SCHOOL OF
CIVIL ENGINEERING

INDIANA
DEPARTMENT OF HIGHWAYS

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-88/8 - 2

Executive Summary

FLY ASH CONCRETE FOR HIGHWAY USE

Sidney Diamond
Jan Olek

PURDUE UNIVERSITY

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TO: H. L. Michael, Director
Joint Highway Research Project

Mar. 24, 1988

FROM: S. Diamond, Research Associate
Joint Highway Research Project

Project: C-36-19G
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Attached is the Executive Summary of the Final Report of Phase II of the HPR Part II Study titled "Selection and Use of Fly Ash For Highway Concrete." The report is entitled "Fly Ash Concrete for Highway Use" and is authored by Professor Sidney Diamond and Dr. Jan Olek.

The objectives of the Study were accomplished. An appropriate new method of mix design of fly ash concrete for highway purposes was developed, and the properties and behavior of approximately 150 batches of concrete studied, along with studies on reactions in the paste components. It appears that properly-designed fly ash concretes should be entirely suitable for routine use for highway purposes, with benefits in economy, durability, and long-term strength.

A set of recommendations and guidelines for practical application has been included.

The Final Report is forwarded for review and acceptance by all sponsors as fulfilling the objectives of the study. With its approval and subsequent publication the Phase II referenced HPR study will have been completed.

Sincerely,

Sidney Diamond
Research Associate

cc:

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16. Abstract

A series of investigations were carried out to examine the potential for routine use of fly ash in highway concrete, with special reference to Indiana. Existing methods of mix proportioning of fly ash concretes were reviewed in detail, and a new method developed to better assure good durability characteristics despite expected fluctuations in fly ash properties. Extensive investigations were carried out on the properties of concretes designed by this method and using representative Indiana fly ashes of both Class F and Class C varieties. In general these concretes exhibited compressive strengths and other mechanical properties at least as satisfactory as those of presently specified plain portland cement concretes, and the potential durability appeared to be significantly improved. The development of early flexural strengths was found to lag those of plain concretes somewhat, but after several months this lag disappeared. Provision of an adequate air content is necessary to assure freeze-thaw durability, and it was found that the necessary dosage of air entraining agent varied with the fly ash, but could be determined very easily by use of the foam index test. A number of technical conclusions were drawn with respect to reactions within the fly ash concretes, and a chapter on recommendations and cautions has been supplied.

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EXECUTIVE SUMMARY

FLY ASH CONCRETE FOR HIGHWAY USE

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and

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Purdue University
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March 24, 1988

EXECUTIVE SUMMARY

The formal objectives of this project were originally stated in the project proposal as follows:

"The primary objective ... is that of studying the details of the performance and behavior of concrete produced with fly ashes representative of those that may be used in highway concrete in Indiana."

"A secondary objective is .... to develop the maximum of objective scientific information concerning the behavior and influences of fly ashes in general, when incorporated in concrete."

"The final objective is to report the findings and results in such a way as to provide the maximum possible utility, first to IDOH materials and construction engineers who will be involved in specifying and supervising the placement of fly ash concrete in highways and associated structures, and then to the technical community at large."

After a thorough review of the technical literature on the mix design of fly ash concretes, it was decided that existing mix design methods for fly ash concrete would probably not be adequate to guarantee performance of field highway concrete in the face of expected major variations in fly ash quality and properties from job to job, and even within large jobs. In particular, no existing method concerned itself with the important areas of concrete durability.

Accordingly, we developed a new method to meet this need, the so-called "Constant Paste Quality" (CPQ) method, the details of which has been thoroughly and carefully presented in this report. Parenthetically, the method has been presented at a symposium on fly ash mix design held by the American Concrete Institute, and the paper describing it has been approved for publication.

The method has been used to design all of the concrete produced in this project. The concrete was designed to meet minimum criteria according to present IDOH requirements, with a constant water:(cement + fly ash) ratio of 0.49.

Selection of materials for this investigation was carried out with the advice and assistance of IDOH. A representative suite of five fly ashes (three of the low calcium type and two of the high calcium type) was assembled, two different representative cements widely used in Indiana were chosen, and representative coarse and fine aggregate materials selected. Preliminary investigations were carried out on the effectiveness of air entrainment when fly ash is used at several replacement levels. It was found that by use of the foam index method, it was possible to predict the specific demand of each mix for air entraining agent, so that all batches could be prepared with air contents required to insure freezing and thawing durability.

As part of the preliminary studies on mix design, a limited analysis of the economic effect of using fly ash in highway concrete was carried out. It was concluded that with the CPQ mix design procedure, the increased volume proportion of aggregates that could be used did lead to some economic advantage, but the main cost savings in using fly ash still derives from the lower cost of the fly ash as compared to the cement it replaces.

