Improving Portland Cement Concrete Mix Consistency and Production Rate through Two-Stage Mixing

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Final Report
September 2007

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16. Abstract

A two-stage mixing process for concrete involves mixing a slurry of cementitious materials and water, then adding the slurry to coarse and fine aggregate to form concrete. Some research has indicated that this process might facilitate dispersion of cementitious materials and improve cement hydration, the characteristics of the interfacial transition zone (ITZ) between aggregate and paste, and concrete homogeneity.

The goal of the study was to find optimal mixing procedures for production of a homogeneous and workable mixture and quality concrete using a two-stage mixing operation. The specific objectives of the study are as follows: (1) To achieve optimal mixing energy and time for a homogeneous cementitious material, (2) To characterize the homogeneity and flow property of the pastes, (3) To investigate effective methods for coating aggregate particles with cement slurry, (4) To study the effect of the two-stage mixing procedure on concrete properties, (5) To obtain the improved production rates. Parameters measured for Phase I included: heat of hydration, maturity, and rheology tests were performed on the fresh paste samples, and compressive strength, degree of hydration, and scanning electron microscope (SEM) imaging tests were conducted on the cured specimens. For Phases II and III tests included slump and air content on fresh concrete and compressive and tensile strengths, rapid air void analysis, and rapid chloride permeability on hardened concrete.

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IMPROVING PORTLAND CEMENT CONCRETE MIX CONSISTENCY AND PRODUCTION RATE THROUGH TWO-STAGE MIXING

Final Report
September 2007

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EXECUTIVE SUMMARY

A two-stage mixing process for concrete involves mixing a slurry of cementitious materials and water, then adding the slurry to coarse and fine aggregate to form concrete. Research has indicated that this process might facilitate dispersion of cementitious materials and improve cement hydration, the characteristics of the interfacial transition zone (ITZ) between aggregate and paste, and concrete homogeneity.

The goal of the study was to find optimal mixing procedures for production of a homogeneous and workable mixture and quality concrete using a two-stage mixing operation. The specific objectives of the study are as follows:

1. To achieve optimal mixing energy and time for a homogeneous cementitious material
2. To characterize the homogeneity and flow property of the pastes
3. To investigate effective methods for coating aggregate particles with cement slurry
4. To study the effect of the two-stage mixing procedure on concrete properties
5. To obtain the improved production rates

This study is divided into three phases: (1) laboratory investigation of the interaction between cement hydration and mixing methods and times for the formation of cement paste, (2) laboratory investigation of concrete, and (3) field investigation of concrete.

In the Phase I study, two mixers (a high shear mixer and a low shear mixer) were used, with varying mixing times and speeds for slurry mixing. Pastes made with different binder combinations of cement, fly ash, and slag were tested. Heat of hydration, maturity, and rheology tests were performed on the fresh paste samples. Compressive strength, degree of hydration, and scanning electron microscope (SEM) imaging tests were also conducted on the cured specimens.

The Phase I study results indicate that increasing the mixing energy (mixing speed and time) produces a more workable and uniform slurry. This conclusion is supported by the results from degree of hydration and rheology tests of paste. After mixing energy reaches a certain level, rheological properties of a given paste may show little or no significant change with increased mixing time. For a given mixing time, a high shear mixer generally produces pastes with higher early-age strengths than those produced using a normal mixer. Based on these tests, an optimal mixer and mixing time were recommended for the Phase II study on the two-stage mixing process of concrete.

In the Phase II study, the laboratory concrete study results showed that air entrainment was difficult when the air entraining agent was added in the slurry. A weak relationship exists between the total air content and the spacing factor as determined by the rapid air void analyzer. The 28-day compressive strengths were 10 percent stronger for the two-stage mixed concrete.

In the Phase III field study, two sites (Jordan, MN and Highland, IL) were visited using two different two-stage mixing techniques. A suitable location for a field site in Iowa was not able to be achieved. Tests included slump and air content on fresh concrete. Hardened concrete tests included compressive and tensile strengths, rapid air void analysis, and rapid chloride permeability. The two-stage field test results from two projects showed that two-stage mixed concrete performed better overall when compared to conventional ready-mixed concrete. Two-stage mixed concrete was generally more resistant to chloride penetration with increased tensile strengths. The analysis of tensile strength results showed a more homogeneous concrete.

INTRODUCTION

Background

Thorough mixing of concrete ingredients is essential to producing a homogeneous mixture that permits uniform particle distribution and hydration of cement particles in the concrete system. As fine cementitious materials, low water-to-binder ratios, and high binder content are increasingly common in modern concrete, the agglomeration of fine cementitious particles often occurs, which not only impairs the uniformity of hydration of cementitious materials, but also reduces the workability of concrete. Also important is the proper coating of the aggregates in the mixing operation with proper paste that eliminates undissolved cement particles. Hence, optimal quality mixing becomes increasingly important and a method or technique is needed to help ensure the optimum quality of cement paste and coating of the aggregates.

One such method is a two-stage process in which the first stage consists of premixing water, cement and additives to prepare the paste and the second stage consists of coating the aggregate. The concept is to allow the cement and the additives to chemically combine with water in an adequate manner. By not allowing the cement and additives' undissolved particles to attach to the aggregate, the coating of the aggregate (Stage 2) in a separate operation should improve, along with the uniformity of the paste between the aggregate particles.

Traditional concrete mixing practice today is regulated by a specific mixing time required to achieve specified performance of the fresh and hardened concrete. The mixing time is based on a long experience of developed correlations between the mixing process and the concrete performance, and is generally detailed in specifications. The effects of the mixing procedure on the materials in concrete is an important area of research. A complete understanding of these procedures on a step-by-step basis, in theory and through empirical relationships, will lead to increases in the efficiency of the mixing process and improvements in concrete properties.

A two-stage mixing process for concrete involves mixing a slurry of the cementitious materials and water, then adding the slurry to the coarse and fine aggregate form concrete while mixing. The technology of cement paste preparation by high intensity mixing is being used in other industries and it is believed that this technology could be applicable in highway PCC construction. It is believed that the pre-mixing process might facilitate dispersion of cementitious material and improve cement hydration, concrete homogeneity, and the interfacial transition zone (ITZ) between aggregate and paste.

Objectives

The goal of the study was to find optimal mixing procedures for production of a homogeneous and workable mixture and quality concrete using a two-stage mixing operation. This was to be accomplished by characterizing the mixing process and mixing order to produce a homogeneous cementitious material to improve production rates while maintaining durability and quality.

The specific objectives of the study are as follows:

1. To achieve optimal mixing energy and time for a homogeneous cementitious material
2. To characterize the homogeneity and flow property of the pastes
3. To investigate effective methods for coating aggregate particles with cement slurry
4. To study the effect of the two-stage mixing procedure on concrete properties
5. To obtain improved production rates

To accomplish the objectives, the project was divided into three phases, described in the following sections.

Phase I

Phase I entailed a laboratory experimental study of cement pastes using varying energy inputs. In the experimental work, various cementitious materials, including ordinary portland cement (PC), ground granulated blast furnace slag (GGBFS), class C fly ash (FA), and combinations of these materials were selected for paste slurry. High-shear and low-shear mixers with varying mix time and speed were used for slurry mixing to provide the varied energy input. Compressive strength, degree of hydration, and scanning electron microscope (SEM) imaging tests were performed on cured specimens. Heat of hydration, maturity, and rheology tests were conducted on fresh paste binder samples. The optimum mixing time and intensity were then determined, based on the paste properties tested.

Phase II

In Phase II, an experimental study of concrete mixing technology focusing on two-stage mixing and the effects of two-stage mixing on concrete properties was conducted. Various cementitious materials including PC, GGBFS, and FA were selected for the concrete study. Based on the results of the paste studies, a limited set of combinations of the cementitious materials were tested. A conventional dry batch process (60 second mix time) was compared with a two-stage mixing process with concrete batched for 30 seconds and 60 seconds. Slump and air content were measured on fresh concrete samples. Compressive strength, tensile strength, rapid chloride permeability, and rapid air void analysis was conduced on hardened concrete samples.

Phase III

Field use of two-stage mixing was the focus of Phase III. Two field locations using two-stage mixing processes were found, including sites in Jordan, Minnesota and Highland, Illinois. Attempts by the research team during the summers of 2005, 2006, and 2007 to bring a two-stage mixing operation to Iowa for a field study were unsuccessful. Difficulty ensued in finding a suitable project location for a field-study in Iowa. For the field studies, fresh concrete properties measured include slump and air content. Hardened concrete properties measured include compressive strength, tensile strength, air void structure, and rapid chloride permeability.

PHASE I: LABORATORY INVESTIGATION OF MIXING EFFECTS ON PASTE PROPERTIES

Literature Review

Slurry Optimization According to the American Petroleum Institute

The literature survey has shown that cement slurries are an extremely crucial part of the oil well drilling process and are very important to the petroleum industry. Cement slurries are used to seal the walls of an oil well as the hole is being drilled, which requires high workability and early strength of the slurry. The American Petroleum Institute (API) has done extensive research to optimize the slurry mixing process for this application and provides lab testing specifications for oil well cement slurry mixing (API 2002).

API classifies oil well cements according to the chemical requirements of the American Society for Testing and Materials (ASTM) C 465 and special performance abilities of the cement (API 2002, ASTM 1998d). The mixing and lab testing procedures for oil well slurries are set forth by the API in Specification 10A (API 2002). API Specification 10A also states the requirements for the mixer and includes mixing speed and time.

API Lab Testing Procedures for Cement Slurries

Standard API lab tests for cement slurries include free fluid test, thickening time test, and compressive strength test (API 2002). Free fluid is defined as colored or colorless water that has separated from cement slurry. Thickening time is defined as time for cement slurry to develop a specified consistency, expressed in Bearden units. Free fluid and thickening time tests are performed with a pressurized consistometer. These test procedures, equipment, and specifications are described in detail in API Specification 10A, *Specification for Cements and Materials for Well Cementing* (API 2002).

According to API, important cement slurry properties such as rheology, thickening time, free water, fluid loss, and compressive strength can all be tied to a single parameter, mixing energy, which is primarily related to mixing speed and time for a given mixer. These properties are optimized when the specific mixing energy (SME) is close to the API recommendation of 5.5 kJ/kg. SME for a blender style mixer was defined by work per unit mass of slurry and is shown in the following equation.

$$E / M = (k \times w^2 \times t) / V$$

Where:

E = energy (kJ),
M = mass (kg),
$k = 6.4 \times 10^{-9}$ N.m/kg.m^{-3}/rpm (experimental constant),

w = rotational speed (rpm),
t = time (min), and
V = volume of slurry (m^3).

Orban, Parcevaux, and Guillot (1986) compared the effectiveness of field mixing procedures for oil well cement slurries with the effectiveness of API lab procedures. To accomplish this, the researchers normalized all the various mixing conditions to a single SME. The researchers prepared slurries using various types of field mixing techniques and according to API Specification 10A (API 2002). Rheological behavior, free water, fluid loss, thickening time, and compressive strength were tested for each mixing method. Field mixing operations used a conventional jet mixer, a recalculating type mixer, and a batch mixer to produce cement slurry. The SME was calculated and the cement slurry properties were tested for each mixer type that would be compared with the API lab procedure. The results showed that the optimum SME is valid. As the SME for the field mixing procedures approached the optimum value set by the API (5.5 kJ/kg), the cement slurry properties improved. The researchers believed that this improvement was caused by a greater deflocculation of cement particles, leading to a larger total surface area of exposed cement and promoting better contact between the water and cement.

Vidick and Schlumberger (1990) investigated the effects of mixing energy on cement slurry quality from a physical and physicochemical process. The researchers followed API lab procedures (API 2002) but varied the mixing speed from 500 rpm to 12,000 rpm and the mixing time from 15 seconds to 50 seconds. The SME was calculated for each mixing procedure; rheological behavior, fluid loss, plastic viscosity, and thickening time tests were also completed. The mixing process includes wetting the cement powder, deflocculation of the cement agglomerates, and stabilization of the suspension. The results show that deflocculation is the most crucial step in this process and it serves as a function of mixing energy. Measuring the plastic viscosity can help one determine the minimum mixing energy required to deflocculate a slurry; slurry properties are optimum at this minimum mixing energy. Above this point, slurry properties become independent of the mixing energy.

Effect of Mixing on Cement Paste Rheology

Rheology is the science of deformation and flow of matter as studied through the relationships of stress and rate of strain (Banfill 2003). Flow of cement slurry is determined by the interaction of adjacent cement particles as they move past each other in suspension. The concentration, shape, and size of the particles affect this behavior.

A typical result from a rheology program is shown below in Figure 1. Yield stress, plastic viscosity, peak stress, and the hysteresis loop can be defined from this curve. The yield stress, identified in Figure 1, is determined by extending the linear portion of the down curve to the y-axis. It is the minimum stress required for a material to start flowing/deforming (Schramm 1994).

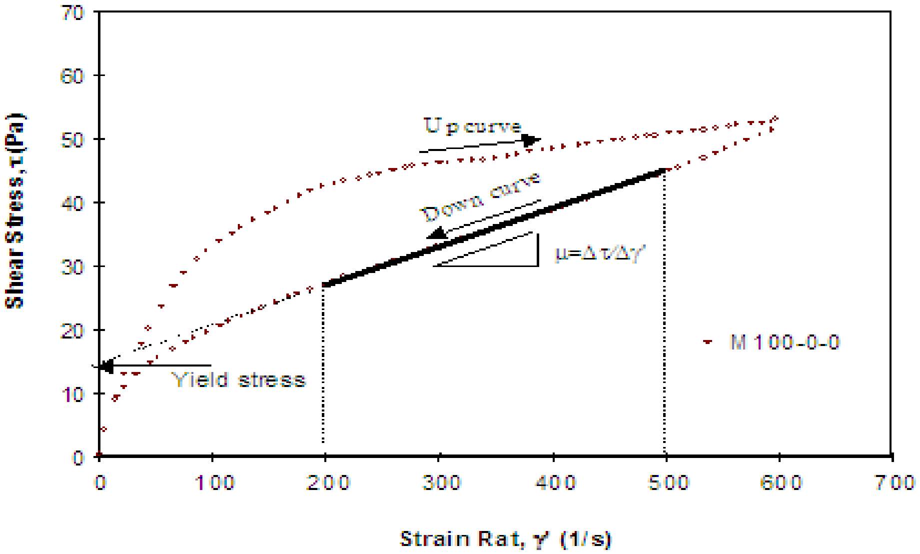


Figure 1. Typical rheology flow curve (Wang, Konsta-Gdoutos, and Shah 2001)

The plastic viscosity is the ability of a material to resist flow. Plastic viscosity (μ in Figure 1) is found from the slope of the linear portion of the down curve. High plastic viscosity is characteristic of a less flowable suspension.

The hysteresis loop is the area between the up and down curves of the flow diagram. The loop is created from a phenomenon called thixotropy, where there is a shear thinning behavior of the material. This is caused by a decrease in the viscosity as stress is applied, followed by recovery as the stress in removed (Mindness, Young, and Darwin 2003). The area of the hysteresis loop has units of energy and is related to the energy required to break down inter-particle attractions and weak bonds in the material. For cement slurries, the viscosity is not fully recoverable and the material is considered pseudo-thixotropic.

Williams, Saak, and Jennings (1999) studied the influence of the shear rate on the rheological properties of cement paste. In this study, cement paste samples were mixed using four methods with increasing shear rates. Mixing methods included hand mixing, paddle mixing, high shear mixing, and no fines concrete mixing. Cement paste samples prepared by each mixing method were tested in a constant rate rheometer while being subjected to increasing pre-shear rates. Pre-shear refers to the initial mixing in the rheometer prior to measurements being taken. In this study, the samples were pre-sheared for 60 seconds, rested for 60 seconds, and then subjected to the rheology program. The shear rate was steadily increased from $0s^{-1}$ to $100s^{-1}$ over 60 seconds and then from $100s^{-1}$ to $0s^{-1}$ over the next 60 seconds. The effectiveness of each mixing method was quantified by the area of the hysteresis loop generated and by the plastic viscosity. These parameters reveal the relative amount of structural breakdown in the cement paste sample. The results show that the hysteresis loop area and the plastic viscosity decreased with increased shear during mixing, indicating greater structural breakdown at high shear rates. The results for samples not subjected to pre-shear are shown below in Table 1.

Table 1. Hysteresis loop area and plastic viscosity for samples not subjected to pre-shear (Williams, Saak, and Jennings 1999)

Mixing method	Hysteresis loop area (J/m^3s)	Plastic viscosity (Pa-s)
Hand mixing	13,000	0.44
High shear mixer (500 rpm)	13,500	0.42
Hobart paddle mixer	8,800	0.36
High shear mixer (1500 rpm)	6,500	0.33
No fines concrete	7,100	0.31
High shear mixer (2500 rpm)	4,000	0.23

Initially, well-mixed samples were less sensitive to an increasing pre-shear rate, reinforcing the conclusion that greater mixing shear rates result in increased structural breakdown, shown in Figure 2 and Figure 3 below.

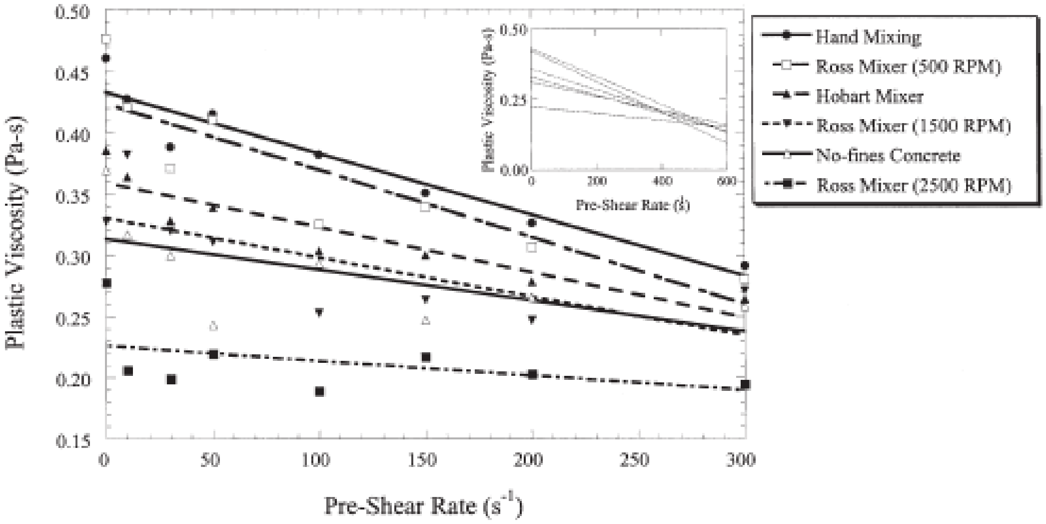


Figure 2. Plastic viscosity as a function of pre-shear rate (Williams, Saak, and Jennings 1999)

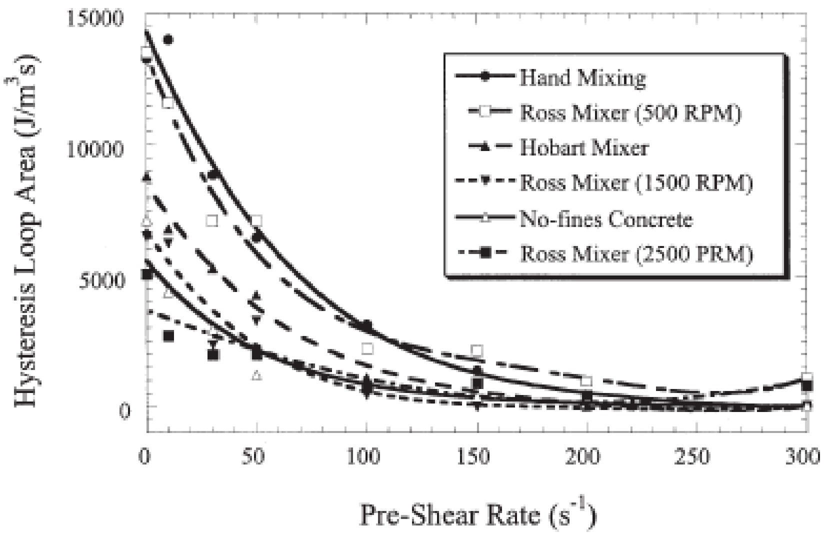


Figure 3. Hysteresis loop area as a function of pre-shear rate (Williams, Saak, and Jennings 1999)

Yang and Jennings (1995) investigated the influence of mixing intensity on the rheological properties and microstructure of cement paste. Rheological properties have typically been studied qualitatively, but the effect of mixing intensity on the microstructure of the cement particles is poorly understood. The authors wanted to determine the structural defects that occur from insufficient mixing and how these defects influence rheological behavior. Three mixing methods of increasing intensity were used: hand mixing, mixing in an ASTM C 305 standard paddle mixer (ASTM 1998c), and mixing with a high-energy mixer. The results, shown in Figure 4, show the peak stresses measured at different hydration times for each mixing method. The peak stresses for hand mixing and mixing in the paddle mixer increased faster and at a much more dramatic rate than the hand mixing of sieved cement and mixing in the high-energy blender.

This result suggests that the high peak stresses measured could be caused by agglomerates of cement paste that did not get broken down during mixing, and that the agglomerates could contribute significantly to the flow behavior. The authors reinforced this theory by physically observing the texture and consistency of the cement pastes under a microscope. The hand- and paddle-mixed cement pastes each had a rough texture and observable agglomerates about 0.3 mm in diameter, making up about 30 percent of the slurry. The hand-mixed with sieved cement and high energy-mixed samples had a homogenous, creamy texture and contained no observable agglomerates.

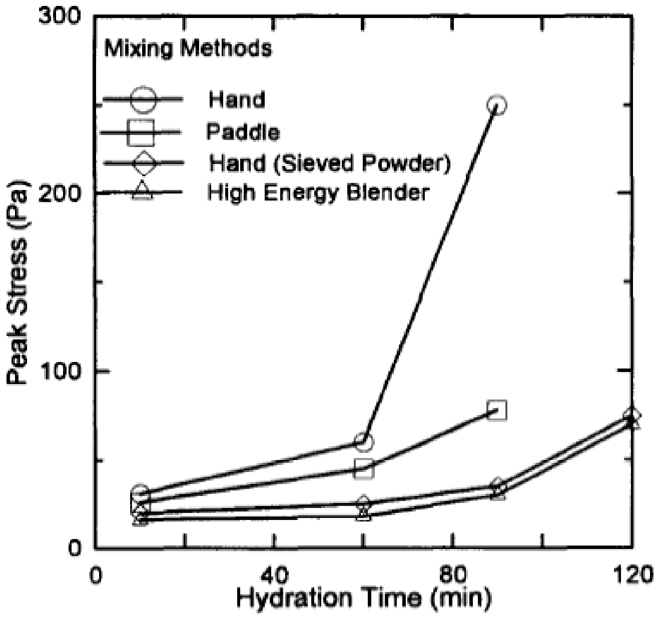


Figure 4. Effect of mixing methods on peak stress of cement paste (Yang and Jennings 1995)

Vlachou and Piau (1997) investigated the rheological effects of subjecting a slurry to slow, continuous stirring after its initial mixing. Cement slurries were prepared using a high shear blender following API specifications (API 2002) and then separated into two portions. The first portion was stirred continuously at 150 rpm and the other was kept at rest. Rheological properties were measured at six stages over 18 hours for both cement slurries. The results show that continuous stirring of the cement slurry can delay the set time and improve the rheological properties of the slurry for up to 15 hours after mixing, as shown in Figure 5. The set time and rheological properties for the cement paste that was not stirred increased at a much more dramatic rate over the 18 hours. Scanning electron microscope (SEM) and x-ray diffraction (XRD) analyses showed that stirring does not stop hydration; rather, it inhibits hydration products and crystals from forming bonds, allowing the slurry to be more workable for a longer period of time.

