splitting tensile strength (psi)

P = Ultimate load applied (lb)

L = Specimen Length (in)

D = Diameter (in)

3.5 Grinding System

Fly ash contains small particles that are collected from the exhaust of coal power plants. Fly ash particles are hot when they are collected, while fly ash is cooling, the small particles tend to adhere to the surface of larger particles. A study of electro microscopic images of ground and un-ground fly ash (Ramseyer and Beth) at the

University of Oklahoma shows that the grinding of fly ash can change the topography of the fly ash particles by removing the small particles adhering to the surface. Figure 3.1 illustrates the fly ash particles before and after grinding.

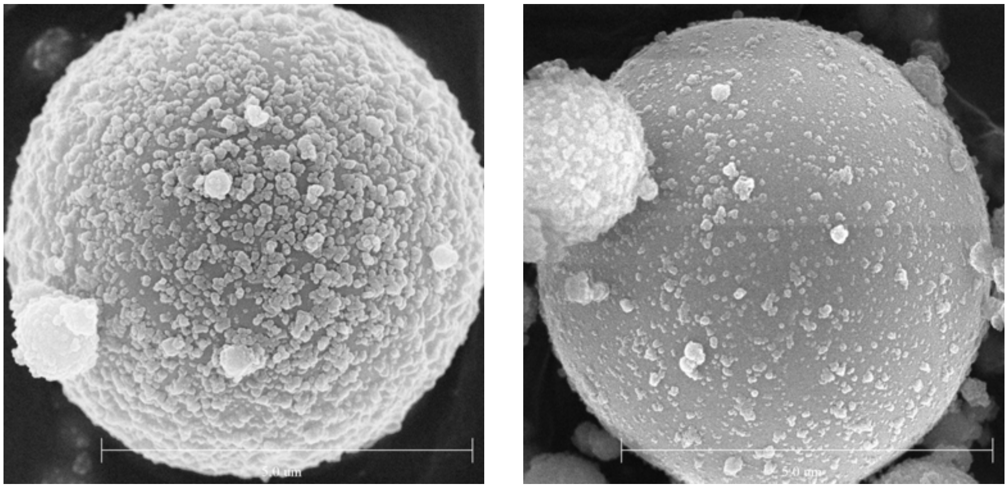


Figure 3.1 Fly ash particles before and after grinding

Cleaning the fly ash topography by removing the small particles creates a larger available reaction surface area overall. Higher reaction surface area is an important factor to shortening the setting and curing time of concrete. The size distribution and chemistry of the fly ash particles depends on the type of coal and method of operation of the power plants. Using a fly ash with a smaller size distribution increases the reaction surface area, which theoretically would improve the curing and setting time. However, studies conducted by Beth Brueggen show that grinding the fly ash does not change the size distribution of fly ash particles significantly. This supports the hypothesis that grinding the fly ash improves the reaction surface of the fly ash and does not crush the particles into finer irregular particles. **Error! Reference source not found.** illustrates the size distribution of fly ash particles before and after grinding.

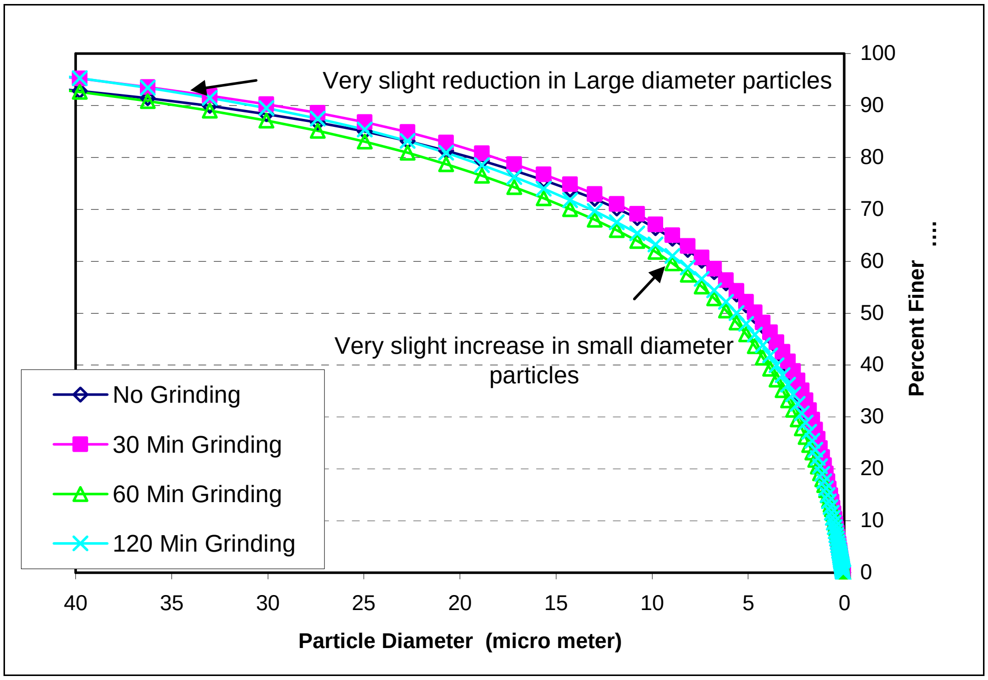


Figure 3.2 Changes of fly ash size distribution due to grinding.

The grinder used in this study was a cylindrical steel ball mill with the diameter and depth of sixteen inches. The ball mill spun around a horizontal axis. The revolution rate, weight of balls, and fly ash load for each grinding time was arbitrarily selected and kept constant throughout the entire study.

Three paddles were added inside the mill to provide better lifting and dropping. The speed of the drum was reduced from 50 rpm to 38 rpm to ensure a cascading motion. Figure 3.3 shows the motion of the balls in the grinding system. The ball mill was filled with 20 pound of fly ash and 175 pounds of steel balls with various sizes during each grinding period. Twenty milliliters of Propylene Glycol grinding agent were added to avoid any caking and clumping of the fly ash together. This grinding agent is commonly used in cement production plants during grinding of the clinker to prevent adhering the small particle to the bigger particles.

Figure 3.3 Balls motion in the grinding system

3.6 Laboratory Batching and Curing Procedures

All concrete testing was conducted at Fears Structural Engineering Laboratory at the University of Oklahoma and followed ASTM C 192, "Standard Practice for Making Curing Concrete Test Specimens in the Laboratory." The concrete mixer used in the testing was a Stone® 6 cubic foot, electric drum mixer.

To reduce any uncertainties in the water binder ratio in the samples, the aggregates were weighed and stored in 5 gal buckets with sealed lids one night prior to batching. Representative samples of sand and rock were collected and placed in the oven with a controlled temperature of 110 ºC for over six hours to determine the moisture content of the aggregates. The moisture present in the aggregates was deducted from the water required while batching.

After appropriate mixing, the slump test and air content test were performed on the fresh concrete. Concrete cylinders were cast and placed in the controlled environmental chamber maintained at 73.4° F and 50% relative humidity.

Chapter 4

Results

4.1 Fresh Concrete

For the fly ash quantities tested, the addition of fly ash has a great effect on the workability of the concrete mixture. The trend is for workability to increase significantly with the increase of the fly ash portion. Ground fly ash in most cases slightly decreases the slump. However, experience shows that the fresh concrete with ground fly ash has the same workability as that of with un-ground fly ash.

Fly ash is a powdery material and it remains in a powdery state after grinding. Grinding did not cause caking or clumping in any of the fly ash tested in this research. Each mix was tested visually for a possible sign of clumping of the fly ash particles to each other or to cement particles. No evidence of incomplete mix of fly ash with the other of components of the concrete was noted so, no special mixing method or admixture are needed to facilitate the mixing procedure.

The addition of fly ash does not seem to change the entrapped air content substantially. The results of this research did not show any particular trend in entrapped air content of the concrete due to changes of fly ash content or the grinding duration.

4.1.1 Mix-A Fresh Concrete Properties

The results of slump, air content and unit weight on Mix-A are provided in Table 4.1 and Table 4.2.

Table 4.1 Fresh concrete properties

Mix #	Fly Ash Source	Mix Designation		Slump (in)	Air Content (%)	Unit Weight (lb/ft^3)
		Fly Ash (%)	Grinding Time (Min)			
1	**N/A**	100% Portland Cement		0	1	152.8
2	**Red Rock Fly Ash**	**20**	**0**	1.75	2.4	152.88
3			**30**	0.5	3.4	151.44
4			**120**	0.75	2.7	153.44
5		**40**	**0**	3.25	2	152.64
6			**30**	4.25	3.4	151.16
7			**120**	2.5	3.1	152.00
8		**60**	**0**	5	3	151.24
9			**30**	4	3.5	150.72
10			**120**	2.5	2.5	151.68
16	**Oologah Fly Ash**	**20**	**0**	0.75	3.2	152.04
17			**30**	0.5	3.2	154.00
18			**120**	0.5	2.9	154.12
19		**40**	**0**	2.25	3.10	151.96
20			**30**	3.75	2.5	151.4
21			**120**	3	2	153.88
22		**60**	**0**	2.75	2.9	152.00
23			**30**	2	2.1	153.64
24			**120**	2	2.5	153.12
30	**Muskogee Fly Ash**	**20**	**0**	0.25	2.5	153.48
31			**30**	0.25	4	149.56
32			**120**	0.25	3.5	154.96
33		**40**	**0**	2.75	2.6	151.80
34			**30**	2	1.5	153.76
35			**120**	2.5	1.5	153.44
36		**60**	**0**	4	0.6	150.68
37			**30**	3	1.4	150.36
38			**120**	4.75	3	150.04

Table 4. 2 Fresh concrete properties (continue)

Mix #	**Fly Ash Source**	**Mix Designation**		**Slump (in)**	**Air Content (%)**	**Unit Weight (lb/ft^3)**
		Fly Ash (%)	**Grinding Time (Min)**			
45	**Boral Fly Ash**	20	0	0.25	N/A	153.24
46			30	1.25	2	152.76
47			120	0.5	2.9	152.24
48		40	0	2.25	2.3	151.04
49			30	1.5	2.8	152.48
50			120	1.5	3.2	153.56
51		60	0	2.5	N/A	152.32
52			30	2.75	2.9	151.8
53			120	2.5	3.0	152.2
60	**Amarillo Fly Ash**	20	0	0.25	N/A	152.76
61			30	0.5	1.3	154.68
62			120	0.5	3	152.84
63		40	0	1.75	1.3	153.6
64			30	1.5	2.5	153.32
65			120	1	1.3	154.48
66		60	0	3.5	3.5	151.68
67			30	4	2.5	151.64
68			120	2.75	2.5	153.16
75	**Pampa Fly Ash**	20	0	1.75	N/A	N/A
76			30	0.5	2.2	154.00
77			120	0.5	2.1	154.20
78		40	0	0.75	2.7	153.88
79			30	1	2.7	152.84
80			120	1	2.3	153.08
81		60	0	3.25	N/A	153.20
82			30	1.75	3.5	153.12
83			120	1.5	3.1	151.60

4.1.2 Mix-B Fresh Concrete Properties

Table 4.3 shows the results of the testing on a Mix-B fresh concrete.

Table 4.3 Fresh concrete properties of Mix-B

Mix #	Fly Ash Source	Mix Designation		Slump (in)	Air Content (%)	Unit Weight (lb/ft^3)
		Fly Ash (%)	Grinding Time (Min)			
B-1	**Red Rock**	100% Portland Cement		1.5	2.2	153.24
B-2		**20**	0	4.4	1.5	152.53
B-3			30	3	1.5	152.71
B-4			120	1	1.3	152.44
B-5		**40**	0	6	1.2	153.38
B-6			30	2.25	1.8	152.82
B-7			120	1	2.3	152.79
B-8		**60**	0	5.5	2	153.42
B-9			30	N/A	N/A	N/A
B-10			120	1.25	2.2	152.18

4.1.3 Mix-C Fresh Concrete Properties

The results of testing of a Mix-C fresh concrete is provided in Table 4.4.

Table 4.4 Fresh concrete properties of Mix-C

Mix #	**Fly Ash Source**	**Mix Designation**		**Slump (in)**	**Air Content (%)**	**Unit Weight (lb/ft^3)**
		Fly Ash (%)	**Grinding Time (Min)**			
C-1	**Red Rock**	100% Portland Cement		1.75	1.9	152.44
C-2		**20**	0	2	1.4	152.31
C-3			30	1.5	2.1	152.18
C-4			120	1.5	2.1	153.06
C-5		**40**	0	3.25	2.8	152.53
C-6			30	2	3.2	152.87
C-7			120	2.5	2.8	153.13
C-8		**60**	0	4	3.1	152.79
C-9			30	3.25	3.5	153.53
C-10			120	3.5	2.1	152.33

4.2 Compressive Strength

The results of the compressive strength are presented in this section. It should note that the grinding and its duration have different affect on compressive strength of samples with vary fly ash. These changes will be discussed in detail separately in chapter 5.

4.2.1 Mix-A Compressive Strength

The compressive strength of the Mix-A is provided in Table 4.5 and Table 4.6.

Table 4.5 Compressive strength of Mix-A. *(All units are in psi)*

Mix #	**Fly Ash Source**	**Mix Designation**		**Age at Testing**				
		Fly Ash (%)	**Grinding Time (Min)**	**1-day**	**7-day**	**14-day**	**28-day**	**56-day**
1	**N/A**	100% Portland Cement		3400	6040	6280	6500	6860
2	**Red Rock Fly Ash**	**20**	**0**	2480	5640	6010	6200	6820
3			**30**	2540	5800	6190	6760	7050
4			**120**	2580	6420	6820	7350	7660
5		**40**	**0**	1460	5350	6070	6500	6880
6			**30**	1350	5320	5970	5830	6740
7			**120**	1310	6080	6860	7330	7610
8		**60**	**0**	180	1850	2310	2370	2330
9			**30**	90	3520	5120	5550	6020
10			**120**	160	4560	6340	7010	6978
16	**Oologah Fly Ash**	**20**	**0**	3020	6060	6780	7340	7320
17			**30**	2830	6160	6890	7310	7390
18			**120**	2720	5900	6820	7150	7410
19		**40**	**0**	2250	5820	6260	6720	6930
20			**30**	1870	5680	6620	6900	6890
21			**120**	1880	5640	6640	6940	6890
22		**60**	**0**	530	4350	5130	5610	5720
23			**30**	220	4320	5110	5720	5570
24			**120**	130	3580	4650	5030	4990

Table 4.6 Compressive strength of Mix-A (continue). (All units are in psi)

Mix #	Fly Ash Source	Mix Designation		Age at Testing				
		Fly Ash (%)	Grinding Time (Min)	1-day	7-day	14-day	28-day	56-day
30	Muskogee Fly Ash	20	0	3650	6712	6985	7217	7597
31			30	3330	6348	6779	7393	7514
32			120	3390	6068	6686	7219	7382
33		40	0	1550	5195	5947	6341	6623
34			30	1850	5752	6361	7179	7287
35			120	1520	5507	5895	6320	6279
36		60	0	5502	4257	4869	4924	5248
37			30	359	4193	4976	5126	5307
38			120	240	4105	4807	4821	5473
45	Boral Fly Ash	20	0	3238	6413	7068	7668	7628
46			30	2746	6203	6799	6688	7126
47			120	3320	6546	7305	7648	7968
48		40	0	2250	6284	7213	7077	7401
49			30	2420	6475	7213	7538	7845
50			120	2210	6429	6999	7540	7714
51		60	0	2510	5859	6523	7259	7362
52			30	2227	5726	6485	6979	7127
53			120	1880	5405	6111	6400	6928
60	Amarillo Fly Ash	20	0	3834	6854	7800	7726	7688
61			30	3478	6986	7361	7621	7873
62			120	3651	7133	7662	7864	8264
63		40	0	2767	7136	7824	8062	8417
64			30	2444	7357	8337	8507	8677
65			120	2520	8679	8654	9180	9706
66		60	0	1654	4136	5800	6120	6240
67			30	1705	4264	5673	6530	6620
68			120	1765	4412	6514	6600	6830

4.2.2 Mix-B Compressive Strength

The results of compressive strength of the Mix-B samples are presented in detail in Table 4.7.

Table 4.7 Compressive strength of Mix-B. *(All units are in psi)*

Mix #	**Fly Ash Source**	**Mix Designation**		**Age at Testing**			
		Fly Ash (%)	**Grinding Time (Min)**	**7-day**	**14-day**	**28-day**	**56-day**
B-1	**Red Rock**	100% Portland Cement		6810	6830	7120	7480
B-2		**20**	**0**	6400	6780	6930	7110
B-3			**30**	6500	6950	7240	7460
B-4			**120**	6890	7080	7670	7670
B-5		**40**	**0**	5020	5480	5610	6030
B-6			**30**	6450	7150	7280	7520
B-7			**120**	6700	7220	7330	7710
B-8		**60**	**0**	3740	4260	4250	4270
B-9			**30**	N/A	N/A	N/A	N/A
B-10			**120**	5410	7120	7110	7570

4.2.3 Mix-C Compressive Strength

Table 4.8 presents the results of compressive strength of Mix-C fly ash concrete.

Table 4.8 Compressive strength of Mix-C *(All units are in psi)*

Mix #	**Fly Ash Source**	**Mix Designation**		**Age at Testing**			
		Fly Ash (%)	**Grinding Time (Min)**	**7-day**	**14-day**	**28-day**	**56-day**
C-1	**Red Rock**	100% Portland Cement		5410	6210	6540	6750
C-2		**20**	**0**	5240	5400	5690	6290
C-3			**30**	6480	6790	7430	7470
C-4			**120**	5310	5500	5850	5960
C-5		**40**	**0**	4620	4880	5550	5860
C-6			**30**	5770	6390	6620	6440
C-7			**120**	5290	6200	6320	6180
C-8		**60**	**0**	4090	4230	4440	4460
C-9			**30**	4000	4100	5270	5200
C-10			**120**	4070	4820	5220	5000

4.3 Splitting Tensile Strength

The results of this research shown no specific trend in the splitting tensile strength of the samples when fly ash content of grinding duration changes. However it should be noted that the samples with higher compressive strength have generally higher splitting tensile strength. The results of splitting tensile strength are provided in next section.

4.3.1 Mix-A Splitting Tensile Strength

The splitting tensile strength of the Mix-A is presented in Table 4.9 and Table 4.10.

Table 4.9 Split tensile strength of Mix-A. *(All units are in psi)*

Mix #	**Fly Ash Source**	**Mix Designation**		**Age at Testing**
		Fly Ash (%)	**Grinding Time (Min)**	**28-day**
1	**N/A**	**Portland Cement Concrete**		545
2	**Red Rock Fly Ash**	**20**	**0**	360
3			**30**	425
4			**120**	408
5		**40**	**0**	392
6			**30**	304
7			**120**	385
8		**60**	**0**	263
9			**30**	393
10			**120**	455
16	**Oloagha Fly Ash**	**20**	**0**	524
17			**30**	527
18			**120**	452
19		**40**	**0**	508
20			**30**	530
21			**120**	562
22		**60**	**0**	415
23			**30**	430
24			**120**	315
30	**Muskogee Fly Ash**	**20**	**0**	647
31			**30**	547
32			**120**	581
33		**40**	**0**	526
34			**30**	467
35			**120**	524
36		**60**	**0**	408
37			**30**	393
38			**120**	317

Table 4.10 Split tensile strength of Mix-A (continue). *(All units are in psi)*

Mix #	**Fly Ash Source**	**Mix Designation**		**Age at Testing**
		Fly Ash (%)	**Grinding Time (Min)**	**28-day**
45	**Boral Fly Ash**	**20**	**0**	572
46			**30**	473
47			**120**	480
48		**40**	**0**	469
49			**30**	465
50			**120**	433
51		**60**	**0**	422
52			**30**	455
53			**120**	430
60	**Amarillo Fly Ash**	**20**	**0**	575
61			**30**	491
62			**120**	512
63		**40**	**0**	496
64			**30**	471
65			**120**	521
66		**60**	**0**	N/A
67			**30**	N/A
68			**120**	N/A
75	**Pampa Fly Ash**	**20**	**0**	N/A
76			**30**	N/A
77			**120**	N/A
78		**40**	**0**	N/A
79			**30**	N/A
80			**120**	N/A
81		**60**	**0**	N/A
82			**30**	N/A
83			**120**	N/A

4.3.2 Mix-B Splitting Tensile Strength

The results of splitting tensile strength test of Mix-B are tabulated in Table 4.11

Table 4.11 Split tensile strength of Mix-B. *(All units are in psi)*

Mix #	**Fly Ash Source**	**Mix Designation**		**Age at Testing**
		Fly Ash (%)	**Grinding Time (Min)**	**28-day**
B-1	**Red Rock**	Portland Cement Concrete		540
B-2		**20**	**0**	420
B-3			**30**	340
B-4			**120**	490
B-5		**40**	**0**	430
B-6			**30**	390
B-7			**120**	520
B-8		**60**	**0**	430
B-9			**30**	N/A
B-10			**120**	490

4.3.3 Mix-C Splitting Tensile Strength

Table 4.12 shows the results of splitting tensile strength of the Mix-C samples.

Table 4.12 Split tensile strength of Mix-C. *(All units are in psi)*

Mix #	**Fly Ash Source**	**Mix Designation**		**Age at Testing**
		Fly Ash (%)	**Grinding Time (Min)**	**28-day**
C-1	**Red Rock**	Portland Cement Concrete		520
C-2		**20**	**0**	423
C-3			**30**	487
C-4			**120**	395
C-5		**40**	**0**	445
C-6			**30**	487
C-7			**120**	428
C-8		**60**	**0**	467
C-9			**30**	488
C-10			**120**	428

Chapter 5

Discussion of the Results

5.1 Introduction

The scope of this research is to investigate the effect of fly ash on the performance of the concrete, in its fresh and hardened state. In this chapter the results of the testing will be discussed separately for each three mix designs that were described in detail in section 3.3. The slump test and compressive strength of the samples are two major characteristic of the concrete that were significantly sensitive to the fly ash content and grinding duration of the fly ash used in the mix. Therefore, the slump and compressive strength of the each sample are compared with the other samples to illustrate the performance change of the concrete due to these parameters.

5.2 Fresh Concrete Test Results

Slump test performed on each sample following batching to determine workability of the fresh concrete. In this section the slump test results will be discussed after they been present in the bar chart format for each type of fly ash separately.

5.2.1 Mix-A Slump Test

Six types of fly ash were tested using Mix-A. Slump test results of each fly ash are presented separately in Figure 5.1 to Figure 5.5.