Effects of Fly Ashes on Fresh Concrete Properties

It was found that the mix design method, properly applied, provides for very consistent control of the slump and air content of fresh concrete, regardless of the specific fly ash used and the level of cement replacement. In addition, the method was found to provide for very close control of concrete unit weight, regardless of difference in fly ash density.

The fly ash concretes were found to show qualitative improvements in ease of placing and finishing over the reference plain concretes batched at the same slump. These indications were confirmed in the reduced VeBe times found for the fly ash concretes.

It was found that all of the fly ash concretes are retarded with respect to set. The extent of retardation varied from minimal to as much as 5-1/2 hours, and depended on the specific cement used, as well as the specific fly ash and the replacement level. One particular high calcium fly ash gave consistently higher set retardations than any of the others, and probably would necessitate use of an accelerating agent when used in practice.

Influence of Fly Ash on Properties Measured On Fresh Cement Pastes

It was found that fly ashes affected a number of properties of fresh cement pastes. The pastes studied were batched to simulate the paste in the specific concretes studied in all respects except that no aggregate component was included.

It was found that only small effects were measured for the "spread" of the various pastes as determined using the minislump cone.

Set retardations produced by the fly ashes in cement pastes were found to be generally similar to those produced by the same fly ash in concrete.

All of the fly ashes delayed the temperature build up associated with early cement hydration, and all reduced the maximum temperature achieved, but there were significant differences among the different fly ashes in this regard. Pastes batched with the high calcium fly ashes achieved significantly higher maximum temperatures than those with the low calcium fly ashes, although the times to achieve these maxima were extended. Also, all of the fly ashes were found to increase the dormant period in cement hydration to some degree.

Effects of Fly Ashes on the Mechanical Properties of Hardened Concrete

A considerable body of information has been acquired on the effects of fly ash on the mechanical properties of hardened concrete.

Elastic Properties

Measurements of longitudinal and transverse strain were linearly related to loading with very high degrees of precision, and accurate measurements of static modulus of elasticity and Poisson's ratio were made.

The Young's moduli recorded for the fly ash concretes ranged between 3.2 and 5.6 million psi, well within the normal concrete range. Young's modulus was found to be a precise and linear function of the compressive strength of the concrete concerned. These test concretes ranged in age from 2 days to 6 months, and in compressive strength from less than 2400 psi to as much as 6300 psi.

Measured values of Poisson's ratio ranged between 0.17 and more than 0.23, and like the Young's modulus, were found to be closely and linearly related to compressive strength. These relationships may hold generally for fly ash concretes. If they do, they can provide easy estimates of elastic parameters at various stages of concrete development from a knowledge of the strength gain curve for a particular mix.

The dynamic modulus of elasticity was measured on the entire suite of fly ash concretes at ages ranging from 1 day to 6 months, using the pulse velocity method. The values found were significantly higher than the static moduli for similar concretes. This is to be expected in view of the fact that the dynamic measurements are done in the wet state, and are done so rapidly that no creep component can affect the measurement. It was found that the dynamic modulus as a function of age for the plain reference concretes varied depending on the specific cement used, but that when fly ash was incorporated, these cement-specific effects largely disappeared. However, strong differences in the dynamic modulus vs. age relationship were detected between similar concretes batched with different fly ashes.

It was found that the dynamic elastic modulus for the fly ash concretes, while initially lower than those of the plain reference concretes, could match or exceed them after 28 days.

Compressive and Flexural Strengths

It was found that concretes batched with the fly ashes attained generally similar compressive strengths to reference plain cement concretes at each age. A relatively narrow band of strengths was observed for the different fly ashes at the lower replacement level, but this band was found to broaden at the 25% replacement level, where differences among the fly ashes became more prominent. At this higher level the compressive strengths for the first 3 days did not quite match the reference concretes, and even at 28 days there was a slight reduction observed for two of the less reactive low calcium fly ashes.

On the other hand, in many cases it was found that by 90 days the fly ash concretes achieved compressive strengths substantially higher than those of the reference plain cement concretes.

It was found that the effects of the fly ashes on the development of flexural strengths were somewhat different from those described above. Incorporation of fly ash concretes were usually found to have lower flexural strengths than the reference concrete at any given age, but especially at 7 and 28 days. The high calcium fly ashes did somewhat better in this regard than the low calcium ashes.

These differences in effect between compressive strength and flexural strength measurements may imply that the usual relationship found between the two for plain concretes does not necessarily extend to fly ash concretes, a point of some concern for designers.

It was found that for plain cement concrete, the specific cement used had a significant influence on flexural strength development, but this influence was lost when fly ash was incorporated. This behavior for flexural strength parallels similar behavior for dynamic modulus described earlier in this Chapter.

