proportioning concrete mixes

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SCOPE

The purpose of this paper is to present a proportioning technique whereby concrete mixtures containing pozzolan as an ingredient can be produced within the framework of ACI 211.1-70 "Recommended Practice for Selecting Proportions for Normal Weight Concrete" (8) with predictable results. The method provides a first approximation of proportions of normal-strength structural grade concrete intended to be checked by trial batches in the laboratory or field and adjusted to produce concrete characteristics which are required. This paper concerns itself with "plastic" concrete mixtures only. No slump concrete is not considered.

INTRODUCTION

No history of concrete as it is made and used today would be complete without reference to the expanding use of pozzolans as an ingredient in concrete. It has been stated (1) that pozzolans along with other finely divided mineral admixtures are used in mass concrete, structural concrete, pavements, dams locks, canal linings, tunnels, sewage works, waterworks, high-rise residential and commercial structures, and residential concrete including sidewalks, driveways, and parking areas. In short, concrete containing pozzolan as an ingredient is being used in virtually every application for which concrete is used. The literature provides much information on the desirable effects of pozzolans in concrete. The history of

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the use of pozzolans approaches the history of the recorded works of man. About 2000 years ago Greeks, Romans and other Mediterranean peoples discovered the value of using pozzolans (fine volcanic ash) with burned lime to build historic structures - some are still in use today. Earliest methods of proportioning with pozzolan in this country consisted primarily of substituting pozzolans on a pound for pound or volume for volume basis for portland cement. Modern building practices have required however that a new method of proportioning with pozzolans be developed whereby rapid construction can be coupled with long range owner satisfaction. These procedures are in accord with ACI 211.1-70.

BACKGROUND

The American Society for Testing and Materials (2) defines pozzolan as "... a siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties". In briefer terms, pozzolans are powders which when combined with lime and water at ordinary temperatures will harden. In concrete the lime is provided as a by-product of the hydration of the portland cement in the mixture. A commonly accepted amount of lime produced by hydration is 15%, by weight, of the portland cement.

There are in general two types of pozzolans: natural and man-made. Natural pozzolans are found in the earth's crust and include volcanic ashes, pumicites, tuffs, diatomaceous earths, opaline cherts and shales and certain processed clays, shales and diatomites. Some natural pozzolans are capable of being used in concrete with minimal preparation such as screening and grinding whereas others require calcination and finish grinding to provide satisfactory properties.

Man-made pozzolan refers almost exclusively to fly ash. Fly ash is defined (2) as "... the finely divided residue that results from the combustion of ground or powdered coal and is transported from the combustion chamber by exhaust gasses." Some factors affecting the chemical and physical characteristics of fly ash are the chemical composition or type of coal, duration of time in open-air storage, fineness of grind and other factors relating to combustion.

Most recognized specifications for pozzolans in the United States of America are written to cover both natural pozzolans and fly ash with the properties of each arranged in convenient tables. Some of these specifications are ASTM C 618-71 (2) "Fly Ash and Raw or Calcined Natural Pozzolans For Use in Portland Cement Concrete", CRD C262-63 (3) "Corps of Engineers Specifications For Pozzolan For Use in Portland Cement Concrete" and SS-P-570b (4) "Federal Specification for Pozzolans for Use in Portland Cement Concrete". The characteristics of the pozzolan intended for use must be known before any attempt can be made to proportion concrete with it. For example, a favorable particle shape and fineness of the pozzolan are necessary if low-water demand is to be achieved. Coarse pozzolan of unfavorable shape (such as a volcanic glass) may cause an increase in mixing water requirements with consequent excessive bleeding and segregation. Other characteristics such as the tendency of high-carbon fly ash to reduce entrained-air should also be known prior to proportioning. Highway Research Board Special Report No. 119 (5) "Admixtures in Concrete" contains much of this type of information helpful to the proportioner. Selected data from that report are shown in Figure I.

