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PROPORTIONING NORMAL WEIGHT AND LIGHTWEIGHT STRUCTURAL CONCRETE MIXTURES USING SHRINKAGE COMPENSATING EXPANSIVE CEMENTS

By
Cedric Willson

Synopsis: Presents basic principles of proportioning shrinkage compensating concrete mixtures using currently available expansive cements and relates them to proportioning mixtures using Type I cement. Properties which are common to all expansive cements and their differences are discussed. Conditions under which slump loss may occur when using some expansive cements are reviewed and methods for adjusting mixing water to compensate are given. Recommendations for the use of admixtures are made and the importance of proper curing and adequate internal restraint are discussed briefly.

Keywords: admixtures; cement content; compressive strength; concretes; curing; expansive cement, type K; expansive cement, type M; expansive cement type S; expansive cements; hydration; mix proportioning; portland cement, type I; shrinkage compensating cements; slump tests; temperature.

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INTRODUCTION

In considering the selection of proportions for structural concrete mixtures using shrinkage compensating expansive cements it is desirable to first establish two pertinent definitions in order to make clear the type of concrete with which we are dealing.

Expansive cement - a cement which, when mixed with water, forms a paste that during the early hardening period increases significantly in volume. This cement also contains calcium silicate, alumina and iron compounds such as those characteristic of the standard types of portland cement.

Shrinkage compensating concrete - a concrete made with expansive cement in which expansion, if properly restrained, will induce compressive stresses that approximately offset tensile stresses in the concrete induced by drying shrinkage.

It should be emphasized that the principal purpose for using this concrete is to eliminate or greatly minimize drying shrinkage cracks. Cracks formed by action other than drying shrinkage are not effected.

Three types of shrinkage compensating expansive cements are presently available in the United States. They are Type K, also known as ChemComp, Type M and Type S. Their compositions and methods of production are somewhat different but they have a number of common properties which should be recognized in proportioning structural concrete mixtures. The most important are:

1. Each of these cements will produce structural concrete having approximately the same compressive strength as an average Type I cement concrete when used pound for pound in a mixture using the same aggregates and having the same slump or consistency.
2. When used in a concrete mixture pound for pound, each will result in the development of expansion within the same range of values.

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3. In order to eliminate or minimize drying shrinkage cracks, the expansive force in these concretes must have adequate restraint which is usually accomplished by reinforcement.
4. Complete development of the potential expansion for each type, K, M and S, requires adequate curing and there is a relationship between mixing water requirements and proper curing which differs somewhat for each type. In designing concrete mixtures this should be taken into account and will be discussed in the sections on Mixing Water and The Trial Batch.
5. Each of the three available expansive cements contain only about 10% of the compounds which develop expansion during hydration. Approximately 90% are the familiar compounds which are characteristic of all types of standard portland cement. It follows that the basic principles and methods for proportioning structural concrete mixtures using these cements are the same as those generally used for proportioning mixtures using Type I and Type II portland cements. The only exception is in handling the mixing water due to the characteristics of the particular cement used.

AGGREGATE PROPORTIONING

We have established that the same methods used for designing structural concrete mixtures using Type I and Type II portland cements are equally satisfactory for expansive cement concretes.

Therefore, sections 5.2.6, 5.2.7 and 5.2.8 in ACI 211.1-70 are recommended for selecting aggregate proportions for normal weight or heavy weight concretes. When the aggregates to be used are from a known source and satisfactory proportions of fine and coarse have previously been established, they may be used.

For lightweight concrete, the aggregate producer can usually provide reliable information on proportions of fine and coarse aggregates and the total uncombined volumes (dry-loose basis) required to produce 1 cu.yd. of concrete. When information from this source is not available, section 3.2 of ACI 211.2-69 is a recommended guide.

The PCA "Design and Control of Concrete Mixtures, 11th Edition" is also an excellent reference and guide for both normal and lightweight concrete aggregate proportioning.

CEMENT CONTENT

The same as for Type I and Type II portland cements, the selection of an appropriate expansive cement content to meet specified concrete strength requirements should be based upon tests made on concrete mixtures

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containing the materials which will be used in the construction. The required strength may then be interpolated from a cement content vs. compressive strength curve. If data on past performance of the expansive cement to be used is not available, the following table may be used as a guide for setting up the test program. (Refer to section 4.2 of ACI 318-71.)

Guide for the Relationship Between Water-Cement
Ratio and Compressive Strength of Shrinkage Compensating
Concrete using Expansive Cements

Compressive Strength at 28 Days, psi	Water-Cement Ratio by Weight	
	Non-Air Entrained Concrete	Air-Entrained Concrete
6000	0.42 - 0.45	---
5000	0.51 - 0.53	0.42 - 0.44
4000	0.60 - 0.63	0.50 - 0.53
3000	0.71 - 0.75	0.62 - 0.65

Most producers of expansive cement recommend a minimum cement factor in the range of 510 lbs. per cu.yd. with approximately 0.15% reinforcement in order to assure adequate restrained expansion. Expansion increases as the cement factor is increased and, under normal conditions of reinforced concrete design, additional reinforcement is recommended to provide a corresponding greater internal restraint. This should be kept in mind when determining the water-cement ratio.

ADMIXTURES

When the durability of exposed concrete must be considered, it has been found that air entraining admixtures which comply with ASTM C 260 may be used for the same purpose and with the same beneficial effects with shrinkage compensating concretes as with Type I or Type II cement concretes. Generally, the same amount of a given admixture will produce the same percentage of air in both types of concrete, all other conditions being the same.

Water reducing and water reducing-retarding admixtures of all types which comply with ASTM C 494 have been used in shrinkage compensating cement concrete. It has been found that some of these admixtures are not compatible with certain shrinkage compensating cements. If definite knowledge of a satisfactory performance record is not available, it is urged that such admixtures be tested before acceptance using the shrinkage compensating cement and other materials selected for the job. Special attention should be given to their effect on slump loss and restrained expansion since it has been found that the use of certain Type A and Type D admixtures with some expansive cements have resulted in excessive slump loss and/or a substantial loss of expansion. Generally, admixtures which are acceptable may

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be used in the normal dosage recommended for Type I cement concrete under moderate temperature conditions. During extreme hot weather (concrete temperatures of 85 F and higher) accompanied by conditions which contribute to high water loss from evaporation, larger than normal dosages of acceptable water reducing-retarding types have been successfully used to delay initial setting time.

Calcium chloride to accelerate setting time in cold weather should be used with caution due to its effect on expansion and/or subsequent drying shrinkage. It should be used only under extreme conditions and then limited to a maximum of 1% by weight of cement. It is recommended that the effect of calcium chloride be reviewed with the producer of the expansive cement being used before it is incorporated in the mixture. If used, calcium chloride should be added in solution in accordance with accepted good practice for Types I and II cement concretes.

MIXING WATER

It has been found that additional water is required to satisfy the chemical reactions which result in formation of the expansive compound ettringite and this creates a demand for more water to achieve complete hydration of expansive cements than is required for the hydration of Type I or II portland cements. The formation of ettringite begins soon after mixing water is added for all expansive cements. However, the rate of hydration varies for each of the three types and this must be considered in dealing with mixing water requirements, particularly for ready mix concrete.

Total time from batch plant to placement including delivery and possible unloading delays on the job may require from 30 minutes to 1 hour or even 1.5 hours. In some Type K and S cements, ettringite commences to form during this period resulting in a significant loss in slump. In this case additional initial mixing water should be added at the batch plant to assure that the specified or desired slump is obtained when concrete is placed at the job. This generally increases the water-cement ratio about 0.05 to 0.10 over a similar mixture using Type I or Type II cement. This slump loss is usually somewhat greater for Type K than for Type S but with both cements, this factor should be taken into account when developing the mix design.

During hot weather (concrete temperature above 85 F), when all hydration reactions are accelerated, a determination of the proper initial water demand is even more important and cannot be over-emphasized. Methods for accomplishing this are suggested in The Trial Batch section which follows.

Type M cement concrete does not have the slump loss associated with Types K and S while in the plastic stage due to a slower rate of ettringite formation. Concrete mixtures using Type M should be designed in the same manner as Type I or Type II cements without increasing the water-cement ratio.

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It should be remembered that additional initial mixing water, when required to offset slump loss, combines chemically with compounds in the expansive cement to form ettringite and has little or no effect on concrete properties because the free "water of convenience" is not increased. Job tests have shown that shrinkage compensating concrete develops compressive strength and other engineering properties which are comparable to Type I cement concrete at the same cement content and using the same aggregates when placed at the same slump although the slump may have been greater when it left the batching plant. Slump recommendations for placing shrinkage compensating concretes are 4" to 6" for normal weight and 3" to 4" for lightweight. Under hot weather conditions and where slump loss may be involved, greater expansion and better finishing properties may be expected if concrete is placed at the high end of each range.

THE TRIAL BATCH

The importance of determining initial mixing water requirements for shrinkage compensating concrete has been discussed in general terms in the Mixing Water section. We have learned this very important factor varies for some expansive cements depending on expected job conditions. Therefore it is appropriate to review mixing water requirements with specific recommendations for each cement.

When concrete temperatures will not exceed approximately 75 F and total time from mixing to final placement does not exceed 30 to 45 minutes, the total mixing water requirements for all three types, K, M and S will be comparable to Type I for the same placement slump. Examples are dry batching to a paver with machine screeding and finishing; dry batch ready mix truck delivery with job site mixing; or short travel time to the job with immediate truck mixer unloading.

When concrete temperatures are above 75 F or when total elapsed time from mixing to unloading is from 45 minutes to 1.5 hours or there is a combination of these conditions, special test methods are recommended for Types K and S expansive cements to determine the proper initial mixing water in the trial batch in order to obtain the specified placement slump. Both of the following trial batch procedures have been used with success:

First Method

- Step 1. Follow accepted methods as for Type I portland cement concrete except add 10% additional water for Type K or 5% for Type S.
- Step 2. The initial mixing should follow 5.1.2 of ASTM C 192.

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- Step 3. Immediately at end of the 2 minute mixing period following 3 minute rest, determine slump and record as initial slump.
- Step 4. As quickly as possible, return concrete used for slump test to mixer and continue mixing for 15 minutes.
- Step 5. Determine slump and record as placement slump. If this slump does not meet specification requirements, repeat batch with appropriate mixing water adjustment.
- Step 6. Mold strength and restrained expansion specimens. Determine yield and the air content if required.

Second Method

- Step 1. Follow ASTM C 192 methods using mixing water required to develop the specified placement slump.
- Step 2. Confirm slump after mixing in accordance with 5.1.2 of ASTM C 192.
- Step 3. Without further mixing, cover batch with wet burlap for 20 minutes.
- Step 4. Remix for 2 minutes adding water to produce the specified placement slump. Add initial water to remix water to determine the initial mixing water required at batch plant to provide the specified placement slump after 30 to 45 minutes total delivery time.
- Step 5. Mold strength and restrained expansion specimens. Determine yield and air content if required.

If trial batch data are lacking, these approximations have provided satisfactory results when Type K or Type S are used:

1. Use an acceptable ASTM C 494 water reducing admixture and maintain the same amount of mixing water as for a similar, Type I cement mixture without the admixture.
2. Add 10% for Type K or 5% for Type S to the mixing water required for similar mix if Type I cement was used.

When Type M expansive cement is used, the total mixing water required for shrinkage compensating concrete is comparable to a similar mixture using Type I cement including delivery and placement under hot weather conditions. When the requirements of ASTM C 94 are followed, the slump loss from batch

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plant to placement at the job, if any, is approximately the same as Type I cement concrete under the same conditions.

