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An Investigation of Compressive Testing of Concrete

Gilbert R. Williamson

COMPRESSIVE TESTING OF CONCRETE - WILLIAMSON

NAME AND ADDRESS	DATE

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By

Gilbert R. Williamson

B.S.C.E. Ohio Northern University

1952

A Thesis

Submitted in Partial Fulfillment of the

Requirements for the Degree of

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MASTER OF SCIENCE

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Thesis committee

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I. INTRODUCTION

History.--The use of concrete as a building material dates back two thousand years to the days of the Roman Empire. The Romans, using a natural volcanic cement in combination with lime, built many concrete structures, some of which are still standing today. However, following the Romans, the cement arts had a long period of dormancy. It wasn't until 1756 when John Smeaton, a British engineer, in preparation for the rebuilding of the Eddystone light-house, evolved a process for the manufacture of a natural cement. In 1824, an English bricklayer named Joseph Aspdin obtained a patent for making artificial stone. This artificial stone was made from the first portland cement. Despite the fact that portland cement produced a concrete superior to that of natural cement, a widespread use of concrete was slow in developing. It wasn't until after 1900 that any significant progress was made. The rapid continuous expansion of the use of portland-cement concrete since 1900 has been brought about by three developments; (1) recognition of the many advantages and adaptibility of reinforced concrete, and the development of design and construction technique for its use, (2) the development of the automobile and its demands for paved highways, and (3) the ushering in of the era of large dams and similiar structures.

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With the increased use of concrete, a need developed for a code of practice for both plain and reinforced concrete. In 1904, the First Joint Committee on Specifications for Concrete and Reinforced Concrete was organized. Its final report, published in 1916, set the pattern for concrete practice throughout the United States and much of the world. A second and third joint committee were later organized, and reports were issued in 1924 and 1940 respectively. The American Concrete Institute (A.C.I.) was organized in 1905, and is probably the leader in the field today. Important contributions to the establishment of a code of practice have also been made by the American Society for Testing Materials (A.S.T.M.). While the A.C.I. concerns itself primarily with design criteria, the A.S.T.M. covers the field of the testing of concrete. In this country, most designers specify that the concrete (and other materials) used in their designs be tested in accordance with specifications as published by the A.S.T.M. in their books of Standards.[2] It is with some of these A.S.T.M. specifications for compressive testing of concrete that this paper is concerned.

The Problem.--The strength of most materials is affected by the rate of application of the load and concrete is no exception. However, the effect of a varying rate of loading on the compressive strength of concrete has not been too fully investigated. This effect is one of the problems covered in this paper. The first investigation along these lines was done in 1917 by Duff Abrams of the Structural

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Materials Research Laboratory, Lewis Institute, Chicago.[3] In 1936, Paul G. Jones and F.E. Richart, working at the University of Illinois Engineering Experiment Station, reported the results of their experiments of the effect of speed of loading on both the compressive strength and the stress-strain relationship of plain concrete.[4] The most recent work, and perhaps the most complete, was done by D. Watstein in 1953.[5] A review of the data published by the above named and other investigators was presented at the fifty-eighth annual meeting of A.S.T.M. in 1955. The review was presented by Douglas McHenry and J. J. Shideler.[6] They concluded that additional work in this field was needed.

The two other problems discussed in this paper are concerned indirectly with the making of compression test cylinders. The problems are: (1) how does a cylinder rupture when it fails, and (2) why does it rupture in this manner.

Purpose.--Of the five years that have elapsed since the author received his first engineering degree, four have been spent in the building construction industry as either a field engineer or superintendent. Previous to this, the author was employed for a year as a construction laborer. During this time, he has helped to pour or helped to supervise the pouring of between thirty and forty thousand cubic yards of structural concrete. It was here that the author developed a great interest and respect for this most widely used of building materials. However, this feeling is not shared by most

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of the people who do the actual building with concrete. The author has seen, time and time again, instances where men who have handled concrete all their lives never knew that excessive water lowered the strength of concrete; that excessive vibration produced an inferior product; that test cylinders were to be made according to certain specifications, and not by the method that happened to suit the concrete foreman at the time. It was while witnessing these and many other abuses in the handling and placing of concrete that the material earned the respect of the author. Despite this great mishandling, the strength of the concrete itself is rarely the cause of a failure. This leads to the belief that concrete is stronger than is generally believed. Since the design strength (compressive) is based mostly on the twenty-eight day strength of standard test cylinders, it was decided to investigate this method of testing, the objective being to determine whether test cylinders are a satisfactory specimen. The author is of the opinion that they do not give a true indication of the strength of the concrete, but rather a lower value. If this is true, then millions of dollars are wasted each year in the over designing of concrete. The author is also of the opinion that with improved methods of batching and handling and testing, the permissible percentage of the twenty-eight day strength now used in design could possibly be increased, thus resulting in a great savings. It was to this aim that the investigation

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of the rupturing of test cylinders was undertaken.

To the knowledge of the author, no previous work has been done in the manner presented in this paper concerning the failure of test cylinders. The numerous publications in existence all seem to agree that there are three types of failures, shear, cone, and columnar. Whether this has been established by several investigators, or by one and accepted by all, is not known by this author. However, when testing cylinders, it is easily seen how the above conclusion could be stated. The difference in results presented herein from those of other investigators seems to hinge on the speed in which the testing machine was shut off after failure. Also, no work has been found concerning which portion of the test cylinders failed. Because of this, the density of a cylinder has probably never been investigated as done by this author.

The reason for investigating the effect of a varying rate of loading on the compressive strength of concrete is the same as for the investigation listed above--namely, to help effect a change in design criteria so as to reduce the cost of concrete. This subject has been investigated previously; however, as stated by McHenry and Shideler earlier, more work is needed on this subject before the results can be accepted as fact and applied to concrete design. It is hoped that the data presented herein will be evaluated along with previous work and lead to the acceptance of the conclusions presented. The results of previous investi-

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To the knowledge of the author, no previous work has been done in the manner presented in this paper concerning the failure of test cylinders. The previous publications in existence which mention the subject give three types of failures; shear, bond, and cohesion. Whether this may been established by several investigators, or by one and accepted by all, is not known by this author. However, when testing cylinders, it is easily seen how the above conclusion might be reached. The difference in results presented herein from those of other investigators seems to hinge on the speed in which the testing machine was shut off after failure. Also, no work has been found concerning which portion of the test cylinders failed. Because of this, the density of a cylinder has probably never been investigated as done by this author.

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gators, correlated to a base rate of about thirty pounds per square inch per second, is as follows: (1) Bureau of Reclamation,[8] using 8" by 16" and 6" by 12" cylinders with loads varying from five to one hundred pounds per square inch per second found that the strength increased from ninety-six to 105 per cent of the base rate; (2) Jones and Richart, using standard test cylinders with loads varying from one to one thousand pounds per square inch per second found that the strength varied from eighty-nine to 110 percent respectively: (3) Thaulow,[9] using 10 by 20 centimeter cylinders with loads varying from ten to 320 pounds per square inch per second found that the strength varied from ninety-five to 110 per cent of the base rate; (4) Evans,[10] using two and three inch cubes found no increase in strength up to a rate of one-thousand pounds per square inch per second, but for loads between one thousand and five hundred thousand, the strength increased to 125 percent of the base rate; (5) Watstein, using 3" by 6" cylinders and a weak and strong concrete, (2500 and 6500 pounds per square inch) with a loading rate that varied from ten to ten million pounds per square inch per second found that the strength increased to approximately 185 per cent, using six pounds per square inch per second as a base rate. If this characteristic of concrete can be accepted as fact and incorporated into the design of structures subject to impact loads, a considerable savings in cement could be effected.

gators, correlated to a base rate of [illegible] pounds per square inch per second, is as follows: (1) Bureau of Reclamation,[8] using 6" by 12" and 8" by 12" cylinders with loads varying from five to one hundred pounds per square inch per second found that the strength increased from [illegible] to [illegible] per cent of the base rate; (2) Jones and Richart, using standard test cylinders with loads varying from one to one thousand pounds per square inch per second found that the strength varied from eighty-nine to 115 per cent respectively; (3) Thaulow,[9] using 10 by 20 centimeter cylinders with loads varying from ten to 720 pounds per square inch per second found that the strength varied from ninety-five to 120 per cent of the base rate; (4) Evans,[10] using two and three inch cubes found no increase in strength up to a rate of one-thousand pounds per square inch per second, but for loads between one thousand and five hundred thousand, the strength increased to 125 per cent of the base rate; (5) Watstein, using 3" by 6" cylinders and a weak and strong concrete (2500 and 6500 pounds per square inch) with a loading rate that varied from ten to ten million pounds per square inch per second found that the strength increased approximately 185 per cent, using six pounds per square inch per second as a base rate. If this characteristic of concrete was accepted as fact and incorporated into the design of structures subject to impact loads, a considerable savings in material could be effected.

II. METHODS AND PROCEDURE

The making and testing of the concrete cylinders was done according to the following A.S.T.M. standards:

C 39-49 Compressive Strength of Molded Concrete Cylinders.

