is used is quite simple, and the unit cost of testing is very much less than the cost of making crushing tests on samples taken in the field and shipped to the laboratory.

THE RELATION OF MODULUS OF RUPTURE OF CONCRETE TO CHARACTER OF CONSTITUENT AGGREGATES

Owing to the rapid growth in the use of the cross-bending test it seems likely that this test will supersede the crushing test as a method of field control for the quality of the concrete Hence, the cross-bending test of plain concrete is likely to be a very important test and engineers should appreciate all the factors which affect the chief strength measure of this test, the modulus of rupture

There has been considerable study made, notably by the Structural Materials Laboratory of the Portland Cement Association, to show the effects of the water-cement ratio, the grading of aggregate, proportion of cement, and age upon the modulus of rupture, but to date there is very little information correlating the effect of shape and surface condition of the constituent aggregate particles with the modulus of rupture of the concrete From results of tensile tests of mortars which have been made, it appears that the shape of the aggregate particles has considerable effect on the tensile strength Since the tensile strength is the most important criterion of the modulus of rupture, it would appear that shape might therefore materially influence the modulus of rupture It seems important to the Committee that numerous tests to determine the effects of these factors on the modulus of rupture should be made In making such tests, the relation of the transverse strength to the crushing strength should be determined By so doing a suitable factor may be established for each aggregate so that the crushing strength of the concrete may be estimated from its modulus of rupture

FIELD CONTROL OF CONCRETE MAKING—A STUDY OF LATE PRACTICE

R W Crum
Iowa State Highway Commission, Ames, Iowa

Research into the basic principles that control the quality of Portland cement concrete has been going on ever since this material came into general use Practical application of the results of research, on a large scale, are comparatively recent It is the purpose of this study to review some cases in which the actual concreting operation has been carefully controlled according to scientific principles Even without supporting data, there can be no doubt that a manufacturing operation in which the different processes are controlled according to definite knowledge of the effects of the factors involved, will produce superior results The data reviewed merely emphasizes the desirability of such control.

This paper does not attempt to review all of the literature bearing on this subject.

RECOGNIZED PRINCIPLES

The four principal characteristics of concrete for which control is needed are, strength, uniformity, durability, and economy of mixture

Strength—The strength of concrete must depend upon the actual amount of solid matter present in a unit volume, and upon the relative amounts of inert and cementing material present. This relation has been demonstrated by various investigators (see Proceedings Highway Research Board, 1925, Report of Committee on Character and Use of Road Materials), and is sometimes expressed as the ratio of voids to cement In the green mixture the voids would be the space occupied by air and water This relationship has been of great value in studying concrete mixtures, but inasmuch as the voids cannot be known until the concrete is made, the above function cannot be used directly in the design of concrete mixtures.

Professor D A Abrams first called attention to the now commonly accepted fact, that the strength of concrete varies with the amount of water used in mixing, and the water-cement ratio proposed by him as a criterion of strength has been generally accepted as governing the strength of concrete within the range of workable mixtures Inasmuch as this ratio can be predetermined, it can be used to establish strength in advance In well-made concrete, the air voids in the freshly mixed material should be very small and therefore the voids-cement ratio of the molded concrete should correspond very closely to the water-cement ratio used in mixing

Uniformity—The fundamental criterion for uniformity has been well stated by Mr R B Young "A uniform mix of *all* materials is the basis of uniform concrete" Uniform molding and curing are also necessary in the securing of a uniform result It is in securing uniformity that the most difficult problems of field control are to be found The measurement of cement and most aggregates can be accurately accomplished, but the measurement of water, especially on moving mixers, offers difficulties that have yet to be overcome

Absorptive aggregates complicate both the water and aggregate measurement Stationary mixing plants are much easier of control than the moving plants ordinarily used on paving work

Durability—Durability requires sound materials so combined as to offer maximum resistance to the forces which tend toward deterioration. These forces may be the natural ones, due to exposure to the elements, or those due to the service for which the concrete is constructed In many cases, especially in concrete pavements, fatigue due to repeated stresses is a most important factor Density is important in resistance to elements Uniformity is, of course, necessary for maximum durability

