



Fly ash based concrete blocks
by Dean Patrick Wanzek

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering

Montana State University

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Abstract:

Fly ash is a waste material derived from the burning of coal in power generating plants. As the demand for electricity increases so does the production of fly ash. Since its disposal is costly and environmentally unsound, much research is currently underway to find engineered uses for this waste material. This investigation was undertaken in an effort to formulate mix proportions incorporating large amounts of a Montana Class C fly ash in concrete masonry units (CMU's).

Mixtures of fly ash, cement, and sand were designed, mixed, and evaluated in three phases to develop a material that meets the strength requirements for ASTM concrete masonry units. ASTM procedures were followed as practical. Relationships between the cement to fly ash ratio and unconfined compressive strengths are demonstrated. Strength development relationships for normal and accelerated conditions are plotted. Additional mixtures establish general correlations between paste volume and strengths to demonstrate a weakening effect on some of the previous mixtures.

It is concluded that high volume fly ash blocks containing small amounts of cement meet the strength requirements for ASTM CMU's. As little as 2 percent cement in a stiff mix was found to meet the requirements for non-load bearing CMU's. A stiff mix with 3.3 percent cement was found to exceed the requirements for type S hollow and solid load bearing CMU's. A 5 percent cement mix was found to meet the requirements for type N hollow load bearing units. A 6.7 percent cement mix meets the requirements for Type N solid load bearing units. It is believed that even better results can be achieved through the use of aggregates with a higher fineness modulus or through incorporating more paste volume in mixes notably affected by insufficient paste volume. Additional research is needed to establish this materials suitability for concrete masonry units, particularly with regards to freeze-thaw durability.

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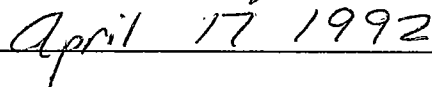


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ABSTRACT

Fly ash is a waste material derived from the burning of coal in power generating plants. As the demand for electricity increases so does the production of fly ash. Since its disposal is costly and environmentally unsound, much research is currently underway to find engineered uses for this waste material. This investigation was undertaken in an effort to formulate mix proportions incorporating large amounts of a Montana Class C fly ash in concrete masonry units (CMU's).

Mixtures of fly ash, cement, and sand were designed, mixed, and evaluated in three phases to develop a material that meets the strength requirements for ASTM concrete masonry units. ASTM procedures were followed as practical. Relationships between the cement to fly ash ratio and unconfined compressive strengths are demonstrated. Strength development relationships for normal and accelerated conditions are plotted. Additional mixtures establish general correlations between paste volume and strengths to demonstrate a weakening effect on some of the previous mixtures.

It is concluded that high volume fly ash blocks containing small amounts of cement meet the strength requirements for ASTM CMU's. As little as 2 percent cement in a stiff mix was found to meet the requirements for non-load bearing CMU's. A stiff mix with 3.3 percent cement was found to exceed the requirements for type S hollow and solid load bearing CMU's. A 5 percent cement mix was found to meet the requirements for type N hollow load bearing units. A 6.7 percent cement mix meets the requirements for Type N solid load bearing units. It is believed that even better results can be achieved through the use of aggregates with a higher fineness modulus or through incorporating more paste volume in mixes notably affected by insufficient paste volume. Additional research is needed to establish this materials suitability for concrete masonry units, particularly with regards to freeze-thaw durability.

INTRODUCTION

General Remarks

Fly ash, an artificial pozzolan, is a waste material collected from the flue gases produced during the combustion of coal in power generating plants. An estimated 64 million tons of fly ash is produced annually in the United States (Golden 1991). Its incorporation in concrete and other uses amounts to less than 25 percent of the fly ash produced (Golden 1991; Bergeson and Overmohle 1991; DiGioia et al. 1991). Disposal of the remaining ash is environmentally difficult and costly to industry, the government, and society. Increased production of ash has resulted in increased research to find beneficial uses of this waste product.

Objectives and Scope

The objective of this research was to derive a material for building blocks that contained fly ash as its primary binding agent and cement as an activator. This material is technically considered high fly ash concrete since it replaces more than 40 percent of the cement in a mix with fly ash. High volume replacement has not been extensively practiced or researched, but recently is attracting more attention.

Interest in a block material was stimulated from research into adobe blocks. Since clay, particularly a non-expansive clay, for adobe manufacture is scarce in many areas and is also vulnerable to moisture, it was decided to search for an alternate material. Desirable features of such a replacement included that it possess hydraulic

properties, was readily available, and was relatively inexpensive. Fly ash met all of these criteria. Fly ash is well known from its hydraulic properties, i.e. its ability to set into a hardened mass when mixed with water. It is also readily available from any coal combustion plant, and presently most of its cost is associated with its transportation to the user.

All fly ashes exhibit some pozzolanic behavior. Fly ashes with high lime content exhibit self-cementitious characteristics in addition to pozzolanic behavior and thus may possess more value in certain applications. In the past, little research on high lime fly ash was conducted since it was somewhat unavailable (Roy, Luke, and Diamond 1985). Presently, researchers are investigating high lime fly ashes to take advantage of their cementitious properties by incorporating larger quantities in concrete than was common in the past. This cementitious behavior has driven this research to explore the use of high lime fly ash as the primary cementing agent in concrete masonry units.

Investigations were undertaken to develop an adequate block mix that incorporated high volumes of fly ash and low volumes of cement. A mix design that effectively uses more fly ash and less cement is generally appealing, both economically (since cement is relatively expensive), and environmentally (by utilizing large quantities of a waste material and also by decreasing energy intensive cement manufacture). In any given application, the economic aspects of fly ash utilization would depend on a myriad of variables.

Concrete mixes with varying proportions of fly ash and sand with cement as an activator were designed, mixed, and evaluated in three separate phases of the project. The first phase of the investigation intended to attain a starting point for

further investigations and to identify relationships that would exist from incorporating significantly higher volumes of fly ash than is common in concrete. Investigations in phase two were conducted to establish the strength development at normal and accelerated curing conditions of mixtures with fly ash as the primary binder. From observations and evaluation of these mixtures, further investigations in phase three with mortar cubes were undertaken to quantify relationships between: 1) cement to fly ash ratio and unconfined compressive strengths and 2) the influence of the paste volume on mortar strengths and flowability.

BACKGROUND ON FLY ASH

History

Pozzolans can be defined as "siliceous or siliceous and aluminous materials which in themselves possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide (lime) at ordinary temperatures to form compounds possessing cementitious properties" (ASTM 1990). There are two basic types of pozzolans, natural and artificial. The natural pozzolans are volcanic in origin, although some types of diatomaceous earths and siliceous rocks are also pozzolanic (Lea 1973). Some of the European natural pozzolans, utilized for centuries, include the Italian pozzolans, Santorin Earth from the island of Santorin, and Rhenish trass deposits in Germany, Romania, and the U.S.S.R. Rhenish trass has been utilized for some 2,000 years as evidenced in the old Roman buildings along the Rhine.

The earliest attempts at using natural pozzolans in modern construction practice were aimed at reducing the thermal cracking in mass concrete resulting from the heat generated during hydration of the cement. Additions of pozzolans to concrete can reduce thermal cracking upon hydration because the chemical reactions are substantially slower and thus the heat generated from the reactions is spread over a longer period of time. Pozzolans have been used in Europe for centuries, particularly in waterfront applications. The first large scale use of pozzolans in the United States was the Los Angeles aqueduct which was constructed in 1903 using a locally

available volcanic pozzolan (Price 1975). Natural pozzolans have been used in major Western United States structures such as the San Francisco Bay Bridge, the Golden Gate Bridge, the Bonneville Dam, and the Glen Canyon Dam.

The artificial pozzolans include burnt clays and shales, spent oil shales, burnt molar, and fly ash collected from coal burning power plants (Lea 1973). Burnt clays were utilized by the Romans by grinding clay bricks and tiles as a substitute for naturally occurring pozzolans. Burnt clay as an addition to fat lime mortars to obtain hydraulic properties has also been long known in India and Egypt. The Assuan Dam in Egypt initially used lime-burnt clay mortar for the hearting, but its use was discontinued due to difficulties in production of the material at the required rate. The Sennar Dam, built from 1919-1925 on the Blue Nile, used a portland cement and burnt clay pozzolan cement as a mortar.

The first uses of fly ash in the United States came in the early thirties when utilities sought a means to profitably use this waste product in concrete applications (Price 1975). In 1948 fly ash was used to construct the Hungry Horse Dam in Montana. The cement in the dam was replaced by a fly ash from the Chicago area at about a 32 percent replacement level. Since these early successful applications fly ash has been utilized extensively in numerous concrete applications. Most concrete produced today will have part of the cement replaced with fly ash for economic reasons as well as to obtain desirable properties of the fresh and hydrated states of concrete.

Description

ASTM Classifications

ASTM C 618 (1990) classifies pozzolans as class N, raw or calcined natural pozzolans, class F, fly ash normally produced from burning anthracite or bituminous coal, and class C, fly ash normally produced from lignite or sub-bituminous coal. To be used in concrete, all the above classes must meet the applicable requirements of the specification. Class F fly ash has pozzolanic properties, while class C fly ash, characteristic of higher lime contents, has pozzolanic as well as self-cementitious properties.

When a pozzolan is combined with portland cement, pozzolanic behavior results when the free lime liberated from the cement hydration reacts with the aluminosilicates present in the pozzolan to form cementitious products (Mehta 1984). Fly ashes containing analytical CaO (lime) of 10 to 40 percent will have all or part of this lime available for reaction and are thus self-cementing. Higher CaO contents will usually result in higher cementitiousness, but this relationship depends on how much of the lime is free lime and available for reaction. High-lime content fly ash concretes have been found to obtain greater strengths at all ages than low-lime content fly ash concretes (Erdogen 1991).

Composition and Morphology

Sixty to ninety percent of fly ash is composed of amorphous, glassy, spherical particles of about several tenths of a micrometer to several hundred micrometers with

most of these spheres under twenty micrometers (Halstead 1986; Mehta 1984). These spheres are a complex composition of Silica, Ferric Oxide, and Alumina. Other particles of unburned carbon and certain crystalline forms are also present to some degree. Crystals are usually embedded within the glass matrix itself and sometimes are found as surface deposits on the spheres (Roy, Luke, and Diamond 1985). The characteristics of fly ashes vary from location to location, including: the relative proportions of spherical and other particles, the size distributions, the kind of crystal present, the nature of the glass, the types of surface deposit, the nature and proportion of unburned coal, and the overall chemical composition. The variations of these parameters are dependent upon the composition of the coal burned, the burning process, the dust collecting system, and the storage of the fly ash.

The glass in low calcium fly ash is of the siliceous type; whereas, fly ash with high calcium contents will likely contain glass with a calcium aluminate or calcium aluminosilicate type structure, a melilite type silicate structure, or some mixture of glass types (Roy, Luke, and Diamond 1985). The calcium aluminosilicate glasses of the high calcium fly ashes are thought to be more reactive than the aluminosilicate glasses of low calcium fly ashes (Mehta 1984).

The most common crystals found in low calcium fly ashes are quartz, mullite, hematite, sillimanite, and magnetite (Mehta 1984). Anhydrite may also be found in low calcium fly ashes as well as in Class C fly ashes. In high calcium ashes, the principal crystalline materials are generally quartz and C_3A (cement nomenclature, C_3A = Tricalcium alumine ferrite), which is the most reactive component of portland cement. The high calcium fly ashes contain numerous other crystalline components, many of which are calcium-bearing compounds which may be active in cementing

reactions (Roy, Luke, and Diamond 1985). Many of these crystals can become involved in hydration reactions and thus are of particular interest in concrete applications. It is these reactions that give rise to labeling Class C fly ash as cementitious and pozzolanic. Class F is labeled as pozzolanic due to its slow reacting glass that hydrates in the presence of alkalis or lime and crystalline components that remain inert in the concrete.

There are other differences documented between low and high lime fly ashes. The high lime fly ashes typically have higher specific gravities of 2.4 to 2.8, have finer particle sizes, and fewer cenospheres than the low calcium ashes (Roy, Luke, and Diamond 1985). Cenospheres are hollow particles which can be removed by flotation methods.