Compressive strength specimens may be made with single-use molds in accordance with Section 2.2.2 of ASTM C 192. Steel cylinder molds provide early restraint which usually increase strength values from 5% to 10% over single-use molds. However, the normal factor of safety in concrete mixture design generally compensates for this strength loss.

Special 3"x3"x10" prism molds which restrain the concrete are used to cast specimens for determining restrained expansion. Producers of expansive cement can furnish information on prism mold construction and complete details of the test method.

GENERAL NOTES

While the selection of proportions for shrinkage compensating concrete mixtures using expansive cements is not specifically concerned with reinforcement, job placement or curing, I would like to add these precautionary notes:

In order for this type of concrete to provide satisfactory performance, it is desirable that reinforcement for developing restraint in floors or slabs-on-grade be placed in the upper half approximately one-third of its' thickness from the top surface. To be certain of adequate restraint, the percentage of such reinforcement should not be less than 0.15%.

I wish to stress the importance of following the hot and cold weather concrete temperature and protection recommendations in ACI 304 on Measuring, Mixing and Placing Concrete, Chapter 18; ACI 305 on Hot Weather Concreting; ACI 306 on Cold Weather Concreting and Section 804 in ACI 301, Standard Specifications for Structural Concrete for Buildings. Shrinkage compensating concrete should be placed at temperatures between 50 F and 90 F, the same as recommended for all types of portland cement concrete in these excellent publications.

As has been pointed out, the hydration and expansion of concrete containing compounds which form ettringite requires additional mixing water when compared to similar Type I portland cement concrete regardless of the rate at which ettringite forms. When the rate of ettringite formation is such that it is not necessary to add additional water to compensate for slump loss, it is highly desirable to provide the additional water requirement during the first 3 to 7 days after placement by wet curing. If slump loss during delivery makes it desirable to add additional water when the concrete is first mixed, the application of a curing compound complying with ASTM C 309 or curing by covering the concrete with polyethylene sheets or similar covering is generally adequate although wet curing is preferred.

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This calls attention again to the importance of using the placement slump rather than initial slump at the batch plant as the proper criterion for determining concrete consistency. It should also be noted that a total time limit of 1 hour from batching to placement will provide better utilization of the expansive potential in shrinkage compensating concretes using all types of expansive cement.

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FACTORS INFLUENCING PROPORTIONING OF AIR-ENTRAINED CONCRETE

By

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Synopsis: A discussion of the effect of purposefully entrained air on the properties of concrete. Factors which affect the entrainment of air in concrete such as cement, sand, and mix temperature are discussed. Strength reductions to be expected and suggested air contents as related to maximum size aggregate are shown.

Keywords: admixtures; aggregate size; aggregates; air entrained concretes; air entrainment; cement content; compressive strength; mix proportioning; pozzolans; temperature.

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Contrary to the belief of many, the use of air entrainment in concrete is not confined to the northern part of the United States and Canada. It is true that the first advantage realized from air entrainment was that of reducing the detrimental effects of freezing and thawing on concrete highway surfaces, but subsequent studies have indicated that it also improves the durability of mass, structural concrete and concrete in contact with alkali soils (1, 2). Air entrainment has also been found useful in plasticizing harsh mixes, particularly where the concrete has to be placed in heavily reinforced sections. It reduces the water-cement ratio required for a given slump and thereby minimizes segregation and bleeding.

Air entrainment in concrete may be achieved through the use of air-entraining cement or by the addition of an air-entraining admixture to the concrete. At one time the use of air-entrained cement was popular, but with the advent of higher air requirements and the need for tailoring the air content to job requirements, the use of air-entrained cement is minimal, at the present time.

Air-entraining cement is manufactured to comply with ASTM Designation C 150 for Types IA, IIA, and IIIA. It contains a fixed quantity of agent, and, therefore, the air content is strictly dependent on such factors as mix design, sand grading, and water-cement ratio. If insufficient air is entrained it is necessary to add an air-entraining admixture to the concrete. If too much air is entrained it is necessary to treat the concrete with an air-detaining admixture. Relatively small quantities of this type of material

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are required making it difficult to adjust to a specific air content. Either of these procedures is an added step in the production of concrete and one which does not always produce satisfactory results.

An air-entraining admixture added at the time of batching the concrete provides flexibility and control of the air content of the concrete. It also eliminates the necessity of a separate storage facility for air-entrained cement and the possibility of batching plain cement when air-entrainment is specified. The use of an admixture, therefore, provides for a much more flexible operation.

Dispensers conforming to State and Federal specifications are available for proportioning the proper quantity into the concrete mix within specific tolerances. Since air-entraining agents should not be premixed with other admixtures such as water reducers, retarders or accelerators the time and place of discharge is predetermined to avoid direct contact prior to entering the mixer. In general the air-entraining admixture should be added with the water.

Purposefully entrained air should be a stable bubble of uniform size and distribution through out the mix. This type of entrained air acts as a lubricant for the fine aggregate in the mix. The air bubbles perform the same function as tiny ball bearings. They in a sense, supplement the cement paste.

A great deal of research involving hundreds of thousands of tests have gone into the development of the proper air-entraining agents to use with concrete. There are many materials which will generate air in a concrete mix, but very few which will not have detrimental side effects on the resultant concrete. At the present time there are three general types of materials which are commonly used as air-entraining agents. These are wood resin derivatives, sulphonated hydrocarbon and a tall oil derivative.

The air bubbles formed by these materials in the concrete are unique in that they average 100 microns or less in diameter. In average air-entrained concrete there are about 4 million of these bubbles per cubic inch. Other types of air producing materials, such as detergents, that have not been found acceptable for use in portland cement concrete, produce a much larger bubble well over 100 microns in size. As a result, for the same total air content, such materials entrain in the range of only 400,000 bubbles per cubic inch. In addition to this

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the bubble is not encapsulated by a stable film and, therefore, breaks down or merges with other bubbles to form relatively large voids.

The spacing factor of these air bubbles is very important and has been carefully studied by research people at the laboratories of the Portland Cement Association, Bureau of Reclamation and the Waterways Experiment Station of the Corps of Engineers. These studies have shown that a spacing factor in the order of less than 0.008 inches is required to develop durable concrete.

There are many factors which effect the quantity of air entrained in a concrete mix.

Four factors are commonly associated with excess air--(1) increased percentage of sand (2) same percentage of sand, but more 30-70 mesh sizes, (3) increase slump, up to 6 inches, and (4) lower temperature of the concrete mix.

On the other hand, there are four factors which are commonly associated with reduced air contents; namely (1) increased percentage of fines in the mix, e.g., the minus 200 mesh size or fine mineral fillers such as fly ash and pozzolans (2) increased cement content (3) greater angularity of the sand and (4) higher mix temperatures.

Type of cement can be important. For example, Type III cement (High Early Strength) is ground much finer than either Type I (regular) or Type II (moderate sulfate resisting or moderate heat of hydration) cement, and hence has a greater inhibiting effect on air entrainment. It is usually safe to estimate at least 50% more air-entraining agent required for a given air content with Type III cement.

But fineness is not the only cement variable which affects air entrainment. Chemical type may be important, too. For example, white cement which is low in iron content requires more, but high alumina cement requires less air-entraining agent than regular portland cement. And cements containing hydrated lime, ground limestone and/or ground silica for plasticity and water retention purposes require considerably larger than normal quantities. The amount of air-entraining admixture required may also vary inversely with the alkali content of the cement. This is particularly true if the solids of the air-entraining solution are not completely saponified.

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Probably the most important single factor in promoting or inhibiting air entrainment is the sand or fine aggregate used because (1) it has the greatest effect of any one variable, and (2) it is subject to large variations. Whereas, changing from Type I to Type III cement may increase the air-entraining agent requirements 50%, changing types of sand can effect these requirements by several hundred percent. Control of the uniformity of the sand on a job greatly simplifies control of the air content of the concrete.

Also, we can generalize by saying that the finer the sand, the more air there will be in the concrete. For example, a sand having a fineness modulus of 2.6 will bring about the entrainment of substantially more air than a sand having a fineness modulus of 3.1; when used in concrete with a given amount of air-entraining agent. This is due in part to the predominance in fine sand of those sand sizes which favor air entrainment. In most instances manufactured fine aggregate can induce an inhibiting effect on the air content of concrete, when compared with a similar mix using natural fine aggregate and an equivalent volume of air-entraining admixture. This is partly due to the presence in stone sand of inordinately high amounts of particles finer than the 100 and 200 mesh sieve. Such particle sizes are notoriously difficult and expensive to remove in the process of manufacturing fine aggregate, with the result that it is not uncommon for this size fraction to appear in the finished sand in magnitudes of 15 to 20% finer than the 100 mesh. This characteristic of manufactured sand can easily increase the air-entraining admixture demand several times over, when compared with a fine aggregate whose fines content is more nearly the optimum.

Moreover, the harsh, angular particle shape of most stone sands tends to require greater amounts of air-entraining admixture, although the demand is manifested largely through the influence that particle shape has on the workability and plasticity of concrete. Hence, undesirable particle shape in stone sand may be said to influence indirectly the amount of air-entraining admixture necessary to produce equivalent plastic characteristics of concrete in which the stone sand is used. Simply stated, poor particle shape is inherently detrimental to workability and thereby demands a greater volume of air bubbles--with attendance lubricating effect to partially overcome particle interference.

Since it is basic in the concept of air entrainment in concrete that only the mortar phase is entrained with the

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system of air voids, the incidence of influence of coarse aggregate on air content is less than for fine aggregate. In a sense, however, several of the factors that have been demonstrated to influence air content in fine aggregate also find application in the coarse aggregate. The depressing effect on air content of minus 100 fines--when occurring in the coarse aggregate in the form of crusher dust, degradation from handling, inadequate washing, etc.--is as noticeable when such fines exist in the coarse aggregate as when they are found in excessive amounts in the fine aggregate. Likewise, undesirable particle shape in coarse aggregate--if the percentage of poor shapes to total aggregate approaches predominance--produces damaging effects on workability and plasticity of the concrete.

The influence that the consistency of concrete has on the air content is fairly well established, i.e., plastic mixes up to a limit of about 6" slump (beyond this point the air starts to drop down) will entrain air with greater facility than dry, stiff mixes, the quantity of air-entraining admixture and mixing time being held constant in both cases. This behavior is largely due to the mechanical process by which air is introduced to the mortar. If we consider that the mixer is the medium by which air entrainment is accomplished--not the admixture per se--then we can readily understand how air can be produced easier in a relatively fluid mix than with a dry mix. The higher-slump concrete will respond more easily to the mixing action of the blades and will accordingly permit the sudsing of the admixture to quicker become an integral part of the mortar phase of the concrete. Conversely, drier mixes oppose the folding and cascading action of the mixer blades to a greater extent than the more fluid mixes and, consequently, do not become air-entrained as easily.

Discussing the influence of consistency on air content it was stated that the mixer is the mechanical agent that actually accomplishes the job of sudsing and foaming the admixture into an intimate blend with the fine aggregate and water, thereby entraining air into the mix. In this connection, we can go still further and say that several conditions surrounding the mixer can likewise influence to a marked degree the uniformity and magnitude of the air content of the concrete. Foremost of these conditions are (1) time of mixing (2) size of batch (3) revolving speed of the drum and (4) the condition of the blades.

