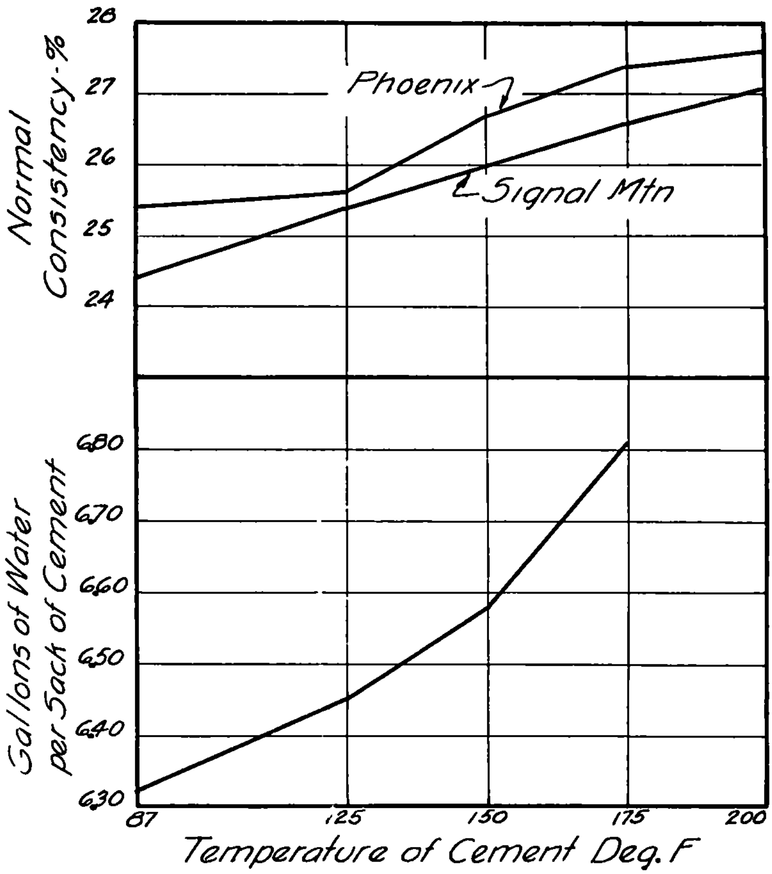

Figure 3. Effect of Cement Temperature upon Normal Consistency of Cement, and upon Amount of Water Required to Produce Equal Flows in 1: 2·4 Concrete

RESISTANCE OF CONCRETE TO FROST ACTION AS AFFECTED BY THE WATER-CEMENT RATIO

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SYNOPSIS

On account of the growing tendency in some localities toward decreasing the amount of cement in concrete for highway use on the assumption that strength is the controlling factor, the committee has reviewed the evidence concerning, the relation between resistance to frost action and water-cement ratio, the maximum water-cement ratio allowable for concrete exposed to the weather, and the relation between strength and durability The available test data show a decided relation between water-cement ratio and durability

Your committee notes with some concern an apparently growing tendency on the part of certain highway engineers to use concrete mixtures for pavements and other types of exposed structures which contain considerably less cement per unit volume of concrete (and consequently higher water-cement ratios) than was formerly required This condition is probably due, at least in part, to the fact that, for an equivalent cement content, the average present-day portland cement will produce a much higher early strength concrete than was the case a number of years ago. Also, in the practice of designing concrete mixtures to conform to specified strength requirements, it is sometimes found that certain aggregate combinations will produce considerably higher strength concrete than other combinations

These facts have been used to justify reductions in cement content below what was formerly considered good practice provided only that the concrete has the required strength The assumption is, of course, that strength is the controlling factor, and that the other necessary characteristics will depend upon the strength which is developed This method of design may be justified in the case of concrete which is protected from the weather and where load-carrying capacity is the essential requirement However, in the opinion of your committee, there is some question as to whether it should be applied to concrete to be used in various types of highways structures, such as pavements, bridges, etc , which, in addition to fulfilling certain requirements as to strength, must provide maximum durability or resistance to weathering

