5-1961

The Influence of Water-Reducing Admixtures on the Curing of Concrete

Wallace Don Budge

THE INFLUENCE OF WATER-REDUCING ADMIXTURES ON THE CURING OF CONCRETE

by

Wallace Don Budge

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil Engineering

Approved:

Major Professor

Head of Department

Dean of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

1961

ACKNOWLEDGEMENTS

Sincere acknowledgement is extended to Professor William A. Cordon who supervised the research and gave generous assistance.

Appreciation is also expressed for the use of Civil Engineering Department facilities, equipment, and materials.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The use of water-reducing admixtures in concrete has grown continuously since their introduction over 25 years ago, with a present estimated usage in the production of 25 million cubic yards of concrete annually in the United States alone. Opposition to anything added to concrete, other than cement, aggregates, and water, is gradually disappearing, and considerable recognition is being given to the value of using other ingredients.

The research contained in this study may be divided into two portions: tests to determine the rate of volume change of cement paste and compressive strength tests to indicate the effect of moist curing on rate of strength gain. Both portions were carried out with plain (no water reducer added) and treated (containing water reducer) mixes.

The results indicate that a much greater volume change occurs in admixture-treated cement pastes than in plain pastes. The theory is advanced that this greater volume change, when a water-reducing admixture is used, represents a more rapid combination of cement and water. This supports the strength test results showing that water reducers lead to high early compressive strength of concrete.

REVIEW OF LITERATURE

Nature and Function of Water-Reducing Admixtures

Water-reducing admixtures are materials generally consisting of certain organic compounds or mixtures which, when added to portland cement concrete, markedly increase the fluidity, other than that effected through air entrainment of the concrete. When such admixtures are used to produce concrete of slump equal to that of plain or plain air-entrained concrete of the same design, a significant reduction in water content is thereby made possible. This is desirable from the standpoint of both fresh and hardened concrete properties. Water-reducing admixtures are normally designed to have negligible effect on the setting properties of concrete, but may be modified for special purposes to produce either an accelerating or retarding effect on the concrete when desired.

When retardation is desired, the admixture is designed to delay in a controlled manner initial and final set beyond the normal setting time for the plain or plain air-entrained concrete. Thereafter, however, it is to have no effect upon the rate of strength development or the properties of the concrete. Generally, these set-retarding admixtures also permit water content reduction and thus combine the functional benefits of water reduction with initial retardation.

Prior and Adams (9)* further state that although there are some differences in the chemical nature and chemical composition of the

---

*This and similarly designated numbers refer to references in the Literature Cited section.

water-reducing and the set-retarding admixtures, and although there may be some difference in the effect that these admixtures have on some of the qualities of plactic and hardened concrete, the fundamental influences on water requirement and retardation are basically the same.

The commonly used water-reducing and set-retarding admixtures may be classified in the following categories:

1. Lignosulfonic acids and their salts.

2. Modifications and derivatives of lignosulfonic acids and their salts.

3. Hydroxylated carboxylic acids and their salts.

4. Modifications and derivatives of hydroxylated carboxylic acids and their salts.

Many substances have been considered as water-reducing or set-ratarding admixtures for concrete. Many of these substances were suggested for certain specific applications. Some had undesirable effects upon the properties of the plastic or hardened concrete, and few attained technical or commercial significance. It is generally recognized that present day usage of water-reducing admixtures and initial-retarding admixtures in concrete had a beginning in the disclosures by Tucker,[1] Scripture,[2] and Winkler[3] of the effect of small quantities of organic compounds on the fluidity of portland cement pastes and concrete mixtures. These investigators showed that the

---

[1]G. R. Tucker, U. S. Patent No. 2,141,569 (1938)
[2]E. W. Scripture, U. S. Patent No. 2,169,980 (1939)
[3]K. Winkler, U. S. Patent No. 2,174,051 (1939)

addition of small quantities, on the order of 0.02 and 0.50 per cent based on the weight of the cement, of certain chemical substances profoundly affected the fluidity of the paste such that a significant reduction in the water-cement ratio could be made to produce concrete mixtures of a slump equal to that of the untreated concrete. Thus, in accordance with Abrams' (1) finding, that for a given combination of materials the strength and other desirable properties of concrete mixes vary almost directly with the ratio of cement to mixing water, concrete of greater strength would result. Subsequent investigations have shown that strengths greater than those anticipated by the water-cement ratio law are usually obtained (4,9,12,13).

According to Prior and Adams (9), portland cement, in its normal state, is flocculated to some degree; that is, particles are held together, weakly, by forces of attraction between them. In the paste of portland cement concrete, we are dealing with suspensions of particles which are unstable physically and chemically, due to hydration which commences immediately when the particles are wetted. In the presence of a water-reducing admixture and at the time of initial contact with water, dispersion phenomena predominate. This does not mean that each cement particle is free to act independently of all others. But it does mean that the reduction in the forces of attraction between them permits greater mobility of the particles; that water freed from the restraining influence of a highly flocculated system is now available to lubricate the mix and provide a wetter consistency. As a result, the water content of a concrete mixture of a given consistency may be substantially reduced.

The cement flocs are not dispersed by the addition of a dispersing agent, but rather the particles are held apart once the flocs have been broken up; that is, the breaking up of the flocs is accomplished by mechanical action of a mixer and then the particles are held apart by physicochemical means. The separation of the particles of cement by the dispersant results in minimum resistance to movement of the grains which, in effect, is lubrication; and this lubricating effect results in decreased water requirement for any given consistency.

Powers (8) has stated that the attraction between cement and water is so strong that each cement grain becomes completely surrounded by water even though in dilute suspension the grains are clustered. Scripture (10) has suggested that experience with other hydrophilic solids, such as clays, would indicate that complete wetting of the surfaces of the flocculated cement is improbable. One of the effects of deflocculation or dispersion would be to expose more surface area of the cement to water and to possibly more complete hydration at earlier ages of the concrete. This, together with a more uniform distribution of the cement throughout the concrete and over the surface of the aggregate, could account for observed strength increases greater than those anticipated by Abrams' law.

Cordon (2) indicates that more rapid combination of cement and water which may result in more complete cement hydration would be highly desirable considering the lack of curing on some structures. It has been noted in the field that small quantities of concrete that spill out of forms and dry in the sun were much stronger when water-reducing admixtures were used.

Uses and Practical Aspects of Water-Reducing Admixtures

Mielenz (6) indicates that the purposes for which water-reducing admixtures and set-retarding admixtures are used in concrete construction include the following:

1. Economy of proportioning of the concrete mixture, such as use of minimum cement content, use of aggregate characterized by high water requirement, and improved uniformity of concrete.

2. Economy in concreting operations, such as reduction of the total cost of concrete making materials, early form removal and reuse, and ease of placing and finishing.

3. Meeting requirements of job specifications, such as maximum permissible water-cement ratio, early strength development, minimum development of strength and elasticity, and retention of workability.

4. Improvement of the quality of fresh concrete, such as improved and prolonged workability, reduced water content for given consistency or increased slump at constant or reduced water content, improved finishing qualities, control of bleeding and segregation, and control of plastic cracking.

5. Improvement of quality of hardened concrete, such as increased early and ultimate strength and elasticity, decreased permeability and absorption, increased resistance to scaling and deterioration due to freezing and thawing, increased abrasion resistance, decreased crack development, and increased bond with reinforcement.

6. Inducing desirable properties, such as controlled retardation to compensate for adverse ambient conditions or to permit introduction of special concreting practices.

In practice, then, water reduction is the corresponding effect of making a given water content go farther. In so doing a greater slump is provided without exceeding the water content for a lower, but sometimes impractical slump. Water reduction may be used to compensate for job conditions or equipment that inherently demand more water and sometimes more slump than others. One example is to offset to some degree the higher water requirement at higher temperatures. Another is to offset the higher water requirement used for higher slumps to allow for greater slump loss in concrete hauled long distances in truck mixers, particularly in warm weather. Another is to compensate for higher slumps than are sometimes desired in order that truck mixers may discharge expediently (12).

Beneficial application of water reducers may be made in at least the specific areas of prestressed concrete, tunnel linings, pavement and other slabs, slip forming, prefabricated concrete units, and mass concrete.

Effect of Water-Reducing Admixtures on Concrete Properties

The addition of a water-reducing admixture in a mix causes several changes in concrete properties, some of which are desirable, some may be undesirable.

Among those properties which may be notably affected are:

1. Strength
2. Workability
3. Consistency
4. Bleeding

Strength

Tuthill, Adams, and Hemme (12) point out that ordinarily, at the same cement content and slump, reduction in mixing water is expected to increase strength in accordance with the long recognized strength water-cement ratio relationship. Within the common range of water-cement ratios for good concrete, say 0.45 to 0.58, 28-day strength increases, in very round numbers, are about 100 psi for each reduction of 0.01 in water-cement ratio. An 8 per cent reduction in mixing water requirement would reduce a water-cement ratio of 0.50 to 0.46. According to this "approximate rule," there would be a resulting strength increase of about 400 psi at 28 days.

