1932

Tests on consistency and strength of concrete having constant water content, Proc. ASTM, Vol. 32 (1932), p. 629, Reprint No. 32 (32-7)

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PROCEEDINGS OF THE AMERICAN SOCIETY FOR TESTING MATERIALS
PHILADELPHIA, PA.
Volume 32, Part II, 1932

TESTS ON CONSISTENCY AND STRENGTH OF CONCRETE HAVING CONSTANT WATER CONTENT

BY INGE LYSE[1]

SYNOPSIS

In this paper test data are presented which show that the consistency of the concrete remains nearly constant regardless of the richness of mix, if the type and gradation of the aggregates and the water content per unit of fresh concrete remain constant. One series of tests included five different brands of cement and showed that the brand of cement had a slight effect upon the consistency of the concrete, while the richness of the mix for each cement had practically no effect. Another series of tests included nine different concrete aggregates and showed that the type and gradation of aggregates had a great effect upon the water requirement for a given consistency of the concrete, while for a given type and grading of aggregates and a constant water content the consistency was nearly the same for all mixes. Since the cement and aggregate contents were the only variables in these concrete mixes, the strength of the concrete was necessarily determined primarily by the cement content. It is shown that the relation between the cement-water ratio and the strength of the concrete was a straight line, and therefore the relation between the strength and the cement content was also a straight line for mixes of constant water content. Thus the following conclusions are drawn: The cement is the strength-giving element in concrete. Above a given minimum number of cement particles necessary to give workability and binding strength to the concrete, the strength increases in direct proportion to the increase in number of cement particles in a unit of water. For ordinary aggregates, a change in the richness of a concrete mix of a given consistency is accomplished by keeping the water content constant and substituting 0.85 lb. of aggregate for each pound decrease in the cement content, or *vice versa*.

INTRODUCTION

The consistency of concrete as measured by the slump cone has been found to remain practically constant, regardless of the richness of the mix, if the water content per unit of concrete and the type and gradation of the aggregates remain the same. In order to investigate this important property of concrete two series of tests were carried out at the Fritz Engineering Laboratory of Lehigh University during the winter of 1931–1932. In one of these series of tests the type and gradation of aggregates were the same throughout the

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series and the water content per cubic yard of concrete was kept constant also. Thus the only variables were the cement content and its complement, the corresponding aggregate content. Five different brands of cement were included in the tests, and four mixes of different richness were used with each brand of cement.

In the second series of tests aggregates from nine different sources were included and the water content was kept the same for all mixes containing a given aggregate. The gradation of each aggregate and the brand of cement used were the same for all mixes. Three mixes of different richness were used with each aggregate.

OUTLINE OF TESTS

The aggregates used in the first series of tests were the same as those which have been used in ordinary concrete investigations at the Fritz Engineering Laboratory during the preceding two years. The aggregates were siliceous sand and gravel from the Warner Co. plant at Morrisville, Pa. The sand had a fineness modulus of about 2.80 and was well suited for concrete. The gravel was graded so as to contain 40 per cent by weight, between No. 4 and ⅜-in. sieves and 60 per cent between ⅜- and ¾-in. sieves. The sand-coarse aggregate ratio was 1:2 by volume of dry rodded materials. The mixes by weight of the dry materials were: 1:1.64:3.26, 1:2.19:4.35, 1:2.74:5.43 and 1:3.29:6.51. The net water content was 36 gal. or 300 lb. per cu. yd. of freshly placed concrete for all the mixes, regardless of the brand of cement.

The concrete was mixed in a 2½ cu. ft. capacity power mixer and a slump test was taken on each batch immediately after mixing. Standard 6 by 12-in. concrete cylinders were made and tested at the ages of 7 days and 3 months. The 7-day specimens were cured in the moist room for 3 days and then in the air of the laboratory for the remaining 4 days. The 3-month specimens were cured in the moist room until the day of test.

The mixes in the second series of tests were so designed as to have cement-water ratios of 1.25, 1.61 and 2.25 by weight, which correspond to water contents of 9, 7 and 5 gal. per sack of cement, respectively. The aggregates included river sand and gravel, and also crushed limestone as fine and coarse aggregates. The sand-coarse aggregate ratio was 1:1½ by weight for all mixes, and the gradation of each aggregate was as received from the dealer.

In designing the mixes, a trial batch was made for each type of aggregate in order to determine the water requirement for a given slump. In making a trial batch a 1:2:3 mix by weight was used.