This report will review and discuss the available test data covering the subject of durability with the specific purpose of answering, in so far as our present knowledge permits, the following questions:

> "Assuming that the constituent materials are sound, the aggregates properly graded, and the consistency such as to insure uniform, homogeneous concrete with the methods of placing to be employed:
>
> "(1) How is the resistance of concrete to frost action affected by variations in the water-cement ratio ?
>
> " (2) What is the maximum water-cement ratio which should be permitted in concrete to be exposed to alternate freezing and thawing
>
> "(3) For a given water-cement ratio, to what extent do variations in strength, due either to quality of cement or aggregates, or both, affect the durability of concrete ? "

Before discussing the experimental data bearing on the subject it will be of interest to review briefly the developments which have taken place during the past 14 years in the application of the basic water-cement ratio strength law originally stated by Abrams in 1918 It seems advisable to do this because of the very definite relation which appears to exist between the water-cement ratio and durability, as revealed by an examination of the available test data

The application of this basic law to the design of concrete mixtures seems to have progressed in three distinct stages The first of these involved the use of that water-cement ratio which, according to the original Abrams formula, would give the required strength So effectively was this basic principle demonstrated for many years after its introduction that many large users of concrete, particularly in the railroad and architectural fields, are using it today practically in its original form

It will be observed that the entire basis of the design is strength—the assumption being that the securing of the specified strength through the use of the designated water ratio will automatically insure concrete of satisfactory quality in all respects.

The second stage in the development of the water-cement ratio specification resulted from attempts to compensate for the influence exerted by the quality of the various constituent materials, particularly the cement and aggregates, on the strength which would be obtained for a given water ratio

The result was the so-called " trial " method of design This, in effect, provided for the use of that water-cement ratio which, for the particular materials employed, would give the required strength

This method appealed to many users for economic reasons and has been used to a considerable extent both in the highway and building fields. This method also recognizes strength as the governing factor However, it differs from the original or basic method in that it makes possible the use of a relatively wide range in water ratios, corresponding to a given strength Under this method, the use of materials having high strength characteristics would permit the use of relatively high water ratios as compared to other materials having low strength characteristics.

As previously noted, the use of the newer type of high strength cements, coupled in some cases with aggregates having high strength characteristics, has actually resulted in the use of such high water ratios (and consequently low cement factors) as to arouse considerable concern regarding the durability of the concrete, even though the requirements for strength have been met.

This brings us to the third stage in the development of the water-cement ratio specification, namely, the matter of limiting the maximum water-cement ratio to be permitted so as to insure concrete of maximum durability even though the strength attained may be higher than necessary from the standpoint of structural design It is the recognition of this new element which distinguishes the investigator from many users of concrete at the present time, because in general, the user, when he thinks of designed concrete at all, still thinks in terms of strength alone.

The investigator, on the other hand, is beginning to question the wisdom of relying entirely on strength. A new interest is being created in the subject of permanence in concrete as affected by various factors and many laboratory investigations have been started looking to a solution of some of the problems involved. These researches have in some cases progressed to the point of warranting the release of data and it is the purpose of this report to summarize and comment upon such data along this line as are now available and which bear upon the specific questions which have been cited.

The paper presented before the board last year by C H Scholer (1)[1] throws considerable light on this problem This paper is devoted in large part to a study of the effect of unsound aggregates on the resistance of concrete to frost action The author, however, presents certain data bearing on the effect of quality of cement paste on durability. He distinguishes between "quality" of cement paste as affected by the quality of the cement itself and the "quality" of the paste as influenced by the water-cement ratio

The author shows that resistance to freezing and thawing is affected by both factors. The data indicate that, for a given cement, there is a very definite relation between water-cement ratio and resistance to frost action He also shows that, for a given water-cement ratio, a mortar containing a certain high early strength cement was much more resistant than a similar mortar containing a normal portland cement. The data bearing on this particular point are shown in Figure 1

This observation is significant in view of the second question which has been raised, and indicates that the quality of the cement may be just as influential as the quantity of water in controlling durability Experimental verification of this indication is lacking at the present time, in so far as the committee is aware Practically all the work which has been done so far, has been done along the line of developing a conventional relation between water-cement ratio and durability, just as the original relation between water-cement ratio and strength was developed.