The temperature of concrete has been found by laboratory and field tests to have a marked and consistent influence on the air-entraining effectiveness of the admixture under observation. The air content of a given mix has been found to vary inversely

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as the temperature. In tests conducted in the laboratories of the National Ready Mixed Concrete Association, it was reported that the air content of a standard concrete mix is approximately 30% greater at 50F than at 70F; these tests also showed that the air content at 110F is approximately 30% less than at 70F.(5)

It is immediately apparent that the four basic influences, fine aggregate, consistency, cement content, and temperature, cited as having an effect on air content are familiar in that they likewise are recognized as governing other properties of plastic concrete i.e., uniformity and homogeneity, and thereby strength, consistency, plasticity, etc. Since air entrainment has been nominated and accepted as "The Fifth Ingredient of Concrete" the air-entraining admixture merits and requires the same degree of consideration in the manufacture of concrete as the other ingredients, if it is to yield maximum benefits. As an ingredient of the mix, the air-entraining admixture must be mixed with the other ingredients a sufficient length of time to permit the system of air bubbles to be created and uniformly distributed throughout the batch. Unless this is assured, the air content of the mortar phase will exist in unbalanced amounts- and the resultant concrete may be "over" air entrained in one area and "under" air entrained in the other. The plastic qualities of the concrete are immediately affected to an undesirable extent and the serviceability of the hardened product is impaired.

Overloading the mixer-beyond the capacity recommended by the manufacturer or as capacity is influenced by the overall condition of the mixer-inhibits the air content through a reduction of mixing efficiency. Without prolonged mixing the air system simply cannot be created because of less effective agitation, cascading, etc. Similarly, excessive drum speeds create a tendency for the concrete to "ride" on the internal periphery of the drum (through centrifugal force) and the reduction in agitation results in less air than is desired. Worn, thin, or improperly placed blades in the mixer rob it of efficiency in mixing with attendant loss of potential air entrainment.

The quality and uniformity of concrete is in many respects related to mixing time as it in turn is related to the efficiency of the mixer. In general the air content of a mix will increase up to about 5 minutes of mixing in the average truck mixer. After that period the air will remain at a given level for another 5-10 minutes of mixing before exhibiting signs of dropping off. The time required to reach the maximum air content for a given set of mix conditions when using a drum or

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turbo type mixer is much less because of the vigorous nature of the mixing. It is difficult to assign a specific mixing time to achieve maximum air for a given mix because of other variables such as those previously mentioned which do influence the air content.

Among the many factors that effect air entrainment there is one which is often overlooked. This is water. At one time not too long ago there were numerous complaints of high air when no admixture was used. This problem was finally traced to the presence of non-degradable detergents in the water. The U. S. Public Health Service has taken care of this problem by requiring that only bio-degradable materials may be used in detergent preparations. Low air entrainment has also been caused by water. It has been well documented that hard water inhibits the entrainment of air. It is particularly serious if the admixture is premixed with the water.

Other factors which may inhibit air entrainment or reduce it are finely divided particles such as are found in carbon black or pozzalans and the mixing of calcium chloride with some chemical admixtures prior to adding them to the mix. Excessive vibration will also tend to remove air from the plastic mix. As much as, 50 percent of the air could be lost by vibrating for 2-3 minutes.

Air entrainment occupies space and, therefore, increases the volume of the batch which must be adjusted to maintain proper yield. This is accomplished by reducing the fines (sand) of the mix and by the reduction in water brought about by the lubricating effect of the air bubbles. The reduction in sand is generally 10-12 percent depending upon the aggregate characteristics.

When the proper adjustments have been made to the mix to compensate for the added air and thus maintain the designed cement factor the strength will not be seriously reduced. The strength reduction is affected by the cement content of the mix and the air content. Cement factors below 517 pounds with 1 1/2 inch maximum size aggregate and not over 5 percent air will produce concrete strengths equal to or greater than equivalent non-air entrained concrete. Above the 517 pound level, strengths will be reduced as the cement factor and/or air content is increased. This is due to the fact that the added cement increases the plasticity of the mix thus negating the effect of air as a water reducer. For example, the loss in strength for 1 1/2 inch maximum size aggregate containing 564 pounds of cement is shown in Table I. It is apparent that a sizable loss of compressive strength occurs with the higher air

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contents. This is a generalization based on numerous tests during the last few years. Cement composition, aggregate characteristics, mix design, and slump will have an affect on the values obtained under a given set of conditions. An example of results obtained for a specific set of conditions is illustrated in Figure A. (6)

Since the higher air contents reduce the strength significantly and do not appreciably improve durability there appears to be a justification for limiting the air content of a given mix.

Air entrainment, when first introduced was used with caution. Seldom, if ever was the air content permitted to go over 6 percent, but in recent years the trend has been toward higher values. It is not uncommon at the present time to find state highway specifications up to 9 percent and inspectors trying to maintain at least 8 percent air. Air contents of this magnitude not only cause a severe reduction in strength, but also reduce the abrasion resistance of the surface. The little, if any, improvement in durability does not seem to be justified under these conditions.

Air entrainment, within the normal limits acceptable in concrete, does not effect the setting of concrete. This is true regardless of the concrete temperature as shown in Table II. The setting time does, however, change with a change in temperature regardless of air entrainment, hence this fact must not be overlooked where the time of set is critical. Under such conditions a check should be made to determine the setting time of the concrete batched with the materials to be used on the job and at the expected temperatures.

Air entrainment does change the finishing characteristics of concrete. However, knowledgeable finishers can handle it as well if not better than non-air entrained concrete. The major problem of the uninitiated finisher is the lack of bleed water. He has a tendency to start finishing before sufficient set has taken place. This is one of the reasons for the erroneous belief that air entrainment delays the set. If time as well as "feel" of the concrete is taken into account and the proper tools are employed no trouble will be experienced. For example, the floating should be delayed for 30-45 minutes after the concrete is placed depending primarily on temperature conditions. Magnesium bull floats and hand floats are much easier to use on this type of concrete and results in a tighter surface. Final steel troweling should be started when thumb pressure slightly dents the concrete surface. The trowel will not ring as

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noticeably with air-entrained concrete as non-air entrained concrete.

It was mentioned earlier that the use of air entrainment is not confined to northern climates. The durability of concrete in the presence of sulfate waters or other corrosive chemicals is also important. Normally, the disintegration of concrete due to the attack of sulphate waters is greatly delayed by air entrainment. Air entrainment helps in this connection because it reduces the permeability of concrete and prevents the corrosive chemicals from getting inside the concrete.

Another use of air entrainment which will no doubt come as a surprise, but which has the support of the Portland Cement Association is in hot weather concreting. The entrainment of 4-6 percent of air in concrete placed in 100F, 10 percent relative humidity weather conditions produced a more dense, workable and finishable slab at 1 1/2 - 2 inch slump than the customary 8 inch slump material previously regarded as a necessity.

Since the air bubbles are entrained in the mortar phase of concrete, it follows that the more mortar there is, the more entrained air there will be in the concrete. For example, if by careful handpicking so that no mortar is removed, some of the particles of coarse aggregate are removed from plastic concrete, pressure air meter tests will show increasing concrete air contents as the coarse aggregate content is decreased. Since larger percentages of sand mean greater mortar contents, they also mean greater air contents as well. Conversely as the maximum size of the coarse aggregate is increased the percentage of entrained air in the total concrete is decreased. This is because only the mortar phase contains the system of air voids. Hence, as the coarse aggregate is increased the proportion of mortar is decreased. The air content in the mortar phase actually remains fairly constant.

It is the air that is entrained in the mortar phase of the concrete that is what is generally designated as purposefully entrained air. It is this air that is beneficial to concrete. Tests have indicated that a mortar air content of about 10 percent is optimum for most concrete. The actual air measured in the concrete will vary with the maximum size of the aggregate. The larger the maximum size aggregate the less total air because the ratio of mortar to coarse aggregate is less. This range will be from 10 percent in mortar to about 3 percent in 6 inch maximum size material. Table III lists the suggested air contents for maximum durability and strength as related to the maximum size of aggregate. Similar figures were first suggested

air-entrained concrete

by Klieger. (7)

As has been suggested, many factors influence the purposeful entrainment of air in concrete. These factors must be taken into consideration in the design of air-entrained concrete in order to obtain the full benefits of the air. Trial mixes should be conducted with job materials to establish the proper mix proportions for optimum results.

References

1. ACI Committee 212, "Admixtures for Concrete," ACI Journal, Proceedings V.60, No. 11, Nov. 1963, pp. 1481 - 1524.
2. ACI Committee 212, "Guide for Use of Admixtures in Concrete," ACI Journal, Proceedings V.68, No. 9, Sept. 1971, pp. 646 - 676.
3. Mielenz, R. C.; Wolkodoff, V. E.; Backstrom, J. E.; Burrows, R. W.; and Flack, H. L., "Origin, Evolution and Effects of the Air Void System in Concrete," ACI Journal, Proceedings V.55, July 1958, pp. 95 - 122; Aug. 1958, pp. 261 - 272; Sept. 1958, pp. 359 - 376; and Oct. 1958, pp. 507 - 518.
4. ACI Committee 212, "Admixtures for Concrete," ACI Journal, Proceedings V.60, No. 11, Nov. 1963, pp. 1481 - 1524.
5. Walker, Stanton and Bloem, Delmar L., "Studies of Concrete Containing Entrained Air," ACI Journal, Proceedings V. 42, June 1946, pp. 629 - 640.
6. Private communication.
7. Kieger, Paul, PCA Bulletin No. 40, Oct. 1942.

Table I - Approximate Loss in Strength

Air Content Percent	Strength Loss Percent	Percent Total Loss from 4 Percent Base
4 to 5	5	5
5 to 6	6	11
6 to 7	7	18
7 to 8	8	26
8 to 9	9	35

proportioning concrete mixes

Table II - Time of Set (ASTM Designation C 403)

	Reference	DAREX AEA
CF (sks /yd)	5.42	5.42
Water (gals /sk)	6.83	6.33
Slump (in.)	4.0	4.0
Air (%)	0.9	4.1
Curing Temperature 60F		
Initial Set (hr:min)	6:58	7:08
Final Set (hr:min)	9:29	9:43
Curing Temperature 80F		
Initial Set (hr:min)	5:26	5:23
Final Set (hr:min)	7:41	7:54
Curing Temperature 100F		
Initial Set (hr:min)	4:18	4:57
Final Set (hr:min)	5:48	6:24

Table III - Recommended Air Content vs. Maximum Size of Aggregate

Maximum Size Aggregate, in.	Average Air Percent	Air Range Percent
6	3	2 - 4
2	4	3 - 5
1 1/2	4 1/2	3 1/2 - 5 1/2
1	5	4 - 6
3/4	6	5 - 7
1/2	7	6 - 8
3/8	8	7 - 9