C 192-55 Concrete Compression and Flexure Test Specimens, Making and Curing in the Laboratory.

C 136-46 Sieve Analysis of Fine and Coarse Aggregate.

D 75-48 Sampling Stone, Slag, Gravel and Sand for Use as Highway Materials.

Two different concrete mixes were used in this investigation. Design mix no. 1, which at times will be referred to as the weak mix, was designed to produce a compressive strength of between twenty-five hundred and three thousand pounds per square inch at twenty-eight days, with a slump of three to three and one half inches. This is a mix of medium consistency. Design mix no. 2, which at times will be referred to as the strong mix, was designed to produce a compressive strength of between forty-five hundred and five thousand pounds per square inch at twenty-eight days, with a slump of about one inch. This would be classed as a dry mix. The designs of the two mixes are given on pages 34 and 35. Mix no. 1, when tested at the rate recommended by A.S.T.M. (thirty pounds per square inch per second), had an average strength of 2,740 pounds per square inch.

Mix No. 2 had an average strength of 4,922 pounds per square inch.

The cylinders were made in batches of five or six, using a one cubic foot mixer driven by an electric motor. A waxed cardboard mold was used throughout. The cylinders were not capped with a metal or glass plate as is specified in A.S.T.M. standard C 192-55 for the simple reason that it is not general practice to do so. After casting, the cylinders were kept in a heated building for between twenty and twenty-four hours, at which time they were removed fom the molds and placed in a heated moist room to cure for twenty-eight days. The capping was done with an approved sulfur-clay compound. The instrument used for molding the caps was the type that permitted both ends to be capped at once, almost assuring that the caps would be perpendicular to the axis of the cylinder. The ends of the molding instrument, when checked with a straight edge and a 0.002 inch feeler gage, showed no concavity or convexity.

An attempt was made to produce enough cylinders in one batch of each mix to cover the six different rates of loading used in investigating the lower rates of loading. This would tend to eliminate any variation that might occur in batching and mixing from day to day. For investigating the lower rates of loading the following rates were used: 3, 15, 30, 50, 80, and 105 pounds per square inch per second. The maximum and minimum rates of loading were dictated by the practical limits of the testing machine. The testing machine used was a Tinius Olsen hydraulically

Mix No. 2 had an average strength of [illegible] pounds per square inch.

The cylinders were made in batches of five or six, using a one cubic foot mixer driven by an electric motor. A waxed cardboard mold was used throughout. The cylinders were not capped with a metal or glass plate as is specified in A.S.T.M. standard C192-59, for the simple reason that it is not general practice to do so. After casting, the cylinders were kept in a heated building for between twenty and twenty-four hours, at which time they were removed from the molds and placed in a heated moist room to cure for twenty-eight days. The capping was done with an approved sulfur-clay compound. The instrument used for molding the caps was the type that permitted both ends to be capped at once, almost assuring that the planes would be perpendicular to the axis of the cylinder. The ends of the molding instrument, when checked with a straight edge and a 0.002 inch feeler gage, showed no irregularity.

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operated unit, with a three hundred thousand pound capacity. It was checked, upon completion of the testing, with a Morehouse proving ring for a range up to 150,000 pounds. For loads below 30,000 pounds, the machine did not meet A.S.T.M. specifications, but for loads from 30,000 to 150,000 pounds, it was in excellent adjustment. At a load of 120,000 pounds, the error was slightly over the permissible one per cent (1.23). However, at this particular loading, the testing machine was extremely sensitive, and it is believed that the error was probably due more to the inability of the operators to obtain an accurate reading, rather than to any maladjustment of the machine.

The testing machine was equipped with a load rate indicator. The various rates of loading were obtained by using a stop watch to time the rate indicator for from three to five minutes. The desired rate of loading was set in the machine before inserting a cylinder for testing. It should be mentioned at this point that a slight deviation was made in the procedure for loading the cylinders from that specified in A.S.T.M. standard C 39-49, which covers the method of testing cylinders. The specified procedure requires that no adjustment be made in the loading while a specimen is yielding rapidly immediately before failure. At the lower loading rates, three, ten, and fifteen pounds per square inch per second, this specification was impossible to meet. As the failure load was approached for these lower

Mix No. 2 had an average strength of [illegible] pounds per square inch.

The cylinders were made in batches of five or six, using a one cubic foot mixer driven by an electric motor. A waxed cardboard mold was used [illegible]. The cylinders were not capped with a metal or glass plate as is specified in A.S.T.M. standard C192-59T, the simple reason being that it is not general practice to do so. After casting, the cylinders were kept in a heated building for between twenty and twenty-four hours, at which time they were removed from the molds and placed in a heated moist room to cure for twenty-eight days. The capping was done with an approved sulfur-clay compound. The instrument used for molding the caps was the type that permitted both ends to be capped at once, almost assuring that the planes would be perpendicular to the axis of the cylinder. The ends of the molding instrument, when checked with a straight edge and a 0.002 inch feeler gage, showed no irregularity [illegible].

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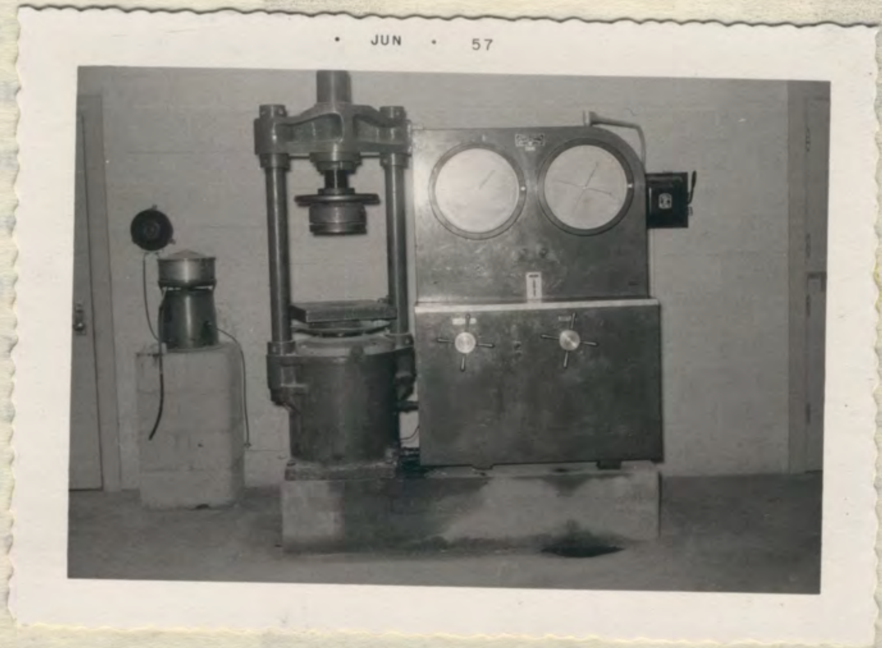

Fig. 1 Tinius Olsen hydraulic testing machine, used for testing concrete cylinders.

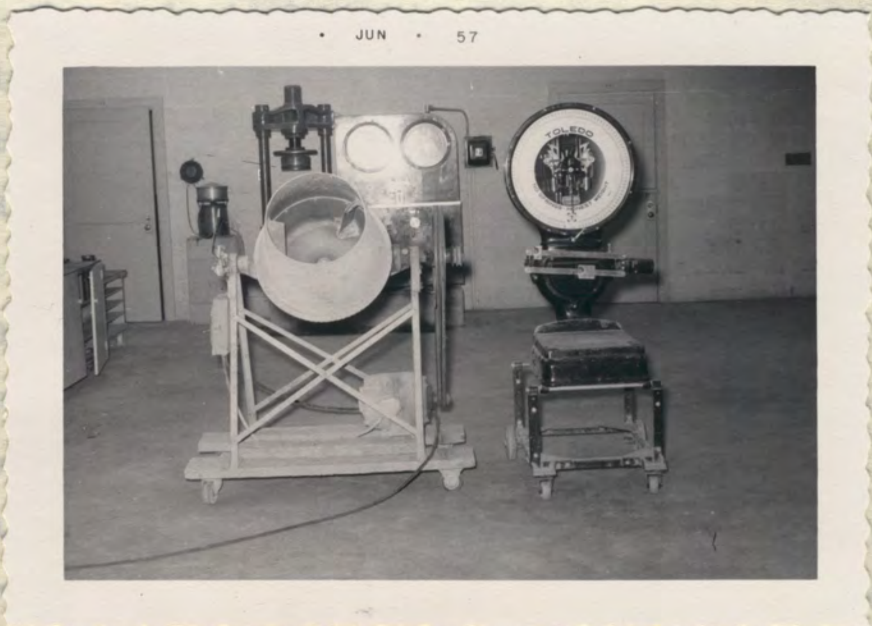

Fig. 2 A one cubic foot mixer and Toledo scale used in batching and mixing the concrete.