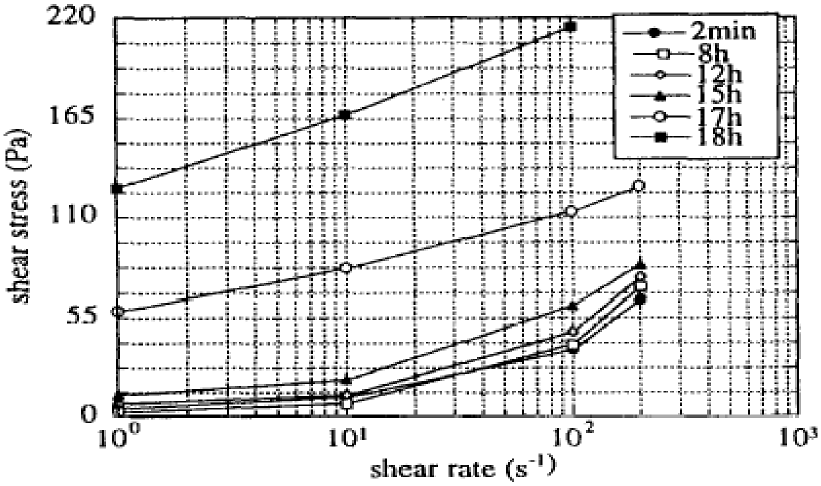


Figure 5. Delayed increase in rheometric properties due to continued stirring (Vlachou and Piau 1997)

There are a number of rheological models—such as the Bingham model, the Herschel and Bulkey method, and the Casson method—that are used to fit to the properties and the specific curves formed from different materials (Dzuy and Boger 1985). Yield stress is one of the most common measurements, but even for a given material, values can vary under different experimental conditions. Dzuy and Boger (1985) performed a study demonstrating that yield stress values of flocculated slurries can consistently be determined using a simple vane apparatus. In this study, the theory of each rheology model was described, but the comparison was not solved analytically. Rather, the above-mentioned conventional models were used to fit data gathered using a capillary rheometer and data were then compared to results gathered for the same material using the vane method of rheometry testing. These tests were repeated over a range of moisture contents. The results show a direct relationship between the yield stress values obtained for the convention models and the vane method, as shown in Figure 6 below.

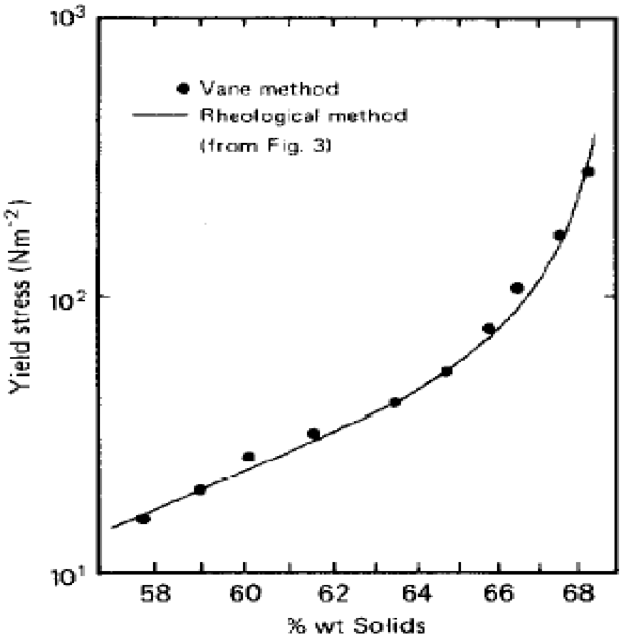


Figure 6. Yield stress relationship between conventional rheological models and the vane method (Dzuy and Boger 1985)

Summary of Phase I Literature

Cement paste slurry has been commonly used in the oil well industry. The American Petroleum Institute (API) has developed standard tests for slurry, including free fluid (bleeding test), thickening time (pseudo set time), and compressive strength. Additionally, for oil well studies, specific mixing energy has been used to normalize mixing conditions for comparison.

A review of the literature shows that deflocculation of cement particles, or cement agglomerations, is the most crucial element in a mixing process that consists of wetting cement particles, deflocculating agglomerations, and stabilizing the suspension. Rheology results in the literature point to this effect and best differentiate the differences between mixing methods. Results indicate that increased shear mixing leads to a greater structural breakdown of agglomerations, as noted by visual observation using a microscope. Rheology results also show that continued mixing of pastes can delay set time. Literature states that the set time is delayed; although hydration is not stopped, the mixing inhibits bonds from forming. No information regarding the effects of mixing energy on strengths of pastes was found in the literature review.

Experimental Work

For the paste study, a testing plan was formulated to effectively evaluate the influence of high shear mixing and normal mixing methods on the properties of paste. This included tests on fresh paste and hardened paste at different stages of the curing process. Testing was concentrated on the high shear mixing technique, because this technique will most likely be used in a two-stage concrete mixing process in concrete practice. Samples were prepared using each mixing method at different mixing times and mixing speeds. The cementitious materials used for the samples included Type I portland cement (PC), ground granulated blast furnace slag (GGBFS), and class C fly ash (FA). Rheology tests were conducted on freshly mixed slurry. Heat of hydration, or heat signature curves, were developed for the pastes as samples cured; compressive strength and degree of hydration tests were completed on the hardened paste binders; and SEM images were taken on select hardened paste samples. The results from all tests were compared for all mixing time/mixing speed combinations of the high shear and normal mixing methods.

Paste Materials and Mix Proportions

Holcim Type I portland cement, Port Neal IV Class C fly ash, and Holcim GGBFS were used. The chemical composition and fineness of each binder are detailed in Table 2 below. The combinations and proportions of the selected blended cements are used by the Iowa Department of Transportation (Iowa DOT 2002). These proportions are shown below in Table 3. Cold tap water was used for all mixing water; the water-to-cementitious material ratios (w/cm) were calculated and are presented below in Table 4.

Table 2. Chemical composition and fineness of binders

		Holcim Type I cement	**Holcim GGBFS**	**Port Neal Type IV fly ash**
Chemical composition, %	CaO	64.24	37.09	27.85
	SiO_2	20.80	36.79	34.23
	Al_2O_3	5.55	9.20	18.91
	Fe_2O_3	2.25	0.76	5.54
	MgO	1.91	9.50	—
	K_2O	0.50	0.41	—
	Na_2O	0.19	0.34	—
	SO_3	2.96	—	2.68
	TiO_2	0.26	0.44	—
	P_2O_5	0.48	0.02	—
	SrO	0.05	0.04	—
	Mn_2O_3	0.05	0.55	—
	S	—	1.07	—
Fineness (m^2/Kg)		399	534	12.44%*

* % retained on #325 sieve

Table 3. Binder proportions by volume

Mix	Cement	Fly ash	Slag
1	100%	0%	0%
2	85%	15%	0%
3	65%	35%	0%
4	65%	0%	35%
5	50%	15%	35%

Table 4. Binder proportions by weight

Mix	Cement		Fly ash		Slag		Water		w/cm
	lbs/yd^3	kg/m^3	lbs/yd^3	kg/m^3	lbs/yd^3	kg/m^3	lbs/yd^3	kg/m^3	
1	663.7	393.8	0.0	0.0	0.0	0.0	285.5	169.4	0.430
2	564.1	334.7	84.3	50.0	0.0	0.0	285.4	169.3	0.440
3	431.3	255.9	196.7	116.7	0.0	0.0	285.4	169.3	0.455
4	431.3	255.9	0.0	0.0	216.8	128.6	285.4	169.3	0.440
5	331.9	196.9	84.3	50.0	216.8	128.6	285.5	169.4	0.451

Paste Study Mixing Methods

The normal mixing process followed ASTM C 305, *Standard Practice for Mechanical Mixing of Hydraulic Cement Paste and Mortars of Plastic Consistency* (ASTM 1998c). The mixer used, shown in Figure 7, is a standard Hobart model N50 mixer. The sequence for adding the ingredients followed ASTM C 305, but the mixing times were changed.

The high shear mixing process was adapted from slurry mixing procedures for oil well cement slurries specified by API Specification 10A (API 2002). A Chandler Engineering Waring Blender model 3070 high shear mixer was used. The model 3070 high shear mixer, shown in Figure 8, meets the mixer requirements specified in API Specification 10A. The exact order of adding the ingredients was the same for high shear mixing as for normal mixing methods, following ASTM C 305 (except for the above-mentioned deviations).

The mixing procedure was as follows: (1) water was added to the mixing bowl, (2) dry binder was added over approximately 15 seconds, and (3) the mixer was started on the selected mixing speed for a selected mixing time.

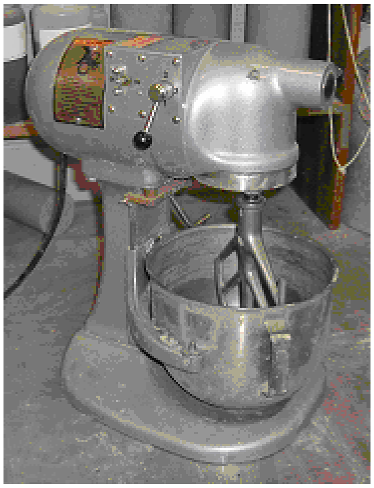


Figure 7. Hobart mixer

Figure 8. Chandler Engineering Waring Blender

Paste Study Test Variables—Mixing Time and Speed

Mixing time and speed were the two variables investigated for each mixing method. The variations of mixing times and speeds were the same for each batch mixed. The combinations of mixing times and speeds are shown below in Table 5. Note that speed 1 is slow and speed 2 is fast.

Table 5. Combinations of mixing time and mixing speed

Mixer	Mixing time (seconds)	Speed (mixer setting)
Hobart mixer	15	1, 2
	30	1, 2
	45	1, 2
	60	1, 2
High shear mixer	15	1, 2
	30	1, 2
	45	1, 2
	60	1, 2

Speeds one and two were different for each mixing method. For the high shear mixing method using the Waring blender, speed one was 6,000 rpm and speed two was 14,000 rpm (Chandler Engineering 2003). For the normal mixing method using the Hobart mixer, speed one was 140 ±5 rpm and speed two was 285 ±10 rpm (ASTM 1998c).

A testing matrix was created where each mix design in Table 4 was mixed by each combination of mixing time and speed in Table 5 using the high shear mixer. Only mix one (100% cement) was mixed using the Hobart mixer, for comparison to high shear mixing. There is an abundance of literature about the effects of mixing on slurry properties for the Hobart mixer, because it is specified for paste mixing by the ASTM Standards (ASTM 1998c). All combinations of mixing time and speed were completed with mix one using the Hobart mixer, with the exception that all mixes using speed two on the Hobart mixer had to be mixed on speed one for 15 seconds first. This added mixing time on the lower speed was necessary to premix the binder and water into a paste. If the Hobart mixer was started on speed two without premixing, much of the water and some binder would be thrown from the mixing bowl due the high mixing speed.

Paste Test Methods

Five different tests were conducted: rheology, heat signature and maturity, degree of hydration, compressive strength, and scanning electron microscope (SEM) imaging.

Rheology

Rheology samples prepared as above were immediately transferred into a 3 x 6 in (75 x 150 mm) cylinder for testing using a Brookfield R/S SST 2000 soft/solid rheometer. Rheometer results were obtained through the use of a 40 x 80 mm four-bladed vane, with the exception of the Hobart mixer on speed one. The material for the Hobart mixer on speed one exceeded the maximum shear stress capabilities of the rheometer; therefore, these data were collected using a 15 x 30 mm four-bladed vane.

Heat Signature and Maturity

The heat signature, or curing temperature, was measured using iButtons programmed with five minute reading intervals, embedded in 50 x 100 mm (2 x 4 in.) cylinders of fresh paste. Samples were prepared using each mixing method for each binder combination, placed in the cylinder mold, and sealed in a vacuum thermos Dewar cylinder to retain as much of the generated heat as possible. The Dewar cylinders were then placed in a Styrofoam container and stored in a room at a temperature of 21.1°C (70°F). After four days, the samples were crushed to remove the iButton and the temperature data was downloaded to a computer. The maturity was calculated from the measured temperature history in accordance with ASTM C 1074, *Standard Practice for Estimating Concrete Strength by the Maturity Method* (ASTM 1994b).

Degree of Hydration: Furnace Method

Three 50 x 50 mm (2 x 2 in.) paste cubes were prepared for each mixing method and binder combination and were cured for seven days. After this time, a powder sample passing a number 16 sieve was drilled from the center of each cube using a drill press. Approximately 3 g of the powder sample was placed in a 10 ml crucible. The crucibles containing the powder samples were placed in an oven at a constant temperature of 105°C (221°F) for 24 hours. After this time, the crucible and samples were weighed again to obtain the weight of evaporable water (W_{105}) driven off during heating. The crucibles and samples were then placed in a furnace, heated to 1000°C (1832°F), and kept at that temperature for one hour. After being removed and reaching room temperature, the crucibles and samples were weighed again to obtain an estimation of the hydrated water, or non-evaporable water (W_{1000}). The amount of non-evaporable water is determined by the difference of the two weights at 105°C and 1000°C.

Compressive Strength

The compressive strength tests were performed on 50 x 50 mm (2 x 2 in.) paste cubes, according to ASTM C 109/C 109M, *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)* (ASTM 1998a). Twelve samples were prepared using each mixing method for each binder combination. Three samples from each batch were tested at 3, 7, 14, and 28 days.

SEM Imaging

Samples representing the lowest mixing energy (Hobart mixer, speed one for 15 seconds) and the highest mixing energy (high shear mixer, speed two for 60 seconds) were prepared for SEM imaging. Two binder combinations (100% PC and 85% PC–15% FA) were prepared using the previously mentioned mixing methods. Samples were cast in 25 x 50 mm (1 x 2 in.) cylinders and cured for 24 hours. To stop the hydration reactions, procedures reported by Lam, Wong, and Poon (2000) were followed. The samples were polished prior to SEM analysis. A Hitachi S-2460N vP scanning electron microscope in backscatter mode was used to collect all images. Three sets of four pictures were taken at different locations on each sample at magnifications of

50x, 150x, 500x, and 1500x. An imaging program was used to estimate the percent area of unhydrated cement particles in the samples. It should be noted that corrections were made for the white lettering portion in each image. The lettering made up 1.25 percent of the overall area of the images, so this portion was subtracted from the area of the white unhydrated cement particles in the computer-adjusted images.

Paste Test Results

Rheology Results

The following results, shown in Figure 9 through Figure 11, were collected using a 40 x 80 mm four-bladed vane. The results for the Hobart mixer, shown in Figure 9, are only for speed two. Tests for the Hobart mixer at speed one exceeded the maximum shear stress capabilities of the rheometer, so no data were collected for the 40 x 80 mm vane. Data for the Hobart mixer at speed one was collected using a 15 x 30 mm vane and is presented in the following section. Complete rheology results for each mixing method and binder can be referenced in Hermanson (2005).

Figures 9 through 11 present the rheology results for the 100% PC binder (Hobart mixer and high shear mixer). Results show the shear stress values decrease with the addition of supplementary materials in the binder. Decreases were greater with the addition of fly ash than with slag.

The longest mixing time for speeds one and two using both mixers produced a rheology curve with the lowest shear stress values in seven of the eleven tests. The shortest mixing time resulted in a rheology curve with the highest shear stress values for eight of the eleven tests. This indicates that there is no variation in rheology parameters for those mixing methods and binder combinations. Another important trend, shown in Figure 9 and Figure 11, is that the shear stress values for the same binder combinations are lower for the high shear mixer than the Hobart mixer.

Rheology tests were duplicated for the 100% PC binder combination using the Hobart mixer and high shear mixer. This was necessary because the slurries prepared at speed one in the Hobart mixer exceeded the shear stress capacity of the rheometer for the 40 x 80 mm vane. Using a smaller (15 x 30 mm) vane reduced the shear stress values to the measurable range. Since a different vane size was used, the values in the results below are not comparable to those collected by the 40 x 80 mm vane. The results for the high shear mixer were collected to allow for comparison between the data collected using the 15 x 30 mm vane.

The trends in the data for the 15 x 30 mm vane, found in Hermanson (2005), follow those presented above for the 40 x 80 mm vane. The rheology curves for slurries mixed in the high shear mixer had lower shear stress values than the slurries mixed in the Hobart mixer. Values ranged from 65 to 90 Pascals (Pa) for the high shear mixer and 110 to 170 Pa for the Hobart mixer.

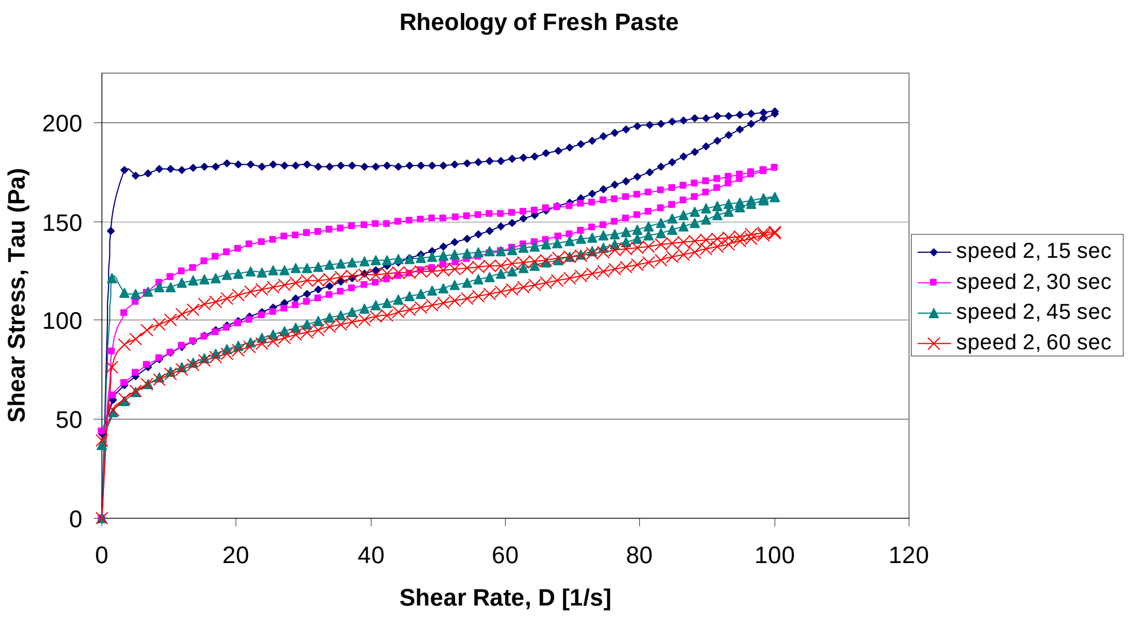


Figure 9. Rheology results for speed two, 100% PC, Hobart mixer

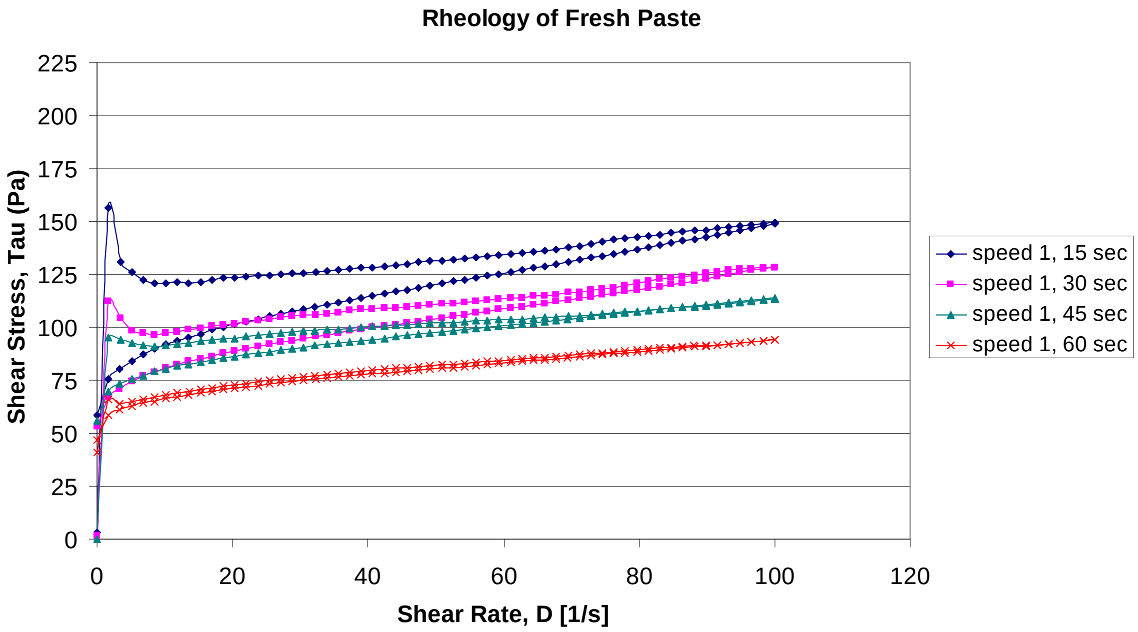


Figure 10. Rheology results for speed one, 100% PC, high shear mixer

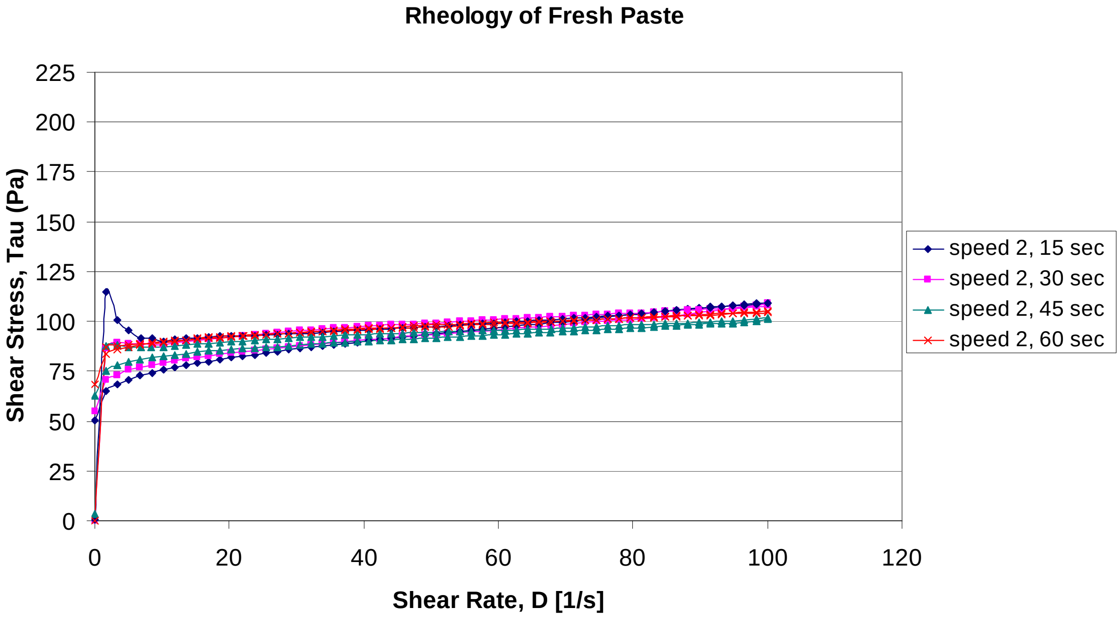


Figure 11. Rheology results for speed two, 100% PC, high shear mixer

Comparison of Rheology Parameters

The yield stress data for all of the rheology tests are presented in Figure 12 for the 40 x 80 mm vane and Figure 13 for the 15 x 30 mm vane. The results clearly show that the yield stress values decrease with the addition of supplementary materials in the binder. This decrease was greater for the addition of fly ash than slag. The general trend in yield stress values for all mixing methods is linear as mixing energy increases. In both figures, there is a slight decease in yield stress as mixing time increases for speed one, but the opposite trend can be seen for speed two. These trends are somewhat inconsistent, as the yield stress values show some variation. It is also important to note that there is little variation in the yield stress values produced by the 100 percent cement binder for the high shear mixer and Hobart mixer.

Viscosity data are presented in Figure 12 and Figure 13. The results show that viscosity values decrease with increasing mix time for both speeds one and two, and the viscosity values at a mixing time of 15 seconds are lower at speed two than speed one. A 15-second mixing time on speed one produced the maximum viscosity values for each mix, and the 60-second mixing time on speed two produced the minimum viscosity values for each mix. These trends are consistent throughout the viscosity results. In both Figure 12 and Figure 13, a large decrease in viscosity can be seen between the slurry prepared by the Hobart mixer and the high shear mixer, with the viscosities for the Hobart mixer being much higher.

Trends similar to the viscosity results can be seen in the thixotropic area results, shown in Figure 14. The thixotropic area, or area of the hysteresis loop, decreases with increased mixing time for both speed one and speed two. This trend is consistent for each mixer. In addition, the thixotropic area produced by the Hobart mixer is much larger than that produced by the high shear mixer.