When such a water reduction is obtained by use of a water-reducing admixture, the increase in strength is usually considerably more than would be expected from the "approximate rule." Twice the expected increase is common, and an even greater increase is not unusual.

With the use of retardant admixtures, the question naturally arises as to its influence on strength at the time forms must be removed. Tuthill, Adams, and Hemme (12) report 10-, 12-, or 16-hour strengths obtained with several admixtures and 12-hour strengths at various initial temperatures and dosages of concrete used in tunnel linings. From these values it appears evident that in most cases normal dosages of the admixtures tested do not reduce early strength significantly below that of concrete in which no admixture was used. It was also shown that neither concrete with or without an admixture would be strong enough in 12 hours for form removal where initial temperatures were below 70 to 75 F.

Even with no reduction in water content, strength is sometimes slightly improved. Often a combination of some increase in slump, some reduction in water, and some increase in strength is obtained from using a water-reducing admixture.

Wallace and Ore (14) reported test results which show that even with lower cement content, concretes incorporating the water-reducing agents generally had higher strengths than companion control specimens at all ages through 5 years. The possibility of obtaining both cement reduction and higher quality concrete is indicated by tests performed with Glen Canyon materials. In these tests, the addition of a lignin agent more than offsets the strength diminishing effect of a 5 per cent cement reduction. The 28-day compressive strength of 18- by 36-inch cylinders containing lignin agent and 5 per cent less cement exceeded that of the control cylinders by 22 per cent.

Properly formulated retarders should delay the rate of initial hardening (4) but not interfere with early strength development. As a matter of fact, a reliable retarder of the water-reducing type should accomplish both functions.

Workability

According to Wallace and Ore (14), the principal contribution of water-reducing retarding agents toward improved workability is through their ability to extend the length of time in which concrete can be consolidated by vibration, thus reducing the risk of obtaining cold joints.

Additional benefits include surface retardation which, under moderate temperature and humidity conditions, permits more time between floating and troweling operations. In some cases, this may be desirable. Furthermore, water-reducing agents may lessen the effort required to pump concrete through pipelines.

Vollick (13) indicates similar findings; reporting that water reducers and set retarders may improve workability over that of plain concrete at a given water content or water-cement ratio by decreasing the work necessary for manipulation. They may increase compaction, which is reflected in higher unit weight. Retarders increase the period over which fresh concrete can be mixed, placed, and compacted.

Tuthill, Adams, and Hemme (12) report that no noticeable difference could be observed in the workability of concrete with and without the admixtures when the slump and air content of the concretes were the same.

Consistency

Flow characteristics or mobility of plastic concrete is improved when water reducers or set retarders are incorporated in the mixture. If the water content is maintained constant, slump is increased. An increase in slump may be particularly important where concrete with very low water content is used. Admixtures have increased slump 2 to 3 inches without increasing water or reducing strength when additional mobility was required for placing (13).

Presumably because most of the water-reducing admixtures were also retarders in that they increase the time required to reach the vibration limit (12), it has been taken for granted by many that these admixtures also reduce or postpone slump loss. Unfortunately, such a helpful effect is not confirmed in many tests of slump loss.

Wallace and Ore (14) state that the ease of handling concrete, as gaged by slump loss, is not greatly changed by the addition of water-reducing retarding agents. In fact, in a few cases, these agents have induced an increased rate of slump loss.

Cordon (2), in referring to rapid slump loss of concrete made with water-reducing admixtures, stated that this loss may be partially explained by increased rate of absorption. Mixes containing identical proportions of cement and water indicate that the increased wetting action of water containing water-reducing admixtures increased the rate of absorption of water by cement.

Bleeding

Vollick (13) states that water-reducing and set-retarding admixtures that entrain air will reduce bleeding and settlement of plastic concrete compared with plain concrete having the same mix proportions and slump. Bleeding can be reduced by air entrainment alone, but greater reduction in bleeding at the same air content can be obtained if the concrete contains a water-reducing admixture. Reduced bleeding in admixture concrete is attributed to the reduction in water requirement in addition to the air-entraining effects.

Water-reducing or set-retarding admixtures that do not entrain air may modify bleeding characteristics by increasing the rate and capacity to bleed clear water. Rapid bleeding reduces the total amount of water in the plastic concrete and may be partially responsible for the increased strengths obtained with concrete containing admixtures that promote bleeding.

Cordon (2) indicates that the "drying out" problem on concrete slabs before the concrete sets can be traced to reduced bleeding. The surface dries before the final finish is applied and finishers complain of sticky concrete. Admixtures alone do not control bleeding, and in concrete which tends to bleed excessively, the admixtures are a definite benefit to the finisher.

Effect of Cement Composition on Properties of Concretes Containing Water-Reducing Admixtures

During early investigations with water reducers and with set retarders for use in grouts and in concretes, Polivka and Klein (7) report the observation that the effectiveness of these admixtures was influenced by the composition of the portland cement. As a result of these findings, more comprehensive investigations were carried out to evaluate the properties of a large number of concretes containing various portland cements and the most common types of water reducers and set retarders.

It was demonstrated that the portland cement composition has a significant influence on the effectiveness of water reducers and set retarders in performing their function at both early and later ages of concrete hardening.

Although some water reducers cause entrainment of air, the presence of additional air in the concretes did not seem to affect the general relationship between their performance and the chemical composition of the portland cement.

The effectiveness of a water reducer in improving compressive strength appears to be related to the alkali and C_3A contents of the portland cement. The admixture is more efficient in improving the compressive strengths of concretes containing the cements of moderate alkali content (cements Nos. 3 and 4) than of those containing the high alkali cements (cements Nos. 1 and 2).

Average values show that the admixture when used in concretes containing type II cements produced an increase in compressive strengths that was on the average about 10 per cent greater than that observed for concretes containing type I cements.

Other than the relations of water reducers to cements noted for C_3A and alkalies, there appears to be no other significant relationship between composition of cement and performance of admixture.

It may also be pointed out that induced retardation may increase exponentially with dosage. This indicates clearly the danger of accidental overdosage with some retarders when used with certain cements.

This overdosage may result in excessive retardation, delay removal of forms, and necessitate longer curing periods. Normally the dosage recommended by the manufacturer should be used, unless a specific degree of retardation is desired and tests have been made to determine the correct proportion of admixture required. Cordon (2) indicates that field and laboratory experience leads to the conclusion that the quantity of water-reducing admixture used in concrete is not critical within reasonable limits (0.15 to 0.30 per cent by weight of cement).

Vollick (13) points out that proven retarders will not cause permanent damage to concrete if accidentally used in excess, provided the concrete is protected from drying by fog spraying or other methods, and forms are not removed until control cylinders indicate satisfactory strength has been attained.

Air Entrainment

Vollick (13) states that some of the basic chemicals used and some of the products marketed as water reducers or set retarders cause entrainment of air in concrete, in addition to influencing water requirements or setting time of concrete, or both. Air entrainment also increases plasticity and is partly responsible for the water reduction possible with these materials.

Class 1 admixtures generally entrain 2 to 3 per cent air, but higher air contents are sometimes obtained. Class 3 admixtures do not ordinarily entrain air. Either class may be modified to entrain air and become class 2 or 4 admixtures, respectively. Class 2 and class 4 admixtures may or may not entrain air depending upon the modifications that were made. If the modifications do not include the addition of an air-entraining agent, they will not entrain air or will entrain only limited amounts.

The amount of air entrained may vary with the quantity of admixture added, the cement brand or type used, the temperature, and the mix consistency (lean mixes entrain more air than richer mixes).

Water and cement reduction

Manufacturers of water-reducing admixtures properly claim increased workability of the concrete with the use of their admixture. Put another way, the desired slump may be maintained while the water content is reduced (5). If the water is reduced, cement may also be reduced with no loss of compressive strength. This planned reduction of cement in a concrete design is sometimes beneficial and economical. The per cent of water reduction to maintain original slump is generally 5 to 15 per cent. Polivka and Klein (7) indicate that water reducers used in amounts appropriate to the composition of a given cement will usually allow this same 5 to 15 per cent reduction in cement content without loss in compressive strength.

Variability

Cordon (2) presents data indicating that considerably less water needs to be added to increase slump from 2 inches to 8 inches when a water-reducing admixture is used than when none is used, and that the decrease in strength resulting from such a change is correspondingly less. Test results would indicate that with a water-reducing admixture, we have a built-in factor of safety for high water requirements which greatly reduces the variation of water-cement ratio and variations in quality.

