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Scope of Study: The purpose of this study is to determine the effects of the different types of admixtures on concrete. The admixture field was divided into groups according to their effects on concrete. The groups include accelerators, retarders, air-entraining agents, gas-forming agents, pozzolans, alkali-aggregate expansion inhibitors, dampproofing and permeability reducing agents, workability agents, grouting agents, and miscellaneous agents.

Findings and Conclusions: Admixtures help to produce concrete properties that are specifically designed to meet the requirements of a given project. Whether or not to use an admixture in concrete depends on its effectiveness in producing the specific properties desired in concrete. Admixtures, when used properly, can improve workability, accelerate setting time, improve durability, reduce bleeding, retard setting time, impart color, control volume change, reduce segregation, and aid in curing of concrete. An admixture should be selected for a specific project based on the results obtained with the same type concrete that will be placed on the project. The amount of an admixture added to a batch of concrete must be carefully controlled because too much of the admixture may impart undesirable characteristics in the concrete. Admixtures should always be obtained from reliable producers who can provide a uniform product. Some type of admixture is added to most of the concrete placed today.

ADVISER'S APPROVAL ______________________________

CONCRETE ADMIXTURES

By

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CONCRETE ADMIXTURES

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PREFACE

Admixtures are substances used in cements, mortars, and concretes for the purpose of improving certain properties. The use of admixtures, a practice that was originally frowned upon by the cement-making and concrete-making industries, is responsible for considerable progress towards obtaining the ideal concrete. Admixtures can, under certain conditions, impart desirable characteristics which cannot be obtained as economically by other methods.

The purpose of this report is to describe the effects of the different types of admixtures on concrete.

The author wishes to thank Professor R. L. Peurifoy for his guidance and encouragement in all phases of the construction of this paper.

Gratitude is expressed to the American Concrete Institute and the American Society for Testing Materials for the literature they furnished on admixtures.

Finally, I wish to acknowledge my indebtedness to the United States Air Force and the Air Force Institute of Technology for making my advanced studies possible.

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CHAPTER I

INTRODUCTION TO ADMIXTURES

History of Admixtures

An admixture is considered to be any substance, other than cement, aggregate, and water, that is added to a batch of fresh concrete for the purpose of altering any of the properties of the concrete.

The use of admixtures in the manufacture of concrete is probably as old as concrete-making itself. It is well known that the Romans added to their pozzolans such materials as lard, blood, and milk. Hemoglobin, we know, is a powerful air-entraining agent and plasticizer. It is probable that many of the old Roman structures made with pozzolans contained blood or other agents which entrained air. Most likely, the purpose of such admixtures was to increase placeability of the concrete. The effect of air entrainment on durability certainly was not known.

In the United States, the use of admixtures in concrete was originally frowned upon by the concrete-making industries. Admixtures were not considered an important part of concrete technology until the early 1930's. Since the 1930's, however, there has been an ever-growing use of admixtures in concrete.

Today, a great percentage of all concrete placed in the United States contains an admixture which, in addition to its other functions if any, will entrain some air in the concrete.

Before the advent of air entrainment, many admixtures had been offered for use in the manufacture of concrete. But many of these admixtures were essentially the well-known accelerator, calcium chloride, usually disguised with some coloring matter or equally inert material. The use of such admixtures was limited to the promotional activities of the various manufacturers within certain geographical locations. This was the rule, although there were exceptions involving nationally promoted admixtures which had a very wide acceptance.

However, because of the early experience with many admixtures, which often affected the resulting concrete adversely, the original attitude of the construction industry in resisting admixtures is understandable. The use of admixtures was prohibited by early ASTM specifications.

In the early 1930's, extensive research programs on admixtures were begun by such organization as the ASTM, ACI, and PCA. In a few short years, there occurred a transition from the almost complete prohibition of admixtures to a reasonable and useful acceptance of them. It is now possible for the manufacturer or the sponsor of a proprietary admixture to establish the acceptability of his material simply by making the necessary evaluation tests to show compliance with the requirements of the recognized authorities. Thus, a major obstacle to the intelligent use of admixtures has been removed. As a result, the research worker and the manufacturer have a greater incentive to develop new and desirable admixtures.

General Effects of Admixtures on Concrete

Usually an admixture is used to modify the properties of the concrete in such a way as to make it more suitable for the work at hand. Under some conditions, use of an admixture may impart desirable characteristics which cannot be secured as economically by other methods.

Admixtures are used for the following purposes:

1. To improve workability of fresh concrete.
2. To accelerate setting and/or hardening and thus to produce high early strength or to prevent damage by early freezing of the fresh concrete.
3. To improve durability of the hardened concrete.
4. To promote a pozzolanic reaction with lime liberated by cement during hydration.
5. To impart water-repellant or waterproofing properties.
6. To control alkali-aggregate expansion.
7. To reduce bleeding.
8. To reduce the evolution of heat.
9. To retard setting.
10. To impart color.
11. To reduce or offset shrinkage during setting.
12. To improve penetration and pumpability for grout mixtures.
13. To reduce segregation.

14. To cause dispersion of the cement particles when mixed with water.
15. To aid in curing.
16. To increase bond to steel reinforcement.

Many admixtures can be useful and effective in accomplishing their intended purposes. However, for some admixtures there have been made extravagant claims which are not fully justified. In making a decision as to whether or not an admixture is desirable or necessary, the following factors should receive consideration: (a) the possibility of accomplishing the desired result by a small modification in the basic mix; (b) many admixtures affect more than one property of concrete, sometimes affecting desirable properties adversely; (c) the effects of some admixtures are modified by such factors as wetness and richness of mix, by aggregate grading, and by character and length of mixing; (d) the specific effects of some admixtures vary with the type and with the brand of cement used; and (e) the additional cost of using the admixture as against the additional cost of a modified basic mixture.

Classification of Admixtures

The wide scope of the admixture field precludes a detailed listing of commercial admixtures and their effects on concrete. For this report, the admixture field is divided into groups according to their effects on concrete. The groups are as follows:

1. Accelerators.
2. Retarders.
3. Air-entraining agents.
4. Gas-forming agents.
5. Pozzolans.
6. Alkali-aggregate expansion inhibitors.
7. Dampproofing and permeability reducing agents.
8. Workability agents.
9. Grouting agents.
10. Miscellaneous agents.

Some types of admixtures possess properties identifiable with more than one group. In this report, these admixtures are considered as belonging to the group that describes their most prominent or important effect on the concrete.

CHAPTER II

ACCELERATORS

General

Accelerators are added to concrete to shorten the time of set and to increase the rate of hardening. Although an accelerator is not an antifreeze agent, it may act as such by causing concrete to set before freezing occurs. The purposes for using accelerators to increase the rate of early strength development in concrete are to: (a) hasten the time that a structure can be placed in service; (b) reduce the curing period; (c) permit forms to be removed earlier; (d) offset the retarding effects of low temperatures; and (e) compensate for the retarding effects of some other admixtures. Often, the engineer must decide between using a high early strength cement or an admixture.

Agents which accelerate setting and hardening include calcium chloride, silicates, triethanolamine, fluosilicates, aluminous cements, and some soluble carbonates. Present information concerning accelerators other than calcium chloride is inadequate. Therefore, general recommendations on the use of these other accelerators cannot be given. Generally, other types should be used only on the basis of adequate preliminary tests, satisfactory experience, or competent technical advice.

Calcium Chloride

The most commonly used accelerator is calcium chloride. The effectiveness of calcium chloride in promoting early strength in concrete is dependent upon many factors, including richness of mix, temperature of concrete, curing conditions, type and brand of cement, and amount of calcium chloride used.

The rate at which concrete develops strength depends to a large extent upon the temperature at which a concrete mass is placed and cured. Calcium chloride compensates for the normally low strength development of concrete placed during cold weather by increasing the rate of early heat development and accelerating the set.

Generally, calcium chloride can be used safely in amounts up to 2 but not more than 3 percent by weight of portland cement. It can be added either dry or in solution. If added in solution, proper mixing must be insured. Calcium chloride should be added to water and not water to calcium chloride because a coating may form which is difficult to dissolve. It is not advisable to use calcium chloride in the dry form. However, if it is used care must be taken to insure that the material is not caked due to poor storage conditions.

Calcium chloride increases the early strength of all types of cement. Typical results are shown in Figure 1. These data were obtained in the laboratories of the Bureau of Reclamation (1), but numerous investigators have reported similar results. Cylinders were made from similar mixes containing each of the five types of cement, with a 0.55

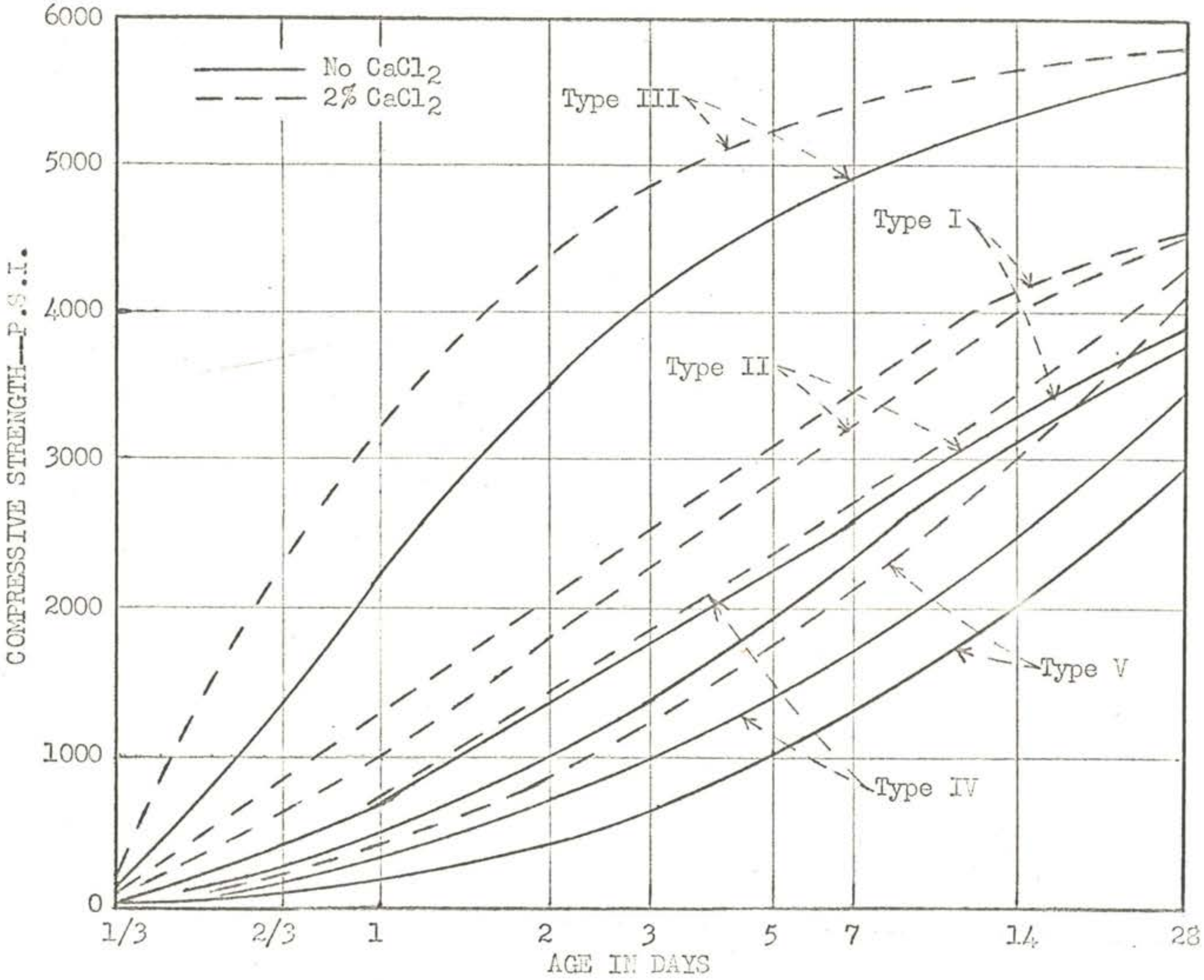

Figure 1. $CaCl_2$ increases the compressive strength of concretes made with all types of cement.

water-cement ratio, a cement content of 5.8 sacks of cement per cubic yard, either with or without an addition of 2 percent calcium chloride. Each of the cylinders was cast at 70 degrees Fahrenheit, and cured at 100 percent relative humidity and 70 degrees Fahrenheit. The results show that the addition of calcium chloride considerably improved the early strength development of each of the concretes. The calcium chloride developed strengths in each of these concretes in less than 1½ days equal to the 3-day strength of concrete without calcium chloride. Tests made at 40 degrees Fahrenheit indicate that, although the early strengths developed are lower, the increase in strengths obtained with 2 percent calcium chloride are of the same order as those obtained at 70 degrees Fahrenheit.