The author draws the following conclusions:

1 Alternate freezing and thawing is a valuable method of studying the durability of concrete and concrete aggregates.

2 The durability of concrete is greatly affected by the quality of the cement paste.

[1] Figures in parenthesis refer to reports listed in the bibliography

3. A water-cement ratio of 0.8 or more is not likely to give a concrete of adequate durability if the conditions of exposure are severe.

Mr Scholer's conclusions regarding the dangers of using high water ratios in concrete subjected to frost action are borne out by other investigators. Numerous tests made in the laboratory of the Portland Cement Association reveal a very definite relation between this factor and resistance to frost action. In a recent paper on the subject (2), Messrs Gonnerman and Ward report the results of tests on a large number of mortar cubes in which the water content ranged from 4 5

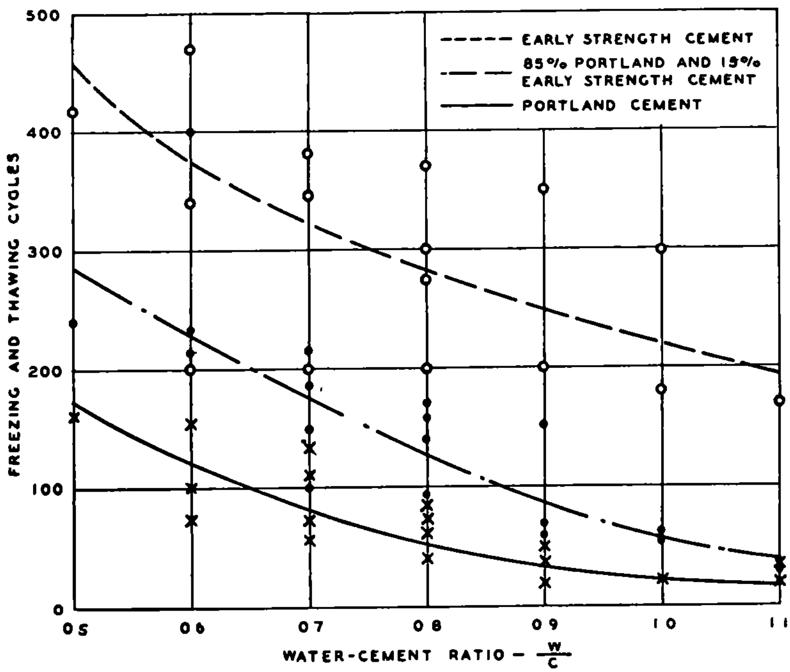

Figure 1. Resistance to Freezing and Thawing as Affected by the Cement and Water-Cement Ratio (Scholer—Kan. State Coll.)

to 9 0 gallons per sack of cement and in which a large number of different sands were used Here again the primary study was on the effect of aggregate on durability

Confining, this discussion to the effect of water content, these data showed at the end of 200 cycles of freezing and thawing, a loss in weight of less than one per cent for a mix having a water ratio of 0.6 as compared to four per cent for a mix having a water-cement ratio of 0 93 and over 12 per cent for a mix having a water ratio of 1.2. These data also seemed to indicate that the ability of the mortars to resist frost action decreased at a greater rate than the water-cement ratio increased For instance, an increase in water ratio from 0.6 to 0 73 resulted in increasing the loss only one per cent, based on the original weight of the specimens, whereas an increase in water ratio from 0 73 to 0 93 increased the loss about 2 5 per cent This would indicate that changes in water ratios in the leaner mixes have a greater proportional effect on durability than do changes of the same magnitude in the richer mixes A portion of Figure 3 of the paper appearing in the National Sand and Gravel Bulletin for May, 1931, is reproduced as Figure 2, to illustrate this point These tests, in general, substantiate the recommendation of the Portland Cement Association (3)

