CONSIDERACIONES QUE AFECTAN EL PROPORCIONAMIENTO DE LA MEZCLA DE CONCRETO CONTENIENDO CENIZA VOLANTE

por

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Sinopsis: Se presentan los resultados de tres años de estudio sobre las propiedades del concreto que contiene ceniza volante. Se reportan las propiedades de tanto el concreto fresco como el endurecido usando cemento Tipo I, grava de río, arena natural y cenizas volantes de diferentes y variadas fuentes. Se hizo el proporcionamiento de las mezclas para que tuvieran revenimientos iguales y compuestos cementantes constantes, en peso. Se demuestra que el concreto puede ser diseñado con igual resistencia, propiedades reológicas buenas, igual o mejor durabilidad cuando se usa apropiadamente la norma ASTM C618 ceniza volante Clase C o F. Se presentan los datos de las pruebas de laboratorio hechas a más de 1,600 especímenes para detectar la resistencia al congelamiento y descongelamiento, resistencia a la flexión, resistencia a la compresión, flujo, retracción y resistencia a la abrasión. Se usaron contenidos de ceniza volante de 0% a 35% en peso del cemento portland con cenizas volantes de la Clase C y Clase F. Se presentan pautas para la selección de materiales y sus proporcionamientos para producir concretos conteniendo ceniza volante que cumplan con las especificaciones existentes para carreteras de concreto.

Palabras clave: Ceniza volante, propiedades del concreto, durabilidad, resistencia a la flexión, flujo, retracción, resistencia a la abrasión.

CONSIDERATIONS AFFECTING MIX PROPORTIONING OF CONCRETE CONTAINING FLY ASH

By

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Sinopsis: The results of a three year study are presented on properties of concrete containing fly ash. Both the fresh and hardened concrete properties are reported using Type I cement, river gravel, natural sand and fly ashes from several different sources. The mixes are proportioned to have equal slumps and a constant cementitious contents, by weight. It is shown that concrete can be designed with equal strength, good rheological properties and equal or better durability when a suitable ASTM C618 Class C or F fly ash is used appropriately. Test data on over 1600 laboratory field specimens tested for freeze-thaw resistance, flexural strength, compressive strength, creep, shrinkage and abrasion resistance are presented. Fly ash contents ranging from 0% to 35% by weight of portland cement are used with both Class C and Class F fly ashes. Guidelines for the selection of materials and their proportions for producing concrete containing fly ash to meet existing highway specifications for concrete are presented.

Keywords: Fly ash, pozzolans, concrete properties, durability, flexural strength, creep, shrinkage, abrasion resistance.

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INTRODUCTION

Fly ash has been used in concrete for over 50 years in the United States. Initially fly ash was used in mass concrete to reduce the heat of hydration and cracking at early ages. More recently fly ash has become what some consider a necessary component of high strength concrete. While the chemical and physical characteristics of fly ash vary greatly between sources of ash, many individual sources of fly ash are collected with uniformity through good quality control techniques. The uniformity in the chemical and physical composition of the fly ash allows mix designers to predict the behavior of concretes containing different fly ash-portland cement combinations through analysis of fly ash characteristics, trial batching and performance records.

The use of fly ash as a component of structural and pavement concretes has become increasingly important in recent years. Technical and economic considerations will continue to expand the use of fly ash in these grades of concrete. In the past, several methods have been developed to proportion concrete containing fly ash and include factored volume and weight replacement schemes. These methods use a base mix design containing portland cement, which meets the appropriate job specification, and replaces a prescribed amount of cement with a factored amount of fly ash. In general, these methods do not directly consider the individual characteristics of different fly ash sources or the effects of different fly ash contents on the strength and durability of the concrete containing fly ash.

When designing a concrete mix containing fly ash, emphasis should be placed on the performance requirement of the concrete in the field. The mix designs must be proportioned so that the concrete will meet current job specifications, which include rheological properties, strength requirements, and long term durability.

This paper shows that, provided a good quality uniform fly ash source is available, fly ash can be used to produce concrete with the following properties:

(1) flexural and compressive strengths equal to or greater than concrete without fly ash.