Economy—There is no doubt that equal strength can be secured with many different combinations of materials With the information now available, it is possible through adaptation of recognized principles and study of available aggregates to arrange mixtures to give concrete of the desired quality at least cost

Broadly stated, maximum economy will result, when for a given amount of water and cement, the greatest amounts of the cheapest aggregates available are used that will yield a workable mixture Three methods of arriving at this result are reported in the papers reviewed herein

In the one method, the water-cement ratio only was specified, leaving it to the contractor to put in whatever quantity of aggregate he wished, so long as the concrete was within the range of workability required In the second method, careful preliminary studies and tests were made of the available aggregates for each job, the proportions established for all materials In the third method as used on highway construction, studies extending over several years are used to arrange a table of proportions from which the contractor can choose the combination most economical to use The first has the advantage that it is to the advantage of the concrete as well as the contractor to use as much aggregate as possible for a specified amount of water and cement In the second the engineer has the advantage of knowing in advance just what will be used, and has a possibility of greater control over uniformity The third is especially applicable to those cases in which the engineer cannot know in advance what particular material will be used, but where the characteristics of the materials available are known Also both engineer and contractor can make advance estimates of the quantities of materials.

The largest factor affecting economy is the grading of the aggregates The better gradings being those which will yield workable mixes with the least water Either the "Fineness Modulus" of Professor Abrams, the "Surface Area Method" of L N Edwards, or the "Mortar-Void Theory" of Dr Talbot, can be used in a study of materials to secure the greatest economy

It is to be expected that more complete field control of concrete making, according to scientific principles, will result in the following desirable features —

(a) Pre-knowledge of average and minimum strength
(b) Uniform strength
(c) Pre-knowledge of quantities of materials to be used
(d) Uniform yield
(e) Record of quantities of materials used
(f) Maximum economy.
(g) Increased durability
(h) Minimum friction between contractor and engineer or architect

A study of the following reported instances of thorough field control may indicate the extent to which we may hope to realize these desirable results

"Use of the Water Ratio Specification on the Portland Cement Association Building," by F R McMillan, and Stanton Walker, Proceedings American Concrete Institute, 1926

This article describes the experience and results secured with a specification having the following principal features.

"The principal feature of this specification was the limitation of the maximum quantities of mixing water with little restriction on the proportions of cement to total aggregate or of fine to coarse aggregate other than that plastic and workable mixes be produced Maximum slumps for the different portions of the work were stated to avoid any possibility of argument over unnecessarily wet mixtures or the accumulation of laitance The usual clauses concerning quality of aggregates were included Clauses fixing suitable limitations on the grading were also included The maximum size of the coarse aggregate was required to be not greater than would permit of proper placement"

The authors of this paper are of the opinion that the quality of concrete in this structure was successfully controlled without the use of special equipment and without the need of a testing organization, solely by means of the specification outlined above The data submitted show that in general the average crushing strength was well above the design strength, and except for one set of data, only a few individual tests fell below the designed strength A considerable variation in strength for each class of concrete is to be noted.

The specification stated merely a maximum water ratio which must not be exceeded Under this clause the contractor was permitted wide latitude and accordingly chose to use the simplest possible type of measuring equipment which results in a wide range in the nominal water ratio used Also for a given nominal water ratio the data show the variation in strength to be about 2,000 lbs per square inch The authors ascribe about 500 lbs of this to differences in temperature, about 700 lbs to the usual variations in testing, and the remaining 800 lbs to actual differences in water ratio caused by inaccuracies in measuring water and aggregates

The authors state that there were no conflicts with the contractors over consistency or quantities because the contractor's desire to have plastic workable mixes, with a minimum cement content, resulted in suitable mixes throughout.