EXPERIMENTAL DESIGN, MATERIALS, MIXING, CURING AND TESTING

Experimental Design

The experiment was set up in 3 series. Series 1 consisted of 4 to 5 control or plain specimens and 3 specimens containing water-reducing admixture for each length of curing period. The control and treated mixes were identical except for the addition of the reducer to the treated mortar. Both had a water-cement ratio of 0.55.

In series 2 the water content was reduced so that the consistency of this mix compared with that of the control in series 1. All specimens in series 2 contained water reducer, the control being the same as for series 1.

Series 3 consisted of specimens with both reduced water and cement content. The water reduction was the same as that of series 2, and the cement was reduced an amount such that the water-cement ratio equaled that of series 1 or 0.55.

All specimens were tested in compression 16 days after casting.

Materials

Aggregate

Sand was the only aggregate required in the concrete mix. To reduce the possibility of test variation due to this constituent, all sand used in the study was thoroughly mixed and placed at saturated and surface-dry condition in air-tight containers to prevent moisture loss before testing began.

Table I shows the results of a sieve analysis on the sand used.

TABLE I

SIEVE ANALYSIS OF SAND

Sieve Number	Weight Retained (g)	Per Cent Retained
4	0	
8	102	17.4
16	122	20.8
30	113	19.2
50	125	21.3
100	100	17.0
Pan	25	4.3
Total	587	100.0

Cement

Three cement brands within each of type I and type II cements were used throughout the experiment. These brands will be designated as I, E, and M.

The chemical analysis and calculated compound composition of each of these cements are given in Table II.

Volume change of cement paste. Each cement used in the study was tested for the rate of volume change at 0.55 water-cement ratio and 0.00 and 0.20 per cent water-reducing dosage by weight of cement. In addition, tests were conducted to determine the shrinkage rate of brand I, types I and II, at 0.45 and 0.65 water-cement ratios and 0.15 and 0.25 per cent admixture dosages by cement weight.

These tests were made, using only cement paste, in the following manner:

Mixing water was prepared containing the determined dosage of water reducer. The correct proportion of cement was then added to the rotating mixer, Figure 1. Mixing continued 45 seconds after which the

TABLE II

CHEMICAL ANALYSIS AND CALCULATED COMPOUND COMPOSITION OF CEMENTS

Cement Brand	Type I			Type II		
	I	E	M	I	E	M
PCA Lot No.	19691	19693	19695	19692	19694	19696
SiO_2	21.05	21.58	22.06	22.35	22.83	21.83
Al_2O_3	5.63	5.67	5.64	4.82	4.77	5.07
Fe_2O_3	2.75	2.29	2.80	3.45	2.83	4.54
CaO	62.70	64.16	64.00	62.80	64.54	63.91
MgO	2.76	1.83	1.05	2.94	1.56	0.87
SO_3	2.65	1.79	1.69	2.01	1.91	1.87
Na_2O	0.17	0.16	0.13	0.23	0.09	0.10
K_2O	0.67	1.02	0.80	0.46	0.64	0.68
Tot. Alk. as Na_2O	0.61	0.83	0.66	0.53	0.51	0.55
Loss on Ign.	1.70	1.52	1.67	1.13	1.08	1.25
Ins. Res.	0.40	0.17	0.15	0.28	0.09	0.19
Free CaO	0.76	1.56	1.02	0.69	0.70	0.64
Fineness Blaine sq.cm. per g	3550	3025	2970	3190	2945	3100
Calculated Compound Composition % *						
C_3S	45.9	50.6	46.1	42.7	47.6	48.3
C_2S	25.8	23.8	28.6	31.9	29.6	26.2
C_3A	10.3	11.2	10.2	6.9	7.9	5.8
C_4AF	8.4	7.0	8.5	10.5	8.6	13.8

*Not corrected for free CaO.

paste was quickly discharged into two Erlenmeyer flasks holding approximately 560 milliters each. At 2 minutes after mixing began, the flasks were screeded level full with a straight edge or brought up to this level, if necessary, by adding water from burette tubes, Figure 2. The burette levels were recorded at this 2-minute time, at each 2-minute interval up to 12 minutes, and at 30 and 60 minutes in each instance bringing the total volume in the flasks up to the 2-minute level before reading. The difference between any two successive readings on each burette gave the volume change of the paste over that corresponding time interval for that flask. The average of the two burette readings was considered to determine the volume change of a particular paste. This change was then expressed in terms of a per cent volume change by dividing by the flask volume.

Water-reducing admixture

The water-reducing admixture used throughout was of class 1 (lignosulfonic acids and their salts). In its commercial form, this admixture is in powder form. For application convenience, the powder was dissolved in water to form a 10 per cent solution of admixture by weight of water. Sufficient reducer was prepared for the complete study before testing began and was added, at the appropriate dosage by weight of cement, to the mixing water at the time of batching.

Mixing water

Mixing water was plain culinary water which, for the purpose of reducing variations due to temperature, was placed in a tank and allowed to assume a constant temperature.

Mixing

The concrete mortar was all mixed with a small electric-driven mortar mixer. All mix components except the admixture were batched by weight to the nearest gram; the admixture was measured in by volume having been prepared in liquid form. The cement was mixed with the water forming a slurry followed immediately by the sand. In the case of the admixture-treated mixes, the water reducer was added to the mixing water.

To insure uniform mixing, all mortars were mixed 1 minute after all ingredients had been added, permitted to rest 2 minutes, and finally mixed 1 minute.

Curing and Testing

Unit weight

Immediately after mixing, a mortar sample was rodded, in two layers at twenty blows per layer, into a cone penetrometer (3) container. The container, which has an approximate volume of 400 milliliters, was screeded level full with a straight edge and weighed, Figure 3. This weight together with the empty container weight and the known volume of the container permitted the unit weight determination.

Air content

Knowing the unit weight of the batch permitted calculation of the batch volume. Assuming specific gravities of 3.15, 2.65, and 1.00 for cement, sand, and water respectively, the total solid volume of the batch could be calculated. The difference between batch and solid volumes gave the volume of air in the batch, which was expressed as a percentage of the batch volume.

Consistency

The consistency of the concrete mortar was measured by a cone penetrometer following the preparation and weighing of the sample for unit weight determinations. The consistency of each batch was determined as the distance, in millimeters, the inverted cone penetrated the sample according to the method described by Cordon (3), Figure 4.

Preparation and curing of specimens

After mixing and taking weight and consistency measurements, the cement mortar was placed in 2-inch by 2-inch cube molds according to ASTM procedures (ASTM C 109-56) (11), Figure 5. Fifteen to twenty-five specimens were molded from each batch and placed immediately in a moist cabinet where the humidity was near 100 per cent. Three admixture-treated and, in most cases, five plain specimens were cast for each moist curing period of ½, 1, 3, 7, and 14 days. After 12 hours, the molds were removed, the ½-day specimens placed in an oven at 100 C temperature, and the remainder submerged in water for curing. As each determined curing period terminated, the cubes were placed in an oven where they remained until age 16 days at which time strength tests were made.

Testing

All specimens were tested to failure in compression at each curing period according to ASTM procedures (11) on a Tinius Olsen hydraulic machine at age 16 days, Figure 6. Strengths which differed by more than 10 per cent from the average value of all test specimens made from the same sample and tested at the same period were discarded (11). The average strength of the remaining specimens was then determined in terms of pounds per square inch.

It was thought that the compressive strength test variability might be reduced by using a small compression apparatus composed of a steel ball and two hardened steel plates, Figure 7. The probability is high that the large head on the testing machine does not swivel sufficiently to permit equal stress distribution across the surface of the cube, especially at low loads. The small head devised was extremely sensitive and thus adjusted to misalignment of the large head with negligible pressure.

Each of the hardened steel plates is one inch thick and two inches square. The plate sockets, into which the 3/8-inch steel ball fits, are 1/8-inch deep leaving a 1/8-inch space between plates.