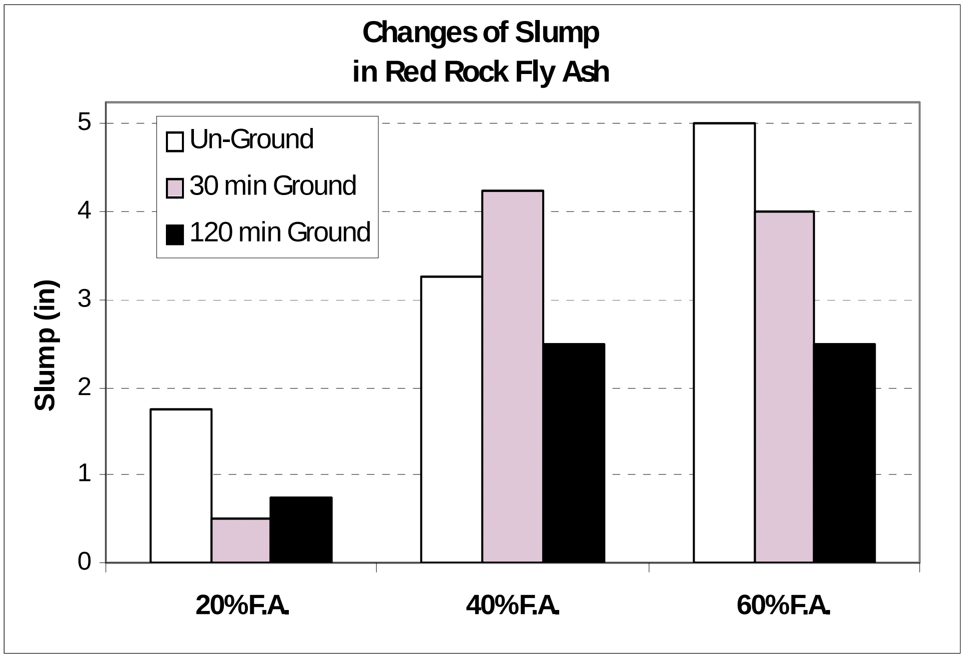


Figure 5.1 Changes of slump in Red Rock fly ash concrete due to changes of fly ash portion and grinding duration.

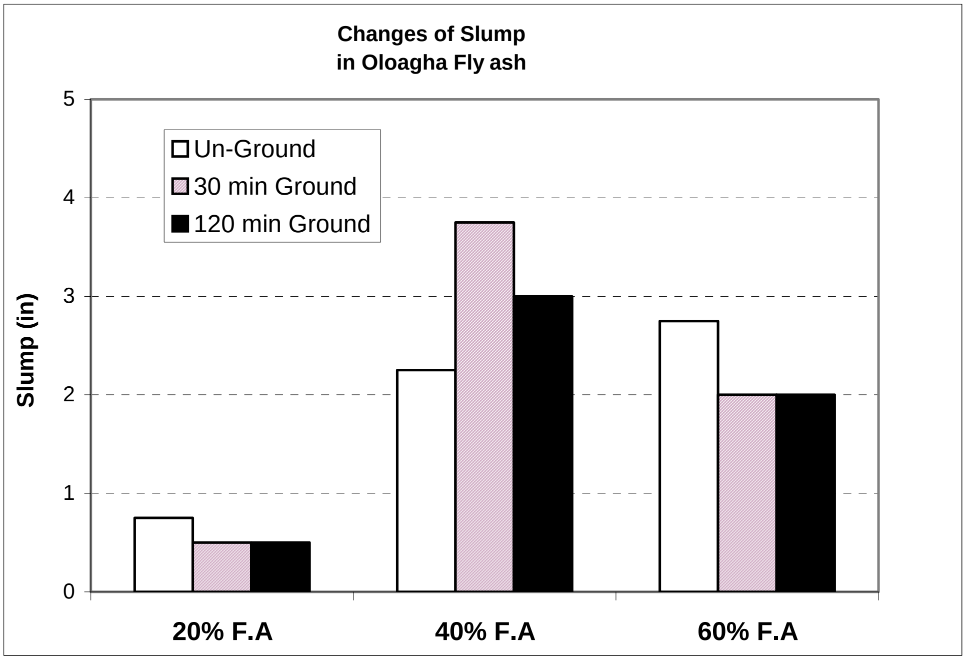


Figure 5.2 Changes of slump in Oloagha fly ash concrete due to changes of fly ash portion and grinding duration.

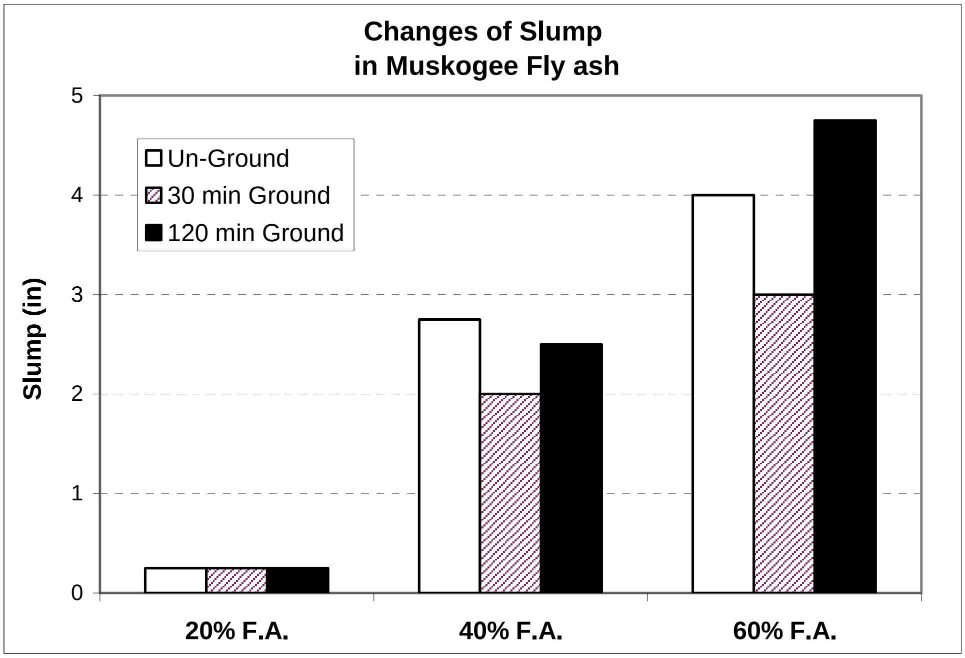


Figure 5.3 Changes of slump in Muskogee fly ash concrete due to changes of fly ash portion and grinding duration.

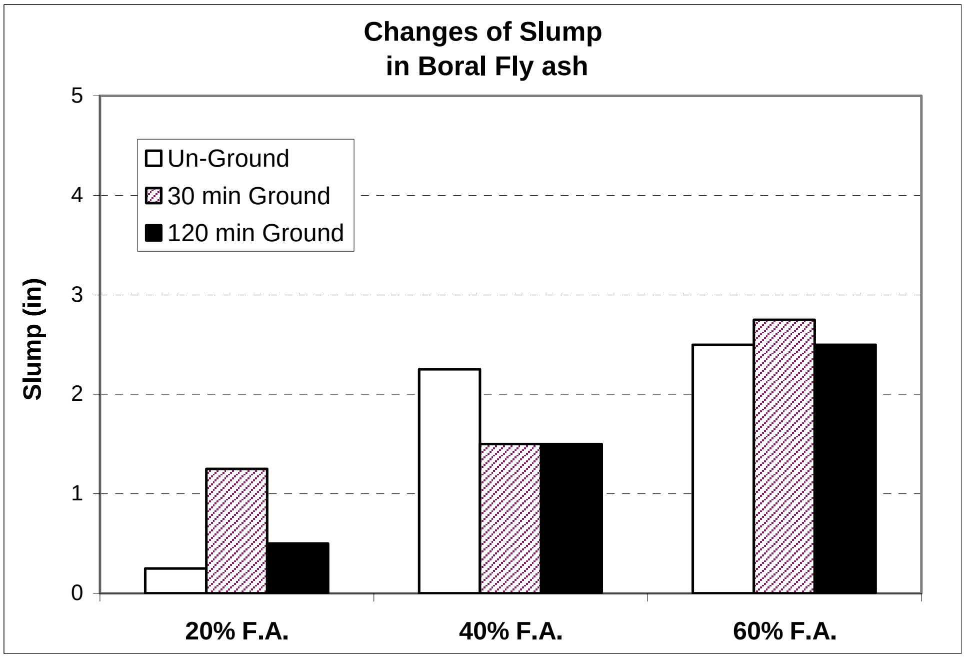


Figure 5.4 Changes of slump in Boral fly ash concrete due to changes of fly ash portion and grinding duration.

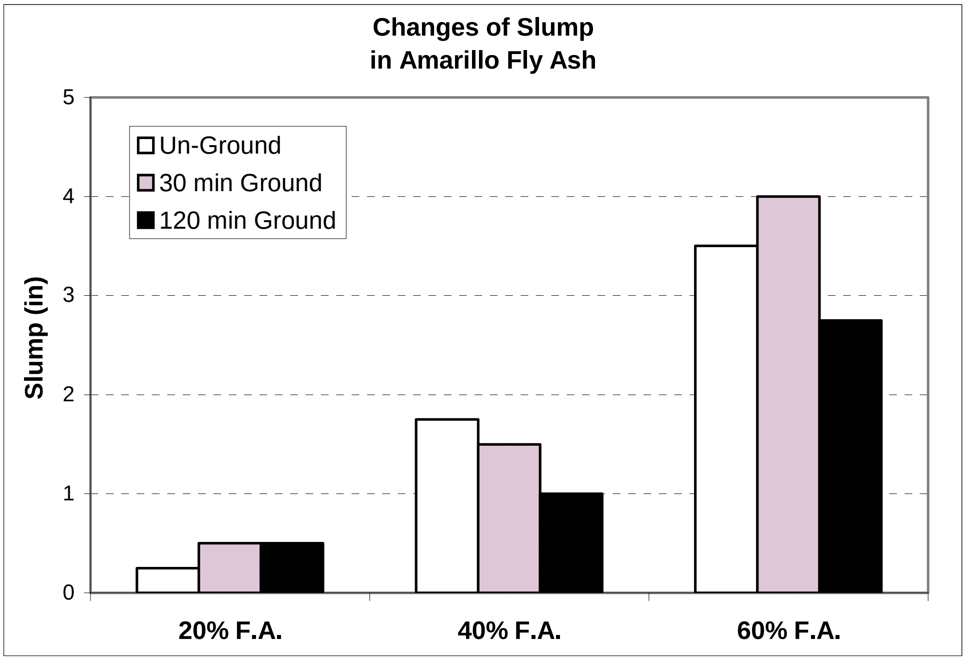


Figure 5.5 Changes of slump in Amarillo fly ash concrete due to changes of fly ash portion and grinding duration.

The slump test results show that the samples with higher unground fly ash content have higher slump there for have higher workability. This Slump increase is significantly large in cases such as Red Rock and Muskogee and relatively small in samples contain Boral fly ash.

In general, sample with higher ground fly ash content has higher workability. Workability of the concrete reduces only in samples containing 60% of Oloagha fly ash (see Figure 5.2). The sample containing 60% of 30 minutes Oloagha fly ash has 1.75 inches slump than samples contain 40% of the same fly ash, this reduction is one inch for 120 minutes ground fly ash.

Fly ash samples contain 30 minutes fly ash in most cases have the same or slightly lower workability that samples contain the same amount of unground fly ash; Muskogee, Boral and Amarillo. Grinding the fly ash for 120 minutes case slump reduction in all the cases but Muskogee fly ash as it illustrates in Figure 5.3.

5.2.2 Mix-B Slump Test

The slump results of the samples with Red Rock fly ash for Mix-B are provided in Figure 5.6. The slumps of the samples with this mix have almost the same behavior of slumps Mix-A slump. Higher portion of fly ash increases the workability and grinding the fly ash reduces the slump. It should be noted that Mix-B has higher binder content. Therefore, fly ash has higher effect on the slump properties of this mix than Mix-A.

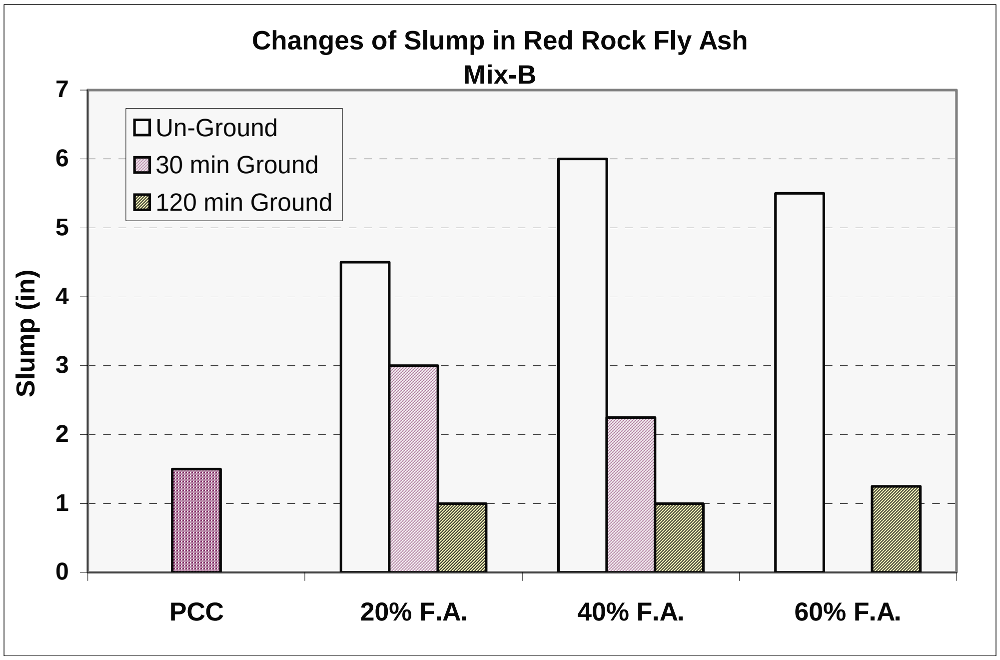


Figure 5.6 Changes of slump in Red Rock fly ash concrete due to changes of fly ash portion and grinding duration (Mix-B).

5.2.3 Mix-C Slump Test

The slump result of Figure 5.7 illustrates the slump test results of Mix-C incorporated with Red Rock fly ash. Mix-C has higher water content that Mix-A, 0.39.

Therefore, it was expected that the Mix-C samples have higher slump than the samples with Mix-A. Notice that the increase of fly ash content increases the slump, and grinding the fly ash reduces the slump slightly in all cases.

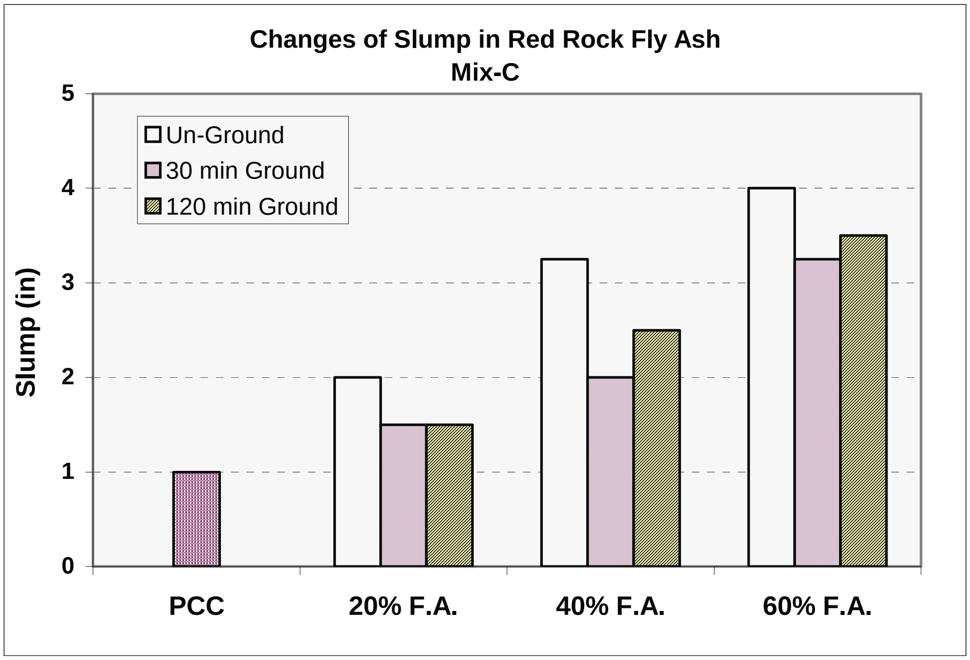


Figure 5.7 Changes of slump in Red Rock fly ash concrete due to changes of fly ash portion and grinding duration (Mix-C).

It should be noted that the parameters that influence on the concrete slump such as water content and amount of Superplastisizer were kept constant throughout the research. Temperature of the fresh concrete it the other factor that has an effect on the workability. The temperature of the fresh concretes was kept close to 85 ºF by adjusting the temperature of the water.

In general, samples with higher fly ash content have higher slump. The results of this study show that the samples tend to have lower slump if ground fly be used. Longer grinding duration cause greater slump lost in most cases.

Concrete slump is sensitive to both the amount of fly ash and the grinding duration of the fly ash. However, the results based on direct observation indicate that the samples with higher portion of fly ash have higher workability, even though the slump test indicates otherwise. The samples with 120 minutes ground fly ash are reported as highly workable although the slump test indicates a reduction of workability. This reduction can be the result of higher binder volume in the mixture because of the lower unit weight of the fly ash than concrete. More water would be required to coat the fly ash particles reducing the slump. However the spherical fly ash particles in the mix behave like ball bearings and help the workability of the mix in term of mixing, placing and finishing.

5.3 Hardened Concrete Test Results

Compressive strength of the fly ash concrete is governed by numbers of parameters such as type, grinding duration and portion of the fly ash used in concrete. In this section the compressive strength of the concrete samples will be discussed individually for each type of fly ash. The compressive strength of samples with the same fly ash will be compare together and with the samples with different type of fly ashes separately. The test results were presents in three different formats in this chapter to reduce the difficulties of the comparison between different charts, as follow:

1- Affect of un-ground fly ash on compressive strength of concrete.

2- Affect of grinding duration on samples with the same fly ash portion

3- Affect of changes of fly ash portion for the samples with the same fly ash.

5.3.1 Mix-A Compressive Strength

5.3.1.1 Effect of Unground Fly Ash on Compressive Strength

Fly ash has lower hydration reaction rate in comparison to traditional Portland cement. Slow reaction rate of fly ash particles results in the low compressive strength of fly ash concrete in early age, also the samples with higher fly ash content tend to have lower compressive strength. Fly ash reaction with lime, the by product of cement hydration, and water produces additional CSH in the mix. Therefore, it is expected that fly ash concrete have low compressive strength in early age and gain strength slowly as it ages.

Fly ashes from various sources have significantly different properties and performance while they use in concrete. However, strength reduction when fly ash is what most of the experts in concrete industry are agree on. Figure 5.8 to Figure 5.13 show the traditional affect of unground fly ash on the compressive strength of the concrete.

In these figures, PCC represents the traditional Portland Cement Concrete without incorporation of fly ash. The percentages stand for the portion of binder weight that has been replaced with fly ash, and ultimately the number followed by "Min-*G*", example: "*30 Min-G*", symbolize the grinding duration in minutes. Therefore, "*20% 30 Min-G*" represents the sample that 20 percents of the binder weight were replaced with 30 minutes ground fly ash.

Samples with higher portion of Red Rock fly ash have lower compressive strength at early age, see Figure 5.8, than Portland cement concrete. The results show that the strength of the samples with 20 and 40% of un-ground fly ash are similar to PCC after

28 days. However, the sample with 60% un-ground Red Rock fly ash strength curve has a plateau after 14 days without gaining any additional strength.

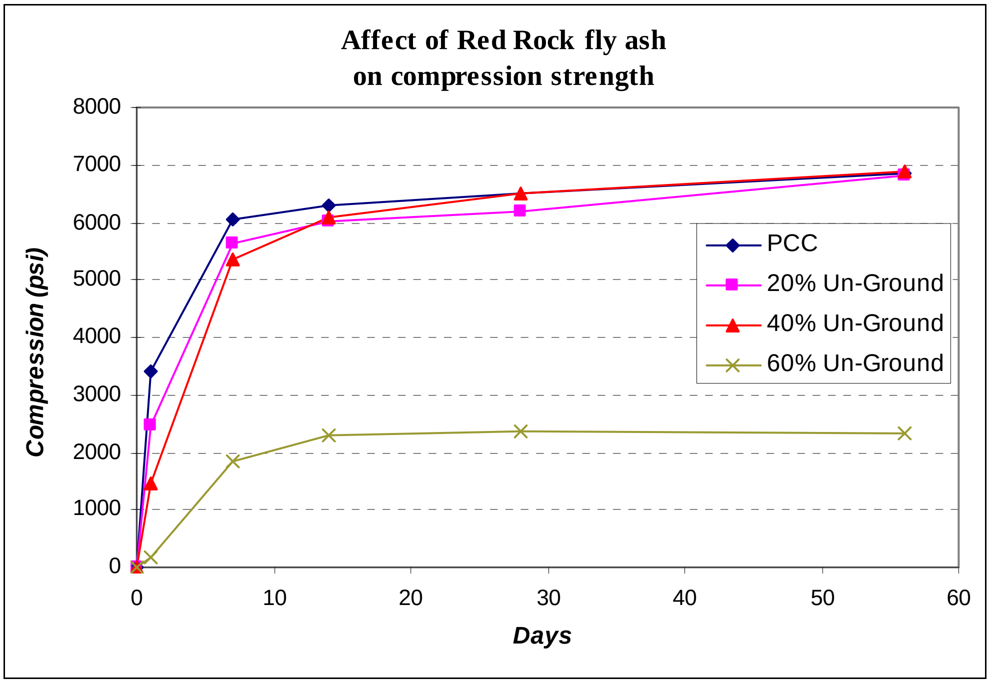


Figure 5.8 Effect of un-ground Red Rock fly ash on the compression strength of the concrete.

The sample with 20% of un-ground Oologah fly ash shows slightly lower strength in the first 14 days. However, its compressive strength reach PCC at 14 days and stays slightly above PCC after two weeks, see Figure 5.9. This study shows the samples with 40% of un-ground Oologah fly ash has almost the same compressive strength as PCC. The strength of the samples with 60% of un-ground fly ash is approximately 1000 psi below the strength of Portland cement concrete for the 56 days of research.