Early proportioning of concrete with pozzolans in this country was concerned almost exclusively with mass concrete. Since the proportioner of mass concrete is concerned with producing a mixture having a low heat of hydration and since the structure itself will probably not sustain design loads for many months or years and since most of the concrete used in the mass will not be exposed to freezing and thawing, certain procedures were developed whereby the quantity of portland cement was held to an absolute minimum and the pozzolan used therefore comprised a very high percentage of the total cementitious ingredients. However, in proportioning the concrete for use in structures an entirely different set of criteria have to be applied. For example, most structures have a required design strength at 28 days. Further, floors in many high-rise buildings receive higher loadings during the construction period than they ever do when they are turned over to the owner. A cube of brick or concrete block resting on concrete which is 7 days old causes more damaging stress than a stenographer seated at a typewriter in a two year old building. Concrete in the structural market is also invariably designed for higher strength than mass concrete. Further, since many of these structures are designed in areas which experience freezing and thawing the exposed concrete must be air-entrained. Even in those parts of the building not exposed to the elements air-entrainment may be required by the designer because of the volume of reinforcing steel in the thin members and the need to improve the workability of the concrete.

Under the above conditions then it became imperative that a new method of proportioning concrete for the structural market be developed.

Lovewell and Washa (6) reported the development of a method of proportioning concrete mixtures using fly ash. Basically, the method showed that with relatively few tests a designer could develop data which allowed him to proportion concrete containing fly ash with predictable results. This was further elaborated on by Cannon (7).

The method which follows is based on the references previously cited and includes additional data developed for mixtures containing fly ash and two types of chemical admixtures. The authors have found that the procedures outlined have proved valid with fly ashes conforming to ASTM C-618 and with a great variety of aggregates and brands of portland cement. The procedure has been proven to be satisfactory by the excellent performance of many millions of cubic yards of structural concrete made with fly ash with and without chemical admixtures. With a minimum number of check tests the procedure can also be applied to natural pozzolans.

PROCEDURE

As is pointed out in ACI 211.1-70 (8) compressive strength is not the only important characteristic of concrete. Workability, durability, wear resistance and other characteristics may be equally or even more important. "Guide for Use of Admixtures in Concrete" (1) discusses the effects of admixtures in concrete. Assume that based upon this guide and other data the designer requires that a pozzolan and perhaps other admixtures be used. Other requirements are also specified such as strength, slump, air content, maximum size of aggregate, type of portland cement and type of chemical admixtures. The following steps should be followed:

a) Selection of slump: If the designer has not specified a minimum and maximum slump the values of Table 5.2.1 of ACI 211.1-70 should be used.

b) Selection of aggregate: The designer may have specified a certain aggregate size and perhaps even shape. However, if this has been left open the proportioner should in general select the maximum size of coarse aggregate that is economically available and one which can be placed readily in the structure. Other considerations should be taken into account such as whether the concrete is intended to produce a very high strength, or whether it is intended for pumping through small lines in which case a smaller aggregate size may be selected and a specific particle shape may be desired. In no case should the maximum size of the aggregate exceed one-fifth of the narrowest dimension of the size of the form or one-third the depth of slabs or three-fourths of the minimum clear spacing between individual reinforcing bars, bundles of bars, or pretensioning strands.

c) Estimate of mixing water and air content: Table 5.2.3 of ACI 211.1-70, reproduced here as Figure IIA, gives an estimate of the mixing water required with a given size and shape of aggregate to produce a given slump. The table also gives an estimate of the amount of entrapped and entrained air normally present in non-air-entrained concrete. This table is for concrete which does not contain a pozzolan and/or a chemical admixture.

If no other data is available the proportioner can use Table 5.2.3 (Figure IIA) and apply a correction factor based on other information such as HRB Report 119, (5) Wallace and Ore (9),or other available sources. However, the producer or vendor of the pozzolan proposed for use may have useful information of this type. As an example of what may be available to the proportioner Figure IIB and Figure IIE give the approximate mixing water requirements of concrete containing fly ash, at different slumps made with rounded or angular coarse aggregate of the maximum sizes commonly used in structural concrete. These curves,while not absolute, are sufficiently accurate to provide the proportioner with a figure he can use to develop a first trial mixture. They have been developed over many years and much field work.