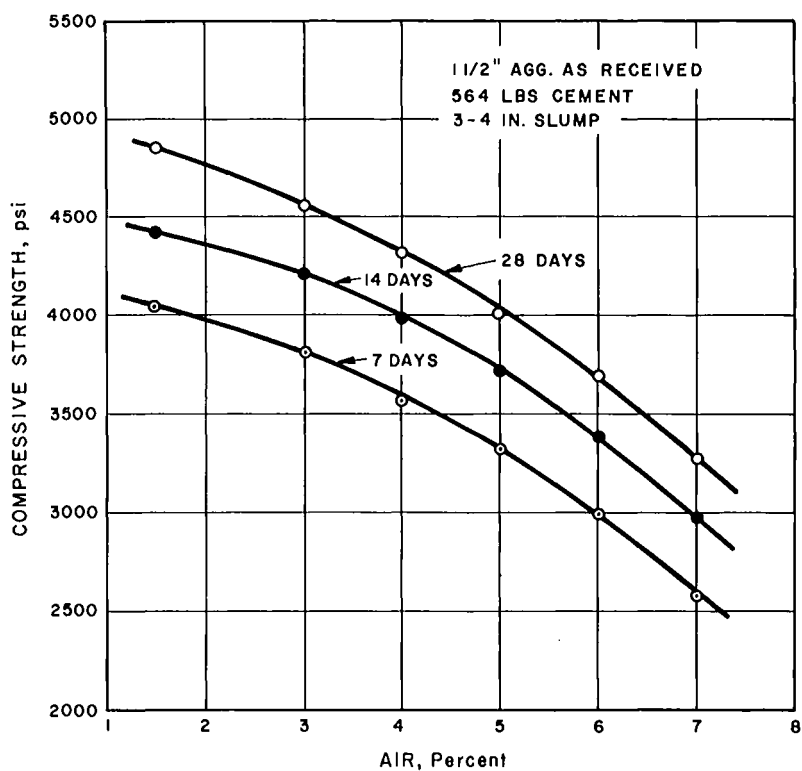
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Fig. 1—Strength loss vs air content

SP 46-3

CONCRETE MIX PROPORTIONING FOR PUMPING — SOME INFLUENCES OF MATERIAL PROPERTIES — A GRAPHICAL APPROACH TO OPTIMUM GRADATION

By
Francis C. Wilson

Synopsis: For practical placement via pipe and hose, concrete, in addition to other requisite properties, should be pumpable, a property closely related to workability, and influenced by variations in the properties of the mix ingredients. Good structural concretes designed with well prepared materials by ACI 211 or other approved method usually pump, and improvements to enhance pumpability usually also improve other properties of the concrete. Good gradation however obtained is the prime requisite for pumpability. Desired gradations, ways of obtaining same, alternates, substitutes, adjustments, slump, porous aggregates, water migration, additives are discussed. The need for more extensive application of routine testing on pump placement is established along with a discussion of strength and coefficient of variation gains. The pumpability of a mix is substantially influenced by gradation in all sizes and in the five-fines or cement sizes; by quantity, grind fineness, particle shape, additives and relation to voids in the aggregate; in the sand sizes; by quantity, FM, shape, blends, additives, portion of crusher product; and in the coarse aggregate sizes by quantity, size distribution, particle shape and surface texture, porosity, saturation, surface area; and related influences. Next to good gradation, constantly repeated uniformity of aggregate production, of handling, and mixing is desirable to insure continued practical pumping. Pump performance records are summarized. A graphical method is presented for combining aggregates for workability and for predicting the influence of changes and adjustments.

Keywords: admixtures; aggregate gradation; fineness; mechanical properties; mix proportioning; particle size distribution; placing; porosity; pumped concrete; pumping; sands; saturation; water-cement ratio; workability.

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INTRODUCTION

To obtain the cost advantages of placing via pipe and hose, concrete shall provide strength, durability and other properties required for the work and in addition should be pumpable.

The principal requirements for a pump mix are good gradation and repeated uniformity, carried right down to each shovelful. Thorough consistency is desirable for many reasons but it is sometimes troublesome to maintain in the realities of handling large volumes of relatively low cost materials, particularly by persons accustomed to the forgiving indulgences of less exacting placing methods. However alert designers and contractors can take advantage of the closer consistency and self inspection features of the pump to save cement, and to get much better work, at lower cost in place.

A few classes of concrete are inherently not pump mixes:

- Large rock (over 40 percent of the I.D. of the line),
- Excessively Porous Aggregates, not treated, (including many lightweight aggregates)
- Purposely gap graded mixes, including most exposed aggregate mixes,
- Sand too coarse (over 3.00 F.M.),
- Sand too fine (under 2.30 F.M.),
- Sand 100 percent crushed rock,
- Sand: too much, too little, or bleeding.

In general, however, good structural concrete will be pumpable.

Special concretes: colored, expansive, fast setting, white, grouting, refractory, set controlled retarded or accelerated, extreme strength, are usually handled better by pumps than otherwise. Where problems arise they usually are not related to the special aspect but to the fundamentals discussed below, likely gradation. Sensible precautions for special features are in order and the men promoting the special products will generally be well versed in recommended practices.

placing and pumping concrete

MIX PROPORTIONING FOR PUMPING

Pumpability is very similar to workability, flowability, trowelability - the properties needed for strength, finishing, good form filling. Since local men usually know how to adjust local materials for good finishing, it should be relatively easy to use their familiar techniques to adjust a good mix if required for better pumping.

Testing for pumpability in the lab has been tried several ways, with results well worth studying ^{1,2,3,7,15,19,20}. There is no practical substitute for full scale testing, particularly because the first passage thru the system is all that has any significance. A practical method is to arrange to dispose of full scale test batches into appropriate lower spec work such as footings. In most instances experienced pump operators and concrete suppliers can accurately predict pumpability.

Mix proportioning by usual procedures such as ACI 211,³ generally produce a mix that will pump, though frequently small changes well within specification can improve pumpability. Changes to improve pumping and workability and finishing almost invariably enhance strength, economy, appearance and other properties. The recently added tolerance in ACI 211 allowing up to 10 percent extra sand for pumping should be used sparingly inasmuch as adding extra quantities of a marginal sand may create other problems without improving pumpability. Better to seek the basic improvements of gradation and uniformity.

Some early mix proportioning methods deserve a reminder discussion because of the pertinence of the principles involved.

The "Box" Method--(Maximum Density of Combined Materials)--Simply combine the available ingredients in a variety of trial proportions until the trial volume (box) attains the heaviest weight.

Maximum Density - Least Voids Method--To seek maximum density at the least total voids is an excellent short statement of desired objectives in gradation for pumping and will incidentally tend to best strength, cement economy, and least shrinkage.

Minimum Voids - Minimum Area--An excellent concept particularly useful in graphical gradation work. Lesser voids require less fine fines for "fill." Lesser surface areas, which can be very substantially less if the large size fractions are increased, improve the coverage "efficiency" of the paste. In these concepts lie substantial opportunities for cement economy and obtaining good workability with less water, less cement. Reference 3 describes a void testing device and work indicating that pumpability is influenced by the relation of void content to available fine fines content.

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Often related to local materials and available expedients, there exist many rule of thumb and empirical mix proportioning methods which deserve notice for they reflect hard won experience.

One lab in Seattle seeks to have not in excess of 7 cu ft of "paste" (cement and fines) per yard, in gravel mixes to have not over 56 percent of net solids in large aggregate and not over 51 percent in crushed rock. The "sure-fire" pump mix formula of one experienced lab in St. Louis requires that the total of cement and all fines under #4 screen be 275 to 315 lb in excess of the coarse aggregate weights.

Some designers work to a combined F.M. of 4.60 to 4.70 for sand and gravel, 4.30 to 4.40 for sand and crushed stone.

The use of experience-developed combined grading limits in graph form for pumpability has had extensive use in most advanced work on pumping and a useful summary is given in the last part of this report.

In developing a feel for reliable pump concrete it is well to note the wide experience in tunneling since 1934, on work where no alternate was available and where no interruptions could be tolerated. A thorough discussion by men who have pumped 7,000,000 yd in all kinds of situations⁶ emphasizes the constant care that experienced men deem appropriate. As better aggregate handling, better pumps and better concrete controls are available, the tendencies to oversand and be extra generous with cement described in the article can be improved, but unrelenting attention to detail is the route to practical pumping.

Testing procedures assume special importance where pump placement is well used. With very few exceptions pump and pipe transit of good structural concrete produces an increase in the strength of the mix, often up to 15 percent clearly indicating that the nature of the concrete is altered to a degree of consequence. It is desirable that a sufficient series of tests be performed on the concrete both before and after pump transit to establish the true nature and extent of the differences almost certain to be present. Recent tests about to be published confirm that there is also a very favorable narrowing of the coefficient of variation. The combination of up to 40 percent improvement in variation coefficient and up to 15 percent increase in strength can be used by alert designers and contractors to effect substantial cost savings along with the advantages of reduced overdesign, more uniform deflections, less heat, less shrinkage, and better overall control.

Concrete pumped through aluminum conduit can abrade metal to generate hydrogen gas in reaction with cement, resulting in a substantial loss of strength quite like the rule of thumb that one percent entrained air (gas) reduces strength 5 percent. References 7 and 8 discuss principally the dangers of the aluminum reaction and have led to a general limitation on aluminum conduit. Equally important are 2 of the other conclusions of References 7 and 8:

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A. Concrete can be substantially altered by pump transit, hence full adequate testing at both feed and discharge is requisite for control.

B. In the steel pipe tests, the strength of highway bridge mixes is enhanced by pump transit, up to 17 percent in some instances. Coefficient of variation tests about to be published by others will indicate substantial improvement.

Concrete quality testing is done for a variety of purposes. For example the ready mix supplier controls the concrete to the end of his chute and tests for his compliance shall logically be made at that point. The owner's representative most likely is concerned with results of testing done as close as possible to final placement. The question arises "What is the difference?" and this question deserves careful investigation, particularly because important savings in cost and considerably improved control can be the result.

Testing for air content is too slow to obtain significant information on air content at various times during transit. In general the air content tends to revive from compressed levels during transit to delivered levels at or near the input air content.

INFLUENCE OF MATERIAL PROPERTIES ON PUMPABILITY

Cement and Fine Fine Materials

From the standpoint of the pump and during the usual 20 to 90 seconds the mix is in the pump system, cement is merely a fine aggregate taking its place along with all other particles under the 100 or 200 mesh screen. The tests of Reference 3 show that if a sufficient volume of particles in the cement size range are present to approximately fill the voids in the aggregate, pumping goes well. A small deficiency or a substantial excess of fine fines renders pumping difficult. If the required quantity of fine fine particles can be partially provided from sources other than cement there may be cost savings and other advantages as well. Reference 10 describes a workability test whereby the effect of finely divided mineral additives was compared. Several common materials - pozzolans, fly ash, diatomaceous earth, bentonites, fine beach sand, etc. were shown to effect improvements better than the addition of a like amount of cement. ASTM C33, the basic aggregate specification, has a provision that in net effect allows obtaining the requisite fine fines from any suitable source, which allows using cement only as required for strength. There are differences in the contribution to workability of various cements due to: finer grinding, beneficial additives, and a balanced gradation of particle sizes. Some chemically compensated cements pump much better, apparently because of better particle shape and size spread. In the cement sizes, a sufficient quantity is a requisite but beyond that; particle shape, and the ever significant matter of gradation, are also influential on workability.

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Sand size materials must be present in sufficient but not excess quantities, usually ACI 211 or other conventional solid volume mix design methods provide an appropriate quantity. Reference 13 includes a thorough discussion of sand with graphs of limits and recommended gradations. As a general rule the sand for pumping should have an F. M. over 2.30 and not over 3.00. The centerline of the ASTM C33 sand limits works out to an F.M. around 2.75, a good level.

However, it is in the sand sizes that the detail of gradation and particle shape is critically important and investigation well beyond mere quantity and F.M. is usually indicated, almost always beneficial.

Reference 1 reports extensive work initiated because mixes containing sand that is 100 percent crushed seldom pump. It was found that small blends of natural sand, as low as 10 percent, but usually 20 percent, have far reaching effects. The tests seem to strongly underline the importance of particle shape and further to suggest that there is a strong likelihood that a blend of any two materials may well tend to have a better workability than single source sands. There is a natural complement in sizes between natural river or bank sands and crushed sands. Careful sieve analysis allows graphical methods to be used to easily find optimum blend combinations, to compare blend candidates, to adjust crushers and screens, and to improve the resultant sand.