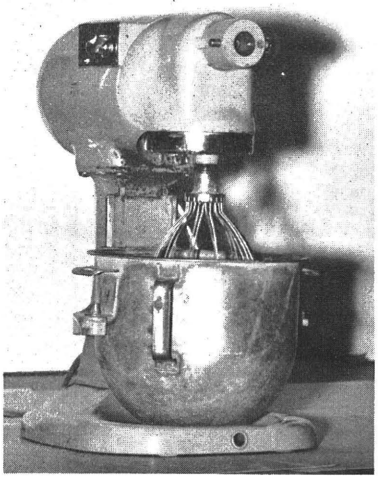

Figure 1. Electric Mortar Mixer

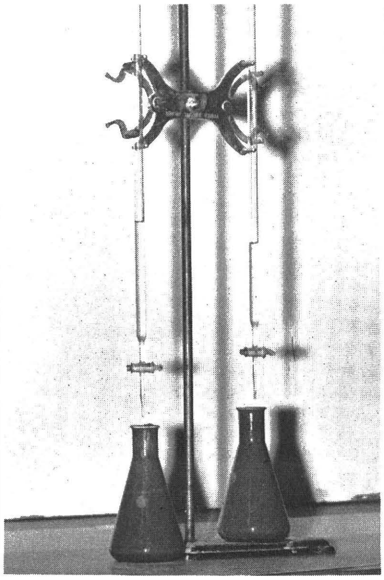

Figure 2. Determining Cement Paste Volume Change

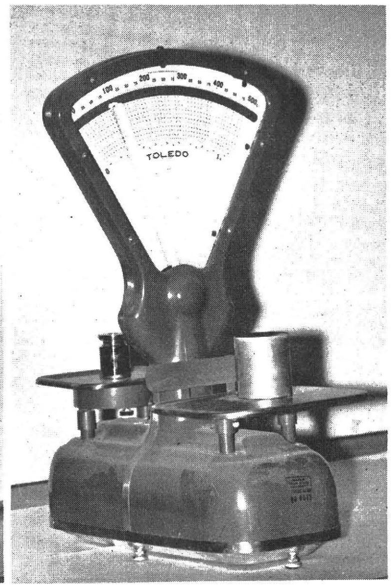

Figure 3. Unit Weight Measurement

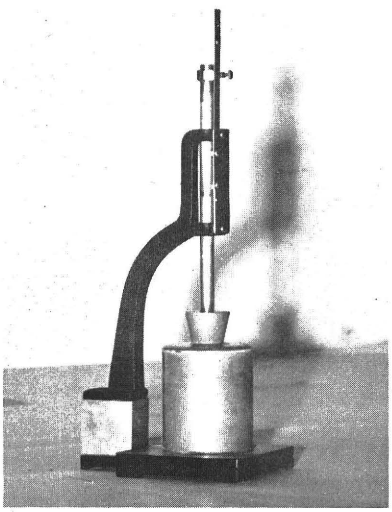

Figure 4. Cone Penetrometer

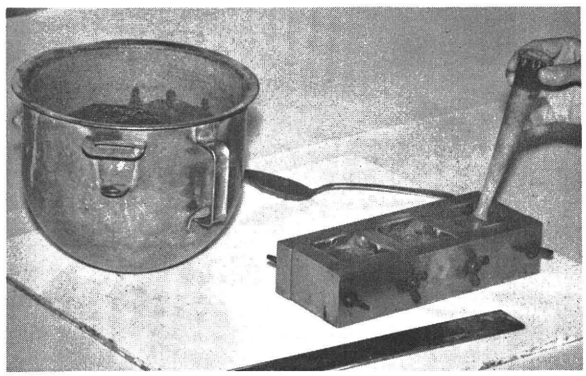

Figure 5. Preparing Mortar Cubes

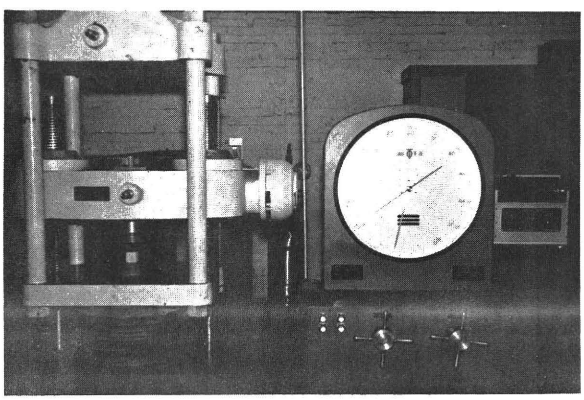

Figure 6. Hydraulic Press

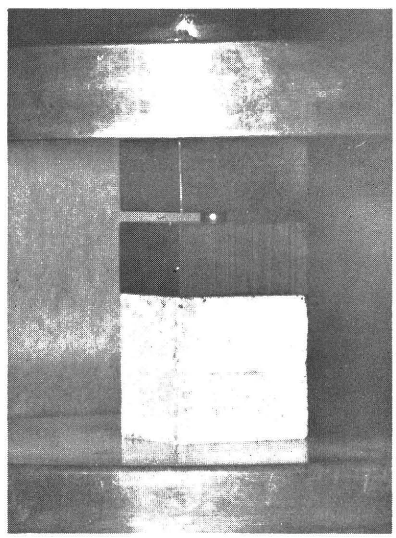

Figure 7. Small Compression Head

RESULTS OF TESTS

Materials

Cement paste volume change tests

Table III summarizes the results of shrinkage tests performed on all brands of both type I and type II cements with a constant water-cement ratio of 0.55 and a water-reducing admixture (WR) dosage of 0.20 per cent by weight of cement. Each value is an average of two volume changes as already explained.

TABLE III

RATE OF CEMENT PASTE VOLUME CHANGE

w/c = 0.55

Cement Type	Cement Brand	WR % wt.cem.	% Volume Change at Time (min.) 2	4	6	8	10	12	30	60
I	I	none	0	.072	.072	.089	.089	.107	.214	.411
I	I	.20	0	.179	.250	.286	.358	.358	.375	.428
I	E	none	0	.036	.054	.172	.172	.072	.107	.125
I	E	.20	0	.072	.179	.268	.322	339	.411	.518
I	M	none	0	.036	.036	.036	.036	.036	.125	.304
I	M	.20	0	.161	.250	.357	.464	.518	.625	.750
II	I	none	0	0	0	0	0	0	.072	.107
II	I	.20	0	.179	.232	.268	.304	.340	.411	.482
II	E	none	0	.036	.036	.036	.036	.036	.036	.036
II	E	.20	0	.143	.179	.286	.393	.428	.554	.625
II	M	none	0	.018	.018	.018	.036	.036	.072	.196
II	M	.20	0	.125	.196	.304	.375	.464	.571	.661

For the purpose of determining the effect of varying both water-cement ratio and admixture dosage on the rate of volume change, tests were made using types I and II of brand I cement with water-cement ratios of 0.45 and 0.65 and reducer dosages of 0.15 and 0.25, in addition to those tests on these cements described in the previous paragraph. The results of these tests appear in Table IV together with the results of brand I cement recorded in Table III.

To better compare the volume change rates of plain and treated pastes, the average changes for types I and II and brands I and E were averaged and plotted in Figure 8. The shrinkages for both types of brand M cement were omitted because of excessive amounts of air which were entrained in the treated pastes.

Representative plots from Table IV appear in Figures 9 and 10 and indicate the effects of the water-cement ratio and admixture dosage, respectively, on the volume change rate of cement.

TABLE IV

RATE OF CEMENT PASTE VOLUME CHANGE

CEMENT BRAND I

Cement		WR	% Volume Change at Time (min.)							
Type	w/c	% wt.cem.	2	4	6	8	10	12	30	60
I	.45	0	0	.054	.089	.089	.125	.125	.304	.482
I	.55	0	0	.072	.072	.089	.089	.107	.214	.411
I	.65	0	0	.036	.056	.071	.107	.143	.214	.357
I	.45	.15	0	.125	.197	.268	.304	.322	.357	.500
I	.55	.15	0	.196	.304	.322	.357	.393	.482	.589
I	.65	.15	0	.125	.196	.304	.339	.393	.464	.535
I	.45	.20	0	.161	.214	.250	.304	.339	.411	.535
I	.55	.20	0	.179	.250	.286	.358	.358	.375	.428
I	.65	.20	0	.178	.268	.321	.339	.375	.375	.411
I	.45	.25	0	.107	.178	.214	.232	.250	.286	.428
I	.55	.25	0	.143	.178	.232	.250	.286	.357	.446
I	.65	.25	0	.054	.125	.178	.232	.250	.322	.428
II	.45	0	0	.018	.036	.036	.036	.036	.054	.125
II	.55	0	0	0	0	0	0	0	.072	.107
II	.65	0	0	0	0	0	0	0	0	0
II	.45	.15	0	.071	.143	.214	.268	.268	.392	.500
II	.55	.15	0	.107	.178	.250	.286	.321	.357	.393
II	.65	.15	0	.054	.143	.214	.268	.321	.375	.411
II	.45	.20	0	.054	.143	.286	.304	.357	.500	.606
II	.55	.20	0	.179	.232	.268	.304	.340	.411	.482
II	.65	.20	0	.089	.125	.196	.232	.268	.321	.357
II	.45	.25	0	.143	.196	.286	.339	.375	.518	.625
II	.55	.25	0	.107	.125	.178	.196	.250	.322	.446
II	.65	.25	0	.143	.286	.375	.428	.518	.607	.660