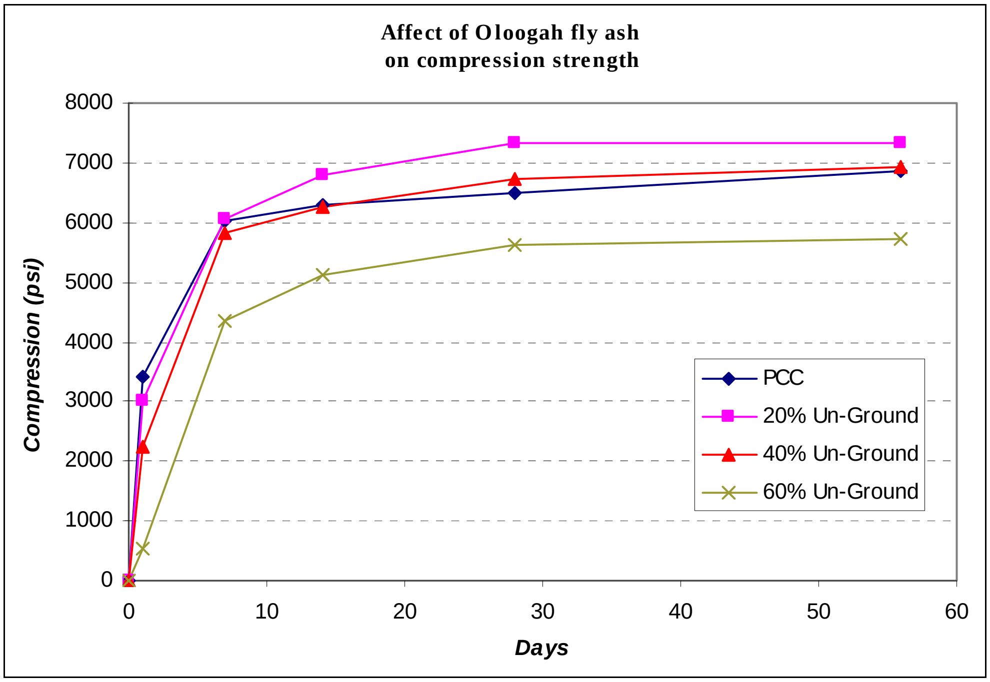


Figure 5.9 Effect of un-ground Oologah fly ash on the compression strength of the concrete.

The Muskogee and Oologah fly ash have identical affect on the strength of the concrete samples; compare Figure 5.9 and Figure 5.10. The sample with 20% of un-ground Muskogee fly ash has slightly higher strength than Portland cement concrete. However consumption of the samples with 40% of un-ground Muskogee fly ash in the mix does not cause significant changes in the strength of the concrete in comparison to Portland cement concrete, and the samples with 60% of un-ground fly ash have low strength.

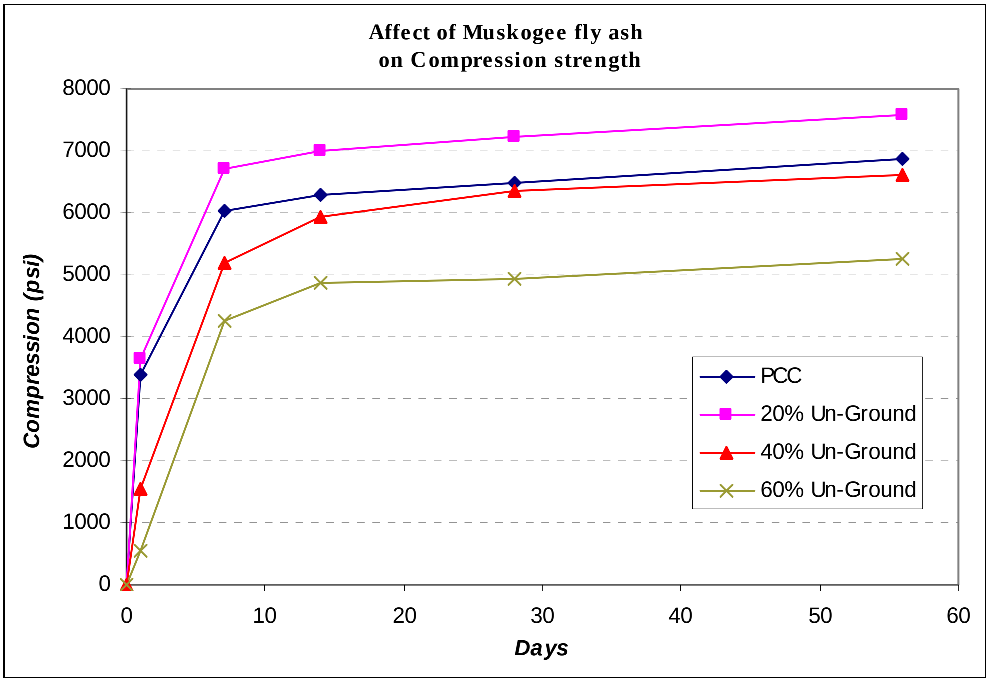


Figure 5.10 Effect of un-ground Muskogee fly ash on the compression strength of the concrete.

Sample with Boral, and Amarillo fly ash have the same performance of the strength of the concrete. The compressive strengths of these two fly ash concretes are illustrated in Figure 5.11 and Figure 5. 12. The samples with 20% and 40% of un-ground fly ash have significantly higher strength than Portland cement concrete at 14 days. The strength of the samples with 60% of un-ground Boral fly ash is tight with Portland cement concrete strength in early age, before 14 days, and will reach the strength of the samples with 20 and 40% of un-ground fly ash strength after 28 days.

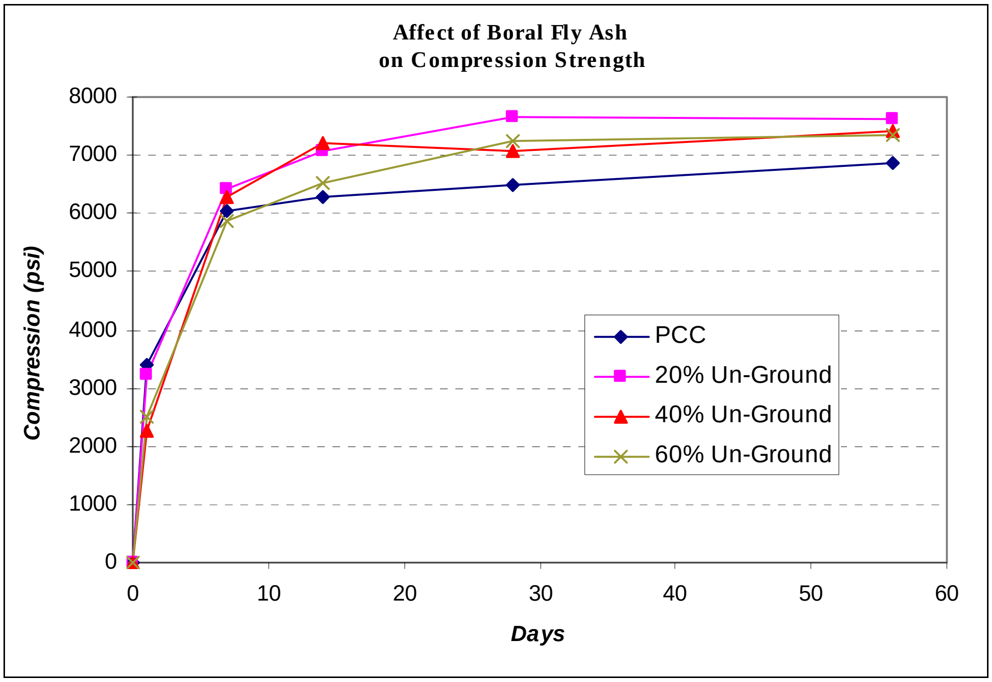


Figure 5.11 Effect of un-ground Boral fly ash on the compression strength of the concrete.

The study shows that the samples 20 and 40% of un-ground Amarillo fly ash have higher strength than PCC after seven days, see Figure 5. 12.

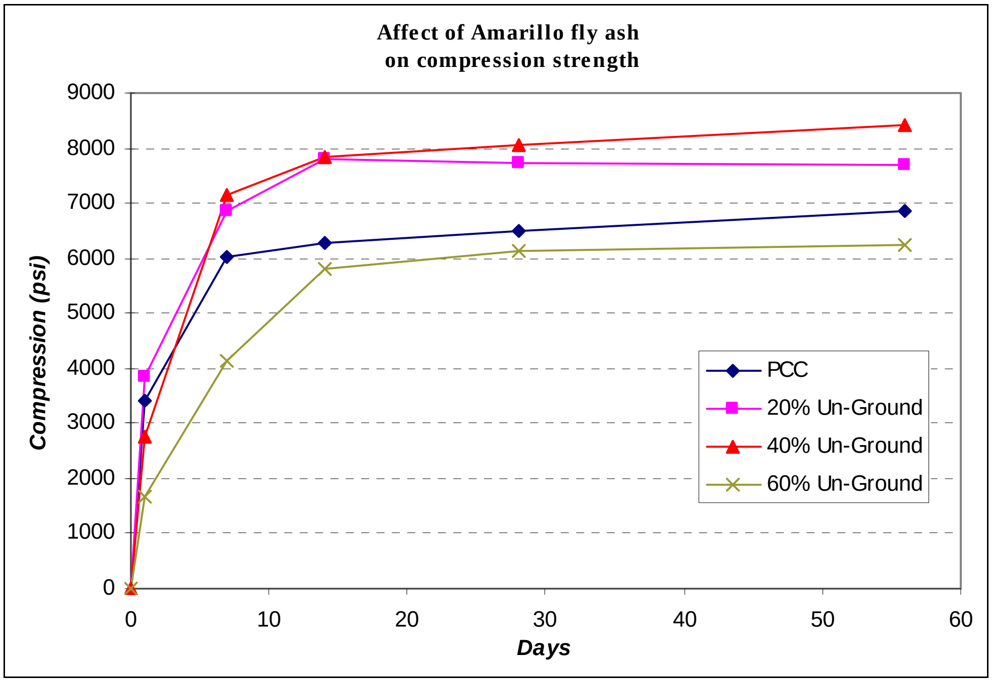


Figure 5. 12 Effect of un-ground Amarillo fly ash on the compression strength of the concrete.

Pampa fly ash is the most reactive fly ash tested in this research. The compressive strengths of the sample after one day reach 6000 psi and after seven days reach 7000 psi which is the ultimate strength of the PCC after 56 days. This study shows the samples with 40% unground fly ash have higher strength than the samples with 20% fly ash. However, additional fly ash in the mix doesn't provide additional strength and the samples with 60% fly ash have almost the same strength as 20% fly ash samples. It should be noted that the sample with 60% unground fly ash have almost 2000 psi strength higher than PCC after 28 days, see Figure 5.13.

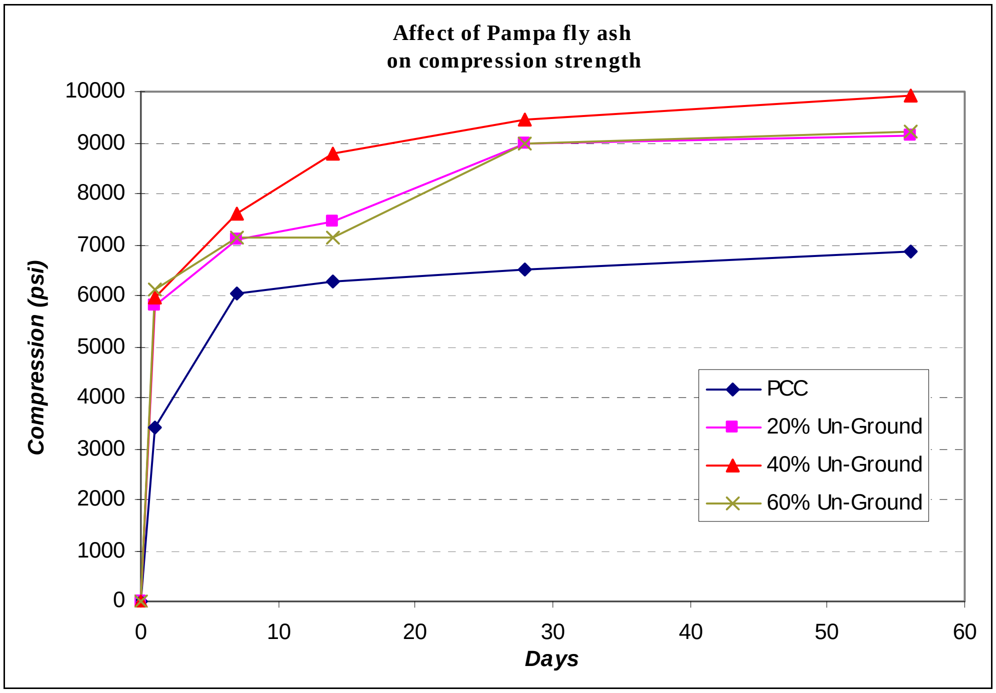


Figure 5.13 Effect of un-ground Pampa fly ash on the compression strength of the concrete.

5.3.1.2 Effect of Grounding the Fly Ash on Compressive Strength

Two grinding duration, 30 and 120 minutes, were selected to investigate the effect of grinding duration in compressive strength of concrete. The compression strength of samples with different grinding duration was compared with that of the samples with

100% Portland cement. In this chapter the results and changes of compression strength of fly ash samples in respect to grinding duration will be presented separately for each fly ash and portion of fly ash used in concrete.

- **Red Rock fly ash**

Figure 5.14 shows the compression strength of the samples with 20% Red Rock fly ash. The results of this study show that the samples with thirty minutes ground fly ash have almost the same strength than samples with un-ground fly ash and Portland cement concrete at 7 days and 56 days. However, at 28 days, samples with un-ground fly ash have slightly lower strength and samples with 30 minutes ground fly ash have slightly higher strength than PCC. Samples with 120 minutes ground fly ash show 700 psi higher strength than samples with unground samples after 7 days.

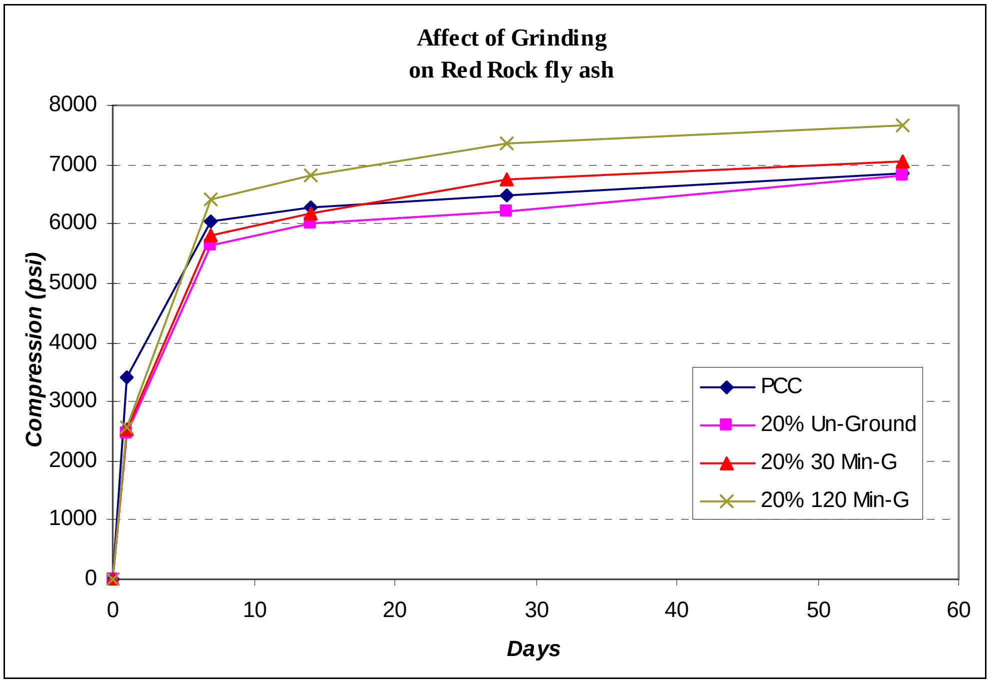


Figure 5.14 Effect of grinding duration on 20% Red Rock fly ash concrete

The Changes of compressive Strength for the samples with 40% Red Rock fly ash are illustrated in Figure 5.15. Thirty minutes grinding does not make significant changes in the strength of samples and the compression strength of the sample stay the same as the samples with 40% un-ground fly ash. However, the strength of the samples with 120 min ground fly ash is 700 psi greater than Portland cement concrete after seven days.

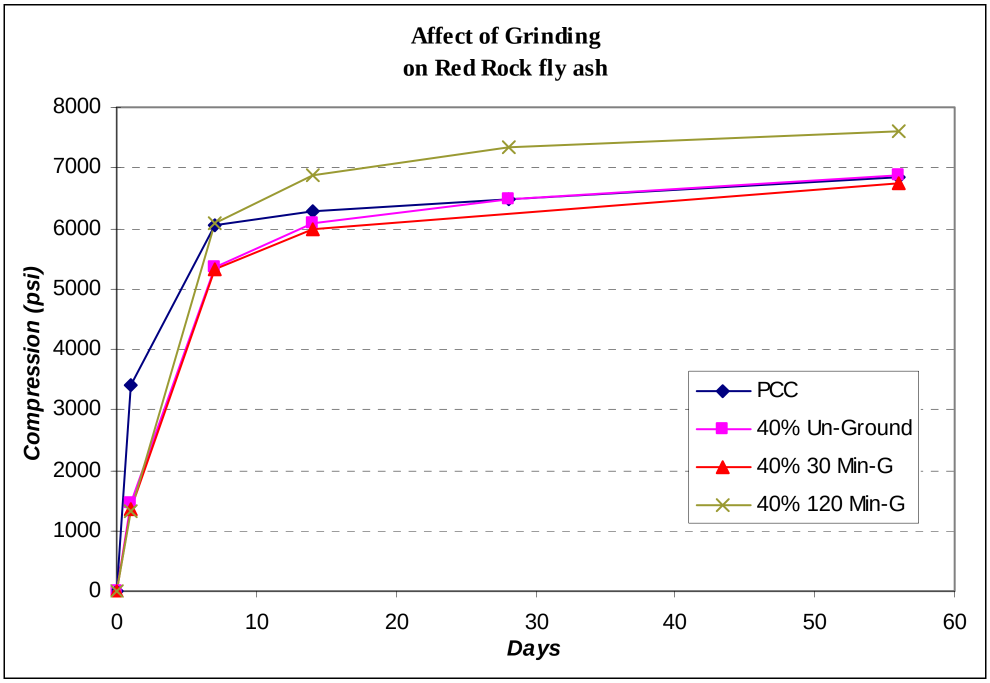


Figure 5.15 Effect of grinding duration on 40% Red Rock fly ash concrete

Figure 5.16 shows the changes in the compression strength of 60% Red Rock fly ash concrete due to grinding. In this case, the strength of the sample decreases significantly if 60% of cementitious material be consisted of un-ground fly ash. However, the results show that thirty minutes grinding the fly ash increases the strength of 60% fly ash concrete for 4000, and 4500 psi after 28 and 56 days relatively. The strength of the samples with 120 minutes ground fly ash are below Portland cement concrete in early age, first 14 days, and slightly above it after 14 days.

To learn more about how the longer grinding duration might affect the strength of the 60% fly ash concrete, the sample with 240 minutes, four hours, was tested. The results show that grinding the fly ash for four hours reduce the strength. The concrete with four hours ground fly ash has lower strength than concrete with two hours ground fly ash, and perform similar to 30 minutes ground fly ash sample. Further investigation revealed that the grinding agent that were used in this research losses its effectiveness after two hours, witch may cause caking and clumping the fly ash particles in the durations longer than two hours, thus reduces the strength of the samples.

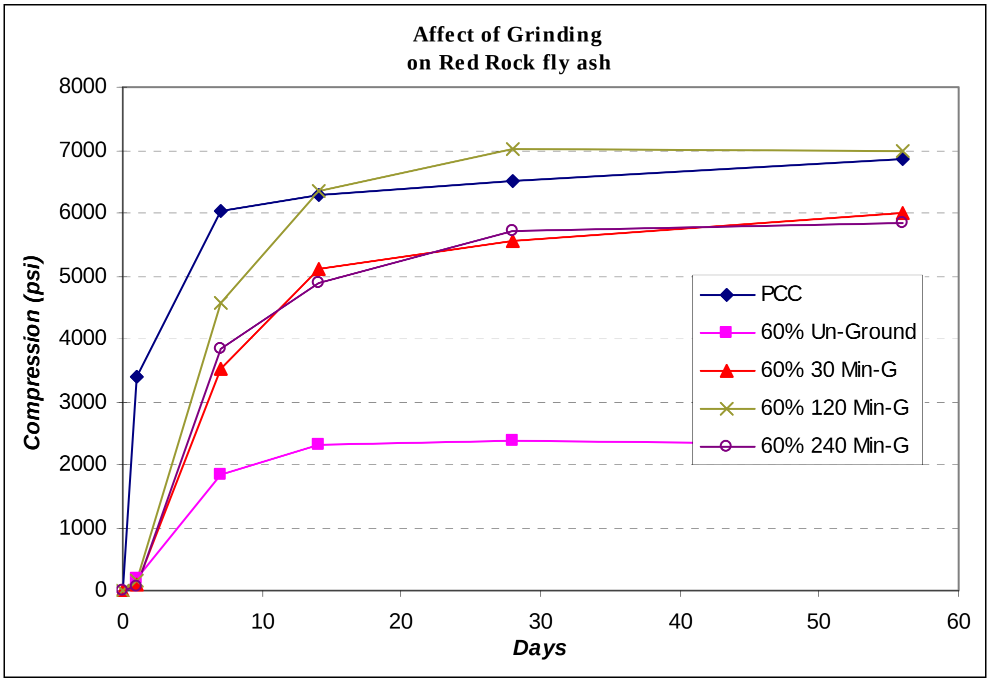


Figure 5.16 Effect of grinding duration on 60% Red Rock fly ash concrete

- **Oologah fly ash**

Figure 5.17 and Figure 5.18 show the effect of grinding duration on 20% and 40% concrete samples with Oologah fly ash. In both cases, the strength of samples with un-ground fly ash concrete is slightly higher than Portland cement concrete after 14 days. The results show that grinding the Oologah fly ash does not improve the strength of concrete in these cases.