ASTM Requirements

ASTM C 618 (1990) specifies requirements for fly ash and other pozzolans to be used in concrete. The total content of the oxides: silicon dioxide, aluminum oxide, and iron oxide, must be at least 70 and 50 percent for class F and C, respectively. These oxide contents assure enough oxides for substantial reactions. Additionally, the sulfur trioxide content must not exceed 5 percent, the moisture content must not exceed 3 percent, and the loss on ignition must not exceed 6 percent for both class C and F. Loss of ignition gives a reliable indication of the carbon content. Too many carbon particles will reduce soundness.

ASTM C 618 specifies the minimum pozzolanic activity indexes for fly ash mixed with lime and cement. These tests are used to evaluate the contribution that can be expected from the pozzolan to long term strength development. As stated in the specification, these indexes are not intended to be used to determine the

compressive strength of concrete containing the mineral admixture. ASTM also specifies a maximum of 34 percent retained on a No. 325 sieve with a maximum variation of 5 percentage points from the average for all three mineral admixture classes. The particle size limitation assures that enough small particles will be present for reaction, since it is the large surface area to volume that is attributed to the formation of adequate reaction products. The smaller the fly ash particles, the more reactive it will be. There is an additional requirement for autoclave expansion or contraction of .8 for all classes. Table 1 displays these ASTM chemical and physical requirements for fly ash to be used in concrete. Although these standards give some assurance that the fly ash will be reactive, the only really good way to determine if a fly ash is adequate for its purpose is to test it for its particular use.

The ASTM requirements are a broad classification scheme designed to assure that the fly ash will behave adequately when used in concrete. Literally hundreds of different ashes are being produced which have compositions and behaviors that vary quite significantly. Roy and his colleagues discuss the state of the various physical, chemical and mineralogical characterization methods and procedures and their relations to the reactivity and performance of fly ash in concrete. They state:

It is commonly found that the results or the standard procedures are by themselves inadequate to explain behavior, and in view of the complexity and variability of fly ashes this is not surprising. It is thus necessary to consider a significantly longer list of methodologies which may serve in due course as a source for upgrading standard procedures (Roy, Luke, and Diamond 1985).

Thus, it seems inevitable that a new classification scheme will be enacted in the future. New classification schemes are being proposed based on other chemical and physical characteristics of the material than those presently considered,

particularly lime content, which influence the cement-admixture interactions (Roy, Luke, and Diamond 1985; Mehta 1984).

Table 1. ASTM classification requirements.

ASTM C-618 requirements		
Property	ASTM class F	ASTM class C
Chemical composition		
SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃	70 % min.	50 % min.
CaO	NR	NR
SO ₃	5 % max.	5 % max.
Available alkali, as Na ₂ O	1.5 % max.	1.5 % max.
Loss of ignition	6 % max.	6 % max.
Physical properties		
Moisture content	3 % max.	3 % max.
Soundness autoclave expansion	0.8 % max.	0.8 % max.
Fineness (retained on # 325 sieve)	34 % max.	34 % max.
Pozzolanic activity - w/ lime	800 psi min.	NR
Pozzolanic activity - w/ portland cement	75 % min.	75 % min.
Water requirement - % of control	105 % max.	105 % max.

NR = no requirement

APPLICATIONS

General Remarks

The utilization and acceptance of fly ash as a building material has been slow in coming due to chemical, mineralogical, and physical composition differences within fly ashes from different sources as well as within fly ash from the same source. Nonetheless, due to its intrinsic properties, fly ash has found numerous engineering and material applications as a constituent in concrete, high-strength concrete, autoclaved cellular concrete, engineered fills and backfills, pavements and liners, subbase and pozzocrete, soil stabilization, waste disposal, reef blocks and building blocks, and numerous material applications such as the making of aggregate to be used in concrete, filler in fired clay bricks, and mineral wool. Of particular interest to this investigation are applications in concrete, pozzocrete, subbase, reef block, and building block.

Concrete Applications

Fly ash incorporated into concrete influences the rheological properties in the fresh state and the physical properties in the hydrated state. Due to its spherical shape, fly ash exhibits a lubricating effect in concrete mixtures which usually results in increased workability or a decrease in water content for a given workability. Free lime liberated from cement hydration reacts with the fly ash and results in increased watertightness and increased long term strengths (Berry and Malhotra 1980). In

Europe, fly ash is typically incorporated into portland cement to obtain a blended cement. In the United States, fly ash is incorporated into concrete at the time of batching in three ways (Berry and Malhotra 1980):

- (1) As a partial replacement for cement
- (2) As addition as fine aggregate with no cement decrease
- (3) As partial replacement of both cement and fine aggregate

The first approach which uses a direct replacement for cement by fly ash has been shown to obtain lower strengths than conventional concrete up to about 3 to 6 months with increases in strengths beyond that. The second approach is used mainly to take advantage of the lubricating effects of the fly ash particles which improves workability or decreases water content. The third approach can be utilized to obtain the short term strengths of a control mix with no substitution. The concretes studied in this research fit the third approach, particularly in which more fly ash than the amount of cement replaced is incorporated.

Numerous studies have been undertaken in order to evaluate the effects of pozzolans, particularly fly ash, in concretes. Many beneficial effects may result and include (Mehta 1984 and 1986; Halstead 1986; Berry and Malhotra 1980):

- * greater workability or reduced water requirement
- * reduced bleeding
- * greater pumpability
- * reduced thermal cracking
- * higher long-term strengths
- * more resistance to ingress of aggressive liquids and reinforcing bar corrosion
- * reduced alkali-silica reaction
- * economy

- * increased water tightness resulting in increased resistance to chloride and sulfates.

Adverse effects, especially if an inferior pozzolan or excessive volumes are used, could include (Halstead 1986, Berry and Malhotra 1980):

- * reduced rate of hardening and strength development
- * increased drying shrinkage
- * increased water requirement
- * low freeze-thaw resistance
- * increased air entrainment compound requirement

The durability of concrete is usually determined using ASTM C 666 (1990), where concrete specimens are surrounded with 1/32 to 1/8 inch of water and exposed to 300 freeze-thaw cycles or until its relative dynamic modulus of elasticity reaches 60 % of the initial modulus. The durability is determined by calculating a durability factor from the relative dynamic modulus, which is a measure of the specimens loss of strength from its initial strength. It has been maintained that fly ash concretes will have as good of durability as cement concretes if the air content and strength at the time of the freeze thaw tests are the same (Berry and Malhotra 1980). Haque, Langan, and Ward (1984) investigated the durability of high volume fly ash concretes and determined them to have good freeze-thaw durability even at 75 % replacement for cement.

High Volume Fly Ash Blocks

While high volume replacement of fly ash for cement has not commonly been practiced, a number of researchers have recently investigated beyond 40 percent

replacement of cement by fly ash (Huang et al. 1991; Maher and Balaguru 1991; Hanson 1990; Naik and Ramme 1987; Ravina and Mehta 1986 and 1988; Gopalan and Haque 1985; Haque, Langan, and Ward 1984). Researchers have found that at high replacement levels, fly ash definitely has an inhibiting effect on cement hydration, particularly in the early ages. Fly ash in low to intermittent levels of replacement will usually increase the long term strength of concrete. Class C fly ash with 50 to 60 percent replacement have also obtained greater strengths in the long term than control concretes, i.e., no replacement (Naik and Ramme 1987). This increase in strength can be attributed to fly ash oxides reacting with the lime released during cement hydration as well as to the reactivity of the fly ash itself. Most of this pozzolanic activity takes place weeks to months after mixing and is evidenced by significant increases in strengths for up to 3 years (Hansen 1990). Twenty percent replacement for cement and 40 percent replacement for natural sand with a class F fly ash has been found to be an "engineered-economic application" (Huang et al. 1991). Concretes incorporating larger volumes of fly ash have also been found to have increased water tightness (Maher and Balaguru 1991). Some of this increased watertightness is accredited to the fly ash lime reaction in the pore spaces of the concrete which tend to "close" these capillary channels to the ingress of water and harmful fluids.

After reviewing the literature, it was determined that the relative proportion of cement to fly ash should control the strength of a fly ash concrete at a constant water content and aggregate ratio (Gopalan and Haque 1985; Haque, Langan, and Ward 1984). The cementitious paste of any mix would contain products of the cement hydration, the fly ash hydration (mostly in Class C fly ashes) and pozzolanic

reaction, as well as any unreacted fly ash particles. The unreacted fly ash particles consist of coarse spherical particles as well as unburned carbon fragments (Roy, Luke, and Diamond 1985). These reactions are quite complex and vary between different fly ashes. The reaction products also vary with the relative proportions of each constituent.

Block Criteria

If a particular application does not require high early strengths, then high volume replacement may be desirable and economical. In block manufacture, high volume replacement may be feasible, if adequate early strengths are reached through steam curing. However, the curing time may be increased more than the lower volume concrete units and may prove to be uneconomical because facility usage may have to be increased. Perhaps, in the future, low temperature passive solar curing could be utilized and result in energy savings both through decreased usage of cement and fossil fueled steam rooms.

Compressive strength is used as a measure of a blocks ability to withstand environmental conditions and structural stresses. This investigation used unconfined compression strengths to quantify the suitability of a specific block mix. Ultimately a number of other attributes need also be investigated, including freeze-thaw resistance, shrinkage, etc. There are four types of building blocks made of concrete that are specified by ASTM (1990): Hollow non-load-bearing CMU's, hollow and solid load bearing CMU's, and concrete building brick.

For hollow load-bearing concrete masonry units ASTM C 90 specifies average minimum gross compressive strengths of 1000 psi and 700 psi for grade N and S.

units, respectively, which correspond to net compressive strengths of about 1925 psi and 1345 psi, respectively, for a standard 8" x 8" x 16" unit (assuming 52 % core area). For hollow non-load-bearing concrete masonry units, ASTM C 129 specifies a gross strength of 600 psi, which corresponds to a net strength of about 1155 psi for hollow CMU's.

For solid load-bearing concrete masonry units ASTM C 145 specifies average gross strengths of 1800 psi and 1200 psi for grade N and S units, respectively. Solid blocks are defined as having 75 % or more net area. Thus, for a block with a net area that is 75 % of the gross area, the average net compressive strengths would be 2400 psi and 1600 psi for grades N and S, respectively. For the fourth type of concrete masonry, concrete building brick, ASTM C 55 requires average gross compression strengths of 3,500 psi and 2,500 psi for grades N and S, respectively. The minimum block strength for design procedures outlined in the UBC is 1250 psi (ICBO 1988).

MIXTURE DESIGN AND EVALUATION

General Remarks

From researching ASTM requirements and block manufacturing processes, the following criteria were deemed necessary for a block material:

- (1) A minimum unconfined compression strength of 1250 psi to be obtained within 28 days. This would meet the criteria for non load-bearing units. Strengths in excess of 1345 psi and 1925 psi would meet the requirements of hollow load-bearing type S and N units, respectively.
- (2) A minimum unconfined compression strength of 300 psi obtained within 3 days under normal or accelerated conditions. Blocks generally have to be stacked and transported shortly after casting to optimize facility usage. Conventional concrete blocks manufactured by Kanta in Three Forks, Montana, for example, are cured at elevated temperatures using steam for approximately 10 hours, after which they are moved outside and stacked (Neuhaus, 1991). Fly Ash materials gain strength more slowly than cement based materials, and therefore a longer accelerated curing period at a lower temperature was considered relative to that used for cement based block.
- (3) Zero slump (no flow in the fresh state). Building blocks are extruded from the forms immediately after casting, and, therefore, a very stiff mix is required to prevent slumping of the free standing fresh concrete.

- (4) Good resistance to deterioration from freeze-thaw cycles.
- (5) Low shrinkage and cracking for improved durability.
- (6) Low permeability.
- (7) Uniform, attractive appearance and desirable color.

High volume fly ash concrete mix designs were pursued that would satisfy the first three requirements, particularly with regards to strength. The other requirements were evaluated through qualitative observations in this investigation and will be more formally addressed in further research.

Laboratory experiments were undertaken to develop a block material incorporating as little cement and as much fly ash as possible and meet the above requirements. This investigation consisted of three phases. Phase one was designed to target general relationships that exist with higher volume mixes. Phase two was designed to evaluate the strength development of high fly ash content mixes. Phase three was designed to quantify the relationship between the cement to fly ash ratio and compressive strength and to determine the influence paste volume may have had on previous mixtures.