In actual practice concrete sand can be the residual after plaster, asphalt, and masons sand are sized out at the plant. The simple reintroduction of a small fraction of a size complementing blend can effect substantial improvement in pumping.

Sands produced in dredging operations or vigorously washed may have a deficiency in the fine fractions. Rock crusher waste has much merit to make up such a deficiency.

Sands with a smooth curve near the center of the ASTM C33 limits, no gaps, no excesses, 3 to 5 percent passing the 100 screen, 15 - 20 passing the 50 screen, usually keep pumping operations running reliably. Many less than ideal sands also have satisfactory records. In general where the concrete supplier has thoroughly explored sand blend potentials, and available inert additives; overall costs, concrete quality control and pumping have all been brought under the easy routine control that assures troublefree operations. Sand is the key and proper sand gradation is far more significant than the mere addition of extra sand. Where good sand is available the extra sand allowance of ACI 211 is not required. Sand proportioning should be examined for possible improvement before the addition of more sand.

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Coarse Aggregates

The varying sand requirements of crushed rock versus natural gravel are almost wholly provided for in ACI 211 mix proportioning by the differences in dry rodded void content of the materials. Given good sand, crushed rock can generally be pumped well. Presence of high contents of slivered long particles or exceptionally sharp, angular rocks can cause problems. Gap grading is quite likely to cause problems.

It is well to first assure that pea gravel or rock sizes, #4 to 2 in., are present in balance.

Reference 11 in very careful testing establishes that as a function of aggregate size alone, the best strengths are attained in structural concretes with 3/8 in. to not over 3/4 in. maximum aggregate sizes.

There is considerable merit in using a liberal quantity of large rock, near the upper limit of a "balanced" gradation as determined in the graphical methods described below. This is quite in line with the "least voids, least area" method of Reference 3 and bears up well under logical analysis, for the reduced surface area of large size rock mixes greatly increases the actual effectiveness of the available paste which is the key to workability. On one tunnel project, sand was cut to 55 percent of original specification, the major replacement being a fraction of large crushed gravel up to the maximum that a smooth combined gradation curve would allow - with these results: slump for comparable workability was reduced 1½ in. strengths rose consistently and pump pressures were slightly reduced. In order to use large rock to the fullest advantage, good control of all the aggregates through all steps is desirable. The B/B₀ table 5.2.6 of ACI 211 discloses that as maximum rock size is increased, the optimum quantity of coarse aggregate increases markedly which favors the minimum voids - minimum area theory and increases the effectiveness of the available cement paste. With good sand the use of a balanced largest rock fraction of a size not to exceed 40 percent of the line ID is practical and the benefits can be of consequence.

Proper gradation as suggested for pumping usually also improves strength, economy, finish, appearance, density, weather resistance and impermeability. One manufacturer of high quality precast architectural products reconstitutes his mixtures from bins containing 17 separate size fractions, with excellent results.

Three considerations dominate the recommendations for good practice in producing pumpable concrete (1) gradation of the fine fines, (2) gradation of the sand, and (3) gradation of the coarse aggregates.

proportioning concrete mixes

Water (and Slump)

Quality of the water has no effect on pumpability and the quantity of water has less effect than is inadvertently presumed in the universal urge to wet up the mix to "make it go." Excessive slump, usually 6 in. or over tends towards segregation in the line, particularly during delays, virtually assuring a blockage. Optimum slump for pumping is generally in the 3 to 5 in. range. In old fashioned large lines over long distances where the concrete spent up to 20 minutes in transit, initial set and temperature changes could materially affect slump before and after transit but these now are very nominal influences in the usual modern small line, short run, setups. Slumps down to $3\frac{1}{4}$ in. have been pumped for slope paving and other requirements but there is a tendency for power requirements to rise precipitously as slump tightens up. Proper gradation particularly in the sand can aid considerably in moving mixes in the 2 in. or lower slump ranges. As cited elsewhere improvements in gradation and reductions of the total surface area in the mix can provide equivalent workabilities with less water and with lower slumps. The most serious problem in slump occurs in porous aggregate mixes where water under the force of the pump pressure migrates into the rock and back out. Water forced from the paste into the pores of the aggregate alters and usually improves the w/c ratio of the mix and later provides an internal wet cure. Both of these phenomena contribute to the explanation of why pumping tends to increase break strengths. Pumping is aptly described in Reference 6 as continuous round troweling. When the "trowel cream" on which the mix slides or trowels through the line is destroyed by migration of an excessive portion of the mix water into the aggregate, pumping halts abruptly. If gradation is good and mix proportions are reasonable and uniform, slumps in the usual 3 to 5 in. ranges of good practice pump well. If the basic requirements are deficient altering slump has light if any real potential for rendering a mix pumpable.

Lightweight Aggregate--The water migration problem cited above frequently is troublesome in lightweight large pore aggregates particularly in the coarse sizes. One lightweight coarse aggregate when completely "saturated" in the ordinary meaning takes up $2\frac{1}{4}$ percent of its weight in water. However when originally "supersaturated" by any of several processes the same aggregate will take up $\frac{1}{2}$ percent of its weight in water. The extra water represents enough water in a typical mix of that aggregate to account for a theoretical variation of 17 in. of slump. While this is an obvious absurdity it emphasizes that the particular aggregate when saturated by usual methods still has a latent capacity to absorb further water under pressure from the mix sufficient to eliminate any remainder of "trowel cream" on which to move the mix along the pipe walls. The supersaturated aggregate mix with no changes in the mix proportioning (the $\frac{1}{2}$ percent water occupies no extra volume, requires no more cement for same w/c) moves with ease, like hard rock concrete with no change in slump during or after transit. Furthermore and not

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quite incidental the supersaturated mix reaches the same ultimate unit weight and equilibrium moisture content as the ordinary saturated mix but attains substantially higher strength due in part to the lower slump at which it can be handled and particularly due to the optimum internal wet cure provided by the extra forced absorbed water.

Lightweight aggregates tend to be distinctively different from each source, particularly manufactured products. Claims of ceramic seal coating fail in practice and also in theory when tests repeatedly show the degradation in sizes due to grinding and crushing actions in handling mixing and pumping. Reference 9 via wet sieving of hard rock concrete shows 5 percent more sand after pumping, with further attrition in handling and mixing. Attempts to control the erratic thirsts of porous aggregates can be difficult and may take the work beyond reasonable control to excessive slumps, unless some pretreatment close to supersaturation is applied.

Usually the aggregate supplier can indicate what expedients if any can render porous lightweight aggregate mixes pumpable such as:

- Use natural sand.
- Reduce the coarse lightweight aggregate.
- After all "saturation" efforts in storage etc., batch the lightweight and water for 20 to 40 revolutions of the mixer.
- Reduce wetting agent type additives.
- Use air entraining agent or air entraining foam.
- Add finer sand, pozzolans, fly ash, diatomaceous earth.
- Blend the sand to the center of C33 limits.
- Use pumping aid type additives.

Approximately 70 percent of the lightweight is pumped where saturation processed aggregate is available and produces a product in place, at same unit weight, of greater strength and better cost.

Additives

The role of inert fine additives to improve workability has been discussed under aggregate gradations 3,6,10,12 (and ASTM C33). Where grading deficiencies cannot be directly improved by blending etc., the addition of finely divided particles can do much, particular with a favorable shape such as the hard surfaced spherical shape of electrostatical precipitated fly ash. Reference 10 rates fly ash roughly twice as effective as cement in enhancing workability hence pumpability. Reference 12 details the use of fly ash in concrete mixes both as a fine aggregate, and as a cement substitute. The suppliers of commercial fine fine additives can cite considerable testing to aid proper usage.

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Pumping aid type additives are being introduced and at least one supplier is conducting exhaustive tests on "thickening" type additives. Reference 3 also has a suggestion that where nominal porosity or bleeding or excessive voids may impair pumpability the use of wetting agent effect additives may be detrimental.

Water reducing admixtures generally aid pumping. Where reasonable good sand and overall good gradation are present the mix will move on reduced water mixes at least as well as the same mix before the admixture. Since the specific benefits are not consistent in different mixtures, results are not wholly predictable but generally good.

Air as an additive loses much of its effectiveness when compressed during pump transit so its value in masking over gradation deficiencies is much less for pumpability than it is for subsequent finishing. Air content generally recovers nearly or fully to original values after pump transit. Air contents up to the usual 6 or 7 percent in structural work pump well. Above 8 percent the old short stroke pumps on big diameter lines had trouble as "bounce" or resilience in the line resulted in no net delivery.

Attention is being devoted to treated fiber glass and small size steel fiber reinforcement for concrete mixes. A few of these mixes have been pump-handled and other trials have not been successful. The construction of the pump will be a factor with no particular troubles once the mix is moving in the line. The material kneading action of the massage tube type pump would be stoutly resisted by the crossed fibers. Rigs with large reduction such as 8 in. piston to 4 in. line, and with sinuous passages and right angle turns in the internal flow pattern might encounter severe resistance from the action of the fibers. In all concretes single valve design, direct short passages, nominal reductions, elimination of the siamese, are features of pump construction that should contribute to the pumpability of harsh, low slump mixes and to maintained high volume.

In summary, certain additives generally aid pumping and the experienced assistance of the additive field men is usually very valuable. Even where uniformly good gradations are available and maintained, judicious use of additives usually enhances pumping, economy and quality of the concrete in place.

GENERAL COMMENTS ON PUMP MIXES

Mixes oversanded with excessive fine sand or excessive fine fines have a "salvy" surface creating severe friction and demanding very high pump pressures if not actually blocking. A good mix is plastic but not slick under the trowel.

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Lightweight aggregate mix proportions require special considerations in Reference 13 and the suppliers recommendations. Batching by volume is recommended with close limits on F.M. variations and corrections for the size fraction variations in specific gravity.

Good planning and management of the whole concrete process from pit to finisher can improve pumping performance. Well organized men can attain good operation with mediocre equipment, but the best of plant tends to run poorly unless provided an alert organization of men.

One pump manufacturer has published a "Pump Performance Calculator" graph from which slump, line distance and put through volume can be predicted. Output is reduced by extra bends, extra height, use of hose versus steel pipe, smaller line sizes and lower slump. Testing is underway to develop true formulas for the performance of concrete in conduits, fluid formulas being not applicable. Concrete is not a fluid and the differences are significant. Concrete develops a static load of 1 psi for every foot of height, and actual line pressures in the field up to 850 psi in extreme cases have been observed. Concrete tends to move as a slug in the conduit with no velocity gradient over the cross section except in the trowel cream at the contact surfaces. Through velocities of $6\frac{1}{2}$ ft per second have been reported (a claim of 120 yd per hour rate in a $\frac{1}{4}$ in. boom pipe!) velocities under $\frac{1}{4}$ ft per second (50 yd per hour in $\frac{1}{4}$ in., 100 in 5 in.) are recommended. Note that moving up from a $\frac{1}{4}$ in. line to 5 in. increases put-through volume over 50 percent but the friction surface only 20 percent which together with the better tolerance for large rock and for inadvertent foreign material, provides improvements in reliability quite beyond first expectations.

There is no "twilight" area of any consequence between "Go" and "No-Go" mixes. The fringe, if any, is far narrower than ordinary variations in aggregate preparation and batching. Since the pump cannot handle a single shovelful of out of line mix, the margins necessarily provided to assure continued smooth pumping are "one way" and only as close as aggregate and mix quality control will allow.