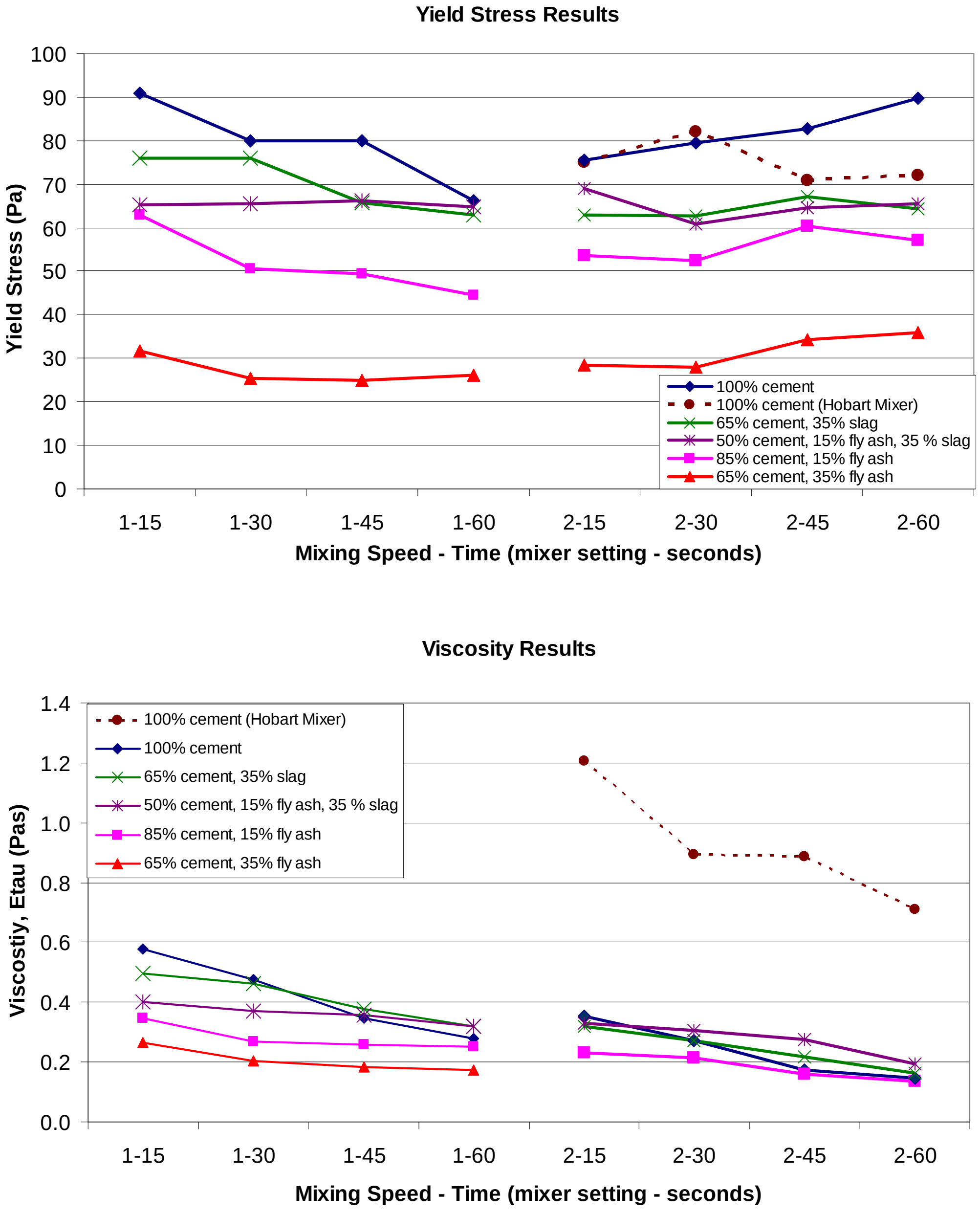
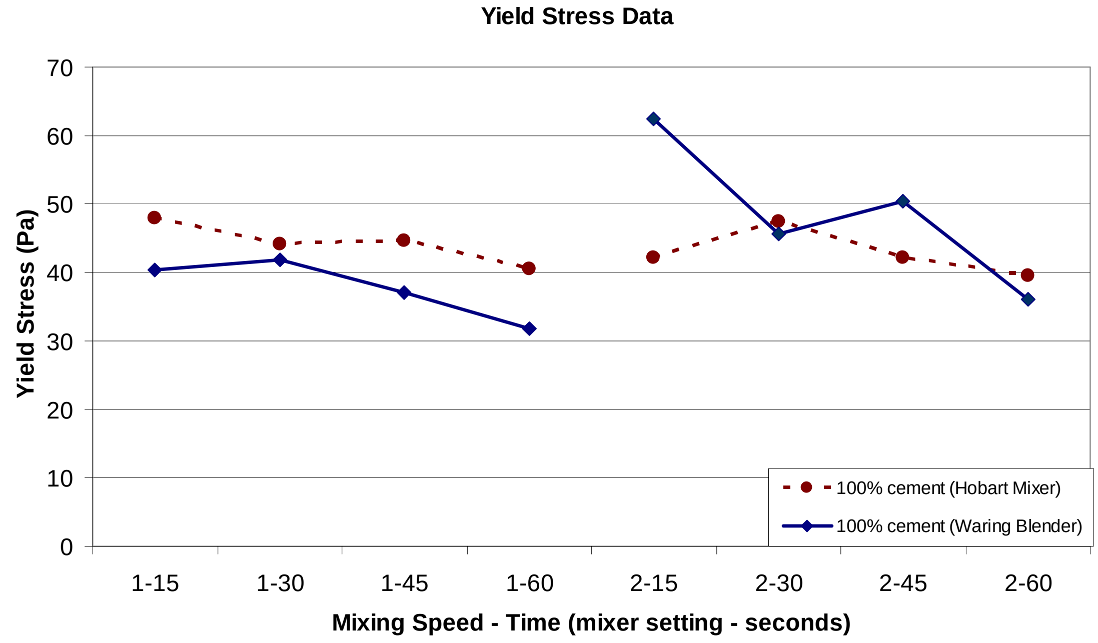


Figure 12. a) (Top) Yield stress results for the 40 x 80 mm vane b) (Bottom) Viscosity results for the 40 x 80 mm vane



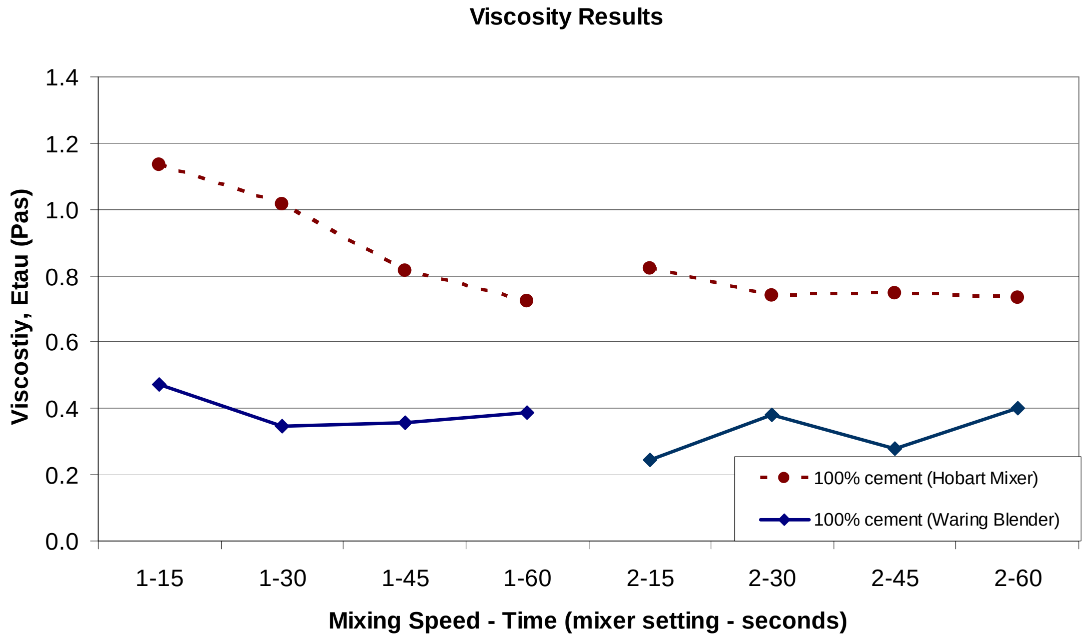
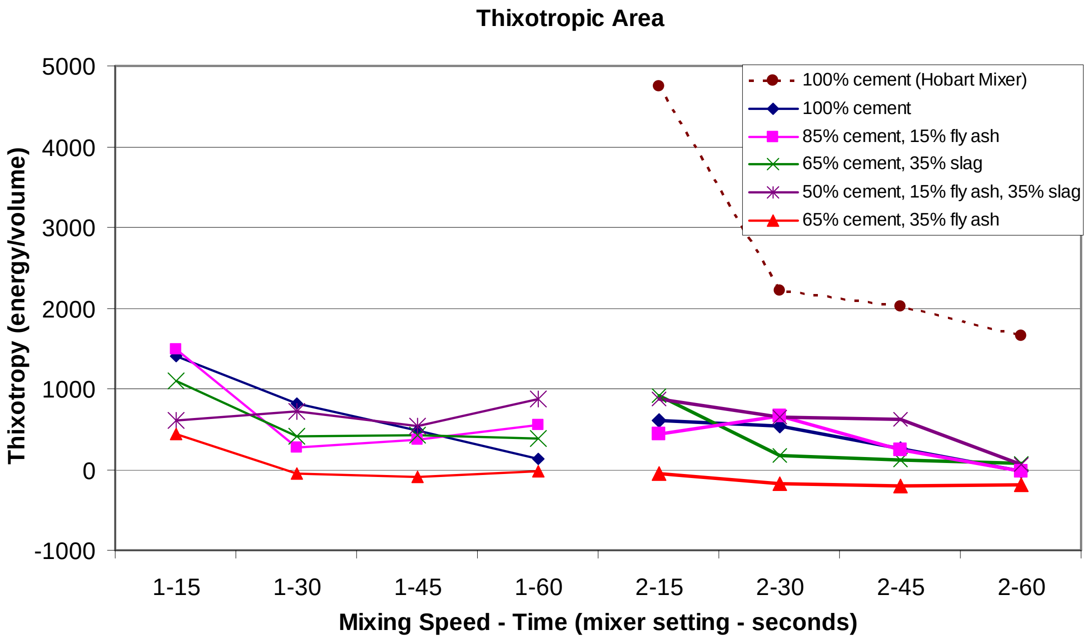


Figure 13. a) (Top) Yield stress results for the 15 x 30 mm vane b) (Bottom) Viscosity results for the 15 x 30 mm vane



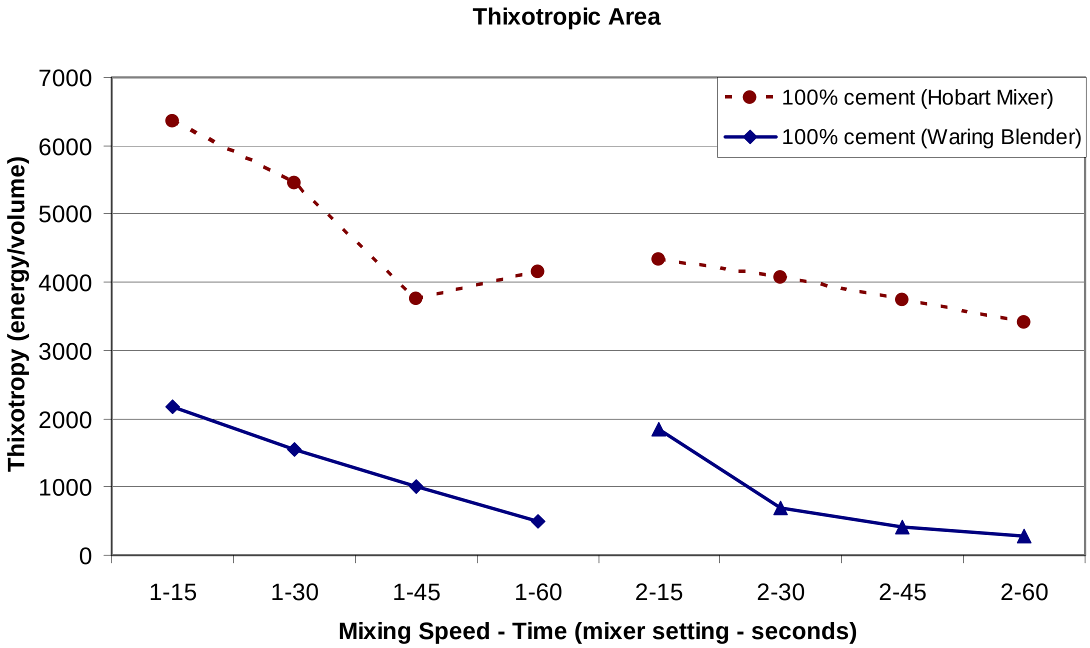
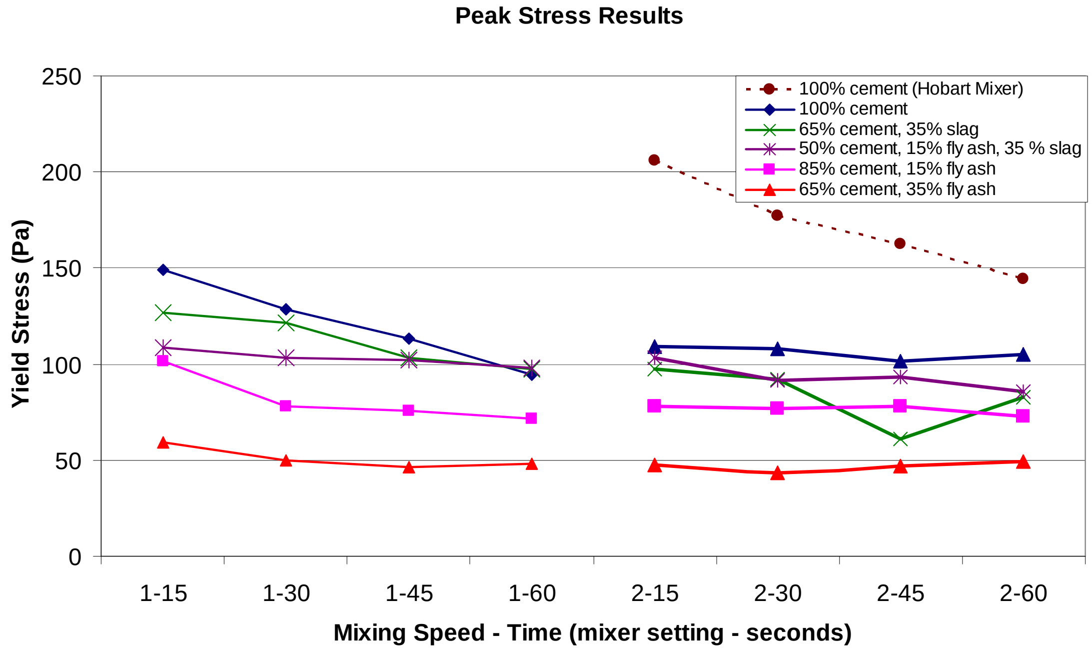


**Figure 14. a) (Top) Thixotropic areas for the 40 x 80 mm vane
b) (Bottom) Thixotropic areas for the 15 x 80 mm vane**

The peak stress results shown in Figure 15 are similar to viscosity and thixotropic area results. The peak stress values decrease slightly with increased mixing time for speeds one and two. The peak stress values produced by the Hobart mixer are much greater than the peak stress values produced by the high shear mixer.



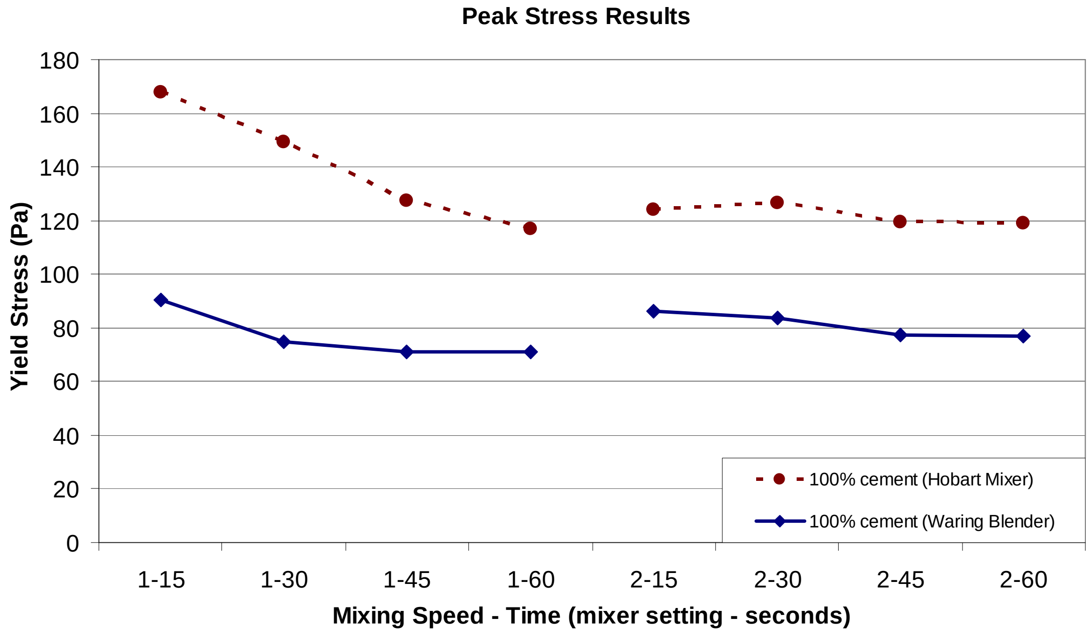


Figure 15. a) (Top) Peak stress results for the 40 x 80 mm vane b) (Bottom) Peak stress results for the 15 x 30 mm vane

The rheology results shown clearly display the effects of mixing time and speed, providing an excellent source for drawing conclusions about the effectiveness of each mixing procedure. Generally, high mixing energy produced low shear stress values. This indicates that increasing the mixing energy improves slurry flowability. The viscosity results show that the high shear mixer produced more flowable slurries than the Hobart mixer.

Increasing mixing energy decreases the thixotropic area generated, indicating that there are fewer agglomerations in the slurry. The Hobart mixer produced thixotropic areas much larger than the high shear mixer, showing that the high shear mixer provided much more energy to the system and created a greater structural break down of the slurry than did the Hobart mixer.

Another important trend shown in both the viscosity and thixotropic area results is that the values for each begin to converge as mixing energy increases. At some point, at a mixing energy greater than what is represented in this study, the points will converge. When this happens, there would be no increased benefit of continued mixing. Based on the tested parameters, this would be the optimum point. Any further decrease in these values when trying to achieve convergence would be minimal.

The peak stresses generated by the Hobart mixer are much greater than those produced by the high shear mixer, showing that the overall shear strength of the slurry suspension produced by the high shear mixer is less than what is produced by the Hobart mixer, making the slurry easier to mix.

Heat of Hydration and Maturity Results

The heat of hydration results for 100% PC are shown in Figure 16 and Figure 17. The heat of hydration results for the remaining mixes can be found in Hermanson (2005). The results show trends that the rate of hydration, or rate of heat generation, increases with increased mixing speed. In four of the six mixes prepared, the mixing combination of speed two at 60 seconds produced the greatest rate of hydration. For two of these sets of samples, the mixing combination of speed two at 15 seconds produced the second greatest rate of cement hydration.

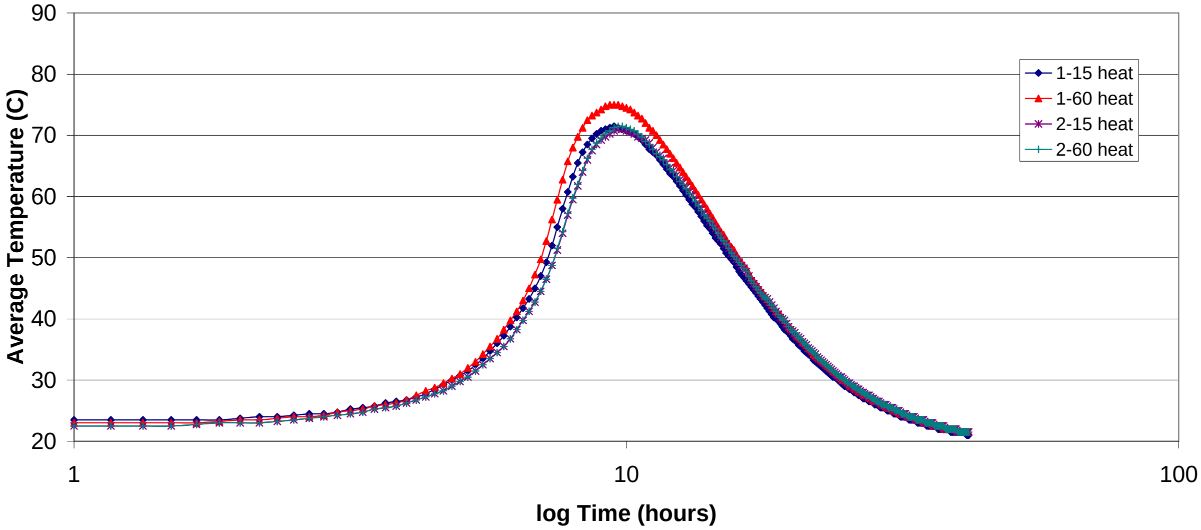


Figure 16. Heat of hydration results for 100% PC, Hobart mixer

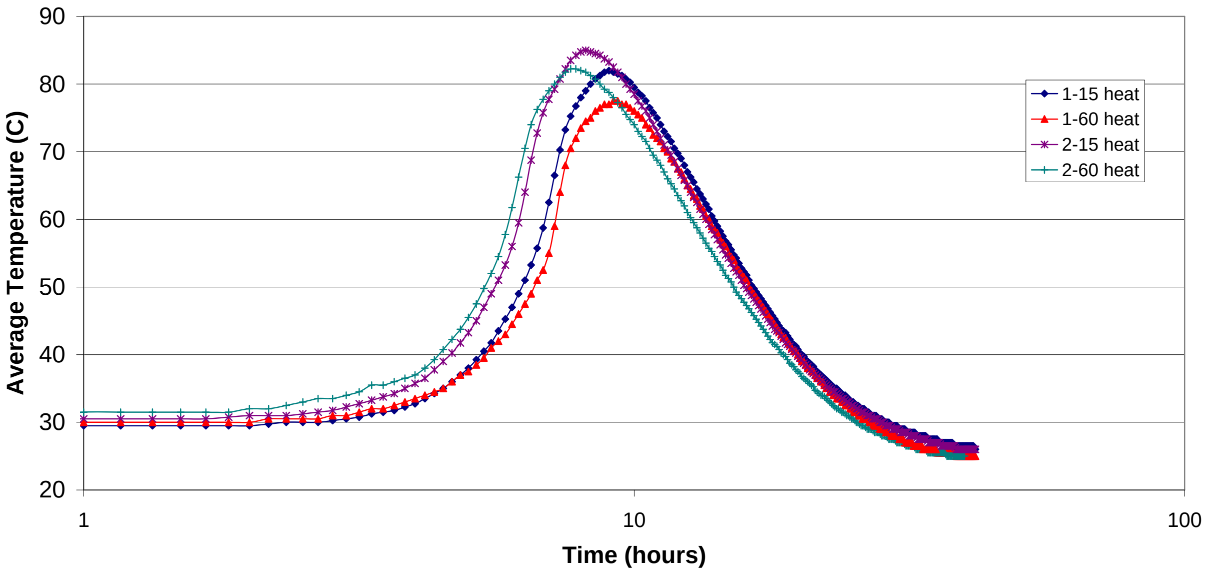


Figure 17. Heat of hydration results for 100% PC, high shear mixer

In perfectly mixed slurry, where all cement particles are uniformly coated with water and evenly distributed in the paste, the rate of the initial hydration reaction and the maximum heat generated should increase and the time the hydration reaction takes should decrease. This trend is not consistent throughout the results, but the maximum mixing energy of mixing speed two for 60 seconds did produce the highest rate of hydration in four of the six sets of samples. This trend supports the statement above and the conclusion that increased mixing energy increases the rate of cement paste hydration. The trend in the maturity data reflects this same result.

Degree of Hydration Results

The degree of hydration results show that high shear mixing always provided the paste with a higher degree of hydration than the Hobart mixer, by an average of about 6 percent. These results are shown in Figure 18.

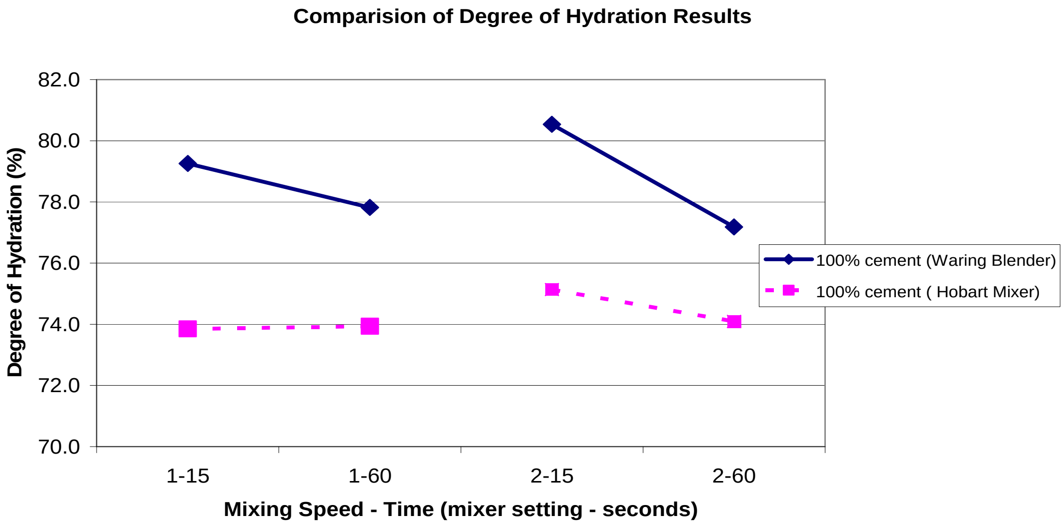


Figure 18. Comparison of degree of hydration for the high shear mixer and Hobart mixer

The degree of hydration decreased with the addition of supplementary cementitious material (SCM) as shown in Figure 19. The high shear mixer 100% PC and 85% PC–15% FA samples produced similar degree of hydration results. The degree of hydration decreased about 12 percent with the addition of 35% FA, 25 percent with the addition of 35% GGBFS, and 30 percent with the addition of 35% GGBFS and 15% FA.