Materials

The high fly ash concretes were made using sand, Type I-II portland cement, and a Montana Class C fly ash. Locally available sands were used. Their gradations are presented in Table 2. Sand A was used in phase one of the investigation. After completion of phase one, changes in the sand supply resulted in subsequent use of sands B and C. Phase two used sand B and phase three used sand C, which was

sand B with the No. 8 sieve and larger sizes removed to meet ASTM specifications for mortar sand.

The fly ash came from the Corette coal generation plant in Billings Montana, operated by the Montana Power Company. This fly ash is marketed by Mineral Specialties of Billings, who provided the physical and chemical properties along with the statistical analysis that is displayed in Table 3 (Vollmer 1991). Although it meets the requirements of class C and class F (Table 1), the Corette fly ash should be classified as class C since it is from a sub-bituminous coal and has cementitious properties due to its high lime content. The high activity indexes of this fly ash indicate it has good reactivity and would provide significant contribution to the strength of a material. Note that the major chemical constituents of the fly ash (the total oxides and lime) are fairly constant. The variability of the physical properties is also fairly low, with the exception of autoclave expansion. The variations would influence the results obtained within this investigation, but would be minimized within a group of mixes utilizing fly ash from the same shipment.

Table 2. Gradation of sands.

Sieve size	Sand A	Sand B	Sand C
	Accum. % retained	Accum. % retained	Accum. % retained
No. 4	2.4	1.7	0.0
No. 8	14.9	10.3	0.1
No. 16	33.2	23.0	16.4
No. 30	53.2	43.6	40.5
No. 50	79.6	79.7	73.9
No. 100	96.6	95.0	95.7
Fineness modulus	2.8	2.5	2.3

Table 3. Corette fly ash properties.

Chemical properties - Date: 09/18/90						
Property	Average value	Number of tests	Variance	Standard deviation	High test	Low test
SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃ (%)	74.05	81	8.75	2.96	NG	NG
Sulfur Trioxide - SO ₃ (%)	1.05	81	0.07	0.26	NG	NG
Moisture content (%)	0.06	81	0.002	0.05	NG	NG
Loss on ignition (%)	0.37	81	0.07	0.27	NG	NG
Available alkali (%)	0.51	81	0.08	0.28	NG	NG
Calcium as CaO (%)	17.85	81	3.74	1.93	NG	NG
Physical properties - Date: 06/14/90						
Density	2.44	76	0.0018	0.04	2.52	2.36
Fineness # 325 sieve	17.41	76	8.09	2.84	25.50	10.05
Activity with lime (psi)	1486	61	NG	440	2833	931
Activity with portland cement (% of control)	105	76	94	10	132	83
Water requirement (% of control)	91	76	5.77	2.40	96	84
Autoclave expansion (%)	0.07	75	0.002	0.05	0.26	0.01
Drying shrinkage (%)	0.01	43	0.00002	0.00	0.02	0.0

NG = value not given

Phase One- Preliminary Investigations

General Remarks

Preliminary investigations were undertaken primarily to target appropriate proportions to be used in high volume blocks. These mixes were used to identify that reasonable strengths were obtainable and to generally establish a relationship between the cement to fly ash ratio and unconfined compressive strength.

Mix Details

The details of the preliminary mixtures, designated as A-F, are given in Table 4. Three separate aggregate percentages of 50, 60, and 70 percent by weight of solids were used. Within each aggregate percentage, cement contents of 5 and 10 percent were used. The remaining weight consisted of fly ash. Thus the ratio of cement to fly ash ratio varied from 0.5 to 0.11 (by weight). All mixes contained more than enough paste material to completely encase all of the sand aggregate (calculated paste volumes are given in the appendix). Thus, the ratio of fly ash to cement was expected to control the strength of these mixes over the ratio of aggregate used. The water to cementitious materials ratio was nominally controlled and varied from 0.28 to 0.38. The mixes were not measured for flowability, but they were all judged to be of the same stiff, smooth consistency at the time of mixing. These mixtures were hand mixed and hand tamped in the laboratory. 4 x 8 inch cylinders were cast and cured at a constant 73 degrees fahrenheit and 100 percent relative humidity in a fog room. They were tested in unconfined compression at 7 and 28 days.

Results and Discussion

Table 4 displays the compressive strengths of these mixes at 7 and 28 days. Figure 1 is a plot of the compressive strengths with age and Figure 2 demonstrates the variation of strength with regards to the cement to fly ash ratio. This ratio appeared to be the controlling influence in the mixes, even when the absolute amount of cement was constant, i.e. at either 5 percent (B,D, and F) and 10 percent (A,C, and E). As the cement to fly ash ratio increased from 0.11 to 0.50, the 7 day compressive strengths increased from 260 psi to 2825 psi, respectively.

Table 4. Phase one mixes, details and compressive strengths.

Preliminary mixes							
Mix #	Sand % wt of solids	Fly Ash % wt of solids	Cement % wt of solids	Water to cementitious ratio	Cement to fly ash ratio	7 day f'c (psi)	28 day f'c (psi)
A	50	40	10	0.29	.25	915	4850
B	50	45	5	0.28	.11	260	3305
C	60	30	10	0.30	.33	1650	5160
D	60	35	5	0.31	.14	225	3660
E	70	20	10	0.38	.50	2825	5525
F	70	25	5	0.34	.20	695	4470

Correspondingly, the 28 day compressive strengths increased from 3305 psi to 5525 psi, respectively. The mixes with lower cement to fly ash ratios gained proportionally more strength from 7 to 28 days than the higher cement to fly ash ratio mixes, reflecting the relatively slow nature of the reactions as compared to the faster reacting cement hydration. Since the aggregate ratio and the water to cementitious materials ratio were varying, no attempt was made to concisely characterize the relationship between the ratio of cement to fly ash and compressive strength. All of the mixtures seemed promising since they met the block criteria with respect to strength. In particular, the mixes with only 5 percent cement all had 28 day strengths in excess of 3,000 psi, therefore meeting the strength requirements for hollow and solid load bearing CMU's as well as for type S concrete building brick.

Figure 1. Phase one mixes, age vs. compressive strength.

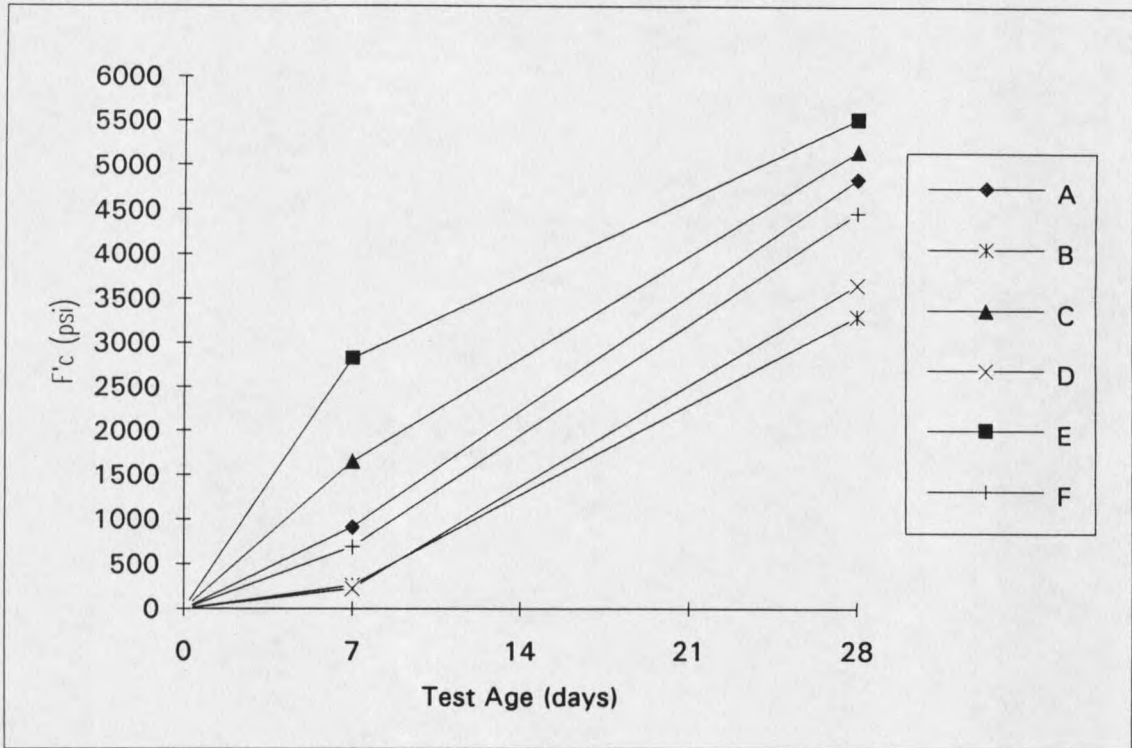
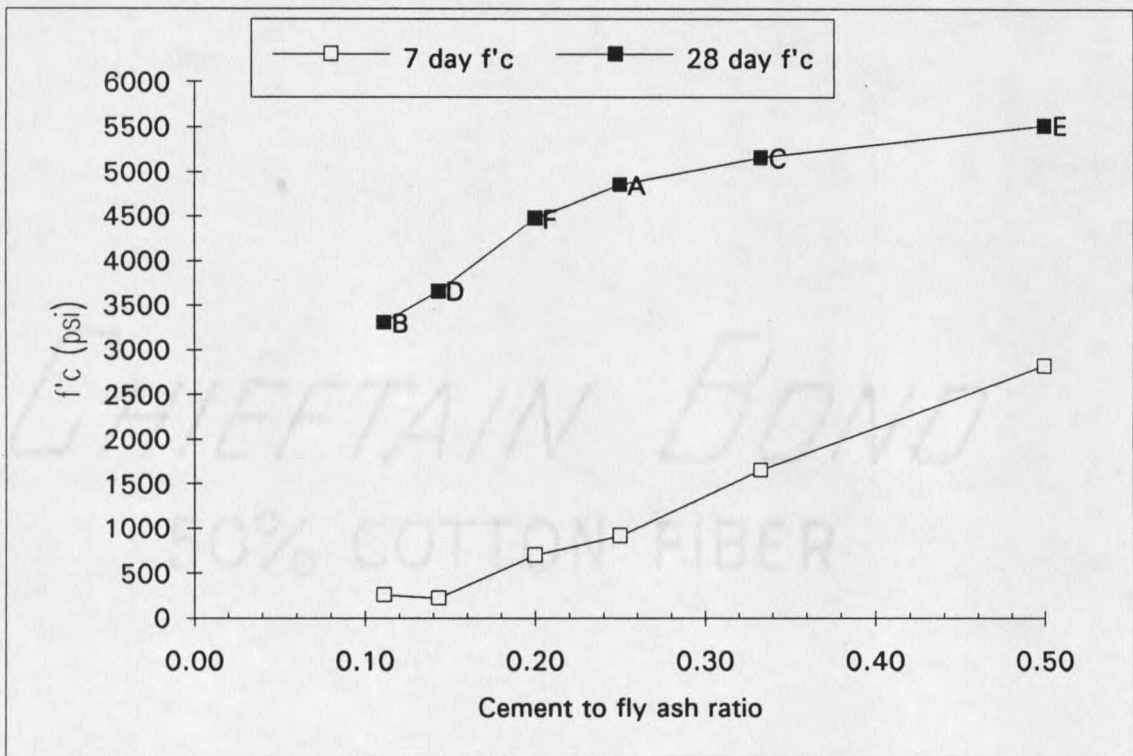


Figure 2. Phase one mixes, cement to fly ash ratio vs. f'_c .



Phase Two Investigations- Strength Development Relationships

General Remarks

From phase one results, it was extrapolated that almost pure fly ash pastes could obtain 28 day strengths sufficient to be used in concrete block under normal curing conditions. Therefore, the phase two mixes were designed to demonstrate the strength development resulting from small additions of cement to activate the fly ash paste. Accelerated curing was used (1) to determine a correlation between the strengths obtained at accelerated curing conditions and the long term strengths obtained at normal curing conditions and (2) to give some indication of the effectiveness of accelerated curing to increase early strength gain of the fly ash mixtures and overcome the disadvantage of slower pozzolanic reactions.