The water was added in known amounts until the desired slump of the mix was reached. A computation of the volume of the concrete in the trial batch gave the amount of water per unit of concrete. The net water content per unit of concrete was kept constant for all the mixes which had the same aggregate as that used in the trial batch. The cement content was determined by multiplying the net water content by the given cement-water ratio, and the change in richness of the mixes was accomplished by substituting 0.85 lb. of aggregate, of the type and gradation used, for each pound decrease in cement content, or *vice versa*. An amount of water corresponding to one per cent of the weight of the dry aggregate was added to all mixes in both series of tests to allow for absorption. The consistency of these mixes was measured by means of the slump test.

TABLE I.—SLUMP OF CONCRETE MIXES CONTAINING FIVE DIFFERENT BRANDS OF CEMENT.

Mix by Volume of Dry Rodded Materials	Mix by Weight of Dry Materials	Slump, in.					
		Cement A	Cement B	Cement C	Cement D	Cement E	Average
1:1½:3	1:1.64:3.26	2½	1½	3	2½	5½	3
1:2:4	1:2.19:4.35	2¼	1½	5¾[a]	2½	4½	3¼
1:2½:5	1:2.74:5.43	3¾	1½	5	2	4½	3½
1:3:6	1:3.29:6.51	3	1½	2½	3	5	3
Average		3	1½	4	2½	5	3¼

[a] Fell down.

TEST DATA

The slumps of the concrete mixes used in the first series of tests are given in Table I. The average strength of three cylinders of a kind is plotted in Fig. 1 for 7-day tests and in Fig. 2 for 3-month tests. The slumps observed in the second series of tests are given in Table II.

CONSISTENCY OF CONCRETE HAVING CONSTANT WATER CONTENT

In Table I the slumps have been tabulated for all the mixes included in the first series of tests. It is noted that for cement A the slump varied from a minimum of 2¼ to a maximum of 3¾ in. for the four different mixes. The other cements showed similar relations. Cement B had 1½ in. slump for all mixes, cement C varied from 2½ to 5¾ in., cement D from 2 to 3 in. and cement E varied from 4½ to 5½ in. The last column of Table I gives the average slump for the same mix regardless of the brand of cement used. These average slumps are very nearly the same for the four mixes, being 3, 3¼, 3½ and 3 in. It is noted from this table that the variation between the slumps for concrete containing different brands of cement was considerably greater than the variation between slumps of concrete mixes containing the same cement. For the aggregates used in this series of tests the slump remained nearly constant for all mixes which had the same brand of cement and which had a constant water content of 36 gal. or 300 lb. per cu. yd. of concrete. It is also noted that the brand of cement had a consistent effect upon the slump of the concrete. This effect was so small, however, that it is reasonable to

TABLE II.—SLUMP OF CONCRETE MIXES CONTAINING NINE DIFFERENT AGGREGATES.

	Type of Aggregate		Net Water Content, gal. per cu. yd.	Slump, in.			
	Fine	Coarse		Mix Having Cement-Water Ratio of 2.25	Mix Having Cement-Water Ratio of 1.61	Mix Having Cement-Water Ratio of 1.25	Average
No. 1	Limestone screenings	Crushed limestone	45.3	2	$2\frac{3}{4}$[a]	$2\frac{3}{4}$[a]	$2\frac{1}{2}$
No. 2	Sand	Gravel	37.0	2	3[b]	3[b]	$2\frac{3}{4}$
No. 3	Sand	Pea gravel	44.1	$3\frac{1}{2}$	$3\frac{1}{2}$	4	$3\frac{3}{4}$
No. 4	Sand	Gravel	38.0	$1\frac{3}{4}$	1	$1\frac{1}{2}$	$1\frac{1}{2}$
No. 5	Sand	Gravel	45.3	5	5	6	$5\frac{1}{4}$
No. 6	Limestone screenings	Crushed limestone	43.0	$\frac{1}{2}$	1	1	$\frac{3}{4}$
No. 7	Sand	Gravel	40.5	$\frac{1}{2}$	$2\frac{1}{4}$[c]	$2\frac{1}{4}$[c]	$1\frac{3}{4}$
No. 8	Sand	Pea gravel	41.5	$4\frac{3}{4}$	5	$3\frac{1}{2}$	$4\frac{1}{2}$
No. 9	Sand	Gravel partly crushed	41.5	$3\frac{1}{2}$	5	3	$3\frac{3}{4}$
Average				2.6	3.2	3.0	2.9

[a] 0.7 gal. per cu. yd. added to mix.
[b] 0.5 gal. per cu. yd. added to mix.
[c] 1.0 gal. per cu. yd. added to mix.

conclude that in most cases a mix which is placeable when one brand of cement is used will also be placeable when another brand is used.