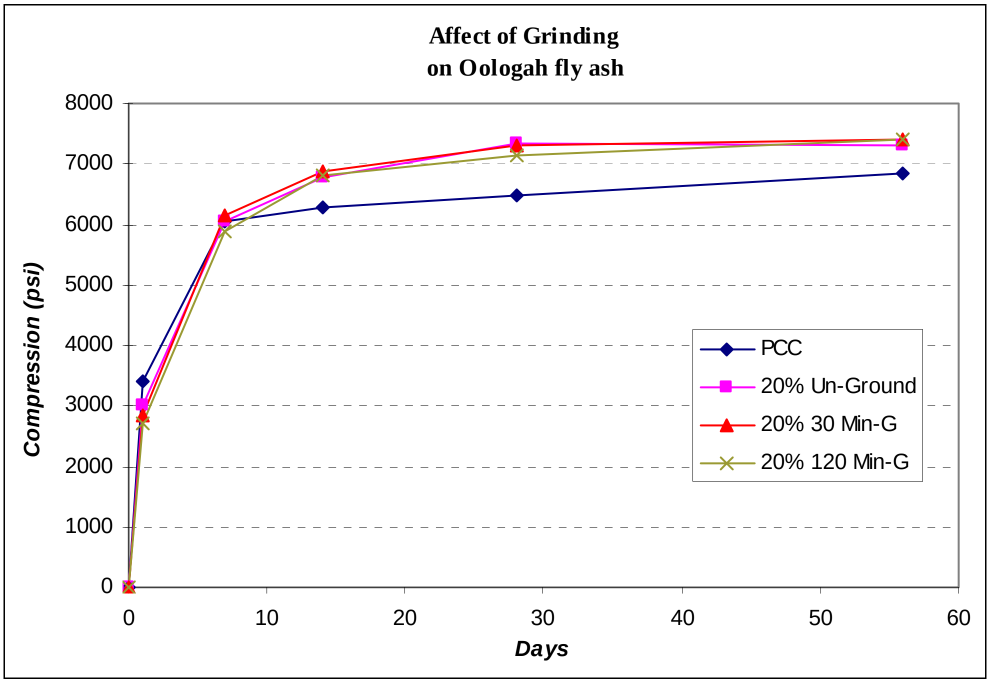


Figure 5.17 Effect of grinding duration on 20% Oologah fly ash concrete

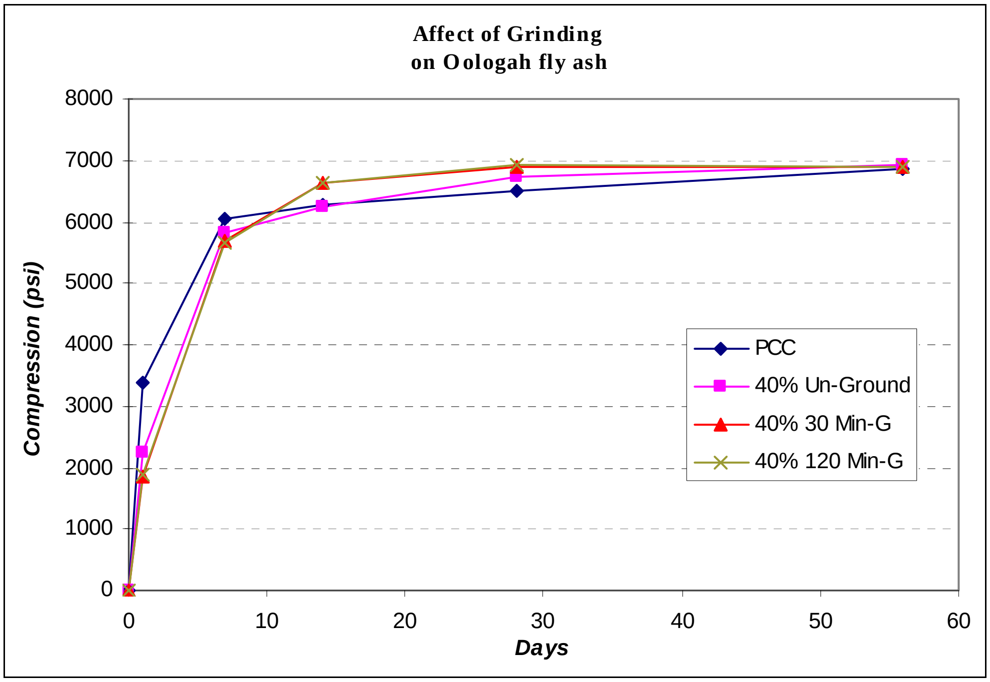


Figure 5.18 Effect of grinding duration on 40% Oologah fly ash concrete

The results of samples with 60% Oologah fly ash are illustrated in Figure 5.19. Thirty minutes grinding the fly ash in this case does not change the strength of the concrete significantly. However, the samples with 120 minutes ground fly ash tend to have strength slightly below samples with un-ground fly ash.

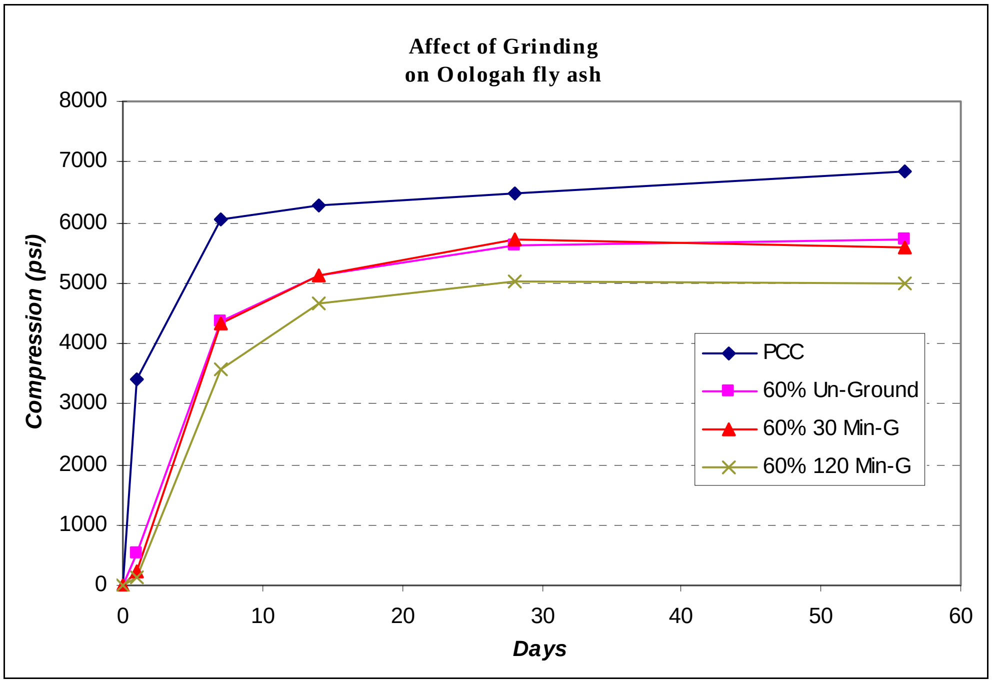


Figure 5.19 Effect of grinding duration on 60% Oologah fly ash concrete

- **Muskogee fly ash**

Figure 5.20 to Figure 5.22 shows the affect of grinding on Muskogee fly ash. The respond of this fly ash to grinding and grinding duration is almost identical to Oologah fly ash. The results illustrate that the grinding does have significant affect on the strength of concrete samples with Muskogee fly ash.

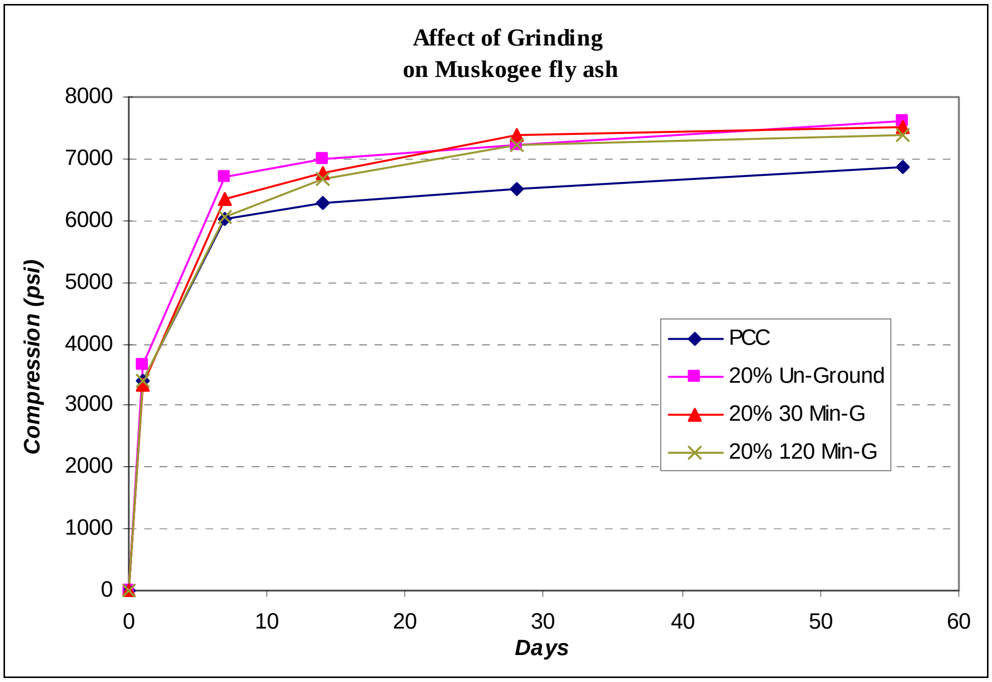


Figure 5.20 Effect of grinding duration on 20% Muskogee fly ash concrete

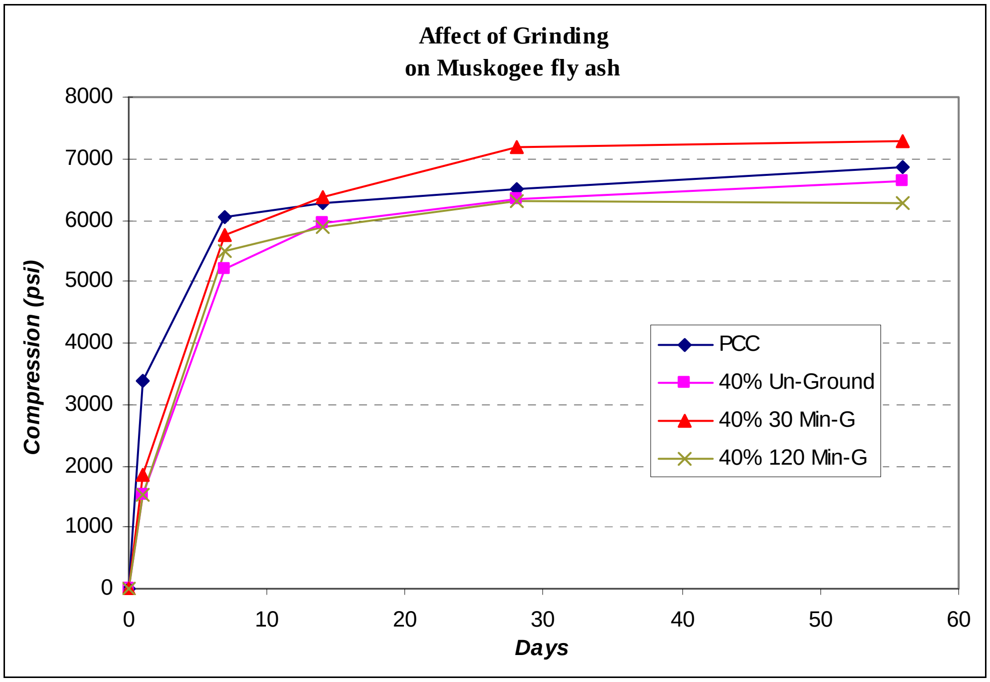


Figure 5.21 Effect of grinding duration on 40% Muskogee fly ash concrete

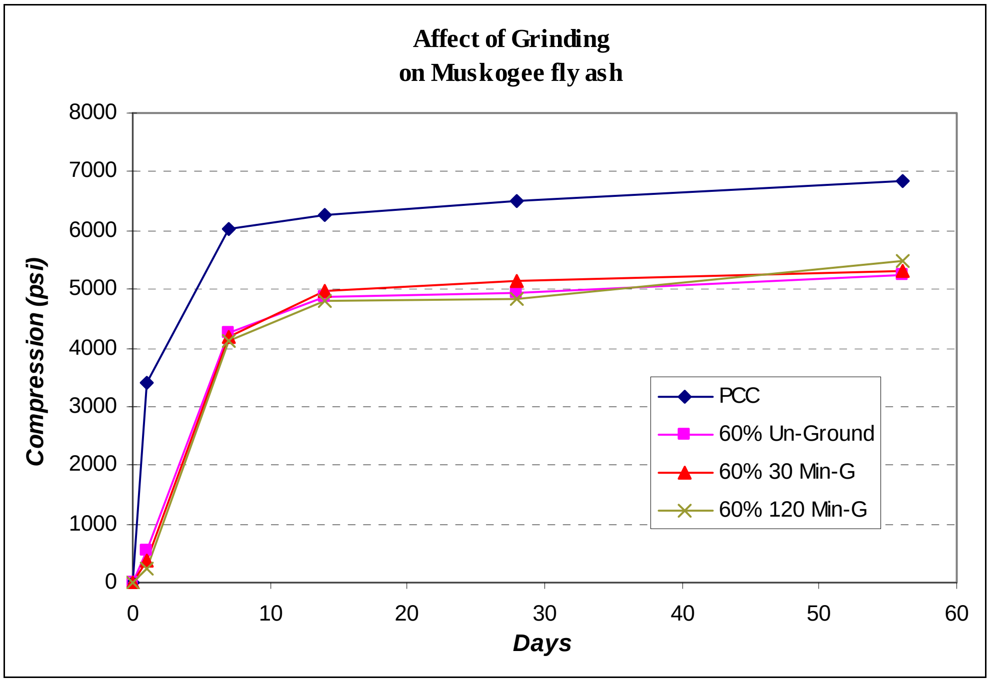


Figure 5.22 Effect of grinding duration on 60% Muskogee fly ash concrete

- **Boral fly ash**

Figure 5.23 to Figure 5.25 shows the affect of grinding on strength of Boral fly ash concrete. The results illustrate that the grinding does not have significant affect on the strength of concrete samples with Boral fly ash.

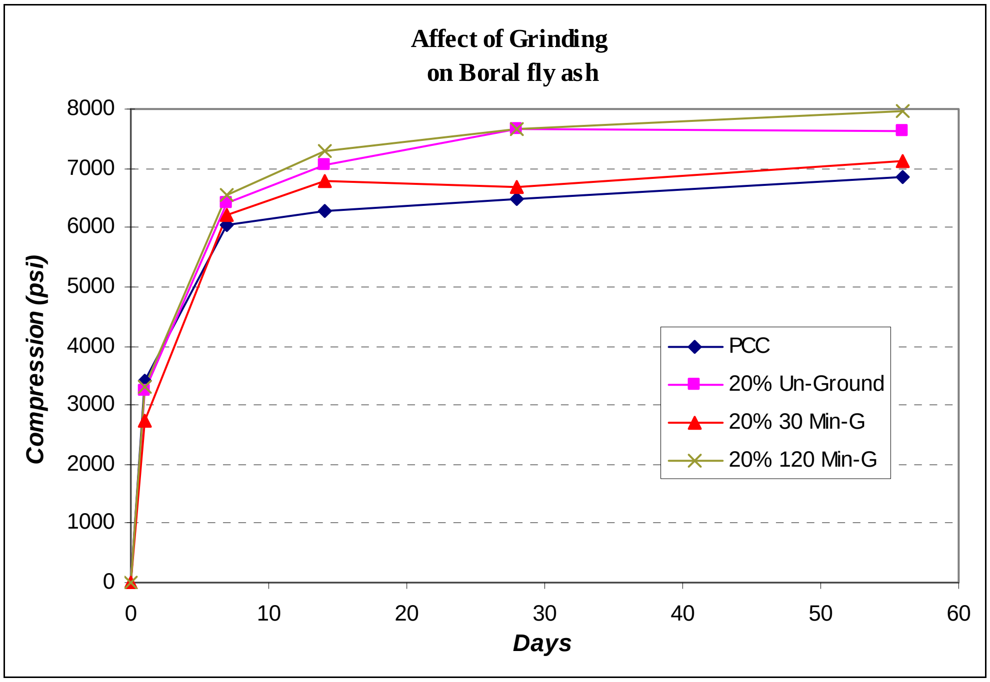


Figure 5.23 Effect of grinding duration on 20% Boral fly ash concrete

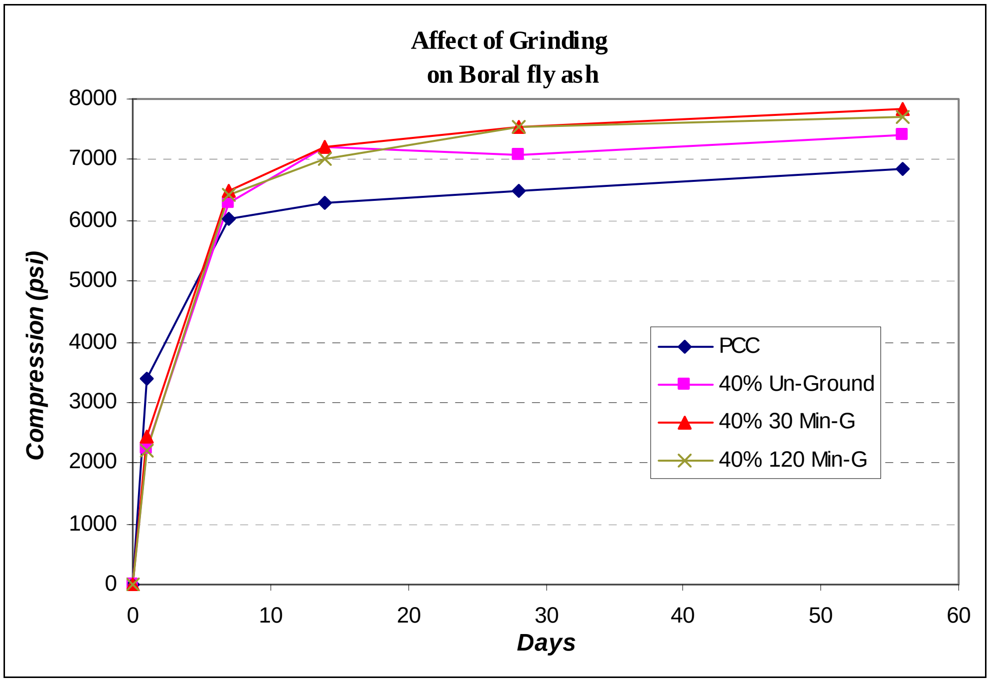


Figure 5.24 Effect of grinding duration on 40% Boral fly ash concrete

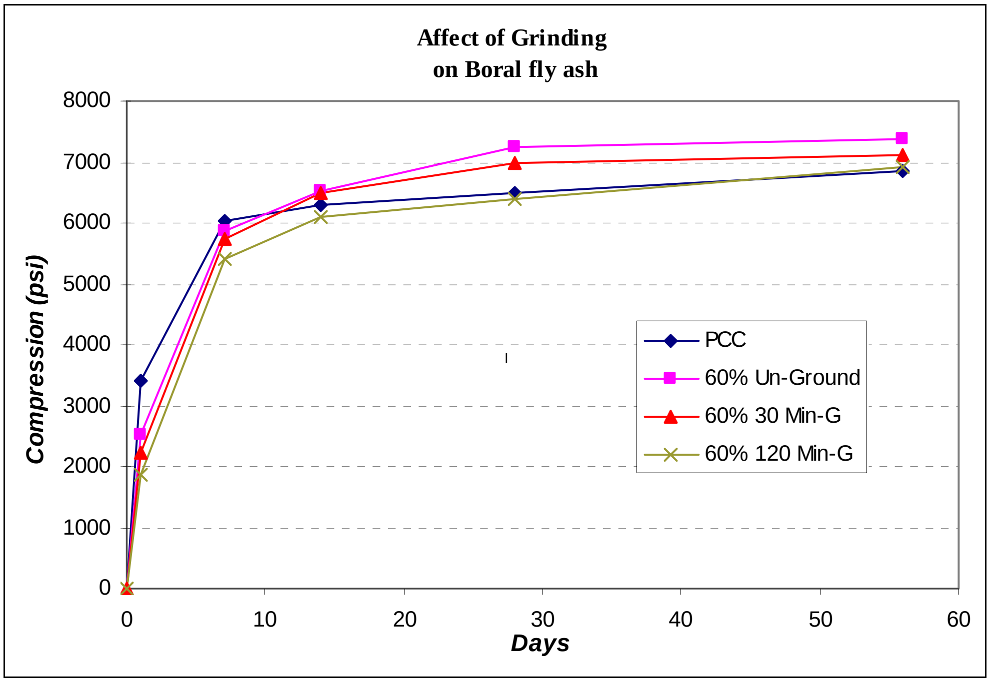


Figure 5.25 Effect of grinding duration on 60% Boral fly ash concrete

- **Amarillo fly ash**

Between the fly ashes studied in this research Amarillo fly ash has one of the highest cementitious properties. The strength of the concrete samples with 20% un-ground Amarillo fly ash is approximately 1000 psi greater than Portland cement concrete, see Figure 5.26, and reaches 7688 psi at 56 days. Grinding the Amarillo fly ash does not make any significant changes in the strength of the concrete at 28 days. However, using 120 minutes ground fly ash increases the compressive strength of the samples to 8264 psi, 1350 psi higher than unground fly ash samples.

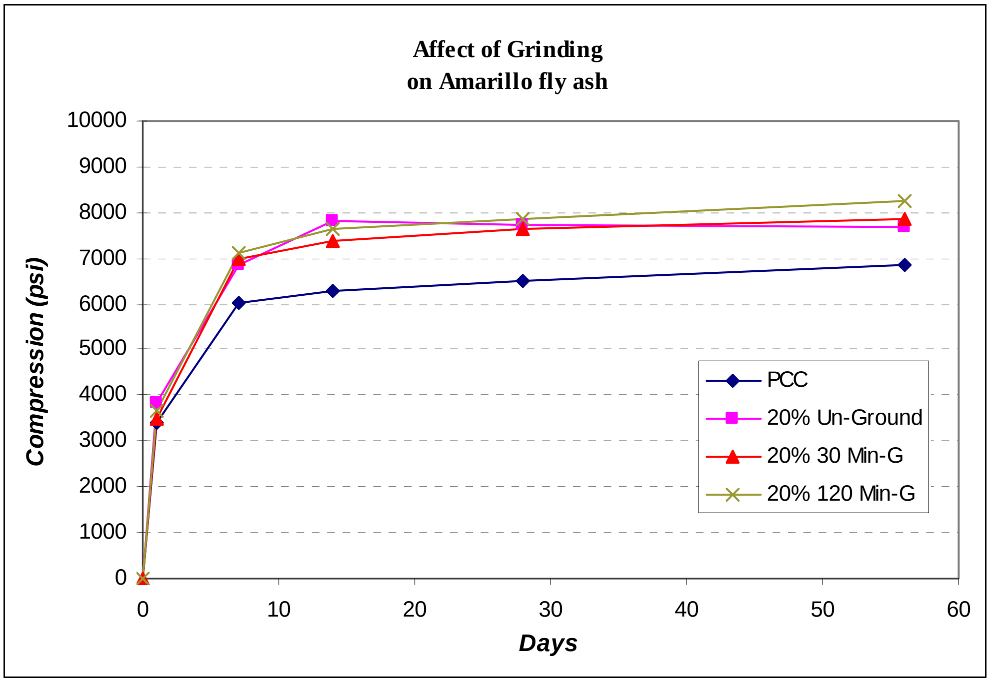


Figure 5.26 Effect of grinding duration on 20% Amarillo fly ash concrete

The concrete samples with 40% un-ground fly ash are approximately 1500 psi stronger in comparison with Portland cement concrete. Figure 5.27 illustrates the strength of the concrete samples with 40% fly ash. Grinding a fly ash for thirty minutes slightly increase the strength of the samples. However, the samples with higher grinding duration, 120 min, have significantly higher strength than other Portland cement and other 40% fly ash concretes. The strength of the samples with “40% 120-Min” fly ash is approximately 1600 psi higher than Portland cement at seven days (8679 psi). The strength of this sample reaches the 9700 psi at 56 days, which is 2850 psi higher than that of Portland cement concrete.