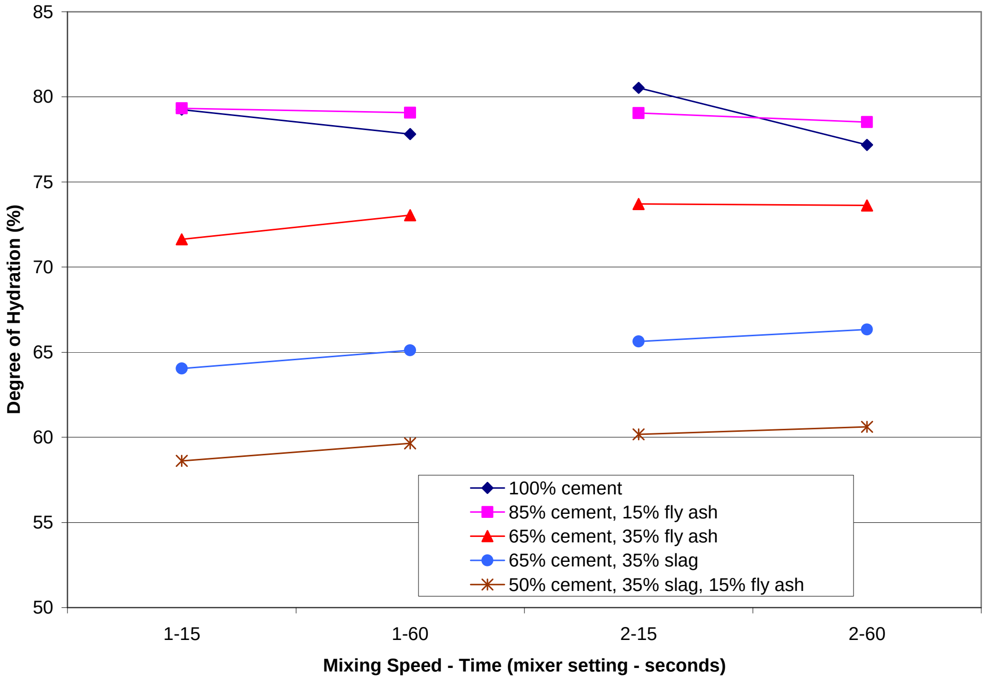


Figure 19. Degree of hydration results for the high shear mixer

Compressive Strength Results for the Paste Study

The effects of mixing methods on paste compressive strength are illustrated in Table 6 and Table 7. For the individual sets of samples, the compressive strength increased significantly with age. The differences in compressive strength are clear for the different mixes. Note that the strength of paste mixed with the high shear mixer appears slightly higher than that of paste mixed with the Hobart mixer.

Table 6. Average compressive strengths for the Hobart mixer for 100% PC mix 1

		Cure Time (Days) and Compressive Strength *(psi)			
	Mixing Speed-Time	3	7	14	28
100% PC	1-15	6,508	8,774	9,166	10,318
	1-30	6,129	8,184	8,330	9,634
	1-45	6,037	7,806	9,039	9,705
	1-60	6,111	8,118	8,359	9,109
	1-15, 2-15	6,614	7,907	8,492	10,145
	1-15, 2-30	6,381	7,840	9,394	10,229
	1-15, 2-45	6,487	7,857	9,556	10,106
	1-15, 2-60	6,363	8,053	9,442	10,294

Table 7. Average compressive strength for the high shear mixer for all mix designs

		Cure Time (Days) and Compressive Strength *(psi)			
	Mixing Speed-Time	3	7	14	28
100% PC	1-15	7,047	8,008	9,103	10,433
	1-30	6,881	8,062	9,735	10,252
	1-45	6,893	8,417	9,215	9,561
	1-60	6,216	8,276	8,347	9,914
	2-15	6,721	9,325	9,845	10,162
	2-30	6,784	8,683	9,956	10,084
	2-45	6,879	8,777	9,756	9,566
	2-60	6,175	8,271	9,140	9,732
85% PC – 15% FA	1-15	5,507	7,231	8,101	9,554
	1-30	5,094	6,116	7,696	9,295
	1-45	5,006	5,521	8,030	8,668
	1-60	5,434	7,513	8,419	9,261
	2-15	5,128	7,526	8,852	9,137
	2-30	5,029	5,883	8,240	9,166
	2-45	4,965	5,668	8,014	9,561
	2-60	5,616	7,610	8,577	8,903
65% PC – 35% FA	1-15	2,953	4,750	5,508	6,578
	1-30	2,943	5,201	6,385	6,184
	1-45	3,056	4,638	5,631	6,490
	1-60	3,048	4,667	6,303	6,771
	2-15	2,864	4,847	5,659	6,902
	2-30	2,997	4,489	6,356	6,967
	2-45	3,154	5,194	6,177	6,287
	2-60	3,278	5,221	6,136	6,512
65% PC – 35% GGBFS	1-15	4,073	6,363	8,474	10,079
	1-30	4,142	6,380	8,250	9,251
	1-45	4,017	5,924	8,354	8,320
	1-60	3,945	6,133	7,936	9,000
	2-15	3,960	6,099	7,970	10,294
	2-30	3,926	5,993	7,853	8,723
	2-45	3,981	5,992	7,916	8,883
	2-60	4,422	6,563	8,409	9,780
50% PC – 35% GGBFS – 15% FA	1-15	2,290	3,859	5,562	7,423
	1-30	2,311	3,588	6,407	7,453
	1-45	2,198	3,960	5,528	7,999
	1-60	2,152	3,818	6,245	7,461
	2-15	2,070	3,867	6,537	7,502
	2-30	2,310	3,881	6,168	7,613
	2-45	2,500	4,123	5,480	7,692
	2-60	2,617	4,237	6,627	8,208

*Results are an average of three samples

Observations from the compressive strength data show that the compressive strength increases significantly with age; the differences in compressive strengths are clear for different mixes. Note that the compressive strength of paste mixed with the high shear mixer appears to be slightly higher than that of paste mixed using the Hobart mixer. Mixing time has little effect on the compressive strength. These observations may be affected by the sensitivity of the compressive strength test equipment and method. Compressive strength charts and individual strength results for all mixes can be found in Hermanson (2005).

The results (see Table 6 and Table 7) show that mixing time has little effect on the compressive strength. The high shear mixer produced higher early-age compressive strengths than the Hobart mixer. This trend can be seen in the three-day results. The high shear mixer produced higher three-day compressive strengths for seven out of the eight samples. The compressive strength increased by an average of 6 percent. These trends are shown in Figure 20.

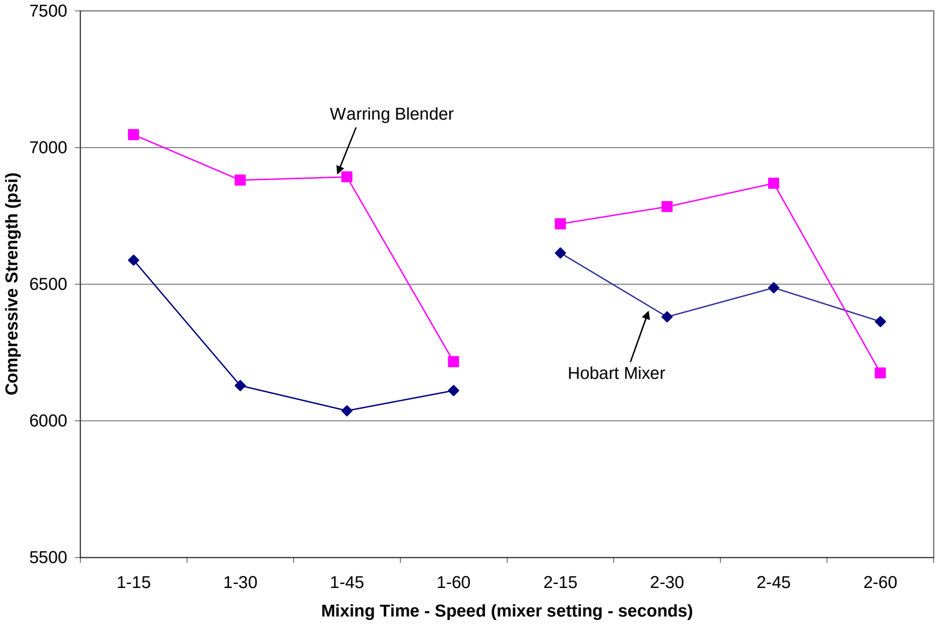


Figure 20. Three-day compressive strength for 100% PC

SEM Imaging Results

Scanning electron microscopy images were prepared to characterize the hydrated and unhydrated cement particles in the paste specimens. Figure 21 and Figure 22 show the SEM and computer-adjusted SEM image for 100% PC samples prepared using the high shear mixer speed 2 at 60 seconds. SEM images were obtained from specimens from three mixes using the high shear mixer and two mixes using the low shear mixer. SEM images collected and the computer-adjusted images for the other four mixes can be found in Hermanson (2005).

Table 8 presents the percentage of unhydrated cement particles in samples prepared by the Hobart mixer and the high shear mixer. The minimum mixing produced about two times the average area of unhydrated particles than the maximum mixing energy produced for each binder combination. It should be noted that the computer alteration of the images did require some interpretation and could influence the consistency of the results.

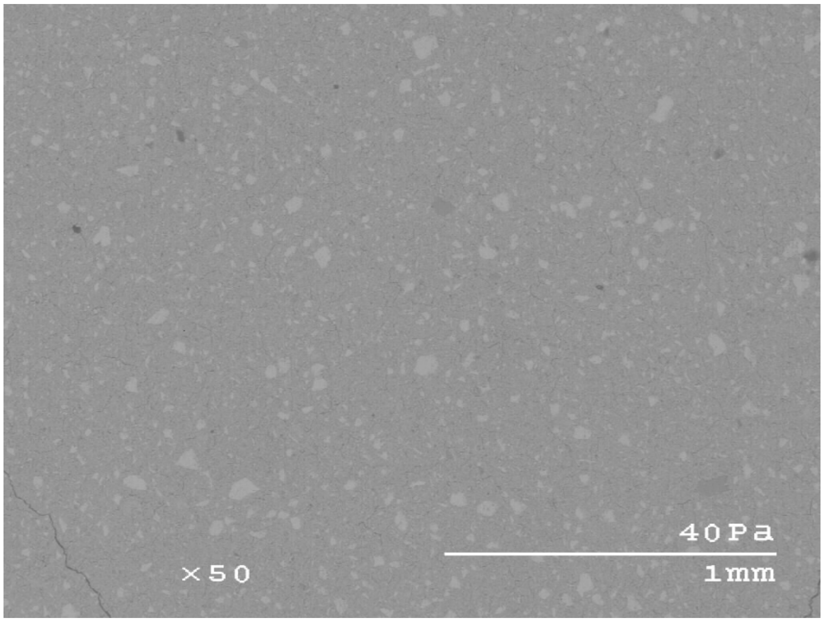


Figure 21. SEM image for the high shear mixer, 100% PC, speed two, 60 seconds

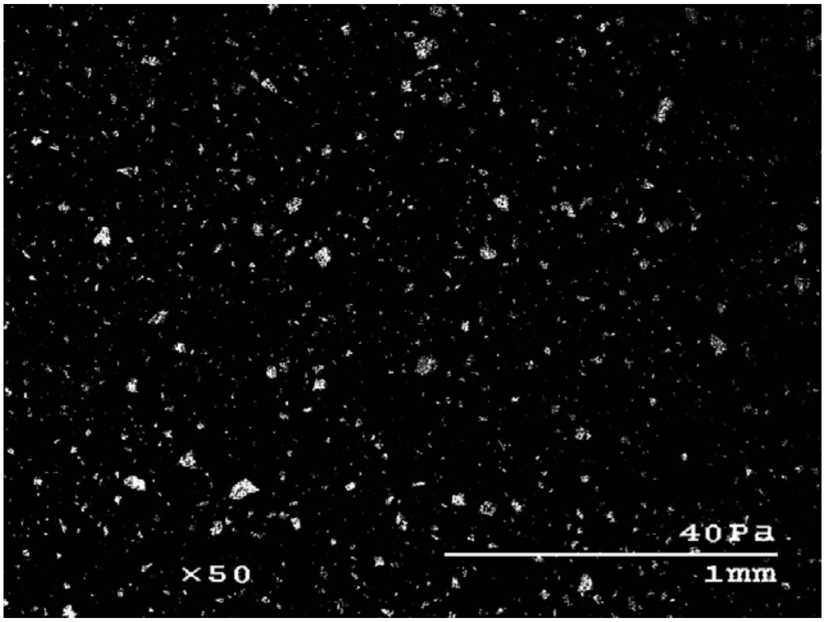


Figure 22. Computer-adjusted SEM image for the high shear mixer, 100% PC, speed two, 60 seconds

From the computer interpretation of the area of unhydrated cement particles, it is clear that the maximum mixing energy produced a lower amount of unhydrated particles. These results show more complete mixing and a greater percentage of cement agglomerates being broken down during high shear mixing.

Table 8. Percentage of unhydrated cement particles for 100% cement

Mixer	Mixing speed - time (Setting - seconds)	Binder combination	Area % of unhydrated particles
Hobart	1-15	100% cement	15.49 15.41 14.32 average = 15.07
High shear mixer	1-15	100% cement	9.85 9.79 9.42 average = 9.69
High shear mixer	2-60	100% cement	7.04 6.81 6.65 average = 6.83

Summary of Phase I Findings

Among all tests conducted for the pastes in the present study, rheology testing is the most suitable test that clearly shows the differences in mixing energies (expressed by mixing time and speed). The heat of hydration, compressive strength, and degree of hydration are less affected by mixing method.

Results from the paste study show that concretes produced by two-stage mixing with high shear slurry mixing will provide more workable concrete with a greater degree of hydration and improved compressive strengths, especially at early ages.

In addition, the following findings occurred during the Phase I study:

1. The rheology test results in this study show that increasing the mixing energy (high mixing speed and long mixing time) reduces the plastic viscosity, thixotropic area, and peak stress generated by a given rheology test procedure. This trend is consistent through all of the data sets and indicates that increasing the mixing energy produces a more thoroughly mixed slurry. When mixing energy reaches a certain level, increased mixing may not significantly improve the paste’s rheological properties. This indicates that, once that point has been reached, the slurry has been mixed uniformly and further mixing is not necessary.
2. Pastes consisting of different material and mix proportions have different mixing energy requirements for reaching optimal uniformity. Pastes containing fly ash generally require

lower mixing energy to reach their optimum uniformity than pastes containing only cement.

3. Mixing energy influences the cement hydration process. Heat signature tests show that major heat generation occurs earlier for pastes mixed with higher mixing energy. The high shear mixer, at mixing speed two and 60 seconds of mixing time, produced the earliest hydration reactions.
4. The degree of hydration tests indicate that high shear mixing always produces a slightly greater degree of hydration than normal mixing, and that the degree of hydration decreases with the addition of supplementary cementitious materials.
5. High shear mixing generally produces pastes with slightly improved compressive strength when compared to normal mixing. In this study, the improvement was greater at early ages of three and seven days. This is consistent with results from heat signature and degree of hydration tests.
6. SEM image analysis shows that high shear mixing produces a smaller percent of unhydrated cement particles that increases with increased mixing time, confirming the degree of hydration test results.

PHASE II—TWO-STAGE LABORATORY STUDY ON CONCRETE

Literature Review

Concrete Mixers

There are three main types of concrete mixers: drum mixers, pan mixers (which are considered batch mixers) and continuous mixers (Ferraris 2001). Drum mixers have a large rotating drum with blades attached to the inner sides of the drum. The concrete materials are mixed by the blades lifting the materials while rotating and then dropping the materials back into the center of the drum. The rotational speed of the drum is controlled to ensure proper mixing for the mix design and batch size.

Drum Mixers

Variations of drum mixers include a reversing drum (where the rotational direction can be reversed and the concrete constituents are loaded from one end and discharged from the other) and tilting angle drums (where the centerline axis of the drum can be increased from horizontal, forcing the concrete to mix in the bottom portion of the drum). Tilting axis drum mixers are loaded and discharged from the same end. Drum mixers that operate at a zero degree angle, completely horizontal, provide more energy to the concrete mixing process, because the concrete materials are lifted to the largest height by the blades before being dropped. Typical concrete truck mixers fall into the tilting drum category, rotating at 2 rpm for premixed concrete and 15 rpm when all the separate concrete ingredients are added and mixed in the truck mixer. Concrete truck mixers typically have a 15 degree angle of tilt. Figure 23 below shows a typical cross-section of a drum mixer.

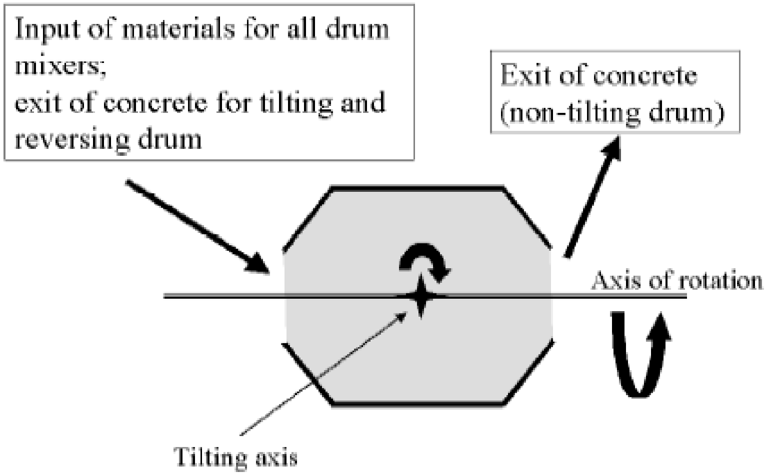


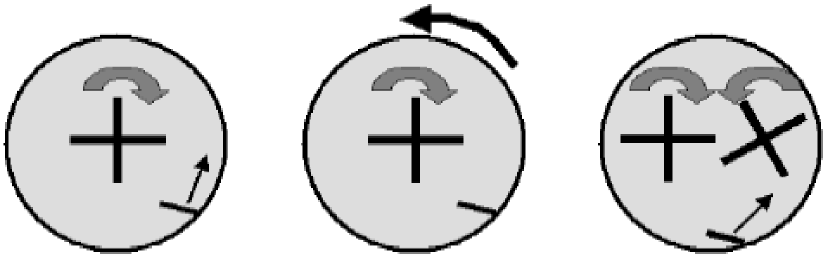
Figure 23. Cross-section of a drum mixer (Ferraris 2001)

Pan Mixers

Pan mixers employ a flat cylindrical pan to hold the concrete constituents. The pan is either stationary or rotating and has mixing blades separate from the pan that rotate inside it. If the pan is rotating, the blades rotate in the opposite direction. A separate blade is fixed against the inside edge of the pan and scrapes the material off the side, moving it towards the center where the mixing blades are rotating. Figure 24 shows the various configurations of blades. Note that the configurations of the blades may vary, but all have the same effect. Large pan mixers—those greater than 0.2 m^3 (0.26 yd^3)—typically discharge from a door in the bottom of the pan. Small pan mixers—those less than 0.2 m^3 (0.26 yd^3)—discharge by removing the material from the top of the pan.

Continuous Mixers

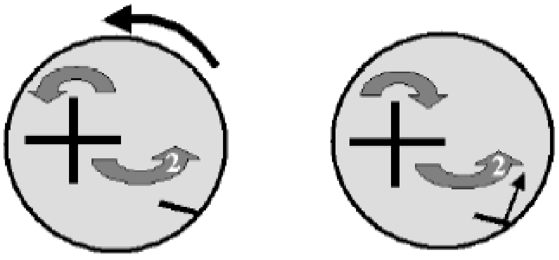
Continuous mixers load material at the same rate that it is discharged. They are usually non-tilting drum mixers with a screw-type blade configuration that mixes the material as it is pushed through the mixer. These mixers are used for situations that require a short mixing time, have small batches, or are located in remote sites not convenient for ready-mix truck delivery. Portable batch plant mixers that produce low slump concrete are often continuous mixers.



a. Center shaft
(Pan fixed/scraper moving.)

b. Center shaft
(Pan rotating/scraper fixed.)

c. Dual Shaft
(Pan fixed/scraper moving.)



d. Counter-current motion
(Pan rotating/scraper fixed. The shaft is also rotating following Arrow 2.)

e. Planetary motion
(Pan fixed/scraper moving The shaft is also rotating following Arrow 2.)

Figure 24. Various blade configurations for a pan mixer (Ferraris 2001)

Effects of Mixing on Concrete Properties

Concrete mixing is a complex process in which many factors influence the quality of a final concrete product. These factors include loading sequence, mixing time, mixer type, and the time and rate of the addition of chemical admixtures

Variations in Traditional Mixing Processes

The American Society for Testing and Materials (ASTM) standards C 94 and C 305 outline guidelines for standard mixing procedures for concrete (ASTM 1994a, ASTM 1998c). ASTM C 94 specifies that (1) some water and the aggregates should be added and mixed, (2) cement is added and mixed, and finally, (3) the remaining portion of the water is added with no more than one-fourth of the total mixing time elapsed. Liquid admixtures are added with the mixing water. ASTM C 305 specifies a different order for adding cement components. This procedure calls for initially mixing the water, cement and fine aggregate into a uniform mortar, then adding the coarse aggregates.

Ferraris (2001) defined concrete quality by the homogeneity of the final product, influenced primarily by the loading period and mixer efficiency. These parameters need to be matched to the mixer type to produce quality concrete. The loading period includes the time in which all ingredients are added into the mixer and the order in which the ingredients are added. Dry mixing and wet mixing processes are included as long as ingredients are still being introduced. The loading period is mixer specific and should be determined by quality of the final concrete. Mixer efficiency includes the loading rate, discharge rate, and mixer energy, defined as the power consumed during mixing. Mixer efficiency is determined mainly by the concrete’s homogeneity but also by its workability, density, air content, and compressive strength. Mixer efficiency is also influenced by the proportions of the concrete ingredients and the batch size.

Gaynor (1996) studied the influence of concrete truck mixers on concrete properties. He concluded that non-uniformity in truck-mixed concrete is caused by agglomerations of concrete materials inside the mixer, including head packs and cement balls. To remedy the non-uniformity problems, Gaynor suggested that one-fourth of the mixing water be added as the last ingredient and that the mixer rotate at 20–22 rpm.

Soga and Takagi (1986) reported that the addition rate of the mixing water and the rotational speed of the mixing drum control fresh concrete characteristics. In particular, the bleeding rate of fresh concrete decreases as the addition rate of water decreases and the rotational speed of the mixer increases.

Similarly, Tamimi (1994) and Mitsutaka and Yasuro (1982) studied the effects of adding the mixing water at two separate times during the concrete mixing process. In the first stage, the aggregate and a weight of water equal to 25 percent of the weight of the cement were mixed for 30 seconds. The cement was added next and mixed with the other ingredients for 60 seconds. In the final stage, the remaining water was added and mixed for 90 seconds. Concrete produced by this technique was labeled “sand enveloped with cement concrete” (SEC). The goal of the studies was to investigate the effectiveness of this new mixing technique in reducing the bleeding rate of fresh concrete and increasing the compressive strength at various stages of curing. Tamimi (1994), Mitsutaka and Yasuro (1982) concluded that this method did in fact reduce the bleeding rate of fresh concrete and improved the compressive strength over conventionally-mixed concrete. Tamimi (1994) took the research further to prove that adding water using this formula leads to a greater gel-to-space ratio in the interfacial transition zone (ITZ), creating a more intimate bond, lower porosity, and increased micro-hardness in the ITZ. The increase in micro-hardness is shown in Figure 25 below.