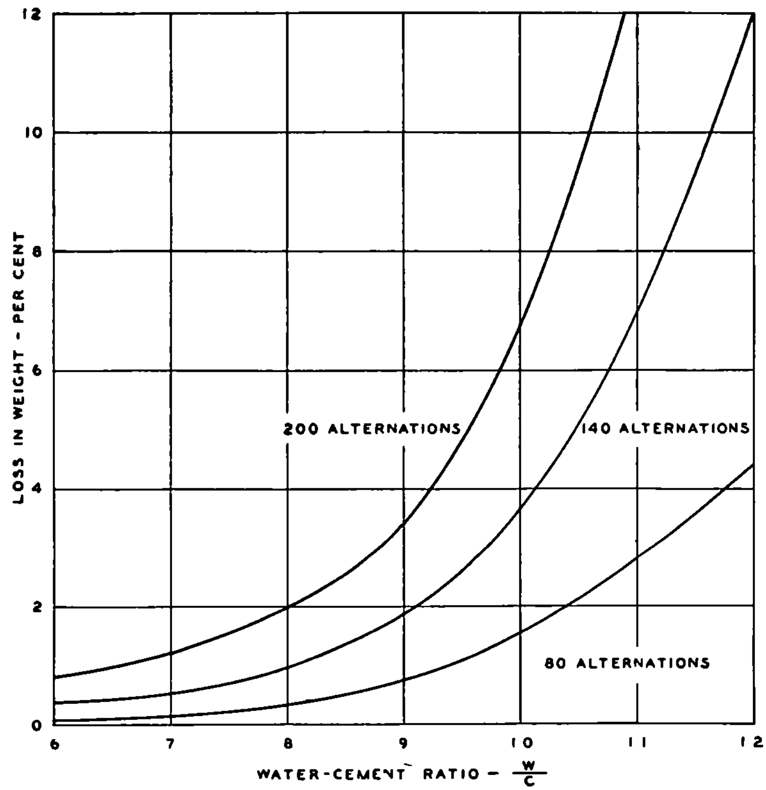

Figure 2. Effect of Water-Cement Ratio on Resistance of Mortar to Freezing and Thawing (Gonnerman & Ward—P. C. A)

that concrete subjected to severe exposure should not contain more than 6 0 gallons of water per sack of cement.

In another series of tests conducted by the Portland Cement Association (4), mortar specimens ranging in water-cement ratio from five to nine gallons per sack of cement were subjected to alternate freezing and thawing for various durations up to 375 cycles Here again the data indicate that there is an intimate relation between water-cement ratio and durability A portion of the data are reproduced in Figure 3, which shows the number of alternations required to produce a condition equivalent to 50 per cent of total failure in the specimens These specimens were cured three days in moist air and 28 days in the air of the laboratory before being tested