The use of calcium chloride will result in other effects which include a small increase in workability of the fresh concrete, a reduction in bleeding, and a slightly lower freezing point of the concrete. It also increases the rate of heat evolution at early ages and increases the expansion caused by any alkali-aggregate reaction. Where temperature differentials within the concrete are important factors, the effect of early heat development of accelerators should be taken into consideration before they are used. Calcium chloride increases expansion under moist curing; it increases shrinkage but decreases moisture loss under drying conditions. Freezing and thawing durability is increased at early ages by calcium chloride, but is reduced at later ages. It increases the resistance of concrete to erosive and abrasive action. It is not detrimental to embedded steel.

Use of Accelerators in Concrete Products

Materials which accelerate the hardening and promote early strength development of concrete prove advantageous in the manufacture of a variety of concrete products. For example, the early attainment of strength in a building block reduces the curing period, compensates in part for slow hardening during cold weather, and decreases the time required to produce a fully mature block. Similar advantages may be obtained in the manufacture of other concrete products. The use of accelerators in concrete made during hot weather should be considered with caution because of the possibility of premature stiffening of the mix. Many concrete plants employ only high temperature curing during summer months, and a combination of high temperature curing with an integral accelerator during the winter months.

CHAPTER III

RETARDERS

General

The main purposes for using retarding admixtures in concrete are to eliminate the tendency of some cements to develop false set, to delay the early stiffening action of concrete when difficult conditions of placement occur, and to offset the accelerating effect of hot weather on the setting of concrete. Also, solutions may be applied to forms to inhibit the set of a surface layer so that it can be readily removed by brushing, thus exposing the aggregate and producing unusual surface texture effects.

Probably the most common retarder known is calcium sulphate or gypsum, which is used as an ingredient in the manufacture of portland cement. It is interground to retard what otherwise might result in flash set of the cement. One of the most commonly known retarders as an admixture is common sugar. Tests have proven that the addition of excessive amounts of sugar to concrete may delay set indefinitely, thus greatly impeding construction progress. However, if very small amounts of sugar are used, a satisfactory retarding effect may be obtained without detrimental effect on ultimate strength. Most retarders cause a reduction in early strength which is attributed to delayed hydration. These reductions in early strength usually do not carry through to later ages.

Plastiment is known as a densifying retarder. A dispersing agent may also act as a retarder. Both of these retarders cause a substantial reduction in the water-cement ratio, which at least partly offsets the lower strengths due to the retardation.

There are numerous other chemicals that have a retarding effect on the normal setting time of portland cement. Some chemicals will retard the set of certain cements and accelerate the set of others. Some act as retarders when used in certain quantities, and accelerators when used in other amounts. It is not well known what effects these chemicals have on other properties of concrete, although, usually, some reduction in early strength accompanies the use of organic retarders. Therefore, great care must be taken when using these materials as retarders. Before using a certain chemical as a retarder, advance experiments should be conducted to determine the extent of its effects on the setting time and other properties of the concrete.

By use of admixtures, the setting time of concrete can be delayed considerably. Figure 2 shows the effect of various admixtures on the hardening rate of concrete. The retarder used in these tests was calcium sulphate. The quantities of calcium sulphate shown on the figure are pounds per sack of cement.

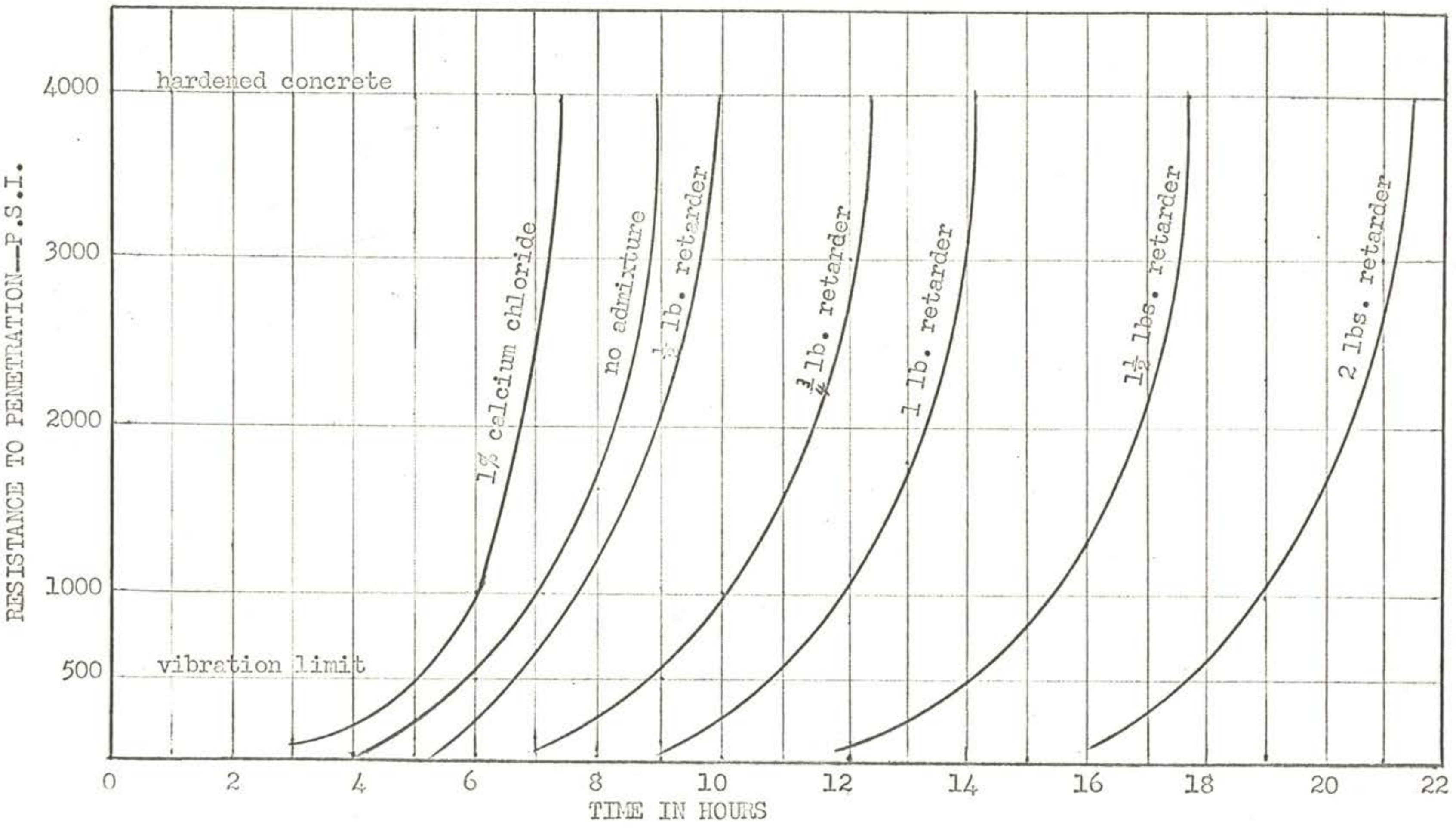

Figure 2. Effect of various admixtures on the hardening rate of concrete.

Application of Retarders to False Set

False set in cement is evidenced by a definite stiffening or loss of consistency during mixing or shortly after. In extreme cases, the concrete may hang up in the top of the mixer drum or stiffen in buggies, truck bodies, or buckets while in transit to such a degree that picks and shovels may be required in the discharging operation. Frequently, however, concrete afflicted by false set in the cement will escape detection on the job. This may result from extended periods of mixing or agitation which break through the stiffening, restoring the concrete to nearly normal consistency. Premature concrete stiffening on the job delays construction, causes excessive bleeding, makes uniform control of concrete quality practically impossible, and increases handling, placing, and finishing costs.

There have been many theories propounded regarding false setting in cements, but it is now generally agreed that the usual cause of the phenomenon is the reduction in the effective content of gypsum which reduces the retarding properties of the cement. The most common cause of ineffective gypsum in cement is high grinding mill temperatures. Storage temperatures, aeration, and moisture may also render gypsum ineffective as a retarder. As the causes of false set are generally related to the process of manufacture of the cement or conditions to which the cement may be subjected prior to delivery, it is in most cases more economical to correct these causes before shipment of the cement to the job.

Certain admixtures may be used as retarders to correct false set when economy dictates that remedial measures be employed at the job site. In some cements, false set has been corrected by adding 1 to 2 percent gypsum, by weight of cement, at the mixer. The addition of an excessive amount of gypsum may cause undesirable expansion in the concrete. For this reason, adequate inspection and control should be available when using gypsum for the purpose of reducing false set. Other admixtures which have been used as retarders are calcium acetate, music acid, and the commercial products RDA, ray lig binder, and SRDA. Preliminary tests should be made, employing the same materials and mixes as are to be used on the job, to determine the appropriate admixture with respect to type and quantity. Also, control tests at frequent intervals should be made to insure that the type and quantity of admixture remains adequate.

CHAPTER IV

AIR ENTRAINING AGENTS

General

The primary action of any concrete admixture used chiefly for air entrainment is that of a foaming agent. When a small quantity of an air-entraining agent is added at the mixer, billions of microscopic air bubbles are dispersed throughout the concrete mix. These spheroids of air greatly facilitate the internal movement of the rigid ingredients of the mixture, thus lessening the need for water as a lubricant. For a given slump, the unit water content may be reduced about three to four gallons per cubic yard of concrete, thus reducing large water channels in the mass and minimizing the natural movement of water to the surface (bleeding). The air bubbles simulate particles of fine sand but with complete flexibility of shape. They reduce the internal friction of the mix and increase workability. The air spheroids do not readily collect together nor migrate to the surface of the concrete. By reducing segregation and bleeding, a more uniform cohesive mass will be obtained (2).

The general effects of air entrainment are to increase workability, increase durability, decrease density, decrease strength, and reduce bleeding and segregation. Air entrainment makes possible a reduction in the sand content of the mix in an amount approximately equal to the volume of the entrained air. Also, each percent of entrained air permits a reduction in mixing water of about 3 percent, with no loss in slump. The decision concerning whether to use air entrainment, or how much air to entrain, generally depends upon the degree to which strength can be sacrificed in the interest of improved durability. Usually, each percent of air entrained causes a reduction in strength of about 3 or 4 percent. Unless the air content is greater than about 3 percent, marked improvement in resistance to freezing and thawing does not occur. The most commonly used air contents are in the 3 to 6 percent range for an average concrete with 1½ inch aggregate, but the finer the aggregate, the greater the required air content. For mortar, the optimum air content is about 9 or 10 percent.

Generally speaking, all air-entraining agents fall into one or more of the following classes: (a) natural wood resins and their soaps; (b) alkali salts of sulphonated or sulfated organic compounds such as a synthetic detergent; and (c) animal or vegetable fats or oils, their fatty acids and their soaps. It may be seen from this general classification that there are innumerable materials which will entrain air. Such materials vary widely in their effects on concrete for reasons not too clearly understood. Some differences might be explained by the solubility or insolubility of the calcium soaps or other compounds formed. Before specifying or permitting the use of an air-entraining admixture in concrete, the user should satisfy himself that the material actually does function as an air-entraining agent and that none of the essential properties of the concrete are seriously impaired.

The simplest method of obtaining entrained air is by the use of air-entraining cement. Air-entraining cement is cement that contains air-entraining agent which has been interground with it during its manufacture. Some engineers prefer using air-entraining cement because of the convenience of using it. For best results it is probably desirable to add an air-entraining admixture at the concrete mixer because different amounts are necessary to produce the optimum results in various products. There are on the market a large number of commercial admixtures for which air-entraining properties are claimed and some of these are being used extensively.