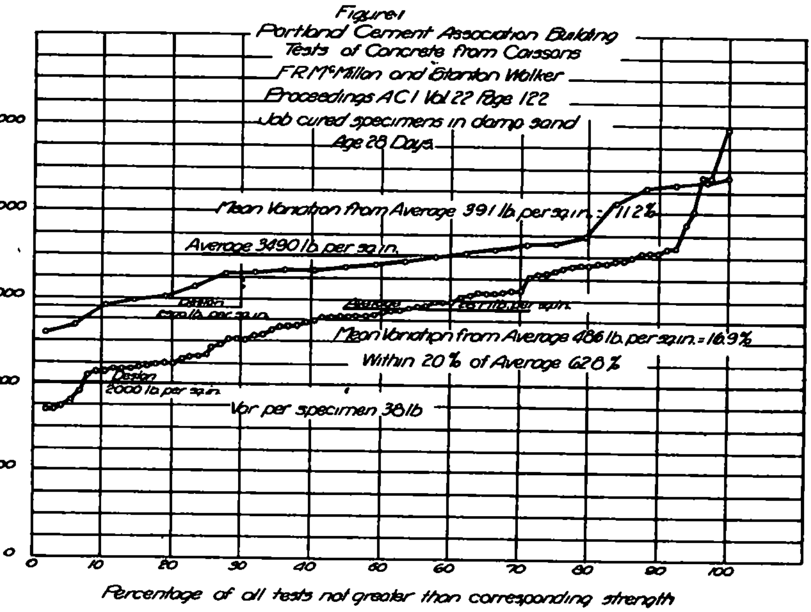

Figure 1

Figures 1 and 2 show progressive strength diagrams of the data reported in this paper These curves may be compared with each other and with the following diagrams for other data to give an idea as to relative uniformity In comparing series of tests in this way in which there are different numbers of specimens in the series, it is necessary to assume that the tests reported are representative of the concrete in the structure and that any number of tests that might have been made would have fallen upon the same curve Therefore all of the curves are so plotted that the horizontal space is the same regardless of the number of tests The slope of the major portion of the curve is an index of the uniformity as shown by the tests The flatter the curve, the more uniform are the tests The mean variation in pounds per square inch is a function which gives approximately the same comparison as the curves

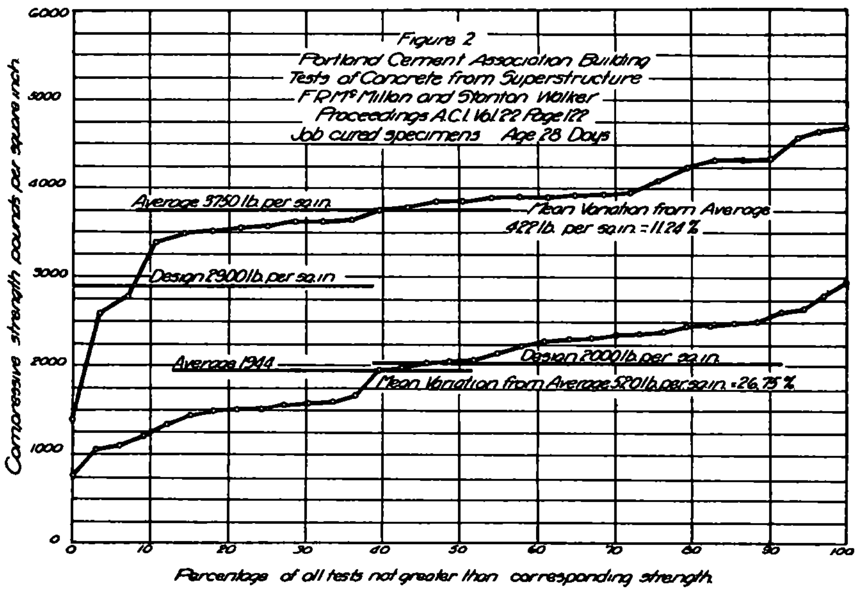

Figure 2

"Seven Years of Experience with the Job Control of the Quality of Concrete," by R B Young, Proceedings American Concrete Institute, 1926

The present practice of the Hydro-electric Power Commission of Ontario is founded upon the basis that the strength is governed by the water-cement ratio, but for each job the ratio of cement to aggregates is also predetermined A preliminary series of tests of concrete of different classes using the cement and aggregates to be used upon the job in question, is made Having the data from these tests, the moisture content of the aggregates, weight per cubic foot of aggregates, the size of the mixer to be used and the class of concrete required, the field engineer calculates the quantities of all materials per batch Changes are made as required to take care of varying conditions

The author's opinion as to the principal lessons to be learned from the seven years' experience of the Hydro-electric Power Commission are as follows:

1 The field control of concrete on the job is practicable and profitable

2 The control of concrete on the job is applicable to work of all kinds and sizes

3 The control of the quality of concrete is not a matter of designing mixtures nor of following some particular theory, but it involves every step in the production of concrete from the selection of the materials to the curing of the product.