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loading rates, the load indicator needle would fall back as if the specimen had failed, whereas, actually it had not. Therefore, to keep the load from falling away, and to bring the specimen to actual failure, an adjustment in the loading had to be made. Since this was necessary for the lower loading rates, it was decided to follow this procedure for all the loading rates. Therefore, a constant loading rate was maintained until failure of the specimen in all cases.

To obtain some idea as to what happens at a very high rate of loading, some of the cylinders were loaded at a rate of one hundred thousand pounds per second. The procedure for applying this load was as follows. The specimen was placed in the testing machine in the ordinary manner. Then a load of ten thousand pounds was applied slowly in order to seat the sperical head. Once the head was seated, the loading mechanism was turned on full. This produced a loading rate of 3,670 pounds per square inch per second.

Since A.S.T.M. standard C 39-49 specifies that compression cylinders are to be broken at a rate between twenty and fifty pounds per square inch per second, it was decided to investigate this region more thoroughly. From one days batch, for each mix, six or eight cylinders were taken, half of which were broken at a rate of twenty pounds per square inch per second and half at fifty. On a succeeding day, the same procedure was followed for rates of ten and thirty pounds per square inch per second.

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Of the ninty-six cylinders made, seventy-nine were used to investigate the effect of the rate of loading on the compressive strength of concrete.

After the cylinders were broken, they were examined to determine the method of rupture. To be certain that only the initial plane of failure appeared in the cylinder, the testing machine had to be shut off immediately after failure of the specimen. If the machine were left running for any length of time after failure, numerous cracks would appear throughout the cylinder. This, in the author's opinion, gives a false picture as to the method of rupture and plane of failure. After the cylinders were examined, and the cracks noted, they were then struck on the end with an iron bar in order to completely break the cylinder. This was done to determine beyond any doubt that the cracks that showed externally on the cylinder were a true indication of where the failure plane had occurred.

Since there is always the possibility that an investigator, during the course of his experimentation, could unknowingly be guilty of an erroneous procedure, thereby consistently producing erroneous results, a separate observation was made regarding the method of rupture. On three different occasions the author visited the Albuquerque Testing Laboratory, Albuquerque, New Mexico, to witness the testing of concrete cylinders. These cylinders were made by various people and included both seven and twenty-eight day tests. The strengths ranged from fourteen hundred to fifty-five hundred pounds per square inch. The

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Since there is always the possibility that an investigator, during the course of his experimentation, could unknowingly be guilty of an erroneous procedure, thereby consistently producing erroneous results, a separate observation was made regarding the method of rupture. On three different occasions the author visited the Albuquerque Testing Laboratory, Albuquerque, New Mexico, to witness the testing of concrete cylinders. These cylinders were made by various people and included both seven and twenty-eight day tests. The strengths ranged from fourteen hundred to fifty-five hundred pounds per square inch. The

cylinders were tested at a loading rate of thirty pounds per square inch per second. Outside of requesting the operator to shut off the testing machine immediately upon failure of the specimen, as explained above, the author had nothing to do with either the making or testing of these cylinders. A total of forty-six cylinders were reveiwed at the Albuquerque Testing Laboratory.

When photographing the cylinders, the break lines were marked with crayon or ink for clarity. In some instances the marks did not photograph will. In these cases, the photographs themselves were touched up.

Throughout the paper, reference is made to a base rate. This rate was taken as thirty pounds per square inch per second. The strengths at other rates of loading are expressed as a percentage of the base rate. Six by twelve inch cylinders were used throughout.

When reference is made to the "top" of the cylinder, it is meant that portion which is cast last. It makes no difference which way the cylinder is placed in the testing machine.

IV. DISCUSSION

Varying Rate of Loading.--There is no doubt that as the rate of loading increases, the compressive strength of a concrete cylinder increases. This is clearly shown by the graphs Figures 3-6. These graphs were drawn from the data listed in table 3. From this data it is seen that in only one instance was there any deviation from this trend. This occurred at a loading rate of 105 pounds per square inch per second for the strong mix. At this rate, the average compressive strength was sixty-seven pounds per square inch less than that obtained at a rate of eighty pounds per square inch per second. For both design mixes, the plot of strength versus loading rate produced a fairly smooth curve except at the point on the curves corresponding to the rate of fifty pounds per square inch per second. In both cases the value at this rate fell below the curve, indicating that the increase in strength for rates from thirty to fifty pounds per square inch per second was not as great as for other intervals along the curve. This trend was also shown by the results listed in table 4. Here it is seen that for the weak mix there was no increase in strength between the values of twenty and fifty pounds per square inch. For the strong mix, there was an increase of 315 pounds per square inch. The overall picture shows the least percentage of gain to be in this

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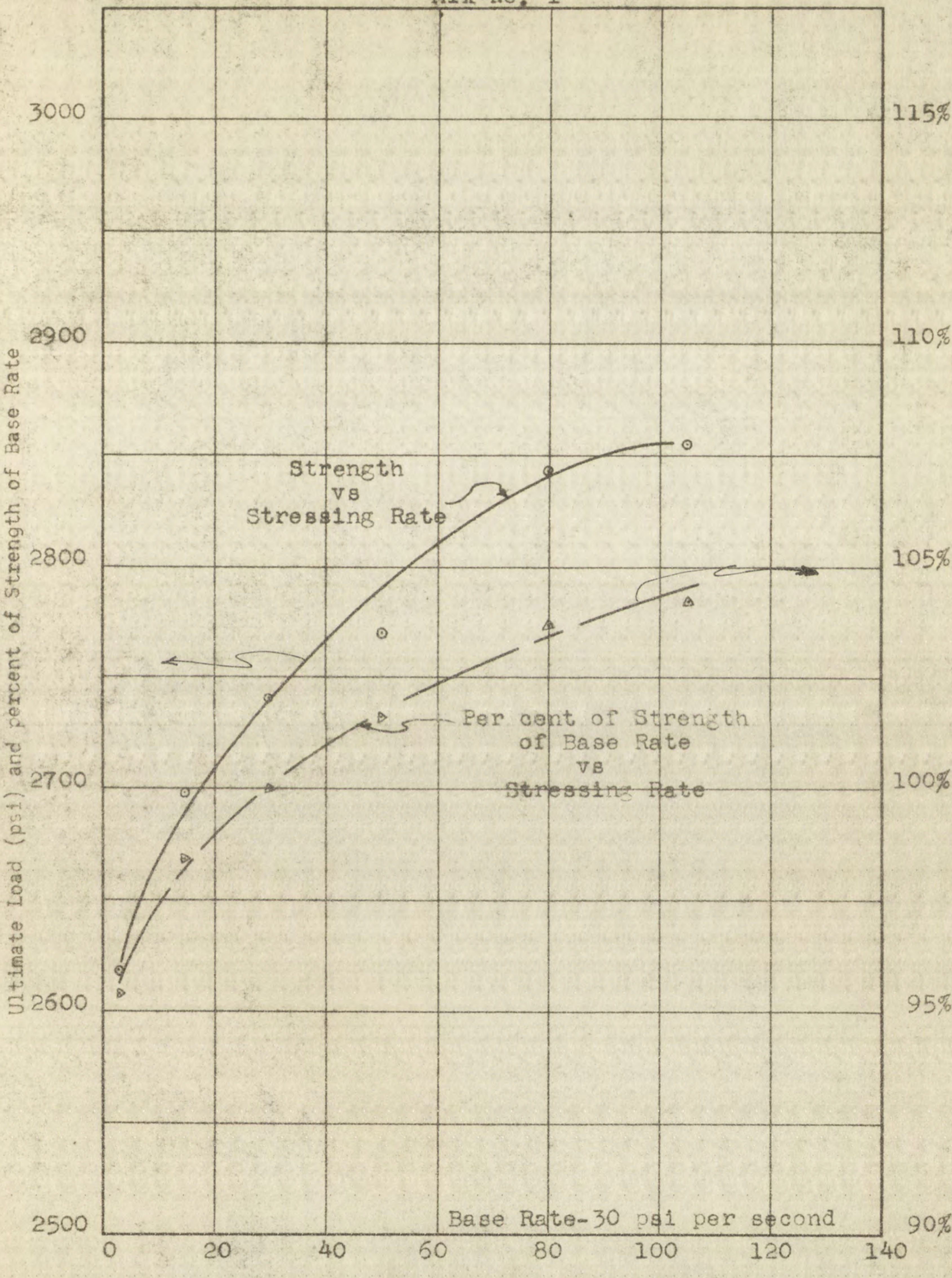
ULTIMATE LOAD vs RATE OF LOADING
Mix No. 1