(2) adequate workability and cohesiveness to provide easy placement, consolidation and finishing.

(3) long term durability to provide material and structural performance throughout the life of the structure.

EXPERIMENTAL PROGRAM

Test Procedures

A three year laboratory study was performed to determine the effects of fly ash on the mix proportioning procedures for concrete required to satisfy rheological, strength, and durability specifications. In 5 test series, over 1600 specimens were cast from concrete containing between 0 and 35 percent fly ash by weight of cementitious material. Each test series had a unique cementitious content; i.e. cement + fly ash, by weight. A list of mix designs are presented in Table 1.

The cementitious contents ranged from 517 to 658 pounds (5.5 to 7.0 sacks) per cubic yard of concrete and two separate and distinct sources of fly ash were used throughout the laboratory study. The concrete mixes were batched to satisfy a slump range requirement of 3 1/2 +-1/2 inches. Since the water demand of concrete containing fly ash is different from that of portland cement concrete, mixes in each series were adjusted to maintain a constant yield by varying the fine aggregate content appropriately. Although the w/(c+p) ratios varied between mixes, the workability of each was nearly identical.

Beam specimens, 6"x 6"x 20" (152mm x 152mm x 508mm), were cast and tested for flexural strength according to ASTM C293 with center point loading. Compressive strength of 6"x 12" (152mm x 305mm) cylinders was determined according to ASTM C39. Freeze- thaw resistance was determined by testing 3"x 4"x 16" (76mm x 92mm x 366mm) specimens according to ASTM C666 Method A. Abrasion resistance was tested according to ASTM C944, and creep according to ASTM C512. Shrinkage was measured using a mechanical strain gauge between two positively affixed 8 inch gauge points on opposite faces of 3"x 4"x 16" (76mm x 92mm x 366mm) prismatic specimens. All tests considered at least 3 identical specimens which were measured or tested at the same time.

In addition to the laboratory study, commercially produced high strength ready-mix concrete containing fly ash was studied. This limited test series had cementitious contents ranging from 837 to 960 pounds (8.9 to 10.8 sacks) per cubic yard of concrete. Only flexural strength and compressive strength were determined in this series according to ASTM Procedures C293, with third point loading and C39 on 6"x 6"x 20" (152mm x 152mm x 508mm) and 6"x 12" (152mm x 305mm) specimens, respectively.

Fresh concrete properties of both the laboratory and ready- mix concrete were recorded for each batch. Properties of the concrete tested included slump, air content, and unit weight according to ASTM Procedures C143, C231, and C138, respectively.

Material Properties

The physical and chemical properties of the cement and fly ash used in concrete can alter the rheological characteristics as well as the strength and durability of the concrete. A single source of Type I cement was used in the laboratory portion of this study, and was used as a constant reference throughout this study. In addition, a single source of Type IP cement was used containing 20 percent low calcium, ASTM C618 Class F fly ash which was interground with the portland cement clinker. Both the Type I and Type IP cements had a Blaine fineness greater than 3000 cm^2/gm.

Two primary sources of fly ash were used in this study: a low calcium ASTM C618 Class F fly ash and a high calcium ASTM C618 Class C fly ash. The chemical and physical characteristics of the fly ashes are shown in Table 2.

Carbon in fly ash may have a detrimental effect on the durability of concrete containing fly ash in as much as organic air entraining agents have an affinity for the carbon. LOI values greater than 3 percent may be considered unacceptable according to ASTM Specification C618. The loss on ignition (LOI), which is a measure of the carbon content in the fly ash, was below 0.45 percent for both fly ashes.

A major difference between the two sources of fly ash was the distribution of oxides. The Class F fly ash had a calcium oxide (CaO) content of only 10 percent and a Silicon + Alumina + Iron (Si + Al + Fe) oxide content of 78 percent, whereas the Class C fly ash had a CaO content of 38 percent and a Si + Al + Fe oxide content of 57 percent.