4 While the water-cement-ratio-strength relation is subject to variations, with average well-graded materials, no other means than this is necessary in designing concrete mixtures for a given compressive strength, but economy demands that cognizance be taken of the grading of the aggregates

5 The concrete most economical in cement is not necessarily that having as much coarse aggregate as it is possible to use and still have its mixtures workable, but is usually one in which the sand is slightly in excess of this The best combination of aggregate depends on the grading of both the fine and coarse aggregate

6 Of the several processes in the manufacture of concrete, the measurement of aggregates and the placing of the mixtures are most important from the standpoint of quality

7 Intelligent supervision of the materials and processes of concrete is essential to successful control of its quality

8 The results of field tests of concrete should be interpreted with caution and in light of the conditions under which they were made, cured and tested, and for this reason comparison of field tests from different jobs is difficult

Figure 3 shows the strength data from one project which is presumed to be representative.

"New Experiences in Concrete Control," by J G Ahlers, Proceedings American Concrete Institute, 1926

In this paper is described the methods used by a contractor on several structures in controlling the concreting The water-cement ratio was the basis for the methods used The job procedure was as follows At least 7 days ahead of actual concreting, trial batches using various water-cement ratios and dried aggregates were made to furnish data from which the water-cement ratios required for the various grades of concrete desired, could be determined The fineness modulus of the aggregates was used in determining economical gradings of aggregates and ratios of fine to coarse aggregate

In this paper is also described an interesting apparatus designed for the accurate control of the relative amounts of water and cement going into each batch This is the "Ahlers Concrete Strength Regulator" In principle it is simply a device for measuring the water by causing it to balance a definite weight of cement through a suitable lever system

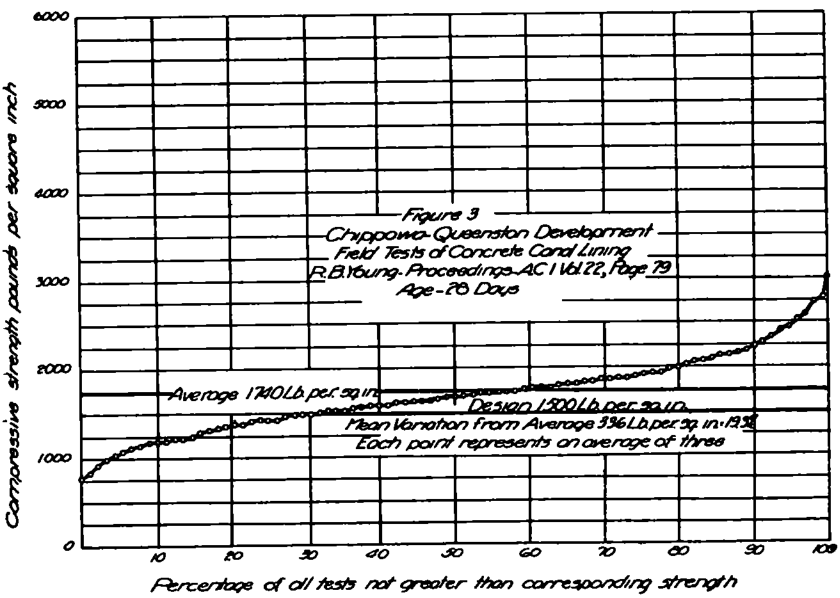

Figure 3

Compensation for the moisture in the aggregates was made by allowance for the maximum average moisture as determined from a number of tests The test data shown indicate considerable variation in strengths, but that nearly all were above the desired strength

"Report on Field Tests of Concrete Used in Construction Work Submitted to the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete," by W A Slater and Stanton Walker Proceedings American Society of Civil Engineers, January, 1925

"This report gives the results of a series of field tests sponsored by the Joint Commtitee, and made under the auspices of a Joint Committee of Contractors, with the object of determining whether the recommendations of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete were practical, especially as regards the provisions for the control of the quality of concrete in the field The tests were made on a building of the Victor Talking Machine Company, and on the piers of the Newark Bay bridge of the Central Railroad of New Jersey " The aim was to make these investigations show the results obtained where good construction methods are maintained, but where no unusual refinements are undertaken