Rate of Stressing, psi per second
Fig. 3

ULTIMATE LOAD vs RATE OF LOADING
Mix No. 2

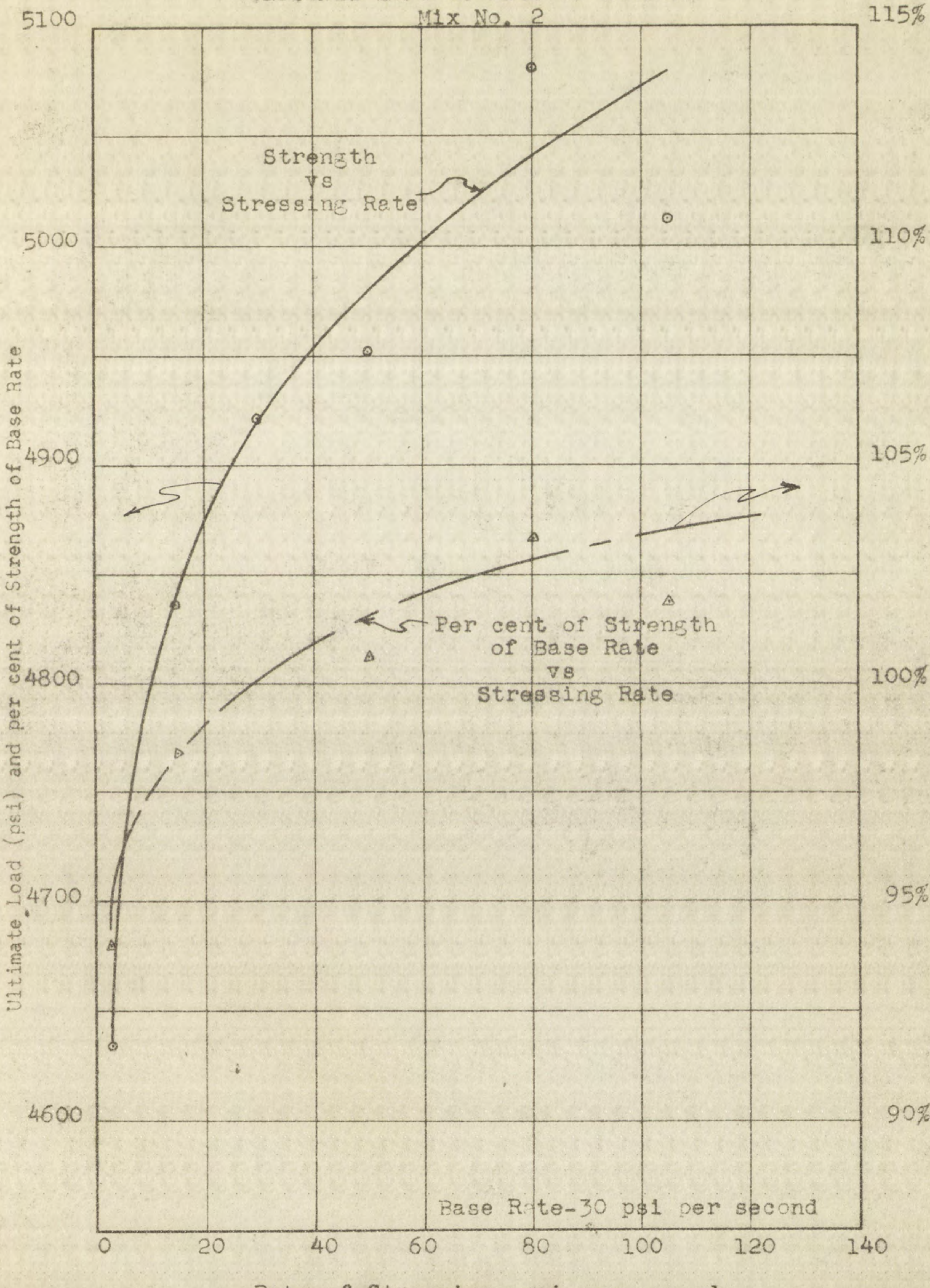


Fig. 4

PER CENT OF STRENGTH OF BASE RATE vs LOADING RATE (LOG SCALE)
Mix No. 1

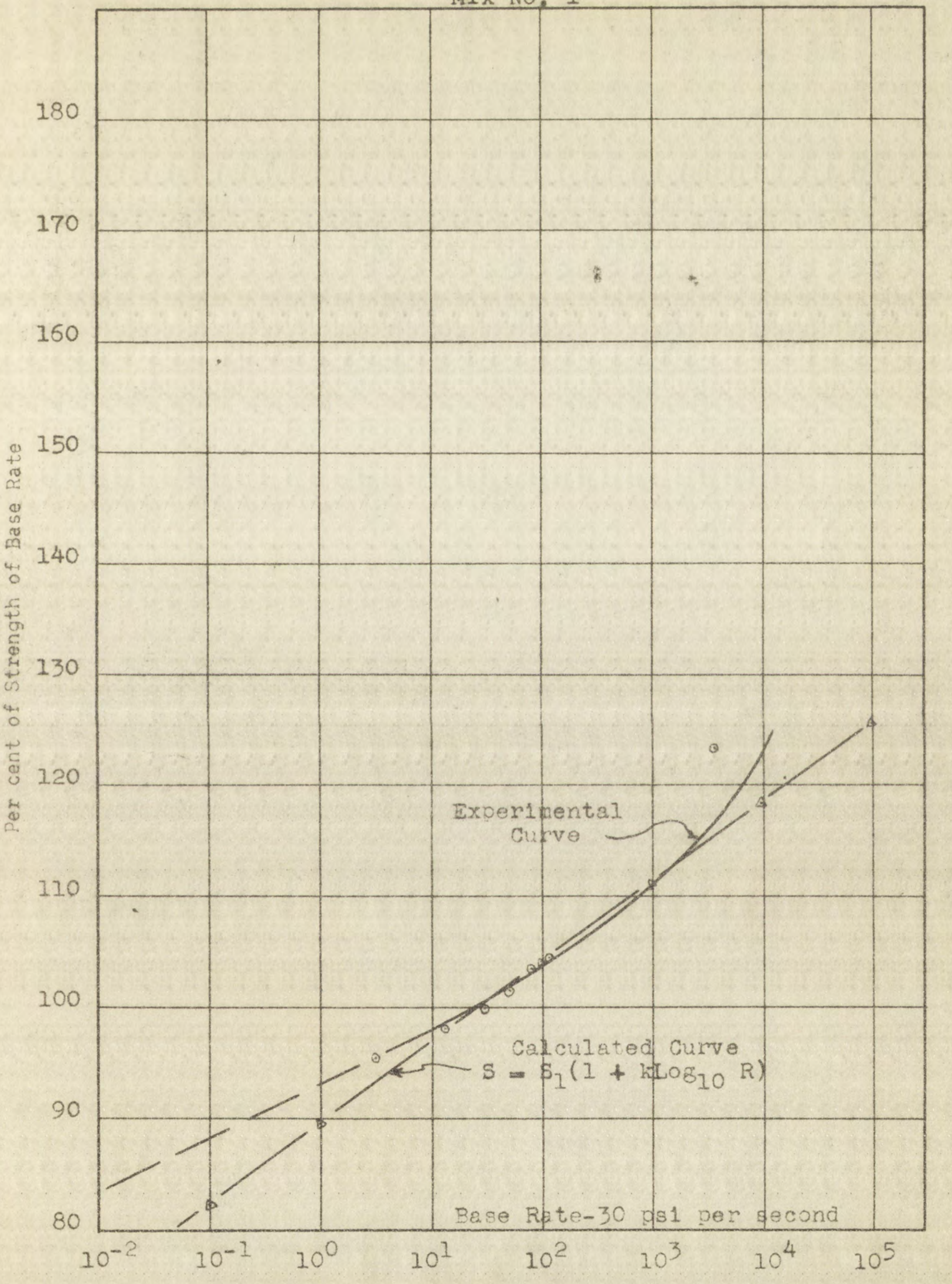


Fig. 5

PER CENT OF STRENGTH OF BASE RATE vs LOADING RATE (LOG SCALE)
Mix No. 2

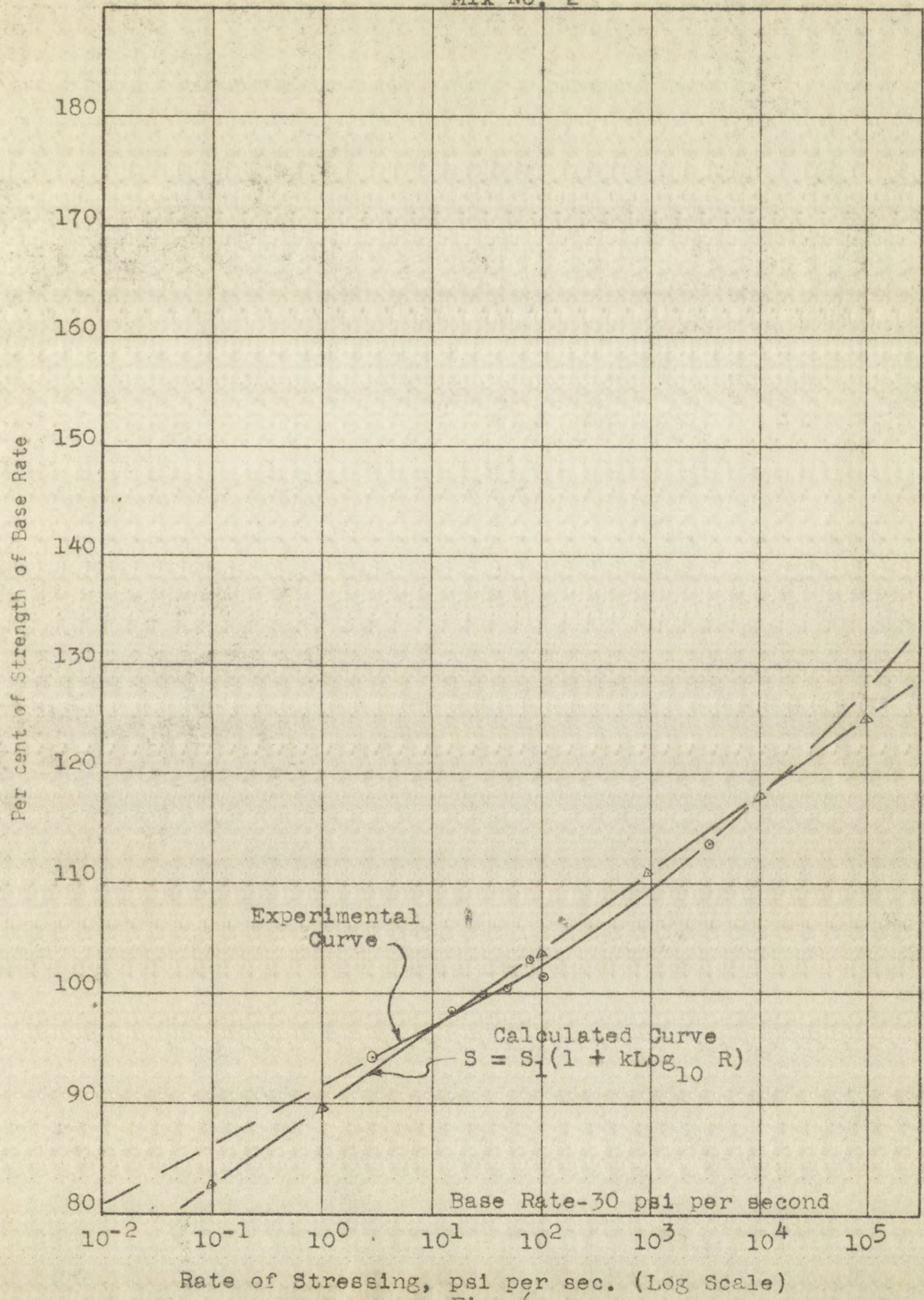


Fig. 6

region. At high rates of loading there is a marked increase in strength. For the weak mix, at a loading rate of 3,670 pounds per square inch per second, the strength was 123 per cent of the base rate. For the strong mix, the strength was 114 per cent of the base rate. As was mentioned earlier, previous investigators have also reported this trend. For this rate Watstien reported that the strength increased to 117 per cent for both weak and strong concrete. This characteristic of concrete is probably due to its ability to absorb strain energy. It is known that concrete will fail in compression at a strain of approximately .001 to .002 inch per inch. If the load is applied at such a high rate that the particles do not have time to realign themselves, the energy is absorbed. When it can absorb no more, the concrete fails; the strong concrete failing violently. The manner in which the cylinders failed, when loaded at a rate of 3,670 pounds per square inch per second, tends to substantiate the theory of strain absorption. At low rates of loading, the cylinders failed in pure shear (to be discussed in detail later), with the plane of failure extending from somewhere near the top and running down into the middle portion of the cylinder. At the high rate of loading, the cylinders broke in shear also, but the plane of failure extended from one side at the top to the opposite side at the bottom, breaking the cylinder on a diagonal into almost two equal pieces. This type of break was more pronounced for the strong mix, but

region. At high rates of loading there is a marked in-crease in strength. For the [illegible] of loading rate of 3,570 pounds per square inch per second, the strength was 123 per cent of [illegible]. For the [illegible] the strength was 111 per cent of the [illegible]. As was mentioned earlier, [illegible] this trend. For [illegible] increased to 117 per cent [illegible]. This characteristic [illegible] ability to absorb [illegible] will fall in [illegible] .002 inch per inch [illegible] rate that the [illegible] selves, the energy [illegible] more, the concrete [illegible] violently. The manner in which the [illegible] when loaded at a rate of [illegible] pounds per square inch per second, tends to [illegible] tion. At low rates of loading the [illegible] pure shear (to [illegible] in detail later), [illegible] plane of failure extending from [illegible] running down [illegible] the high rate of loading [illegible] also, but the planes of [illegible] the top to the opposite [illegible] cylinder on a diagonal [illegible] type of break [illegible]

nevertheless, the failures were of the same type for both mixes. Figure 8 shows a typical break for a high loading rate.

Figures 5 and 6 are graphs for the per cent of strength of base rate versus loading rate (log scale.) for both mixes. Along with these curves is a calculated curve using the equation

$$S = S_1(1 + k\text{Log}_{10} R) \quad \text{where}$$

S--ultimate stress in pounds per square inch
S_1-ultimate stress in pounds per square inch for a loading rate of one pound per square inch per second
k--0.08 for compression tests at 28 days