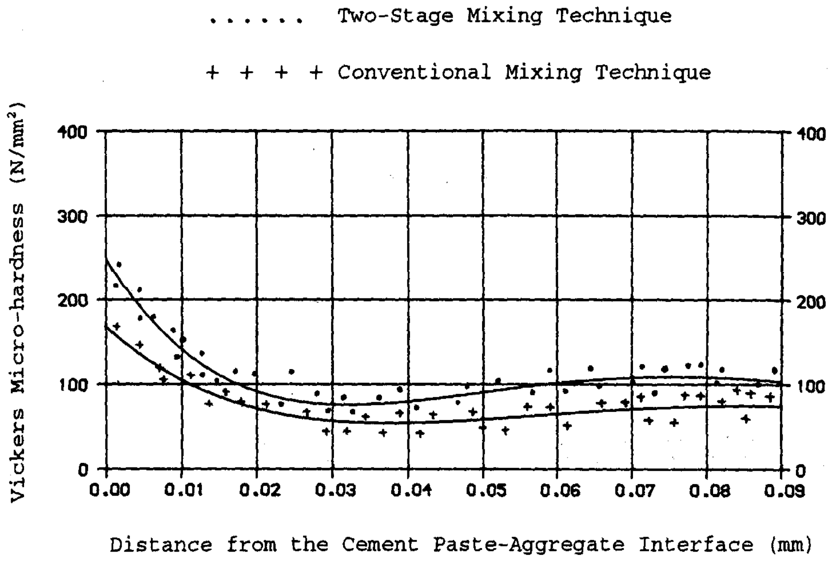


Figure 25. Micro-hardness of ITZ after curing 28 days (Tamimi 1994)

Pope and Jennings (1992) also investigated the influence of adding mixing water in two stages, but with mortars. Coating of the aggregate passing through a No. 4 sieve (97 percent) was achieved in three steps. First, a portion of the mixing water was added to the aggregate and mixed in a large rotary mixer. Then the cement was added and mixed, forming a thick slurry. Finally, the remaining portion of the mixing water was added and mixed for five minutes, forming a homogeneous mortar. Backscatter electron microscopy was used to examine the microstructure at the interface, or ITZ, of the aggregate and cement paste. Compression tests were also completed. The results showed that this mixing method leads to improvements in compressive strength, fracture properties, and uniform microstructure in the ITZ. Similar to Tamimi's research, the improvements in concrete properties can be attributed to the changes in the ITZ (Tamimi 1994). Coating aggregate particles with a low water-to-cement ratio slurry prior to adding the remainder of the mixing water reduces the final water-to-cement ratio at the paste/aggregate interface and reduces the overall thickness of the ITZ layer. This prevents water from building up between the aggregate face and the paste, allowing hydration products to pack more tightly against the surface.

Mixing time is another crucial parameter that has been shown to have a large influence on concrete properties. The ability of a mixer to produce uniform concrete throughout a batch and from batch to batch is characteristic of an effective mixing time. ASTM C 305 defines the mixing time as the time from when all the solid materials are in the mixer until the end of mixing (ASTM 1998c). Insufficient mixing time can lead to lower compressive strength and inhomogeneous concrete. Excessive mixing time can cause aggregate breakdown and decreased air content.

Beitzel (1981) studied the influence of mixing time on the quality of concrete, where quality was defined as the uniform distribution of cement, fine aggregate, and water. Results showed that the optimum mixing time is different for different concrete properties, and that there should be upper and lower limits on the mixing time. Beitzel developed a qualitative empirical representation of the optimum relationship between mix uniformity and separation.

Cable and McDaniel (1998) also investigated the effects of mixing time on a variety of concrete characteristics, including workability, segregation caused by truck mixing, and the air content of cured concrete. They concluded that a minimum mixing time of 60 seconds for all mixer types is effective in achieving an acceptable level of concrete performance from the final product, and this time should only be reduced if steps are taken to ensure that all aggregate particles are completely coated upon discharge from the first mixer.

Kirca, Turanli, and Erdogan (2002) investigated the effects of prolonged mixing and re-tempering after initial mixing on the characteristics of workability and compressive strength. Re-tempering is the process of adding water or a chemical admixture to concrete in order to regain desired levels of concrete performance. In this study, concrete was mixed in a laboratory mixer at 20 rpm for five minutes, and then mixed at 4 rpm for four hours. Two samples were taken after each hour of mixing. One was not changed and the other was subjected to re-tempering. Workability and compressive strength tests were completed on both sets of samples. The results showed that workability of fresh concrete reduces dramatically when subjected to prolonged mixing times, but the workability can be partially regained by re-tempering. Compressive strength did not seem to be affected by prolonged mixing, but was reduced by increasing the water-to-cement ratio through re-tempering. Compressive strength losses were reduced when superplasticizer was used for re-tempering instead of water.

Two-Stage Premixing Processes

Previous research has been completed for several uniquely staged mixing processes that rely on two-stage mixing. In these processes, before being added to the aggregate in a normal mixer, either (1) cement and water are premixed to form a slurry, or (2) cement, water, and fine aggregate are premixed to form a mortar. Preparation of the slurry or mortar is completed separately from concrete mixing.

Rejeb (1996) compared compressive strength and slump tests results of concrete prepared using the above two-stage mixing processes to concrete mixed by normal methods. Concrete was prepared and tested for each mixing method at water-to-cement ratios of 0.40, 0.45, and 0.50. For the normal concrete process, coarse aggregate, sand, and cement were dry mixed for 30 seconds in a normal mixer; then the water and superplasticizer were added and mixed for three minutes in the same mixer. For the first two-stage mix, premixing of water, superplasticizer, and cement occurred for two minutes in a high-speed mixer. Then the cement paste was added to the coarse and fine aggregate in a normal mixer and mixed for an additional two minutes. For the second two-stage mix, premixing of mortar was completed by mixing the water, superplasticizer, cement, and fine aggregate in a high-speed mixer for two minutes. The mortar was then added to the coarse aggregate and mixed in the normal mixer for two minutes. Results, summarized in Table 9, showed that the two-stage mixing process of premixing the mortar had the highest compressive strength, followed by the two-stage mixing process of premixing the paste; the normal mixing method yielded the lowest compressive strength. The compressive strength gain for the premixing of cement paste to normal mixing ranged from 13 percent–15 percent, while the strength gain for premixing of mortar to normal mixing ranged from 14 percent–19 percent. Slump increased by 0.5–1.0 cm at each water-to-cement ratio for both two-stage mixing processes (as compared to the normal mixing method).

Table 9. Comparison of concrete properties mixed by two-stage and normal mixing processes (Rejeb 1996)

Mixing method	Water-to-cement ratio	Slump (cm)	Compressive strength (Mpa)	Compressive strength (psi)
Premixing of cement paste	0.40	4.5	50.97	7393
	0.45	18.5	46.22	6704
	0.50	24.5	42.17	6116
Premixing of mortar	0.40	3.5	51.73	7503
	0.45	18.0	47.15	6839
	0.50	24.0	43.04	6242
Normal mixing	0.40	3.5	45.20	6556
	0.45	17.5	40.38	5857
	0.50	24.0	36.76	5332

Pope and Jennings (1992) also experimented with a two-stage slurry premixing process. In this study, cement and water were premixed in a large bench-top mixer, then added to fine aggregate in a large rotary mixer and mixed into a mortar. The researchers came to the same conclusions for both portions of the study: the microstructure and the paste/aggregate bond were improved by limiting the amount of direct water contact with the aggregate during mixing, and 28-day compressive strengths of samples prepared by the slurry premixing method were greater than the samples prepared by delaying the addition of a portion of the mixing water. These results are shown below in Figure 26.

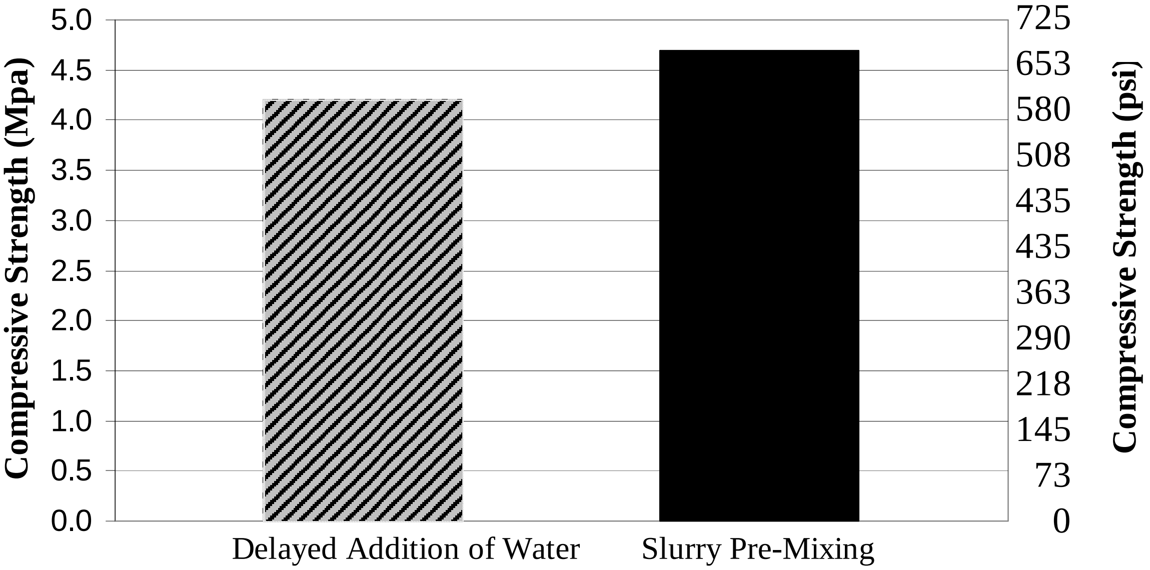


Figure 26. Average 28-day compressive strength values (Pope and Jennings 1992)

Experimental Work

Aggregate Properties

Local aggregates were used for the laboratory study. Natural river sand and crushed limestone were used for the fine and coarse aggregate. For this study, they were used at a ratio of 50:50 coarse aggregate to fine aggregate by volume. The fine aggregate had a fineness modulus and absorption of 2.90 percent and 1.1 percent, respectively. The coarse aggregate had absorption of 3.2 percent.

Mix Design

Three mix designs from Phase I were further investigated in Phase II. Paste study mixtures one, two, and five were chosen for use in Phase II because they are the most common mix designs used by the Iowa DOT. Concrete 1, concrete 2, and concrete 3 were prepared using slurries with binder proportions from Phase I mixes one, two and five, respectively. Table 10 shows the batch weights for the concrete study. For this study, a liquid air entraining agent, Daravair 1400, was used.

Table 10. Concrete mix design proportions

Concrete mixture number	Mixture	PC lbs/yd^3 (kg/m^3)	FA lbs/yd^3 (kg/m^3)	GGBFS lbs/yd^3 (kg/m^3)	Coarse aggregate lbs/yd^3 (kg/m^3)	Fine aggregate lbs/yd^3 (kg/m^3)	Water lbs/yd^3 (kg/m^3)	w/cm
1	100% PC	624.5 (283.3)	—	—	1,449.2 (657.5)	1,467.2 (665.7)	268.0 (121.6)	0.43
2	85% PC – 15% FA	530.8 (240.8)	76.7 (34.8)	—	1,449.2 (657.5)	1,467.2 (665.7)	268.0 (121.6)	0.44
3	50% PC – 35% slag – 15% FA	312.2 (141.7)	76.7 (34.8)	203.9 (92.5)	1,449.2 (657.5)	1,467.2 (665.7)	268.0 (121.6)	0.45

Air-entraining agent was added at the rate of 21 oz/yd^3 (607 ml/m^3)

Concrete Study Mixing Methods

For the concrete study, three mixing procedures were investigated using a drum mixer:

1. Control mixing procedure—The fine and coarse aggregate were mixed with the water together with air-entraining agent (AEA) for 15 seconds. Next, the binder(s) were added and mixing commenced for 60 seconds. During this mixing process, the cement-to-water contact time was 60 seconds.
2. Two-stage mixing with 30-second batch—The cementitious material–water–AEA paste slurry was prepared according to ASTM C 305, deviating from the method though the use of a wire whip to ensure high shear mixing of the slurry (1998c). The coarse and fine aggregate were batched in the drum mixer, and the slurry was then added and mixed for 30 seconds. During this mixing process, the cement-to-water contact time was 2 minutes and 45 seconds.
3. Two-stage mixing with 60-second batch—The cementitious material–water–AEA paste slurry was prepared according to ASTM C 305, deviating from the method though the use of a wire whip to ensure high shear mixing of the slurry (1998c). The coarse and fine aggregate were batched in the drum mixer, and the slurry was then added and mixed for 60 seconds. During this mixing process, the cement-to-water contact time was 3 minutes and 15 seconds.

Concrete Study Test Methods

Immediately after mixing, fresh concrete properties of slump (ASTM C 143) and air content (ASTM C 231) were measured (2003b, 2003c). Fifteen 100 x 200 mm (4 x 8 in) cylinders were cast and placed into a fog room at 23°C (73°F) and 95 percent relative humidity for 24 hours. The specimens were then de-molded and cured according to ASTM C 511 (2003f). The hardened concrete properties investigated included compressive strength at 3, 7, and 28 days; tensile strength at 56 days (ASTM C 39/C 39M) (ASTM 2003a); and rapid air void analysis at 28 days.

The rapid air test was completed on 76 x 100 mm (3 x 4 in.) samples obtained from the center of a 100 x 200 mm (4 x 8 in.) cylinder. The rapid air test is an automated image analysis system that performs an analysis of the hardened air void system according to ASTM C 457 (2003d). The samples are cut, polished, and then prepared using a surface enhancement technique where the final result is a black surface with white air voids. The analysis includes volume of air (%), specific surface, and spacing factor; other items are included in the analysis but are beyond the scope of this study.

Laboratory Two-Stage Mixed Results

Air and Slump Test Results

Fresh concrete properties are important to a contractor for ease of placement and finishing. It is important to ensure proper air entrainment and the desired workability to achieve a durable concrete. The air test results are shown in Figure 27, which indicates a drop in air content for the two-stage premixed concrete samples. This is due to the limited ability of the fine binder materials to entrap air during the slurry mixing.

Figure 28 shows the results for the slump test. For mix one (100% PC), a decrease in slump occurred with the two-stage mixing compared to the conventional mixing. This decrease in slump may be related to an increased degree of cement hydration in the two-stage mixing process. The slump results demonstrate the anticipated increase in slump with the addition of fly ash or fly ash–slag replacement; it is important to note that the slump generally increases with increased mixing energy for those mixtures with fly ash as the only SCM. The slump and air tests were conducted immediately after mixing (about two minutes after cement contact with water) and the cylinder samples were finished about 15 minutes after cement contact with water.

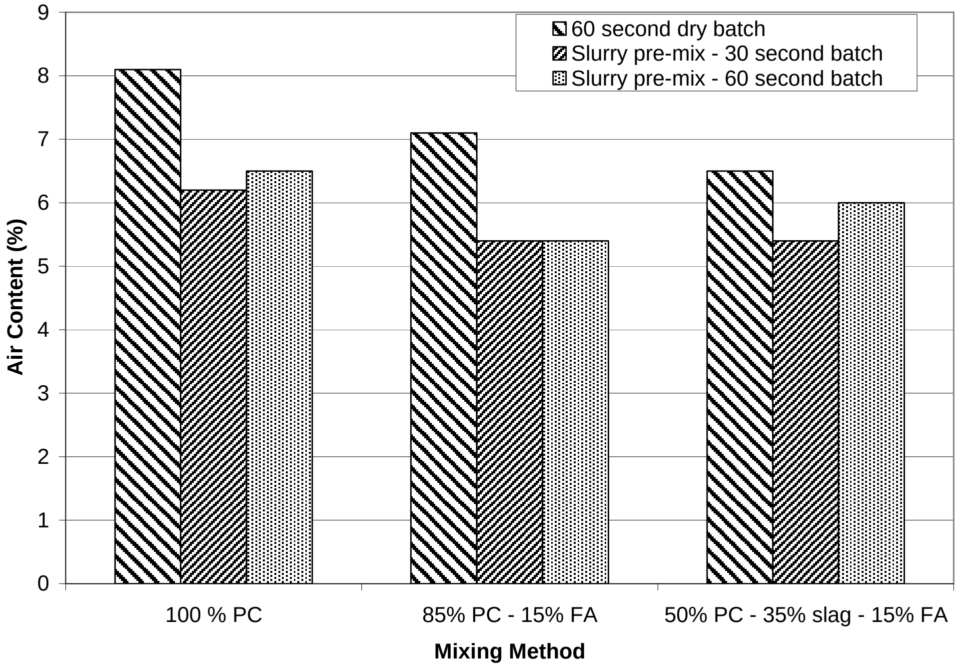


Figure 27. Effects of mixing method on the air content of fresh concrete

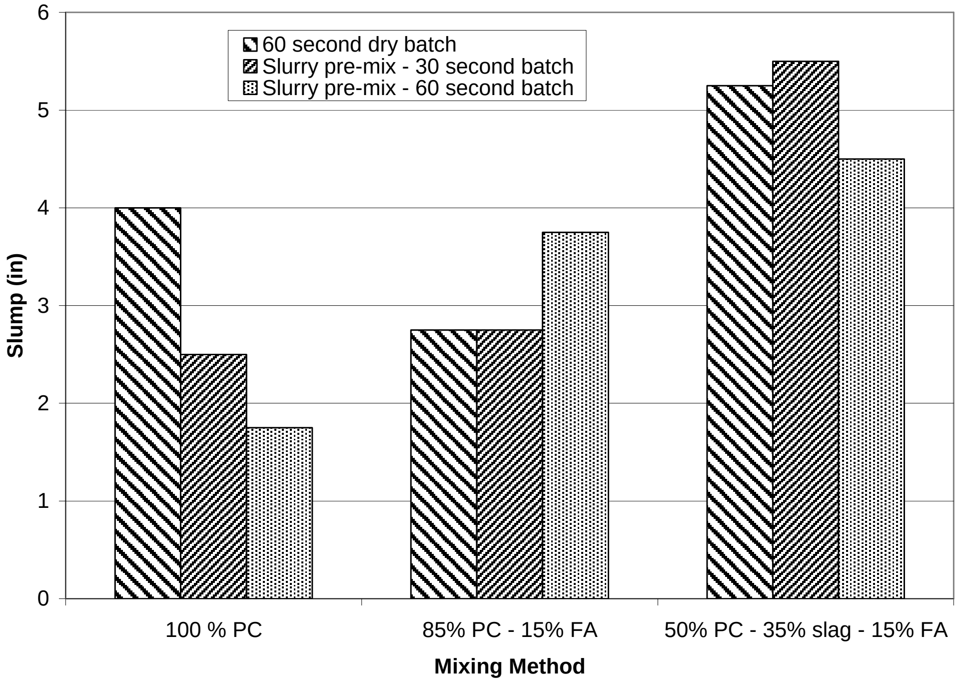


Figure 28. Effects of mixing method on the slump of fresh concrete

Compressive Strength Results for the Laboratory Concrete Study

The compressive strength was measured at 3, 7, and 28 days to determine the effects of the two-stage mixing process on compressive strength development. The compressive strength development over time for mixes one, two, and three are shown in Figure 29, Figure 30, and Figure 31, respectively. Note that the expected decrease in early age compressive strength due to addition of SCM is apparent when comparing between figures.

The compressive strength data indicate that the two-stage mixing process produces nearly equal, or slightly higher, compressive strengths at early ages for mixes two and three, with the two-stage mixed concrete surpassing the standard dry batch process at 28 days. This indicates that two-stage mixing may allow for a slight reduction in cementitious materials and still achieve the same strength. At 28 days, the two-stage, 30-second mix had about a 10 percent increase in strength compared to the standard dry batch. A conservative engineer may opt to use the same amount of cementitious material and use the two-stage mixing process, thus increasing the resultant strength of the placed concrete. It can be noted that for mix three, the data at 28 days shows no advantage for any one particular mixing process. This trend is believed to come from the synergistic action of the GGBFS and FA, allowing for a more uniform homogeneous concrete. These results suggest that for ternary mixtures, the mixing time may be reduced or increased in order to see notable differences.

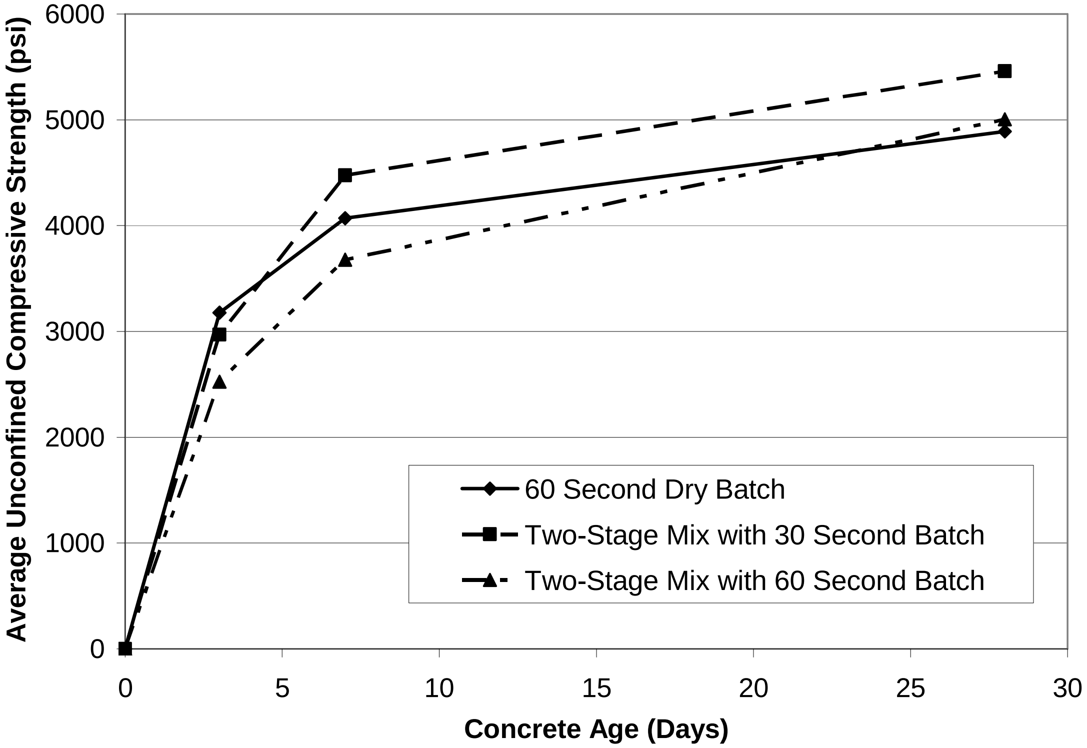


Figure 29. Effect of time on compressive strength for mix one (100% PC)

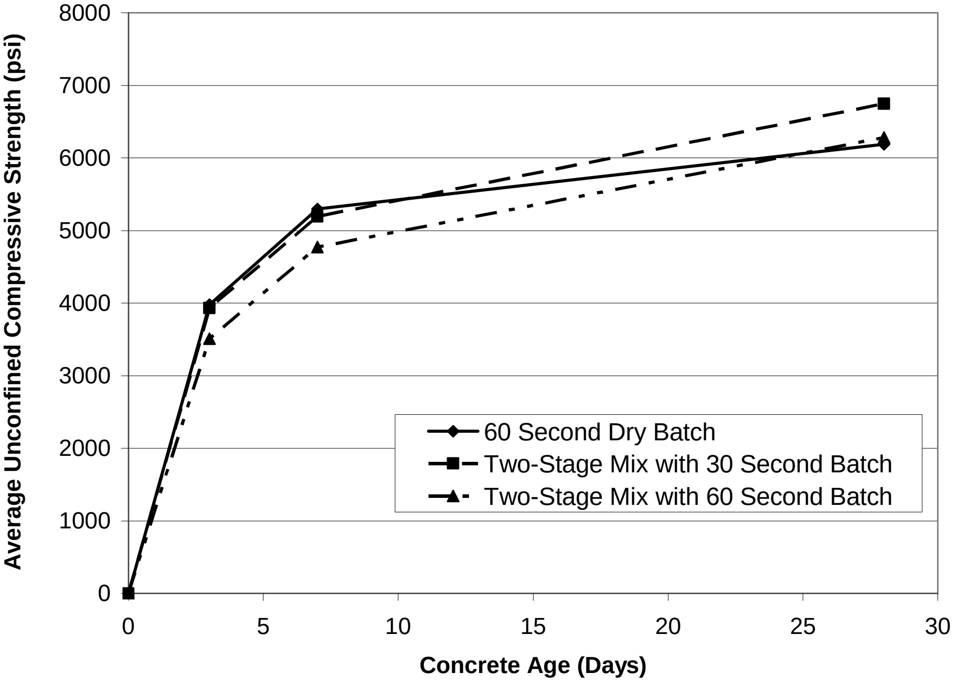


Figure 30. Effect of time on compressive strength for mix two (85% PC–15% FA)

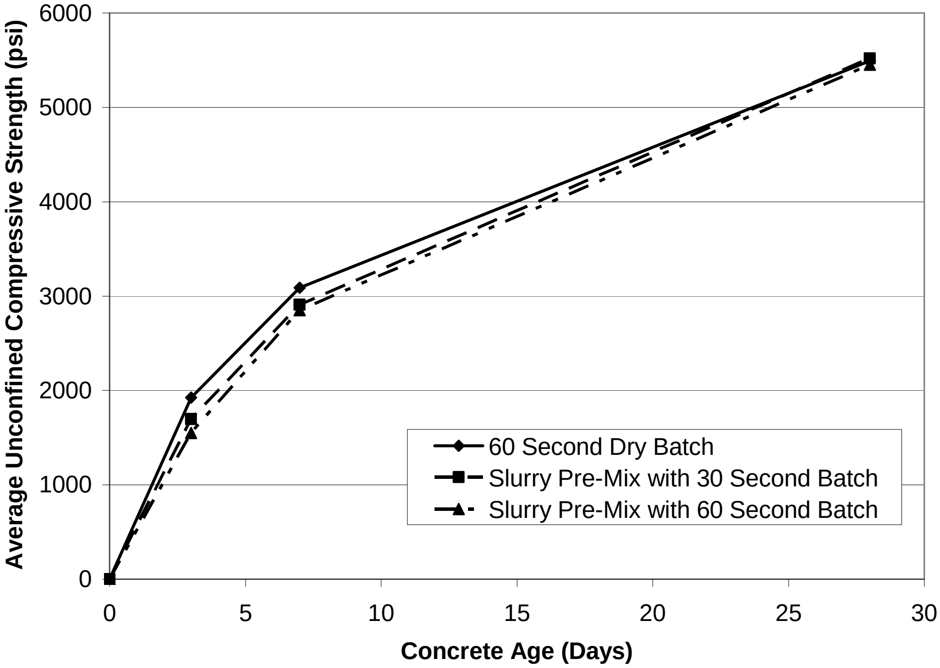


Figure 31. Effect of time on compressive strength for mix three (50% PC–35% slag–15% FA)

Rapid Air Void Analysis

The air void system of hardened concrete is characterized by the total air content, specific surface of the air voids, and a spacing factor. Of the three air void parameters, the spacing factor is the best indicator of concrete durability to freeze-thaw action. Table 11 shows the results for the rapid air void analysis for all concrete mixes studied. One sample per mix was studied with three different threshold levels.