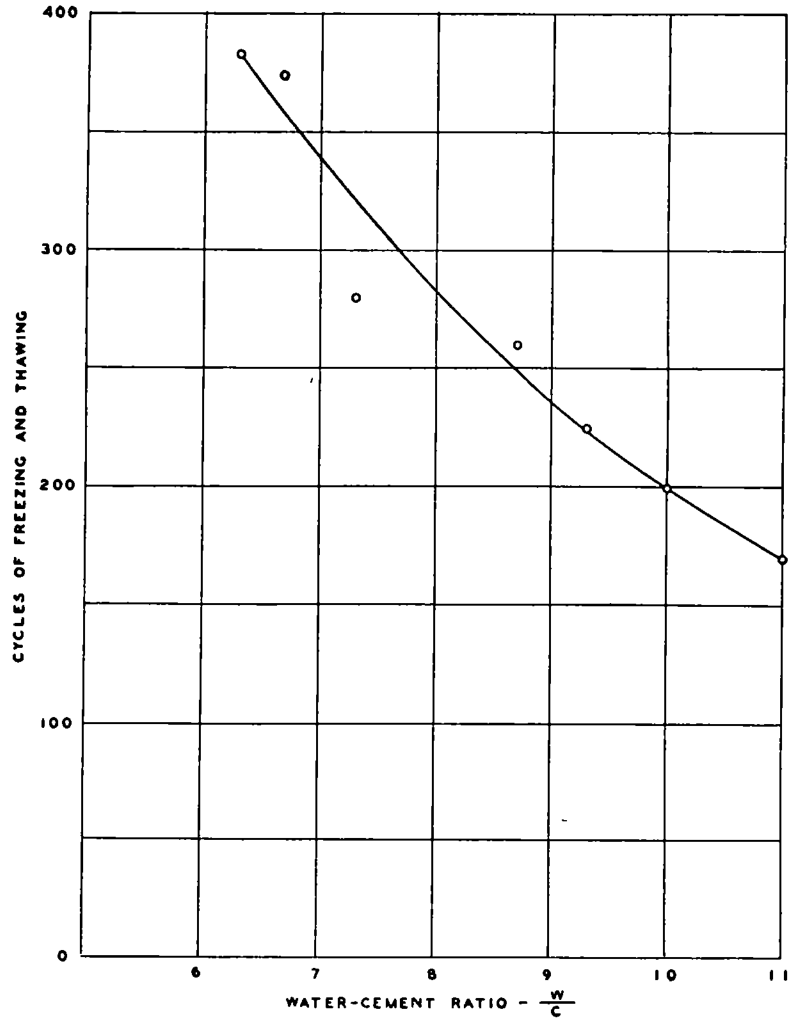

Figure 3. Effect of Water-Cement Ratio on Resistance of Mortar to Freezing and Thawing (Shuman—P. C. A. Unpublished Data)

It will be observed that almost twice as many alternations of freezing and thawing were required to produce a given effect in a mortar containing 4 5 gallons per sack of cement ($W/C = 0$ 60) as in a mortar containing 7.5 gallons per sack ($W/C = 1$ 0). The similarity in form of this and other curves expressing this relation to the conventional water-cement ratio strength curve should be noted

Reference should also be made to the work which has been going on for some time under the direction of Professor Hughes, of the University of Minnesota. In a discussion on durability of concrete aggregates, before the tenth annual meeting of the Board (5), Lang and Hughes presented data showing the relative severity of different freezing cycles, with reference particularly to thawing under pressure in order to completely fill the voids with water

The authors' data show that the percentage of reduction in strength increases as the water-cement ratio is increased. For instance, in Figure 3 of that paper, comparing the strengths obtained on mortar specimens cured under standard conditions for 28 days with the strengths developed by similar specimens similarly cured and then subjected to 36 cycles of freezing and thawed under 50 pounds pressure, it will be noted that the specimens containing 8 0 gallons of water per sack of cement ($W/C = 1\ 07$) showed a reduction in strength of 50 per cent compared to a 43 per cent reduction for the six gallon specimens ($W/C = 80$) and a 24 per cent reduction for the four gallon specimens Similar relations are, in general, shown for the other methods of freezing

Professor Hughes, in a discussion (6) of F. R McMillan's paper "Basic Principles of Concrete Making" (Civil Engineering, April, 1931), presents data from another series of tests which show the same relation between water-cement ratio and durability These tests were made on two inch by two inch mortar cubes, with water ratios ranging from 4 5 gallons to 9.0 gallons per sack of cement

Reference to Figure 2 in that discussion shows, for instance, that, whereas initial failure in the mix containing 9 0 gallons per sack was observed at the end of 10 alternations, nearly 100 alternations were required to produce the same effect in the mix containing 4 5 gallons per sack Intermediate water ratios showed effects intermediate between these two extremes.