R--loading rate in pounds per square inch per second

This equation was first advanced by Jones and Richart. To obtain S_1, the above equation was solved for each loading rate from 3 to 105 pounds per square inch per second, and the values averaged. As a check, the computed S_1 was then used to compute the strength at a loading rate of 3,670 pounds per square inch per second. For the strong concrete the computed value is 5,648 and the actual value is 5,601 pounds per square inch, a difference of 0.8 of one per cent. For the weak concrete the computed value is 3,170 and the actual value 3,380 pounds per square inch, a difference of 6.2 per cent. For values between one and ten thousand pounds per square inch per second, the computed values are in good agreement with the actual values.

An evaluation of the results listed above indicates that concrete has a built-in impact factor of safety, as

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below design strength. [illegible]

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plane of failure [illegible]

The [illegible] of this data [illegible] that the strength of a concrete cylinder, when tested according to A.S.T.M. specifications, is not [illegible].

It has been known for some time that [illegible] concrete varies directly as the density. With this in mind, one cylinder of [illegible] and cut into three equal pieces. [illegible] in three equal lifts. [illegible] three lifts. The density of each of these pieces was then determined. The results are shown in figure [illegible]. [illegible] cylinders [illegible] results, [illegible] third being the [illegible] dense, the [illegible] more dense, and the [illegible]. The difference between the [illegible]

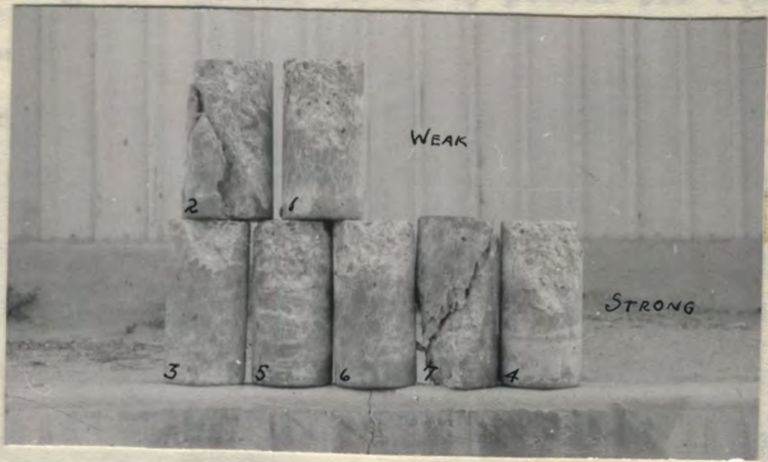

Fig. 7 Cylinders number two and seven were broken at a rate of 3,670 psi per second.

Fig. 8 Three cylinders showing the typical methods of rupture at a high loading rate. These were broken at 3,670 psi per second. Cylinder number one is the weak mix; numbers two and three the strong mix.

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concrete varies in strength [illegible]

mind, one cylinder of each [illegible] at random

and cut into three equal pieces. [illegible]

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three lifts. The density of each of these pieces was

determined. The results are shown in Figure [illegible]

cylinders gave [illegible] results, [illegible]

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dense, and the [illegible]

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far as compressive strength is concerned. It would seem logical to further investigate this characteristic of concrete with the intention of lowering or even abandoning the impact factor now used in design.

The graphs of both the weak and strong mix show that it is possible to obtain a variation in strength of from 98 to 102 per cent of the base rate by varying the rate of loading from twenty to fifty pounds per square inch per second. These rates are the limits specified by A.S.T.M., however, the recommended loading rate is thirty. In view of the facts, it is the opinion of the author that the A.S.T.M. specification would be a better one if no variation in the rate of loading was permitted. While employed in the construction industry, the author has seen many instances where an additional fifty or one hundred pounds per square inch of strength in a test cylinder would have saved many arguments between the designer and the contractor.