The calcium oxide content of the fly ash will determine the time and type of reaction of that fly ash in concrete. Class C fly ashes, which characteristically have high CaO contents, will generally exhibit both cementitious and pozzolanic properties in concrete. This is due to the availability of a limited amount of calcium for reaction with the silicates in the fly ash to form calcium silicate hydrates upon the addition of water. However, the quantity of available CaO in Class C fly ashes is insufficient for complete hydration of the silicates; therefore, the excess silicates react at later ages with the calcium hydroxide which is produced as a by-product of the hydration of portland cement. This later reaction is known as a pozzolanic reaction, whereas the former is a cementitious reaction.

Class F fly ashes, on the other hand, have lower CaO contents than Class C fly ashes, therefore Class F fly ashes generally react in a mostly pozzolanic manner. The pozzolanic characteristics of fly ash may decrease the early strength gain of concrete, effectively lowering the early heat of hydration of the concrete. Where the early concrete temperature is of concern, the use of fly ash may be considered as a means of control against an excessively high heat of hydration of concrete.

The two ashes used in the laboratory portion of this study were chosen because they are readily available locally and are uniformly produced, high quality sources of fly ash. Single sources of 3/4 inch nominal maximum size silicious river gravel and natural sand were used throughout the laboratory portion of the study. Two types of admixtures were used in the laboratory: air entraining agents and a water reducing admixture. The water reducing admixture was used at the manufacturer recommended dosage rate and the air entraining agents were added to obtain specified air contents.

In the high strength concrete mixes, water reducers and a superplastisizer were used addition to crushed limestone coarse aggregate and natural sand, however no air training agents were added.

LABORATORY TEST RESULTS

The comparisons made in this section are for the two particular sources of fly ash and e cement used in this study. The fly ashes in this study are typical of those found in exas. They represent fly ashes with good chemical and physical characteristics, and it these characteristics which determine how a fly ash will perform in concrete.

xural strength

A primary concern in designing concrete for use in highway application is the flexural rength of the concrete. Concrete with low flexural strength will crack excessively due differential shrinkage, temperature variations and applied loads, leading to rapid terioration of pavements or highway structures. The flexural strength or modulus of pture of concrete is an indirect measure of the tensile strength and is the test most often ed by highway departments in evaluating concrete for pavements [8].

In this study, the minimum acceptable 7-day modulus of rupture from a center point ading was 600 psi. Cement was replaced by an equal weight of fly ash at the levels of , 20, 25 and 35 percent for cementitious, c + p, contents of 5.5, 6.0, 6.5 and 7.0 sacks r cubic yard.

The flexural strength of concrete containing Class F fly ash decreased slightly as the rcentage of fly ash was increased for all c + p contents. The concrete containing Class fly ash consistently met the minimum 7-day flexural strength requirement of 600 psi, gardless of c + p content or percent replacement. Test results are shown in Figure 1.

Flexural strength of concrete containing Class C fly ash equaled or decreased slightly the percentage of fly ash was increased. For all but one case, the concrete containing ass C fly ash met the minimum flexural strength requirement. The exception was the se of concrete containing 35 percent Class C fly ash with a c + p content of 5.5 sacks r cubic yard of concrete which reached a 7-day flexural strength of only 550 psi. Test sults for Class C fly ash are presented in figure 2.

A comparison of the 7 and 28 flexural strengths is shown in Figure 3. The average crease in flexural strength in concrete containing 25 percent Class C or F fly ash was percent at 7 days. Flexural strengths at 28 days were within 7 percent of the strength concrete without fly ash. Concrete produced with Type IP cement consistently met the nimum flexural strength requirement and exceeded the strength of the 5.5 sacks per bic yard mix without fly ash.

In general, fly ash concrete met the minimum specified strength and showed a higher rate of strength gain between 7 and 28 days than did concrete without fly ash. However, normal strength concrete containing either Class C or F fly ash displayed reduced 7-day flexural strengths when compared to mixes with the same cementitious content and no fly ash.

Compressive strength

Structural concrete is commonly specified by minimum compressive strength at 28 days. However, the compressive strength of concrete, at early ages is an important consideration during construction and at later ages for long term behavior.

The typical compressive strength development of concretes containing fly ash with age is shown in Figures 4 and 5. The cementitious content (c+p) was varied from 5.5 to 7.0 sacks per cubic yard of concrete in this study, with similar strength development characteristics.