Table 11. Effects of mixing method on hardened concrete air properties

Concrete mixture number	Mixture	Mixing method	Total air content (%)	Specific surface (mm^{-1})	Spacing factor (mm)	Paste–air ratio
1	100% PC	60-second dry batch	10.9	36.54	0.070	2.57
		Two-stage mix with 30-second batch	6.7	28.37	0.147	4.16
		Two-stage mix with 60-second batch	7.1	22.41	0.174	3.91
2	85% PC–15% FA	60-second dry batch	5.7	45.95	0.100	4.86
		Two-stage mix with 30-second batch	5.4	50.23	0.093	5.12
		Two-stage mix with 60-second batch	4.2	46.35	0.133	6.56
3	50% PC–35% Slag–15% FA	60-second dry batch	7.1	52.30	0.075	3.92
		Two-stage mix with 30-second batch	6.9	48.72	0.082	4.00
		Two-stage mix with 60-second batch	4.9	54.63	0.073	5.68

The results of the rapid air void analysis point to several key findings. The total air contents do not correspond well with the air content determined on the fresh concrete measured by ASTM C 231. ASTM C 457 states that the range for the specific surface is 24–43 mm^{-1} (600–1100 in^{-1}) and the range for the spacing factor is 0.1–0.2 mm (0.004–0.008 in.) (2003d).

The following observations can be made from the rapid air results in Table 11:

1. Two-stage mixing generally reduces the amount of air formed in a given mixture.
2. The air content reduces further when the two-stage mixing procedure is applied to concrete containing SCMs.

3. There is a weak relationship between the air void spacing factor and total air content. The air void spacing factor generally increases as the total air content of a concrete mixture decreases.

Therefore, when the two-stage mixing procedure is employed in concrete practice, increased AEA dosage and/or improved AEA application methods need be considered to ensure proper air content and spacing factors in the concrete mixtures.

Split Tensile Strength

The split tensile strengths were measured according to ASTM C 496 at 56 days (2003e). The split tensile strength results show a slight increase in tensile strength for samples produced using the two-stage mixing method with a 30-second batch. It is believed that this increase in tensile strength may be due to quick placement and consolidation of the concrete, allowing more of the tricalcium aluminate (C_3A) bonds to develop rather than be broken down with further mixing. Figure 32 shows the split tensile strength results for all mixing methods.

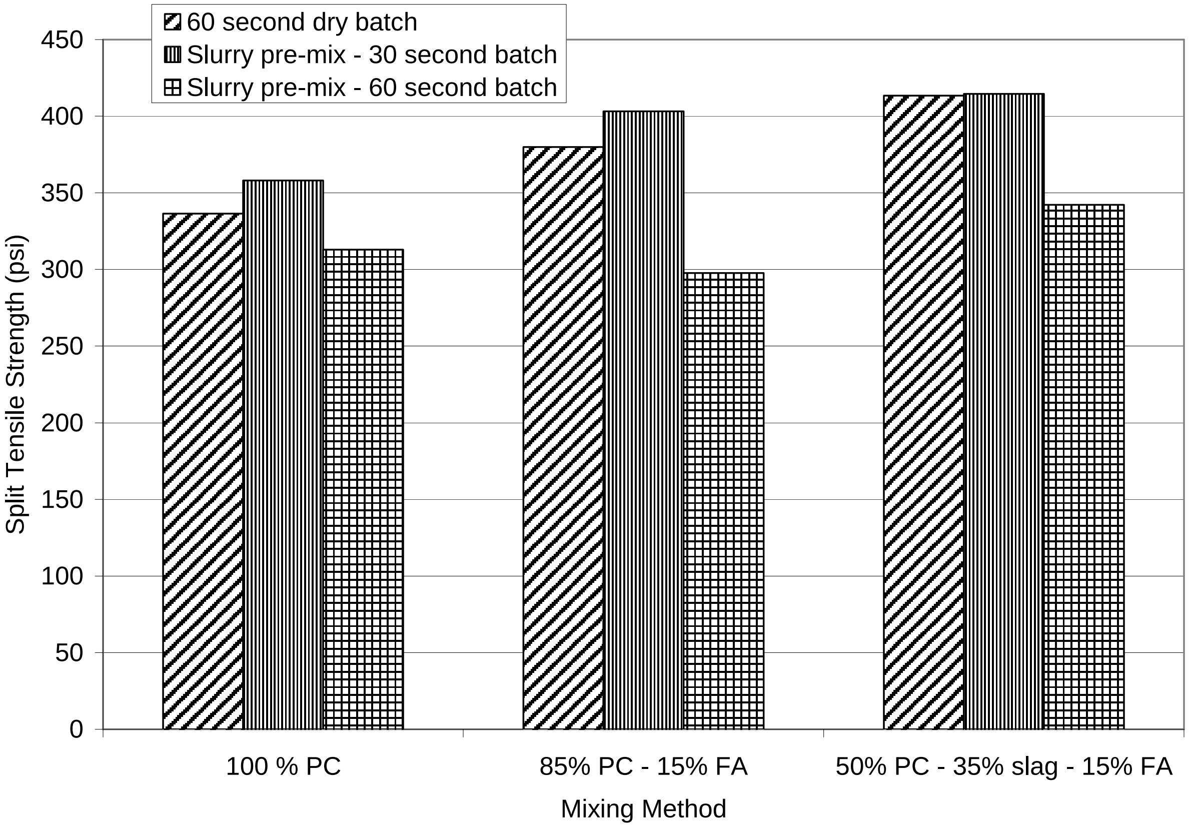


Figure 32. Effects of mixing method on 56-day split tensile strengths (average of three samples)

Rapid Chloride Permeability

The rapid chloride permeability test was conducted to determine the effects of mixing procedures on the chloride permeability of concrete. Table 12 shows the rapid chloride permeability test results. Note that the chloride permeability increased due to the two-stage mixing procedure. Although there is an increase, the increase is not significant, as the permeability class remains the same. Note that with the addition of SCMs, the permeability decreased as expected.

Table 12. Effects of mixing method on chloride permeability

Mixture	Mixing procedure	Charge passed (coulombs)
100% PC	60-second dry batch	4843
	Two-stage mix with 30-second batch	5840
	Two-stage mix with 60-second batch	4543
85% PC – 15% FA	60-second dry batch	3359
	Two-stage mix with 30-second batch	3494
	Two-stage mix with 60-second batch	3380
50% PC – 35% slag – 15% FA	60-second dry batch	1360
	Two-stage mix with 30-second batch	1412
	Two-stage mix with 60-second batch	1490

Summary of Phase II Findings

1. Compressive strength results show that the two-stage mixing process generally produces a 10 percent increase in strength at 28 days, and tensile strength results show equal or 10 percent greater strengths when using two-stage mixing compared to a 60-second dry batch. This is less than the 13 percent to 18 percent strength gains reported in the literature. These results indicate that two-stage mixing has the potential for increased performance in the field. The ternary mixture compressive strength results indicate that a reduced mixing time may be sufficient to fully mix the concrete.
2. Due to the inability of the fine cementitious particles to entrain air, air entrainment is less effective in the two-stage mixing process when the AEA is added in the slurry, and two-stage mixing generally reduces the amount of air formed in a given mixture. A weak relationship exists between the air void spacing factor and total air content. The air void

spacing factor generally increases as the total air content of a concrete mixture decreases. The air content reduces further when the two-stage mixing procedure is applied to concrete containing SCMs. Due diligence will be needed for concretes produced using a two-stage mixing method because the air content is decreased and the spacing factor is increased, thus the concrete becomes more susceptible to freeze-thaw deterioration.

3. The two-stage mixing process generally produced concrete with greater chloride permeability, but the increase in chloride permeability was not significant.
4. The slump results did not provide a clear trend, but two-stage mixing at 30 seconds slightly increases the slump, except for the 100% PC mixture 1.
5. Two-stage mixing at 30 seconds is recommended as the optimal mixing process.

PHASE III—TWO-STAGE FIELD STUDIES

Objectives/Scopes

The laboratory phases established that improved strength and adequate fresh and hardened concrete properties can be obtained using a two-stage mixing process. While laboratory studies can be important indicators of concrete performance, it is necessary to conduct field studies to determine whether the improved performance can be obtained in the field. Consequently, the objective of the field studies was to connect the results from Phase I and Phase II to field performance. Three field studies were planned in Illinois, Minnesota, and Iowa, but only two field studies were performed. A field study was not completed in Iowa due to the lack of a suitable field demonstration site. In the Illinois and Minnesota field studies, the research team had no input or control over the mixes; they were simply opportunities to obtain field data. In these field studies, both two-stage mixing and normal mixing processes were used for field construction. The properties of the concrete for each mixing process were tested and compared. Parameters measured included fresh concrete properties of slump and air content, and hardened concrete properties of compressive strength, tensile strength, air void structure, and rapid chloride permeability.

Field Equipment for Two-Stage Mixing

A variety of equipment is available for two-stage mixing. Mixing methods for the available equipment range from mechanical mixing using rotating arms, high pressure water injection, and high shear mixing action. Details of the equipment are provided below.

Hydromix

A photograph of the Hydromix apparatus, manufactured by Hydromix Inc., is shown in Figure 33. Figure 34 shows a schematic of how the equipment operates. The dry cementitious materials are fed directly into the top and mix water is injected through the black injection nozzles. The Hydromix mixing process is designed to be added to a conventional batch plant underneath the cementitious materials storage bins.

The Hydromix mixing process is a continuous mixing process. Once the cementitious materials are being batched and ribbon fed (slurry), the aggregate belt starts to charge the awaiting ready mix truck with the previously batched coarse and fine aggregate. A 10–12 yd^3 batch of concrete can be produced in about 60–90 seconds. Admixtures such as air entraining agent and water reducer are sprayed onto the aggregate as it is being charged into the ready mix truck. More information on Hydromix operation can be found at www.hydromix.com.

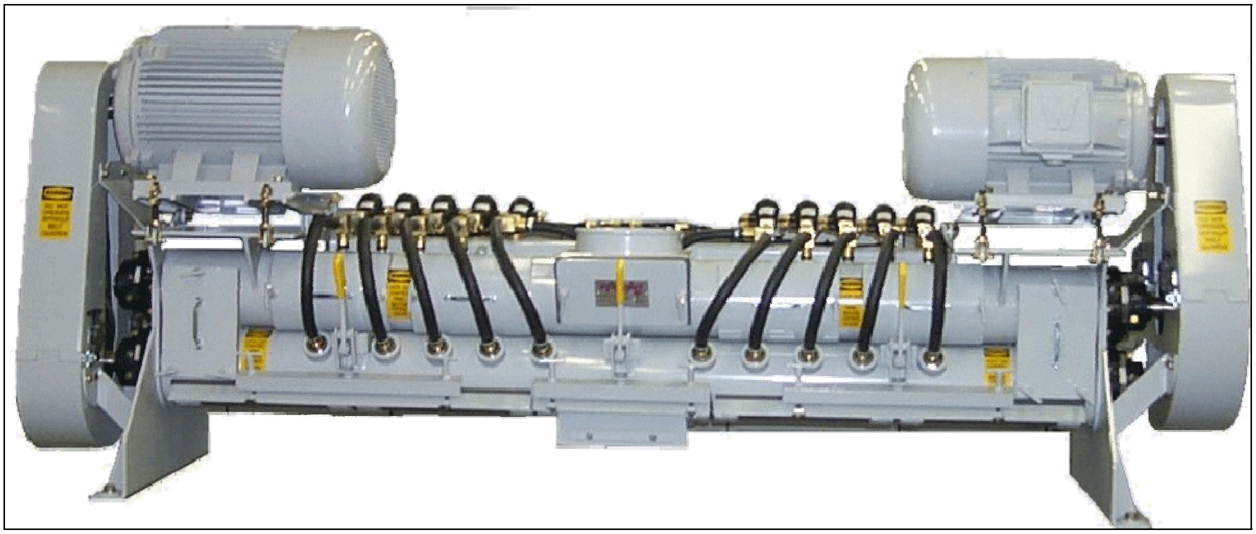


Figure 33. Hydromix apparatus (Hydromix Inc. 2007)

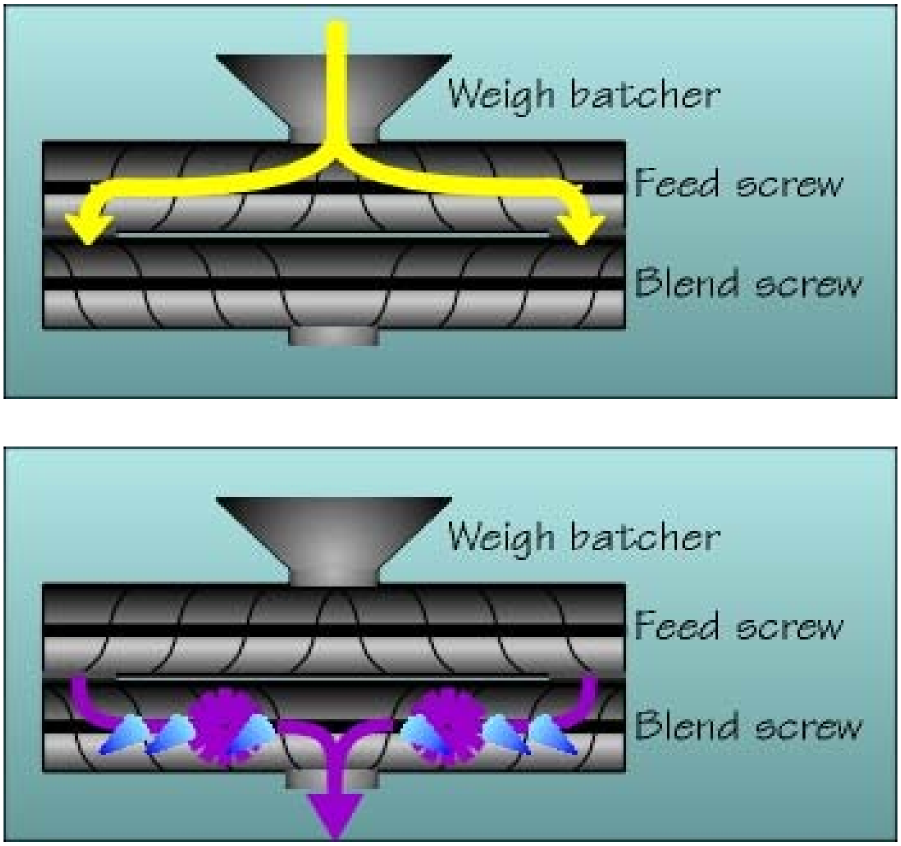


Figure 34. Batching process for the Hydromix two-stage mixing operation (Hydromix Inc. 2007)

Two-Stage Mixing Tower

Another two-stage mixing operation, using a mixing tower, is shown in Figure 35. This operation is a mechanical mixer using rotating fingers in a horizontal drum to pre-mix the slurry before adding it to the aggregate feed. A 10–12 yd^3 batch of concrete can be produced in about 45–60 seconds. The entire concrete plant rests within the footprint of one semi trailer. Figure 36 shows the two-stage mixing plant on site. This plant has the added benefit of being extremely mobile and able to be set up and produce concrete in remote areas. More information on this particular two-stage mixing operation can be found at www.concretemobility.com.

Figure 35. Two-stage mixing plant (Concrete Mobility 2007)

Figure 36. Two-stage mixing plant on site

Countercurrent Concrete Mixers

A countercurrent concrete mixer is one in which four concrete mixing arms rotate around a center vertical axis. This delivers intense countercurrent mixing action and is reported to transfer all the mixing energy directly into the concrete. This mixing procedure could be used to produce large quantities of slurry in a two-stage mixing operation.

Figure 37 shows a countercurrent concrete mixer. Output capacities range from 1/3 yd^3 to 4 yd^3 of fresh concrete. Using this as a sole provider of fresh slurry, one could easily batch a 10 yd^3 batch of concrete using this in a two-stage mixing operation. If a greater output is desired, two countercurrent concrete mixers could work in tandem, as shown in Figure 38. Figure 39 shows a schematic of the countercurrent concrete mixer produced by Advanced Concrete Technologies.

Figure 37. Countercurrent concrete mixer (Advanced Concrete Technologies 2007)

Figure 38. Two countercurrent concrete mixers working in tandem (Advanced Concrete Technologies 2007)

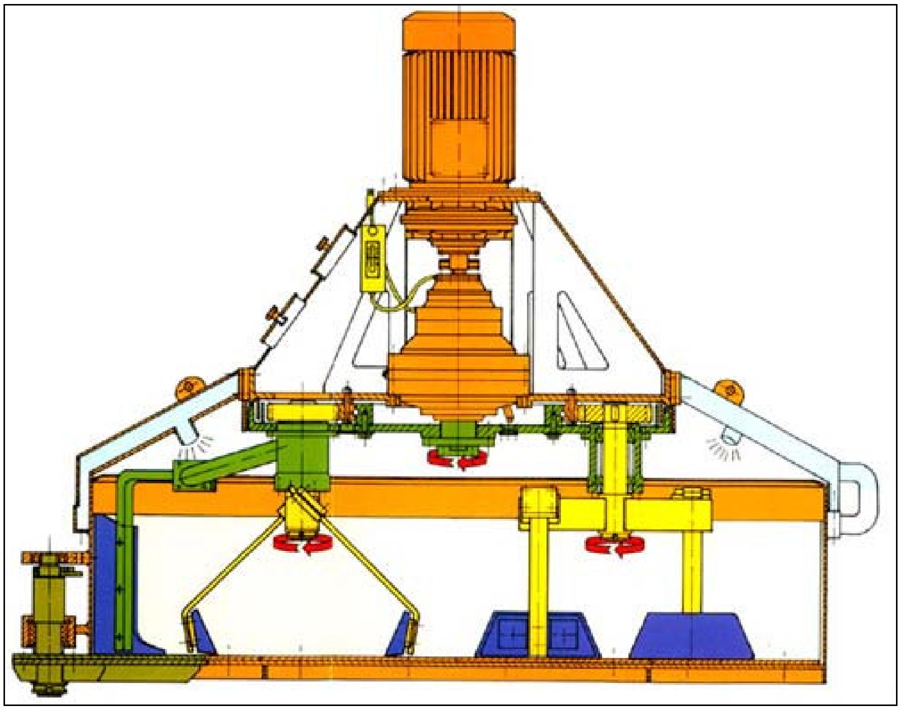


Figure 39. Countercurrent concrete mixer schematic (Advanced Concrete Technologies 2007)

High Shear Mixer

High shear mixers may be used in a conventional batch plant if placed appropriately. High shear mixers can be continuous, with material output ranging from 50–500 gallons of slurry per minute. This mixing method is very efficient and may be a viable alternative for field retrofit. Figure 40 shows a powder-liquid high shear mixer and Figure 41 shows a schematic of how the powder-liquid high shear mixer works. Note that a significant amount of effort will be required to adapt this equipment to a conventional ready-mix concrete plant for production of portland cement concrete.

Figure 40. Powder-liquid high shear mixer (IKA 2007)

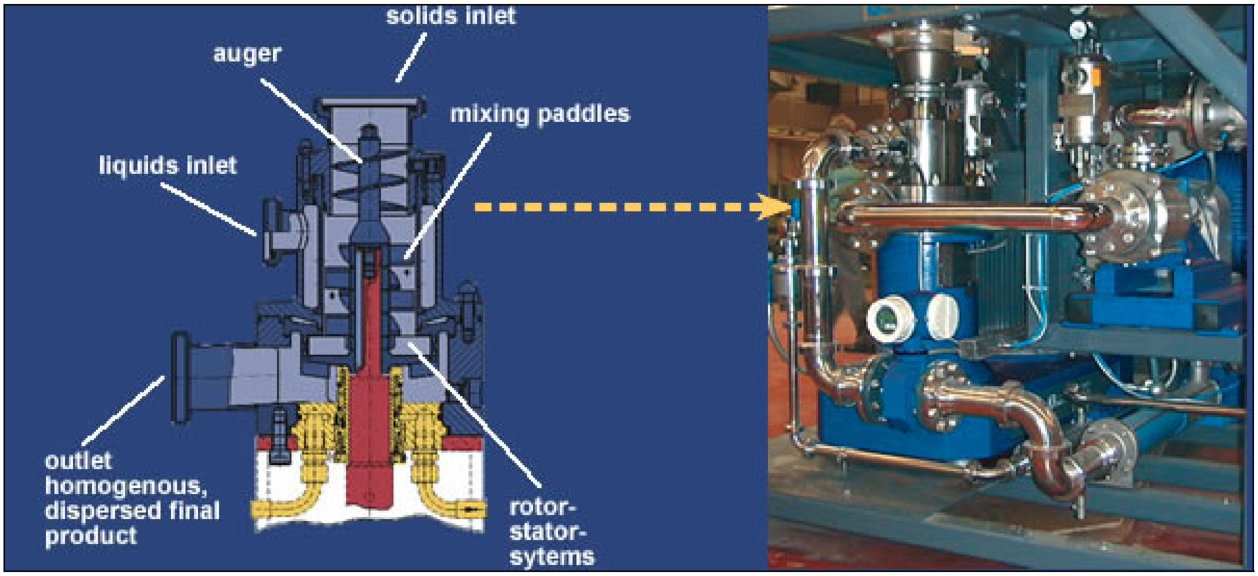


Figure 41. Powder-liquid high shear mixer schematic (IKA 2007)

Water Jet Mixers

A water jet mixer by name uses water jetting action to fully mix a dry powder with water, with no mechanical mixing needed. Figure 42 shows a schematic of a water jet mixer.

The pressurized water stream is converted from pressure-energy to high velocity as the fluid enters the nozzle. The issuing high velocity jet stream produces a strong suction in the mixing chamber, causing a powder, granular material or secondary fluid to be drawn through a suction port into the mixing chamber. An exchange of momentum occurs when the powder intersects with the motive fluid. The dynamic turbulence between the two components produces a uniformly mixed stream traveling at a velocity intermediate between the motive and suction velocities through a constant diameter throat where mixing is completed. The diffuser is shaped to reduce the velocity gradually and convert velocity energy back to pressure at the discharge with a minimum loss of energy (Vortex Ventures 2007).