Effects on Durability

A durable concrete is one which will withstand, in satisfactory degree, the effects of service conditions to which it will be subjected, such as weathering, chemical action, and wear. Entrainment of from 3 to 6 percent air, by use of an air-entraining agent, increases considerably the resistance of concrete to weathering and its resistance to the disintegrating action of freezing and thawing. The entrained air, which is dispersed throughout the concrete in the form of minute, disconnected bubbles,provides spaces where forces which would cause disintegration can be dissipated.

Tests have shown that durability of concrete containing the recommended amounts of air is on the average about four times that of ordinary concrete containing no entrained air. Even though the strength of the concrete for the same water-cement ratio is reduced by as much as 1000 psi because of the entrained air, its durability is still much greater than that of the corresponding concrete containing no entrained air. Figure 3 shows that, within the range of water-cement ratios generally used, concrete containing 3/4 inch maximum size aggregate and 4 percent air is several times as durable as similar concrete without entrained air; also, that low water-cement ratios contribute considerably to the durability of concrete. Mixes containing larger aggregates have lower mortar contents and consequently a smaller optimum percentage of entrained air because the percentage of air in the mortar is not greatly affected by the size of the coarse aggregate. The increase in durability for air contents above 6 percent for concrete containing 3/4 inch maximum size aggregate does not warrant the consequent reduction in strength for higher air contents. The optimum air content for any given mix is dependent, also, upon the quality of the concrete and increases as the quality is reduced. However, it is a known fact that entrained air is not a "cure all" and poor-quality concrete, even though improved many times, cannot be made into high-quality concrete through the entrainment of air. Entrained air also contributes to the durability of concrete because it reduces the water channel structure in the hardened concrete by reducing segregation and bleeding in the fresh concre

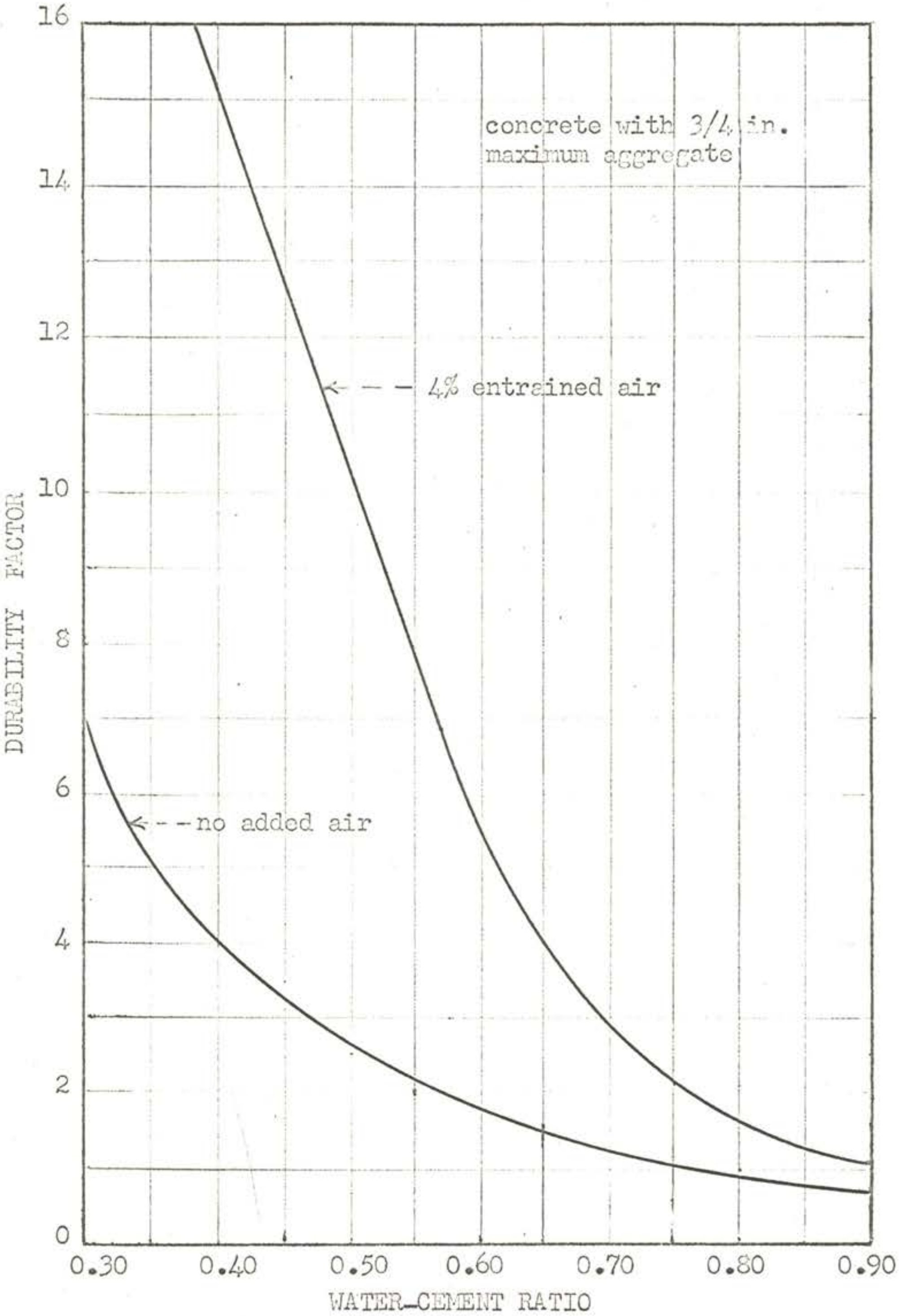

Figure 3. Relation between durability and water-cement ratio for air-entrained and non-air-entrained concrete.

The resistance of air-entrained concrete to sulphate attack is not nearly as pronounced as the resistance to freezing and thawing. Test results indicate entrained air, up to 6 percent, slightly increases the resistance of concrete to chemical attack. This improved resistance is probably effected by the increased watertightness due to the reduction in water channel structure.

Effects on Workability

Workability is the ease with which a given set of materials can be mixed into concrete and, subsequently, handled, transported, and placed with minimum loss of homogeneity. Entrainment of air greatly improves the workability of concrete and permits the use of aggregates less well graded than are required if air is not entrained. Entrained air reduces bleeding and segregation and facilitates the placing and handling of concrete. The reduced bleeding permits earlier finishing of concrete surfaces and usually with less labor. At the same percentage of sand and the same slump, the workability of concrete is increased as the percentage of air in the mix is increased, even though the water in the mix is reduced. The increase in workability is greater for wetter mixes than for drier ones, and for the leaner than for the richer ones.

The improvement in workability has not been satisfactorily explained but it may be due to the lubrication of the fine aggregate by the cushioning effect of the air bubbles.

The air bubbles reduce particle interference by tending to separate the sand particles. It has also been suggested that the air bubbles behave as particles of fine aggregate, which are elastic and have negligible surface friction. But whatever the cause, this improvement in workability makes air-entrained concrete more easily handled than ordinary concrete, and is preferred by laborers working with it.

Effects on Strength

Air entrainment, while improving both workability and durability may have an adverse effect upon strength. For a constant cement content the effect of air entrainment by approved agents on strength varies; for the very lean mixes air entrainment may even result in some increase in strength, the effect varying with richer mixes to as much as 4 percent reduction in strength for each percent of air entrained.

Tests have demonstrated conclusively that the most important factor influencing the strength of concrete is the water-cement ratio. For a given water-cement ratio, an increase in air content results in a loss of strength. But entrainment of air in a concrete mix enables the water-cement ratio and the sand content to be reduced substantially. Therefore, if the cement content is kept constant, the water-cement ratio and sand content will be decreased enough so that very little, if any, reduction in strength, within the practicable range of mixes, will result from entrainment of air.

When designing a concrete mix, the general practice is to require a minimum cement factor to be used to obtain a certain compressive strength. Table I shows the cement factors to be used in designing a non-air-entraining concrete mix. In comparison, Table II shows the cement factors to be used in designing an air-entraining concrete mix employing admixtures. These cement factors are advocated by the National Crushed Stone Association.

Effects on Permeability

Permeability is that property which permits the passage of water through the concrete. The impermeability of concrete is not greatly increased by entrained air. Tests have shown that air-entraining concrete, after it has once dried, is more resistant to the passage of moisture than regular concrete; and it will absorb less water. The small disconnected air voids produced by air entrainment offer a barrier to the passage of water.

Those factors which affect the strength of concrete usually affect the permeability. The permeability increases with an increase in the water content per cubic yard of concrete. The water content is affected by both the richness and the water-cement ratio. Air entrainment permits the water-cement ratio to be reduced with no reduction in slump. By keeping the cement content constant and reducing the water content, the richness of the mix will be increased, which causes an increase in watertightness of the concrete. Aside

TABLE I

Non-Air-Entraining Structural Concrete

Cement Factors (Sacks per Cubic Yard of Concrete) Required for 28-Day Compressive Strengths Listed

Size of Coarse Aggregate, Square Opening Laboratory Sieves		No. 4 to 1/2 in.		No. 4 to 3/4 in.		No. 4 to 1 in.		No. 4 to 1 1/2 in.		No. 4 to 2 in.		No. 4 to 2 1/2 in.	
Slump, in.		3	6	3	6	3	6	3	6	3	6	3	6
Water,[1] gal per cu yd of concrete	Angular Coarse Aggregate	42	41	40	42	38	40	36	38	35	37	34	36
	Rounded Coarse Aggregate	38	40	36	38	34	36	32	34	31	33	30	32
28-Day Compressive Strength,[2] psi		Cement, sacks per cubic yard of concrete											
2000		4.6	4.8	4.4	4.6	4.2	4.4	4.0	4.2	3.9	4.0	3.8	3.9
2500		5.0	5.2	4.8	5.0	4.5	4.8	4.2	4.5	4.1	4.3	4.0	4.2
3000		5.4	5.7	5.2	5.4	4.9	5.2	4.6	4.9	4.4	4.7	4.3	4.6
3500		5.9	6.3	5.6	5.9	5.3	5.6	5.0	5.3	4.9	5.2	4.8	5.0
4000		6.5	6.9	6.2	6.5	5.8	6.2	5.5	5.8	5.4	5.7	5.2	5.5
4500		7.2	7.5	6.8	7.1	6.4	6.8	6.1	6.4	5.9	6.3	5.7	6.1
5000		8.1	8.5	7.7	8.1	7.3	7.7	6.9	7.3	6.7	7.1	6.5	6.9
Entrapped Air, approximate per cent		2.5		2		1.5		1		1		1	

[1] This is the water actually effective as mixing water. See example on page 15 for method of taking into account free water on wet aggregates and absorption of dry aggregates

[2] The 28-day compressive strengths shown are the minimum values to be expected and should be used for design purposes. Laboratory specimens cured under ideal conditions will generally have higher strengths

Note: For concrete to be assisted in place by internal vibration, use 3 in. slump and decrease tabulated water contents by approximately 4 gal. No reduction in cement factor is suggested

TABLE II

Air-Entraining Structural Concrete

Cement Factors (Sacks per Cubic Yard of Concrete) Required for 28-Day Compressive Strengths Listed

This Table Should Always Be Used to Proportion Concrete to Be Subjected to Freezing

Size of Coarse Aggregate, Square Opening Laboratory Sieves	No. 4 to 1/2 in.		No. 4 to 3/4 in.		No. 4 to 1 in.		No. 4 to 1 1/2 in.		No. 4 to 2 in.		No. 4 to 2 1/2 in.	
Slump, in.	3	6	3	6	3	6	3	6	3	6	3	6
Water,[1] gal per cu yd of concrete: Angular Coarse Aggregate	38	40	36	38	34	36	32	34	31	33	30	32
Water,[1] gal per cu yd of concrete: Rounded Coarse Aggregate	35	37	33	35	31	33	29	31	28	30	27	29
28-Day Compressive Strength,[2] psi	Cement, sacks per cubic yard of concrete											
2000	4.4	4.7	4.2	4.4	3.9	4.2	3.7	3.9	3.6	3.8	3.5	3.7
2500	4.9	5.2	4.6	4.9	4.4	4.7	4.2	4.4	4.0	4.3	3.9	4.2
3000	5.6	5.9	5.3	5.6	5.0	5.3	4.7	5.0	4.5	4.8	4.3	4.7
3500	6.3	6.7	6.0	6.3	5.6	6.0	5.3	5.6	5.1	5.4	4.9	5.3
4000	7.2	7.5	6.8	7.2	6.4	6.8	6.0	6.4	5.8	6.2	5.6	6.0
4500	8.1	8.5	7.6	8.1	7.2	7.6	6.8	7.2	6.6	7.0	6.4	6.8
5000	9.2	9.7	8.7	9.2	8.2	8.7	7.7	8.2	7.4	8.0	7.2	7.7
Optimum Entrained Air Content,[3] per cent	6.0		6.0		5.5		5.0		5.0		4.5	

[1] This is the water actually effective as mixing water. See example on page 18 for method of taking into account free water on wet aggregates and absorption of dry aggregates

[2] The 28-day compressive strengths shown are the minimum values to be expected and should be used for design purposes. Laboratory specimens cured under ideal conditions will generally have higher strengths

[3] This optimum entrained air content provides for approximately 9 per cent air in the mortar

from the increased watertightness as a result of the entrainment of air, the greater degree of uniformity in placing the concrete, due to increased workability, reduces permeability.