In a recent report by Withey (7) the results of an interesting series of freezing tests on concrete were reported. These tests involved the use of four cements and three coarse aggregates Three different proportions were used. Figures 4 and 5 were plotted from data taken from Table 8 of that report and show average values for the four cements.

It is interesting to observe that the reduction in strength in pounds per square inch due to freezing is approximately the same for all proportions The percentage of reduction, however, is greater for the leaner mixes, although the increase in percentage with increase in water-ratio is not so great as in the tests reported by Lang and Hughes. In this case the $1:1\frac{1}{2}:3$ specimens ($W/C = 0.61$) showed an average reduction in strength of 19 per cent compared to 27 per

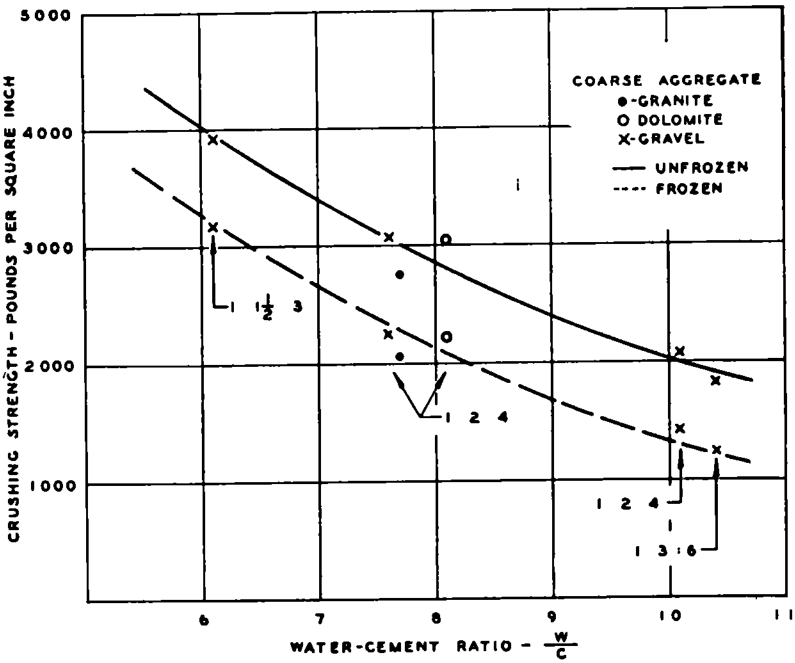

Figure 4. Effect of 20 Alterations of Freezing and Thawing on the Crushing Strength of Concrete. (Withey—Univ. of Wis.)

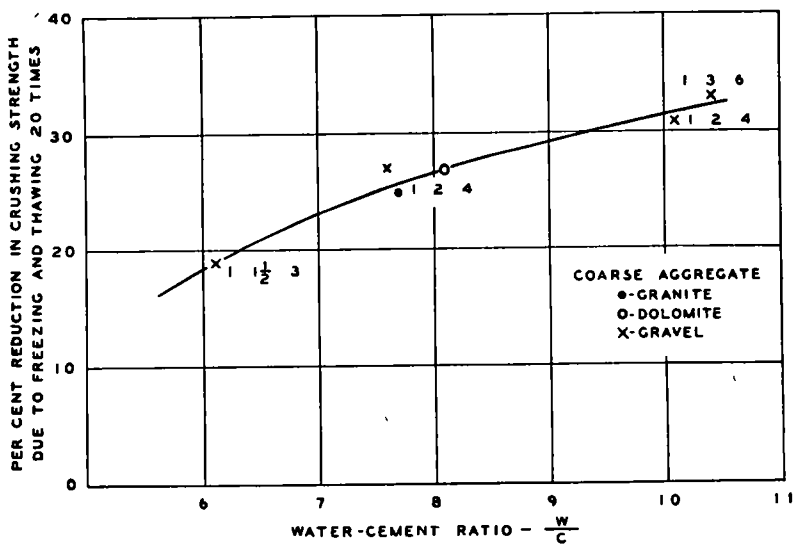

Figure 5. Effect of 20 Alterations of Freezing and Thawing on the Crushing Strength of Concrete (Withey—Univ. of Wis.)