Mix Details

Details of the phase two mixtures, designated A1, B1, A2, B2, and C2, are presented in Table 5. The "A" mixes contained only fly ash as the paste material. The "B" mixes contained 2 percent cement by weight of solids which corresponds to a cement to fly ash ratio of 0.11. Mix "C" contained 5 percent cement by weight of solids, corresponding to a cement to fly ash ratio of 0.25.

The mixes had aggregate to cementitious materials ratios of 4, corresponding to 80 percent aggregate by weight of solids. This ratio is higher than the ratio of 2.75 (73.3 percent) as specified for hydraulic cement mortars (ASTM 1990) and significantly lower than ratios of 8 to 12 for sand or gravel that are commonly used

in the block industry (Columbia block manual). Since the fineness modulus of sand B was somewhat lower than the recommended modulus of 3.7 (Columbia block manual) for concrete blocks it was decided to use 80 percent solids by weight in the phase two mixes, which is about twice the amount typically used in concrete masonry units (typical CMU's contain about 90 percent aggregate). Since high volumes of fly ash were being incorporated in the mix, it was assumed that some of it would act as fine aggregate in the mix.

In order to obtain mixes with the same workability, water was added to all phase two mixes to maintain a constant flow of 65-75 percent with 10 drops in 6 seconds as specified in ASTM C 593 (1990), a standard specification for pozzolans for use with lime. Using 10 drops in 6 seconds was deemed more appropriate than the 25 drops in 10 seconds normally used for hydraulic cement mortars since low cement to fly ash ratios were incorporated. The appendix contains the details of the mixing procedure. Following mixing, the mortar was immediately vibrated into standard four inch by eight inch plastic cylinders and placed in the appropriate curing condition.

Accelerated Curing

An accelerated cure was desired that would be as close to actual block curing as is used in industry. Usual low-pressure steam block manufacturing processes have an initial presteaming period followed by a temperature increase period (ACI Committee 517 1963). The presteaming period is the time from initial completion of molding to the application of steam and is typically one or more hours depending on the maximum steaming temperature used. The temperature is then increased at a optimum rate to the maximum temperature. Since accelerated steam

Table 5. Mix details for phase two.

Phase two mixes						
Mix #	Sand % of solids	Fly Ash % of solids	Cement % of solids	Water to cementitious ratio	Cement to fly ash ratio	Flow in inches
A1	80	20	0	0.72	0.00	6.5
B1	80	18	2	0.62	0.11	6.6
A2	80	20	0	0.56 (0.60)	0.00	6.5 (6.5)
B2	80	18	2	0.48 (0.56)	0.11	6.6 (7.0)
C2	80	15	5	0.56 (0.59)	0.33	6.75 (6.75)

Note: Parenthesis denote values for accelerated mix.

curing was unavailable, a heated tank was constructed to cure four by eight inch cylinders covered and submerged in water at desired temperatures. The specimens were stored at room temperature for at least one hour prior to submersion. Three curing conditions were used:

- 1) Cure I (normal) consisting of a fog room maintained at 73 degrees Fahrenheit and 100 percent RH.
- 2) Cure II (moderate temperature) consisting of a water bath maintained at 130 degrees Fahrenheit for three days and then subsequent curing in condition I. This curing regime mimics that which might be practical in actual block production.
- 3) Cure III (high temperature) consisting of a water bath maintained at a constant 165 degrees fahrenheit for seven days. This curing regime might be useful to obtain an early indication of 28 day strengths.

Series "1" Mixes (A1 and B1) were cured at conditions I and II and were tested at 3, 7, 28, and 84 days for each condition. Series "2" Mixes (A2, B2, and C2) were

cured using cures I and III and were tested at 3, 7, 28, and 84 days for cure I and at 10 hours, 1 day, 2 days, 3 days, 5 days, and 7 days for cure III. All values displayed represent the average of three cylinders tested in accordance with ASTM.

Results and Discussion

The results of the compressive strength tests are given in Tables 6 and 7 and are plotted in Figures 3, 4, 5, and 6. In mixes A1 and B1, it is evident from Figure 3 that the accelerated cure at 130 degrees Fahrenheit resulted in significant early strength gain at 3 days with minimal additional strength gain with subsequent curing under normal conditions. As demonstrated in Figure 4, mixes A2, B2, and C2, also had significant early strength gain at 3 days with little increase beyond. It is apparent that little can be gained by curing longer than three days. By comparison of the accelerated cure strengths with the normal cure strengths, it is evident that the ultimate strengths were adversely affected by the accelerated cure. This is to be expected from hot weather curing effects in normal portland cement concrete (Kosmatka and Panarese 1988) as well as from deviation from actual block practice as discussed above. The high temperature accelerated cure, as expected, was more detrimental to obtainable strengths than the low temperature accelerated cure.

Mix B1, exposed to accelerated cure had 44 percent less strength at 84 days than when it was cured at normal conditions. Mix B2, had a three day accelerated cure strength of 46 percent of the strength at the normally cured 84 day strength. Nonetheless, the 84 day strengths give a good indication that the "B" mixes, containing only 2 percent cement, will meet the targeted block strengths if optimal curing procedures are used. Interestingly, mix A1, containing only fly ash as the paste material, achieved about the same strength as the normally cured specimens,

Table 6. Compressive strengths of mixes A1 and B1.

Unconfined Compression Strength			
Cure and Test Age		A1	B1
Normal cure I	3 days	25	30
	7 days	35	65
	14 days	40	250
	28 days	75	660
	90 days	430	2065
Accelerated cure II	3 days	295	890
	7 days	380	765
	14 days	445	850
	28 days	405	980
	90 days	475	1150

Table 7. Compressive strengths of mixes A2, B2, and C2.

Unconfined Compression Strength				
Cure and Test Age		A2	B2	C2
Normal cure I	3 days	30	50	125
	7 days	40	80	620
	14 days	55	235	1075
	28 days	125	510	1590
	84 days	460	1935	3680
Accelerated cure III	10 hours	55	205	265
	1 day	120	445	855
	2 days	250	640	1390
	3 days	300	760	1710
	5 days	320	820	1695
	7 days	NM	NM	1735

Figure 3. Phase two mixes A1 and B1, age vs. f'c.

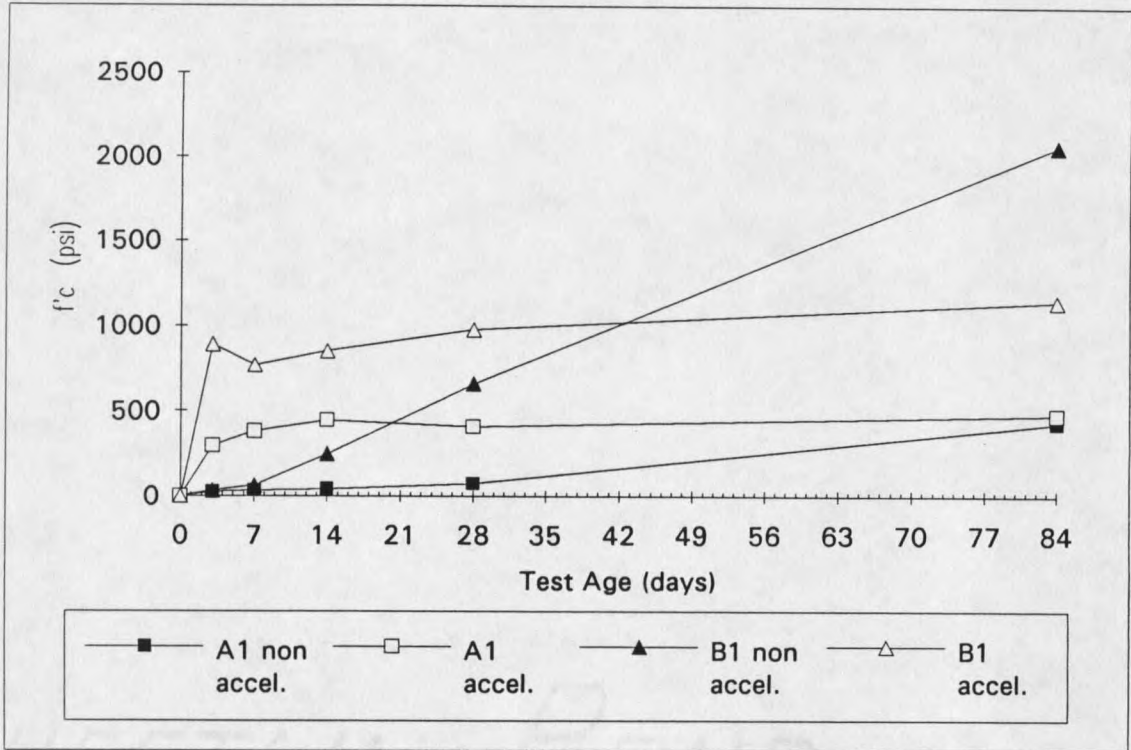


Figure 4. Phase two mixes A2, B2 and C2, age vs. f'c.

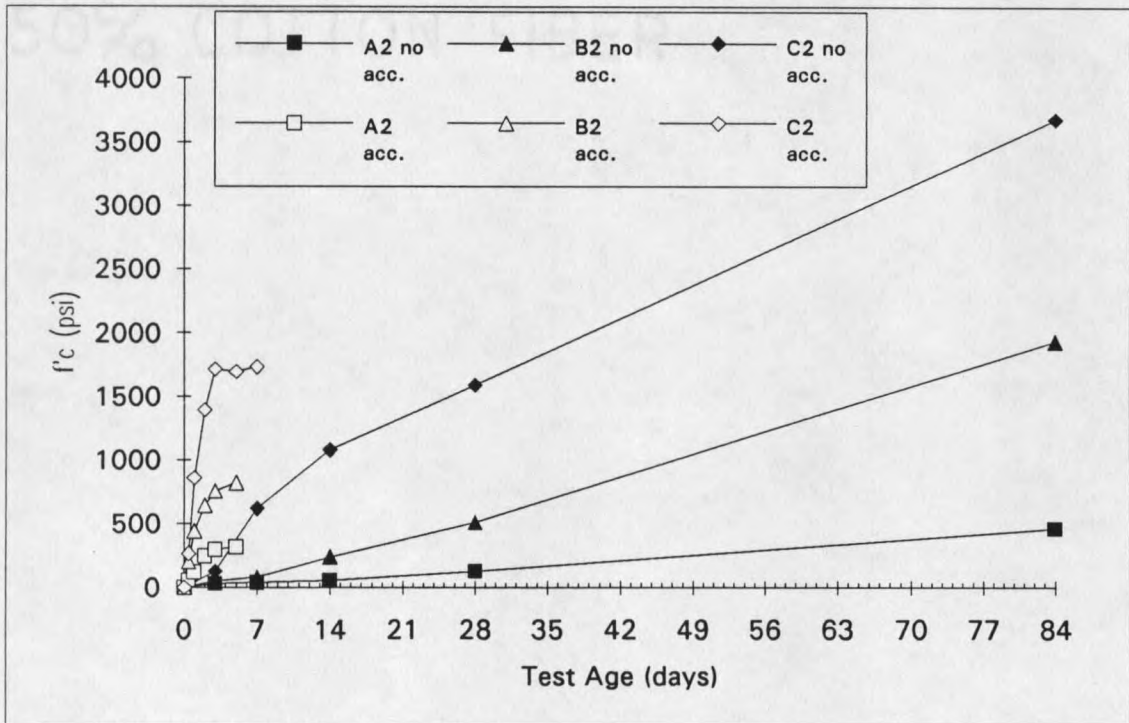


Figure 5. Phase two mixes A2, B2 and C2, accelerated cure age vs. f'c.