CHAPTER V

GAS-FORMING AGENTS

Settlement shrinkage and bleeding in plastic concrete are caused by gravitational settling of the individual solid particles in a semiliquid mixture. If the settlement or bleeding is excessive or occurs under certain concreting conditions, undersirable characteristics may result in the hardened concrete. The accumulation of voids on the underneath side of forms, reinforcing steel, or other embedded parts may reduce bond, watertightness, uniformity, and strength in the concrete and may cause costly cleanup and grouting operations.

To offset this normal settlement in plastic concrete, there are sometimes used agents which produce gas in an amount intended to be approximately equal to the effective change in volume resulting from subsidence. This gas is produced in the form of minute, dispersed bubbles throughout the cement-water matrix. Agents which have been used to produce gas bubbles in concrete are aluminum or zinc powder and hydrogen peroxide. Hydrogen peroxide liberates oxygen, but the action is usually too fact to be highly effective. Aluminum powder, which is the most commonly used, produces hydrogen gas as the result of a reaction with the alkalies of the cement. Figure 4 shows the rates of expansion of 6 concretes,

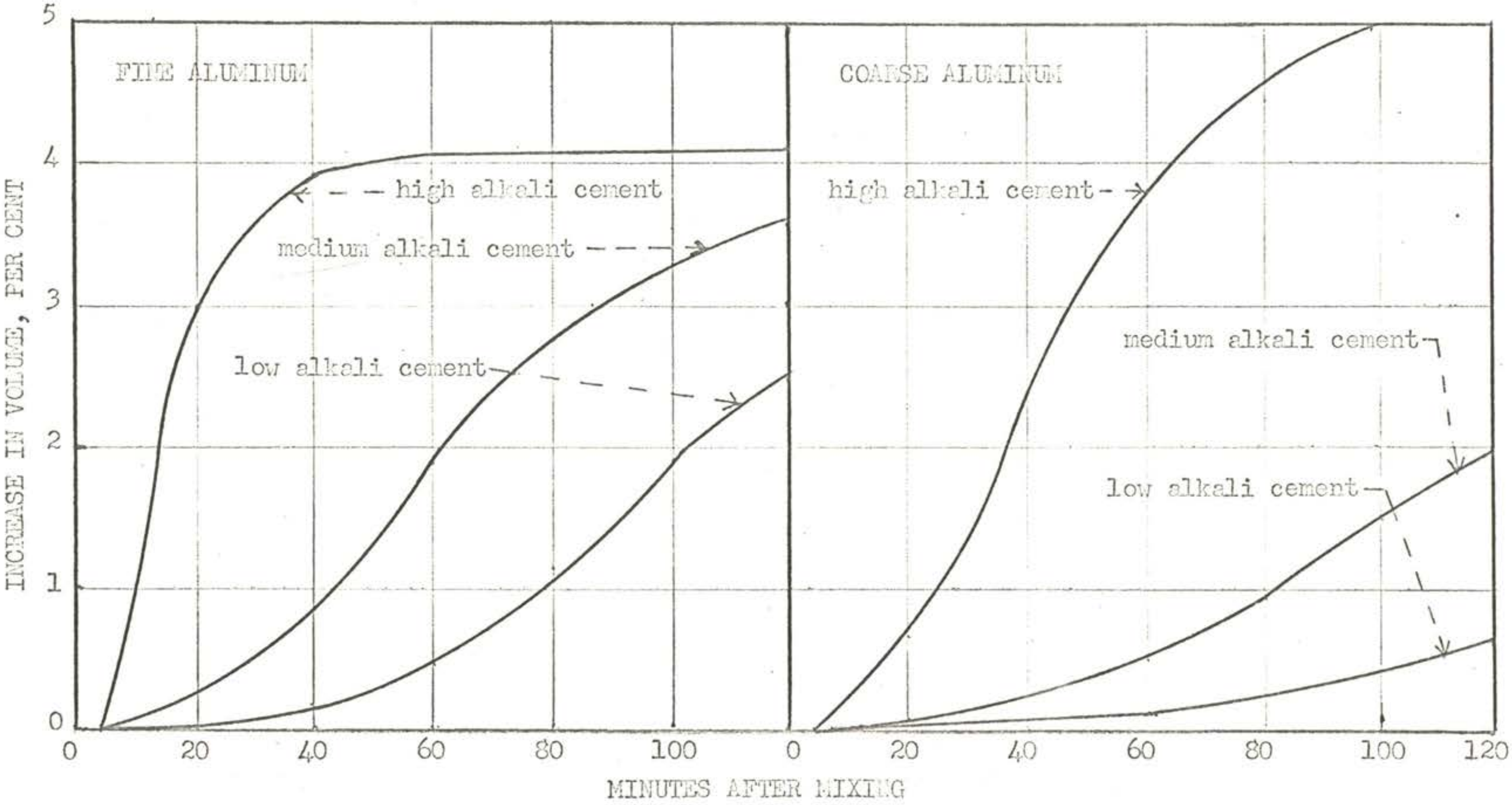

Figure 4. Expansion rates of concrete containing aluminum powder.

comprising 3 cements differing as to alkali content, and 2 grades of aluminum powder. The expansion tests were conducted by the ASTM and were made with a mix of 1 : 4 by weight and an aluminum content of 0.014 percent. The alkali contents of the three cements were 1.2, 0.7, and 0.2 percent respectively. From this figure, it is evident that the expansion rate of the concrete is related to the alkali content of the cement.

The small gas bubbles produced by the use of aluminum powder remain essentially trapped within the concrete paste. The generation of these minute gas bubbles tends to increase the volume and the pressure of the confined paste thereby tending to improve the intimacy of contact of the paste with adjacent aggregate particles as well as with the embedded steel and the confining parts of the mold. Aluminum powder has been very useful for grouting under machine bases and backfilling under horizontal surfaces where complete filling of the cavity is essential. The effect on strength depends to a large extent on the degree to which the tendency of the concrete to expand is restrained. Without restraint the loss of strength may be considerable; but, with complete restraint, the strength is not effected appreciably and, in some cases, may be slightly increased. Therefore, it is important that the forms be tight and that they completely confine the grout or concrete treated with aluminum powder. Usually, the density will be slightly reduced and the durability slightly improved.

During cold weather, the reaction is slowed considerably, and the desired result may not be obtained because the cement sets before the expansive action takes place. On the other hand, during hot weather, the reaction may occur so rapidly that no benefit results because the concrete may shrink normally after the gas generation reaction has ceased. The reaction starts when the materials come in contact and at normal temperatures may last for 1 to 3 hours. At temperatures above 90 degrees Fahrenheit, the reaction may be completed in 30 minutes and subsidence may take place until the concrete takes its initial set. At 40 degrees Fahrenheit, the reaction may not be effective for several hours. Approximately twice as much aluminum powder is required at 40 degrees Fahrenheit as at 70 degrees Fahrenheit to produce the same amount of expansion.

The ultimate extent and effect of the gas-producing reaction within the paste is subject to considerable manipulation. It is influenced by the amount and fineness of the aluminum powder, the type and fineness of the cement, the character of the concrete, temperature, mix proportions, and variety of factors acting to restrain the normal expansion of the paste between the aggregate particles. The amounts of aluminum powder added are usually in the range of 0.005 to 0.02 percent by weight of cement.

CHAPTER VI

POZZOLANS

Composition of Pozzolans

Certain minerals, predominantly siliceous in nature, when in a finely divided state can combine with lime in the presence of water to form cementitious compounds. These pozzolans may be naturally occurring minerals, natural materials to which beneficiating processes have been applied, such as heat and the addition of chemicals, or artifically formed mineral substances such as ground brick, fly ash, and some slags. While the principal constituent of all pozzolans is silica, some pozzolans exhibiting superior performance in concrete contain 40 percent or less of this compound. Most pozzolans contain substantial quantities of alumina and iron oxide, and it seems that all good pozzolans contain at least a small quantity of the alkalies.

Most natural pozzolans require grinding to a high degree of fineness to make them suitable for use in concrete. Also, experience has shown that heat treatment of certain natural pozzolans is an important process in developing their cementing qualities. The beneficiation of pozzolans by this heat treatment is manifest in several ways, the most important of which are: (a) reduced water requirement, (b) improved grindability, (c) increased reactivity with lime, (d) increased rate and level of strength development, and (e) more effective inhibition of alkali-aggregate reaction. There is strong evidence that natural pozzolans can be further improved by the addition of chemicals such as alkalies during the heat treatment process. But too little is known at present about such benefits to bring them into practical use.

Artificial pozzolans come from industrial byproducts or wastes and include fly ash, silica fume, powdered brick, burnt oil shale, and some slags. Probably the most important of these artificial pozzolans in this country is fly ash. Fly ash is the finely divided residue from powdered coal which is caught in electric precipitators in steam power plants. It is composed largely of almost spherical particles of artificial glass while other artificial pozzolans contain glasses produced by fusion or reconstitution of the original constituents. Depending upon the coal and power plant conditions, the carbon content of American fly ashes ranges from less than 1 to more than 20 percent, and their silica content ranges from less than 30 to more than 45 percent. Some of them are considerably finer than normal portland cement.

Cement Replacement

Pozzolans are used in combination with portland cement, often as a replacement for a part of the cement. The optimum amount of replacement can be determined with certainty only by comprehensive long-term tests. However, the results of these tests are available for a considerable number of pozzolans, or classes of pozzolan. These results, along with results of short-time tests on a particular pozzolan, are the main basis for selecting an appropriate percentage of replacement.

The optimum amount of a pozzolan which may be used depends upon such factors as the properties of the concrete which it is desired to enhance, the character and fineness of the pozzolan, the richness of the mix, type, and fineness of portland cement, and the character and grading of the aggregate. As a cement replacement, this optimum amount may be as low as 4 to 6 percent for fine ground diatomite to as high as 50 percent for some of the fly ashes.

The pozzolanic reaction, which occurs with the lime liberated by the hydrating portland cement, requires the continued presence of water. Sustained moist curing is important for successful use of portland-pozzolan cements at normal temperatures.

How Pozzolans Affect Concrete

Most pozzolans, when used as cement replacements in normal amounts, improve the properties of fresh concrete such as plasticity, bleeding, and segregation. For finely divided pozzolans of opaline character, these beneficial effects may be large, particularly for wet mixes and for concretes of low cement content. This ability to improve the properties of fresh concrete seems to depend on the fineness of the pozzolan and also on its mineral composition.