When tandem pumping to go far or high, the second pump can handle a longer haul with feed conditioned by the first pump.

Judicious use of pumping particularly bottom - up or injection pumping even above water by any of several methods to keep the discharge below the surface of the concrete in the forms, can bring quality improvements not otherwise available. Because air entrapped by dropping is substantially eliminated, bug holes are infrequent and the result is a troweled effect with a uniform surface equal in quality to the form surface, free of honeycomb and free of lift planes.

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RECORD PUMP PERFORMANCES

Record pump performances claimed include: 584 ft up 47 stories in 5 in. line, 2200 ft out a breakwater in 8 in. line, 1200 ft out in 4 in. line, 95 yd per hour in an 8 in. double Pumperete, 165 yd per hour in a modern mobile pump (7 in. pistons 5 in. line 200 HP), 1300 ft down into a mine, bottom up in a steel column 190 ft high, 10,000 psi 28 day cylinder breaks on a pumped high rise, $\frac{1}{2}$ in. slump for slope paving under a highway bridge, 40 yd per hour shot-creted on a ditch lining, 200 ft deep wet pile filling, an uninterrupted placement of 80 yd of 15 minute setting expansive concrete on a rocket tracking foundation. Other noteworthy accomplishments include advancing a horizontal tunnel lining slip form by pump pressure, ballasting ships with heavy aggregate concrete weighing 11,000 lb per yd, 5800 yd in 17½ hour pumped into a reactor body, (using 80 trucks, 3 plants and 12 pumps), 6135 yd with 5 pumps in 20 hour averaging 61 yd per hour per pump, maintaining uninterrupted progress of a slip form for 500 hour. The limits are merely the ingenuity of the users, and indications are this may prove to be scant limit.

A GRAPHICAL APPROACH TO OPTIMUM GRADATION

A graphical method for determining the optimum proportions for combining given materials to obtain the most workable concrete and for analyzing related adjustments is presented.

It has been shown that gradation in all its many details is the key to workability and hence the key to pumpability, finishing properties; and to a considerable degree strength, shrinkage and economy.

The mix designer and concrete producer have a substantial interest in how to work with and best use the materials actually in their bins, a further interest in the possible influence of alternate materials that could be obtained at practical costs, and perhaps a theoretical interest in "ideal" gradations.

Fig. 1 and 2 illustrate forms and an example of a method to develop a trial blend that is the most workable combination of given aggregates, which combination may in fact still be harsh or even unworkable. Further steps in the graphical method provide convenient ways to find the deficiencies if any in the aggregates, to indicate corrections that may be desirable, and to predict the influence of possible revisions.

The nature of sources and influences of blend materials, changes in aggregate such as crushing and grading, additives, alternate sands and most of the other expedients available to alter gradation have been covered in the earlier part of this report. The graphical methods using Fig. 1 and 2 provide a convenient way to plan gradation improvements.

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In Fig. 1 the aggregates are graphed individually as screen testing indicates, in the usual fashion. It is fundamental that no analysis can be better than the input information so considerable care is desirable in examining the reliability and true sample aspects of the basic data. In a surprisingly high number of cases, the graphical approach early leads to uncovering better ways of testing and reporting actual aggregate gradations. It is often desirable to enter onto the graph with band type data, giving the routine range of gradations actually encountered rather than an average which could be misleading and somewhat arbitrary, particularly where the actual ranges are wide, erratic, or both. If the plant uses different materials at various times, particularly sand, separate studies are indicated unless the gradations are very closely alike. An example that can distort the work is the ordinary practice of classifying all portions of the small stone passing #4 as merely under #4. If the quantity is substantial, say 15 percent of the stone, it is likely that detail sand size analysis of this "undersize" would be required for useful results for the undersize may well be a blend sand of desirable characteristics. In general, attention to the input data pays off in better understanding and control.

With the individual aggregates gradations entered on Fig. 1 in the familiar and usual method a series of construction lines are drawn as follows:

A. Through each individual gradation line or gradation band, draw a straight line in a median position that is close to the center with areas on either side about equal. The straight lines (A1A1 A2A2, etc.) shall intersect the top and bottom of the graph form which intersections are useful later. (Aggregate Lines)

B. Draw a straight line from the 100 sieve line at the top (100 percent passing) of the graph straight down to the intersection at the bottom (zero percent passing) line of the maximum aggregate size line. (1-1½ in. in the example). This should be the actual maximum size offered in the aggregates, not the top screen with a percent retained. This is an arbitrary procedure, a construction line hereinafter referred to as the Blend line. (BB)

C. Draw construction lines hereinafter referred to as cross lines (C1C1-C2C2, etc.) from the top (100 percent line) intersection of the sand median line of step A to the bottom (zero percent line) intersection of the small stone median line; then from the top of the small stone median to the bottom of the intermediate stone median and proceed until there are such cross lines in number one less than the total of aggregate size ranges graphed.

D. Working from the top down the intersections of the blend line step B with the cross lines of step C will give the optimum percentages of each ingredient for the blend most likely to be the most workable combination of the materials graphed. Record the blend percentages as the vertical percent increments, from the top down, of each intersection.

proportioning concrete mixes

The 4 steps outlined should indicate the best combination of the particular materials for workability, hence for pumpability. The blend thus determined tends to come within the ranges of usual mix proportioning methods. One form of worksheet for use with the graphs is shown in Fig. 3.

To continue the graphical analysis the blend developed in steps ABCD should be graphed as a combined mix on Fig. 2. The zone lines on Fig. 2 are empirical gradation zones reflecting considerable actual full scale pumping experience and study from many sources covering a wide range of aggregates, pumps, and reporting methods. After much study the author has declined to abandon any attempt to substantiate, explain, or apply formulas to the guide lines of Fig. 2 and to represent them for what they presently are: merely an arbitrary summary of reported empirical findings of the usual gradations of pump mixes 1, 3, 13, 16, 17, 22, 23, 24. The user early will develop from his own experience on his own materials a set of limits to replace the arbitrary zones of Fig. 2 and pertain to local experience. The work form Fig. 2 will be available on transparent paper so that blends and their performance can be compared easily. Hopefully with uniform procedures, considerable data can be centrally assembled and compared for the benefit of all, with particular emphasis on adjustments and economies.

If the combined blend from steps ABCD displays a smooth curve in the middle of the "pumpable" zones of Fig. 2, nice workability and good pumping is to be expected. It is the deviations from a smooth, middle area curve that require attention. Horizontal parts of the curve denote deficiencies (gap grading) and vertical portions indicate excesses, both of which can often be tolerated. A combined line that wavers back and forth across the zone or has peaks and sharp changes indicates potential trouble.

It is well to bear in mind that a pump requires each shovelful to be pumpable. The pump cannot "average" out of grade portions but requires all to be within limits. Accordingly the actual gradation range of the mix as it enters the pump has to be borne in mind, much as it was suggested above that the sand and rock sieve reports be shown as a zone or band of a width indicating routine actual ranges. Using this approach it will be recognized that the combined mix gradation can be close to the outer limits of pumpability depending quite directly upon the control over material preparation, batching and all other influences on the uniformity of the concrete production and control. Stated another way, to maintain practical pump performance with a mix that graphs out near the outer limits of desirable gradation requires more uniform concrete. The closer to the limits the greater the need for consistent quality control. It is sometimes quite desirable to use mixes near the "fringe" for compelling reasons including cement economy. Consistent uniformity is the life blood of practical pumping anyway and probably the most desirable single requirement.

placing and pumping concrete

MIX ADJUSTMENT USING GRAPHS

Having gone through steps ABCD and graphed the resultant combined blend to compare with pumpability limits, it is time to consider possible improvements. If the mix is clearly smooth down center pumpable, economy may be the only place for improvement. If the mix appears deficient in gradation or doubtful, then considerations of changes to improve grading are also in order with cost an ever present limitation. The earlier parts of this report outline many of the adjustments and influences to investigate.

On one hydro tunnel where these methods were used, sand was in very short supply. The concept of minimum area, minimum voids mix proportioning tends to suggest that the use of a maximum portion of large rock in a balanced mix would favorably reduce area. Using Fig. 2 in reverse was tried. A combined gradation line was drawn quite close to the lower limits of pumpability with a very steep but smooth final rise incorporating a maximum of 1-1/2 in. rock, one size larger than previously used. The actual batch weights were worked out by taking percentages off of the curve and working backwards on Fig. 3 the worksheet form, making a few minor adjustments. In this extreme case the sand was cut to 55 percent of its former volume, the mix pumped nicely and flowed well in the tunnel arch after the slump was reduced 1-1/2 in. The sand saving was a great economy for the builder, the strengths rose, the finish improved. After the initial success a partial compromise was dictated by the realities in aggregate preparation control which was difficult on this work, and the sand was increased to 65 percent of original.

The adjustments that can be worked out or suggested by the graphical approach and an investigation of options locally available are limited only by the imagination of the mix designer. Using graphical methods concrete for reliable maintained pumping can be predictably produced from a variety of combinations of materials as available.

One more procedure is desirable in order to present an effective comparison of various mixes that have pumped well (or not so well). It is useful to consider all of the solid materials as aggregate by including the cement and other fine fines. In order to maintain the advantages of the familiar usual sieve graph areas, it is suggested the cement and other fine fines be recorded in an appended box below the zero percent line in the under 100-200 sieve areas as shown on Fig. 2. The fine fines are simply entered in pounds with the cement, fine sand and additives weights shown separately, an adequate basis for comparison.

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REFERENCES

1. Gray, J. E. "Laboratory Procedure for Comparing Pumpability of Concrete Mixtures," Proceedings, ASTM, V. 62, 1962, pp. 964-971.
2. Gray, J. E., and Bell, J. E., "Stone Sand," Engineering Bulletin No. 13, National Crushed Stone Association, Washington, D. C., 1964, 70 pp.
3. Kempster, E., "Pumpable Concrete," Current Paper No. 29/69, Building Research Station, Garston, Watford, Aug. 1969, 14 pp.
4. ACI Committee 211, "Recommended Practice for Selecting Proportions for Normal Weight Concrete (ACI 211.1-70)," American Concrete Institute, Detroit, 1970, 16 pp.
5. ACI Committee 211, "Recommended Practice for Selecting Proportions for Structural Lightweight Concrete (ACI 211.2-69)," American Concrete Institute, Detroit, 1969, 18 pp.
6. Tuthill, Lewis H., "Tunnel Lining with Pumped Concrete," ACI JOURNAL Proceedings V. 68, No. 4, Apr. 1971, pp. 252-262.
7. Murdock, L. J., "The Workability of Concrete," Magazine of Concrete Research (London), V. 12, No. 36, Nov. 1960, pp. 135-144.
8. Fowler, E. L., and Holmgren, E. F., "Expansion of Concrete Pumped Through Aluminum Line," ACI JOURNAL, Proceedings V. 68, No. 12, Dec. 1971, pp. 950-953.
9. Stodola Paul, "Results of Wet Sieving Analysis of Pumped Concrete," Laboratory Memo, California Department of Water Resources, Western Pacific R. R. Relocation, Oroville, Oct. 10, 1962.
10. Meissner, H. S., "Effect of Inert Mineral Additives on Workability," Significance of Tests and Properties of Concrete and Concrete Making Materials, STP-169A, American Society for Testing and Materials, Philadelphia, 1966, pp. 404-414.
11. Bloem, Delmar L., "The Influence on Concrete Strength of Maximum Aggregate Size," A Series of Three Bulletins and Discussions from the Field, National Ready Mixed Concrete Association, Silver Spring, Maryland, 1966.