cent for the 1 . 2 · 4 specimens ($W/C = 0$ 76) and 33 per cent for the 1 : 3 : 6 specimens ($W/C = 1$ 04) The three coarse aggregates were used in this intermediate mix only (1 : 2 : 4), the water ratio for this proportion varying from 0 76 for the gravel to 0 81 for the dolomite The strengths of these 1 2 · 4 concretes, both before and after freezing, are, however, practically the same, indicating that the type of coarse aggregate was not an important factor

It is interesting to note that the 1 · 2 . 4 gravel concrete specimens with $W/C = 0$ 76 (Flow = 165) showed a reduction in strength of 27 per cent compared to 31 per cent for the same volumetric proportion, but with the water ratio raised to 1 01 (Flow 250) This illustrates the influence of the quality of the paste in controlling the durability of concrete in cases where the proportions remain the same and changes in water-cement ratio are caused by changes in consistency

An inspection of the data reported by Withey fails to reveal any significant effect due to the particular cement used, except that concrete made with one of the cements (identified as 3 M) seemed to show in general somewhat greater resistance than the others

For a given mix and consistency there appeared to be no relation between the strength developed by a given cement and resistance to frost action Another cement (7 M) gave, in general, the highest strength concrete for a given water ratio For most groups of tests, however, concrete made with this cement was somewhat less resistant than concrete made with cement 3 M These trends, however, are not marked so that the conclusion that " the brands of cement used exercised little effect on resistance to freezing and thawing " seems to be justified

RÉSUMÉ

The test results which have been discussed briefly in this report constitute, in so far as the committee is aware, the only available experimental data bearing on the questions which have been raised The investigations are all in agreement that durability is affected greatly by the quality of the cement paste, in so far as the quality of the paste is affected by the water-cement ratio There seems to be no doubt that durability will be greatly increased by using low water ratios The effect of quality of paste as affected by quality of cement is not so clearly shown Neither are data available which would yield information as to the effect of variations in strength due to the use of different aggregates This is of special importance in connection with the design of paving mixtures to meet definite requirements as to flexural strength, and it is hoped that information on this particular point will be forthcoming in the near future

In view of the lack of any definite correlation between freezing tests and service behavior, it is impossible at this time to draw a definite conclusion from the results of laboratory investigations as to the exact water-cement ratio which should be used in designing mixtures which will be durable

It is, of course, theoretically desirable to secure maximum durability and inasmuch as resistance to frost action is increased by decreasing the water ratio, it may be argued that the water ratio should be reduced to the lowest value possible There are, of course, practical limitations to this course There is danger, also, in producing concrete which is so rich in cement as to have excessive volume change, which is undesirable However, we know from these tests, as well as from observation and experience, that the use of high water ratios are equally undesirable

In view of these facts and, until such time as it is possible to draw more definite conclusions, it seems logical to set an arbitrary limit which will be high enough to insure practical and usable mixtures, and at the same time will produce durable concrete

The committee feels that the weight of available evidence, both theoretical and practical, verifies the conclusion reached by Scholer, that "A water-cement ratio of 0 8 or more is not likely to give a concrete of adequate durability if the conditions of exposure are severe ", and that, until such time as more definite quantitative relationships are established, the necessity of safeguarding durability be recognized by limiting the water ratio to 0 8 in all structures to be exposed to severe weathering, even though the use of this value may result in higher strength concrete than called for by the design of the structure

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4 Unpublished data of Portland Cement Association, used by permission.