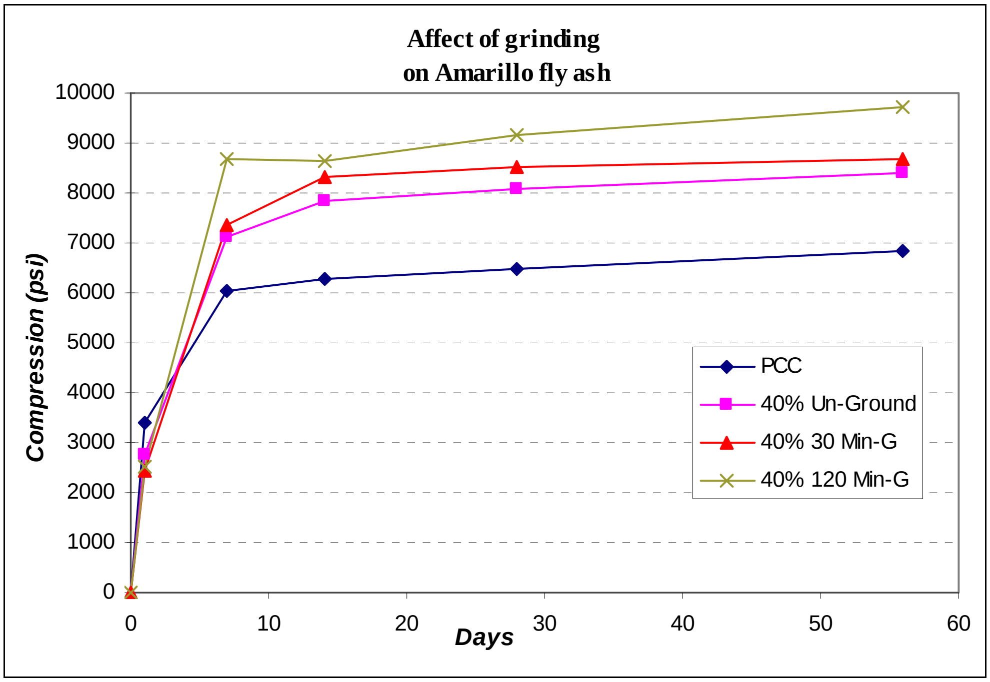


Figure 5.27 Effect of grinding duration on 40% Amarillo fly ash concrete

The results of the compressive strength of the samples with 60% Amarillo fly ash are illustrated in Figure 5.28. The compressive strength of the sample with 60% unground fly ash are similar to PCC throughout the 56 days of this study and the results shows no significant changes in strength of the samples due to grinding.

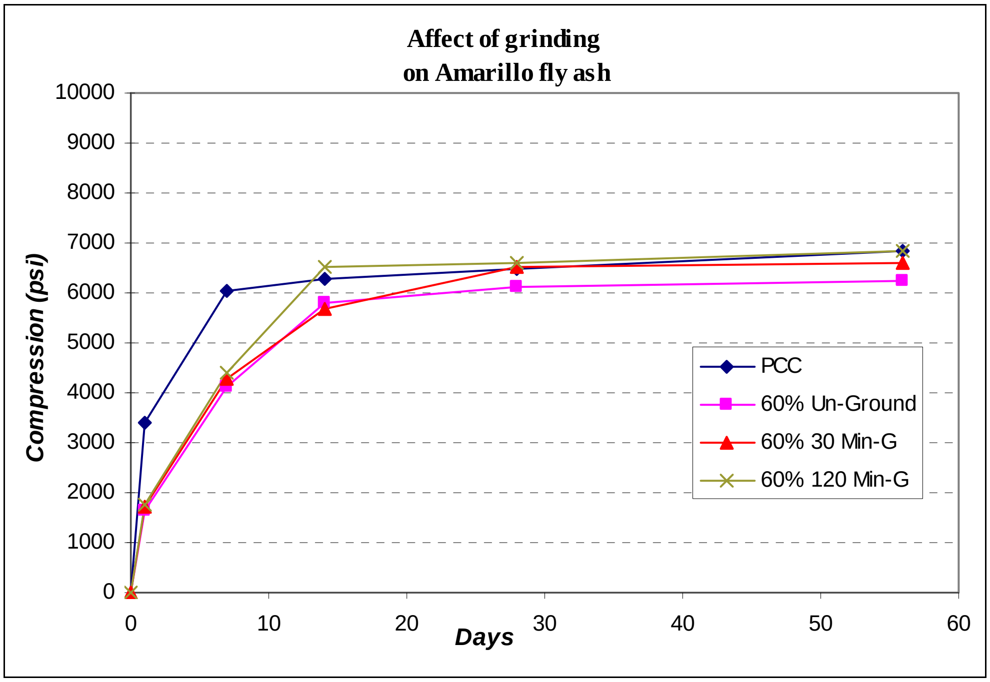


Figure 5.28 Effect of grinding duration on 60% Amarillo fly ash concrete

- **Pampa fly ash**

The strengths of the samples with 20% Pampa fly ash are illustrated in Figure 5.29. The results of this study shows that grinding the Pampa fly ash for 30 minutes reduces the strength of the samples relatively small. However, grinding the same fly ash for 2 hours increases the strength of the samples almost the same amount at 56 days. Small variation in the strength of the samples with such a high compressive strength seems to be expected. Thus, it is realistic to say grinding does not affect the strength of the samples in this case.

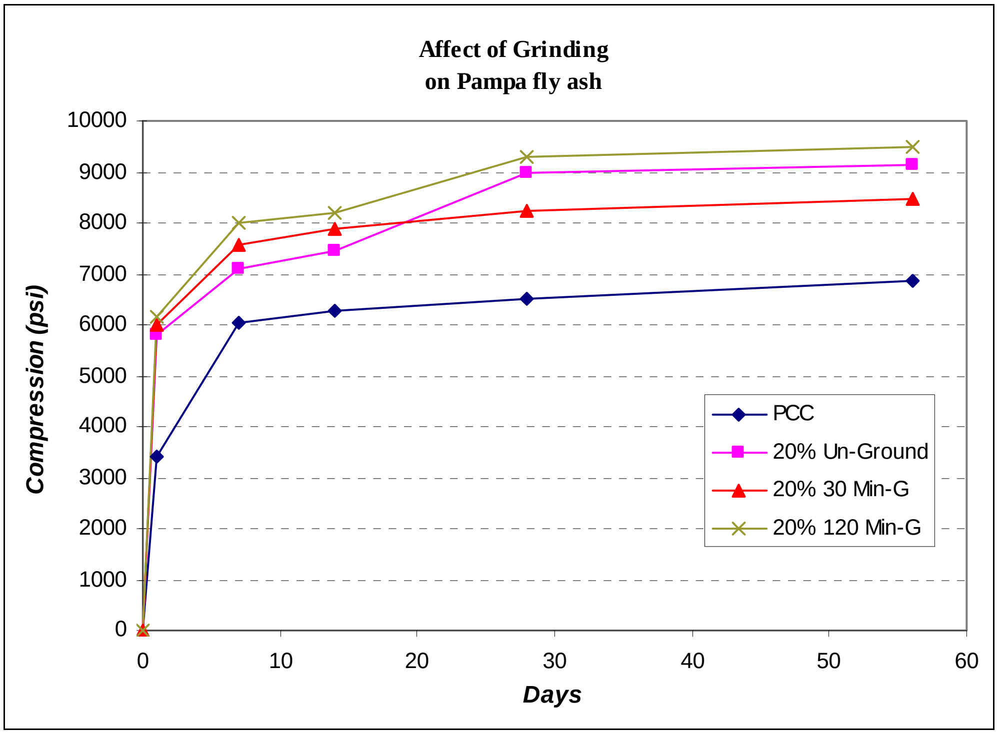


Figure 5.29 Effect of grinding duration on 20% Pampa fly ash concrete

The compressive strengths of the samples with 40 and 60% Pampa fly ash are shown in Figure 5. 30 and Figure 5.31. Grinding the Pampa fly ash in does not change the strength of the samples.

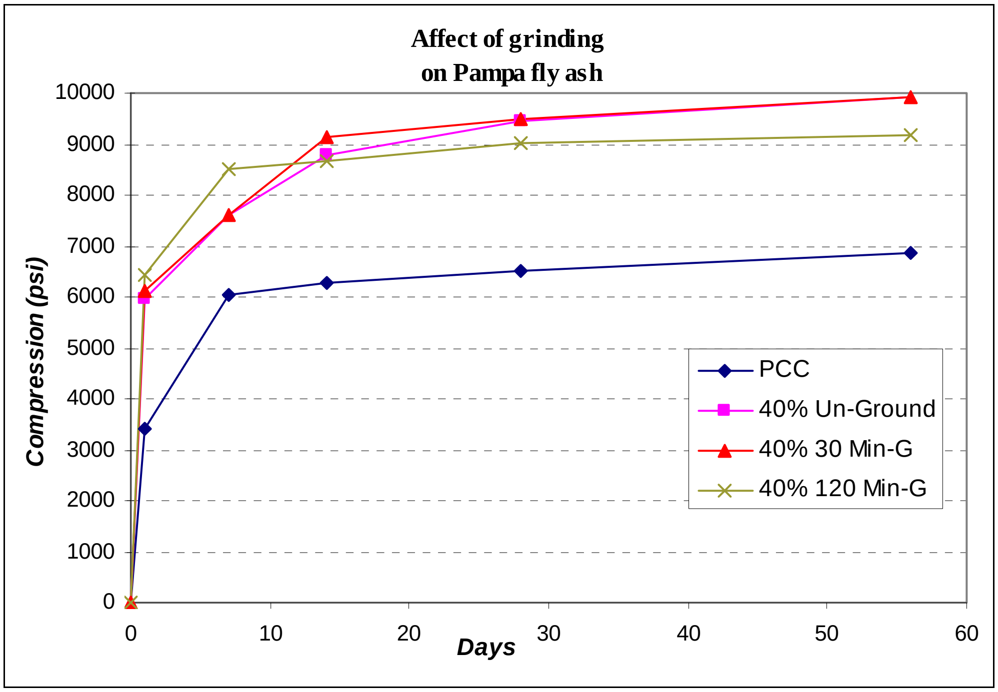


Figure 5. 30 Effect of grinding duration on 40% Pampa fly ash concrete

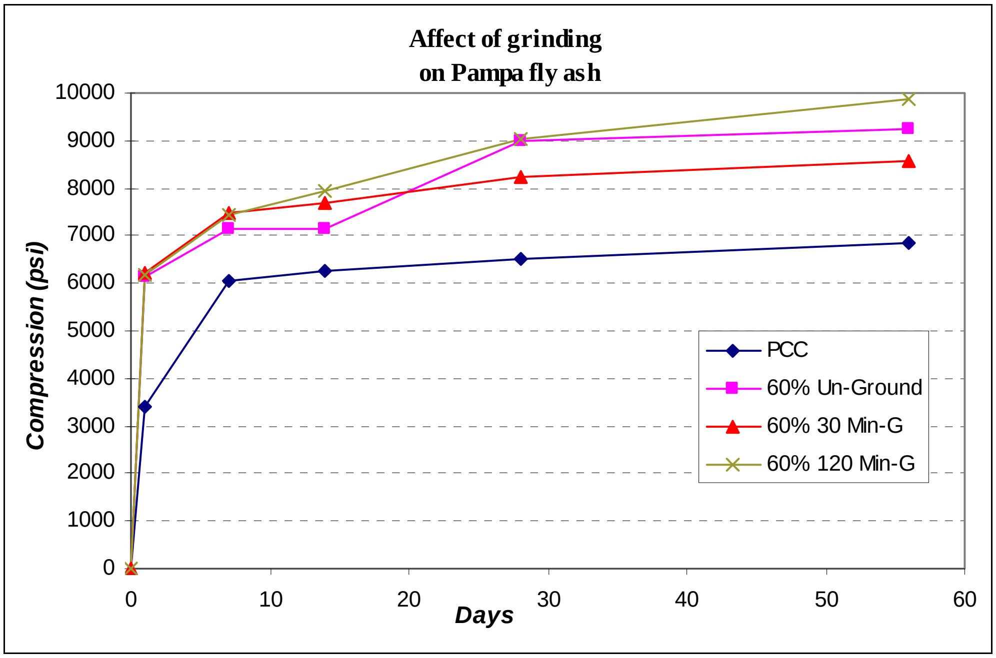


Figure 5.31 Effect of grinding duration on 60% Pampa fly ash concrete

5.3.1.3 Effect of Fly Ash Content on the Compressive Strength

- **Red Rock fly ash**

The results of Red Rock fly ash samples are illustrated in Figure 5.32 base on fly ash content. The results show the samples with 20 and 40% unground fly ash have slightly lower strength in early age. However, the strength of those samples are tight with PCC after 14 days. Therefore, up to 40% of the binder can be replaced with un-ground Red Rock fly ash with out scarifying the strength if the early strength of the concrete is not the main mix design criteria.

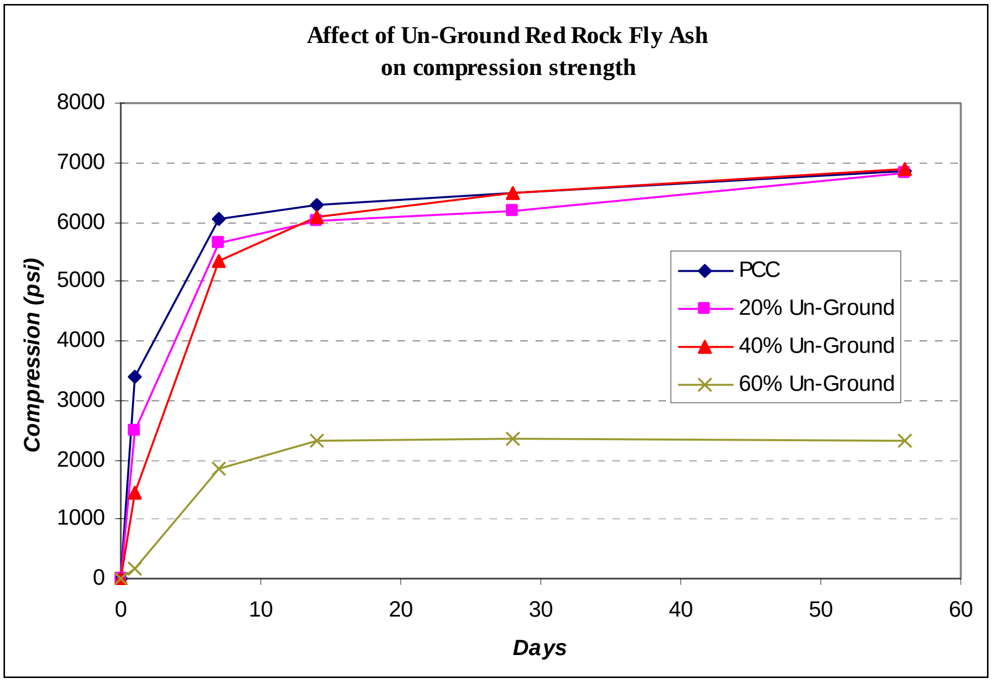


Figure 5.32 Effect of fly ash content on un-ground Red Rock fly ash concrete

The affect of 30 minutes Red Rock ground fly ash is plotted in Figure 5.33. Comparing this figure with Figure 5.32 shows that grinding the fly ash for 30 minutes does not make a different with the strength of the samples with fly ash content of 20 and 40%. However, grinding the fly ash for 30 minutes improve the compressive strength of the samples with 60% fly ash to 6000 psi after 56 days. This sample has a low strength in early age and it is not suitable for time dependent projects.

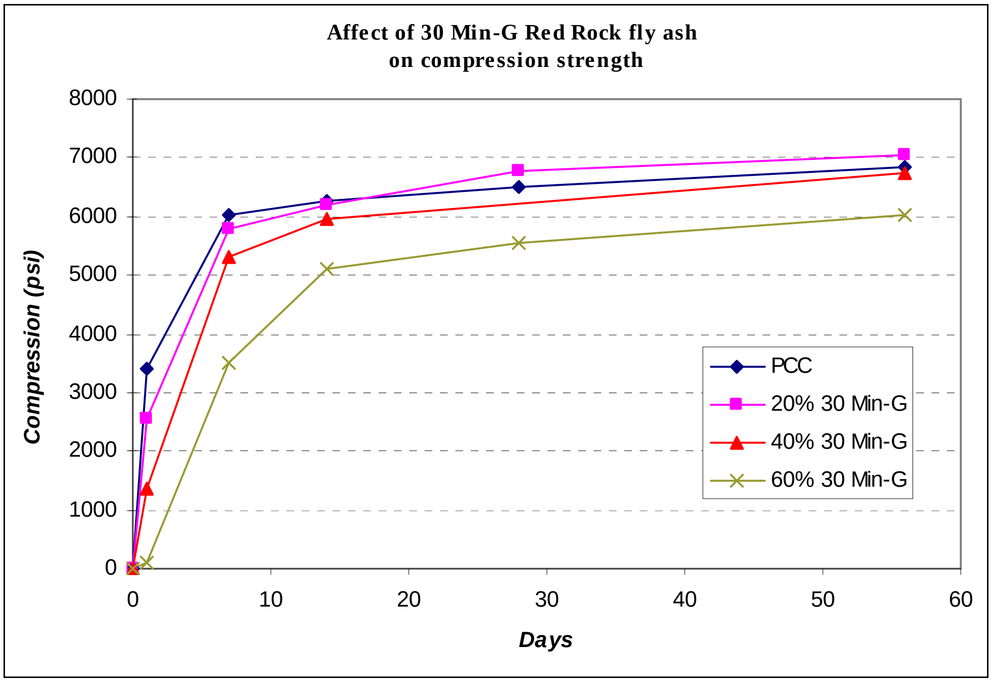


Figure 5.33 Effect of fly ash content on 30 minutes Red Rock fly ash concrete

Figure 5.34 illustrate the affect of grinding the Red Rock fly ash for two hours on the compressive strength of the samples with various fly ash content. The samples with 20 and 40% fly ash have almost the same strength as PCC samples in early age and significantly higher, 500 psi, compressive strength after 14 days.

The samples with 60% of 120 minutes ground fly ash have lower strength than PCC in the first two weeks. However, this study shows the samples with 60% of 120 minutes ground fly ash -G have slightly higher strength than PCC samples after 28 days. Therefore, up to 60% of the binder can be replaced with 120 minutes ground fly ash if early age strength of the samples are not important.

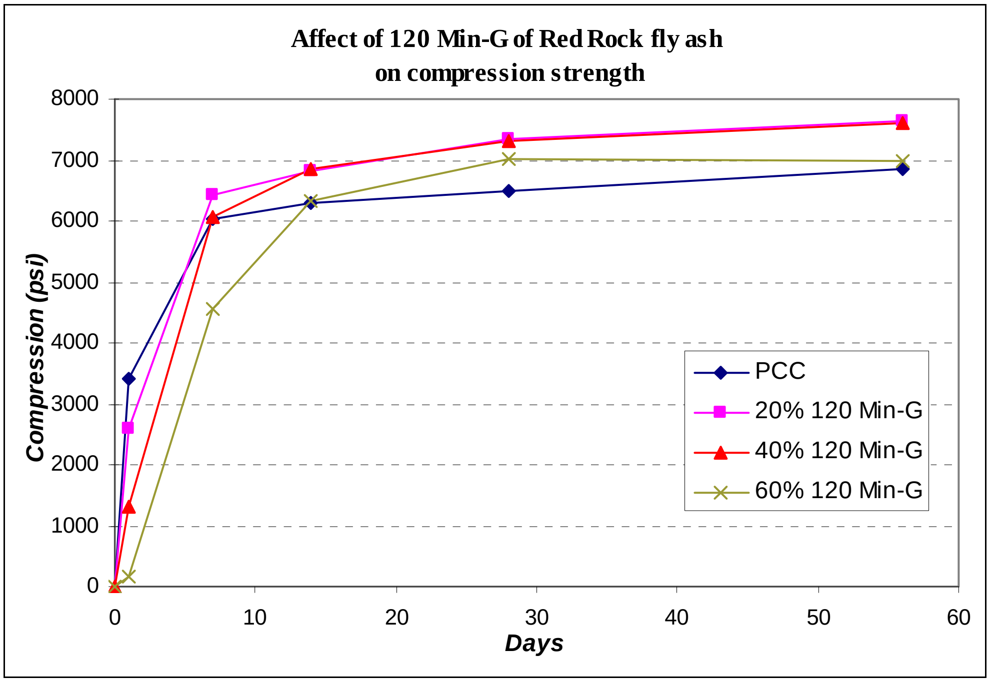


Figure 5.34 Effect of fly ash content on 120 minutes Red Rock fly ash concrete

- **Oologah fly ash**

Figure 5.35 shows the affect of un-ground Oologah fly ash on the samples with different fly ash content. This results shows the samples with 20% of un-ground Oologah fly ash have higher strength than PCC, and samples that 40% of the binder had been replaced with un-ground fly ash have almost the same performance as PCC in term of compressive strength. The samples with 60% of un-ground fly ash have significantly lower strength that PCC and their strength stays below PCC for more than 1000 psi after 56 days. Therefore, it is promising to replace up to 40% of the binder with unground Oologah fly ash without reducing the compressive strength.