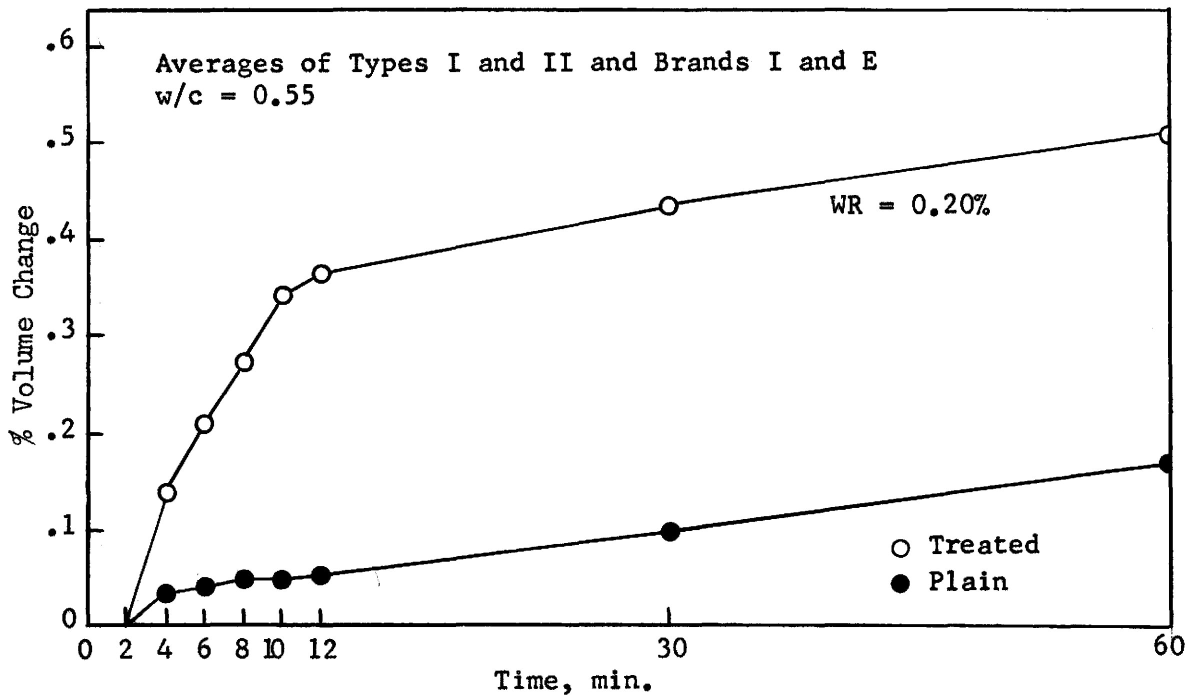

Figure 8. Rate of Cement Paste Volume Change

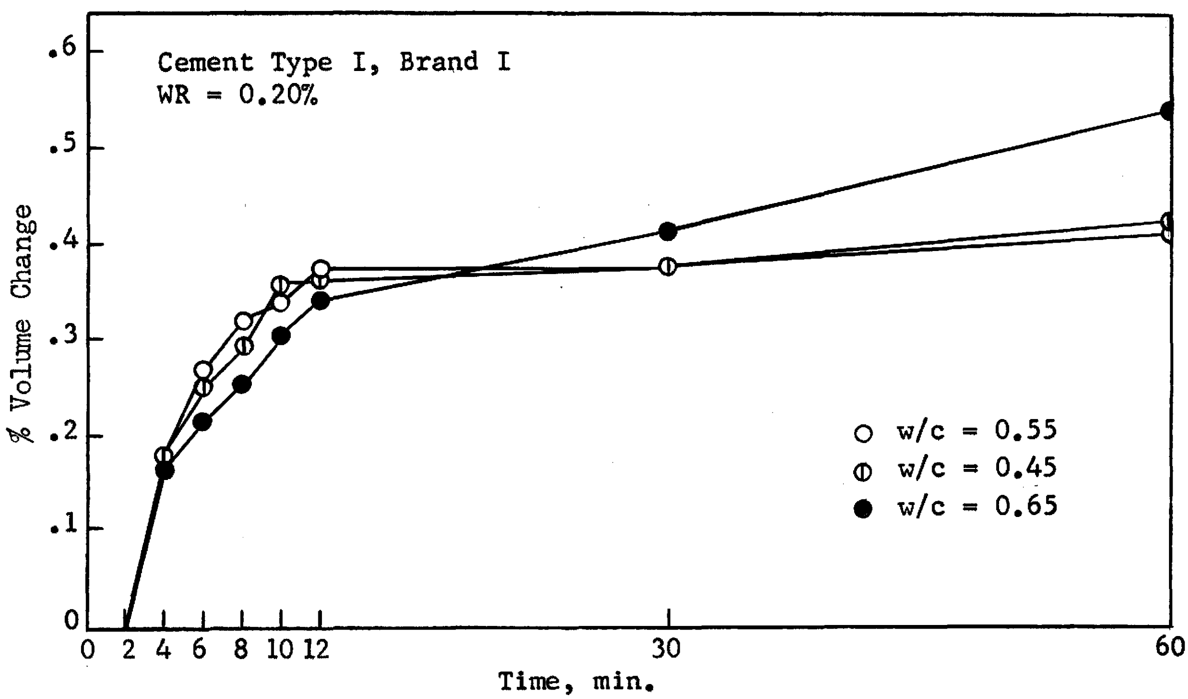

Figure 9. Typical Rate of Cement Paste Volume Change

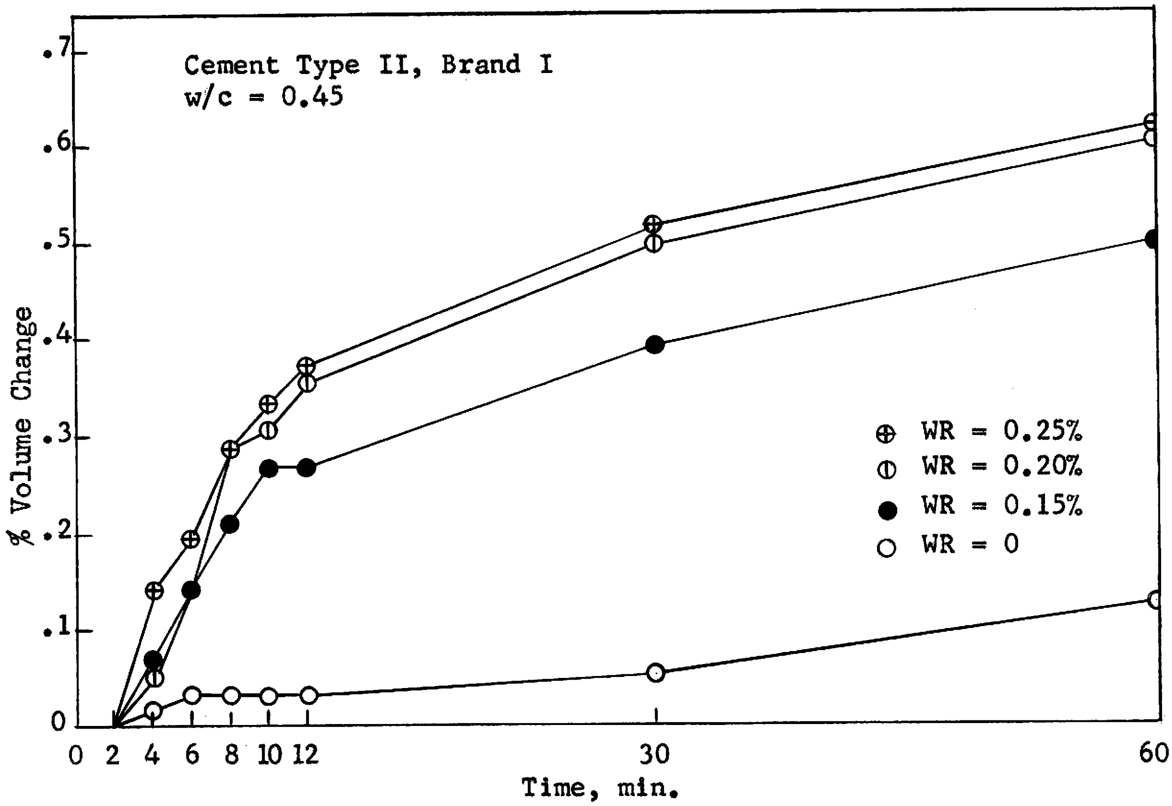

Figure 10. Typical Rate of Cement Paste Volume Change

Fresh Concrete

Unit weight, air content, and consistency

The unit weight, air content, and consistency of each mix are tabulated in Table V. These are considered pertinent, because of their possible effect on the concrete strength, and in the case of consistency, yield an indication of workability.