5 Proc Highway Research Board, 10th Annual Meeting.

6 Civil Engineering, August, 1931, p 1029.

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DISCUSSION ON CONCRETE AND FROST ACTION

ABSTRACTED

Mr. F. R. McMillan, *Director of Research, Portland Cement Association.* The committee report did not comment upon the element of "curing" as one of the factors affecting the quality of cement paste.

It is well recognized that the principal difference between high-early strength cements and normal portland cements is the rate at which they gain their strength during the early period. If normal portland cements are kept under moist curing they tend to approach the high-early strength cements in ultimate strength at from three months to one year. In Professor Scholer's original report (Highway Research Board Proceedings, 10th Annual Meeting, 1930) no statement was made regarding the curing of the specimens upon which the tests shown in Figure 1 of the report were based. It is possible that part of the disadvantage shown for the normal portland cement can be accounted for by inadequate curing. Because of the more rapid rate of hardening of the early strength cement, a higher proportion of the potential strength will be obtained by a few days curing than will be the case for the normal portland cements. Some tests bearing on this point were made in the Portland Cement Association laboratory comparing a number of high-early strength cements with normal portland cements by freezing and thawing concrete cubes in a saturated condition. The accompanying pictures show the condition of the cubes in this series at 202 and 230 cycles of freezing and thawing.

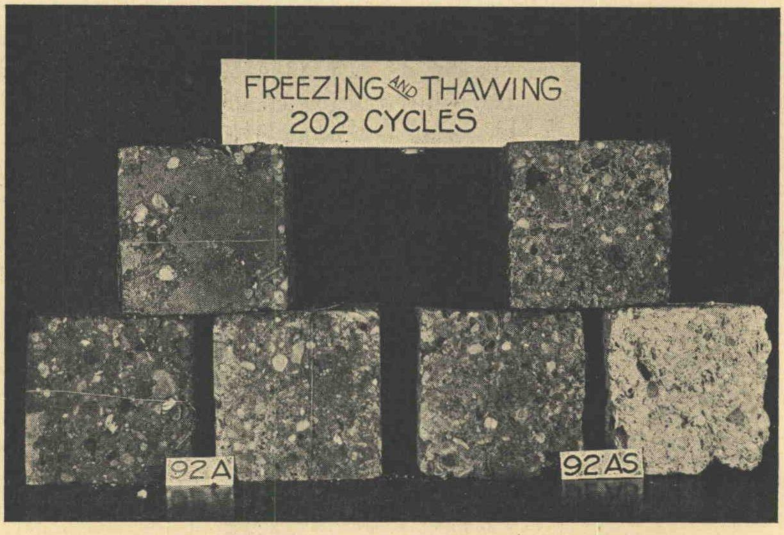

Figure 1

Eight different cements are represented. In Figure 1, the three cubes marked 92A were made from our standard laboratory mixture of four brands. The three cubes marked 92AS were made from an imported special high-early strength cement.

In Figure 2 the cubes at the left, indicated by the letter A, were made from a standard portland cement, and those at the right, indicated by the letters AS, were made from a high-early strength cement produced by the same company, presumably both the normal portland cement and the special cement were made from the same raw materials. The mixtures used in these cubes were 1-2-3, by dry compacted volume, with a water content of six gallons per sack of cement. Elgin sand and gravel aggregates were used, and all the specimens were

Figure 2

cured 28 days in the moist room before being subjected to alternate freezing and thawing.

A study of these pictures shows that there is practically no difference in the condition of the cubes representing a normal portland cement and the high-early strength cement from the same manufacturer. If it is possible to make any distinction from the pictures, it must be said that the normal cements appear to have such slight advantage as exists. In the case of the laboratory mixture 92A, there appears to be a definitely better condition than shown by specimens 92AS of the foreign high-early strength cement.

From these illustrations it is evident that when given sufficient curing to develop a reasonable proportion of their ultimate potential strength, the normal portland cements give as good resistance to freezing and thawing as the high-early strength cements of the same curing.