The use of chemical admixtures, specifically water-reducers or water-reducing-retarders has become wide-spread. These admixtures are used with great frequency in all concrete, including mixtures containing pozzolans. The chemical composition of the water-reducing admixture affects the amount of mixing water required and its characteristics must be understood. Figure IIC and Figure IIF give estimates of mixing water required for mixtures of cement plus fly ash and a chemical admixture with the salt of a lignosulfonic acid (lignin) as its base. Figure IID and Figure IIG give similar information but in this case the chemical admixture has a carbohydrate base.

d) Selection of compressive strength and air-entrainment: The designer will ordinarily specify the required average compressive strength and whether or not the concrete is to be air-entrained, along with the required limits of air-entrainment. If the designer fails to specify average strength and entrained-air content the proportioner may turn to Table 5.2.4 (a) and Table 5.2.4 (b) of ACI 211.1-70. These tables have been reproduced here as Figure IIIA and Figure IIIB.

The durability of concrete containing fly ash or other pozzolans is equal to that of concrete mixtures not containing these materials provided that the mixtures have equal compressive strength and equal air-entrainment (1,5). Thus although Table 5.2.4 (a) and Table 5.2.4 (b) were developed for concrete mixtures not containing fly ash or other pozzolans they may be used safely to determine the required strength and air-entrainment of mixtures containing fly ash and other pozzolans as well.

e) Calculation of cement content: Knowing the required average compressive strength the proportioner now turns to curves which have been previously established or which can be established with relatively few mixtures. An example of such a family of curves is shown as Figures IV A, IV B and

IV C. These figures are averages of hundreds of tests of structural concrete made either in commercial testing laboratories or in laboratories owned and operated by suppliers of ready-mixed concrete. These 3, 7 and 28 day curves are averages of results gained with many different brands of Type I portland cement and various sources of 3/4 inch to 1½ inch coarse aggregate, both angular and rounded. The water-reducing admixtures conform to ASTM C 494-71 (Type A) and had either lignin or carbohydrate bases. The fly ash came from eight different sources, the loss on ignition ranging from 5% to less than 1%. Concrete cylinders used to obtain data were cast in either waxed cardboard molds or single-use metal molds. Testing procedures were standard. The great many variables in materials, molds and laboratories naturally cause some scatter in the points used to plot the curves, yet the authors feel the curves are reasonably conservative and represent a good usable average strength of laboratory fabricated mixtures of structural concrete.

Structural concrete is ordinarily specified on the 28 day compressive strength basis. Therefore selecting the required average 28 day compressive strength of cylinders made, cured and tested in the laboratory on the ordinate scale and proceeding horizontally until intersecting the appropriate curve, and proceeding downward to the abscissa scale the estimated amount of Type I portland cement required to produce air-entrained concrete can be read.

Figures IV B and IV C are similar curves developed to show the relationship of the various mixtures at 7 days and 3 days. Such figures can be invaluable in helping the field engineer determine at an early age whether his concrete specimens will actually approach the desired strengths. They are also helpful in determining when loads may be applied to "green" concrete.

Figures such as IV A, IV B and IV C can also be established for non-air-entrained concrete.

f) Determination of pozzolan content: The optimum amount of the pozzolan can be determined by relatively few mixtures and a curve plotted similar to that shown in Figure V or the producer or vendor of the pozzolan may have such data available. Lovewell and Washa (6) established the curve shown in Figure V for fly ash and experience over the years with this material has shown that the curve is valid with only minor differences. Experience in the field has shown that it is beneficial to increase the value shown in Figure V by about 20% when the sand available for use is extremely coarse or where the concrete is to be pumped. When the sand selected for use is extremely high in 50 and 100 mesh particles it is also beneficial to decrease the amount shown in Figure V by about 20% to avoid stickiness. In all cases it should be remembered that the use of figures and tables in any suggested method of proportioning is for the establishment of a trial mix only and the numbers obtained from such references should be considered as estimates only and modified when appropriate with good judgment by the proportioner.

g) Estimation of coarse and fine aggregate contents: Now having determined the cement and pozzolan contents and an estimate of the approximate mixing water requirements and having determined the entrained air content (if any) the proportioner is now ready to complete his design by returning to ACI 211.1-70 to select coarse aggregate by means of Table 5.2.6 (reproduced here as Figure VI). The proportioner may have sufficient data available on the unit weight of fresh concrete containing the pozzolan with or without a chemical admixture to allow him to solve for the fine aggregate content by the "weight" method described in Paragraph 5.2.7 of the ACI 211.1-70 but the probability is that sufficient background information will not be available and it is suggested that sand content be calculated by the absolute volume method. To do this the specific gravity of the pozzolan in question must be known. Since the specific gravity of one pozzolan can be widely different from another no assumption as to specific gravity should be made. Exact information should be furnished by the producer of the pozzolan or it should be determined by laboratory tests.

h) Adjustments: ACI 211.1-70 shows the methods employed to adjust the first trial mix. The methods of the standard are equally valid when applied to mixtures containing pozzolans with or without chemical admixtures.