The authors of this paper conclude that, "Insofar as general results may be predicted from these tests, they indicate that it is possible to meet requirements based on the Tables of Proportions as contained in the report of the Joint Committee (Proceedings American Society of Civil Engineers, October, 1924), or on average strengths shown by preliminary laboratory tests of specimens using materials from the job under consideration "This assumes that a tolerance which permits about 10 per cent of the strengths to fall below 80 per cent of the average strength is satisfactory" They also note that, "Greater accuracy of measuring quantities of materials on the work than is now generally secured is the feature which seems to be most worthy of future effort"

These data are shown in Figures 4 and 5

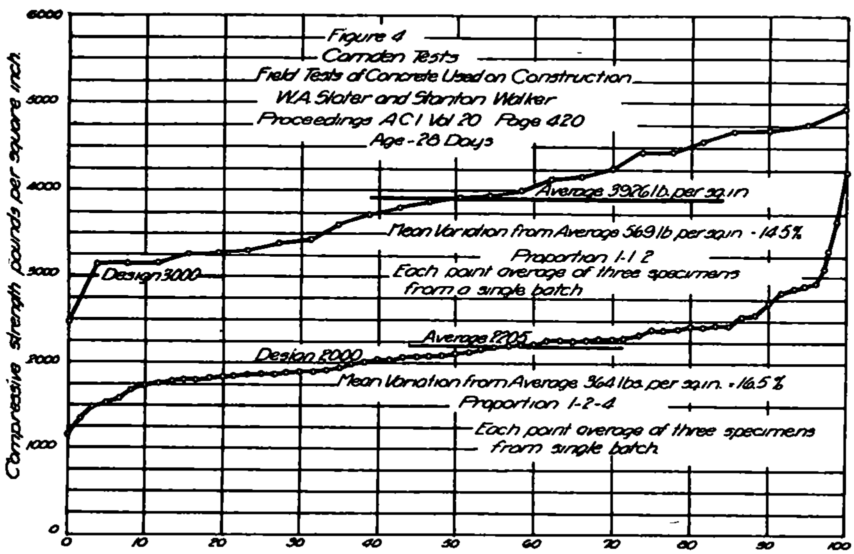

Figure 4

"The Advantages of Weighing Concrete Aggregates" by R W. Crum, American Highways, April, 1925

The Iowa Highway Commission controls quality of concrete for pavements, in the field by carefully weighing the aggregates making due allowance for moisture content and by holding the consistency of the concrete within narrow limits In later specifications, maximum mixing water is also specified

In the opinion of the Iowa Highway Commission, the practice of weighing aggregates, making due allowance for the amount of moisture therein is productive of concrete of more uniform composition More accurate advance estimates of quantities can be made, and a valuable record of actual quantities used is secured. Minimum

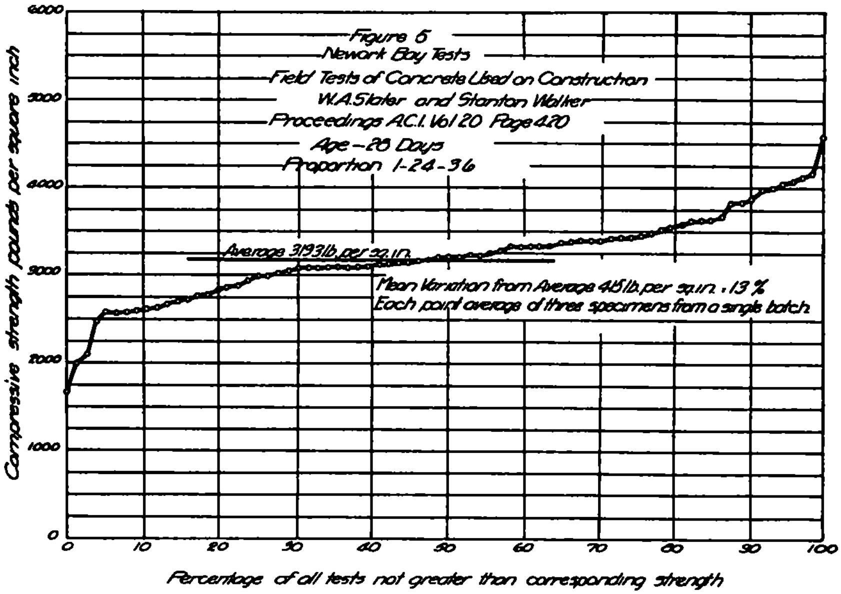

Figure 5

and average strengths secured are satisfactory, but the variation in individual test results in not greatly improved although more uniform averages from job to job have resulted The most important lesson learned from a study of these data is that accurate control of water content within narrow limits is also necessary before more uniform strength can be secured See Figure 6