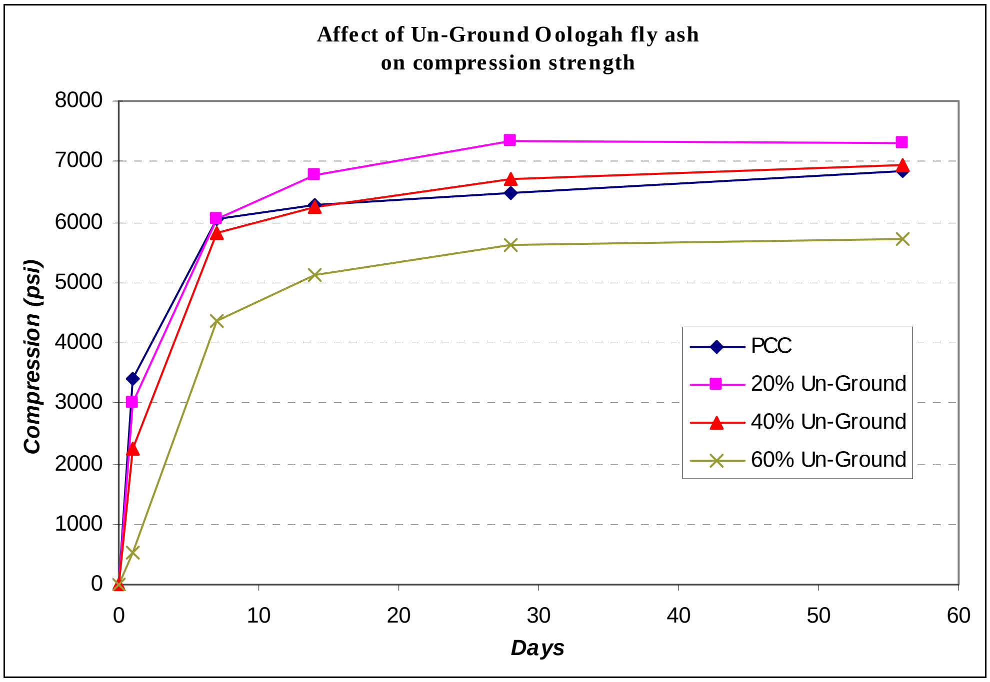


Figure 5.35 Effect of fly ash content on un-ground Oologah fly ash concrete

The compressive strength results of the samples with 30 and 120 minutes Oologah fly ash are presented in Figure 5.36 and Figure 5.37. The trends of strength gaining of samples with 30 and 120 minutes ground fly ash are comparatively the same as unground fly ash samples that were shown in Figure 5.35, but slightly higher. These results point out that grinding the fly ash for 30 and 120 minutes does not affect the compressive strength of the samples in comparison with unground fly ash samples. Therefore, not more than 40% of the binder is recommended to be replaces with 30 minutes Oologah fly ash if compressive strength of PCC is required.

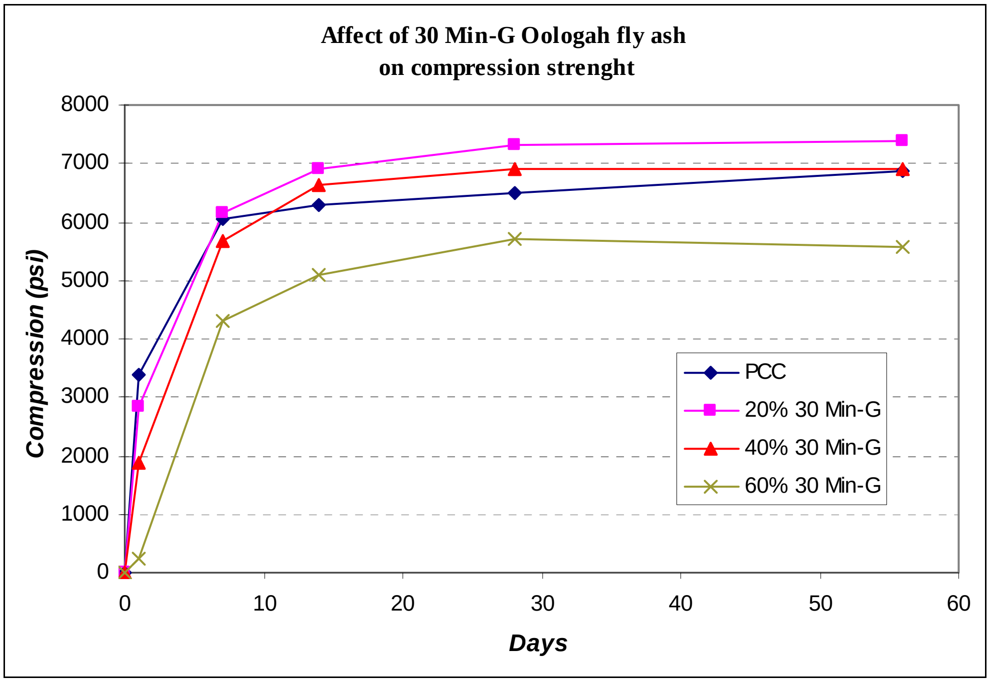


Figure 5.36 Effect of fly ash content on 30 minutes ground Oologah fly ash concrete

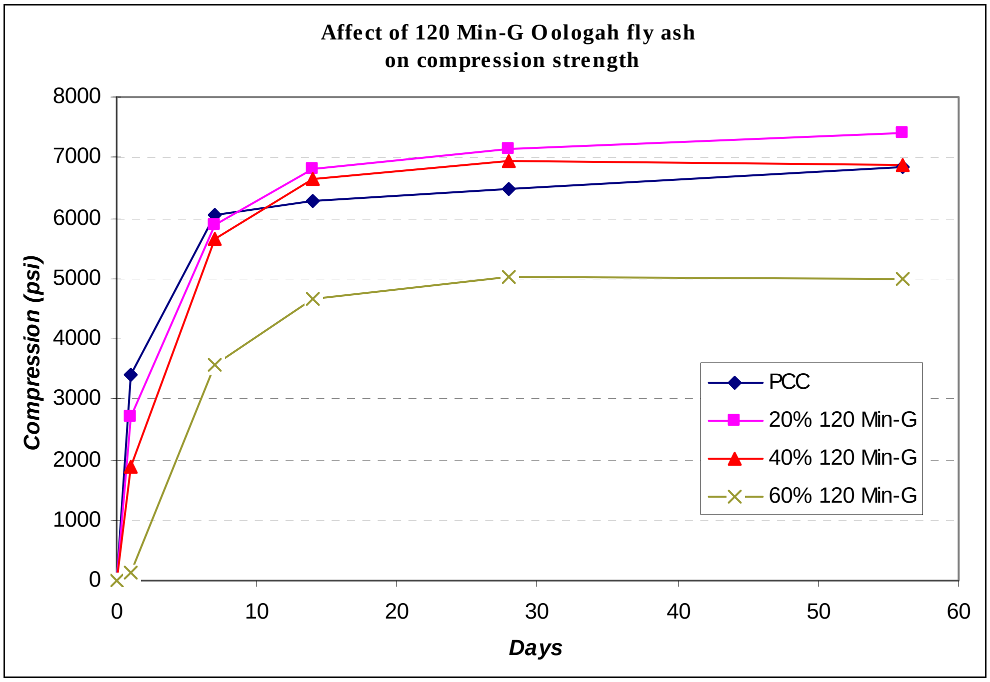


Figure 5.37 Effect of fly ash content on 120 minutes ground Oologah fly ash concrete

- **Muskogee fly ash**

Figure 5.38 shows the affect of unground Muskogee fly ash on the compressive strength of the samples with various fly ash content. This results shows the samples with 20% of un-ground fly ash have higher strength than PCC, and the compressive strength of the samples with 40% unground fly ash are similar to that of PCC after 28 days.

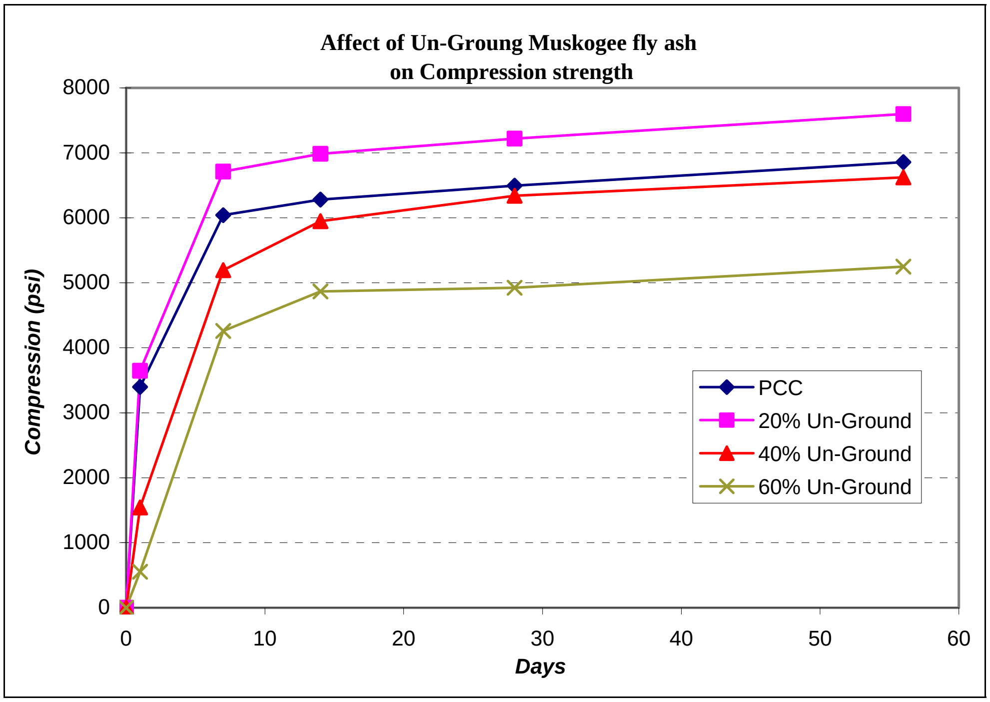


Figure 5.38 Effect of fly ash content on un-ground Muskogee fly ash concrete

Grinding the Muskogee fly ash for 30 minutes improves the compressive strength of the samples in early age. The results presented in Figure 5.39 shows that up to 40% of the binder can be replaced with 30 minutes ground fly ash without loosing the compressive strength of the concrete.

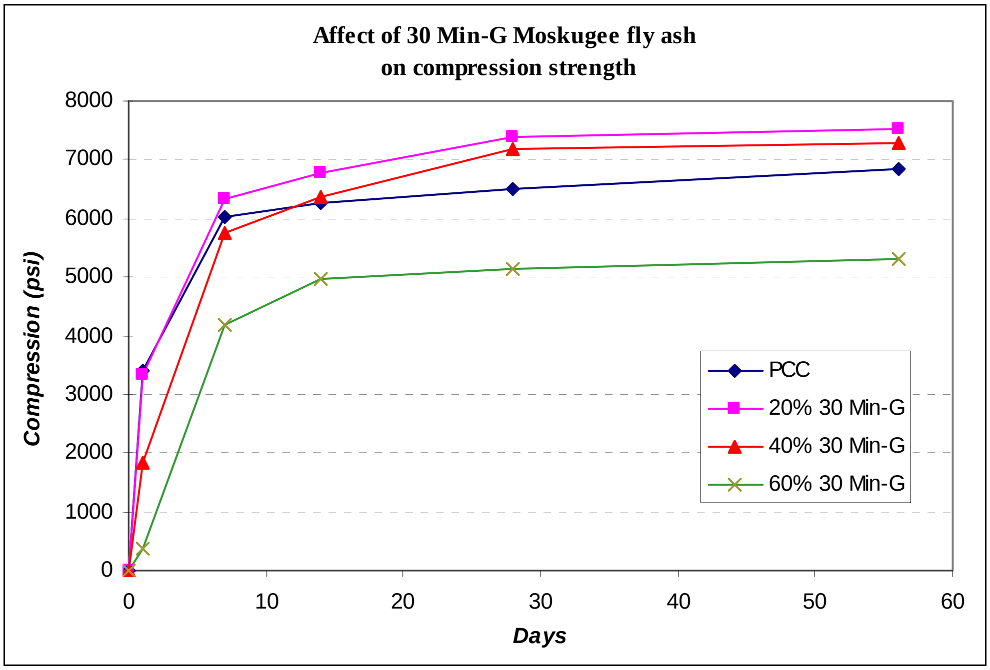


Figure 5.39 Effect of fly ash content on 30 minutes ground Muskogee fly ash concrete

The samples with 20% of 120 minutes ground fly ash have almost the same strength as PCC and higher strength than PCC after 14 days, see Figure 5.40. The results of the samples with 40 and 60% fly ash content are illustrated in the same figure. This study shows the samples with 40% 120 minutes ground fly ash have slightly lower strength than PCC, and replacing the 60% of the binder with this fly ash can reduce the compressive strength significantly, 1400 psi at 28 days and 500 psi at 56 days, see Figure 5.40.

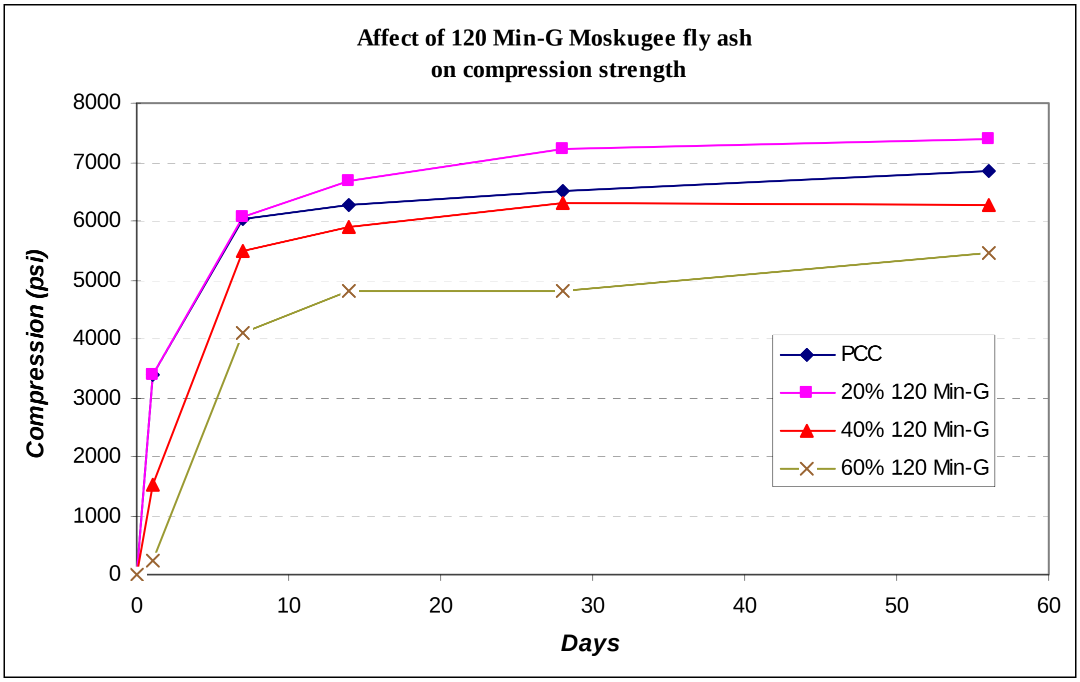


Figure 5.40 Effect of fly ash content on 120 minutes ground Muskogee fly ash concrete

- **Boral fly ash**

The results of the compressive strength of samples with Boral fly ash are presented in Figure 5.41 to Figure 5.43. The compressive strength of the samples with 60% unground fly ash is higher than PCC after 7 days as well as the samples with lower fly as content, see Figure 5.41. The results of the compressive strength of the samples with 30 and 120 minutes ground Boral fly ash indicates that samples with Boral fly ash have high compressive strength initially and grinding does not either improve or reduce the compressive strength of the samples regardless of fly ash content, see Figure 5.42 and Figure 5.43.

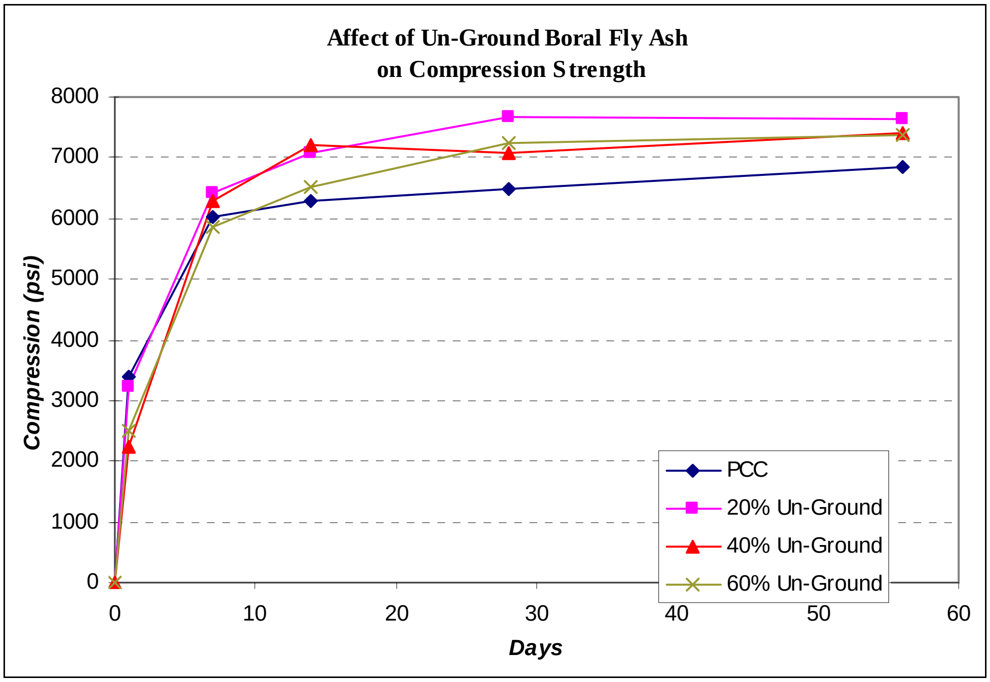


Figure 5.41 Effect of fly ash content on un-ground Boral fly ash concrete

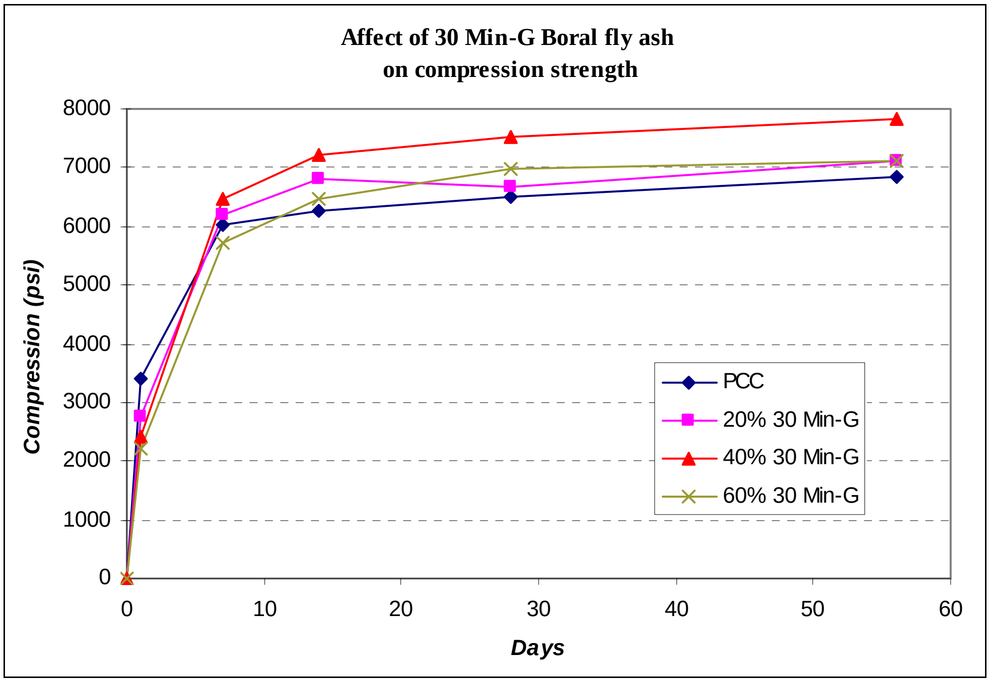


Figure 5.42 Effect of fly ash content on 30 minutes ground Boral fly ash concrete

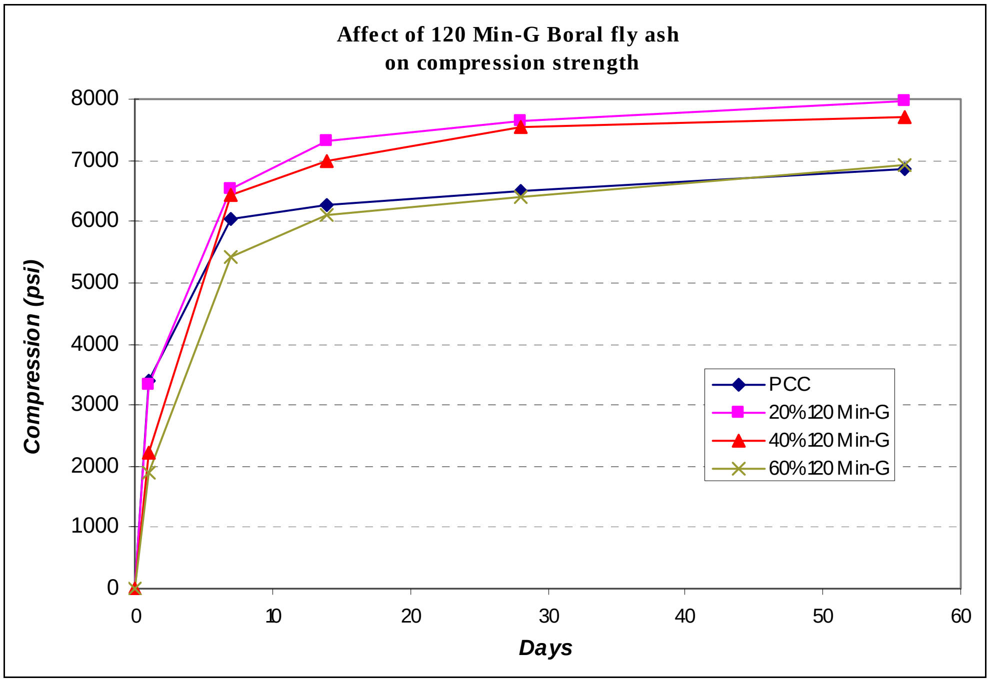


Figure 5.43 Effect of fly ash content on 120 minutes ground Boral fly ash concrete

- **Amarillo fly ash**

The results of the compressive strength of the samples with un-ground fly ash are illustrated in Figure 5.44. The strengths of the samples with 20 and 40% fly ash content are higher that PCC after seven days. This study shows that that samples with 60% unground Amarillo fly ash has significantly lower strength that PCC in early age. However; the strength of this sample increase gradually and stays about 500 psi lower that PCC after 14 days.

The results of the samples with 30 minutes ground fly ash are shown in Figure 5.45. The samples with 20 and 40% thirty minutes Amarillo fly ash have 2000 and 1000 psi higher strength than PCC after 14 days respectively. The samples with 60% fly ash have lover strength than PCC in early age. The strength of these samples reaches the strength of the PCC after 28 day.