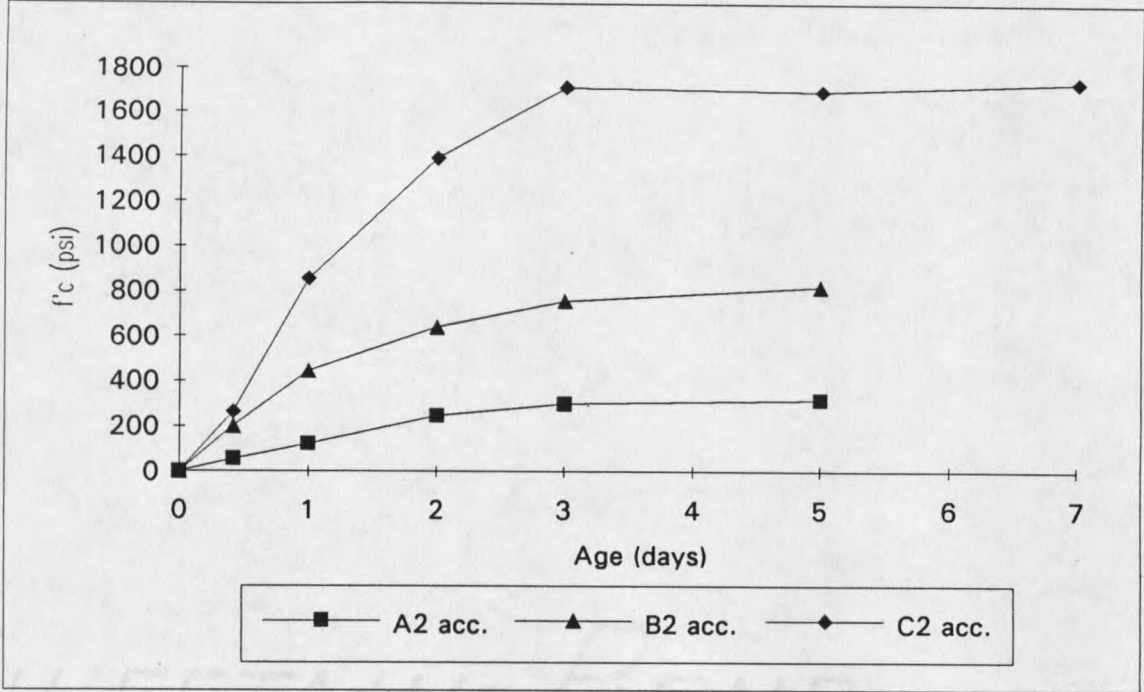
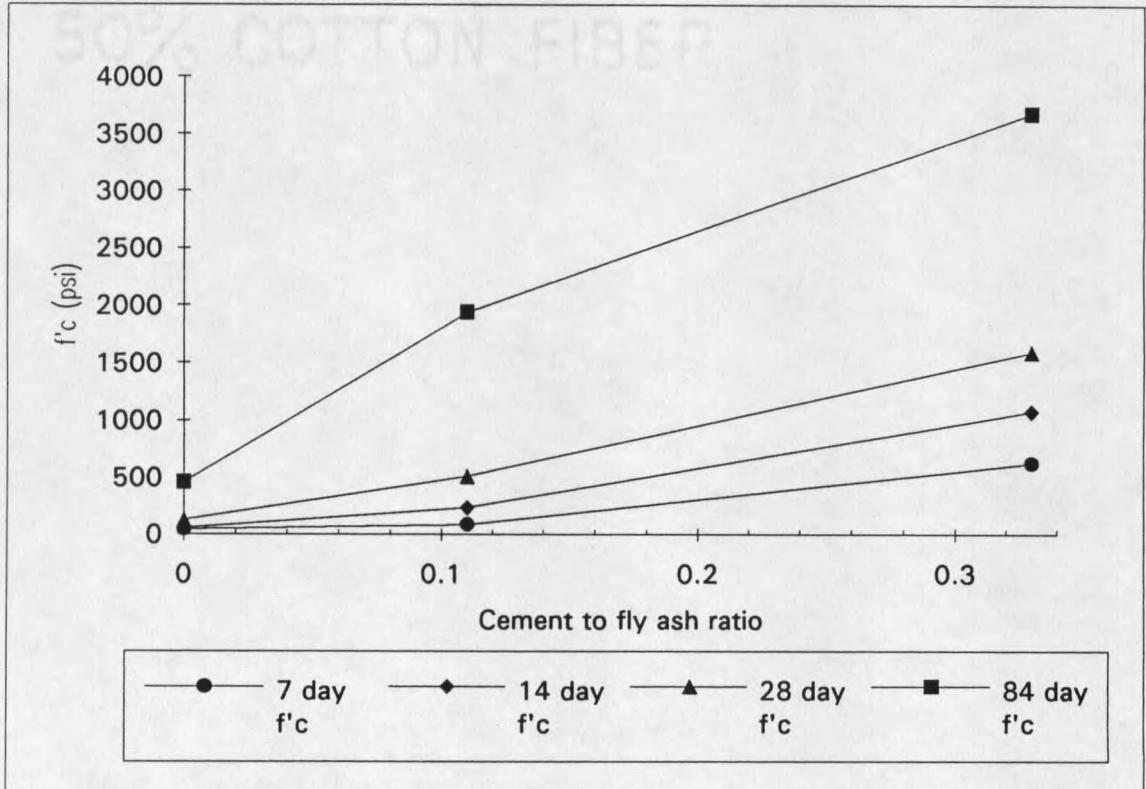


Figure 6. Phase two mixes, cement to fly ash ratio vs. f'c.



at least at 84 days. Since the fly ash reactions are quite slow, it is probable that the pure fly ash mixtures will gain substantially more strength beyond even 84 days. Use of the three day cure at 165 degrees to predict long term strengths of fly ash concretes appears practical. The three day accelerated strengths were 108 %, 148 %, and 242 % of the 28 day normal cure of mixes A2, B2, and C2, respectively. The three day accelerated strengths were 46 %, 39 %, and 65 % of the 84 day non-accelerated strengths of mixes A2, B2, and C2, respectively. Relationships for each particular cement to fly ash ratio would have to be established through further research utilizing a curing procedure less detrimental to obtainable strengths.

Figure 6 demonstrates a general trend of increased strengths with increased cement to fly ash ratios. It appeared that this relationship could be more completely established and motivated research into phase three to investigate this phenomenon further.

Phase Three Investigations- Mixes to Quantify Relationships

General Remarks

Phase three of this investigation was conducted to further investigate the phase one and phase two block mixtures. Two sets of mixes were investigated. The first set (set H-O) more carefully characterizes the effect of varying the ratio of cement to fly ash at constant water to cementitious materials ratios and at the same aggregate percentage as the block mixtures of phase two. The cement to fly ash ratio was varied from infinity to zero with six ratios between. Infinity represents a pure cement paste; zero represents a pure fly ash paste. The second set of mixes (set P-R) indicates the influence of paste volume on previous mixtures. The aggregate

to cementitious materials ratio was varied while the cement to fly ash ratio and the water to cementitious materials ratios were held constant.

Mix Details

Mix details are presented in Tables 8 and 9. Sand C, meeting the requirements for mortar sand, was used in this phase of the investigation. Two inch cubes were molded according to ASTM C 109 (ASTM 1990). All specimens were covered and left in the laboratory for 24 hours and then demolded and placed in a steam room. Difficulties were experienced with the curing room; the curing temperature varied from 73 degrees F. to 80 degrees F., which may have had some influence on those results.

In the first set of mixes two water to cementitious material ratios were used. The first water content of 0.5, designated with a "1" following the mix character designation, resulted in a stiff mix with little or no flow, suitable for concrete blocks. The second water content of 0.75, designated with a "2" following the mix character, had significant flows as measured by ASTM C 593 (see Table 8).

The second set had a cement to fly ash ratio of 0.11 and had sand to cementitious ratios of 3.0, 2.75, and 2.33. The 2.75 aggregate ratio is specified for hydraulic cement mortars in ASTM C 109 (1990). The series one mixtures ("1" following the mix character), with a water content of 0.50, had flow significantly in excess of the targeted no flow criteria. Thus, a second series of mixtures ("2" following the mix character) was prepared at a water to cementitious materials ratio of 0.4. These mixes had very little flow, again suitable for block mixtures.

Table 8. Mix details for series H-O.

Mix series H-O						
Mix #	Sand % of solids	Fly Ash % of solids	Cement % of solids	Cement to Fly ash ratio	Water to cementitious ratio	Flow (inches) 4" = zero flow
H1	80.0	0.0	20.0	*	0.50	4
I1	80.0	20.0	0.0	0.00	0.50	4 1/8
J1	80.0	18.0	2.0	0.11	0.50	4 1/8
K1	80.0	16.7	3.3	0.20	0.50	4 1/8
L1	80.0	15.0	5.0	0.33	0.50	4 1/8
M1	80.0	13.3	6.7	0.50	0.50	4 1/8
N1	80.0	10.0	10.0	1.00	0.50	4 1/16
O1	80.0	6.7	13.3	2.00	0.50	4 1/8
H2	80.0	0.0	20.0	*	0.75	4 3/8
I2	80.0	20.0	0.0	0.00	0.75	6
J2	80.0	18.0	2.0	0.11	0.75	8
K2	80.0	16.7	3.3	0.20	0.75	7 1/2
L2	80.0	15.0	5.0	0.33	0.75	6 7/8
M2	80.0	13.3	6.7	0.50	0.75	6 1/8
N2	80.0	10.0	10.0	1.00	0.75	6 1/2
O2	80.0	6.7	13.3	2.00	0.75	5 5/8

Table 9. Mix details for series P-R.

Mix series P-S						
Mix #	Sand % of solids	Fly Ash % of solids	Cement % of solids	Cement to Fly ash ratio	Water to cementitious ratio	Flow (inches) 4" = zero flow
P1	75.0	22.5	2.5	0.11	0.50	6 1/4
Q1	73.3	24.0	2.7	0.11	0.50	7 3/8
R1	70.0	27.0	3.0	0.11	0.50	8 1/2
P2	75.0	22.5	2.5	0.11	0.40	4 5/16
Q2	73.3	24.0	2.7	0.11	0.40	4 3/4
R2	70.0	27.0	3.0	0.11	0.40	5 3/4

Results and Discussion

Test results of the phase three mixtures, summarized in Tables 10 and 11, indicate the influence of cement to fly ash ratio, sand ratio (weight of sand to total weight), and the water to cementitious materials ratio on the compressive strength and flowability of these particular fly ash concretes. These results can generally be used to design a mixture for certain strength and flow characteristics using different proportions of the basic constituents as desired. The results were used to formulate a final recommendation for high volume fly ash concrete mixtures for concrete block applications.

The influence of cement to fly ash ratio on strength is evident from the graph of compressive strength versus the cement to fly ash ratio presented in Figure 8 for mixtures H-O. Note that while for both mixtures the strength increases with increasing cement to fly ash ratio, the effect diminishes significantly in the series one mixtures. This situation is believed to result from the confounding influence of paste volume in the mixture on concrete strength. Mix H1, containing only portland cement, resembles closely a standard concrete mix. The 28 day strengths of such a mix is well documented, and, in this case, it should be approximately 4800 psi (Kosmatka and Panarese 1988). The actual strength of H1 was about 40 % less than the expected strength. Series one mixes, H1-O1, were notably sandy in appearance and slightly crumbly, indicating that the voids in the sand were not completely enclosed by paste material. The void ratio of sand C was approximated by assuming the specific gravity of the sand was 2.65 and measuring the dry density of the sand slightly compacted in the laboratory. It was determined that the sand contained about

40 percent voids by volume. The corresponding paste volumes were all between 35 and 40 percent (See the appendix for calculated volumes). Series one mixes (H1-O1)

Table 10. Unconfined compressive strengths of mixes H-O.

Mix designation	Compressive strength, psi	
	7 days	28 days
H1	1795	2840
I1	140	425
J1	330	1370
K1	480	1630
L1	835	2040
M1	1140	2460
N1	1615	2605
O1	1775	2790
H2	1605	2440
I2	40	130
J2	105	745
K2	160	965
L2	365	1420
M2	575	1810
N2	1175	2665
O2	1635	3270

Table 11. Unconfined compressive strengths of mixes P-R.

Mix designation	Compressive strength, psi		
	7 days	28 days	90 days
P1	185	1175	2420
Q1	145	990	2110
R1	115	920	2400
P2	275	1535	2190
Q2	335	1775	2780
R2	460	1850	3030

Figure 7. Phase three mixes H-O, 7 and 28 day compressive strengths.