"Control of Mixture and Testing of Wilson Dam Concrete," by John W. Hall, Proceedings of American Concrete Institute, 1926.

This paper is included as illustrative of results secured by thorough inspection under a type of specification formerly much used The significant features of the specification are as follows.

Each cubic yard of concrete to contain 5 or 6 bags of cement as required, 25 cubic feet of broken stone or gravel, and such a quantity of sand as will yield for each cubic yard of concrete 15 per cent more mortar than will be required to fill the voids in the broken stone or gravel The quantity of water for each batch will be such

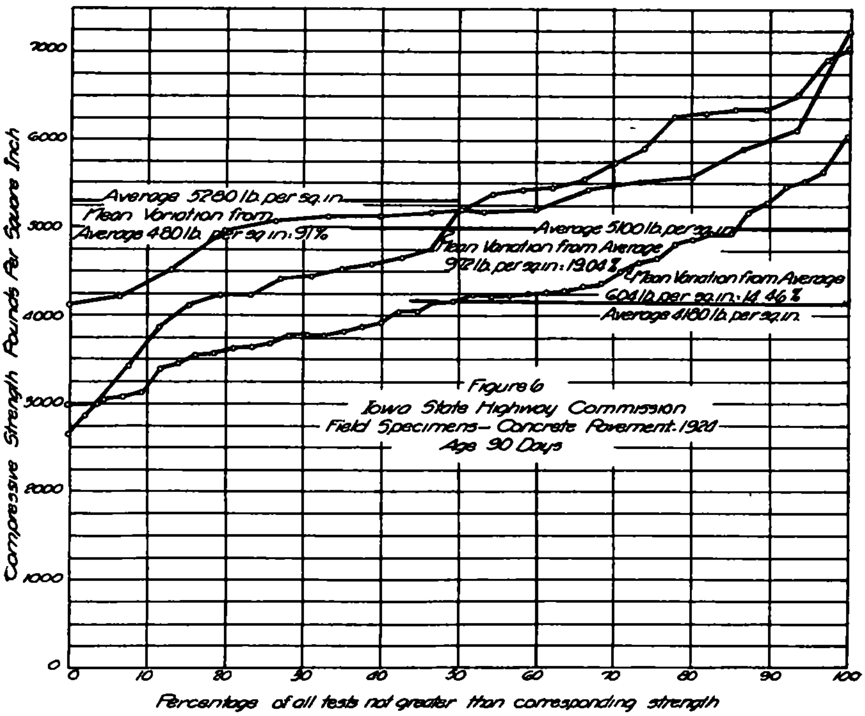

Figure 6

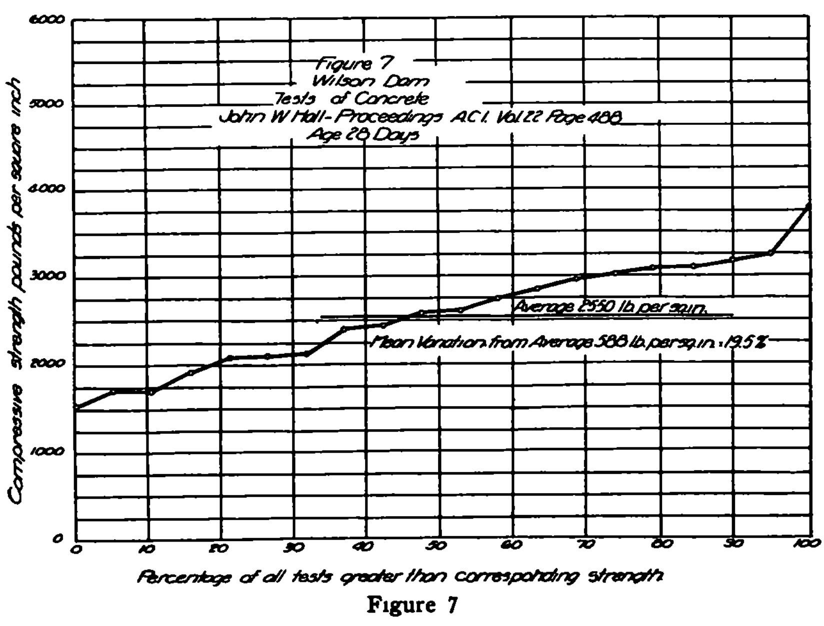

Figure 7

that men dumping concrete buckets do not track deeper than 10 inches nor less than 2 inches in freshly mixed concrete

Figure 7 shows the strength and uniformity secured through careful inspection under this specification

SUMMARY

Review of these reports leads to the impression that under good fabricating conditions, requirements as to average crushing strength can be met by any of the methods of proportioning, but that methods based upon a constant water-cement ratio permit of more accurate advance predictions of compressive strength Studies of most economical mixtures are best made by means of trial batches With respect to uniformity of quality, the impression is that the uniformity is about the same throughout these reports, and is about the best that can be secured with present methods It appears that uniformity is not so much a function of design as it is of workmanship

For maximum uniformity each batch should contain the same absolute volumes of water, cement and aggregates of uniform grading The necessity for uniform grading of coarse aggregate is not so great in mixtures having an excess of mortar as in mixtures in which the mortar is only sufficient to fill the void space

If it be admitted that a uniform mixture of all materials is the basis for uniform concrete, the methods of measurement must be of primary concern Adequate methods for measuring aggregates are available Direct weighing for both fine and coarse aggregates and inundation for fine aggregates are in common use and are known to be accurate The most troublesome factor in measuring the aggregates is the contained moisture The effect of this water is to complicate both the measurement of the mixing water and the measurement of the aggregates It should be determined and taken into account Upon some classes of work it may be satisfactory to use average values for moisture content, but on paving work the actual moisture in the materials being used should be determined