The actual values of flexural strength vs. time for the different fly ash concretes were found to be within a relatively narrow band, virtually independent of the cement used. For long hydration periods (90 days or longer) the general level of flexural strength does approach the level reached by the plain concretes, although it rarely exceeds it. Generally flexural strengths at the 25% fly ash replacement level are slightly less than those at the 15% replacement level.

Effects of Fly Ash on Durability-Related Properties

A considerable portion of this research was aimed at documenting the effects of the fly ashes on measured values of durability related properties. The results in all cases were favorable to the use of fly ash. The specific findings developed are detailed below.

Mercury Porosimetry

The pore structure of mature fly ash pastes and of a reference cement paste, all hydrated for one year, were examined by mercury porosimetry.

All of the fly ash pastes show pore structures finer than that of the reference paste, suggesting that the fly ashes confer at least some degree of additional impermeability to the system. Their use would thus tend to render the concrete more resistant to durability problems.

Chloride Permeability

Chloride permeability measurements were carried out on concrete specimens aged 6 months before the test. It was found that each of the fly ashes reduced the measured chloride permeability significantly. The low calcium fly ashes were more effective in this regard than the high calcium ones, with one of the three being particularly effective. The degree of reduction was greater at the higher fly ash replacement level in all cases. The reference plain concretes had "low" chloride permeabilities; all of the fly ash concretes except one fell into the "very low" category.

The improvement in resistance to chloride penetration was found not to follow the same order as improvement in concrete strength.

In general, the reductions in chloride permeabilities were deemed to be significant enough that real benefit could be expected with respect to rate of chloride penetration into fly ash concrete as compared to plain concrete of the same general class.

Freezing and Thawing Resistance

All of the properly air entrained fly ash concretes, as well as the reference concretes, performed very satisfactorily in the freezing and thawing tests, giving durability factors at 300 cycles of the order of 75 to 80%, and showing no evidence of physical distress or weight change on the test bars.

Pore Solution Parameters

Studies of the effects of the different fly ashes on the chemical composition of pore solutions pressed from mature (7-month old) pastes indicate that there is a reduction of the order of 30% in the OH^- ion concentration for the low calcium ashes, and a lesser reduction for the high calcium ones. The reduction in alkalinity is primarily due to reaction with K^+ ions; Na^+ ions are not significantly removed, and for the high calcium fly ashes, actually seem to be liberated by the fly ash, partly counterbalancing the effect of K^+ ion removal.

The general reduction in alkalinity is a very favorable effect with respect to preventing possible alkali aggregate reaction, although there may be a slight negative connotation with respect to steel corrosion protection.

Effects on Pore Solution Chloride Levels

Pastes in which chloride was deliberately incorporated at the level of a 1% $CaCl_2$ treatment were examined after 3 months. In the reference paste the concentration of dissolved chloride had been reduced to about 1/4 of its original value by reaction with cement. Significant further reductions were found to occur with fly ash incorporation, especially with the high calcium fly ashes, where the residual chloride concentration dropped to about 10% of the original value.

These results indicate that fly ash use results in a concrete that "fixes" most of the dissolved chloride, i.e. renders it ineffective in terms of causing steel corrosion, to a greater degree than plain concrete does. Thus the likelihood of steel corrosion triggered by the presence of chloride is reduced. This would also probably provide benefit in the situation where chloride is penetrating from the outside rather than being incorporated as an admixture. The former is the common case with salt-induced steel corrosion in bridge decks.

Studies of Fly Ash Reactivity

A number of studies on the reactivity and details of the reactions of these fly ashes have led to some surprising findings. In general terms, it appears that the degree of pozzolanic reactivity exhibited by these materials, at least during the first year of hydration, is much less than has been anticipated. The specifics of the results are summarized below.

Pozzolanic Reaction as Measured by Residual Calcium Hydroxide

Determinations of the actual calcium hydroxide content of pastes with each of the fly ashes were carried out for ages up to 1 year. The results showed quite dramatically that the calcium hydroxide content found in almost all cases was approximately that predicted for the same cement, diluted with a chemically inert material in the same proportion as it was with fly ash. This surprising results was found to be true for all of the low calcium fly ashes and for one of the two high calcium ashes. With the other high calcium ash, somewhat more calcium hydroxide than expected on this basis was found over the first few weeks, but apparently this excess declined (by pozzolanic reaction?) to the general level of that found with the other fly ashes.

Non-Evaporable Water Content

The non-evaporable water content in the fly ash pastes was significantly higher than that predicted for the same cement diluted with a chemically inert material in the same proportion as the fly ash used. This was true for both low calcium and high calcium fly ashes, although more strongly pronounced for the latter. Some "excess" non-evaporable water content was detected as early as 1 day, but the effect became pronounced after three days. The interpretation made is that the presence of the fly ash likely stimulated additional cement hydration, and resulted in more nearly complete cement reaction at any given age.