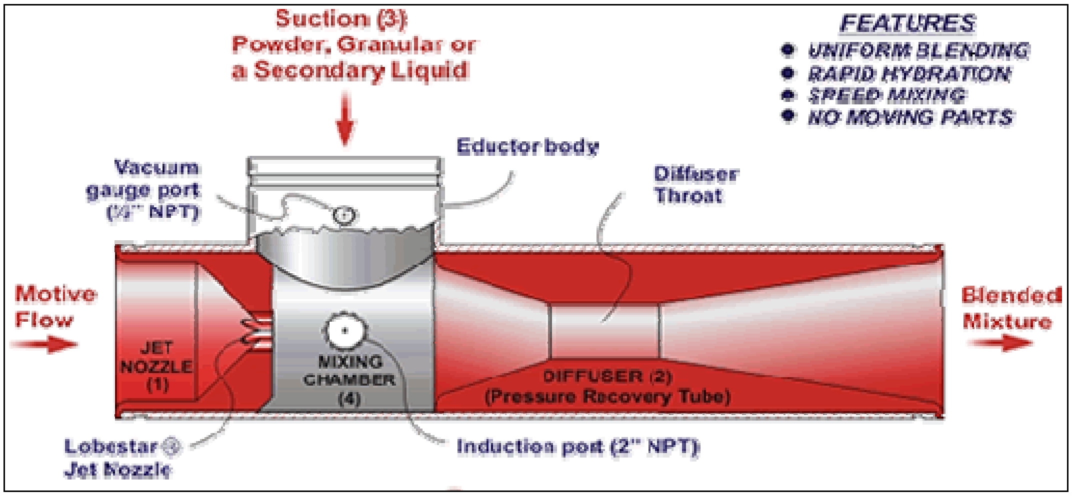


Figure 42. Water jet mixer (Vortex Ventures 2007)

Project One—Highland, Illinois

Project Overview

The first field study was located in Highland, Illinois shown in Figure 43. The two-day study was completed in early May of 2005. The concrete mixers compared were Hydromix slurry pre-mixer and a conventional wet batch ready mix plant. One mix design was used between the two plants, but the wet batch plant concrete had fiberglass fibers incorporated into the mix. This may have skewed the results and more testing may be necessary to validate the results from this project.

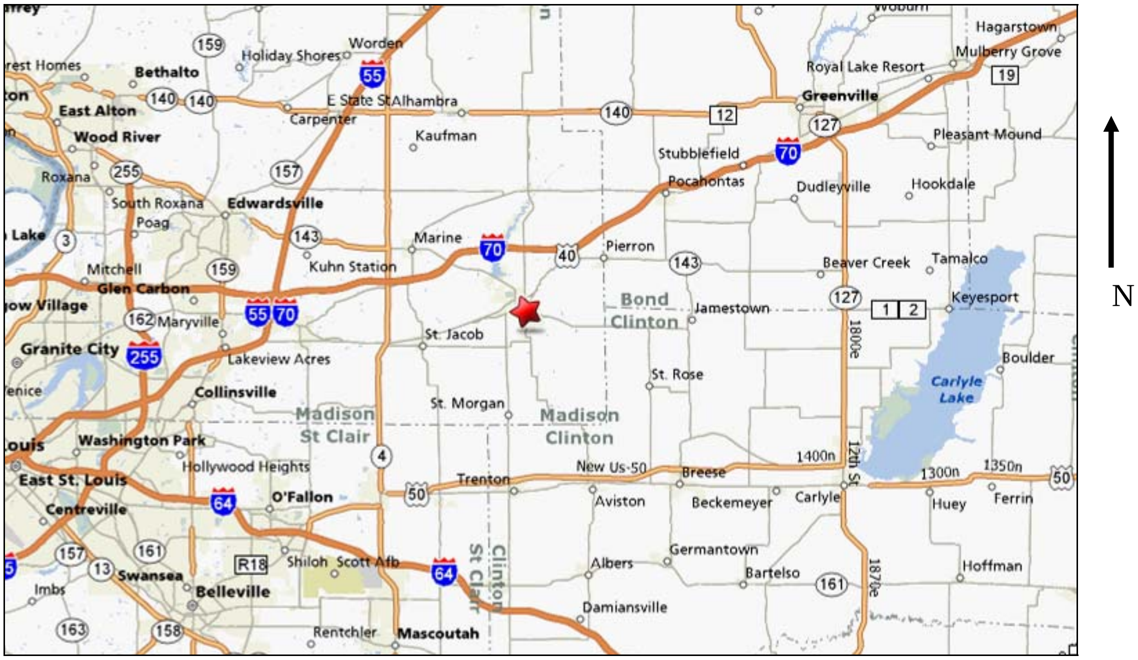


Figure 43. Location of field project one—Highland, Illinois

It is important to note that, for this project, the samples for all concrete tests were from the plant site rather than from the job location. For the Hydromix samples, the aggregate and paste slurry were mixed for 5 minutes in a ready mix truck before sampling.

Plant Operation

Hydromix is unique in that the cementitious materials are mixed using high pressure water jets. The mix water is added in an enclosed auger system with nozzles. Figure 44 illustrates the mixing process using a flow cart. The cement is batched above the Hydromix assembly and metered into the screw auger. Figure 45 shows the underneath side of the Hydromix plant. The combined screw auger movement and high pressure water injection fully mix the paste. Figure 46 shows a close-up of the screw auger case with the high pressure water nozzles.

The mixing process is a continuous mixing process. Once the cementitious materials are being batched, the aggregate belt starts to charge the awaiting ready mix truck with the previously batched coarse and fine aggregates. Admixtures such as air entraining agent and water reducer are sprayed onto the aggregate as it is being charged into the ready mix truck. Figure 47 shows the aggregate belt charging the ready mix truck.

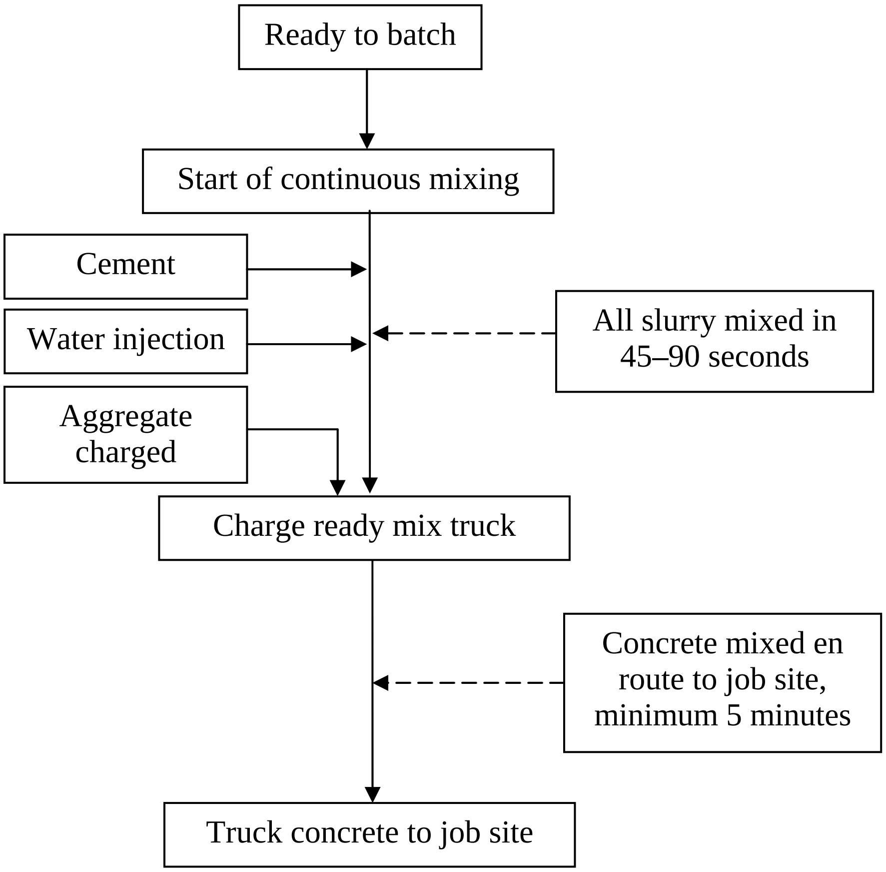


Figure 44. Flow chart illustrating the Hydromix mixing process

Figure 45. Underneath side of the Hydromix plant

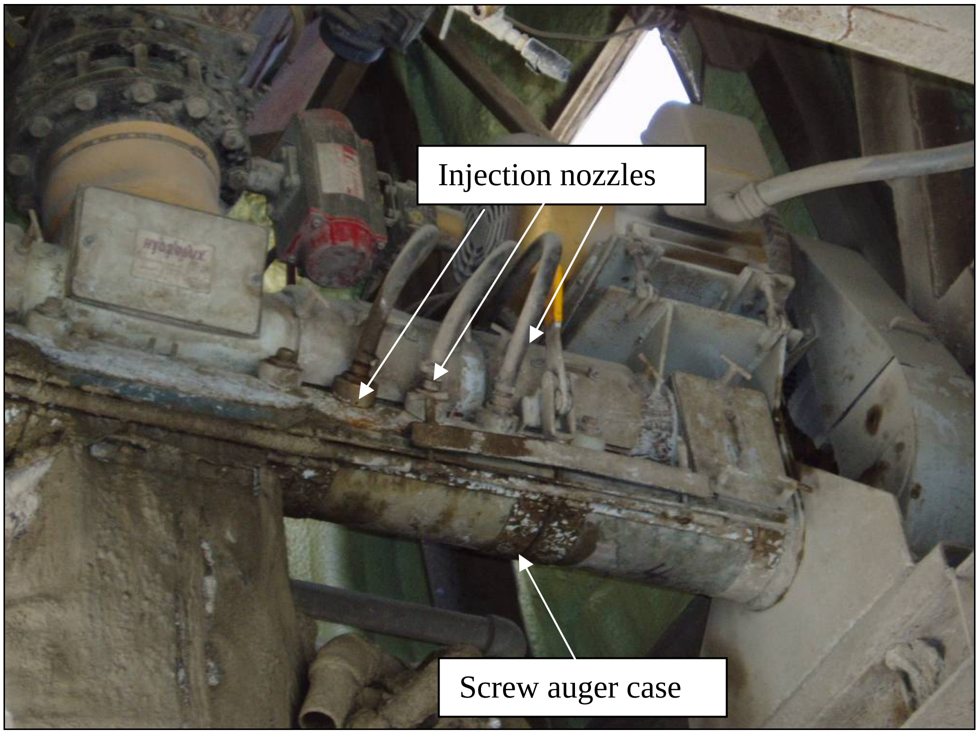


Figure 46. Close-up of screw auger case and water injection nozzles

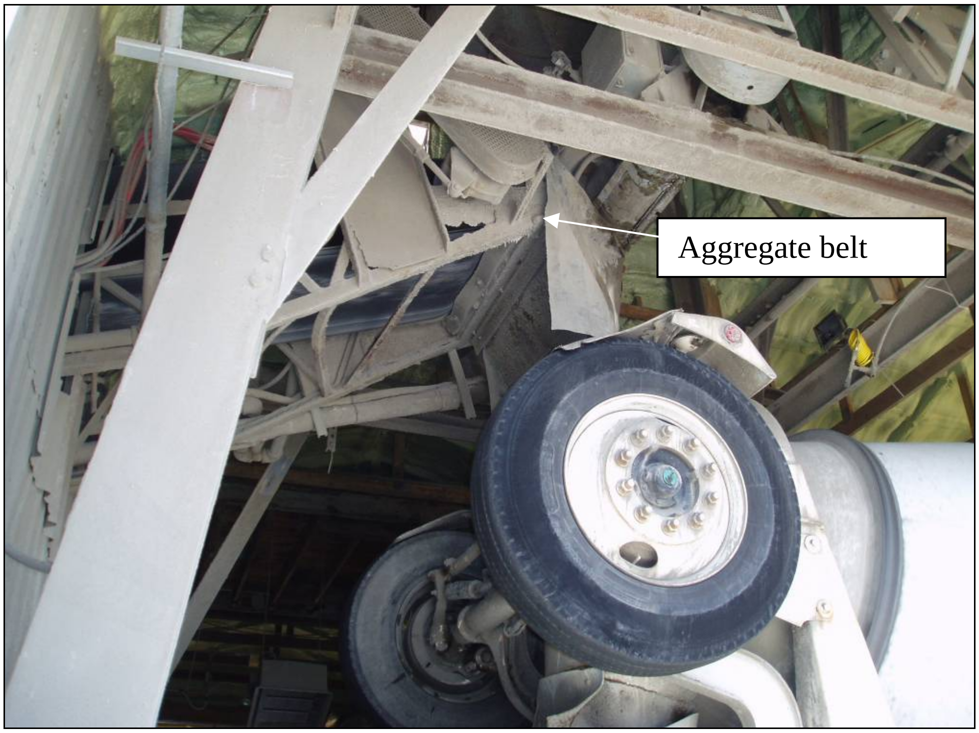


Figure 47. Aggregate belt charging ready mix concrete truck

Material Properties and Mix Design

The materials used in this field study included Type I portland cement, Class C fly ash, air entraining agent, and water reducer. The chemical compositions are shown in Table 13. Table 14 shows the field concrete mix design and w/cm ratio.

Natural river sand and crushed limestone were used for the fine and coarse aggregate. The fine aggregate had a fineness modulus and absorption of 2.98 and 0.6 percent, respectively, and the coarse aggregate had absorption of 1.0 percent. A liquid air entraining agent (GRT Polychem vRC) and a water reducer (GRT Polychem 400NC) were used.

Table 13. Chemical composition of binders used in Highland, Illinois

		PC	FA
Chemical composition, %	CaO	62.80	22.37
	SiO_2	20.50	37.18
	Al_2O_3	4.50	22.74
	Fe_2O_3	3.30	6.01
	MgO	3.40	5.64
	K_2O	0.47	—
	Na_2O	0.23	—
	SO_3	2.50	0.99
	TiO_2	—	—
	P_2O_5	—	—
	SrO	—	—
	Mn_2O_3	—	—
	S	—	—
Fineness (m^2/kg)		355	*12.30%
	C_3S	57.8	—
	C_2S	15.2	—
	C_3A	6.3	—
	C_4AF	10.0	—

*% retained on #325 sieve

Table 14. Concrete mix proportions for Highland, Illinois

PC lbs/yd^3 (kg/m^3)	**FA lbs/yd^3 (kg/m^3)**	**Coarse aggregate lbs/yd^3 (kg/m^3)**	**Fine aggregate lbs/yd^3 (kg/m^3)**	**Water lbs/yd^3 (kg/m^3)**	**w/cm**
440 (261)	110 (65)	1730 (1026)	1325 (786)	267 (158)	0.49

AEA was added at the rate of 0.6 oz per 100 lbs of PC (39.1 ml per 100 kg of PC)
Water reducer was added at the rate of 2 oz/yd^3 (77 ml/m^3)
Fiberglass was added to the wet batched concrete at the rate of 1 lb per yd^3 of concrete

Mixing Methods

For this field study, two mixing procedures were performed:

1. The Hydromix concrete mixing method is a two-stage mixing method in which the portland cement, fly ash and water are mixed prior to the addition of the aggregates. The Hydromix method utilizes twin shaft screws that mix the cement–fly ash paste while water is injected at high speeds. Once mixed, the paste is placed into the concrete truck along with the aggregate, and both are mixed en route to the job site.
2. The central batch plant used was a conventional wet batch plant site. The materials were added and then water was added. The resulting concrete was completely mixed after leaving the batch plant.

Test Methods

Immediately after mixing, fresh concrete properties of slump (ASTM C 143) and air content (ASTM C 231) were measured (2003b, 2003c). Twenty-four 100 x 200 mm (4 x 8 in.) cylinders were cast and allowed to field cure for 24 hours. The samples were then transported back to the lab and placed into a fog room at 23°C (73°F) and 95 percent relative humidity. The hardened concrete properties investigated include compressive strength at 3, 7, and 28 days; split tensile strength at 56 days (ASTM C 496) (2003e); rapid air void analysis at 28 days; and rapid chloride permeability at 56 days (ASTM C 1202) (ASTM 2003g).

Results and Discussion

Fresh Concrete Properties

Determining the fresh concrete properties is important for workability and sufficient air content to ensure long-term freeze-thaw durability. The air and slump test results are shown in Table 15. Note the increase in air content and decrease in slump from the Hydromix to the central plant concrete. The decrease in slump and increase in air content may be attributed to the fiberglass addition to the central plant concrete.

Table 15. Effect of mixing methods on fresh concrete properties

Mixture	Air content (%)	Slump in.	mm
Hydromix	6.0	3.50	90
Central plant	7.8	2.75	70

Compressive Strength

The compressive strength was measured at 3, 7, and 28 days to determine the effects of the Hydromix mixing process on compressive strength development versus central plant mixing.

The compressive strength development over time for the Hydromix and central plant concrete are shown in Figure 48 and Table 16.

Table 16. Compressive strength results for Highland, IL with standard deviation

Mixture	Compressive strength*, psi, and age, days (standard deviation) 3 days	7 days	28 days
Hydromix	3311 (72.4)	4543 (159.1)	5507 (157.6)
Central plant†	2891 (106.0)	4228 (86.7)	5390 (150.2)

*Average of three samples
† Contains fiberglass fibers

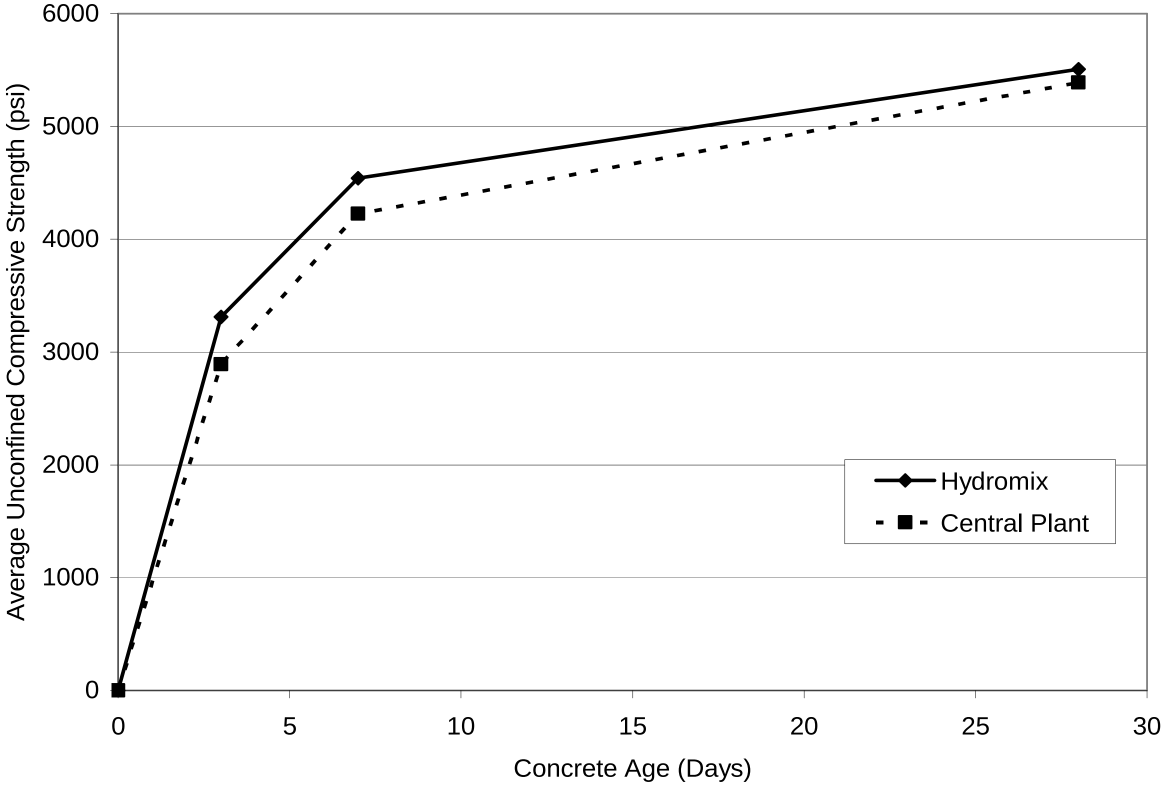


Figure 48. Effect of mixing procedure on unconfined compression strength (average of three samples)

The compressive strength data indicate that the Hydromix mixing process produces slightly higher compressive strengths at all ages of testing. The data indicate that the Hydromix mixing method produced slightly stronger concrete at early ages. Using this knowledge, an engineer who is concerned with early-age strength development rather than the 28-day strength could specify a Hydromix (or similar two-stage mixing method) concrete to better meet specifications.

Tensile Strength

Tensile strength of concrete is important when considering flexural loading. The tensile strength results are shown in Table 17. The results indicate that the Hydromix mixing method produces a concrete with about 15 percent higher tensile strength. Also note the lower standard deviation in the Hydromix results compared to the central plant. These results indicate that the Hydromix mixing method produces a more homogenous concrete, illustrated by a smaller standard deviation when compared to the central plant concrete.

Table 17. Effect of mixing methods on 56-day split tensile strength

Mixing method	Tensile strength* psi	Tensile strength* kPa	Standard deviation
Hydromix	523	3,608	44.6
Central plant†	462	3,184	84.9

*Average of three samples
† Contains fiberglass fibers

Chloride Permeability

Concrete's ability to resist chlorides depends upon several factors, including air content, materials, pore size, and whether SCMs have been incorporated. Resistance to chloride ingress is most important in structures that are subjected to de-icer salts or to a continuous chloride environment. Table 18 shows the effects of mixing method on the chloride permeability. Note that the Hydromix mixing method produced a concrete significantly more resistant to chloride ingress. The central plant concrete may have higher chloride permeability due to the incorporation of fiberglass fibers into the mix.

Table 18. Effect of mixing method on chloride permeability

Mixing method	Charge passed (coulombs)	Permeability class
Hydromix	3668	Moderate
Central plant†	5022	High

† Contains fiberglass fibers

Summary of Findings from Highland, Illinois

1. The air content results showed that the Hydromix concrete air content was significantly lower than the air content of the conventional concrete, which is consistent with the

laboratory study of concrete results. The results may have been affected by the addition of fiberglass fibers to the conventional concrete.

2. The slump test results show an increase in slump, about 30 percent, for the Hydromix concrete when compared to conventional concrete. The increase in slump may be due to the conventional concrete containing fiberglass fibers, thus reducing the slump.
3. Compressive strength results show about a 5 percent increase in strength at 3 and 7 days for the Hydromix concrete, but nearly equal strength at 28 days, even though the conventional concrete had fiberglass fibers.
4. The 56-day tensile strength results show two-stage mixed concrete out-performed the conventional concrete with fiberglass fibers by about 10 percent, while showing lower variability when comparing the standard deviation of the test results.
5. The chloride permeability of the two-stage mixed concrete was significantly lower, about 30 percent, compared to conventional concrete.

Project Two—Jordan, Minnesota

Project Overview

The second field study was located near Jordan, Minnesota and is shown in Figure 49. The two-day study was completed in mid-May of 2005. The field study consisted of the reconstruction of the intersection of US Highway 169 and Minnesota 41. The concrete mixers compared were unique slurry pre-mixer and a conventional wet batch ready mix plant. One mix design was used between the two plants, but the wet batch plant concrete may or may not have used the same cement source as the slurry pre-mixer. This may have skewed the results and more testing may be necessary to validate the results from this project

Site Conditions

The construction site for this field project was small. Reconstruction of the intersection required short slipform paving operations with a great deal of traffic control. The slurry pre-mixing plant site was located adjacent to the project in an abandoned gas station lot. Figure 50 shows the magnitude of the plant site.

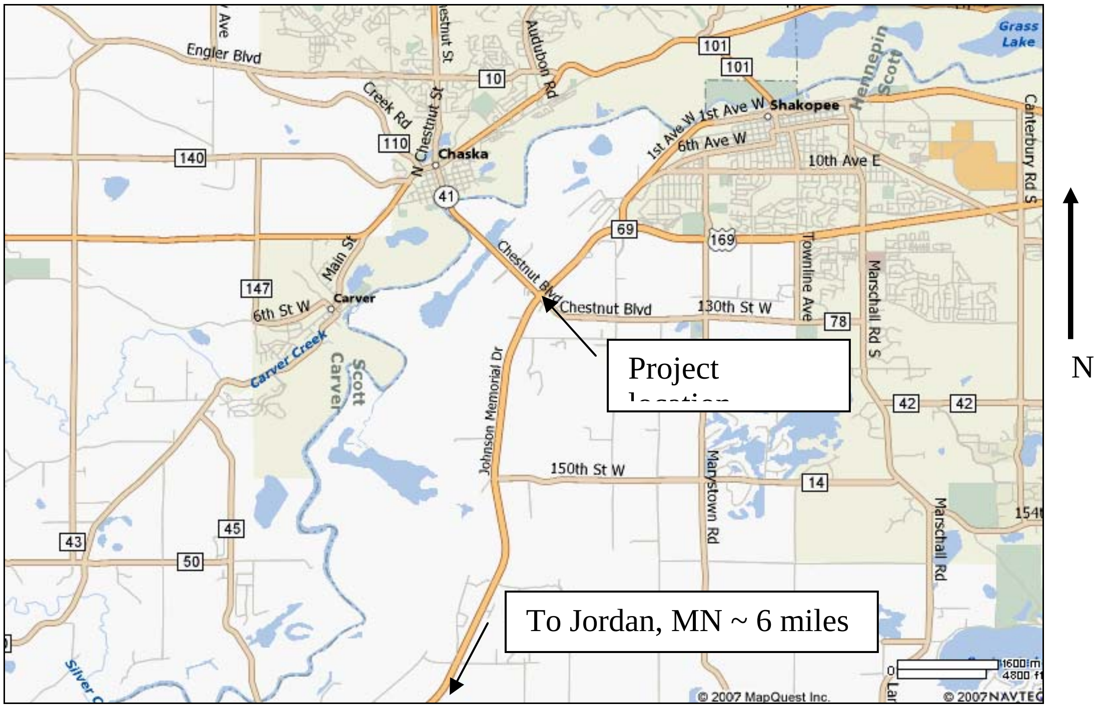


Figure 49. Location of field project two near Jordan, Minnesota

Figure 50. Plant site for project two near Jordan, Minnesota

Plant Operation

The slurry pre-mix plant (see Figure 50) pre-mixes the cementitious materials and water to form a paste. The paste is then added to the aggregate as it is charged into a ready mix truck. The resulting concrete is not fully mixed as it leaves the plant site, but is fully mixed when arriving at the job site. Figure 51 shows the two stage mixing process using a flow chart.