placing and pumping concrete

12. Lovewell, C. E., and Washa, George W., "Proportioning Concrete Mixtures Using Fly Ash," ACI JOURNAL, Proceedings V. 54, No. 12, June 1958, pp. 1093-1102.
13. ACI Committee 304, "Placing Concrete by Pumping Methods," ACI JOURNAL, Proceedings V. 68, No. 5, May 1971, pp. 327-344.
14. Rex, Harry M., and Peck, Robert A., "A Laboratory Test to Evaluate the Shape and Surface Texture of Fine Aggregate Particles," Public Roads, V. 29, No. 5, 1956, pp. 118-120.
15. Glanville, W. H.; Collins, A. R.; and Mathews, D. D., "The Grading of Aggregates and Workability of Concrete," Road Research Technical Paper No. 5, Road Research Laboratory, Crowthorne, Berkshire, 1947.
16. Rueppel, A., "Graph of Pumpable Mix Gradation Limits," A.G. Bernold, Walenstadt, Switzerland.
17. Walz, R., "Prüfrichtlinien Für Beton Zusatzmittel," Bundesbankblatt, No. 4, Apr. 15, 1958, pp. 190-196.
18. Wills, Milton H. Jr., "How Aggregate Particle Shape Influences Concrete Mixing Water Requirement and Strength," Journal of Materials, V. 2, No. 4, Dec. 1967, pp. 843-865.
19. "Concrete Pump Performance Prognosticator," Challenge Cook Brothers, Inc., Industry, California.
20. Hughes, Barry P., "Particle Interference and the Workability of Concrete," ACI JOURNAL, Proceedings V. 63, No. 3, Mar. 1966, pp. 369-372.
21. "Baustoff Beton," EMPA (Swiss Concrete Association), Textbook on Concrete Mix Proportioning.
22. Tobin, Robert E., Graph, "Fine Aggregate Gradation for Pumping," Los Angeles, 1970.
23. Schwing, F. W., Handbook for Concrete Pump Operators, Wanne Eickel, Germany, 1968.
24. "Sieve Lines for Pumpable Concrete," DIN 1045, German Standards Association, Berlin. (An excellent graph derived from DIN 1045 with related field experience is available from TORKRET GmbH, a German pump builder.)

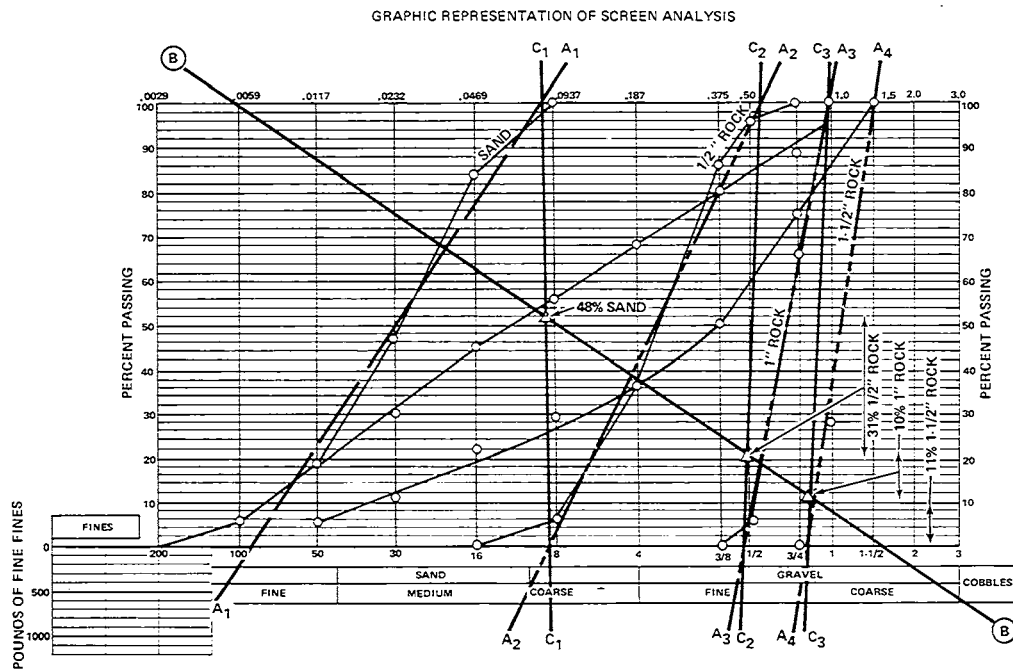


Fig. 1--Graphical method of determining optimum proportions of available materials for workability/pumpability

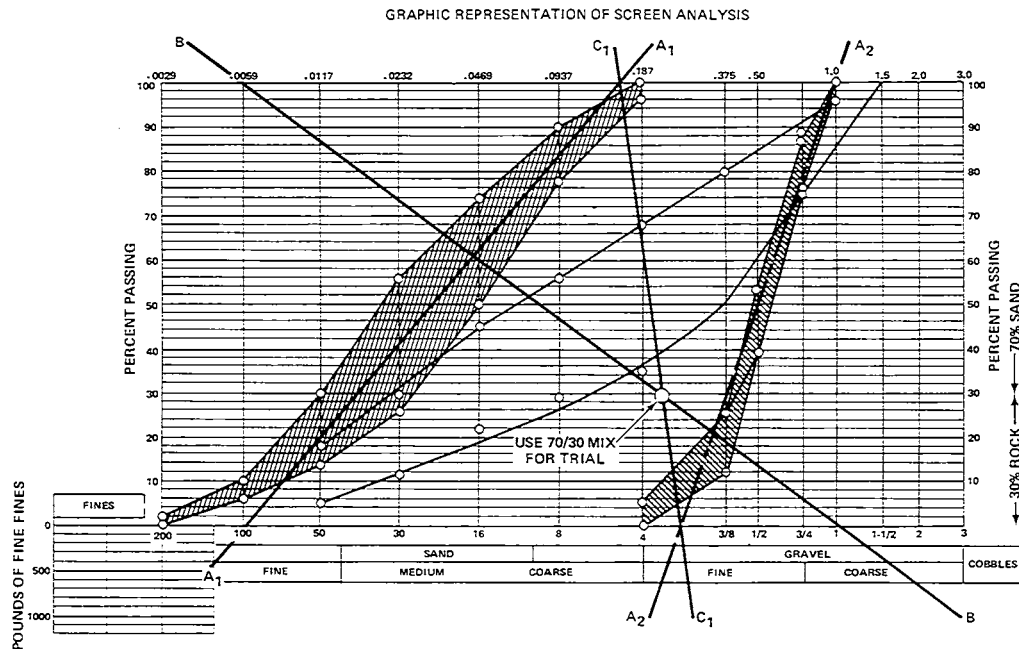


Fig. 1a--Example using daily highs and lows to graph a truer range of gradation

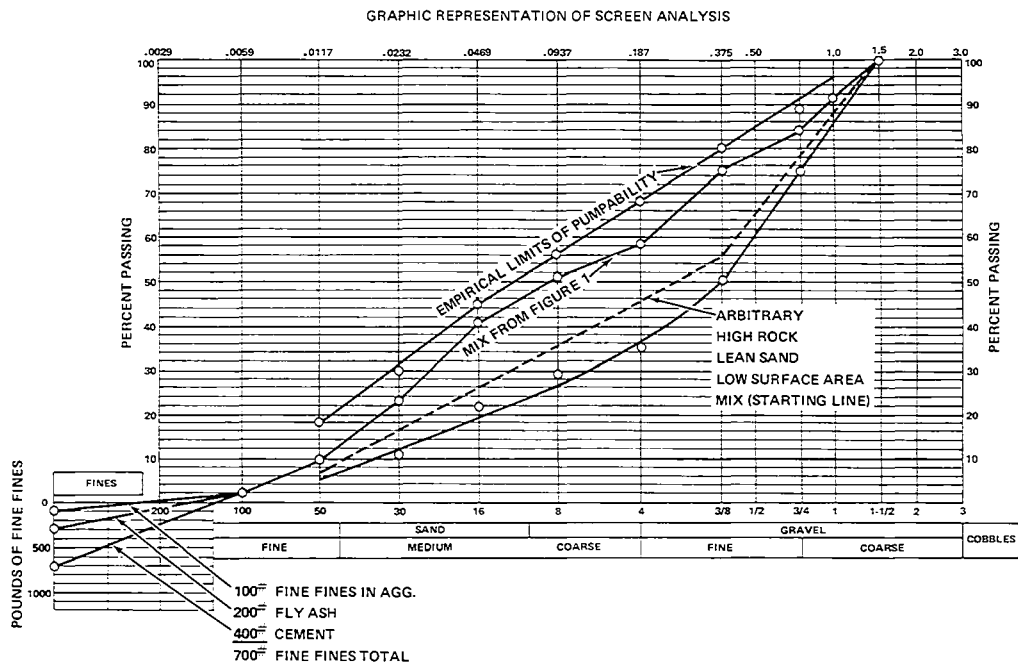


Fig. 2--Combined gradation

SCREEN SIZE	FINE FINE UNDER 100		SAND 100 TO 4		1/2" COARSE AGGREGATE		1" COARSE AGGREGATE		1-1/2" COARSE AGGREGATE		COMBINED AGGREGATE			
	INDIVIDUAL PORTIONS RETAINED													
	%	WT.	%	WT.	%	WT.	%	WT.	%	WT.	%	WT.		
TOTAL	WT.			925		500		203		222		1850		
	%		50		27		11		12		100			
1-1/2"														
1"							0		72	158	9	158		
3/4"					0		34	69	28	64	7	133		
1/2"					4	20	60	122			8	142		
3/8"					10	50	6	12			3	62		
# 4					52	260					14	260		
# 8			0	4	28	140					8	140		
# 16			16	148	6	30					10	178		
# 30			37	340							18	340		
# 50			28	260							14	260		
100			14	130							7	130		
200			5	47							3	47		

TUNNEL CROWN MIX

= 101%

Fig. 3--Worksheet for graphical gradation analysis of solid volumes in concrete

SP 46-4

PROPORTIONING CONCRETE FOR A SPECIFIED CEMENT CONTENT AND/OR A SPECIFIED UNIT WEIGHT

By
Sandor Popovics

Synopsis: A series of formulas are presented for proportioning concrete for a specified unit weight without trial mixes. These formulas cover both the case when the amount of mixing water is specified along with the required cement content, and the case when an adequate workability is required without any specific water content.

In each case the most sophisticated formulas are presented first. From these, additional formulas are derived through gradual simplifications. The more complex the form of any of these formulas, the better the accuracy and the wider the limits of validity. It is shown, however, that even the simplest formulas of those proposed, that is, Eqs. 2), 6), and 15) through 18) provide fair estimates for the aggregate-cement ratio, as well as for the unit weight of the concrete. The limits of validity of the formulas are also given.

The presented formulas can be combined with strength and durability requirements. The formulas are also applicable when the mineral aggregate is a blend of different aggregates, such as conventional sand and lightweight coarse aggregate. An additional advantage of the presented method is that it covers the whole range of structural concretes, that is, lightweight, normalweight and heavyweight concretes as well.

Numerical examples illustrate the use of the formulas. The metric equivalents of the formulas presented in the main part of the manuscript are shown in the Appendix.

Keywords: aggregates; air entrainment; cement content; coarse aggregate; concretes; density (mass/volume); fresh concretes; hardened concretes; heavyweight aggregates; lightweight aggregates; mix proportioning; slump tests; water-cement ratio.