After 28 days concrete containing Class C fly ash displayed varying compressive strengths with respect to cementitious content and percentage replacement of cement by fly ash as shown in Figure 6. Concrete with a c+p content of 5.5 sacks per cubic yard and 15 percent Class C fly ash yielded a 13 percent increase in compressive strength over concrete without fly ash, whereas 25 and 35 percent replacement by weight decreased the 28-day compressive strength by 7 percent.

At a c+p content of 6.0 sks/cu.yd. concrete containing between 20 and 35 percent Class C fly ash exceeded the compressive strength of concrete without fly ash by 8 percent. Mixes with a c+p content of 6.5 sks/cu.yd. showed strengths equal to that of the control concrete, regardless of the Class C fly ash replacement. At c+p contents of 7.0 sks/cu.yd. the 28-day compressive strength of concrete containing 15 percent fly ash was again higher than that of concrete without fly ash, while 25 and 35 percent diminished the strength.

Concrete containing Class F fly ash, displayed compressive strengths greater than that of portland cement concrete in mixes with a c+p content of 6 sks/cu.yd. The 28-day compressive strength of concrete containing Class F fly ash with c+p contents of 5.5, 6.5, and 7.0 was less than that of concrete without fly ash. Test results are presented in figure 7. These figures reinforce that for a given fly ash, an optimum replacement level exists for each different cementitious content. The required strength can be attained by using trial batching and performance records to determine the amount of fly ash needed at given cementitious contents. This is the same manner that commercial concrete mix designs are verified.

At 7 days the compressive strength of concrete without fly ash was higher than that of concrete containing fly ash, regardless of the type of fly ash or percentage replacement. However, the long term compressive strength of concrete containing fly ash exceeds that

of concrete without fly ash. For most concrete tested in this study the compressive strength was equal to or greater in concrete containing fly ash than in concrete without fly ash after 91 days.

In general, a specified 7-day or 28-day compressive strength can be met using concrete containing fly ash by considering the strength gain characteristics of the fly ash in the mix design and adjusting the c+p content or percentage of fly ash or both. When strengths are specified at later dates the required cementitious content will decrease while the percentage of fly ash will increase.

Effect of curing and mixing conditions

The mixing temperature and time, and the curing conditions under which concrete is subjected affect the compressive and flexural strengths. These effects were investigated in this study for concrete containing fly ash.

It was found in this study that concrete containing fly ash is more sensitive to prolonged mixing than is concrete without fly ash . Mixes containing fly ash exhibit a accelerated slump loss when mixed excessively. The increased slump loss is caused by the reduced water demand of concrete containing fly ash. The spherical particles in fly ash provide additional workability to the mix as long as the mix is fluid. Once the hydration of C_3A and C_3S begins and water starts evaporating from the mix the fly ash concrete with the lower water content becomes stiff and less manageable.

The flexural and compressive strength of concretes containing fly ash subjected to different curing conditions is shown in Figures 8 and 9. Concretes containing fly ash cured under hot dry conditions (100 F, 32% RH), moist cured (75 F, 100% RH) or cold cured (40 F, 55% RH) developed flexural and compressive strengths in the same relation as concrete without fly ash under the same conditions. The same relationships were observed at 35 percent fly ash and in 6.5 sack mixes. Compressive strength development of concrete containing Class F fly ash was slightly accelerated by the hot-dry condition, and diminished by cold curing.

Figures 10 and 11 show that fly ash content had a relatively minor effect on the strength development of concrete cured with a membrane curing compound at 100 F and 32% RH. However, the compressive strength development of concrete containing fly ash was substantially impaired by membrane curing at 75 F and 55% RH. The pozzolanic reaction in concrete containing fly ash will realize greater strengths at ambient temperatures when a moist environment is present; the membrane curing compound used was an inadequate moisture barrier for concrete containing fly ash.

When proportioning concrete containing fly ash, site conditions and temperatures should be considered. Excessive delays in the placement of the concrete may result in severe handling problems. It should be noted however that the increased paste-aggregate ratio in most concretes containing fly ash may improve the finishability of the concrete surface and reduce the permeability of the concrete.