The water requirement of concrete is generally greater when a pozzolan is used than when a straight portland cement is employed if the amount of water is based on a given slump. However, slump is not a valid criterion in comparing the workability of concretes containing pozzolans with that of corresponding concretes containing straight portland cement. Some of the pozzolans greatly increase the "fatness" of concrete, and it is a matter of common observation that such a concrete of 1 or 2 inch slump may be just as readily placed as a corresponding straight portland cement concrete of considerably higher slump. For pozzolans of very high fineness, the use of a suitable air-entraining agent results in a water cut substantially greater than that obtained when the same agent is employed in concrete containing straight portland cement. Some fly ashes of low carbon content will bring about a small reduction in water requirement without the use of an air-entraining agent.

The effect of pozzolan upon the strength of portland-pozzolan concrete varies markedly with the particular pozzolan used. Generally the strength development is relatively slow. Other things being equal, the finer and more active the pozzolan, the more rapid the gain in strength at early ages. Concretes containing pozzolans usually have smaller compressive strengths at early ages than corresponding concretes with straight portland cement. At the later ages, pozzolan-cement concretes generally exhibit compressive strengths close to those of corresponding portland-cement concretes. Figure 5 shows the strength gain for concrete containing straight portland cement, for concrete containing 30 percent fly ash and 70 percent portland cement by weight, and for concrete containing 40 percent fly ash and 60 percent portland cement by weight. These data indicate lower strength at 7 to 28 days for concrete containing fly ash, but at 1-year age the strength for concrete containing fly ash approximately equals the strength of concrete made from portland cement alone. The ultimate strengths of concretes of normal richness in which some of the very fine, low-carbon fly ashes have been incorporated may be substantially greater than the strengths of corresponding concretes containing straight portland cement. Usually, pozzolans contribute more to the strength of lean mixes than to rich mixes.

Generally, pozzolan-cement concretes exhibit a greater drying shrinkage than do corresponding concretes containing normal portland cement. For this reason, under severe drying conditions, concretes containing pozzolans may be expected to exhibit more shrinkage cracking. Some of the fly ashes of low carbon content and high fineness produce concretes for which the drying shrinkage is no greater than that of a corresponding concrete containing straight portland cement. Also, certain air-entraining agents, which reduce the water requirement, act to reduce the drying shrinkage of some of the

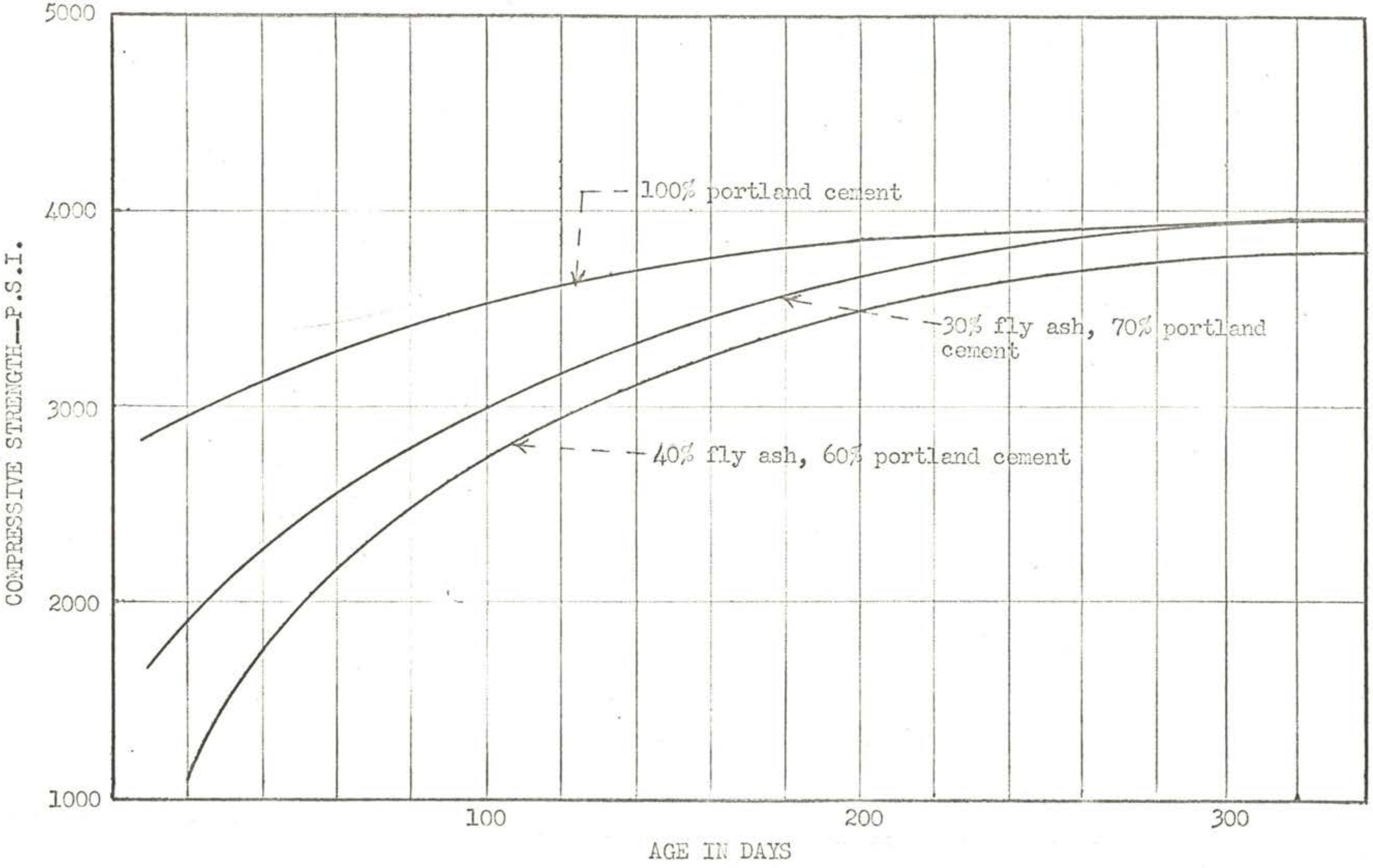

Figure 5. Strength relation between concrete containing fly ash and concrete containing portland cement alone.

pozzolan-cement concretes to a value less than that exhibited by a corresponding concrete containing straight portland cement without an air-entraining agent.

Without purposeful air entrainment, pozzolan-cement concretes will, in general, offer somewhat less resistance to weathering than do corresponding concretes containing straight portland cement. Exceptions are some of the low-carbon fly ashes when used as cement replacements up to about 30 percent, and very finely ground diatomite when used in an amount so small as not to increase appreciably the amount of water that is required by the concrete. Also, when some of the air-entraining agents are employed it has been found that in some instances pozzolan-cement concretes are far more resistant to weathering than are the corresponding air-entraining straight portland cement concretes.

One of the most important characteristics of pozzolan-cement concretes is their high degree of watertightness. The coefficient of permeability at the later ages is generally only a fraction of that of corresponding concretes containing straight portland cement. At early ages, finely ground pozzolans of opaline character, such as diatomite, are much more effective in reducing permeability than are glassy materials, such as fly ash.

Many pozzolans have been found to be very effective in reducing the excessive expansion of concretes due to alkali-aggregate reaction. This reaction takes place between alkalies present in portland cement and certain forms of silica present in small amounts in many aggregates. Other things being equal, those pozzolans that are high in opal are much more effective in counteracting excessive expansion than those which are high in glass.

Concretes containing a suitable pozzolan in appropriate amount are more resistant to sulfate attack than are corresponding concretes containing type I, type II, or type III cements. Most effective are the pozzolans high in opal. Also, in general, resistance of concretes to weakly acid or low pH waters is increased by replacing part of the cement with a good pozzolan. Figure 6 shows the length of time taken for neat cement slabs to fail in a 10 percent sodium-sulfate solution (merriman test). Each bar represents the average of tests on several cements of the type indicated; in the case of pozzolan blends, more than 10 different materials, including diatomaceous earths, pumicites, volcanic ash, silts, and clays were tested. These tests were conducted by the Bureau of Reclamation.

The heat of hydration of a portland-pozzolan cement is less than that of a corresponding straight portland cement. The rate and amount of heat generation is dependent upon the character and fineness of the pozzolan. When a type II cement is used at 70 degrees Fahrenheit, the heat generated by the pozzolanic reaction up to the age of 28 days is about half as great as that of the cement which was replaced.

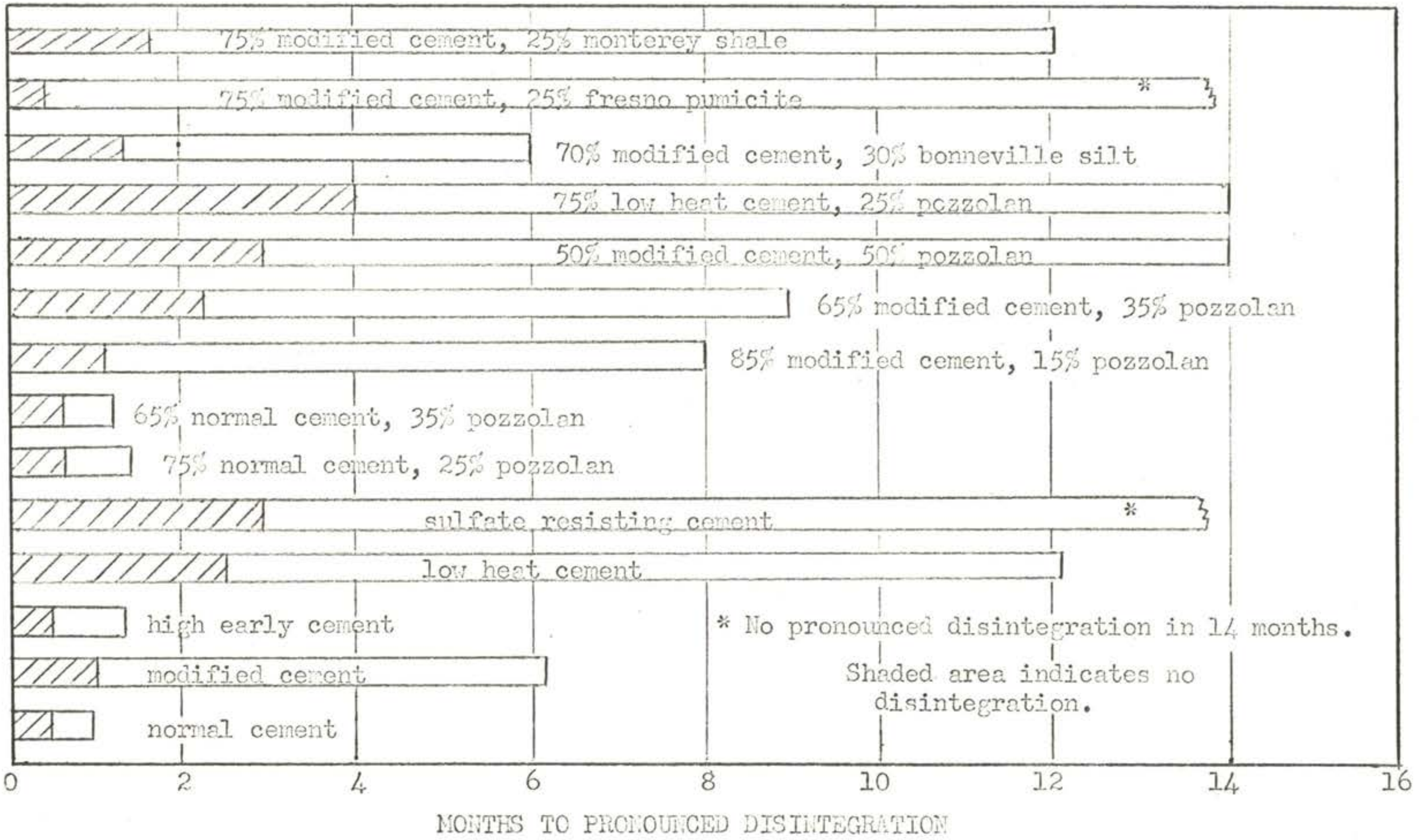

Figure 6. Resistance of portland and portland-pozzolan cements in 10 percent Na_2SO_4 solution.