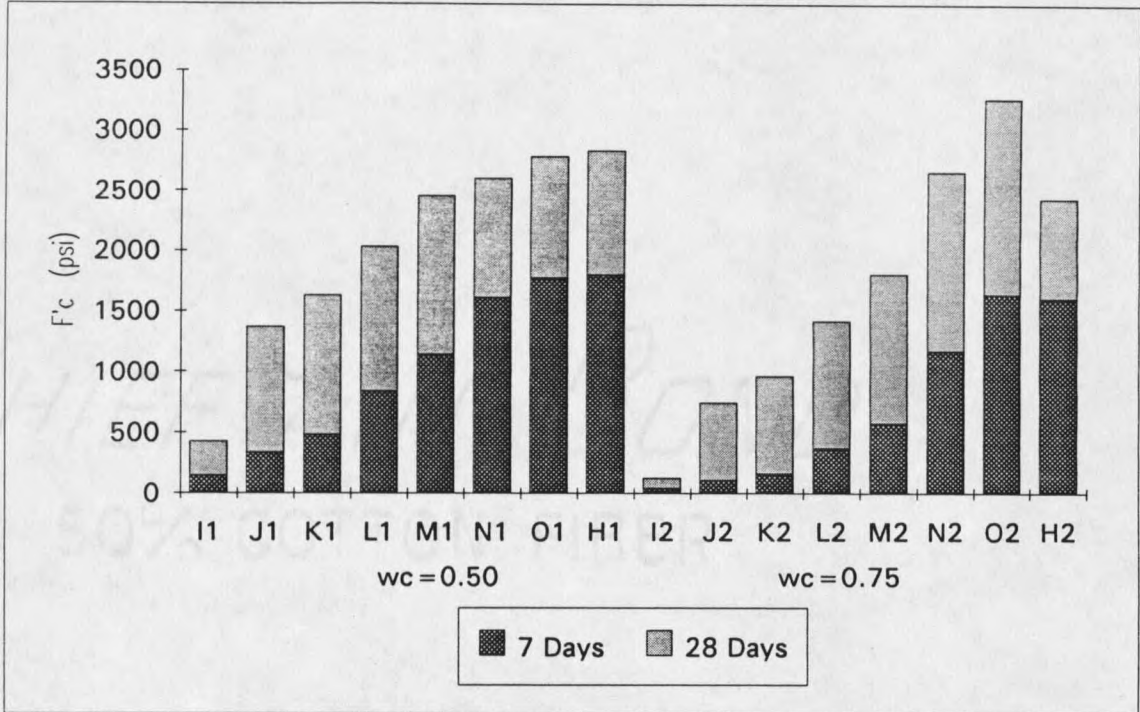
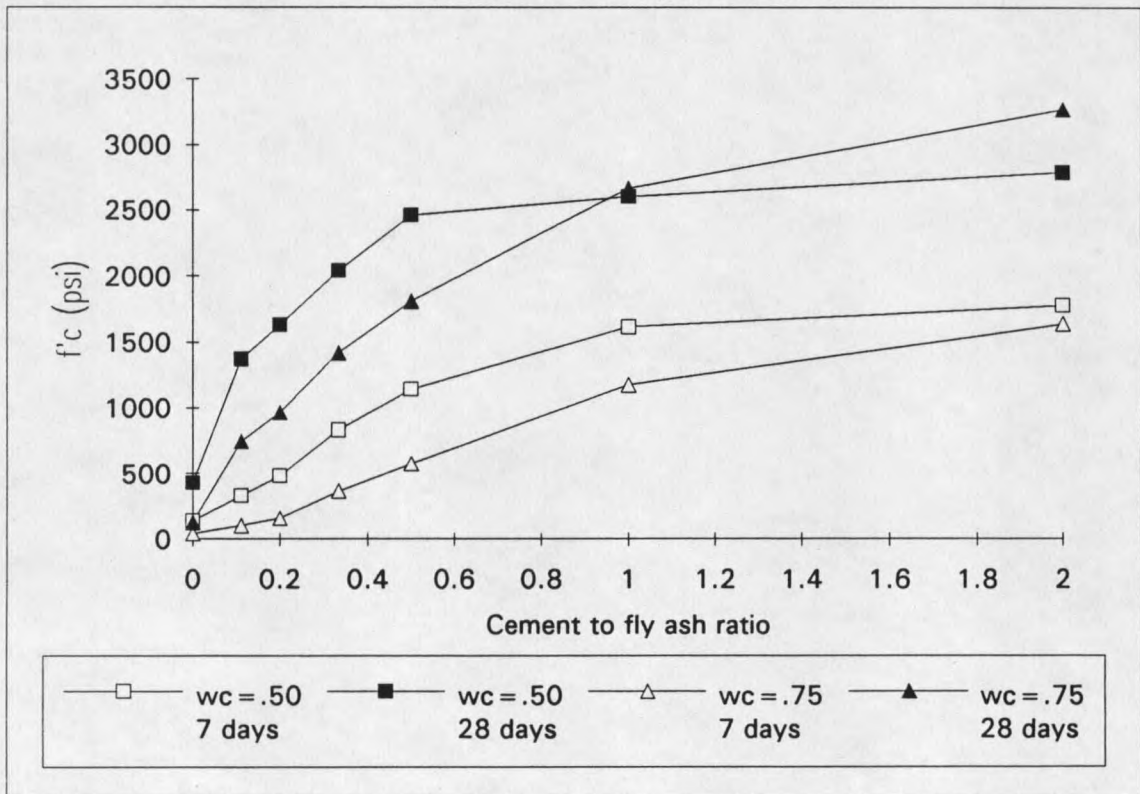


Figure 8. Phase three mixes H-O, cement to fly ash ratio vs. f'c.



did not have enough material to completely fill the voids and coat all the aggregate. Series two mixes (H2-O2) with a higher water content contained more paste volume than void space, since more water was incorporated. These mixes did achieve the strengths expected. Mix H2 had strengths of 1605 psi and 2440 psi at 7 and 28 days, respectively. Expected strengths were around 1500 psi and 2800 psi.

The mixes P-R demonstrate the effect of the paste volume in the mixes on strength. The compressive strengths are presented in Tables 11 and are plotted in Figure 9. Figure 10 contains a plot of the compressive strength as a function of the sand ratio. It is evident that the 0.5 water to cementitious materials ratio mixtures had the greatest strengths at the ASTM sand ratio of 0.75. The 0.4 water to cementitious materials ratio mixes had the greater strength at the sand ratio of 0.70. These contradictory results may be explained through paste volume. The lower water content mixtures, containing less paste material appeared to be weakened in the high sand content mixtures. Thus, it is apparent that the previous mixtures of phase two with the lower water to cementitious ratio may have had some loss of strength due to the effect of sand weakening the paste matrix.

Figures 11 and 12 illustrate the general trends of flow decreasing with (a) increasing cement to fly ash ratios (Figure 11) and (b) increasing in the sand ratio (Figure 12). The decrease in flow with increased cement to fly ash ratio can best be explained from the lubricating effects of the spherical fly ash particles. As the cement to fly ash ratio decreased, the fly ash content and its associated lubricating effect on the mix increased. The increased workability of conventional concretes containing small amounts of fly ash is well documented (Berry and Malhotra 1980, Halstead 1986). Note that the pure fly ash mixture had very low flow, a phenomena which is

Figure 9. Phase three mixes P-R, age vs. f'c.

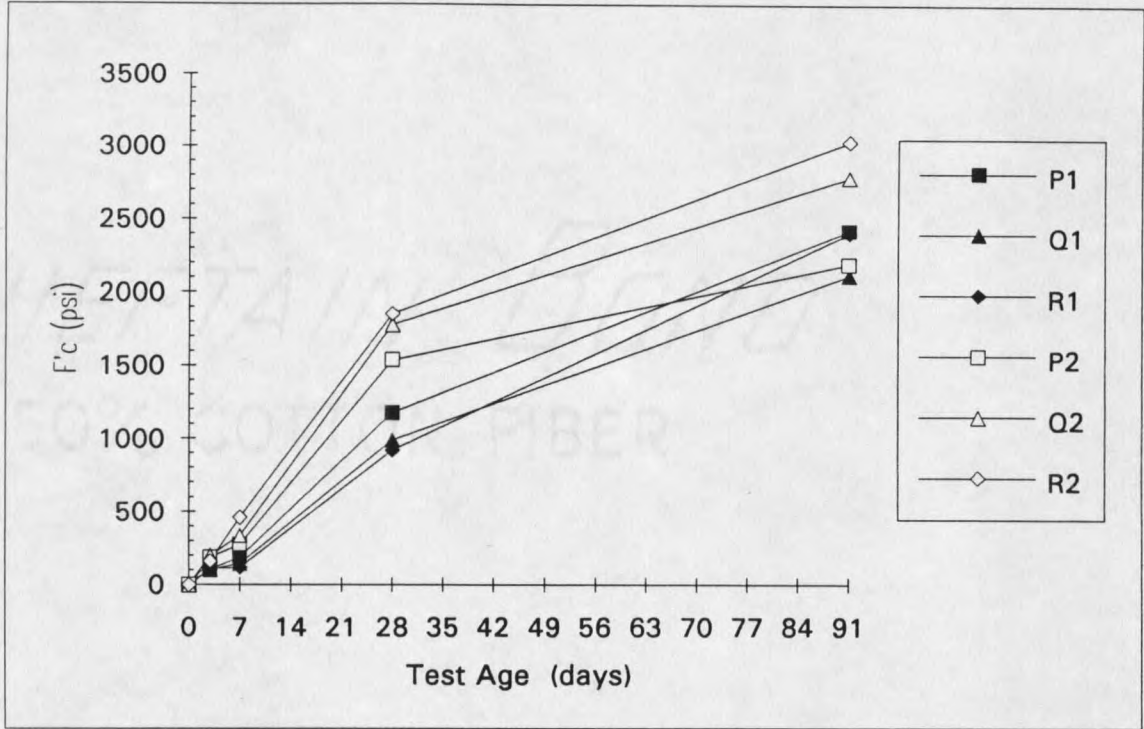


Figure 10. Phase three mixes P-R, sand ratio vs. f'c.

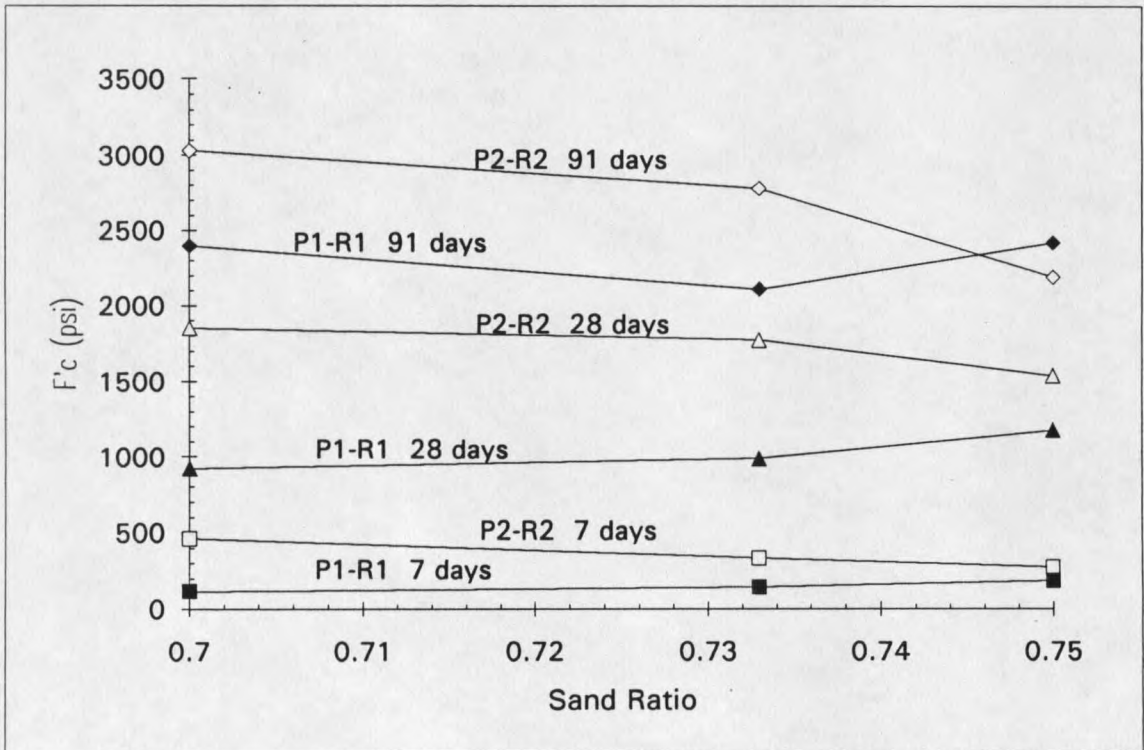


Figure 11. Phase three mixes I2-O2, cement to fly ash ratio vs. flow.