Freeze-thaw resistance

The resistance to freeze-thaw action is a necessary property for concrete exposed to winter environments. Concrete which is not durable under freeze-thaw conditions will spall and crack, and later become unserviceable.

The most important elements in freeze-thaw resistant concrete are an adequate entrained air system and strength. Strength considerations have already been discussed. Fly ash affects the air system in concrete in that organic based air entraining admixture may be adsorbed by carbon particles in the fly ash. An increased dosage rate of air entraining admixture may be needed in concrete containing fly ash to compensate for the loss of admixture. The additional dosage in this study ranged from 0 to 2 times the standard dosage of air entraining agent, depending of the Class of fly ash used and the percentage replacement. Trial batching and previous performance records are the best way to determine the dosage rate of air entraining agents for fly ash concretes.

Tests were conducted on 135 specimens for freeze-thaw resistance according to ASTM C666, Method A. The cementitious content was varied from 5.5 to 7.0 sacks per cubic yard. Both Class C and F fly ashes were used as a direct weight replacement for cement at the levels of 0, 15, 20, 25, and 35 percent. All mixes containing greater than 3.5 percent air maintained a durability factor greater than 60. Average test results of specimens with 6.0 sacks per cubic yard and air contents between 4.5 and 5.5 percent are shown in Figures 12 and 13. Concrete containing Type IP cement completed the 300 cycle test undamaged with air contents as low as 2.5 percent.

Abrasion resistance

Concrete pavements and industrial floors subjected to heavy traffic may be damaged severely by the cracking and spalling associated with poor abrasion resistance. The abrasion resistance of concrete is related to aggregate type, compressive strength, curing conditions and the finished surface condition.

In this study, specimens were cast containing 0 and 35 percent Class C and F fly ash by weight. The cementitious content was 6.0 sacks per cubic yard and the air content was 5 percent in all mixes. In addition, the aggregate source, curing conditions and finishing techniques were identical for all specimens.

Abrasion resistance of concrete was measured as depth of wear caused by a rotating dressing wheel. Concrete containing Class C fly ash exhibited superior abrasion resistance to that of either plain portland cement concrete or concrete containing Class F fly ash.

ilar depths of wear were observed in plain concrete and concrete containing Class F ash, as shown in Figure 14.

Although the concretes had equal strengths at the time of testing, the reduction in ater demand in the fly ash mixes for equal workability reduces the amount of bleed water hich decreases the permeability of concrete, improving the surface hardness.

Furthermore, during the life of the pavement or floor the concrete containing fly ash ll continue to gain strength over that of plain concrete. Increased compressive strength ll add to the wear resistance of the concrete surface.

rinkage

Shrinkage in highway pavements and in exposed structural members can lead to acking and the subsequent deterioration of concrete associated with cracked members, ch as: corrosion of reinforcing bars, reduced freeze-thaw resistance and increased sceptibility to sulfate attack.

Shrinkage was monitored on concrete subjected to hot-dry conditions (100 F, 32% H) after 3 days of moist curing and on concrete exposed to moderate conditions (72 F, % RH), moist cured for 14 days.

Concrete containing Class F fly ash reduced the shrinkage under both hot-dry and derate conditions when compared to concrete without fly ash. Concrete containing % Class F fly ash under hot-dry conditions had 28 percent less shrinkage than portland ment concrete after 120 days, and under moderate conditions an 11 percent reduction as measured after 220 days. Class C fly ash added to concrete did not change the long m shrinkage under hot-dry or moderate conditions when compared to concrete without ash.

eep

The inelastic time-dependent deformation of concrete caused by creep must be nsidered in deflection calculations to properly predict the behavior of both concrete slabs d structures. The primary mechanism of creep is best described as strains induced by e plastic flow of cement gel under load. This gel flow is directly affected by the agnitude of the sustained load with respect to the compressive strength.

Figure 15 shows concrete containing 35 percent Class F fly ash by weight displayed 0% lower creep deformations than concrete without fly ash, despite being subjected to higher load ratio. Similarly, concrete containing Class C fly ash showed a 5 percent duction in creep over that of portland cement concrete. Class F fly ash displayed a eater reduction because it is more pozzolanic in nature than the Class C fly ash and erefore continues to gain strength over a longer period of time.