Application to Concrete Construction

Portland-pozzolan cements are very useful in the construction of massive structures such as dams and large piers, where low heat of hydration is desired; in structures subject to alkali or acid attack from ground water, sea water, or from industrial wastes; and in hydraulic structures of all kinds, where watertightness is important. Replacement of a portion of the portland cement by a suitable pozzolan is highly desirable for the very lean air-entraining mixes used in dams. This decreases the permeability of the hardened concrete, improves workability, and reduces bleeding and segregation.

Pozzolans have also been used successfully in pavement construction. Tests have shown that a small percentage of some of the pozzolans is many times as effective as entrained air in reducing segregation, preventing bleeding, and producing a concrete slab which is homogeneous from top to bottom. By using a suitable air-entraining agent and a suitable pozzolan, it is possible to construct concrete pavements having low drying shrinkage and high resistance to weathering, and at the same time provide a homogeneous concrete throughout the depth of the slab.

For the construction of buildings, the chief arguments for the use of a pozzolan as a cement replacement instead of straight type I portland cement would most likely be greater workability, less tendency towards segregation and bleeding, and exterior walls and floors less susceptible to the passage of moisture. With a suitable air-entraining agent which would cut drying shrinkage and promote weathering resistance, a suitable pozzolan-cement mixture could be appropriately used for any type of concrete construction, regardless of conditions of exposure.

Pozzolans to Use for Best Results

The use of fly ash as a pozzolan is becoming extensive in some areas of the United States. Fly ashes of high fineness and low carbon contents are excellent pozzolans suitable for general concrete construction. When fly ashes of low carbon content and high fineness are employed as cement replacements in moderate amount (between 20 and 30 percent), the concretes will possess properties of strength, drying shrinkage, and weathering resistance approximately equal to and in some cases somewhat superior to corresponding properties of concrete containing straight portland cement. The use of coarse fly ashes with high carbon content is undesirable except with respect to weathering resistance. The coarse fly ashes should be regarded as a substitute for fine sand instead of a replacement for part of the cement. For jobs where transportation costs are low, it would be reasonable to use coarse fly ashes with a coarser than normal natural sand.

The fly ashes are not the equal of the finely divided diatomites and opaline shales in improving the workability, decreasing the tendency toward bleeding and segregation, and counteracting the effect of alkali-aggregate reaction. Tests have shown that a small percentage of these opaline shales and diatomites treated with a suitable air-entraining agent increases the compressive strength of concrete at the early as well as the later ages, reduces the shrinkage, and increases the resistance to weathering. By using these pozzolans with a suitable air-entraining agent, it is possible to reduce the cement content of concrete as much as a sack per cubic yard without sacrifice of strength and at the same time improve the properties of drying shrinkage and weathering resistance. When opaline shales and diatomites are used in normal amount of cement replacement (from 20 to 30 percent), optimum results are obtained by calcining and then grinding them to a high fineness.

Pumicite and related materials have been used principally for sea walls, dams, canal linings, and concrete pipe. These materials greatly increase watertightness of concrete at later ages. Therefore, they are suitable for hydraulic structures. However, concretes containing these pozzolans are likely to exhibit somewhat lower strengths than do corresponding concretes containing straight portland cement. Also, to prevent extreme drying shrinkage, concretes containing pumicite should have added to them a suitable air-entraining agent.

CHAPTER VII

ALKALI-AGGREGATE EXPANSION INHIBITORS

General

An expansive reaction between certain types of aggregates and high-alkali cements has been found responsible for the random cracking and disintegration of the concrete in many structures. The cracking is usually accompanied by a decline in strength, elasticity, and durability of concrete which may seriously impair the serviceability of the structure.

Several types of aggregates are known to react with high-alkali cement. These reactive aggregates include siliceous limestones, highly siliceous rocks, and certain volcanic rocks. Opaline silica, which is often present in many different kinds of rocks and may form coatings on sand or gravel particles, has been responsible for much disintegration. Although many kinds of aggregates contain small amounts of undesirable reactive materials, it is not known how much of such materials must be present to produce an adverse reaction with cements high in alkali.

The term alkalies as applied to portland cement refers to the sodium and potassium compounds present in relatively small proportions expressed as oxides (Na_2O and K_2O). Tests have shown that reactive aggregates in combination with high-alkali cements cause deterioration of the concrete, but little or no damage is caused when the cements have alkalies of less than 0.6 percent.

The approaches toward minimizing or avoiding deterioration caused by alkali-aggregate reaction are the selection of a nonreactive aggregate, the use of low-alkali cement, and the use of certain proved admixtures. The admixtures used most frequently belong to the pozzolan family.

Types of Effective Pozzolans

The replacement of cement with suitable pozzolans in the correct amount and in the proper physical state produces concrete containing reactive aggregates, without unfavorable expansion. A suitable pozzolan for use in regulating the chemical reactions of aggregates in concrete must be reactive with the solutions in the concrete (3). It must be sufficiently fine and well mixed so as to react with all of the solutions in the concrete. The pozzolan used must also be such that the proper workability and strength in the concrete may be obtained.

The pozzolans most often used to control alkali-aggregate reaction are: (a) certain opaline materials, (b) certain volcanic glasses, (c) certain calcined clays, and (d) certain highly siliceous industrial products. If calcium chloride is added to the mix, the effectiveness of these pozzolans in controlling disruptive alkali-aggregate expansion is generally diminished.

The amount of suitable pozzolan required in a concrete to control the alkali-aggregate reaction will vary with individual aggregates and alkali content of the cement. Proper care must be exercised in the selection and use of pozzolans as their properties vary widely and some may introduce adverse qualities into the concrete, such as excessive drying shrinkage and reduced strength and durability. Also, if used in insufficient proportion, certain pozzolans can increase expansion of concrete by deleterious reaction with cement alkalies. The amounts of pozzolan most generally used ranges from 20 to 35 percent by weight of the cement. These amounts are usually compatible with other physical requirements of the concrete such as strength, workability, and other properties. Before accepting a pozzolan for a specific job, the pozzolan should be tested in combination with the cement and aggregate to be used so as to determine accurately the advantages or disadvantages of the pozzolans with respect to quality and economy of the concrete.

Figure 7 shows the effects of several pozzolans in reducing expansion in concrete caused by alkali-aggregate reaction. The expansions shown were obtained with 1 by 1 by 10 inch bars of 1 : 2.25 mortar made with high alkali cement and crushed pyrex glass as the reactive aggregate. The pozzolan replacement of these tests was only 20 percent by weight of cement, but as can be seen, some of them reduced the expansion of the highly reactive combination to negligible amounts. For ordinary reactive aggregate in concrete, the reduction would be more effective.

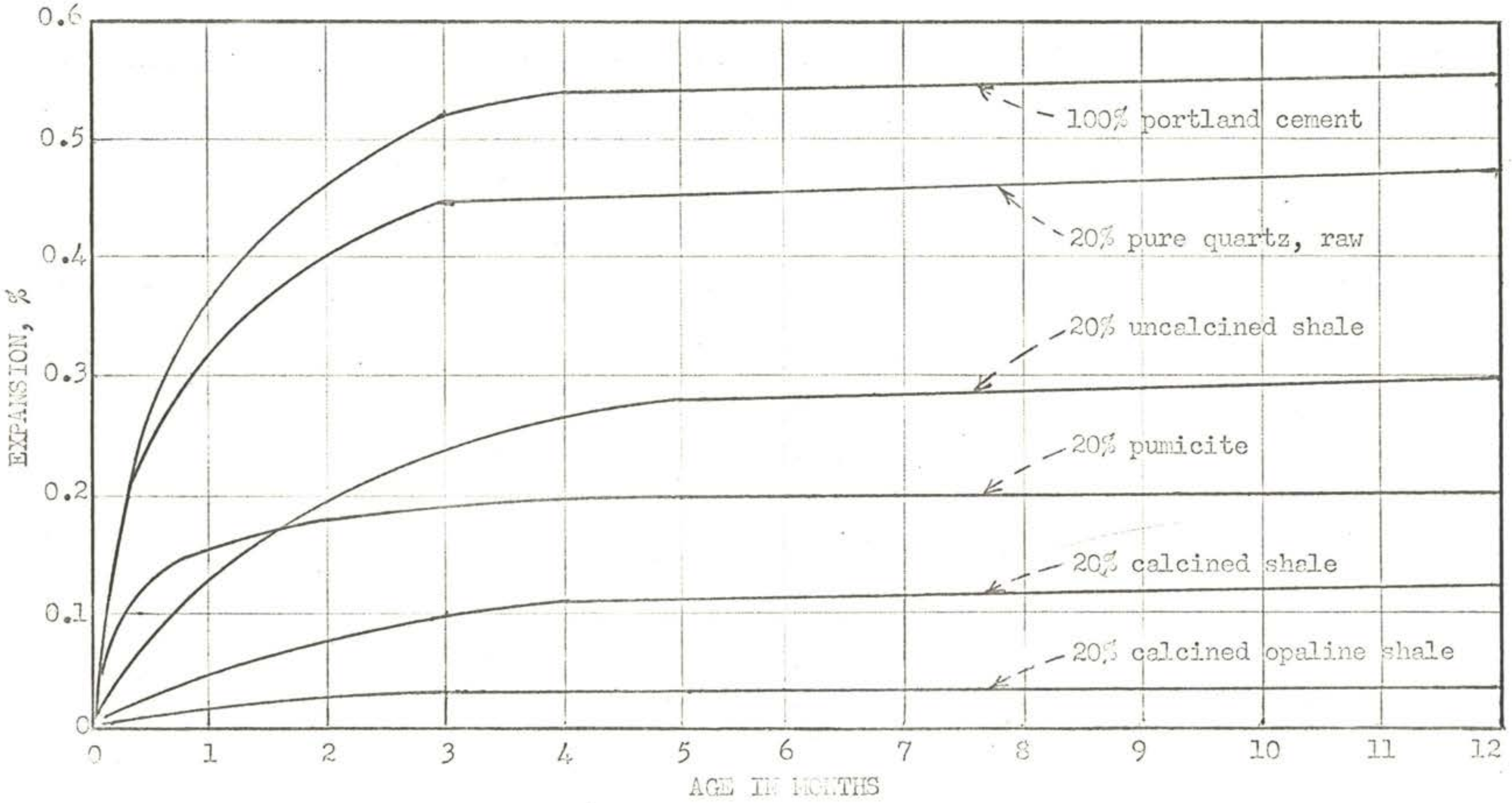

Figure 7. Pozzolans reduce expansion of mortar and concrete owing to alkali-aggregate reaction.

Other Admixtures

Some admixtures, other than pozzolans, have been found to have some effect on the reduction of expansion due to alkali-aggregate reaction. Tests have shown that air-entraining agents will reduce this expansion slightly. Of these agents, the protein type have given moderately good results. The extent of expansion reduction obtained for a given air content varies from one air-entraining agent to another. There is also some evidence that aluminum powder reduces this expansion slightly as the result of gas entrainment. But this agent does not appear too satisfactory for the purpose of expansion reduction because of the difficulty of controlling the amount of entrained gas.

Outstanding reductions in expansion of laboratory mortar specimens have been reported for additions of 1 percent by weight of the cement of lithium salts. The effect of these salts in reducing expansion caused by the alkali-aggregate reaction demonstrates that additions of small amounts of non-air-entraining materials may be used. However, these materials may be too expensive for practical use in concrete.

CHAPTER VIII

DAMPPROOFING AND PERMEABILITY REDUCING AGENTS

General

Certain materials, when added to the concrete as admixtures, have the effect of reducing flow or capillarity of water through concrete. These materials are known as permeability reducing or dampproofing agents, depending upon their effect (4).

Permeability is that property which permits the passage of water through the concrete when subject to pressure. Reduction of permeability may be accomplished by the use of an admixture which renders concrete more resistant to the passage of water under pressure. Moisture may be transmitted through the concrete by capillary attraction when it is not under pressure. Evaporation from surfaces exposed to unsaturated air and the constant replenishment of moisture from the surface in contact with water result in a flow of moisture through the concrete. Dampproofing admixtures are used to reduce this passage of moisture that is not under pressure. Some admixtures may have merit for both reduction of permeability and dampproofing.