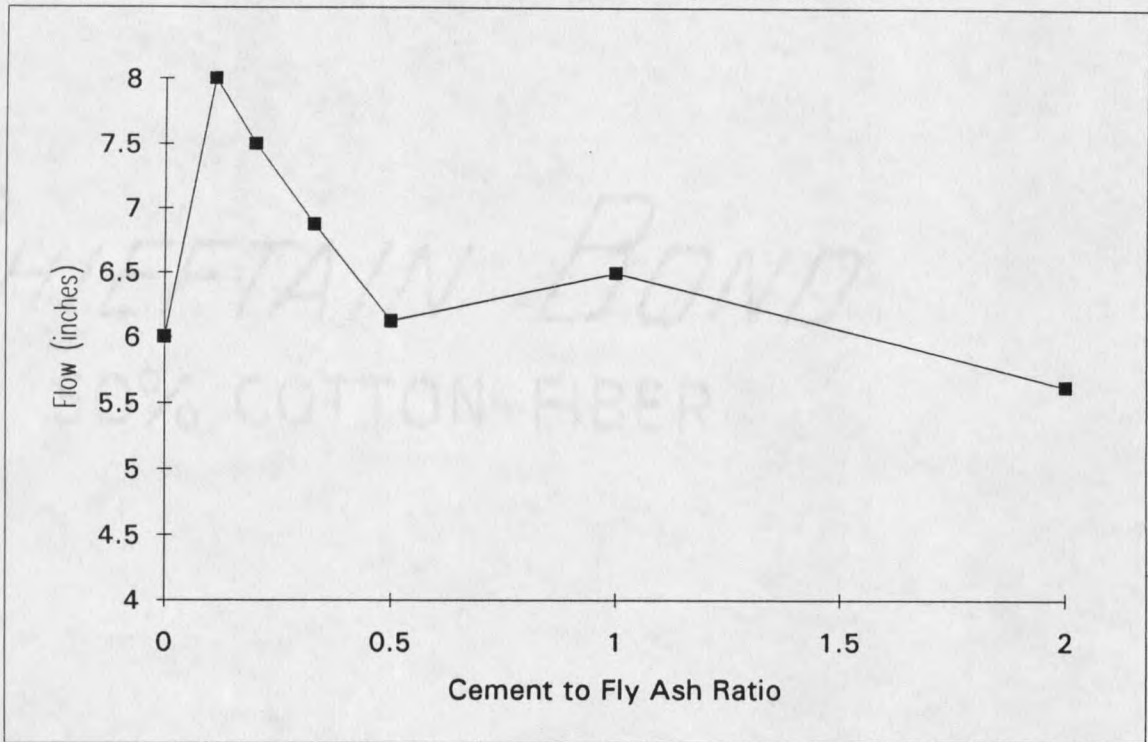
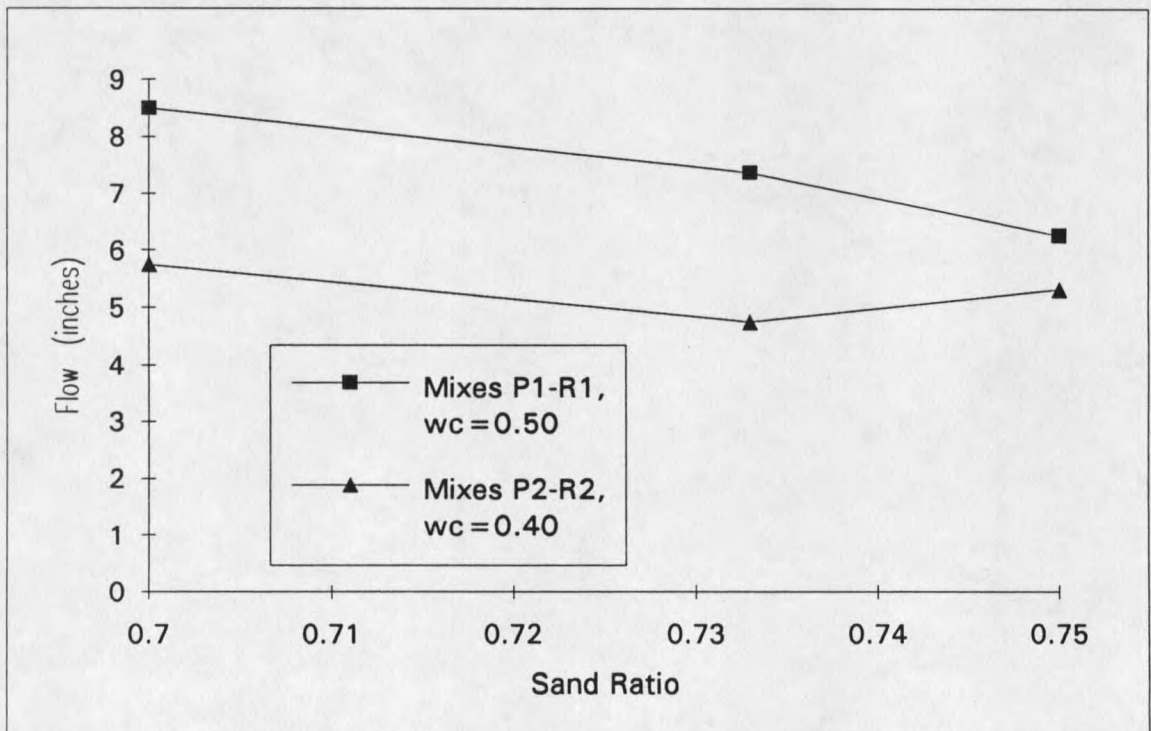


Figure 12. Phase three mixes P-R, sand ratio vs. flow.



also noted in the literature (Haque et al. 1984). This increased workability may be beneficial in block mixtures since less water would have to be added for larger fly ash volumes and greater strengths could be achieved. The decrease in flow with increases in the sand ratio is also expected since more sand means less paste material and less lubrication.

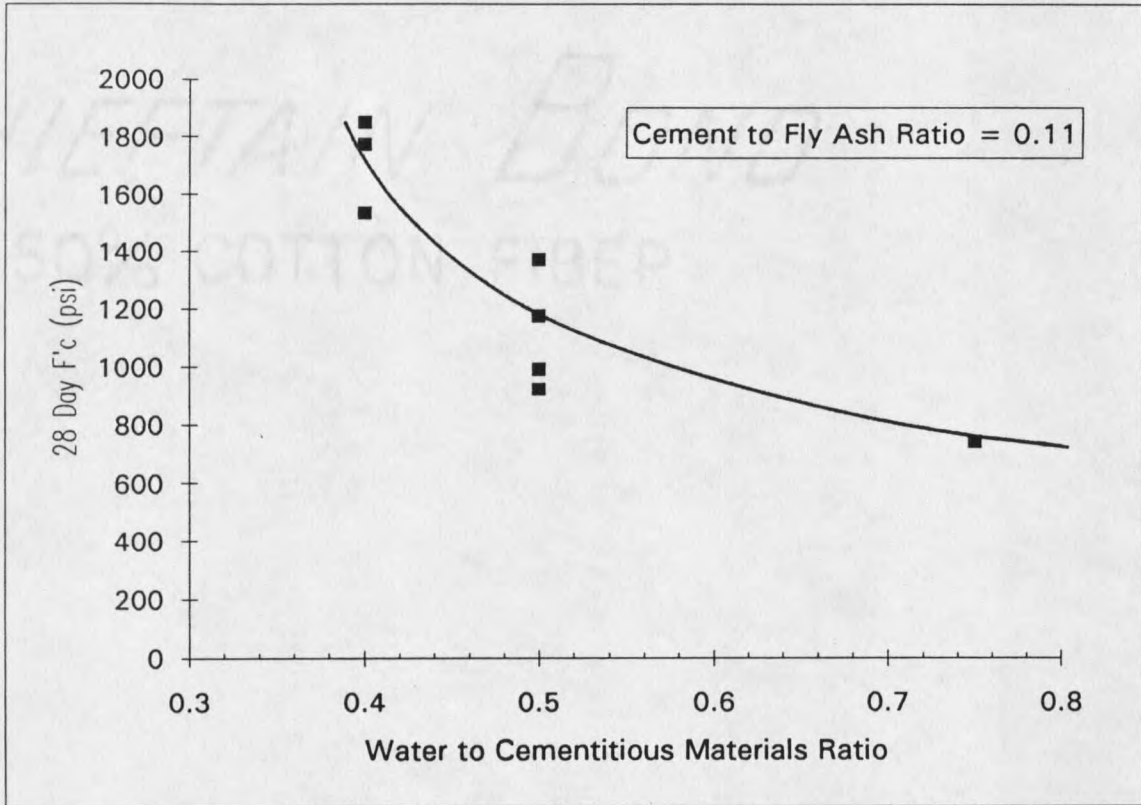
The effect the water to cementitious materials ratio had on strength is depicted in Figure 13. All mixes in phase three with cement to fly ash ratios of 0.11 were plotted. There is a general trend of decreased strength with increases in water to cementitious materials ratio with less effect at higher ratios. A similar effect is well documented in the cement based concrete literature (Kosmatka and Panarese 1988).

Qualitative Observations and Comments

Visual observations were noted in all phases of this research with respect to the physical properties and behavior of the mixtures in the fresh and hardened states. One common observation was that fly ash specimens had a lighter appearance than the non-fly ash specimens due to the inherent white color of the fly ash. The surface of the accelerated specimens appeared glassier than the non-accelerated specimens which may be desirable for a building material. The specimens were also quite smooth which may be undesirable for a building material since paint may poorly bond to this smooth surface.

The mixtures containing 80 percent sand by weight were notably sandy and crumbly, particularly at earlier ages and lower strengths. Conversely, the 75 % sand mixtures at a 0.5 water to cementitious materials ratio were creamy. Mixes H1-O1 containing the least amount of paste volume were affected the most. The low

Figure 13. Phase three mixes, $c/fa = 0.11$, water to cementitious materials ratio vs. 28 day compressive strength.



strength of these mixtures can be attributed to either the lack of paste volume or to improper aggregate selection. Aggregate with a fineness modulus of 3.75 for a 0.80 aggregate ratio or an aggregate ratio of around .75 or less with the fineness modulus of the sands used in this investigation should give greater strengths in the block mixtures.

A flash set was experienced during mixing some of the concretes before molding was completed. This effect disappeared once mechanical energy was imparted to the mixtures in the molding process. This effect is thought to have minimal impact on the results but warrants further investigation.

During testing, long shear and conal type failures were noted with some splitting tensile type failures in the accelerated specimens, indicating they may have less tension capacity. Two splitting tensile tests were conducted. Mix A2 in the accelerated condition at 2 days had a tensile strength of 23 psi with a corresponding compressive strength of 250 psi. Mix C2 in the normal cure had a 28 day tensile strength of 125 psi with a corresponding compressive strength of 1590 psi. Ductile type failures were observed except in the high strength mixtures of phase one.

Recommendation for a Block Material

From all phases of this research a final recommendation for a block material was formulated. The first issue is one of sand content. Normal CMU's contain around 8 to 10 percent cement by weight of solids, significantly less than any of our mixtures in all phases. The block industry typically attempts to maximize the aggregate content since less aggregate means more cement, the most costly constituent of blocks. Thus, block manufacturers have developed ideal block proportions using as little cement as possible to achieve the desired strengths. To achieve no slump blocks and the desired strengths very little water is incorporated and relatively "Harsh" mixtures result. Mixtures incorporating large volumes of fly ash are not limited in the same way. The fly ash particles act as both fine aggregate and cementitious material. Since the fly ash from Montana is fairly reactive, it is thought that most of it is reactive and a small amount acts as fine aggregate in the mixture.