In Table II the slumps are given for the three concrete mixes in which nine different aggregates were used. It is noted that the water requirement for a given slump is quite different for concretes containing different aggregates. While concrete containing aggregate No. 2 required only 37 gal. of water per cubic yard to produce a 2- to 3-in. slump, concrete containing aggregate No. 1 required 45.3 gal. per cu. yd. for the same slump. In other words, for concretes having paste of the same cement-water ratio, the amount of paste required to produce a 2- to 3-in. slump was more than 20 per cent

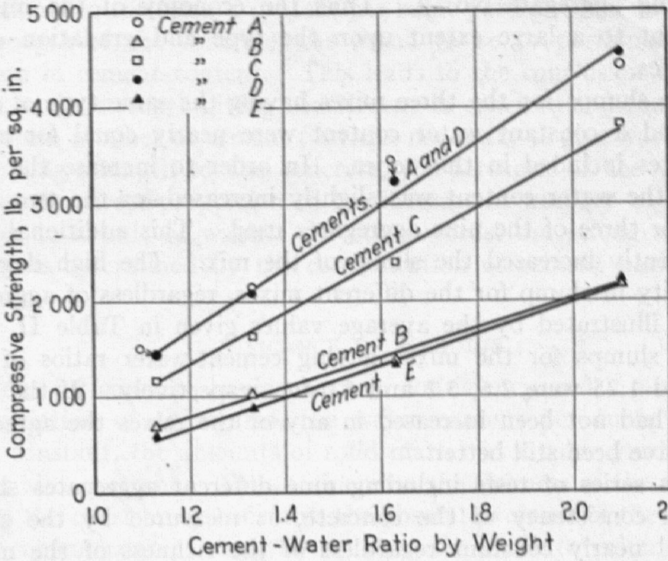

FIG. 1.—Relation Between Strength and Cement-Water Ratio at the Age of 7 Days.

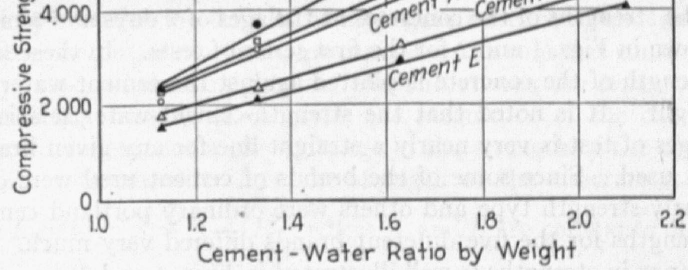

FIG. 2.—Relation Between Strength and Cement-Water Ratio at the Age of 3 Months.

greater for the concrete containing aggregate No. 1 than for concrete containing aggregate No. 2. Thus the economy of the mix was dependent to a large extent upon the type and gradation of the aggregates.

The slumps for the three mixes having the same type of aggregates and a constant water content were nearly equal for all the aggregates included in this series. In order to increase the workability, the water content was slightly increased for the two leaner mixes for three of the nine aggregates used. This additional water consequently increased the slump of the mix. The high degree of uniformity in slump for the different mixes, regardless of aggregates used, is illustrated by the average values given in Table II. The average slumps for the mixes having cement-water ratios of 2.25, 1.61, and 1.25 were 2.6, 3.2 and 3.0 in., respectively. If the water content had not been increased in any of the mixes the agreement would have been still better.

This series of tests including nine different aggregates showed that the consistency of the concrete, as measured by the slump, remained nearly constant regardless of the richness of the mix as long as the type and gradation of aggregates and the water content per cubic yard of concrete remained constant.

This uniformity in the workability for concretes having a given type and gradation of aggregates is very useful in designing concrete mixes. Since the water content remains constant, the amount of solids per unit of concrete is also constant. Thus a change in the cement content requires a corresponding change in the aggregate content if the consistency is to remain the same.

STRENGTH OF CONCRETES OF CONSTANT WATER CONTENT

The strengths of the concretes at the ages of 7 days and 3 months are shown in Figs. 1 and 2 for the first series of tests. In these figures the strength of the concrete is plotted against the cement-water ratio by weight. It is noted that the strength-cement-water relation for both ages of test is very nearly a straight line for any given brand of cement used. Since some of the brands of cement used were of the high-early-strength type and others were ordinary portland cements, the strengths for the five different brands differed very much. This large range in strengths is well illustrated in Figs. 1 and 2.