<u>Method of Rupture</u>.--Of the ninety-six cylinders tested, sixty-four were examined to determine the type of failure. Most text books on concrete state that there are three types of failures in concrete cylinders: shear, cone, and columnar. The author is of the opinion that there is only one type for cylinders made in accordance with A.S.T.M. specifications, and that is pure shear. The cone and columnar types can be produced by merely letting the testing machine run for a short time after failure occurs. This is illustrated in the series of photographs in Figure 9.

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that failures [illegible]
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that the strength of a concrete cylinder [illegible]
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three lifts. The density of each of these pieces was then
determined. The results are shown in Figure [illegible]
cylinders gave almost identical results, [illegible]
third being the least dense, [illegible]
dense, and the [illegible]
difference between [illegible]

(a) Initial failure caused by pure shear.

(b) Additional straining produces columnar type of break.

(c) Excessive straining done so as not to destroy interior planes of shear.

(d) Loose portion dislodged to show inner planes of shear.

(e) Top portion of cylinder showing the original plane of failure by shear.

(f) Bottom portion of cylinder showing cone that caused columnar splitting.

Fig. 9 Shear, cone, and columnar type failures produced in one cylinder.

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below design strength [illegible]

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pounds per square inch [illegible]

It was [illegible]

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The evaluation of this data [illegible]

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and cut into three equal pieces. [illegible]

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three lifts. The density of each of these pieces was then

determined. The results are shown in Figure [illegible]

cylinders gave almost identical results, [illegible] the bottom

third being the least dense, [illegible] more

dense, and the top [illegible]

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For a cylinder to rupture in any manner except pure shear, two or more planes of failure would have to be produced simultaneously. The non-homogeneity of concrete would not permit this, except perhaps accidentally. The author's theory for the failure of a cylinder is as follows: The initial failure, and the only one that is of any interest, will occur on a diagonal plane within the top one-half of the cylinder, the plane beginning somewhere on the top and coming out the side. This is by far the predominate type of break. If the testing machine is allowed to continue to run, the new cracks do not appear in any pattern. Occasionally the plane of failure will begin on one side of the cylinder and extend through to the other side. In this case, if the testing machine is allowed to continue to run, the next plane of failure will also occur in the top one-half of the cylinder and on an opposite diagonal from the original plane of failure, thus producing a cone. This cone then serves as a wedge to split the cylinder in a columnar manner. If the cylinder is broken further, it will usually be found that a cone had also formed at the bottom, but this is probably after the one at the top had been formed. It is also possible for a cylinder to break in shear on one end, and then have a cone form on the other end. The evidence seems to point to the fact that almost any type of break can be produced in a cylinder, but the initial failure will almost always be by shear. The photographs, Figures 7, 10, and 11 illustrate the point the author is trying to make. These cylinders were broken

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It has [illegible]
concrete varies [illegible]
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and cut into three equal pieces. [illegible]
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three lifts. The density of each of these pieces was then
determined. The results are shown in Figure [illegible]
cylinders [illegible]
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Fig. 10. The top photograph shows the external cracks in the cylinders after testing. The bottom photograph shows the same cylinders after having been struck lightly so as to dislodge the concrete along the plane of failure. The cylinders are all sitting with the tops up. Note that the plane of failure is within the top two thirds in all cases, and that the type of break is pure shear. The numbers in the lower left hand corner of the cylinders match the cylinders in the two photographs.

and was [illegible] the [illegible] vation in [illegible] third. Because [illegible] to determine the [illegible] advanced by the author [illegible] the cylinder [illegible] one-third of the [illegible] with a small [illegible] good [illegible] below design strength [illegible] that failures [illegible] pounds per square [illegible] It was [illegible] plane of failure [illegible]

The [illegible] that the strength of [illegible] ing to [illegible]

It has [illegible] concrete varies [illegible] mind, one cylinder of [illegible] and cut into three equal pieces. [illegible] in three equal lifts [illegible] three lifts. The [illegible] determined. The results are shown in Figure [illegible] cylinders [illegible] third being the [illegible] dense, [illegible] difference between the [illegible]

Fig. 11. Another group of cylinders showing the external cracks after testing, and then the cylinders with the concrete disloged along the plane of failure. These cylinders were all broken at a low rate of loading.

and was made during the [illegible] vation in strength of [illegible] the bottom third. Because [illegible] to determine the [illegible] advanced by the author [illegible] the cylinder [illegible] one-third of the [illegible] with a small [illegible] good [illegible] below design strength. [illegible] that failures [illegible] pounds per square inch [illegible] It was [illegible] plane of failure [illegible]

The [illegible] that the strength of [illegible] ing to [illegible]

It has been known for some time that [illegible] concrete varies [illegible] With this in mind, one cylinder of [illegible] and cut into three equal pieces. [illegible] in three equal lifts. [illegible] three lifts. The [illegible] of each of these pieces was [illegible] determined. The results are shown in Figure [illegible] cylinders [illegible] third being the [illegible] dense, and the [illegible] difference between [illegible]

in the usual manner, with the testing machine being shut off at the first sign of failure. Half of the cylinders were placed in the testing machine with the top on the moving head, and half with the bottom on the moving head. After failure, the caps were removed from the cylinders and the cylinders were struck lightly on the end with an iron bar. This caused the concrete to fall off along the plane of failure, leaving the major portion of the cylinder intact. Continued striking would not dislodge any more of the cylinder. As can be seen, there is no evidence of a cone or columnar failure, only pure shear.

Reasoning Behind Method of Failure.--As has been stated previously, the author is of the opinion that the only type of failure in a concrete cylinder is a pure shear failure. A corollary to this statement is that for low rates of loading, the plane along which the cylinder shears will always be within the top two-thirds of the cylinder. Again it makes no difference whether the cylinder is placed in the testing machine with the top adjacent to or away from the moving head. The only stipulation being that the testing machine be shut off immediately upon failure of the specimen. Of the sixty-four cylinders examined, the plane of failure was within the top third on thirty-eight of them, into the middle third on twenty-one of them, and in five the plane of failure was not visible externally. In none of the cylinders did the plane of failure extend into the bottom third, though in a few instances the plane did reach the top of

and was undetermined [illegible]

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one-third of the [illegible]

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cylinders gave almost identical results, [illegible]

third being the [illegible] dense, the [illegible]

dense, and the [illegible]

difference between [illegible]

the bottom third. It was for the purpose of checking on these results that the author visited the Albuquerque Testing Laboratory on three separate occasions. During the first visit, the breaking of twelve cylinders was reviewed. The plane of failure occurred in the top third five times, and into the middle third five times, and was undetermined in two cylinders. On the second visit, of the cylinders reviewed, four planes of failure were in the top third, five into the middle, none into the bottom, and six undetermined. On the third visit, eighteen cylinders were reviewed. The plane of failure was in the top third in eight, the middle third in seven, one failed by crushing at the bottom,

Fig. 12. Nine of the fifteen cylinders reviewed by the author on the second visit to the Albuquerque Testing Laboratory.

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and was undetermined in two. This was the first observation in which a cylinder failed initially in the bottom third. Because of this, the cylinder was later shattered to determine the reason for the departure from the theory advanced by the author. An examination of the inside of the cylinder readily produced the answer. The bottom one-third of the cylinder consisted of nothing but stone with a small amount of mortar. The top two thirds had a good mortar-stone distribution. The cylinder broke far below design strength. Once again, it is to be remembered that failures for only the low rates of loading, 3 to 105 pounds per square inch per second, are being discussed. It was mentioned before that at high rates of loading, the plane of failure extended the entire length of the cylinder.

The evaluation of this data leads to the conclusion that the strength of a concrete cylinder, when made according to A.S.T.M. specifications, is not the same throughout.

It has been known for some time that the strength of concrete varies directly as the density. With this in mind, one cylinder of each design mix was picked at random and cut into three equal pieces. Since a cylinder is made in three equal lifts, the cuts were made to separate the three lifts. The density of each of these pieces was then determined. The results are shown in figure 13. Both cylinders gave almost identical results, with the top one third being the least dense, the middle one third more dense, and the bottom one third the most dense. The difference between the top and middle pieces was only

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one-third of that between the middle and bottom pieces. When one stops and considers the specified procedure for making a test cylinder, these results should not be surprising. The specification calls for the cylinder to be cast in three equal lifts, with each lift being rodded twenty five times. The first lift is to be rodded throughout, the second lift to be rodded so as just to penetrate the first lift, and the third to just penetrate the second. It seems only natural that any force applied to the concrete above the first lift would be partially transmitted down to it. This would be especially true of a dry mix. It then seems likely that the bottom lift would receive the most compaction, and therefore be the most dense. Applying the same theory to the second lift, it should be less dense than the first. The third lift, then, should be the least dense since it receives no compaction from a lift above. In the case of a wet mix, this condition is aided by the great amount of water that rises to the top of the cylinder. The author believes that this excess water not only helps to lower the density of the top third, but that at times produces a weak spot so that when the cylinder fails, it fails very close to the top, as is shown by cylinders no. 1 and 5 Figure 11. This is not an uncommon type of failure. A cylinder that fails in this manner could not possibly give a true indication of the strength of the concrete.