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A contractor may frequently face the task of having to produce a concrete of a specified cement content, or that of a specified unit weight without any direct requirement concerning strength. The first case is the practice of many Highway Departments, the second case is typical of certain application of heavyweight concretes.

Since in these cases the concrete strength is not involved directly in the proportioning process, methods simpler and faster than those employed in the ACI Standards can be used by eliminating the need for trial mixes. The intention of this paper is to describe such proportioning methods for the practicing engineer. It will also be shown that some of the presented formulas can be combined easily with strength or durability requirements to form a complete method of proportioning ranging from structural lightweight concretes to heavyweight concretes. The methods presented are also applicable when the mineral aggregate used is a blend of different aggregates.

In these simplified methods there is no need for the estimation of the amount of mixing water either (a) because it is specified along with the required cement content; or (b) because the amount of mixing water does not matter as long as the fresh concrete has an adequate workability. Both cases will be covered in this paper.

The formulas presented on cement content and unit weight, respectively, are the continuation of the previously published studies by the writer (1)-(5) in the direction of simplification and practical aspects.

The science, or art, of proportioning concrete is as old as the concrete itself. Lea, for instance, quotes Roman authorities of 2000 years ago recommending that "cisterns should be made of five parts of pure gravelly sand, two of the very strongest quick lime, and fragments of hardened lava, not exceeding a pound of each in weight (6)". New methods of proportioning can hardly compete in simplicity with recommendation of the old masters; it is hoped, however, that the approach presented in this paper more than compensates this by improved accuracy and wider limits of applicability.

Mix Proportioning for a Specified Cement Content

Formulas are presented here for the estimation of the mix proportion that is needed to provide a concrete of specified cement content.

When the amount of mixing water, or the water-cement ratio, is specified along with the required cement content, the needed mix proportion can be calculated as follows:

$$n = G[16.85(100 - v)/c - w/c - 0.32] * \quad 1)$$

Eq. 1) can be simplified so that it is still suitable for the majority of concretes for structural purposes, as follows:

$$n = G[1650/c - w/c - 0.32] \quad 2)$$

When the concrete consistency or slump, rather than the water content or the water-cement ratio is specified, different kinds of formulas, semi-empirical in nature, can be obtained. The most accurate such formula to calculate the mix proportion that is needed to provide a specified cement content of a fresh concrete of about 4 inch (10 cm.) slump with a given aggregate, would be the following (1):

$$n = G \left[\frac{17(100 - v) - 30(m - 6)^2 - 235}{c} - 0.5 \right] \quad 3)$$

A similar formula for concretes of about 1 inch (2.5 cm) slump would be as follows:

$$n = G \left[\frac{17(100 - v) - 25(m - 6)^2 - 190}{c} - 0.5 \right] \quad 4)$$

Eq. 3), for $G = 2.65$, $v = 1\%$, and $m = 5$, along with experimental results, is illustrated in Figure 1.

It can be seen that a change in the grading and in the consistency have little effect on the value of n provided that the aggregate is graded within the limits of generally accepted specifications. Therefore Eq. 3) and 4) may be further reduced to the following formula (5):

$$n = G[(17(100 - v) - 225)/c - 0.5] \quad (5)$$

Or, after further simplification which is still suitable for the majority of structural concretes:

$$n = G(1425/c - 0.5) \quad 6)$$

Several values of G are shown in Figure 2. The support of this formula by experimental data is illustrated in Figure 3.

* The metric equivalents of this as well as the other formulas are presented in the Appendix. The List of Symbols is also at the end of the paper.

Proportioning for a Specified Unit Weight

Formulas relating the unit weight of fresh concrete to its composition are obtained in ways similar to those that were mentioned in connection with Eqs. 1) through 6).

When the amount of mixing water, or the water-cement ratio, is specified, the unit weight of fresh concrete can be calculated theoretically from the following formulas:

$$U = 0.037c[1 + G(16.85(100 - v)/c - w/c - 0.32) + w/c] = \quad 7)$$

$$= (c + w)/27 + G[62.4 - 0.6v - (w + 0.32c)/27] \quad 8)$$

Simplified forms of Eg. 7) & 8) that will be suitable for the majority of concrete for structural purposes are:

$$U = 0.037c[1 + G(1675/c - w/c - 0.32) + w/c] = \quad 9)$$

$$= (c + w)/27 + G[62 - (w + 0.32c)/27] \quad 10)$$

When the concrete consistency rather than the water content, or water-cement ratio, is specified, the unit weight of fresh concrete of about 4 in. (10 cm) slump and with a given aggregate, can be estimated by the following formulas (2):

$$U = 0.043c + 10 + G[54 - 0.8(m - 6)^2 - 0.015c - 0.6v] = \quad 11)$$

$$= G \frac{n + 1.2}{n + 0.5G} [54 - 0.8(m - 6)^2 - 0.6v] + 10 \quad 12)$$

Similar formulas for concrete of about 1 in. (2.5 cm) slump are as follows:

$$U = 0.043c + 8 + G[55.6 - 0.8(m - 6)^2 - 0.015c - 0.6v] = \quad 13)$$

$$= G \frac{n + 1.2}{n + 0.5G} [55.6 - 0.8(m - 6)^2 - 0.6v] + 8 \quad 14)$$

Since the effects of the cement content, consistency, and aggregate grading on the unit weight of concrete of a given consistency are minor within practical limits, Eqs. 11) through 14) can be simplified. Therefore, the unit weight of fresh concrete can be estimated by the following formula (5):

$$U = G(45 - 0.6v) + 33 \quad 15)$$

Or, further simplifying

$$U = 43.6G + 33 \quad 16)$$

These unit weight formulas are well documented by experimental results (2) (5). This is also illustrated in Figure 4 for Eq. 16).

The unit weight of concrete may change with the age and ambient conditions but, as a rule, these changes are significant only under special conditions. Such may be the case of concretes for nuclear reactors that are submitted to low relative humidity and high temperature. Under such extreme conditions the hardened concrete can lose all of its free water, thus reach the lower limit of its unit weight, called the "final" unit weight. This final unit weight can be estimated by more or less simple formulas. (2) For instance, for concrete of about 4 in (10 cm) slump:

$$U_f = U - 10 \quad 17)$$

For concretes of about 1 1/2 in. (3.8cm) slump:

$$U_f = U - 8 \quad 18)$$

Eq. 18) is illustrated in Figure 5.

It seems reasonable to suggest that the design of lightweight concrete structures be based on the unit weight of the fresh concrete, while the design of heavyweight concrete structures on the final unit weight.

Combinations of Requirements

The formulas presented above can be generalized for cases when more than one requirement is specified. For instance, when both the unit weight and the cement content of the concrete are specified along with the water content, or water-cement ratio, the needed mix proportion is:

$$n = (27U - w)/c - 1 = \quad 19)$$

$$= 27U/c - (1 + w/c) \quad 20)$$

When the strength and/or the durability is specified along with either the cement content or the unit weight of a concrete, the appropriate minimum water-cement ratios and entrained air contents can be established from values recommended by the ACI. (9) Then any of the presented formulas containing the water-cement ratio, and air content if necessary, can be used for further calculations of proportioning. In the case of lightweight concrete, another simple method is available; namely, a cement content corresponding to the specified strength can be established (10) and then any of the presented formulas containing the cement content can be used for further proportioning.

Application of Blended Aggregates

Eqs. 1) through 20) are also applicable when the mineral aggregate in question is blended of two or more different aggregates, such as the combination of a conventional sand and a lightweight coarse aggregate. The average specific gravity of the combined aggregate, blended of aggregates a and b, can be calculated as follows:

$$G = AG_a + (1 - A)G_b \quad 21)$$

or

$$1/G = a/G_a + (1 - a)/G_b \quad 22)$$

The bulk specific gravity of the coarse fractions of aggregates may be obtained by the procedure described in ASTM C 127. The bulk specific gravity of the fine fractions of normal and heavy weight aggregates may be obtained by the procedure described in ASTM C 128. However, for lightweight fine aggregates the "kerosene method" described by Shideler (7), or the "pycno-meter method" developed by Landgren and his co-workers (8) may be preferable due to the difficulty of determining the saturated surface-dry condition of these fines.

The Reliability of the Proposed Formulas

Eqs. 1), 7), 8), and 19) through 22) are the pertinent mathematical equivalents of the truism that a volume is the sum of the volumes of its components. Thus, they have unlimited validity and accuracy. Their usefulness for practical proportioning is limited only by the fact that almost any given water content can produce a variety of consistencies ranging from dry to fluid. Otherwise, if there is any discrepancy between values calculated by any of the equations and comparable measured values, these must come from the inaccuracies of the measurements.

This unlimited accuracy, of course, does not hold either for the simplified forms of the equations or for the presented semi-theoretical equations. The more complex the form of any of these formulas, the better the accuracy and the wider the limits of validity. However, the rate of return in accuracy resulting from the increasing complexity is diminishing.

The limits of validity of the simplified equations and those of the semi-theoretical equations are represented by the usual range of concrete mixtures for structural purposes. That is, the cement content is between about 350 and 750 lb per cu yard (200 to 450 kg/m³), the slump is between 1 1/2 in. (25 to 35mm), and the fresh unit weight of concrete is higher than 85 lb per cu ft (1350 kg/m³). The upper limit of air content for Eqs. 2), 6), 9), 10) and 16) is about five percent; the other formulas are also applicable for higher air contents.

Values calculated by the semi-theoretical and simplified equations were compared with experimental results that were obtained by various investigators. (5) Part of this comparison is shown in Figures 1, 3, 4, and 5 to demonstrate the goodness of fit.

A simple numerical analysis (11) was also applied to the pertinent experimental data. This showed for Eqs. 3) through 6) average differences of 0.15, 0.18, and 0.24, respectively, between the calculated and experimentally obtained aggregate-cement ratios. Similar comparisons for Eqs. 11) through 14), 15), and 16) showed average differences of 3.3, 3.8, and 4.4 lb per cu ft (50, 60, and 70 kg/m³), respectively, within the unit weight limits of 85 to 200 lb per cu ft (1350 to 3200 kg/m³). That is, the average differences are less than 5 percent in every case. It should be added, however, that the goodness of fit of the presented formulas is not as good for concretes of unit weights below 100 lb per cu ft (1600 kg/m³) as for heavier concretes. One reason for this is the difficulty of determining the bulk specific gravity of such lightweight aggregates, especially that of the fine fractions.

An additional advantage of the presented formulas is that they cover the whole range of structural concretes, that is, lightweight, normal-weight, and heavy-weight concretes as well.

Trial Mixes

When the described accuracy of the presented formulas is not adequate for the given case, the formulas can be used conveniently for the determination of the composition of the first trial mixture. If adjustment is needed in the applied aggregate-cement ratio, a linear interpolation in the cement content is adequate. If the needed adjustment is for the unit weight of the concrete, a modification of the mineral aggregate used is the most effective method. For instance, an increase (or decrease) of 0.1 in the specific gravity of the aggregate causes an increase (or decrease) of about 4 lb per cu ft (65 kg/m³) in the unit weight of comparable concretes.

Illustrative Examples

Example 1: What are the expected fresh and final unit weights of a structural heavyweight concrete if the slump is about 2 in. (5.0 cm), and the aggregate used is a blend of 40 percent, by weight, of magnetite ($G_m = 4.5$), and 60 percent of limonite ($G_l = 3.5$)?

From Eq. 22):

$$1/G = 0.4/4.5 + 0.6/3.5 = 0.260$$

That is, $G = 3.85$

By substituting this into Eq. 16), the calculated fresh unit weight is $U = 200$ lb per cu ft (3200 kg/m³).