Figures 1 and 2 show that the relation between strength and cement-water ratio of a concrete mix is nearly a straight line within a range of mixes varying from 1:1½:3 to 1:3:6, for any given brand of cement. Since the water content per cubic yard of concrete remained the same for all the mixes the cement-water ratio is directly proportional to the cement content per cubic yard of concrete. Thus the strength of the concrete was found to be proportional to the variation in cement content. This leads to the conclusion that the cement is the strength-giving constituent in concrete and that above a minimum number of cement particles necessary to give workability and binding strength to the concrete, the strength of the concrete increases in direct proportion to the increase in number of cement particles in a unit of water. In other words, the strength of the concrete is determined by the concentration of cement particles in the paste.

SIGNIFICANCE OF RESULTS

Since for concrete having a given consistency and a given type and gradation of aggregates, the water content per cubic yard is nearly constant, the amounts of solid matter in a cubic yard of concrete is also constant. Thus to increase the richness of the mix and to keep the consistency constant, the absolute volume of the increase in the cement content must be equal to the absolute volume of the decrease in the aggregate content, and to decrease the richness, *vice versa*.

A change of one pound in the cement content necessitates a change of $\frac{ga}{gc}$ pounds in the aggregate content, where ga and gc are the specific gravities of the aggregate and cement respectively. Common aggregates and cements have specific gravities of 2.65 and 3.10, respectively, so that the relation $\frac{ga}{gc} = \frac{2.65}{3.10} = 0.85$. This leads to the simple conclusion that a change in the richness of the concrete mix is accomplished by substituting 0.85 lb. of aggregate for each pound decrease in cement content or *vice versa*, for concretes of a constant consistency.

By means of the straight-line relation between the cement-water ratio and the strength of concrete, the magnitude of the change in the cement content for a given change in the strength of the concrete is readily determined. Since the strength of the concrete is given by the formula: $S = A + B\frac{c}{w}$ where A and B are constants depending upon the materials used and the conditions of test, and c and w are amounts of cement and water, respectively, the equation for concrete mixes having a constant water content becomes: $S = A + \frac{B}{w}c = A + Kc$. Thus the cement content necessary to produce a given strength is given by $c = \frac{S-A}{K}$. Fortunately the straight-line relationship is applicable for all practical mixes for a given brand of cement so that the change in cement content required for a given change in strength is determined directly from the amount of cement necessary to give the required cement-water ratio.

SUMMARY

1. Concrete mixes having a given type and gradation of aggregates, a given brand of cement and a constant water content per cubic yard of concrete were found to have nearly the same consistency, regardless of richness of mix.

2. The brand of cement used had a slight effect upon the consistency of the concrete.

3. The water requirements for concrete of a given consistency varied considerably with the type and gradation of fine and coarse aggregates.

4. For all the aggregates used the consistency remained practically the same so long as the water content and the type and gradation of the aggregate remained the same.

5. The strength of the concrete mixes increased proportionately with the increase in the cement-water ratio for any brand of cement used and for both ages at test.

6. The conclusion is reached that the cement is the strength-giving constituent in concrete and that above a minimum number of cement particles necessary to give workability and binding strength to the concrete, the strength of the concrete increases in direct proportion to the increase in number of cement particles in a unit of water.

7. Each brand of cement had its own straight-line relation between the strength and the cement-water ratio of the concrete.

8. In designing concrete mixes of equal consistency, the water content per cubic yard of concrete and the type and gradation of aggregates should be maintained the same and the change in richness of the mix should be accomplished by substituting $\left(\frac{\text{specific gravity of aggregates}}{\text{specific gravity of cement}} = \text{approximately } 0.85\right)$ lb. of aggregates for each pound decrease in cement content, or *vice versa*.

DISCUSSION

MR. M. O. WITHEY[1] (*presented in written form*).—In this paper, Mr. Lyse has apparently brought forth a considerable simplification of the method of procedure in designing concrete mixes. The fundamental basis for his method is that the compressive strength of concrete increases lineally with the cement-water ratio by weight. It does not appear to the writer that this relationship always holds. In Fig. 1 of Mr. Lyse's paper, it will be observed that the curve for cement A is not strictly a straight line and that in Fig. 2 the curve for cement D is not a straight line. In Fig. 2 these discrepancies will be more apparent if the strength scale is made the same as in Fig. 1. I believe that similar results will be shown if the data for series 210 of the report of the Director of Research of the Portland Cement Association are plotted. I also have plotted a similar relationship for a series of tests which were made in our laboratory with Janesville sand and Janesville gravel which does not give a linear relationship, particularly for the higher cement-water ratios. These discrepancies lead me to believe that this method affords a good approximation for designing mixes when the basic data are obtained from cement-water ratios which do not differ widely from the ratios to be used in a specific design, but I am uncertain regarding the accuracy of the method when the basic water ratios do differ materially from those used in the design.