That the compressive strength of concrete cylinders is a function of the density was definitely established

one-third of [illegible] the [illegible]. When one [illegible] as making a test [illegible] grading. [illegible] cast in three [illegible] twenty-five [illegible]. The first lift [illegible] the second lift [illegible] lift, and the third [illegible]. It [illegible] only natural [illegible] the first lift would [illegible] practically [illegible]. This would be expected [illegible] likely that the bottom lift would [illegible] and therefore [illegible] to the second lift [illegible]. The third lift [illegible] receives no [illegible] of a wet mix, [illegible] of water that rises [illegible] the cylinder. The author believes that [illegible] water [illegible] to lower the [illegible] and [illegible] thus produce a [illegible] that [illegible]. It falls very close to the [illegible] no. 1 and [illegible] Figure [illegible]. This is [illegible] failure. A cylinder that fails [illegible] possibly give a true [illegible] of the [illegible] of the concrete.

[illegible] the [illegible] is a function of [illegible]

by Talbot and Richart[11] in their monumental work on the strength of concrete published in 1923. Their tests ranged from concrete that weighed 124 pounds per cubic foot and had a compressive strength of 300 pounds per square inch, to concrete that weighed 158.5 pounds per cubic foot and had a compressive strength of 4,200 pounds per square inch. For the range between 2,650 (152.0 pounds per cubic foot,) and 4,200 pounds per square inch (158.5 pounds per cubic foot,) the strength increased approximately 240 pounds per square inch per additional one pound increase in density. If this experiment were performed today with the benefit of modern cement making methods, the increase per pound would probably be much greater. For example, the two cylinders checked for density by the author showed an increase in strength of 740 pounds per square inch for each one pound increase in density. If this held true, then for the weak mix the bottom third would have a strength of 615 pounds per square inch over the top third. For the strong mix, there would be a difference between top and bottom of 815 pounds per square inch. This could be easily the reason the plane of failure never extends into the lower one-third of a cylinder. Because of this, the author is of the opinion that more study should be given to the specifications for making concrete test cylinders, the object being to produce a specimen of equal strength throughout. If this is not feasible, then at least it should be recognized that the ultimate strength of a test cylinder is not really that of the full cylinder, but only that of the top one third or top two thirds.

IV. [illegible]

From the experimental [illegible] and

from the analysis of [illegible] data [illegible] the following [illegible]

and recommendations are made:

1. There is a [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible]

2. In view of the [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible]

3. [illegible] [illegible] [illegible] [illegible] equation [illegible]

4. [illegible] [illegible] [illegible] [illegible]

5. [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] strength.

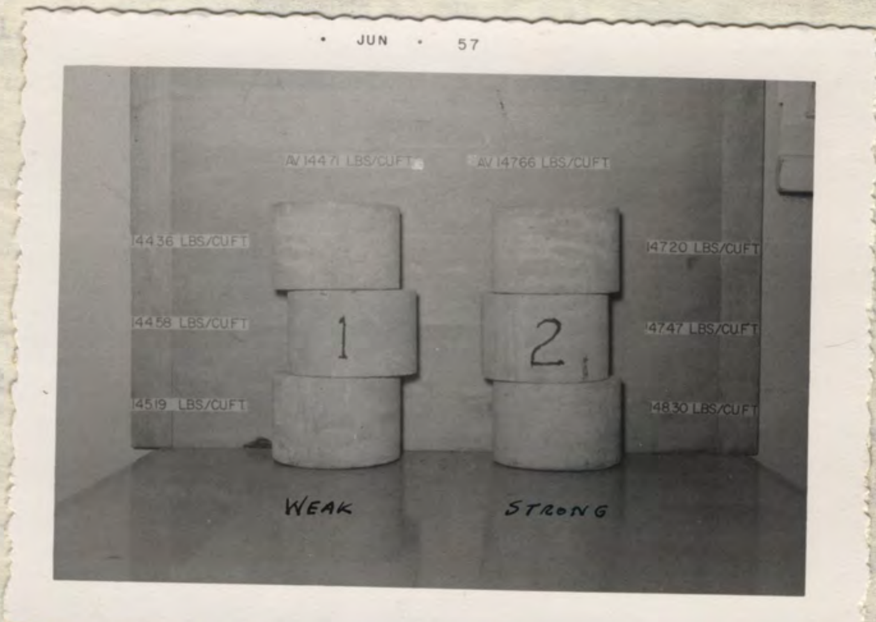
JUN 57
AV 14471 LBS/CUFT
AV 14766 LBS/CUFT
14436 LBS/CUFT
14458 LBS/CUFT
14519 LBS/CUFT
14720 LBS/CUFT
14747 LBS/CUFT
14830 LBS/CUFT
1
2
WEAK
STRONG

Fig. 13

[illegible]

From the experimental [illegible]

from the analysis of test data [illegible] the following [illegible]

and recommendations are made:

1. [illegible]

2. In view of [illegible]

3. [illegible]

4. [illegible]

5. [illegible]

IV. CONCLUSIONS AND RECOMMENDATIONS

From the experimental data presented herein, and from the analysis of said data, the following conclusions and recommendations are made:

1. There is a definite relationship between the rate of loading and the compressive strength of a concrete test cylinder; the higher the rate of loading, the greater the strength. This is probably due to the fact that concrete can absorb strain energy. It is recommended that tests be run, using this principle, on reinforced concrete flexure members to determine if the impact factor now used in design could be lowered or even abandoned.

2. In view of the fact that the compressive strength of concrete is a function of the rate of loading, it is recommended that A.S.T.M. standard C 39-49 specify only one rate of loading (probably thirty pounds per square inch per second) rather than permit a range of between twenty and fifty as it now does.

3. For rates of loading between one and ten thousand pounds per square inch per second, the strength of a cylinder can be defined fairly well by the equation $S = S_1(1 + k\log_{10}R)$.

4. Concrete test cylinders rupture in only one way, and that is pure shear.

5. At low rates of loading, the plane of failure will be found only in the top one-third or top two-thirds of the cylinder, indicating that the strength of a test cylinder is not equal throughout, or even nearly equal. This is probably due to the fact that the bottom portion of a cylinder is more dense than the upper part. It is recommended that additional tests for density of a concrete cylinder be performed in the manner as presented here. In addition to calculating the density of each one third piece, it is suggested that the pieces themselves be tested for compressive strength.

APPENDIX A. MIX DESIGN

Design of Mix No. 1

Materials--natural sand, three-quarter inch crushed stone, type 1 portland cement.

Specific Gravity--sand and stone-2.65; cement-3.15

Fineness Modulus--sand-2.87; stone-6.74

Density of compacted sand and stone--130 lbs./cu.ft.

Water estimated at 7.5 gal. per sack		1.01 cu.ft.
Cement-one sack-94 lbs		0.48
	Volume of paste	1.49 cu.ft.

Assume 5.3 sacks cement per cubic yard.

27.00/5.3 = 5.09 cu.ft. concrete per sack

5.09 - 1.49 = 3.60 cu.ft. aggregate per sack

3.60 x 2.65 x 62.4 = 595 lbs. aggregate per sack

Real mix--595/130 = 4.58 say 1:5

Per cent sand--$r = (M_c - M) / (M_c - M_f)$

$$r = (6.74 - 4.80)/(6.74 - 2.87) = 50.2 \text{ per cent}$$

One sack batch	Adjusted one sack batch
Cement.........94.0 lbs.	Cement.........94.0 lbs.
Water..........62.4 lbs.	Water..........69.0 lbs.
Sand..........298.0 lbs.	Sand..........301.0 lbs.
Stone.........297.0 lbs.	Stone.........280.0 lbs.

Water-cement ratio (adjusted) 7.05 gal. per sack

Slump--3½ inches

APPENDIX A. MIX DESIGN

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Materials--natural sand, three-quarter inch crushed stone, type 1 portland cement.

Specific Gravity--sand and stone-2.65; cement-3.15

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Density of compacted sand and stone--130 lbs./cu.ft.

Water estimated at 7.5 gal. per sack — 1.01 cu.ft.

Cement-one sack-94 lbs — 0.48

Volume of paste — 1.49 cu.ft.

Assume 5.3 sacks cement per cubic yard.

27.00/5.3 = 5.09 cu.ft. concrete per sack

5.09 - 1.49 = 3.60 cu.ft. aggregate per sack

3.60 x 2.65 x 62.4 = 595 lbs. aggregate per sack

Real mix--595/130 = 4.58 say 1:5

Per cent sand--$r = (M_s - M) / (M_s - M_g)$

$r = (6.74 - 4.80)/(6.74 - 2.87) = 50.2$ per cent

One sack batch	Adjusted one sack batch
Cement.........94.0 lbs.	Cement.........94.0 lbs.
Water.........62.4 lbs.	Water.........59.0 lbs.
Sand.........298.0 lbs.	Sand.........301.0 lbs.
Stone.........297.0 lbs.	Stone.........280.1 lbs.

Water-cement ratio (adjusted) 7.05 gal. per sack

Slump--3½ inches

Design of Mix No. 2.