It should be noted that the creep strains in concrete containing Class F fly ash were greater at early ages than those in concrete without fly ash. This is also due to the slower compressive strength gain characteristics of fly ash when compared to portland cement.

FIELD TEST RESULTS

The second portion of this study included high strength concrete mixes made with commercially produced concrete containing fly ash. Three Class C fly ashes, including the same Class C fly ash as was used in the laboratory portion of this study were used in this field study. Nine separate batches of ready-mix concrete were cast.

This portion of the study was conducted to show that Class C fly ash can be consistently used with water reducers and superplasticizers to produce good quality commercial concrete. Furthermore, mixes containing Class C fly ash can be designed with equal or less cementitious material by weight than mixes without fly ash and still produce higher compressive and flexural strengths.

Compressive strength

Concretes with high compressive strengths are being used in a broader range of structural applications in recent years. In addition to high rise construction, the prestressed and precast industries have used high strength concrete in many innovative projects. Fly ash is often an integral part of the high strength concrete mix design.

In this test series concrete containing fly ash is compared to a control mix without fly ash. The results are presented in tabular form in Table 2.

The 28-day compressive strength of concrete containing the Class C fly ash exceeded that of concrete without fly ash in 5 of the 7 fly ash mix designs. In addition, the 56 and 91 day compressive strengths of concrete containing fly ash in 3 of 5 fly ash mixes exceeded that of concrete without fly ash, despite 4 mixes containing fly ash having lower cementitious contents than the control mixes.

Flexural strength

The development of flexural strength of high strength concrete is of significant importance in the precast and prestressed industries. Cracking in concrete can lead to accelerated deterioration of prestressing strand as well as bonded reinforcement. The same concrete mixes used in the preceding section were used to cast flexural specimens tested for the data presented here. These series of tests are presented to indicate that the Class C fly ash can be used to obtain flexural strengths in excess of those obtained without fly ash, without increasing the cementitious content.

The flexural strength of high strength concrete containing fly ash is compared to that of the control concrete without fly ash in Table 3. The flexural strength of concrete containing fly ash depends on the source of fly ash and the amount used as a replacement. Class C fly ash in concrete consistently produced flexural strengths greater than that of concrete without fly ash at 7 days in 4 of 7 fly ash mixes. Even where the cementitious content was decreased by over 6 percent, the fly ash concrete provided greater flexural strengths. The flexural strength of concrete containing fly ash at 28 days was also equal to or greater than concrete without fly ash in 6 of 7 fly ash mixes.

CONCLUSIONS AND RECOMMENDATIONS

The use of fly ash in normal strength concrete produces excellent quality concrete which is durable and meets strength requirements. In addition, fly ash improves workability, reduces both heat of hydration and water demand and furnishes the mix with good fresh concrete rheological properties.

Concrete containing fly ash on an equal weight replacement displays:

*exceptional freeze-thaw resistance when a sound air void system is present,
*reduced creep deformation,
*equal of less shrinkage under either hot-dry or ambient conditions,
*equal or greater resistance to abrasion,
*slightly reduced early age compressive and flexural strengths
*long term compressive and flexural strengths which range from 5 percent lower to 20 percent higher than concrete without fly ash.

Also presented are the results of high strength concrete mixes, which show that concretes containing Class C fly ash may be designed to have:

*higher 28 and 91 day compressive strengths at lower cementitious contents,
*higher 7 and 28 day flexural strengths at lower cementitious contents.

Furthermore, the fly ash used consistently generated reproducible results. This may be the most important part of the study, in that it allows the mix design to be altered to obtain desired properties. Concrete mixes containing fly ash should be designed to meet current specifications, not compared to mixes without fly ash.

In normal strength concrete containing fly ash, higher early strengths can be attained by adjusting the cementitious content or the amount of fly ash. The same effect may be obtained by using a higher calcium or finer fly ash. Increased long term strength can be obtained by using a high silica, low calcium fly ash, using a finer fly ash, or again adjusting the amount of fly ash used.