APPLICABILITY TO LIGHTWEIGHT CONCRETE

In general the method of selecting the proportions of cement and pozzolan with or without the chemical admixture previously described is also applicable to lightweight concrete mixtures. Because the amount of water required in a lightweight concrete mixture is so dependent upon the sizes, shape and texture of the lightweight aggregate and the fineness and amount of natural sand, if that is to be included, it is impossible to generalize on an estimate of mixing water. This must be determined by actual tests although a good estimate of it may perhaps be furnished by the vendor of the pozzolan or by the producer of the lightweight aggregate. Curves showing the relationship of cement, cement plus pozzolan and cement plus pozzolan plus water-reducing or water-reducing-retarding admixture can then be developed. A further curve showing the optimum amount of pozzolan to be used with cement with the aggregates in question should also be drawn. With these two curves in hand it then becomes an easy matter for the proportioner of lightweight concrete to use ACI 211.2-69 to determine a first trial mixture. Anexample of a family of curves developed for concrete containing an expanded shale lightweight aggregate and natural sand is shown in Figure VII. The relationship of fly ash to cement content with this particular combination of aggregates is shown in Figure VIII.

SAMPLE COMPUTATIONS

Example 1: Normal weight concrete is to be proportioned for a structure, part of which will be exposed to frequent freezing and thawing. Structural demands require an average compressive strength of 3500 psi for cylinders fabricated, cured and tested in the laboratory. It is expected that specimens from the field will average over 2500 psi. Job conditions indicate that a slump of 4 in. ± ½ in. should be used and the coarse aggregate will be crushed stone with a maximum size of one inch. The dry rodded unit weight of the coarse aggregate is 96.3 pounds per cubic foot and the bulk specific gravity is 2.64. The fine aggregate is natural sand of 2.66 specific gravity and fineness modulus of 2.70. The designer has required that fly ash be used and its specific gravity is 2.44. The concrete shall be air-entrained 5% ± ½%.

a) As indicated above, the desired slump is 4 inches.

b) The designer has required 5% entrained air plus fly ash with angular coarse aggregate and using Figure IIE it appears that the approximate amount of mixing water to produce 4 inch slump concrete with 1 inch maximum size aggregate is 285 lbs.

c) From Table 5.2.4 (b) of ACI 211.1-70 (Figure IIIB) a water-cement ratio of 0.50 would be required for the structure if cement alone were the cementing material. However, Table 5.2.4 (a) (Figure IIIA) estimates that a water-cement ratio of 0.50 for air-entrained concrete will produce approximately 3800 psi compressive strength at 28 days. Although the designer has required only 3500 psi the 3800 is required for durability and so this higher figure will govern and the concrete should be designed accordingly.

d) Using Figure IV A, entering at 3800 psi on the ordinate axis and proceeding laterally to intersect the curve marked "Fly Ash Mixture" and then dropping down to the abscissa axis, 390 lb./cu.yd of Type I portland cement is estimated as necessary to fulfill requirements.

e) To determine the optimum amount of fly ash for use in the mixture Figure V is used and entering with 390 lb/cu.yd. of Type I portland cement proceeding upward until intersecting the curve, thence laterally to the ordinate scale a value of 125 lb./cu. yd. of fly ash combines with the 390 lb./cu. yd. of Type I portland cement previously determined to give the total weight of cementing material.

f) The amount of coarse aggregate is estimated from Table 5.2.6 of ACI 211.1-70 (Figure VI). With a fineness modulus of the fine aggregate of 2.70 and one-inch maximum size of coarse aggregate the table indicates that 0.68 cubic feet of coarse aggregate on a dry rodded basis may be used in each cubic foot of concrete. Therefore, the coarse aggregate content is 27 x 0.68 = 18.36 cu. ft./cu. yd. Since it weighs 96.3 lb./cu. ft. the dry weight of coarse aggregate is 18.36 x 96.3 or 1768 lb./cu. yd.

g) The quantities of cement, fly ash, coarse aggregate,