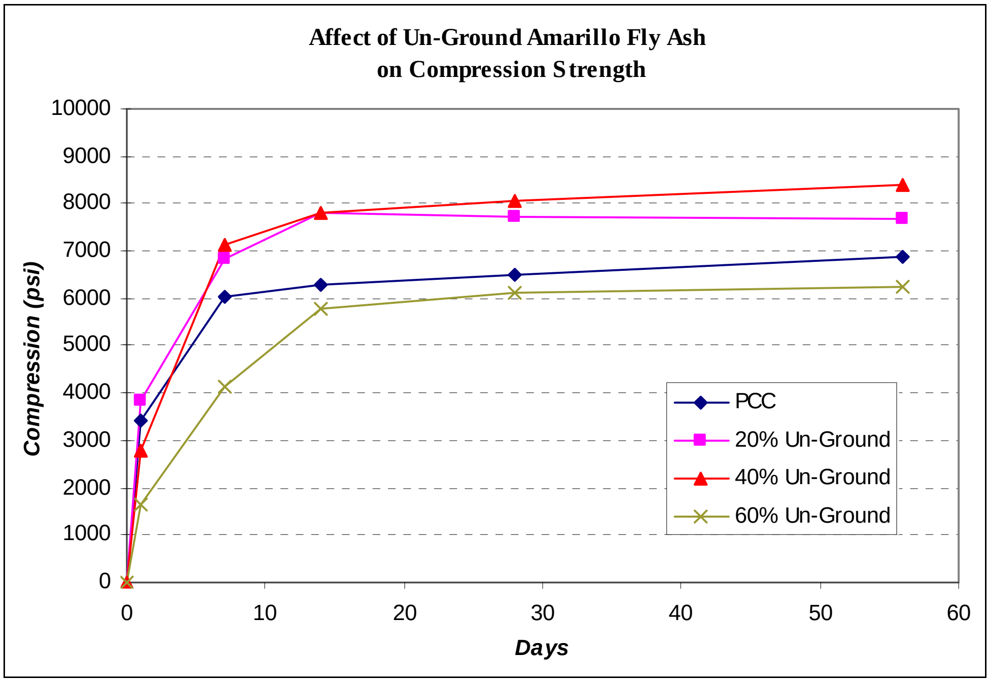


Figure 5.44 Effect of fly ash content on un-ground Amarillo fly ash concrete

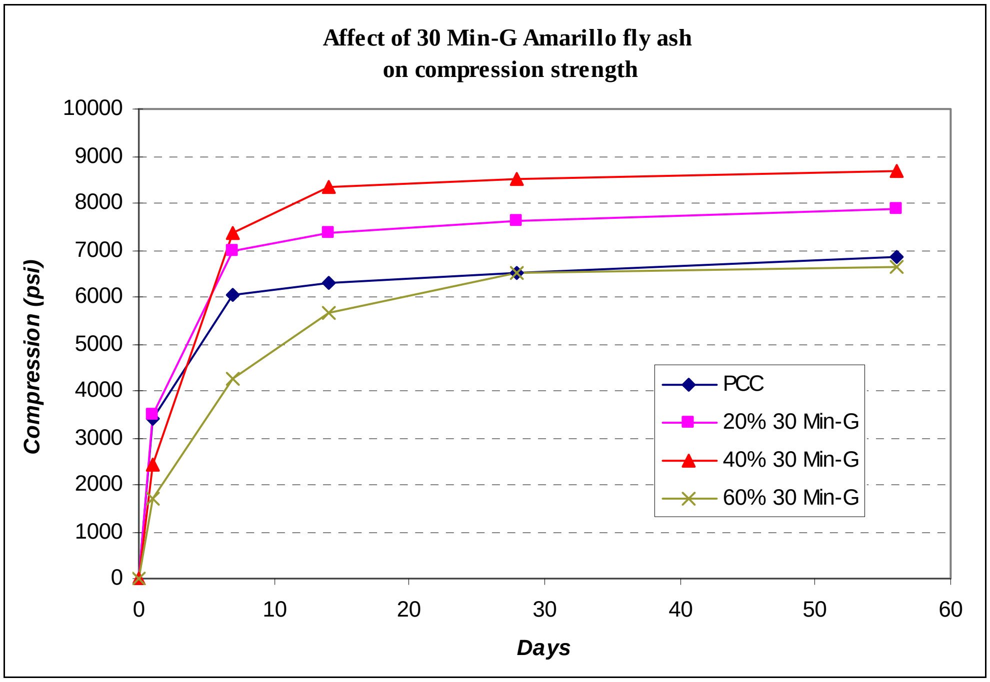


Figure 5.45 Effect of fly ash content on 30 minutes ground Amarillo fly ash concrete

The compressive strengths of the samples with 120 minutes Amarillo ground fly ash are illustrated in Figure 5.46. The samples with 120 minutes ground fly ash have almost the same strength as the sample with 30 minutes ground fly ash, compare Figure 5.45 and Figure 5.46. This study shows that grinding the fly ash more that 30 minutes does not provide additional strength to the samples contain Amarillo fly ash.

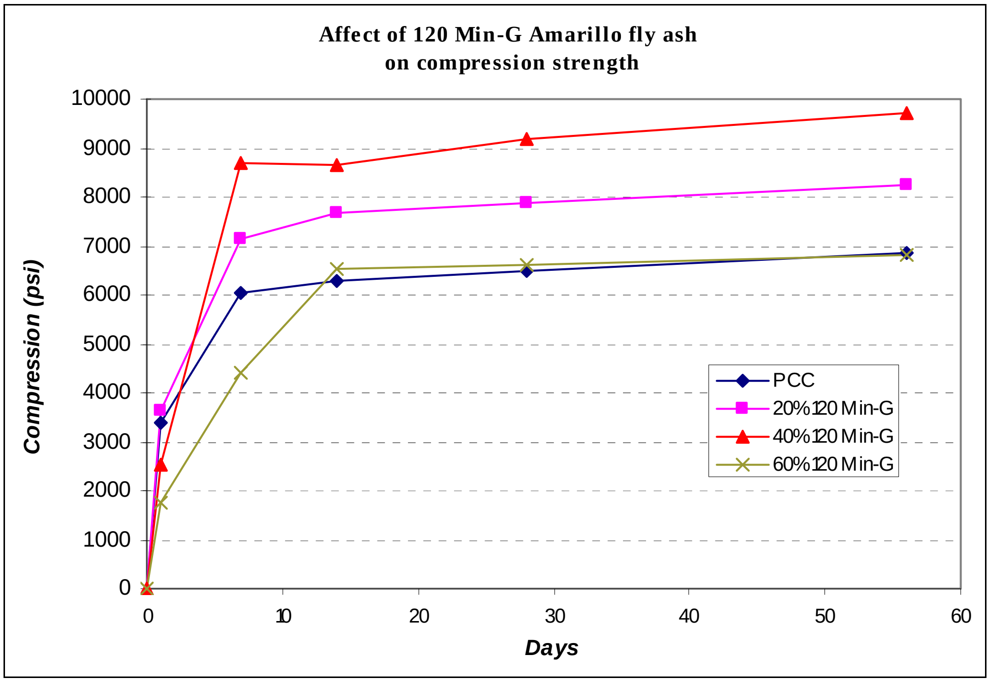


Figure 5.46 Effect of fly ash content on 120 minutes ground Amarillo fly ash concrete

- **Pampa fly ash**

The compressive strength of the samples with un-ground and 30 minutes ground fly ash are illustrated in Figure 5.47 and Figure 5.49. In both cases the strength of the samples with 40% Pampa are greater than the samples with un-ground fly ash. However, this study shows that longer grinding duration, 120 minutes, not only improve the ultimate strength of the samples, but only reduces the strength similar to that the strength of the samples with unground fly ash.

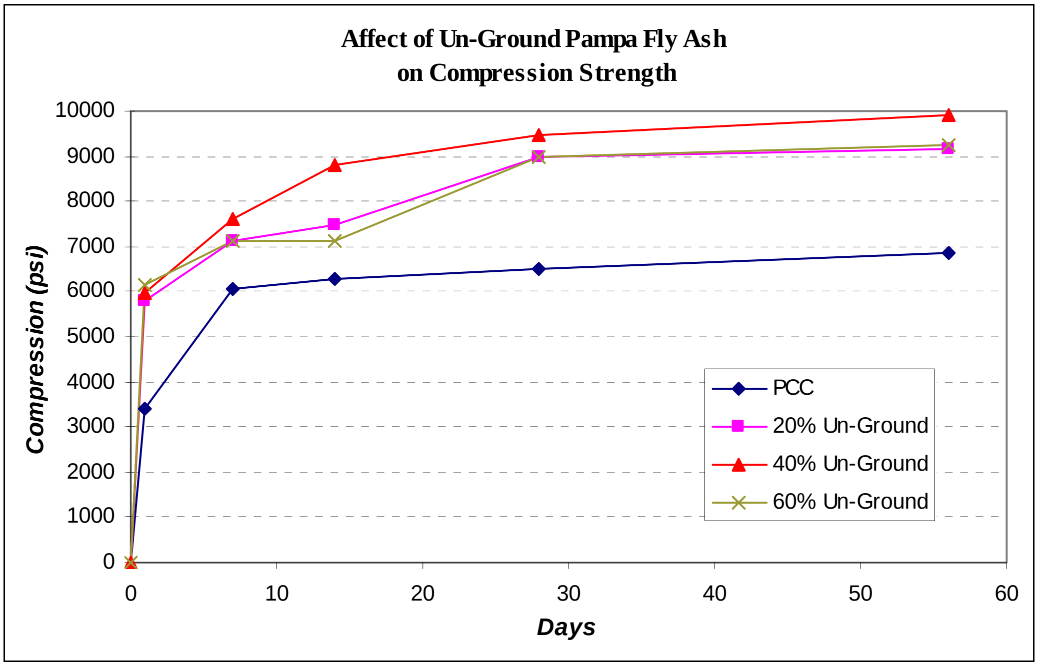


Figure 5.47 Effect of fly ash content on un-ground Pampa fly ash concrete

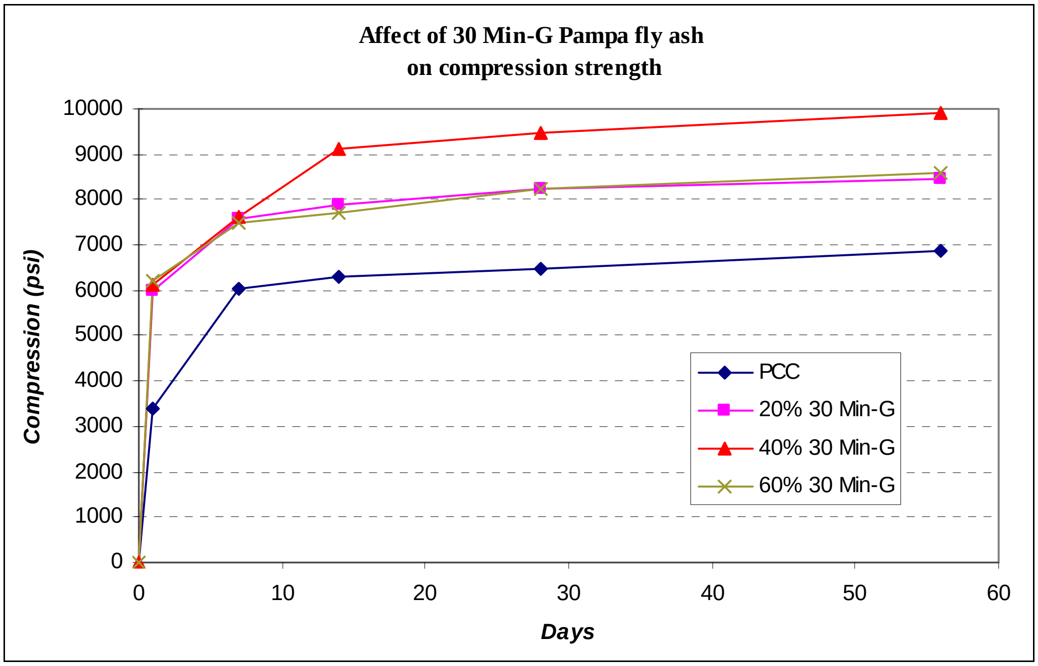


Figure 5.48 Effect of fly ash content on 30 minutes ground Pampa fly ash concrete

The compressive strengths of the samples with 120 minutes ground fly ash are illustrated in Figure 5.49. This results of this research on 120 minutes ground Pampa fly ash shows that the samples with 60% unground fly ash have the same strength as samples with 120 minutes ground fly ash. Therefore grinding the Pampa fly ash in this case does not provide any benefit to the mix in terms of strength.

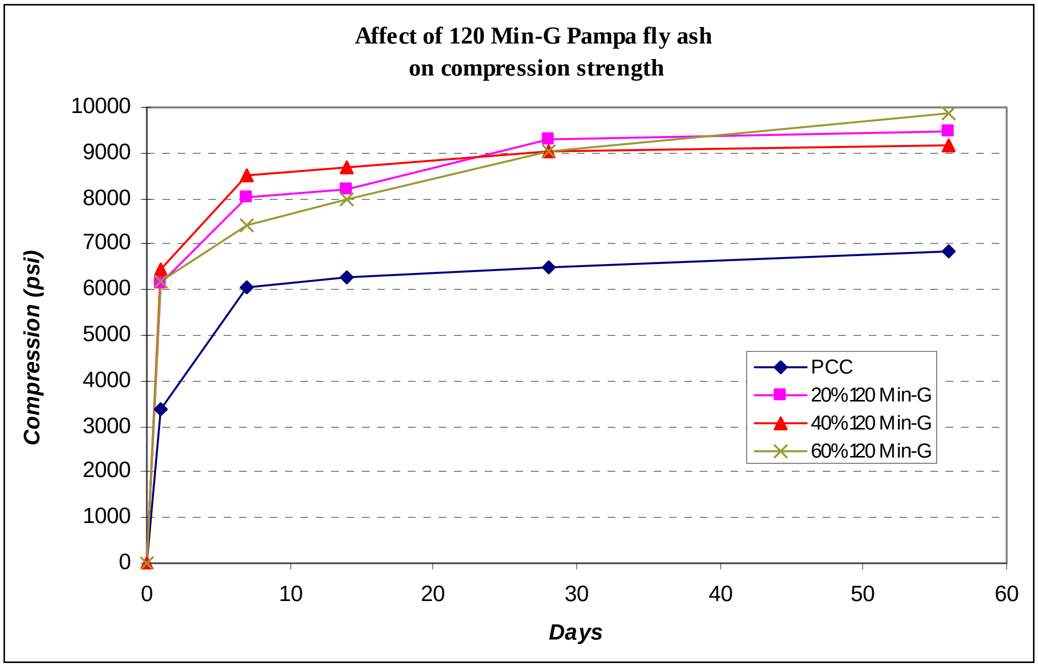


Figure 5.49 Effect of fly ash content on 120 minutes ground Pampa fly ash concrete

5.3.2 Mix-B Compressive Strength

5.3.2.1 Effect of Grinding the Fly Ash on Compressive Strength

To determine the effect of ground fly ash on mixtures with different ingredients proportions, Red Rock fly ash was tested with two other mix designs, Mix-B and C. Mix-B has the same *w/c* ratio and higher binder content than Mix-A. The specific properties of this mix are provided in **Error! Reference source not found.**. The results of the testing the Red Rock fly ash incorporated with Mix-B will be discussed in this section.

The compressive strengths of the samples with 20% Red Rock fly ash are illustrated in Figure 5.50. This graph shows that longer grinding durations increase the compressive strength of the samples slightly. 20% samples with 120 minutes of grinding have a higher strength than PCC at 28 days, by 500 psi. However, this gap slowly decreases at 56 days to 100 psi.

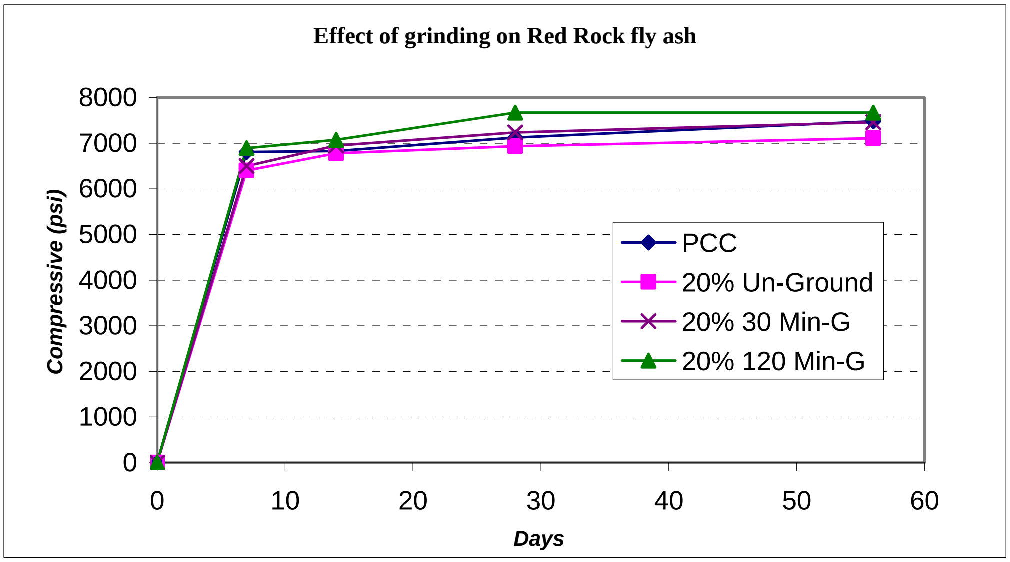


Figure 5.50 Effect of grinding duration on 20% Red Rock fly ash concrete (Mix-B).

Figure 5.51 presents the compressive strength results of the 40% fly ash samples with various grinding durations. This graph shows using 40% unground fly ash as a binder reduces the compressive strength. However grinding the fly ash recovers this lack of strength and the samples incorporated with ground fly ash have almost the same strength as PCC throughout the 56 days testing period. The performance of 40% samples with 30 minutes of grinding is almost identical with the compressive strength of 40% samples with 120 minutes of grinding samples. Thus, grinding durations longer than 30 minutes do not benefit the strength of the samples in this case.

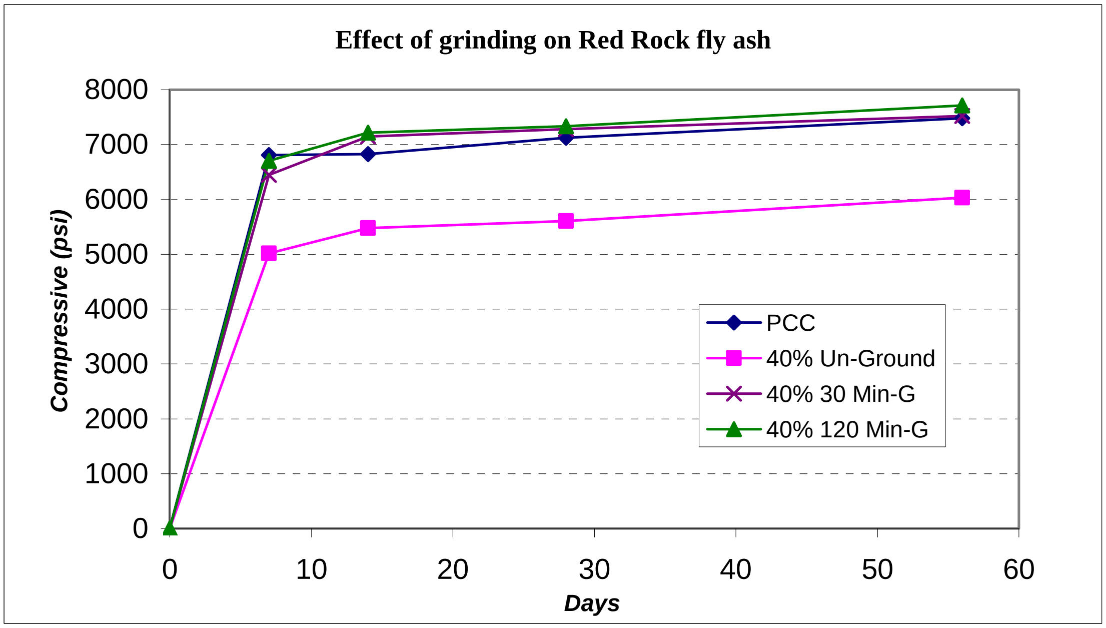


Figure 5.51 Effect of grinding duration on 40% Red Rock fly ash concrete (Mix-B).

As expected, using 60% unground fly ash in the mix reduces the compressive strength of the sample more than samples with 40% unground fly ash. This can be seen by comparing Figure 5.51 and Figure 5.52. Although the compressive strengths of 60% sample with unground fly ash are more than 2000 psi lower than PCC, the results presented in Figure 5.52 shows that grinding the Red Rock fly ash for 120 minutes increases the strength of this sample significantly. The compressive strengths of 60% samples with 120 minutes of grinding are 1000 and 2000 psi higher than 60% samples with unground fly ash at 7 and 14 days relatively, and close to compressive strength of PCC after two weeks, see Figure 5.52.

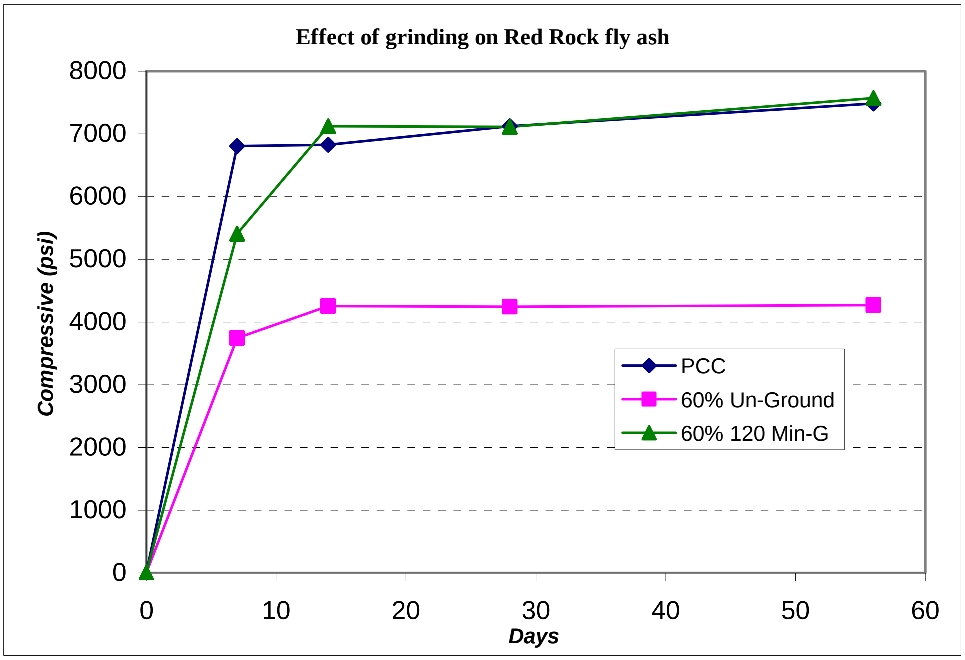


Figure 5.52 Effect of grinding duration on 60% Red Rock fly ash concrete (Mix-B).