<u>SEM Studies</u>

Scanning electron microscopy (SEM) studies indicated that for the low calcium fly ashes, even at 1 year, there was only very small visual evidence of fly ash reaction, taking the form of light etching around the surfaces of the fly ash spheres. The presence of large amounts of calcium hydroxide near, and in some cases completely surrounding, the fly ash grains was evidence that failure to react more extensively was not due to any local shortage of calcium hydroxide. It was found that some of the grains in the high calcium fly ashes showed more visible evidences of having reacted during the year's exposure, but even for these fly ashes most of the spheres were only modestly etched.

<u>Chemical Leaching Studies</u>

Studies of the comparative resistance to leaching of fly ashes by hydrofluoric acid (HF) and by strong alkali hydroxide solutions were carried out for some low calcium fly ashes. An estimate of the chemical composition of the fly ash glass was arrived at from these studies. The potential extent of chemical dissolution of fly ash glass was pictured, and it by comparison with these pictures visually illustrating complete dissolution of the fly ash glass, it is confirmed that the fly ashes in the cement pastes previously discussed have reacted only to a very small degree.

Recommendations And Cautions For Practical Applications

A number of general recommendations and cautions for practical use of fly ash in highway concrete were developed during this work, including the following:

(1) Most fly ashes available in Indiana should be reasonably satisfactory for fly ash concrete if the concrete is properly designed and controlled.

(2) While the the ASTM specifications with respect to selection of fly ash provide only limited protection against the use of inappropriate fly ashes, selection should be restricted to those that do meet the specification. Fly ashes should if possible be selected from those for which testing history is available, and which have shown only limited variations in properties over time. Fly ashes from more modern plants operated in the base load mode are preferable, and are usually available.

(3) With respect to a choice between Class F (low calcium) and Class C (high calcium) fly ashes, it appears from our present results and those of many others, that both can be satisfactory, and that neither rates a clear overall preference per se.

(4) Although the new mix design method developed in this project is recommended, one of the modified replacement methods previously used ought to be satisfactory as well, especially if local history of the successful use of a given fly ash in concrete designed with it is available.

(5) However the final mix design is arrived at, we believe that it is important to provide a larger amount of fly ash per unit volume of concrete than the amount of cement deleted from the mix. We see this "over-replacement" as providing very inexpensive insurance against lower strength and poorer durability that may result in practice from a too small content of cement, especially at early ages.

(6) With respect to the percentage of fly ash to incorporate in highway concrete, we feel that restraint is called for by the nature of the exposure that such concrete undergoes, starting early in its service life. No more than 25% replacement would seem justified.

(7) It is absolutely necessary to test that sufficient air entraining agent is provided that the necessary air content for freeze thaw durability is always achieved. The foam index test is a simple way to determine how much of a given agent is needed with a given fly ash, and it is entirely suitable for field use. Air content tests with properly calibrated and maintained test equipment should be absolutely mandatory and required on a frequent basis with fly ash concrete.

(8) Fresh concrete with fly ash, designed for a given slump value, appears more coherent (dryer and less workable) than corresponding plain concrete at the same slump. However, such appearance is deceptive; usually the fly ash concrete will actually be more workable. The tendency to add water because the concrete appears too dry should be guarded against.

(9) Properly designed fly ash concretes should show less bleeding than plain concretes, and should develop almost no segregation. Because of the relative lack of bleeding, finishing

operations can often start earlier, in the absence of severe set retardation. Fly ash concrete may handle somewhat differently than plain cement concrete, when being placed by paving trains, and some adjustment of paving train operations may be required. In general, we expect that fly ash concrete should be easier to finish, and therefore a greater rate of progress may be expected.

(10) In general, curing of fly ash concrete should be started earlier, without waiting for bleeding to be developed; however greater care needs to be taken that the curing compound used and the dosage applied are adequate to retain enough moisture in the concrete for curing to proceed properly.

(11) Our results indicate that with properly designed fly ash concrete, despite some set retardation, the rate of development of compressive strength may be expected to be little different than with plain portland cement concrete. This is especially true with Class C fly ash of good reactivity. However, with fly ash concrete, one should expect both set retardation and delays in early strength gain to be disproportionately more severe at low temperatures.

(12) Flexural strength development with fly ash concrete is somewhat slower than with plain portland cement concrete, and probably flexural strength development would be further delayed by low temperatures. Where specifications call for attainment of a specified level of flexural strength before new construction can be opened to traffic, as is the case in Indiana, the possible additional delay when using fly ash concrete should be planned for and operations adjusted to take this into account.

COVER DESIGN BY ALDO GIORGINI