It is strongly recommended that a higher fineness modulus be used in future mixtures to keep the cementitious materials content to a minimum. With a higher fineness modulus in the sand the weakening effect due to paste volume deficiency would probably be eliminated. Therefore, around 80 percent aggregates in a block material

incorporating large amounts of fly ash seems practical, if aggregate with a higher fineness modulus is used.

The second issue in formulating a mixture for blocks is one of cement to fly ash ratio. Since the least amount of cement is desired, the lowest cement to fly ash ratio is desired that still provides adequate compressive strength. The mixtures with cement to fly ash ratios of 0.11 would make adequate block material since they meet the 28 day strength requirement and also meet the no flow criteria. These mixtures can be considered to contain the lower limit of the cement to fly ash ratio.

The third issue is one of water to cementitious materials ratio. Figure 13 demonstrates the general relationship of strength variation with this ratio for mixes in phase three with cement to fly ash ratios of 0.11. It appears that 28 day strengths in excess of 1500 psi can be reached for mixes with water to cementitious ratios of less than around 0.40. Mixtures with this ratio meet the no flow criteria.

CONCLUSIONS AND RECOMMENDATIONS

Summary of Results

From phase one investigations it was discovered that adequate strengths for a block material could be achieved with less than five percent cement. Additionally, a relationship between the cement to fly ash ratio and strength was crudely established but predicted that adequate strengths for block material were possible with an almost pure fly ash paste. In phase two investigations strength gain relationships at normal and accelerated cures were established with mixtures with the same workability and same paste volume and three different cement to fly ash ratios, including a pure fly ash paste. The two accelerated cures used resulted in strength losses as expected from known effects accelerated cure has on concretes as well as from the crude curing procedure used in comparison to standard block manufacturing processes. It is believed that some of these mixtures experienced a weakening effect due to inadequate paste volume incorporation. Phase three mixtures H-O more precisely established the relationship between the cement to fly ash ratio and compressive strengths. Again, it was believed that the lower water content mixtures were experiencing a weakening effect. The additional mixes P-R demonstrated that some weakening effect did indeed take place, but did not appear to be substantial.

Conclusions

The following conclusions from this investigation have been drawn:

- (1) Fly ash concretes with adequate strengths for a block material can be made with very little cement. The pozzolanic reactions and hydration of Class C fly ash provide significant contributions to the strength of the material. As little as 3 percent cement in a stiff mix was found to produced strengths at 28 days in excess of 1500 psi, meeting the requirements for hollow load-bearing CMU units.
- (2) Accelerated curing can provide a means to overcome the disadvantage of slower pozzolanic reactions and to attain the short-term strengths that are required for block material. Ultimate strength may be reduced but could be minimized through more appropriate curing regimes. As expected, the lower the temperature used in accelerated curing, the less detrimental accelerated curing was to strength. The effect was also more pronounced in the higher cement content mixtures.
- (3) Correlations between cement to fly ash ratio, water content, and sand ratio to compressive strength for various proportions of aggregate and water ratios can be established for use in formulating mixture designs in industry. Tentative relationships of this type were developed in this investigation over a limited range of these variables.

Recommendations

From this investigation the following recommendations for further research into high volume fly ash blocks are suggested:

- (1) Further investigations with block mixtures containing more paste material or incorporating aggregates with a higher fineness modulus should be conducted.
- (2) A curing procedure that more closely mimics actual block steaming procedures should be investigated. Such a procedure could be fabricated by using the existing fog room at M.S.U. if higher steam temperatures can somehow be introduced and controlled.
- (3) Lower temperature curing at around 100 to 130 degrees Fahrenheit should be investigated. This range of temperatures would be less detrimental to the obtainable strengths. Temperatures in this range could be obtained through solar passive heating (and are possible to obtain for individuals wishing to construct their own blocks out of this material, particularly in developing countries).
- (4) It would be valuable to the ready mix industry to develop cement to fly ash ratio relationships for concretes with standard mix proportions and varying water to cement ratios, similar to work done by Gopalan and Haque (1985).

- (5) Freeze-thaw durability tests should be conducted on any proposed block mixtures incorporating air to enhance durability. Comparisons should be made to concrete mixtures of the same strength and air contents.
- (6) Further investigations should measure the strain during testing to correlate the strain against the stress. These measurements could be used to determine the ductility (energy absorption capability of a material) as well as the modulus of elasticity (the stiffness of a material), both of considerable value in structural engineering design and not readily available in the literature.

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APPENDIX

Mixing Procedures

Mixing and casting procedure for phase two:

1. Add sand, cement, and fly ash to the mixer.
2. Mix one minute or until uniform in texture.
3. Mix while adding most of the water thought to provide the correct flow.
4. Mix for about two minutes and measure the flow.
5. Continue mixing and adding water until the correct flow is obtained.
6. A total mixing time of about 5 minutes.
7. Vibrate the mixtures into 4" by 8" plastic molds in 3 layers.
8. Cover specimens and place in appropriate cure.

Mixing and casting procedure for mortar cubes of phase three:

1. Add water to the mixing bowl.
2. Add cement and fly ash and hand mix for one minute until dissolved.
3. Add Sand to mixing bowl and mix for two to three minutes until uniform in appearance.
4. Measure the flow in accordance to ASTM C-618, which specifies 10 drops in 6 seconds.
5. Mix for an additional minute to assure mix is uniform.
6. Hand tamp mixes into cube molds in accordance with ASTM C 109.
7. Cover and store at room temperature for one day, demold and place in cure room.

Table 12. Phases one and two, mix proportions and paste volumes.

Table of mix proportions and paste volume analysis, Phases One and Two.													
Mix #	Sand		Fly ash		Cement		Water		paste volume	assumed void ratio	paste volume to voids	Equivalent percent replacement	
	grams	volume	grams	volume	grams	volume	grams	volume				by weight	by volume
A	8000.0	35.2%	6400.0	30.6%	1600.0	5.9%	2305.0	26.9%	64.8%	0.4	1.62	NA	NA
B	6000.0	35.3%	5400.0	34.5%	600.0	3.0%	1660.0	25.8%	64.8%	0.4	1.62	NA	NA
C	7005.0	44.4%	3505.0	24.1%	1165.0	6.2%	1415.0	23.8%	55.6%	0.4	1.39	NA	NA
D	7005.0	43.9%	4086.3	27.8%	583.8	3.1%	1424.4	23.7%	56.1%	0.4	1.40	NA	NA
E	8000.0	53.1%	2285.0	16.5%	1140.0	6.4%	1285.0	22.6%	46.9%	0.4	1.17	NA	NA
F	8000.0	53.7%	2857.1	20.8%	571.4	3.2%	1170.0	20.8%	46.3%	0.4	1.16	NA	NA
A1	88005.0	56.4%	22005.0	15.3%	0.0	0.0%	15735.0	26.7%	43.6%	0.4	1.09	100.0 %	100.0 %
B1	80000.0	59.0%	18000.0	14.4%	2000.0	1.2%	12230.0	23.9%	41.0%	0.4	1.03	90.0 %	92.1 %
A2 *	50000.0	59.9%	12500.0	16.3%	0.0	0.0%	7055.0	22.4%	40.1%	0.4	1.00	100.0 %	100.0 %
	50000.0	59.0%	12500.0	16.0%	0.0	0.0%	7490.0	23.4%	41.0%	0.4	1.02	100.0 %	100.0 %
B2 *	50000.0	60.5%	11250.0	14.8%	1250.0	1.3%	6850.0	22.0%	39.5%	0.4	0.99	90.0 %	92.1 %
	50000.0	60.2%	11250.0	14.7%	1250.0	1.3%	6990.0	22.3%	39.8%	0.4	0.99	90.0 %	92.1 %
C2 *	50000.0	60.8%	9375.0	12.4%	3125.0	3.2%	6850.0	22.1%	39.2%	0.4	0.98	75.0 %	79.5 %
	50000.0	59.8%	9375.0	12.2%	3125.0	3.1%	7375.0	23.4%	40.2%	0.4	1.00	75.0 %	79.5 %

Notes:

* Second row contains data of mix made for accelerated conditions

Air content of 1.5 percent assumed for all calculations

NA - Not applicable since high paste volumes incorporated

Table 13. Phase three, mix proportions and paste volumes.

Table of mix proportions and paste volume analysis, Phase Three.													
Mix #	Sand		Fly ash		Cement		Water		paste volume	assumed void ratio	paste volume to voids	Equivalent percent replacement	
	grams	volume	grams	volume	grams	volume	grams	volume				by weight	by volume
H1	3000.0	63.9%	0.0	0.0%	750.0	13.4%	375.0	21.2%	36.1%	0.4	0.90	0.0%	0.0%
I1	3000.0	61.5%	750.0	16.7%	0.0	0.0%	375.0	20.4%	38.5%	0.4	0.96	100.0%	100.0%
J1	3000.0	61.7%	675.0	15.1%	75.0	1.3%	375.0	20.4%	38.3%	0.4	0.96	90.0%	92.1%
K1	3000.0	61.9%	625.1	14.0%	124.9	2.2%	375.0	20.5%	38.2%	0.4	0.95	83.3%	86.6%
L1	3000.0	62.1%	562.5	12.6%	187.5	3.3%	375.0	20.6%	38.0%	0.4	0.95	75.0%	79.5%
M1	3000.0	62.3%	498.8	11.2%	251.3	4.4%	375.0	20.6%	37.7%	0.4	0.94	66.5%	71.9%
N1	3000.0	62.7%	375.0	8.5%	375.0	6.6%	375.0	20.8%	37.3%	0.4	0.93	50.0%	56.4%
O1	3000.0	63.1%	250.1	5.7%	499.9	8.8%	375.0	20.9%	36.9%	0.4	0.92	33.3%	39.2%
H2	3000.0	58.0%	0.0	0.0%	750.0	12.2%	554.0	28.4%	42.0%	0.4	1.05	0.0%	0.0%
I2	3000.0	55.7%	750.0	15.1%	0.0	0.0%	562.5	27.7%	44.3%	0.4	1.11	100.0%	100.0%
J2	3000.0	55.9%	675.0	13.7%	75.0	1.2%	562.5	27.8%	44.1%	0.4	1.10	90.0%	92.1%
K2	3000.0	56.0%	625.1	12.7%	124.9	2.0%	562.4	27.8%	44.0%	0.4	1.10	83.3%	86.6%
L2	3000.0	56.2%	562.5	11.4%	187.5	3.0%	562.5	27.9%	43.8%	0.4	1.10	75.0%	79.5%
M2	3000.0	56.4%	498.8	10.2%	251.3	4.0%	562.5	28.0%	43.6%	0.4	1.09	66.5%	71.9%
N2	3000.0	56.7%	375.0	7.7%	375.0	6.0%	562.5	28.2%	43.3%	0.4	1.08	50.0%	56.4%
O2	3000.0	57.0%	250.1	5.2%	499.9	8.0%	562.5	28.3%	43.0%	0.4	1.07	33.3%	39.2%
P1	3000.2	54.9%	900.2	17.9%	100.4	1.5%	500.4	24.2%	45.2%	0.4	1.13	90.0%	92.0%
Q1	4000.0	52.7%	1309.2	18.7%	145.6	1.6%	727.4	25.4%	47.3%	0.4	1.18	90.0%	92.1%
R1	4000.2	48.7%	1542.4	20.4%	171.7	1.8%	857.1	27.7%	51.3%	0.4	1.28	90.0%	92.1%
P2	3999.9	56.7%	1200.2	18.5%	133.5	1.6%	578.5	21.7%	43.3%	0.4	1.08	90.0%	92.1%
Q2	4000.0	55.7%	1309.2	19.8%	145.6	1.7%	578.0	21.3%	44.3%	0.4	1.11	90.0%	92.1%
R2	4000.4	51.0%	1542.9	21.4%	171.9	1.8%	720.0	24.3%	49.0%	0.4	1.23	90.0%	92.1%

Note:

Air content of 1.5 percent assumed for all calculations

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