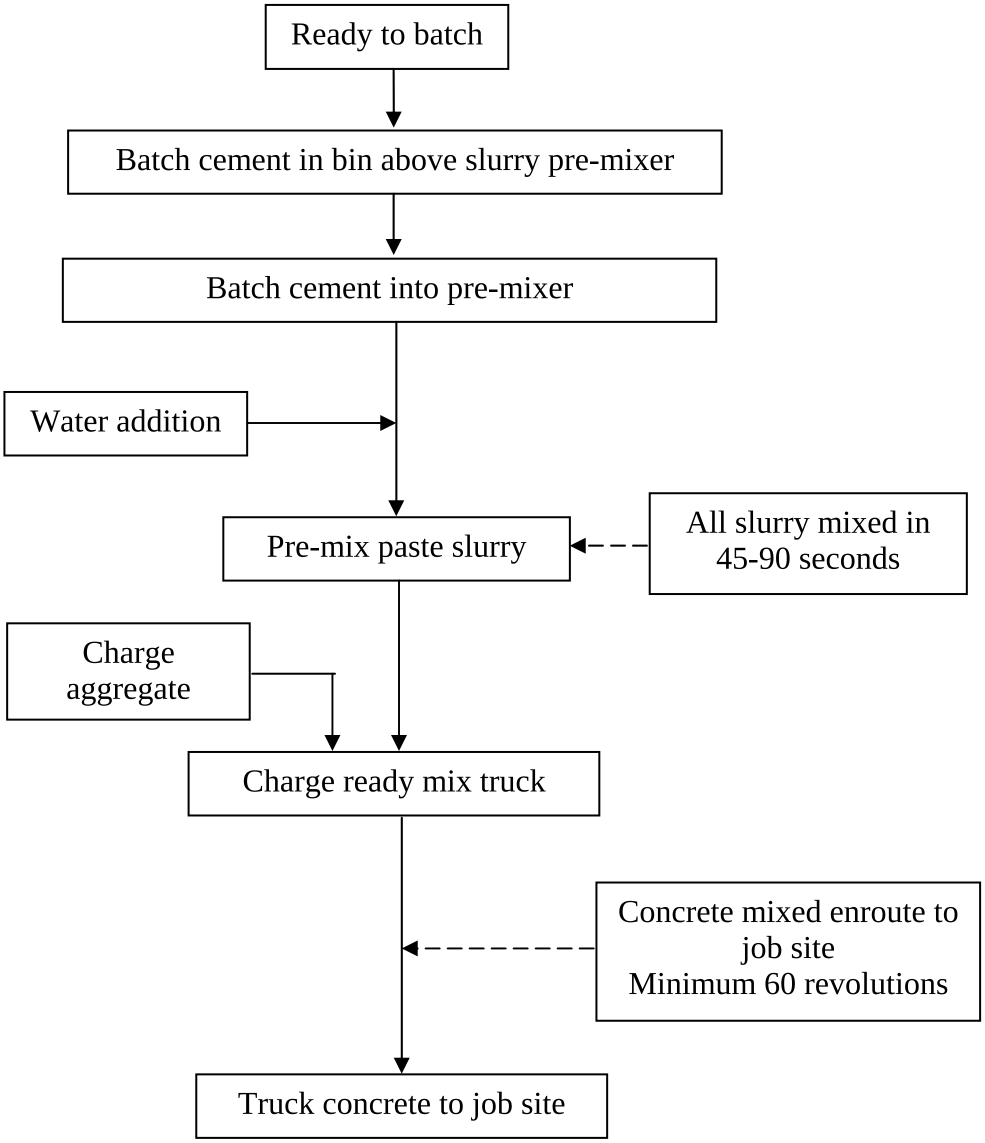


Figure 51. Flow chart illustrating the two-stage mixing process for Jordan, MN

Cementitious materials storage for this plant operation is in a pig. Pneumatic pressure is used to blow the cementitious materials to the top of the batching tower. Once the cementitious materials are batched, they are added with the water in a horizontal mixing chamber. Stationary rods “fingers” are located at the top of the chamber. Mixing is accomplished using rotating “fingers” located on the bottom of the chamber. Figure 52 shows the rotating “fingers.”

Once the cementitious materials have been mixed with the water for about 30 to 60 seconds, the material is charged with the aggregate into a ready mix truck. The material is dispensed out of the mixing chamber via a trapdoor in the bottom. Figure 53 shows the slurry being charged. A belt moves the charged aggregate to the top of the tower for charging. Figure 54 shows the belt location for charging the aggregate. Admixtures such as water reducer and AEA are added onto the aggregate as it is being charged into the ready mix truck.

Figure 52. Rotating fingers in the slurry pre-mixer

Figure 53. Slurry being charged with aggregate

Figure 54. Belt for charging the fine and coarse aggregate

Material Properties and Mix Design

The materials used in this field study included Type I portland cement, fine aggregate, and a blended coarse aggregate. The chemical composition for the portland cement is shown in Table 19. Table 20 shows the field concrete mix design and w/cm ratio.

Natural river sand and crushed granite were used for the fine and coarse aggregate, respectively. The fine aggregate had a fineness modulus and absorption of 2.81 and 1 percent, respectively, and the coarse aggregate had absorption of 0.6 percent. A liquid air entraining agent (Daravair 1000) and a medium range water reducer (Polyheed 1020) were used.

Table 19. Chemical composition of binders used in Jordan, Minnesota

		PC
Chemical composition, %	CaO	63.0
	SiO_2	21.0
	Al_2O_3	4.7
	Fe_2O_3	2.3
	MgO	3.2
	K_2O	—
	Na_2O	—
	SO_3	2.9
	TiO_2	—
	P_2O_5	—
	SrO	—
	Mn_2O_3	—
	S	—
Fineness* (m^2/kg)		381
C_3S		53.7
C_2S		19.7
C_3A		8.6
C_4AF		7.0

*% Retained on #325 sieve

Table 20. Concrete mix proportions for Jordan, Minnesota

PC lbs/yd^3 (kg/m^3)	**Coarse aggregate lbs/yd^3 (kg/m^3)**	**Fine aggregate lbs/yd^3 (kg/m^3)**	**Water lbs/yd^3 (kg/m^3)**	**w/cm**
600	1960	1150	222	0.37
(356)	(1163)	(682)	(132)	

AEA was added at the rate of 5 oz per 100 lbs of PC (325 ml per 100 kg of PC)
Mid-range water reducer was added at the rate of 4 oz per 100 lbs of PC (261 ml per 100kg of PC)

Mixing Methods

For this field study, two mixing procedures were investigated:

1. The two-stage concrete mixing method is one in which the portland cement and water are mixed prior to the addition of the aggregates. This plant utilized a rotating set of fingers that mixed the portland cement and water. Once mixed, the paste was dropped directly onto the aggregate as it was loaded into the concrete truck. The AEA was added directly to the fine and coarse aggregate as it was loaded into the truck. Final mixing of the concrete was completed in the drum of the concrete truck.
2. The central batch plant used was a conventional wet batch plant site. The materials were all added and then water was added. The resulting concrete was completely mixed after leaving the batch plant.

Test Methods

Immediately after mixing, fresh concrete properties of slump (ASTM C 143) and air content (ASTM C 231) were measured (2003b, 2003c). Twenty-four 100 x 200 mm (4 x 8 in.) cylinders were cast and allowed to field cure for 24 hours. The samples were then transported back to the lab and placed into a fog room at 23°C (73°F) and 95 percent relative humidity. Hardened concrete properties investigated include compressive strength at 3, 7, and 28 days; split tensile strength at 56 days (ASTM C 496) (2003e); rapid air void analysis at 28 days; and rapid chloride permeability at 56 days (ASTM C 1202) (ASTM 2003g).

Results and Discussion

Fresh Concrete Properties

The fresh concrete properties of air and slump are shown in Table 21. Note that the two-stage mixing process yields a slightly lower slump and air content. The reduction in air content is negligible, and the reduction in slump is minor. Note that the contractor had a difficult time entraining air in the two-stage mixing method due to the application of air directly onto the aggregate in the absence of agitation or water. Note also that the total mixing time for the two-stage mixed concrete was longer compared to the central plant, thus reducing the slump.

Table 21. Effect of mixing methods on fresh concrete properties

Mixing method	**Air content (%)**	**Slump**	
		in	**mm**
Two-stage mixing	5.9	1.50	38.1
Central plant	6.0	1.75	44.5

Compressive Strength

The compressive strength was measured at 3, 7, and 28 days to determine the effects of the two-stage mixing process on compressive strength development. The compressive strength development over time for the two-stage and central plant mixed concrete is shown in Figure 55 and Table 22. The compressive strength data indicates that the central plant mixing process produces slightly higher compressive strengths at early ages, with the 28-day strengths being equal.

Table 22. Compressive strength results for Jordan, MN with standard deviation

	Compressive strength*, psi, and age, days (standard deviation)		
Mixture	**3 days**	**7 days**	**28 days**
Two-stage mixing	4674 (156.3)	5647 (63.0)	7099 (130.2)
Central plant	5341 (100.3)	6291 (112.1)	7223 (35.0)

*Average of three samples

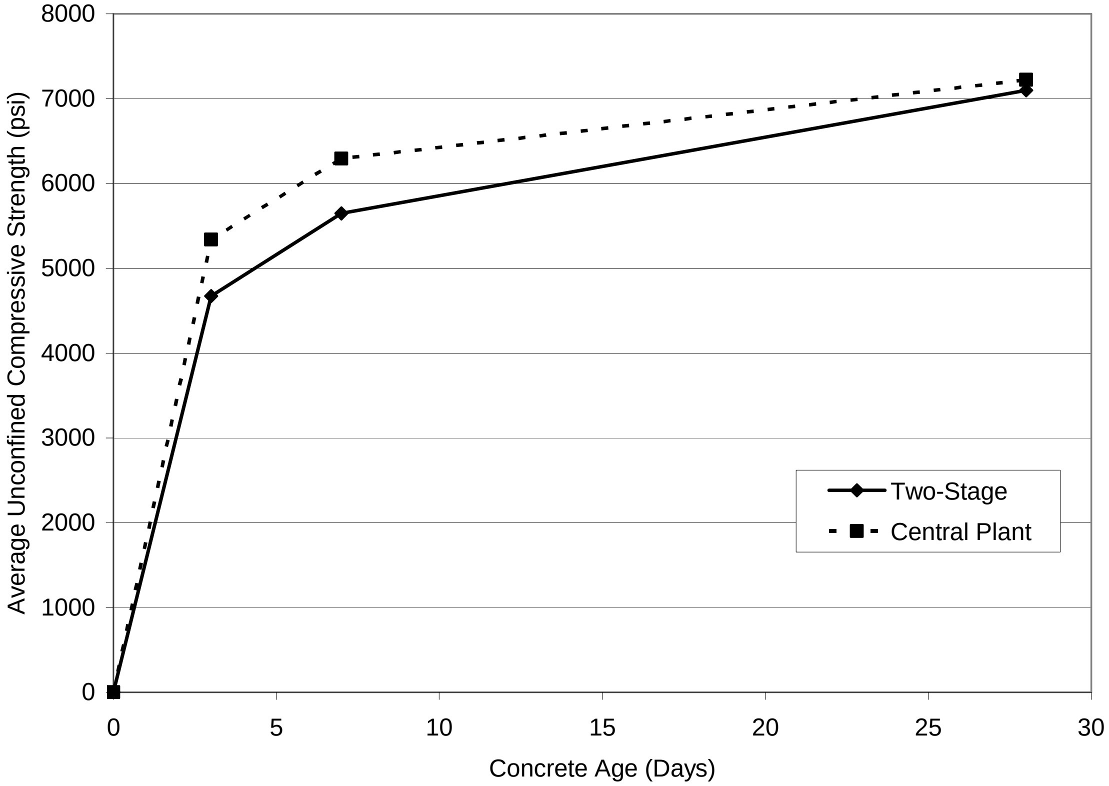


Figure 55. Effects of mixing procedure and time on unconfined compression strength (average of three samples)

Tensile Strength

The tensile strength of concrete is important under flexural loading conditions. Generally, steel is added to aid in the resistance of flexural forces. The tensile strength results, shown in Table 23, indicate identical tensile strengths. Note the standard deviations of the results: the lower standard deviation of the two-stage mixed concrete indicates a better-mixed, more homogeneous concrete.

Table 23. Effect of mixing methods on 56-day split tensile strength

Mixing method	Tensile strength* psi	Tensile strength* (kPa)	Standard deviation
Two-stage mixing	531	3,659	50.1
Central plant	534	3,678	76.7

*Average of three samples

Chloride Permeability

Table 24 shows the effects of mixing method on the chloride permeability for Jordan, Minnesota. Note that the two-stage mixing method produced a concrete slightly more resistant to chloride ingress and that the permeability class remained unchanged even though the charge passed was slightly lower. This indicates that the two-stage mixing method may be advantageous for concretes used in marine environments or concretes exposed to harsh de-icer chemicals.

Table 24. Effect of mixing method on chloride permeability

Mixing method	Charge passed (coulombs)	Permeability class
Two-stage	3,105	Moderate
Central plant	3,410	Moderate

Summary of Findings from Jordan, Minnesota

1. The air content results on fresh concrete showed no significant difference between the slurry pre-mixing operation and a conventional wet batch plant.
2. The slump test results show a decrease in slump when using a two-stage mixing process, which may be due to increased hydration of the cementitious materials.
3. Compressive strength results show about a 10 percent reduction in strength at 3 and 7 days, but equal strength at 28 days. Standard deviation of the compressive strength test results show the central plant produces concrete with lower variability.
4. The 56-day tensile strength results show equal strengths, but the two-stage mixed concrete shows lower variability when comparing the standard deviations of the test results.
5. The chloride permeability of the two-stage mixed concrete was lower than that of conventional concrete, but the permeability class remained the same.

Project Three—Iowa

Project Overview

Upon the completion of Phase II, several attempts were made to obtain a suitable site for a field demonstration in Iowa during the summer and fall of 2005 as well as the construction season in 2006. Due to the difficulty in finding a suitable location, a field demonstration in Iowa was not completed. This section provides a detailed field plan for a follow-up study in Iowa.

Proposed Field Plan

In the previous two field studies, two slurry pre-mixers were discussed. It is the belief of the authors that a field study should be conducted with the slurry pre-mixer discussed in field project two, due to its portable nature. Figure 56 shows the slurry pre-mixer, or two-stage mixing tower.

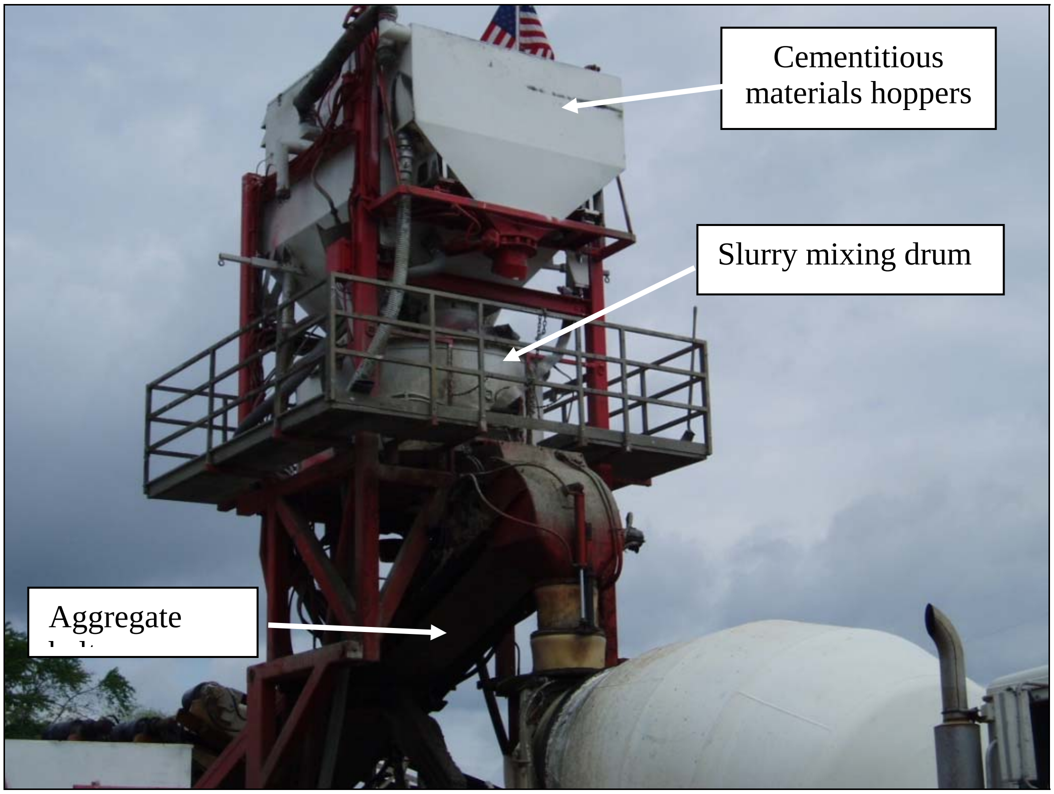


Figure 56. Two-stage mixing tower

The planned field study would be conducted in conjunction with the Iowa Department of Transportation (Iowa DOT) on a project with sufficient length to compare both the two-stage mixing process and conventional ready mixed concrete for slipform paving operations. An ideal length of paving would be about 5,000 ft for each mixing process.

Mix Design

The mix design used for the field study would be either an Iowa DOT approved mix design or contractors choice of mix design with Iowa DOT's approval. The mix design would be identical for each mixing process. Slight adjustments might be needed for admixtures such as water reducer and air entraining agent to ensure workability and freeze-thaw durability.

Testing Plan

For this field project, support from the National Concrete Paving Technology Center's (CP Tech Center) state-of-the-art mobile laboratory would be provided. The mobile lab is shown in Figure 57. The main needs of the mobile lab are access to the plant site for a flat working platform to park the lab and a water source for testing purposes.

Figure 57. CP Tech Center mobile concrete laboratory

Tests to be conducted in the field on fresh concrete include the following: temperature, slump (three times), air content, unit weight, and mortar flow, microwave w/cm, and rheology (is sufficient workability is present). Fresh concrete samples would be taken from each of the mixing procedures for compressive strength, flexural strength, and to measure maturity. Samples would also be taken for determination of time to initial and final set. Air void analyzer samples would also be taken before the paver and after the paver in the finished concrete for analysis of the fresh air void structure.

The proposed testing plan would take place over a time period of about two weeks. It is estimated that the fresh concrete properties would be measured at the point of placement with AVA samples being taken 2–3 times per day. This would provide sufficient data for true comparison between the two mixing procedures.

Upon completion of the testing phase of the project, Iowa State University personnel would take cores from each of the aforementioned testing locations for hardened concrete analysis. Analysis of the cores would include determination of the hardened air void structure using rapid air analysis, compressive strength, tensile strength, rapid chloride permeability, and coefficient of thermal expansion. It is estimated that about 30 cores from each mixing procedure would be needed for a statistically valid comparison.

CONCLUSIONS AND RECOMMENDATIONS

Major Research Findings

Summary of Phase I Laboratory Study on Paste Findings

1. The rheology test results in this study show that high mixing energy generally provides pastes with a low rheology curve. Increasing the mixing energy (high mixing speed and long mixing time) reduces the plastic viscosity, thixotropic area, and peak stress generated by a given rheology test procedure. This trend is consistent through all of the data sets and indicates that increasing the mixing energy produces more thoroughly-mixed slurry. When mixing energy reaches a certain level, increased mixing may not significantly improve the paste's rheological properties. This indicates that, once that point has been reached, the slurry has been mixed uniformly and further mixing is not necessary.
2. Pastes consisting of different material and mix proportions have different mixing energy requirements for reaching optimal uniformity. Pastes containing fly ash generally require lower mixing energy to reach optimum uniformity than pastes containing only cement.
3. Mixing energy influences the cement hydration process. Heat signature tests show that major heat generation occurs earlier for pastes mixed with higher mixing energy. The high shear mixer, at mixing speed two (about 14,000 revolutions per minute) and 60 seconds of mixing time, produced the earliest hydration reactions.
4. The degree of hydration tests indicate that high shear mixing always produces a slightly greater degree of hydration than normal mixing, and that the degree of hydration decreases with the addition of supplementary cementitious materials.
5. High shear mixing generally produces pastes with slightly improved compressive strength when compared to normal mixing. In this study, the improvement was greater at early ages of three and seven days. This is consistent with results from heat signature and degree of hydration tests.
6. SEM image analysis shows that high shear mixing produces a smaller percentage of unhydrated cement particles that increases with increased mixing time, confirming the degree of hydration test results.

Summary of Phase II Laboratory Study on Concrete Findings

1. Compressive strength results show that the two-stage mixing process produced a 10 percent increase in strength at 28 days for two of the three mixtures investigated, and tensile strength results showed equal or 10 percent greater strengths when using two-stage mixing compared to a 60-second dry batch. The ternary mixture compressive strength results were equal for different mixing methods, indicating that a reduced or increased mixing time may be used to show the difference between mixing methods in a future study.
2. Due to the fine cementitious particles absorbing AEA, air entrainment is less effective in the two-stage mixing process when the AEA is added in the slurry, and two-stage mixing generally reduces the amount of air formed in a given mixture. A weak relationship exists

between the air void spacing factor and total air content. The air void spacing factor generally increases as the total air content of a concrete mixture decreases. The air content reduces further when the two-stage mixing procedure is applied to concrete containing SCMs.
3. The chloride permeability results between the conventional and two-stage mixed concrete are not significantly different.
4. The slump results did not provide a clear trend, but the two-stage, 30-second mixing slightly increased the slump, except for the 100% PC mix 1.
5. Two-stage mixing at 30 seconds is recommended as the optimal mixing process.

Summary of Phase III Field Study Findings

The conclusions for the field studies are combined and noted below. Due to different concrete mixes (i.e. fiberglass fibers in the conventional concrete in Highland, IL), no quantitative conclusions can be made from the field test results.

Based on the observations from the field tests and the investigators' judgment (from laboratory experience), the following conclusions may be made.

1. When the given AEA type and dosage is used, lower air content may be found in the concrete mixed with a two-stage mixing method than that in concrete mixed using conventional mixing methods.
2. Due to the increased mixing time, counting from the time the cement is in contact with water to the termination of concrete mixing, the two-stage mixed concrete generally shows a reduced slump.
3. Two-stage mixed concrete may have slightly higher (5-10 percent) strength than the conventionally-mixed concrete. The lower standard deviation of the strength test results indicate that the two-stage mixed concrete can provide the project with better uniformity.
4. Both field studies conducted in the present study demonstrated that the two-stage mixed concrete had lower permeability than the conventionally-mixed concrete.

Recommendations

Based on the research results from the present study, the following recommendations should be considered in continuing research and implementation of the two-stage concrete mixing process:

1. It is believed that the two-stage mixing method will increase concrete strength. Laboratory results from this study showed an 8 percent to 10 percent increase, field results showed a 5 percent to 10 percent increase, and literature results showed a 10 percent to 20 percent increase.
2. The two-stage mixing method will improve concrete uniformity significantly. Additional research/field studies are needed to verify the conclusions from Phases I and II.
3. In future field studies, the same materials and mix proportions should be used for both mixing methods (two-stage and conventional).

4. More repetitions of the designated tests should be conducted. Besides slump testing, mortar (sieved from the field concrete) flowability should be tested using a flow table.
5. Additional studies are needed on the effects of AEA in two-stage mixing methods to overcome potential difficulties in entraining air—namely, dosage rates and sequences.
6. Further investigation is needed in the case of ternary combinations to show the effect of two-stage mixing methods.

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