MR. A. D. CONROW[2] (*presented in written form*).—The test data of the paper seem to show that the consistency of concrete remains nearly constant regardless of the richness of the mix, if the type and gradation of the aggregates and the water per unit of fresh concrete remain constant. This condition is correct for a certain range of mixtures, since the term nearly constant is used. The variation in consistency under the above stated conditions is so small over the range of variation in cement content that is commonly found in concrete, that it may be considered practically constant. The condition, however, is contrary to the well-known fact that the finer the gradation of a mixture of dry materials, the greater the quantity of water required for a given consistency. The richness of the mix may be increased without changing the volume of concrete by adding, say one pound of cement, and removing 0.85 lb. of aggregate when the

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[2] Research Engineer, Ash Grove Lime and Portland Cement Co., Chanute, Kans.

specific gravities of the materials are those common in concrete materials. This results in the addition of one pound of very fine material and the removal of 0.85 lb. of relatively coarse material. The gradation of the new mixture will be finer. More water will be required to bring to the given consistency unless some compensating factor is present. The compensating factor over the range of common mixtures is the greater separation of the aggregate particles by cement paste as a lubricant giving greater mobility to the aggregate particles. The principle set forth here can apply only over a very limited range of richness of mix.

The maximum size of aggregate is not given for Table I, but it is believed to be 1 in. or larger. It is believed that the smaller the size of aggregate, the less is the likelihood that the consistency will remain constant under the conditions given.

The fact that the consistency obtained with different brands of cement in the same mix is not the same has occupied the attention of cement manufacturers for some time, and has resulted in the raising of the question as to whether the strength of concretes of the same water-cement ratio and mix are fair comparisons of the concrete-making qualities of the cements to be compared. A fair comparison of the concrete-making quality of a number of cements should be on the basis of concrete having the same consistency and the same cement content per unit of volume of concrete.

The straight-line relation of strength to cement-water ratio by weight is believed to be a better method of showing the strength and water quantity relations than the familiar curve developed by Abrams of water-cement ratio by volume. The form and equation of the curve is easier to handle.

The cement-water ratio curves of Figs. 1 and 2 of the paper do not show the true relative strengths of the different cements in a given concrete. Cement B shows rather low strength compared to the other cements but observation of Table I shows that more water is necessary to bring concrete made with this cement to the same consistency as was obtained with the others. This would mean that if compared with the same concrete, the cement-water ratio would be lower for the same consistency, and its relative strength would be still lower than is shown by the curves.

The fact that changes in gradation of a concrete mixture causes a change in the water quantity required to bring a mixture to a given consistency, is one which has been taken into account in the methods of design of concrete mixtures for some time, and it is this principle which conflicts with the conditions given at the beginning of the paper, for a change in richness of the mix will cause a change in gradation of the mixture if the gradation of the aggregate remains the same. In the opinion of the writer, this variation in gradation may best be dealt with by use of a fineness modulus similar to that developed by Abrams. Greater accuracy could probably be attained by closer sizing of the sieves but would be somewhat impractical. The water requirements of a mix may be quite closely obtained if the gradation of the mix is known and certain factors obtained which are involved in the nature of the cement used, and the nature of the aggregate particles.

MR. F. R. MCMILLAN.[1]—I think Mr. Lyse has made a distinctly valuable contribution. I do not believe he will disagree with Mr. Withey's comment which will probably be agreed to by anyone who is a careful student of the subject. Unfortunately, we have learned in the field of concrete to worship curves and formulas too much and failed to keep in our minds some of the limitations of our material and the basic data. Any method as simple as that developed by Mr. Lyse and which at the same time predicts the strength as accurately, should be of permanent value to the profession. The very fact that the points from Mr. Lyse's tests do not line up perfectly is evidence that we must not rely too implicitly on formulas or curves. We should, however, recognize any device that will simplify or speed up our calculations and should take full advantage of it within the limits of its application.