Cured Concrete

Compressive strength tests

The comparative ease with which compressive tests may be made has made compressive strength the most important property of structural

TABLE V

UNIT WEIGHT, CONSISTENCY, AIR CONTENT, AND COMPRESSIVE STRENGTH

Series	Brand	Type	Plain or Treated	Unit wt. g/ml	Consist-ency mm	Air Ent. Agent g/yd3	w/c	Air Cont. %	Average Compressive Strength at 16 Days After Moist Curing Period of: ½ day psi	½ day %	1 day psi	1 day %	3 days psi	3 days %	7 days psi	7 days %	14 days psi	14 days %
1	I	I	P	2.16	66	5	.55	5.92	1170	100	1880	100	3220	100	3820	100	4220	100
1	I	I	T	2.14	80		.55	6.26	1300	111	2020	108	3590	112	4490	118	5180	123
2	I	I	T	2.16	69		.52	5.95	1900	178	2260	120	3810	118	5310	139	5260	125
3	I	I	T	2.16	67		.55	6.27	1640	140	2100	112	3380	105	4460	117	5160	122
1	E	I	P	2.12	73	5	.55	7.80	1780	100	1900	100	3540	100	4560	100	5030	100
1	E	I	T	2.17	83		.55	5.08	1840	103	2180	115	4340	123	5330	117	5760	114
2	E	I	T	2.18	71		.52	5.55	2430	142	2660	140	4560	129	5880	129	6080	121
3	E	I	T	2.18	69		.55	5.06	2040	115	2530	133	4370	123	5500	121	5770	115
1	M	I	P	2.16	79		.55	5.48	1270	100	2480	100	2580	100	3940	100	4490	100
1	M	I	T	2.05	89		.55	10.36	820	65	1580	64	1980	77	3360	85	3820	85
2	M	I	T	2.03	78		.52	11.9	840	66	1180	48	2000	78	2640	64	3220	72
3	M	I	T	2.05	82		.55	10.8	880	69	1140	46	2410	93	3140	80	3120	70
1	I	II	P	2.22	71		.55	3.46	1950	100	3010	100	3470	100	5110	100	5720	100
1	I	II	T	2.20	77		.55	3.88	2180	112	2980	99	3710	107	5220	102	5540	97
2	I	II	T	2.20	60		.52	4.74	2660	136	3120	104	4760	137	6090	119	6560	115
3	I	II	T	2.19	61		.55	4.65	1950	100	2380	79	3780	109	5180	101	5470	96
1	E	II	P	2.22	70		.55	3.04	1980	100	2830	100	3910	100	5780	100	6150	100
1	E	II	T	2.20	80		.55	3.88	2000	101	2950	104	4350	111	5940	103	6460	105
2	E	II	T	2.21	68		.52	4.34	2060	104	3080	85	4570	117	6540	113	6810	111
3	E	II	T	2.20	72		.55	4.45	1660	84	2670	74	4720	121	6230	107	6420	104
1	M	II	P	2.15	76	5	.55	6.60	1850	100	1740	100	2710	100	4400	100	4760	100
1	M	II	T	2.14	80		.55	6.27	1860	101	1990	114	2910	107	4280	97	5080	107
2	M	II	T	2.16	78		.52	6.35	1020	55	1670	96	3210	118	4610	105	5020	105
3	M	II	T	2.15	79		.55	6.67	740	40	1480	85	3200	118	4540	103	4840	102

concrete. The average compressive strength of all specimens at 16 days is recorded in Table V. Each strength is also expressed as a percentage of the plain concrete.

The significant comparisons to be made are:

1. How do compressive strengths of plain and admixture-treated concretes compare after various curing periods?

2. Is there a significant correlation between compressive strength gain and the rate at which cement paste volume changes?

The average values of consistency, water-cement ratio, air content, and compressive strength at 16 days for cement types I and II and brands I and E are shown in Table VI. Again, values of brand M were not considered because of high air entrainment. The strengths are also expressed as a percentage of the plain concrete.

TABLE VI

AVERAGE VALUES OF TYPES I AND II AND BRANDS I AND E

				Average Compressive Strength at 16 Days After Moist Curing Periods of:									
	Consist-ency		Air Cont.	½ day		1 day		3 days		7 days		14 days	
Series	mm	w/c	%	psi	%	psi	%	psi	%	psi	%	psi	%
Plain	70	.55	5.05	1720	100	2400	100	3540	100	4820	100	5280	100
1	80	.55	4.78	1830	106	2530	106	4000	113	5240	109	5740	109
2	67	.52	5.14	2260	131	2780	116	4420	125	5960	124	6180	117
3	67	.55	5.11	1820	106	2420	101	4060	115	5340	111	5700	108

Figures 11, 12, and 13 show plots of the average compressive strengths contained in Table VI. Figure 11 compares the strength gain of the plain concrete with that of concrete containing water-reducing admixture. The water-cement ratios are equal.

Figure 12 compares the plain concrete with treated concrete in which the water content has been reduced 5 per cent to induce a consistency comparable to that of the plain mix.

In Figure 13, the water and cement contents of the treated concrete are reduced 5 and 4.8 per cent respectively. These reductions in the treated mix provided consistencies comparable to the plain concrete and made the water-cement ratios of plain and treated mortars equal.