Materials--natural sand, three-quarter inch crushed stone, type 1 portland cement.

Specific Gravity--sand and stone-2.65; cement-3.15

Fineness Modulus--sand-2.87; stone-6.74

Density of compacted sand and stone--130 lbs./cu.ft.

Water estimated at 5 gal. per sack		0.628 cu.ft.
Cement-one sack-94 lbs.		0.480
	Volume of paste	1.108 cu.ft.

Assume 8 sacks cement per yard.

27.00/8 = 3.375 cu. ft. concrete per sack

3.375 - 1.108 = 2.267 cu.ft. aggregate per sack

2.267 x 2.65 x 62.4 = 376 lbs. aggregate per sack

Real mix--443/130 = 3.4 say 1:4

Per cent sand--r = (6.74 - 5.00)/(6.74 - 2.87) = 45.0 per cent

One sack batch		Adjusted one sack batch	
Cement	94.0 lbs.	Cement	94.0 lbs.
Water	41.6 lbs.	Water	41.2 lbs.
Sand	169.0 lbs.	Sand	175.5 lbs.
Stone	207.0 lbs.	Stone	195.5 lbs.

Water-cement ratio (adjusted) 4.95 gal. per sack

Slump--one inch

TABLE I

SIEVE ANALYSIS DATA

Screen Size	Amt. Ret. Ounces	Per Cent Ret.	Amt Ret Cumul. Ounces	Per Cent Ret. Cumul.	Per Cent Passing Cumul.	Per Cent Passing Cumul. A.S.T.M.
Fine Aggregate						
3/8 in.	0.00	0.00	0.00	0.00	100.00	100
No. 4	2.12	5.50	2.12	5.60	94.50	95-100
No. 8	4.05	10.60	6.17	16.20	83.90	
No. 16	3.55	9.30	9.27	25.40	74.50	45-80
No. 30	11.38	29,80	21.10	55.30	44.70	
No. 50	12.20	32.00	33.30	87.20	12.80	10-30
No.100	3.80	10.00	37.10	97.20	2.90	2-10
No.200	1.00	2.60	38.10	100.00	0.00	
						F.M.-2.87
Stone						
3/4 in.	lbs. 0.00	0.00	lbs. 0.00	0.00	100.00	90-100
1/2 in.	6.22	36.60	6.22	36.60	63.40	
3/8 in.	6.44	37.90	12.66	74.50	25.50	20-55
No. 4	4.28	25.20	16.94	99.70	0.30	0-10
To 100				500.00		
						F.M.-6.74

Size of sample--fine aggregate, 38.2 oz.; stone, 17.0 lbs.

Sieves--Tyler Standard, 8 in. round; 18 in. square

Mechanical sievers--Tyler Ro-Tap and Tyler Lab Tester

APPENDIX B. CYLINDER AND RATE-STRESS DATA

TABLE 2. CYLINDER DATA

No.	Date Made	Date Broken	Age Days	Rate Psi Per Second	Load at Failure Pounds	f'c Psi
1	Feb. 9	Feb. 16	7	30	49,700	1,760
2	9	Mar. 9	28	10	73,500	2,600
3	9	9	28	10	82,700	2,930
4	9	9	28	10	80,500	2,850
5	9	9	28	30	84,500	2,990
6	9	9	28	30	82,500	2,910
7	9	9	28	30	76,000	2,690
8	9	9	28	30	72,000	2,550
9	9	Feb. 16	7	30	84,300	2,980
10	9	Mar. 9	28	10	107,500	3,800
11	9	9	28	10	112,500	3,980
12	9	9	28	10	113,500	4,020
13	9	9	28	30	113,750	4,025
14	9	9	28	30	110,500	3,910
15	9	9	28	30	117,750	4,160
16	9	9	28	30	110,250	3,900
17	Feb. 16	Mar 16	28	20	83,000	2,940
18	16	16	28	20	83,500	2,960
19	16	16	28	20	75,200	2,660
20	16	16	28	20	77,000	2,730
21	16	16	28	50	79,000	2,800
22	16	16	28	50	75,700	2,680
23	16	16	28	50	81,000	2,870
24	16	16	28	50	79,000	2,795
25	16	16	28	20	142,500	5,040
26	16	16	28	20	124,000	4,380
27	16	16	28	20	123,000	4,350
28	16	16	28	20	128,000	4,530
29	16	16	28	50	147,000	5,200
30	16	16	28	50	136,500	4,830
31	16	16	28	50	151,000	5,340
32	16	16	28	50	126,500	4,480
33	16	16	28	50	130,000	4,600
34	Mar. 2	Mar. 30	28	30	76,500	2,710
35	2	30	28	50	77,000	2,725
36	2	30	28	80	82,500	2,920
37	2	30	28	105	74,000	2,620
38	2	30	28	3	125,000	4,420
39	2	30	28	30	125,000	4,420
40	2	30	28	50	132,500	4,680
41	2	30	28	80	135,000	4,770
42	2	30	28	105	140,000	4,950

TABLE 2--Continued.

CYLINDER DATA

No.	Date Made	Date Broken	Age Days	Rate Psi Per Second	Load at Failure Pounds	f'c Psi
43	Mar. 9	Apr. 6	28	3	76,000	2,690
44	9	6	28	3	69,500	2,460
45	9	6	28	15	73,200	2,590
46	9	6	28	3,670	85,000	3,010
47	9	6	28	3	130,500	4,775
48	9	6	28	15	132,500	4,680
49	9	6	28	3,670	145,000	5,130
50	9	6	28	----	-------	-----
51	9	6	28	----	-------	-----
52	Mar.16	Apr. 13	28	3	78,500	2,780
53	16	13	28	3	75,000	2,650
54	16	13	28	3,670	103,500	3,660
55	16	13	28	----	-------	-----
56	16	13	28	3	136,000	4,810
57	16	13	28	3	133,000	4,700
58	16	13	28	30	130,000	4,600
59	16	13	28	3,670	168,000	5,940
60	16	13	28	3,670	167,000	5,910
61	Mar.23	Apr 20	28	3	73,500	2,600
62	23	20	28	15	75,000	2,655
63	23	20	28	30	77,208	2,730
64	23	20	28	50	79,000	2,800
65	23	20	28	80	72,500	2,565
66	23	20	28	105	84,500	2,990
67	23	20	28	3	129,300	4,580
68	23	20	28	15	133,000	4,700
69	23	20	28	30	154,000	5,450
70	23	20	28	50	137,000	4,850
71	23	20	28	80	151,000	5,340
72	23	20	28	105	140,500	4,960
73	Mar.30	Apr. 27	28	15	80,500	2,850
74	30	27	28	30	77,500	2,740
75	30	27	28	80	86,000	3,045
76	30	27	28	---	------	-----
77	30	27	28	3,670	98,000	3,470
78	30	27	28	---	------	-----
79	30	27	28	15	145,000	5,130
80	30	27	28	30	147,500	5,220
81	30	27	28	50	152,500	5,390
82	30	27	28	80	145,000	5,130
83	30	27	28	105	145,000	5,130
84	30	27	28	3,670	162,500	5,750

TABLE 2--Continued.

CYLINDER DATA

No.	Date Made	Date Broken	Age Days	Rate Psi Per Second	Load at Failure Pounds	f'c Psi
85	Apr. 13	May 11	28	3	58,500	2,070
86	13	11	28	15	58,500	2,070
87	13	11	28	50	66,500	2,350
88	13	11	28	80	72,500	2,565
89	13	11	28	105	------	-----
90	13	11	28	3,670	75,000	2,655
91	13	11	28	3	131,500	4,650
92	13	11	28	15	115,000	4,070
93	13	11	28	30	125,500	4,440
94	13	11	28	50	112,500	3,980
95	13	11	28	80	116,500	4,120
96	13	11	28	105	113,500	4,020

TABLE 3

RATE-STRESS DATA

Rate Psi Per Second	No. of Cylinders Broken	Ultimate Load Psi	Percentage of Base Rate*
Mix No. 1			
3	5	2,616	0.954
15	3	2,698	0.984
30	7	2,741	1.000
50	6	2,770	1.016
80	3	2,843	1.037
105	2	2,855	1.042
3,670	3	3,380	1.223
Mix No. 2			
3	5	4,633	0.941
15	3	4,836	0.983
30	4	4,922	1.000
50	8	4,952	1.006
80	3	5,082	1.033
105	3	5,013	1.018
3,670	4	5,601	1.138

*Base rate taken as thirty pounds per square inch per second.

TABLE 4

COMPARATIVE RATE-STRESS DATA

Date Made	Rate Psi Per Second	Ultimate Load Psi
	Mix No. 1	
Feb. 9	10	2,793--Av. of 3
9	30	2,785--Av. of 4
	Mix No. 2	
Feb 9	10	3,967--Av. of 3
9	30	3,999--Av. of 4
	Mix No. 1	
Feb. 16	20	2,822--Av. of 4
16	50	2,786--Av. of 4
	Mix No. 2	
Feb. 16	20	4,575--Av. of 4
16	50	4,890--Av. of 5

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