Many investigators believe that concrete, carefully designed, placed, and cured, will be impermeable without the use of any admixture, and that leakage due to cracks, joints, and honeycombing is apt to be of greater magnitude and concern than leakage through the sound mortar. However, since the usual design, placing, and curing leave much to be desired, the use of a well-chosen admixture may prove advantageous where low permeability is required, especially for concrete made from a lean mix.

Even though the best concrete practices are adhered to and the resulting concrete is impervious to water under pressure, passage of moisture due to capillary action may take place if the concrete is in contact with moisture or damp earth. In cases where even slight passage of water is objectionable, the addition of a dampproofing agent may be advisable.

The use of dampproofing and permeability reducing agents should never be considered as a substitute for careful choice of materials and mixes, for skilled workmanship, or for adequate curing. In no case can an admixture be expected to compensate for cracks or large voids in the concrete, although it may minimize the probability of their occurrence.

The effectiveness of an admixture in a given application depends upon many factors. These factors include not only the placing and curing of the concrete but also the properties of all the individual materials and their proportions. The choice of an admixture for a specific job should be made only after experimental work has been conducted or previous experience with similar applications has shown that beneficial results will occur. The materials that are most commonly used as permeability-reducing or dampproofing admixtures will be discussed in the various topics that follow.

Soaps

Admixtures classified as "soaps" are the inorganic salts of fatty acids such as calcium or ammonium sterate. Soaps added to the concrete are effective in preventing the absorption of water by capillary action, even when added in very small amounts if they are added in such a form as to ensure extremely fine subdivision and dispersion in the finished concrete. Tests have shown that concretes into which soaps have been added are more permeable to water pressure than similar ones without such treatment. This has been attributed to the foaming action noted during mixing.

The quantity of soap added to the concrete should never exceed 0.2 percent by weight of the cement. If the quantity of soap added is not allowed to exceed 0.2 percent, the strength of the concrete will not likely be impaired by the soap, provided the concrete is kept damp continuously after pouring until it has attained the desired strength and provided the soap has not caused foaming and consequent entrainment of air. The strength of concrete of a given composition is a function of the amount of cement which has reacted with water and may be plotted as a function of the water held in combination. Plain concrete which has been allowed to dry and subsequently becomes wet will resume the hardening process and gain in strength. Concrete containing soaps gains strength very slowly after it has once become dried because it resists the absorption of water. Special pains must, therefore, be taken to keep concrete containing soaps damp for at least seven days if it is to attain a strength comparable with plain concrete. However, if calcium chloride is added in conjunction with the soap, the concrete will attain the desired strength earlier. In commercial preparations, the soap content is usually 20 percent or less of the calcium chloride-soap mixture, the balance of the material usually being calcium chloride (5).

Butyl Sterate

The action of butyl stearate in concrete is similar to that of the soaps in that it produces a water repellent effect. Unlike the soaps, it does not have a frothing action which results in a decrease in density of the concrete. It may be used, therefore, in much greater quantity than the soaps. To attain greatest uniformity of distribution throughout the concrete it is usually added as an emulsion. A quantity of emulsion found suitable is that which gives the equivalent of 1 percent of butyl stearate by weight of the cement (6).

Butyl stearate is superior to the soaps as a water repellent in concrete. It is noticeably more effective against penetration of water by capillary action when under moderate exposure, and it does not increase the permeability as the soaps frequently do. When used in recommended amounts, its effect on the strength of concrete is negligible.

Finely Subdivided Dry Materials

These materials may be either inert or reactive. The reactive materials generally used belong to the pozzolan family. They combine with lime liberated during hydration of the cement.

Normally, the properties of the particular concrete mix will determine if the use of finely subdivided dry materials will result in a reduction in permeability of the hardened concrete. If the concrete mix is lean or if it is deficient in fine aggregate, the addition of the finely subdivided material will usually be highly beneficial, decreasing permeability and increasing strength. But if the mix is rich and the aggregate poorly graded, the addition of fine material will probably be detrimental since the increased surface area increases the water demand resulting in a less dense and a weaker concrete.

Usually, an increase in cement content will result in a less permeable concrete than if other fine material is added. However, in massive structures it is desirable to maintain the heat evolution and subsequent shrinkage at a minimum. This requires the cement content to be kept as low as possible. For such jobs, finely subdivided materials may be used with good results. But too much fine material may lead to undesirable properties in the concrete. Fine material should not be used as a substitute for proper grading of the aggregates.

As stated, finely subdivided materials may be used to reduce the permeability of concrete, but they have little or no merit as dampproofers.

Petroleum Products

Tests have shown that heavy mineral oil is effective both in rendering concrete water repellent and in reducing its permeability. The oil should contain no fatty or vegetable oil components as these could impair concrete strength. It should contain no petroleum residuals which emulsify with alkali as this might also impair concrete strength. The oil should have a viscosity of approximately SAE 60 so as to be readily miscible with concrete while possessing sufficient body to render the concrete dampproof.

The use of RC-2 and MC-0 asphalt cut-back oils have been tried in quantities up to 10 percent by weight of cement. The tests indicated that strength and workability of the concrete was not seriously affected; however, 10 percent oil increased the setting time by approximately one-fourth.

Asphalt emulsions have also been used. They cause greater concrete strength losses than mineral oils; appear to act in much the same way when the concrete is allowed to dry sufficiently to permit the emulsion to break.

Workability Agents and Air-entraining Admixtures

The production of concrete of low permeability depends to a great extent on successful uniform placing of the material. Therefore, an agent which improves the plasticity of a given mixture without causing deleterious effects or which limits bleeding and reduces the number of large voids could properly be classified as a permeability reducing agent.

There are on the market certain organic mixtures which act as water-reducing agents. In addition to increasing workability, the sulfonated type usually entrains some air and decreases the bleeding while carbohydrate salts in combination with other active or inert materials affect the workability favorably but do not cause air entrainment or reduce bleeding.

Generally, concretes containing air-entraining agents have greater workability and bleed less than those without entrained air. The greater workability causes a reduction in the number of large voids left by poor compaction or by collection of bleeding water under aggregate. The reduction of these voids results in a reduction in permeability. Some people believe that in addition to acting as a workability agent, the small disconnected voids caused by the air-entraining agent offer a barrier to the passage of water. Tests have shown that air-entrained concretes have lower absorption and capillarity than those without entrained air. Therefore, air entrainment may be classed as both a permeability reducing and dampproofing agent.

CHAPTER IX

WORKABILITY AGENTS

General

The cost of concrete construction is influenced by the ease with which concrete can be placed. An admixture which will increase the workability of a concrete mix may prove advantageous. Greater compaction, finer reproduction of mold detail including sharp corners and edges, better flow around reinforcement, and decrease in permeability, may be expected. The workability of concrete should be the maximum obtainable commensurate with desired economy. However, in instances such as the following increased workability is necessary almost without regard to increased cost: (a) where special means of placement are required such as with tremie or pumping methods, (b) if the concrete is harsh because of aggregate characteristics or grading, and (c) if the concrete must be placed around closely spaced reinforcement or in difficultly accessible sections.

Finely Divided Materials

Some of the admixtures used to improve the workability of fresh concrete are mineral powders as fine as or finer than portland cement. Lime, bentonite, celite, kaolin, and silica flour have all been used from time to time. These materials function by increasing the amount of mortar. They are most useful in increasing the workability of harsh mixes deficient in fines, and may do so without it being necessary to add more water. For such mixes, they may help to reduce the rate and amount of bleeding, prevent segregation, and increase the strength. In general, the higher the specific surface of the material the smaller the volume required to produce a given effect on workability. When an appropriate quantity of mineral power is used, no increase in total water content of the concrete is required and drying shrinkage and absorptivity of the hardened concrete are not much affected. If a mineral powder is added to mixtures not deficient in fines, particularly mixtures rich in portland cement, the workability will generally be decreased for a given water content. Therefore, the addition of a mineral powder to such mixtures usually will cause an increase in the total water content of the concrete and may result in an increase in drying shrinkage and absorptivity and a decrease in strength.

Contractors using admixtures report that they get, especially with the leaner mixes, more uniform concrete from batch to batch than when they do not use the admixtures (7). Because of the extreme fineness of these materials they reduce to a minimum the effect of small variations in amounts of mixing water on the workability of the concrete. Moisture contents in aggregates vary from batch to batch and can be compensated by changing the amount of water added.

Surface Active Agents

The group of organic materials may be divided into dispersing agents, wetting agents, and air-entraining agents; but cutting across these three groups is a general group of workability agents which may have some powers of dispersing, wetting, and air-entraining. All these materials are termed surface-active agents because when dissolved in water they tend to concentrate at the boundary between the sand and cement particles and the water.

Under certain conditions, when cement is mixed with water, there is a tendency for the cement particles to gather together in clusters or flocs. This phenomenon is known as flocculation. The function of the dispersing agent is to prevent the flocculation of the very small particles of cement and keep them in suspension. This causes the cement paste to be more liquid and to flow more easily.

Some dispersing agents will simultaneously have slight air-entraining properties and some dispersing properties, particularly when larger percentages are vigorously stirred into the mix. Some dispersing agents become wetting agents if the amount of the agent is increased sufficiently. The increased wetness, attributable to the dispersing agent alone, demonstrates that a reduction in water content can be effected for a given workability. The decreased water content attributable to dispersion may result in an increase in ultimate strength for the hardened concrete. These are excellent potentialities for using dispersing agents in connection with accelerators and air-entraining agents, but the end results would not be attributed to dispersion alone. An agent in wide use today, which is classified as a dispersing agent, is pozzolith. Pozzolith contains a dispersing agent which has water reducing properties, and often contains an accelerator. An air-entraining agent is also incorporated in some types of pozzolith; the amount of agent varying with the amount of air required (8).

Most detergents or soaps are both air-entraining and wetting agents, but there are exceptions. All wetting agents may not act as water-reducing agents in concrete; but all air-entraining agents, like dispersing agents, will consistantly act as water-reducing agents.

Originally, air-entraining admixtures were considered for use principally because of their effect on the durability of concrete. But today, the greatest virtue of air entrainment is the ease with which it can be placed. Air entrainment improves the workability and is accompanied by less segregation and bleeding and results in a more homogeneous mix. Figure 8 shows the effect of air entrainment on the workability of concrete. Vinsol resin was the admixture used to produce air entrainment. The compacting factor is a measure of the internal work required to compact the concrete.

The improvement in workability due to air entrainment is not thoroughly understood, but it may be imagined to be due to the lubrication of the fine aggregate by the cushioning effect of the air bubbles. By tending to separate the sand