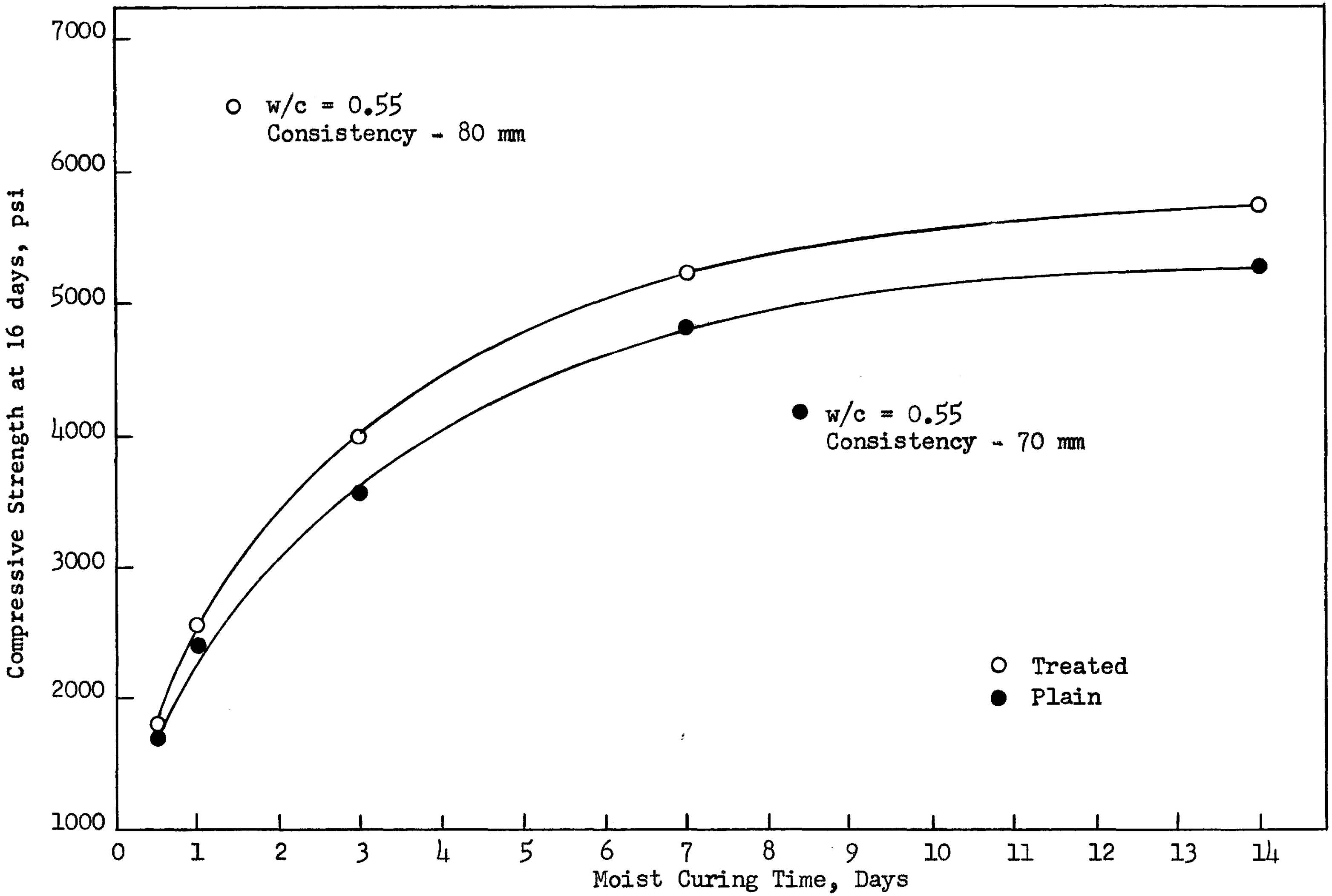

Figure 11. Rate of Strength Gain of Treated and Plain Concrete

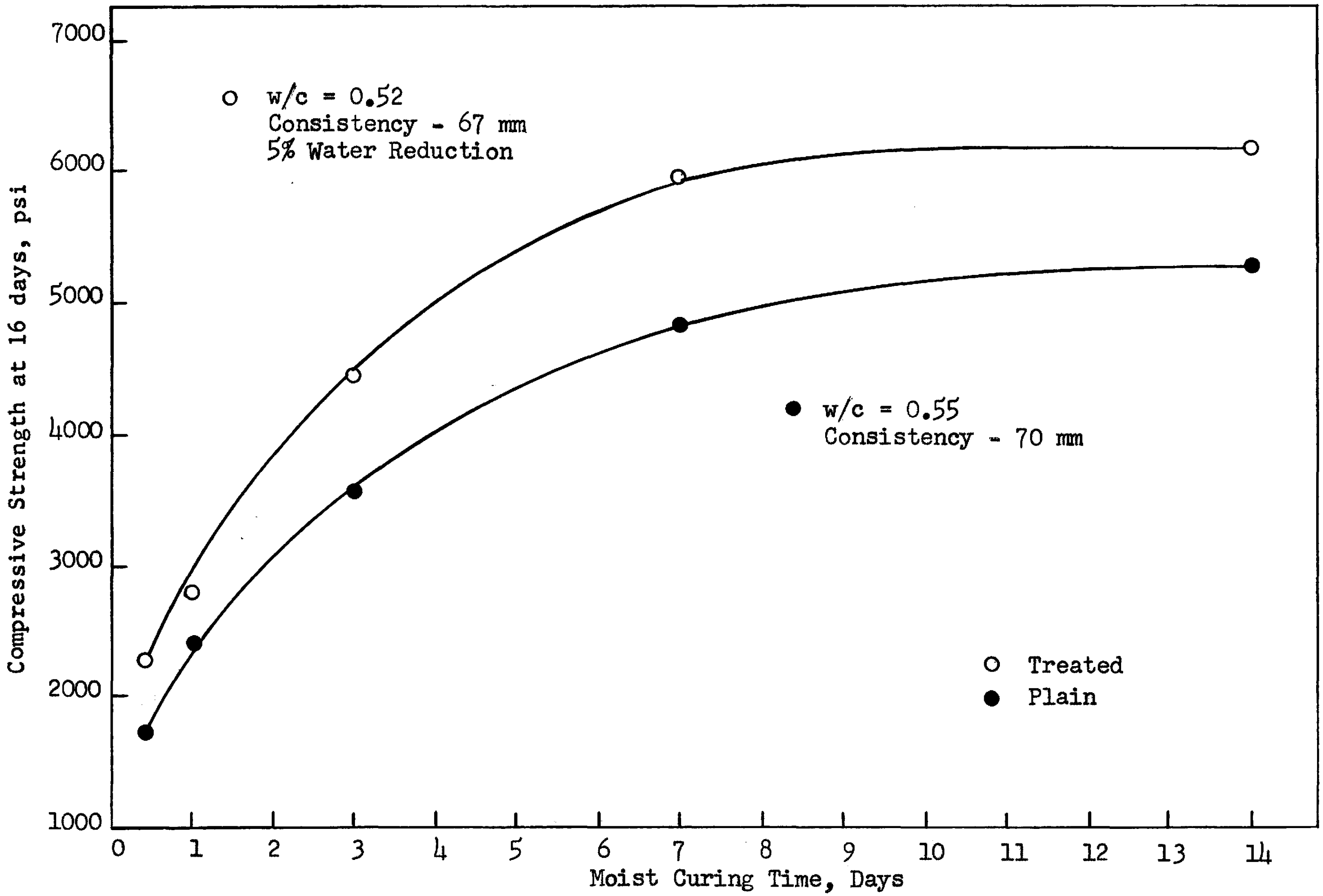

Figure 12. Rate of Strength Gain of Treated and Plain Concrete

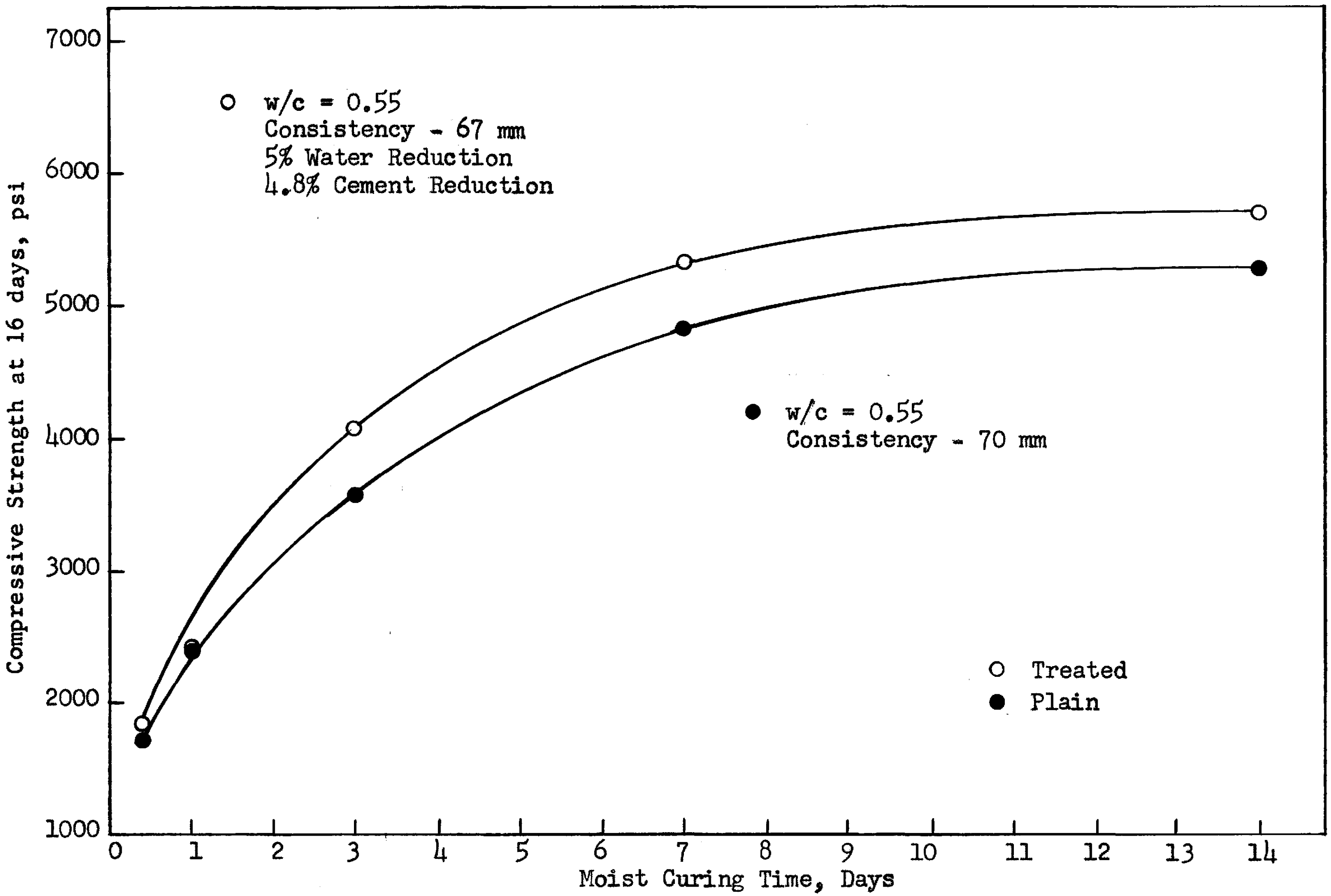

Figure 13. Rate of Strength Gain of Treated and Plain Concrete

CONCLUSIONS

Properties of Fresh Concrete

Unit weight and air content

The effect of the water-reducing agent on the unit weight, and hence on the air content, of the concrete mortars was practically negligible. An attempt was made, through the addition of an air-entraining agent in the plain mix, to keep the air content of treated and plain mixes within cement types and brands constant. However, where the air entrainer was not used, the plain and treated mixes varied in all instances by less than 1½ per cent. This difference in air content would not ordinarily be considered sufficient to cause significant strength differences. The brand M cement of type I entrained large amounts of air in combination with the admixture. This appears to be typical of that particular cement brand and was not included in the analysis.

Consistency

The consistency of a mix is a definite indication of its mobility and workability. The addition of the water-reducing admixture without water reduction accomplished in series 1, increased the consistency, as measured by the cone penetrometer, an average of 10 millimeters over that of the plain mixes.

In order to obtain a treated mix consistency equaling that of a plain mix, a 5 per cent reduction in water was necessary. This 5 per cent reduction was accomplished in the test specimens of series 2. In addition to a 5 per cent water decrease, a 4.8 per cent reduction of cement did not appear to influence the consistency of series 3.