5.3.2.2 Effect of Fly Ash Content on the Compressive Strength

Figure 5.53 illustrates the compressive strength of the samples with unground fly ash for various fly ash contents. The results shows the reduction in compressive strength of the samples when the fly ash content increases. The strength curve of the 20% samples with unground fly ash is similar to PCC. However, samples with 40% and 60% fly ash content have lower strength than PCC.

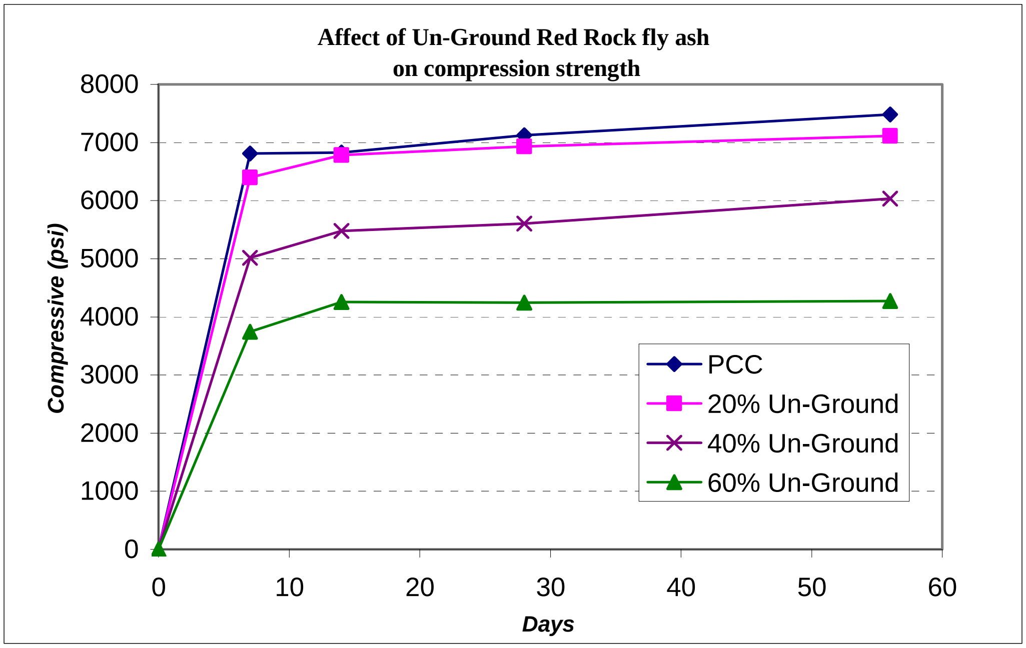


Figure 5.53 Effect of fly ash content on un-ground Red Rock fly ash concrete (Mix-B)

The results of samples with 30 minutes ground fly ash are plotted in Figure 5.54. This data indicates that up to 40% of the binder can be replaced with 30 minutes ground fly ash without reducing the compressive strength.

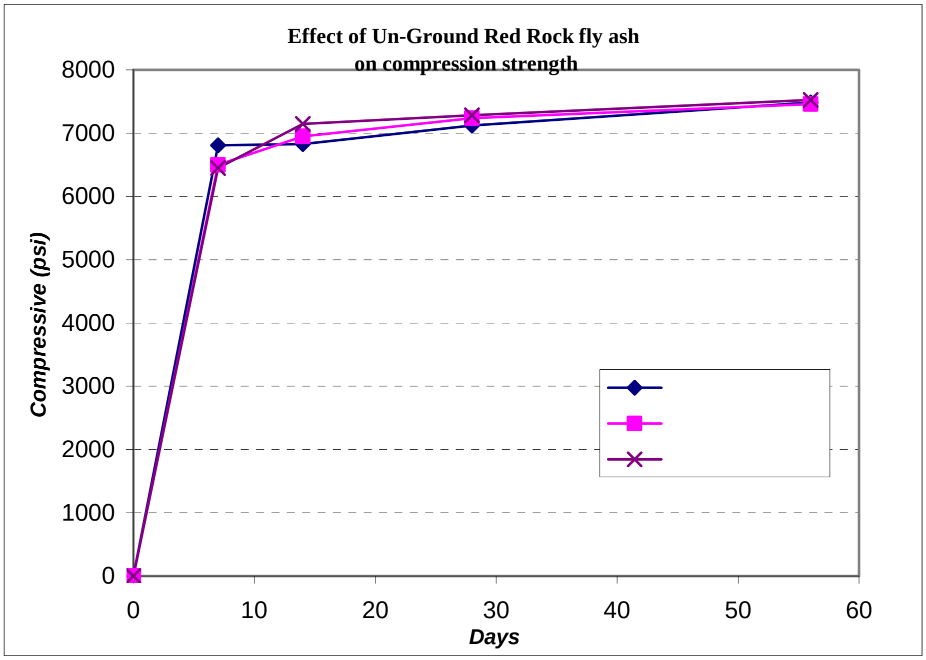


Figure 5.54 Effect of fly ash content on 30 minutes ground Red Rock fly ash concrete (Mix-B)

Figure 5.55 shows the compressive strength of the samples with 120 minutes grinding duration. The results presented in this figure indicated the possibility of replacing up to 60% of the binder with 120 minutes ground Red Rock fly ash without sacrificing strength.

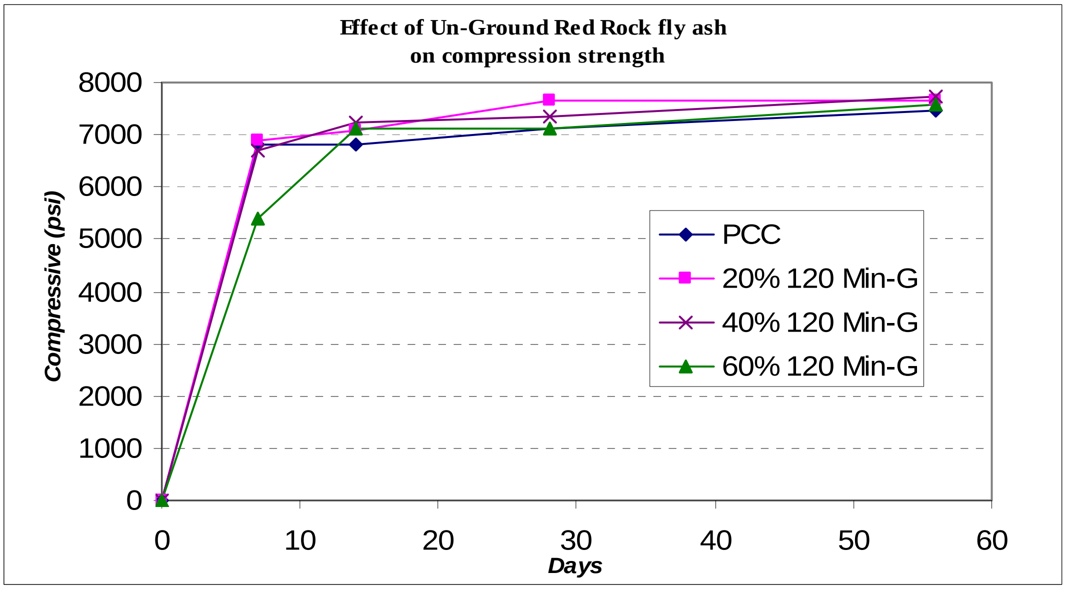


Figure 5.55 Effect of fly ash content on 120 minutes Red Rock fly ash concrete (Mix-B)

5.3.3 Mix-C Compressive Strength

5.3.3.1 Effect of Grinding the Fly Ash on Compressive Strength

The properties of Mix-C are provided in detail in Table 2.5. This mix adopted from Mix-A by increasing the *w/c* ratio to 0.39. These sets of tests were performed to monitor the sensitivity of the fly ash concrete to changes in water content. The results of compressive strength of the samples incorporated with Mix-C are provided in this section.

The compressive strengths of the samples with 20% fly ash are presented in Figure 5.56. The result indicates that replacing the 20% of binder with unground fly ash reduces the compressive strength of the samples by about 1000 psi. However, grinding the fly ash for 30 minutes not only improves this lack of strength but is almost 500 psi strength higher than PCC after seven days. This study shows that a longer duration of grinding sometimes reduces the strength of the samples. Samples incorporated with 20% 120 Minutes ground fly ash have the same performance as 20% Un-Ground samples, see Figure 5.56.

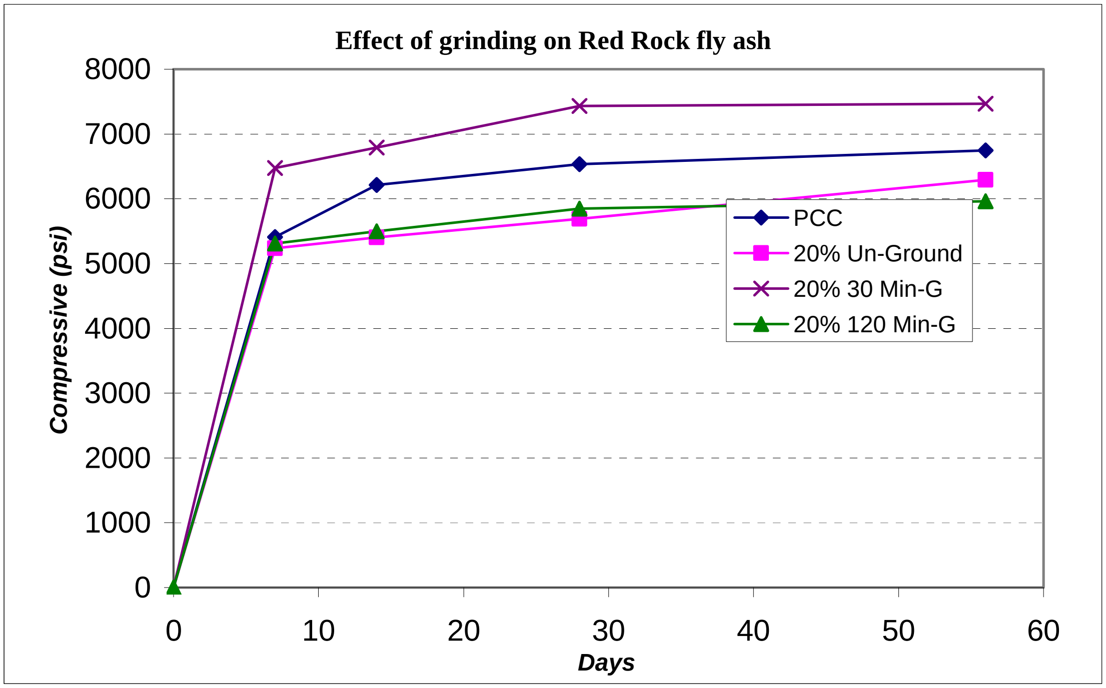


Figure 5.56 Effect of grinding duration on 20% Red Rock fly ash concrete (Mix-C).

The results of 40% fly ash samples are illustrated in Figure 5.57. The performance of the 40% fly ash samples with Mix-C is similar to the 40% fly ash samples with Mix-B. This can be seen by comparing Figure 5.57 and Figure 5.51. The compressive strength of the samples with 40% 30 Minutes ground fly ash is similar to PCC samples. The longer grinding duration, 120 minutes, does not provide additional strength to the samples.

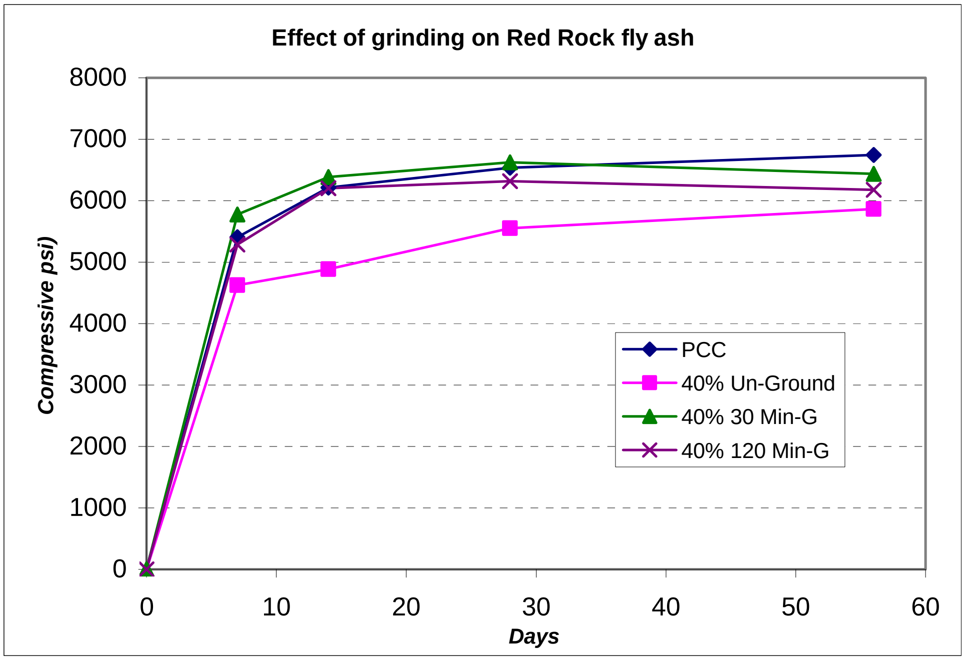


Figure 5.57 Effect of grinding duration on 40% Red Rock fly ash concrete (Mix-C).

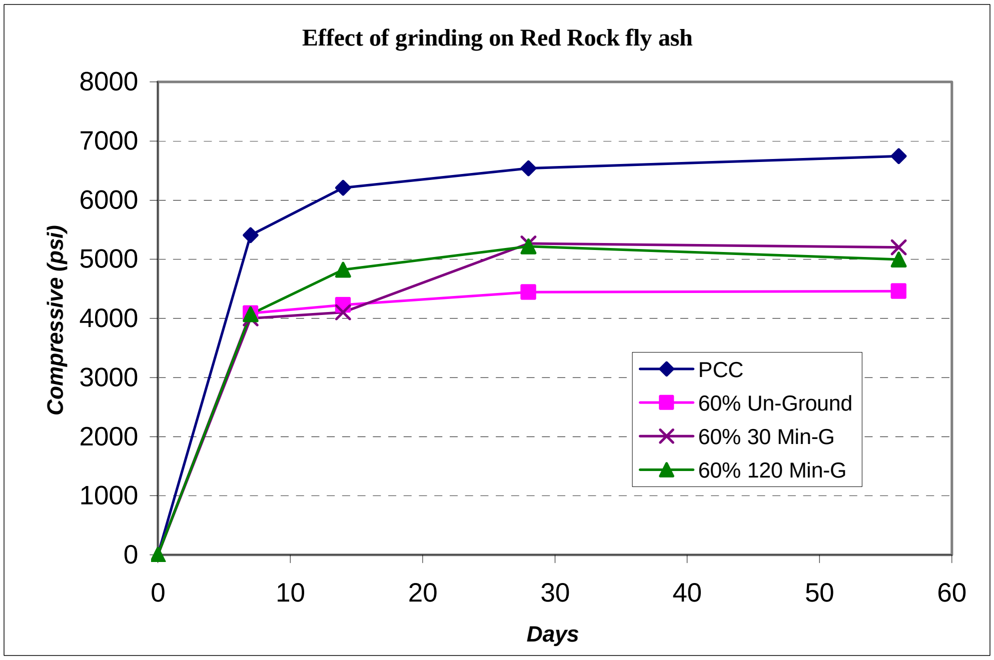


Figure 5.58 Effect of grinding duration on 60% Red Rock fly ash concrete (Mix-C).

5.3.3.2 Effect of Fly Ash Content on the Compressive Strength

The compressive strengths of samples with unground fly ash are presented in Figure 5.59. This figure shows the traditional performance of unground fly ash on the compressive strength of the samples. The samples with higher portion on fly ash have lower strength.

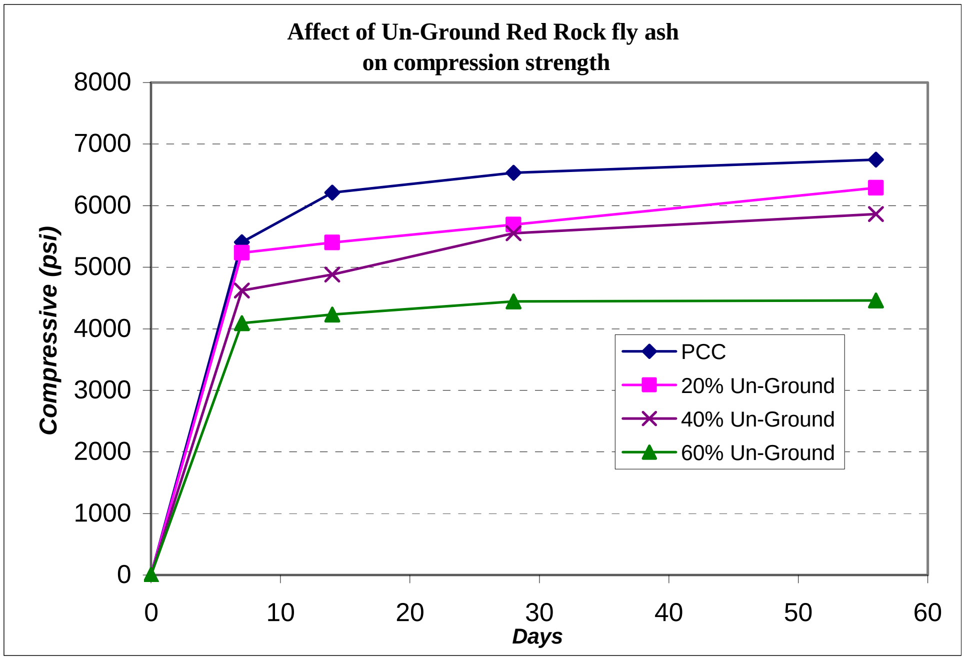


Figure 5.59 Effect of fly ash content on un-ground Red Rock fly ash concrete (Mix-C)

Grinding the fly ash for 30 minutes increases the compressive strength of the samples. These results are plotted in Figure 5.60. Using 20% of this fly ash increases the strength higher than PCC. The performance 40% samples with 30 minutes of grinding follow the same trend as PCC throughout the 56 days of research.

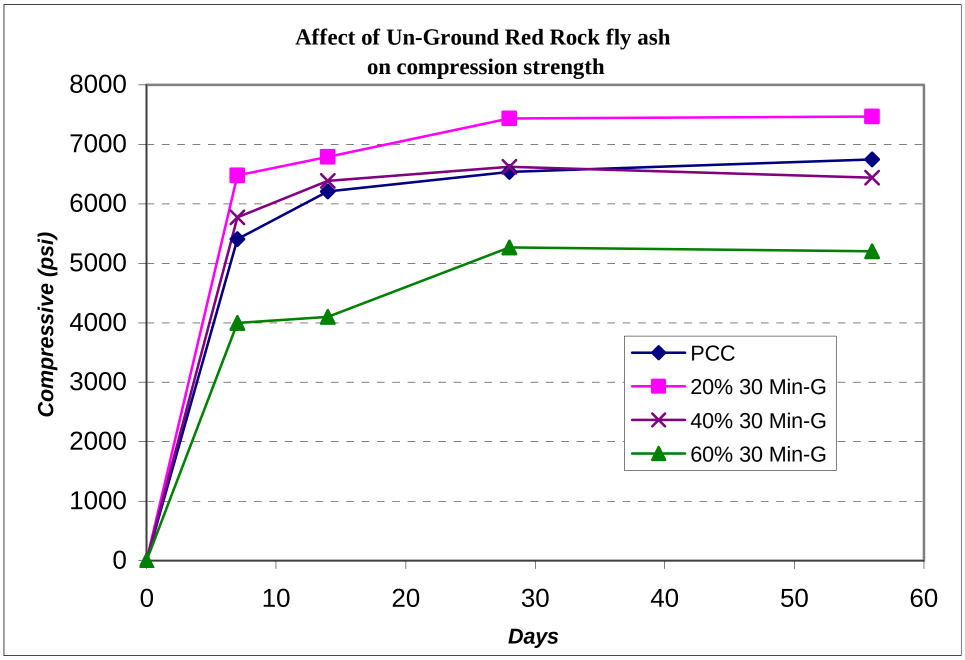


Figure 5.60 Effect of fly ash content on 30 minutes Red Rock fly ash concrete (Mix-C)

The results of the compressive strength of the samples with 120 minutes ground fly ash are presented in Figure 5.61. These results show the improvement in compressive strength of the samples with 120 minutes ground fly ash. However, the samples with higher than 20% fly ash content have lower strength than PCC.

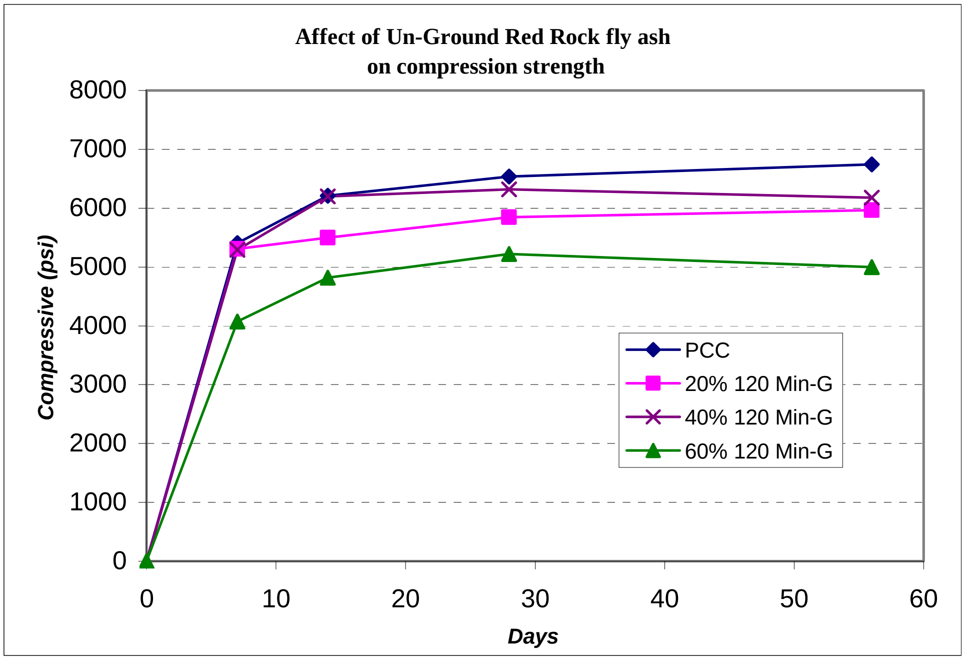


Figure 5.61 Effect of fly ash content on 120 minutes Red Rock fly ash concrete (Mix-C)

Chapter 6

Conclusions and Recommendations

Chapter 7

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