I like very much the simplicity of Mr. Lyse's method and hope to see it quite generally adopted. By it we can establish for any given group of materials a basic relationship for the design of mixtures that is simple and probably involves less error fundamentally than is normally found in the measurement of materials. Our own data show slight variations from Mr. Lyse's data in respect to the constancy in water content for different mixes of the same consistency. For example, on the basis of constant remolding effort (in the remolding test) we find an increase in water content as the mix becomes leaner. On the other hand, our data indicate that the approximate relationship between total water content and consistency holds over a wider range in proportion of sand to coarse aggregate than would appear from Mr. Lyse's discussion.

All that should be expected of any method of design is to give quickly an approximation to a desirable mix which can finally be adjusted at the mixer to give exactly the workability, water ratio, and cement content required. I am glad to see this paper in the

[1] Director of Research, Portland Cement Assn., Chicago, Ill.

records of the Society. All that is needed is to keep in mind the limitations of the method and I think it will be found extremely valuable.

MESSRS. R. B. YOUNG[1] AND H. C. ROSS[2] (*by letter*).—The simplicity of Mr. Lyse's constant water method of designing concrete mixtures makes an immediate appeal to anyone having much of this work to do. The writers, being in this category, have gone to some trouble to examine the method in the light of the accumulated experience and data at their disposal from the extensive operations and experiments of the Hydro-Electric Power Commission.

The field and laboratory experience of the Hydro-Electric Power Commission of Ontario indicates that the constant water method is approximately correct within certain limits, but to maintain a constant consistency it is necessary to increase the water content per unit volume of concrete as the richer mixes are approached. Fortunately the range within which the constant water method may be applied with sufficient accuracy for most purposes is that which includes the mixes commonly used in concreting practice.

In a recent investigation on a set of mixes in which the gradation of the aggregates and the consistency were kept constant, the variation between the water requirements for mixes having cement-water ratios of 1.21 and 1.76 by weight, respectively, amounted to 6 lb. per cu. yd. of concrete. As the richness of the mix was increased beyond this point, a decided increase in water became necessary to maintain the consistency. A mix having a cement-water ratio of 2.2 required an increase of 33 lb. of water per cubic yard over the 1.21 cement-water ratio mix.

Table II of the paper gives the results of tests on nine different aggregates used in mixes with cement-water ratios varying from 1.25 to 2.25. Our experience leads us to believe that the constant water method of design is not sufficiently accurate to be used over such a wide range of mixes but should be applied only within reasonable limits on either side of the value obtained in the trial batch.

The method of designing concrete mixtures used by the Hydro-Electric Power Commission of Ontario has been first to establish experimentally the water-cement ratio curve for the cement and aggregates in question using a ratio of fine to coarse aggregate that experience or test has shown would give a proper workability, then by calculation from the data obtained in establishing the water-

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cement ratio curve, determine the water-cement ratio, cement content and unit weight of a concrete meeting the strength requirements sought. From then on it is a very simple matter to work out the proportions for any sized batch. This method has been used on dozens of different jobs, using many different types of aggregates and for concrete totalling well over a million cubic yards, and our experience has been that seldom do the proportions thus worked out have to be altered when first used in the field unless there has been a marked change in the character of the material used.

MR. INGE LYSE[1] (*author's closure by letter*).—The author is pleased to note the favorable comments made by those who discussed this paper Since any method for designing concrete mixes gives only approximate values for field conditions, final adjustments have to be made on the job. The method of design should therefore be considered only as a convenient tool for the calculation of the approximate quantities of materials for given conditions. The proposed method has it advantage in its great simplicity and its fairly accurate results. Both the straight-line strength relation and the constant water requirement for a given consistency hold only within certain limits, which however, fortunately enough, cover the range of practically all concrete mixes used in present-day design. The proposed method of design has been used exclusively at the Lehigh University since January, 1930. The strength of the concrete has varied from 1000 to 6000 lb. per sq. in. and no difficulty has ever been encountered.

It has been called to the author's attention that the Swiss concrete investigator, Prof. J. Bolomey,[2] as early as 1927, had proposed the use of a straight-line relation between the cement-water ratio and the strength of the concrete, and that other European investigators have supported this proposal. For the sake of simplicity and the better understanding of the fundamentals of concrete making it is hoped that the cement-water ratio will soon be generally accepted as the criterion for the strength giving qualities of the concrete.

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[2] "Durcissement des Mortiers et Betons," *Bulletin Technique* de la Suisse Romande, Nos. 16, 22 and 24 (1927).