Cement is ordinarily used at the allowance of 94 lbs per sack Seldom does this much material get into the mixer There is some variation in the weight of the unopened sacks and from one-half pound to one pound is usually left in the sack

Upon stationary concreting plants, arrangement for accurate water measurement is easily made, but for moving paving mixers, equipment which will deliver a constant known quantity of water and which can be easily changed for other volumes has not yet been provided Several companies are now equipping their mixers with water measuring devices which will deliver a constant quantity of water so long as the pipe line pressure does not vary, but these devices are difficult to calibrate to permit of small changes in volume, and as pipe line pressure is always a variable, these are subject to fluctuation in quantity delivered With the devices now in use on paving work, it would be extremely difficult to specify an exact amount of water per batch, and know definitely that same was being consistently delivered to the mixture The necessary varying correction for moisture in the aggregate seriously complicates this problem The problem of accurate water measurement is capable of solution, and must be solved if the concrete is to attain the uniformity desired

A principal feature of the work of McMillan, Walker, Young and Ahlers is the attention given to economy of mixture Their aim is to so arrange specifications and proportions that for a given strength as established by the water-cement ratio, the maximum amount of aggregate consistent with good work will be used This, of course, involves a study of the grading of available aggregates and the best ratio of fine to coarse aggregates The tendency appears to be to study these factors by means of trial batches. In the practice of the Iowa Hihway Commission, the contractor is given the opportunity of using the most economical combination of fine and coarse aggregate embraced within a range of from 33 per cent fine aggregate to 60 per cent fine aggregate The proportions for the various combinations have been established through research work and years of experience with the materials available throughout the State

RECOMMENDATIONS

The Committee on Road Materials is of the opinion that methods of design to yield concrete of definite strength should be used It is also of the opinion that the highest degree of uniformity attainable is essential to good work, and to these ends recommends —

1 Measurement of aggregates by direct weight, or inundation where applicable

2 Required accurate measurement of water

3 Required use of a definite amount of water per sack of cement.

4 Required use of aggregates of constant grading as predetermined