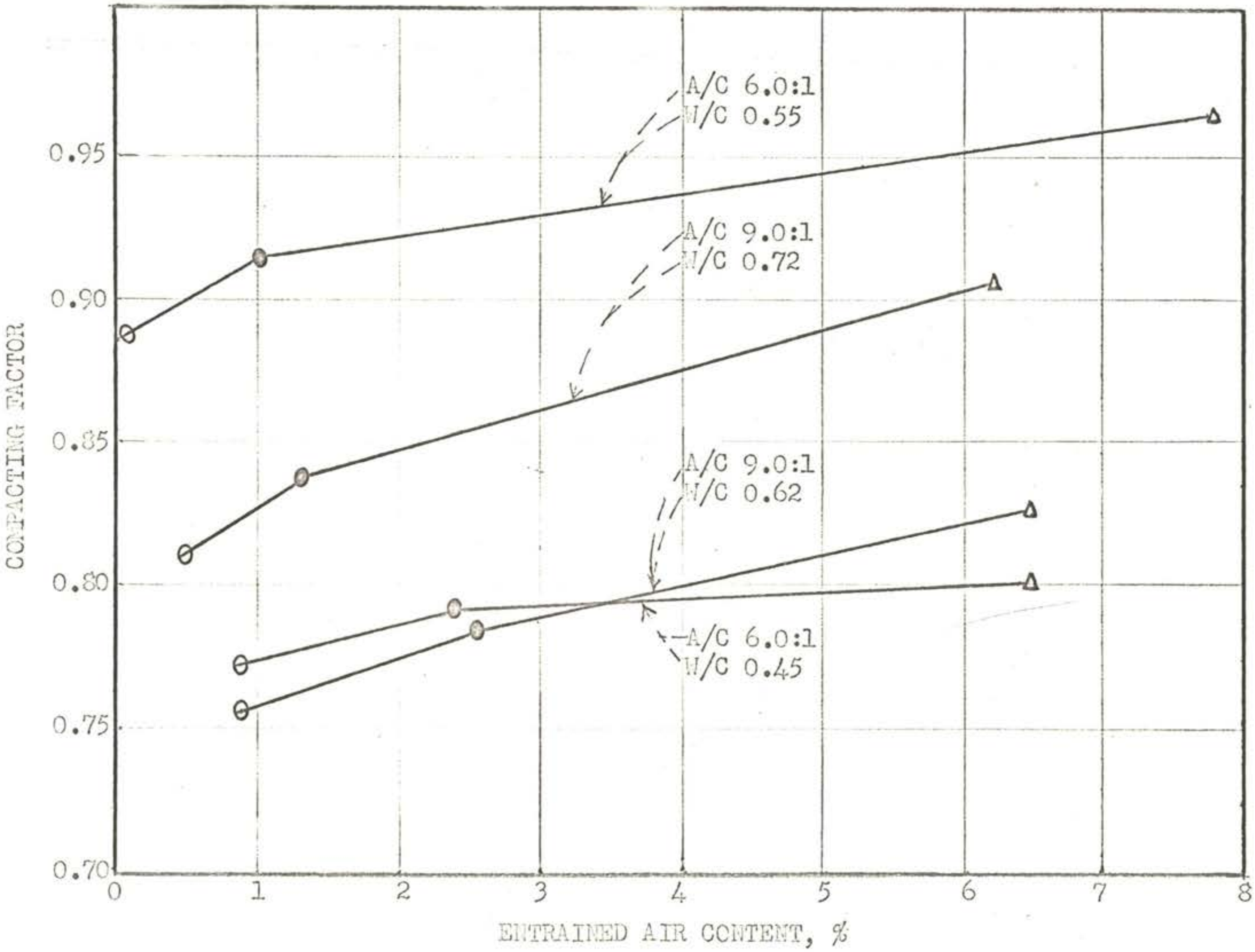

Figure 8. Effect of air entrainment on workability (with 0, 0.01 and 0.03% resin).

particles the air bubbles reduce particle interference. Another theory is that the air bubbles behave as particles of fine aggregate, which are elastic and have negligible surface friction. Neither of the above theories have been proven, but there are arguments for both. Air entrainment also makes a concrete more plastic and, generally, improves its handling qualities.

Most of the surface-active admixtures sold as workability admixtures are marketed under trade names. Many owe their effect to air entraining; but, as this usually reduces strength, this fact is not often stressed. Nearly all of them are mixtures of dispersing, wetting, and air-entraining agents. This makes it impossible to disentangle one effect from another, and no clear guide can be given as to which type should be used. By using certain products from reputable manufacturers, it is possible, however, to increase workability and effect an economy in the total cost with little or no loss in strength.

CHAPTER X

GROUTING AGENTS

General

Grouting mortar must readily and completely fill the space to be grouted and, insofar as practicable, must permanently retain its original volume. Ordinary plastic and fluid mortars are unsatisfactory in these respects because of the inherent tendency of the solid constituents to settle and leave a layer of water at the top surface. This may be minimized by the use of some admixture that possesses the necessary characteristics to produce a grout that can be satisfactorily pumped over long distances at a lower water-cement ratio than is possible with plain portland cement grout.

The water in grout should be kept to a minimum so as to produce a hardened mortar that is dense, impervious, and durable. This will prevent the slow infiltration of water and the consequent leaching out of the cementing medium. The low water-cement ratios needed to produce the desired grout are possible only when the grout mixture includes, in addition to the portland cement and water, a suitable admixture that will "lubricate" the mass, and thus make possible the injection of drier grout mixes at reasonable pressures and without segregation of ingredients.

Some grout mixtures contain sand. For these mixtures, the use of an admixture to entrain air is beneficial in reducing friction during placement. If there is no sand in the grout, no beneficial effect can be obtained by entraining air and, hence, some other solution must be substituted for air entrainment if this effect is desired. When grout is pumped into subaqueous prepacked gravel or any other porous foundation material below the water table, it is mandatory that the ingredients do not segregate as it is deposited under water. Admixtures that will minimize segregation under water are available on the market. Any project on which an extensive grouting program is contemplated should set up a core-drilling and grouting investigation to develop the proper technique for that particular work and to try out various admixtures. There is no other way of satisfactorily solving such problems.

Admixtures Used for Grouting

In situations where grout is used to produce a plugging effect, accelerators may be used in the grout mixture to hasten the setting time. Accelerators most commonly used for grout mixtures are calcium chloride and triethanolamine. Sodium hydroxide and sodium silicate have also been used with success. The use of accelerators is further described in Chapter 2 of this report.

Gas-forming agents can be used when grouting in completely confined areas such as in foundations, in construction joints, or under machine bases. The formation of hydrogen or gas bubbles throughout the mass of the grout results in beneficial effects in the grouting operation and in improvement of grout quality. If unrestrained, free expansion takes place in the grout proportional to the amount of expansive agent. When restrained, the expansive energy in the grout is transformed into pressure. Due to the pressures generated, fine cracks, which otherwise might be bypassed by the flowing grout or be filled with water, may become filled with grout which will set under pressure. The presence of the very small gas bubbles appears to exert a stabilizing influence on the grout mixture in such a manner that the grout is cohesive and water-retentive to a degree not exhibited in corresponding grouts made without expansive agents. These gas bubbles cause reduction in bleeding and segregation, regardless of consistency (9). The most commonly used gas-forming agent is aluminum powder. Because it is generally used in such small quantities (about 1 teaspoonful per sack of cement), and as it has a tendency to float on the mixing water, the powder is usually pre-mixed with fine sand or pozzolan. The use of gas-forming agents is further described in Chapter 5 of this report.

Retarders are especially useful in cement grout slurries, particularly where it may be necessary to redrill grout holes, for grouting over a prolonged period of time, in cases where the grout must be pumped for a considerable distance and where hot water flows are encountered. The retarders, through their dispersing nature, slow down the coalescing of the cement particles. This, in effect, also reduces the amount of water required for the same fluidity. Some of the retarders used in grout mixtures are RDA, SRDA, gypsum, lime sugar, and sodium tannate. The use of retarders is further described in Chapter 3 of this report.

Workability Agents

Admixtures such as diatomaceous earth, pumicite, fly ash, and bentonite may be added to grout mixtures to improve pumpability, reduce settlement, and provide increased economy. Diatomaceous earth and pumicite have a pozzolanic effect and, when added in small amounts, will make a grout thicker and be more cohesive and gelatinous. Fly ash also has a pozzolanic effect and it aids pumpability, retards setting time, and, in some areas, is less expensive than cement. Bentonite aids the retention of the cement particles in suspension during the pumping operation and increases the yield of the hardened grout. The use of workability agents is further described in Chapter 9 of this report.

Where voids are large enough to allow the use of sand-cement grout, the addition of the sand will reduce the cost of the grout mix. The sand-cement grout can be readily pumped by using other admixtures and the proper amount of water. If the voids are small, rock flour and clay may be added to the grout mixture in the interest of economy. However, it must be remembered that the addition of sand, rock flour, and clay to the grout mixture will reduce the strength of the hardened grout.

Admixtures of acceptable quality, properly used, may in some cases effect significant economies and in other cases may make possible construction otherwise difficult or impractical. Though admixtures in general are not a "cure-all" for the many problems of cement grouting, recent developments indicate that admixtures intelligently used contribute to desirable properties of cement grouts. However, since their effects may vary greatly with the chemical and physical properties of other ingredients of the grout mixture, they should not be used indiscriminately. Therefore, careful consideration should be given to the design of grout mixes containing admixtures, and tests to determine their effect should be conducted prior to their use in major construction.

CHAPTER XI

MISCELLANEOUS AGENTS

Cementitious Materials

This group includes natural cements, slag cements, and hydraulic limes. The effects resulting from the substitution of these materials for part of the portland cement generally are an increase in workability and decreases in bleeding, in segregation, in heat of hydration, and, for most of the materials, a decrease in strength. Usually, an increase in mixing water is required when using these materials. This generally causes an increase in drying shrinkage. The curing period needed for development of potential strength is much longer when using these materials for part of the cement than it is when using only portland cement. These materials, when used, are usually substituted for 10 to 25 percent, by weight, of the portland cement. However, larger amounts may be used if lowered strengths are not objectionable.

Coloring Agents

Color can be imparted to concrete by the use of mineral oxide pigments added to the concrete. Coloring pigment suitable for use in concrete should meet the following requirements:

1. It should be of a composition which will not react chemically with the lime of the cement or color.
2. It should be durable under exposure to direct sunlight and also in a lesser degree to diffused daylight.
3. It should possess adequate tinting qualities (10).

Organic pigments should not be used as coloring agents, as they will fade, react with calcium hydroxide, or dissolve in water (10). When color is specified, samples of the colored concrete should be prepared for approval ahead of time, and the same materials used throughout the job. The inspector should see that no changes are made in the sources or proportioning of materials. Pigment should be weighed for each batch and mixed with the cement before placing these materials in the mixer. Uniformity of materials and methods is essential; all batches must be identical in all respects, and all methods of handling the concrete, including finishing and curing, must be unchanged throughout the job.

Mixtures of coloring pigments will produce any desired shade. Depth of color, or varying shades from light to dark, are obtained by controlling the amount of pigment by mixing two or more basic colors such as yellow, red, black, and blue.

When dark colors of concrete are desired, ordinary portland cement may be used in the concrete mix. For the lighter shades such as orange, green, tan, and blue, white cement must be used to obtain maximum color value.

Control of the amount of water in a colored concrete mix is very important. Variations in the intensity and shade of the hardened concrete will occur if there are fluctuations in the amount of water per batch. Too much water will tend to increase the possibility of efflorescence. The mixes should be kept as dry as possible to minimize efflorescence.

Generally, pigments may be safely used in amounts up to 10 percent of the weight of the cement. Since larger quantities of pigment may reduce the final strength of the concrete, it is not advisable to exceed the 10 percent addition of color in any concrete mix. However, this limit may be exceeded with some pigments and under certain conditions.

CHAPTER XII

SUMMARY AND CONCLUSIONS

Today, most of the concrete placed in the United States has added to it an admixture of one type or another. These admixtures play an important role in achieving properly engineered concrete mixes that are specifically designed to meet requirements of a given job at the lowest cost.

An admixture should always be evaluated according to its effectiveness in producing the specific properties desired in concrete. This may require data on its effect on durability, strength, volume change, bleeding, and plasticity including probable reduction of water-cement ratio. These are several ways of obtaining the desired results of each of these properties. The use of an admixture should be considered as only one of the possible means that should be compared. For example, assume it is desired to bring about an improvement in workability. This may be done by enriching the mix, by correction of aggregate gradation, or by the use of any one of many available admixtures. If it is desired to increase the strength of a concrete, it should be remembered that there are several admixtures that will produce this effect, and that an equal increase in strength could be obtained by any of at least four possible changes in mix: changes in consistency, richness, gradation, or size of aggregate.

An admixture, when added to concrete, often changes the volume of the concrete. When this happens, the changes in the amounts (per cubic yard of concrete) of the original materials will be increased or decreased. If the admixture increases the volume of the concrete, the admixture must be regarded as causing a displacement either of part of the original mixture or of the original materials---cement, aggregate, or water. These changes in volume of the concrete must be considered when evaluating the direct effect of the admixture itself, and in estimating the cost of the admixture.

The handling of an extra ingredient, and any effect the use of the admixture may have on the transporting, placing, and finishing must be considered when evaluating the total cost of the admixture.

As can be seen, the use of an admixture may increase the cost of the concrete. Therefore, the value of an admixture should be weighed against its cost before selecting it for a particular job. Also, the accurate evaluation of an admixture requires that its cost be compared with that of other materials or methods which also give the desired results.

The effectiveness of a particular concrete is influenced considerably by the characteristics of the cement and aggregate and their relative proportions. For this reason, the evaluation of an admixture for a particular job should be based on the results obtained with the same type concrete that will be used on the job.

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