Volume Change Rates of Cement Pastes

It may be easily seen from Figure 8 that the influence of a water-reducing admixture on the volume change rate of cement paste is considerable. This rate of volume change is considered to be very significant in that it probably is a result of more rapid combination of cement and water which leads to a more complete hydration of cement.

It is very probable that cement particles which do not combine with water in the first few hours after mixing never combine and hydrate at all. This results in loss of potential strength and cement waste. Concrete with a lower cement content, but with a water-reducing admixture added, may be stronger at early ages than concrete containing considerably more cement because of a higher percentage of cement hydration. This fact is evident in Figure 13 where higher strengths are indicated for treated concrete at each curing period.

Values contained in Table III indicate that the rate of volume change may be greatly affected by the cement type and/or brand. That is, not all cements are influenced to the same degree by the water reducer; however, all showed definite shrinkage rate increases when treated.

It is apparent from Figure 9 that within the water-cement ratio range of 0.45 to 0.65 the ratio has negligible influence on the rate of volume change. Similarly, Figure 10 indicates that within the water-reducer dosage of 0.15 to 0.25 per cent by weight of cement the volume change rate is only slightly influenced by the admixture dosage.

Properties of Cured Concrete

The curves for average rate of strength gain, shown in Figures 11, 12, and 13, permit the definite conclusion that water-reducing admixtures influence the rate at which concrete acquires early strength. The simple addition of a water reducer, without water reduction, yielded strengths which averaged 109 per cent those of the plain concrete for the curing periods considered.

The addition of a water reducer permits the reduction of water without a loss of consistency. This water reduction, then, further increases the strength margin of treated concrete because of the lower water-cement ratio. The total average strength increase of treated concrete, as a result of both admixture addition and water-cement ratio reduction (made practical by the water reducer), is 123 per cent. That is, the admixture contributed directly a strength increase of 9 per cent and indirectly, through the possibility of water reduction, an increase of 13 per cent for the total of 23 per cent.

The series 3 specimens, which had the 5 per cent water reduction of series 2 and also a 4.8 per cent cement reduction, show that the use of a water-reducing admixture may also permit substantial cement reduction without loss of early strength.

There appears to be a definite relationship between the rate of volume change of cement paste and the strength gain rate of concrete. The percentage difference in strength of treated and plain concrete is essentially constant at all ages of curing. This leads to the conclusion that the difference in strength gain occurs at a very early age, possibly within the first few hours.

Consideration of the cement paste volume change data explains why this might be true: Early and rapid combination of cement and water induces more complete cement hydration, and hence higher concrete strengths at early ages. Thus, cement in concretes which are improperly cured, or cured only short periods, have more completely hydrated and gained the advantage of this strength increase before the available water escaped. It is probable, for example, that concrete containing a water reducer may have a 3-day strength equal that of plain concrete after double this length of time, assuming like curing conditions for both concretes. A water-reducing admixture may provide a "built in" cure or at least permit more economical concreting procedures where curing methods are difficult or impossible.

SUMMARY AND RECOMMENDATIONS

Summary

The research contained in this study was designed to determine the effect of water-reducing admixtures on the curing of concrete. An attempt was made to relate the volume change rate of cement paste to the strength gain rate of concrete. The theory is advanced that the increased rate of shrinkage, found when water reducers are used, is a result of accelerated combination of water and cement which induces higher early strengths than those obtained with plain concrete.

Series 1 of the experiment was designed to determine the strength gain of concrete due to the admixture alone. The strength gain due to both water reducer addition and water-cement ratio reduction, permitted by the reducer without consistency loss, was measured in series 2. The treated concrete of series 3 contained reduced water and cement content and indicated the possibility of cement reduction without strength loss.

The volume change tests, conducted on the cement pastes, indicate a definite difference in the shrinkage rate of plain and treated pastes. Thus, the rate of water-cement combination in admixture concrete is theorized to be faster which leads to higher early strengths.

The compression tests show not only an increase in strength of treated over plain concrete as a result of water reducer addition, but also indicate that the increase is essentially constant at all early ages. The resultant conclusion is that the strength advantage of treated concrete is gained at an early age, possibly within the first few hours as a result of the more rapid combination of cement and water induced by the water-reducing admixture.

Recommendations

This study investigated the volume change rate of the cement paste from 2 minutes to 60 minutes after mixing began. It is apparent that this change occurs very rapidly at early stages. Future research might overcome the practical difficulties encountered and, by some devised method, determine the volume change between 0 and 2 minutes.

In this research the cubes were placed in an oven to rapidly stop cement hydration as each moist curing period terminated. It was assumed that this did not have adverse effects on the concrete or that the effect was similar for all curing ages. This assumption may provide an area for further study.

LITERATURE CITED

(1) Abrams, D. A., "Design of Concrete Structures," Bulletin No. 1, Structural Materials Research Laboratory, Lewis Inst., 1918.

(2) Cordon, William A., Discussion of paper by E. L. Howard, K. K. Griffiths, and W. E. Moulton on "Field Experience Using Water-Reducers in Ready-Mixed Concrete," American Society for Testing Materials, Symposium on Effect of Water-Reducing Admixtures and Set-Retarding Admixtures on Properties of Concrete, Special Technical Publication No. 266, 1959.

(3) Cordon, William A., "Evaluation of Concrete and Concrete Mortar Mixes," Reprint 29, Engineering Experiment Station, College of Engineering, Utah State University of Agriculture and Applied Science, Logan, Utah, pp. 571, 1961.

(4) Fischer, H. C., and MacPherson, D. R., "The Effect of Water-Reducing Admixtures and Set-Retarding Admixtures on the Properties of Hardened Concrete," American Society for Testing Materials, Symposium on Effect of Water-Reducing Admixtures and Set-Retarding Admixtures on Properties of Concrete, Special Technical Publication No. 266, 1959.

(5) Howard, E. L., Griffith, K. K., and Moulton, W. E., "Field Experience Using Water-Reducers in Ready-Mixed Concrete," American Society for Testing Materials, Symposium on Effect of Water-Reducing Admixtures and Set-Retarding Admixtures on Properties of Concrete, Special Technical Publication No. 266, 1959.

(6) Mielenz, Richard C., "Water-Reducing Admixtures and Set-Retarding Admixtures for Concrete: Uses; Specifications; Research Objectives," American Society for Testing Materials, Symposium on Effect of Water-Reducing Admixtures and Set-Retarding Admixtures on Properties of Concrete, Special Technical Publication No. 266, 1959.

(7) Polivka, Milos, and Klein, Alexander, "Effect of Water-Reducing Admixtures and Set-Retarding Admixtures as Influenced by Portland Cement Composition," American Society for Testing Materials, Symposium on Effect of Water-Reducing Admixtures and Set-Retarding Admixtures on Properties of Concrete, Special Technical Publication No. 266, 1959.

(8) Powers, T. C., "Should Portland Cement be Dispersed?" Journal, Am. Concrete Inst., Vol. 17 (2), pp. 117-140, 1945.

(9) Prior, M. E., and Adams, A. B., "Introduction to Producers' Paper on Water-Reducing Admixtures and Set-Retarding Admixtures for Concrete," American Society for Testing Materials, Symposium on Effect of Water-Reducing Admixtures and Set-Retarding Admixtures on Properties of Concrete, Special Technical Publication No. 266, 1959.

(10) Scripture, E. W., Discussion of paper by T. C. Powers on "Should Portland Cement be Dispersed?" Journal, Am. Concrete Inst., Vol. 18 (4), pp. 140:1-140:17, 1946.

(11) ________________ Standard Method of Test for Compressive Strength of Hydraulic Cement Mortars (using 2-inch cube specimens), American Society for Testing Materials, Philadelphia, September, 1956.

(12) Tuthill, Lewis H., Adams, Robert F., and Hemme, John M. Jr., "Observations in Testing and Use of Water-Reducing Retarders," American Society for Testing Materials, Symposium on Effect of Water-Reducing Admixtures and Set-Retarding Admixtures on Properties of Concrete, Special Technical Publication No. 266, 1959.

(13) Vollick, C. A., "Effect of Water-Reducing Admixtures and Set-Retarding Admixtures on the Properties of Plastic Concrete," American Society for Testing Materials, Symposium on Effect of Water-Reducing Admixtures and Set-Retarding Admixtures on Properties of Concrete, Special Technical Publication No. 266, 1959.

(14) Wallace, George B., and Ore, Elwood L., "Structural and Lean Mass Concrete as Affected by Water-Reducing, Set-Retarding Agents," American Society for Testing Materials, Symposium on Effect of Water-Reducing Admixtures and Set-Retarding Admixtures on Properties of Concrete, Special Technical Publication No. 266, 1959.