EFFECT OF HIGH RATES OF LOADING ON THE STRENGTH PROPERTIES OF PLAIN CONCRETE

by

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ABSTRACT

A number of investigators have studied the effect of high rates of loading on the strength of concrete. This thesis reviews and compares the published results of investigations of the strength of concrete at high rates of loading with corresponding high rates of straining. Reasons for differences in the results of the different investigations are given. A comparison of the effect of high rates of loading on concrete with the effect of high rates of loading on the strength of rocks is made. Reasons why concrete should show an increase in strength with high loading rates are hypothesized. Recommendations for future research are made.

CHAPTER 1 - STATEMENT OF THE PROBLEM

1.1 Definition of the Problem

Concrete, like other brittle materials, exhibits an increase in strength when subjected to high rates of loading. It is the intent of this thesis to evaluate the experimental results reported in the published literature which describe the nature and extent of the increase, and to compare these results with the results of investigations on other similar materials.

Only plain concrete has been considered in this investigation. For a review of reinforced concrete behavior under rapid loading, see Bate (3)*.

1.2 Definition of Terms

Ultimate strength is defined as the strength, usually expressed as an average stress, at which failure of the concrete specimen under test occurs.

A "high rate of loading" is defined as any loading progressively increasing which causes failure in a time interval at least as short as the standard laboratory test for compressive strength. (American Society for Testing Materials in the 1958 edition of the ASTM Standards, Tentative Method of Test for Com-

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*The numbers in parentheses refer to the bibliography.

pressive Strength of Molded Concrete Cylinders, recommends a testing speed of either 20 to 50 psi per second in terms of rate of stressing or 0.05 inches per minute in terms of rate of straining.) Plain concrete is any concrete which does not have metal reinforcement in the specimen under study.

CHAPTER 2 - EFFECT OF HIGH RATES OF LOADING ON COMPRESSIVE STRENGTH

2.1 Description of Investigations

It has long been recognized that concrete exhibits a different behavior under high rates of loading than under a slow or static loading. There has not, however, been agreement as to the nature of the difference in behavior. Evaluation of the difference has been investigated by means of drop tests, abrasion tests, and other empirical tests which, as often as not, actually measure some quality of the concrete other than its gross behavior under high rates of loading. These tests, while qualitative in nature, nevertheless shed some light on the problem.

A number of workers have attempted to evaluate the resistance of concrete to high rates of loading by means of drop tests. The earliest tests of this nature were by Passov (51), in 1917, who dropped conical hammers onto cubes of concrete. He obtained a measure of impact resistance called the "disintegration point," which represented the product of the weight of the hammer and the height of drop causing breakage with a single blow. He found impact and crushing strength to be unrelated.

Framm (18), in 1920, cropped a conical hammer from a constant height onto specimens of concrete. He found static and dynamic strengths not proportional and concluded that water-stored specimens show a higher impact resistance than air-stored specimens.

Dutron (11), 1930, dropped spherical weights from increasing heights onto cubes and simply supported prisms. He found that crushed aggregates offer higher resistance to impact than do gravel aggregates.

Wenzel (70), 1934, and Guttman and Seidel (30), 1936, using drop tests concluded that, in general, increased compressive strength results in increased impact resistance. Glanville, et al. (23), using drop tests, found no consistent relation between impact strength and static compressive strength. Impact strength was found to be less than cube compressive strength.

Grime (29), 1934, using a quartz piezoelectric gage embedded in reinforced concrete piles obtained strain-time records by photographing an oscillograph trace. Stresses were inferred from a statically measured stress-strain relationship. While no ultimate strength results were reported, it was demonstrated that the boundary conditions greatly influence the character and intensity of the pulse waves traveling through the pile.

More recently Green (27), 1958, made tests using a ballistic pendulum apparatus to evaluate the effect of aggregate type on the impact resistance of concrete. His measure of impact resistance was the number of blows to first crack and to no rebound, using four inch concrete cubes impacted by a hammer weighing 24 pounds with a one inch diameter striking face. The drop was nine inches and the striking velocity was constant in all tests. The validity of using a one inch striking face as a sufficient means of measuring the gross strength effect is supported by a close relationship found between static test results using a one inch diameter face and the standard compression test. (See Figure 2.1.) It was found that concretes made with rough, angular aggregates offer a greater impact resistance than do concretes made with smooth, rounded aggregates.

The number of blows and the energy absorbed to first crack increased with increased crushing strength but the results exhibit considerable scatter (due, in part of course, to the effect of different aggregates). These results are shown in Figure 2.2 and Figure 2.3.

Green's findings support the belief that failure of concrete involves cumulative damage. The fact that a blow which does not cause failure in one application

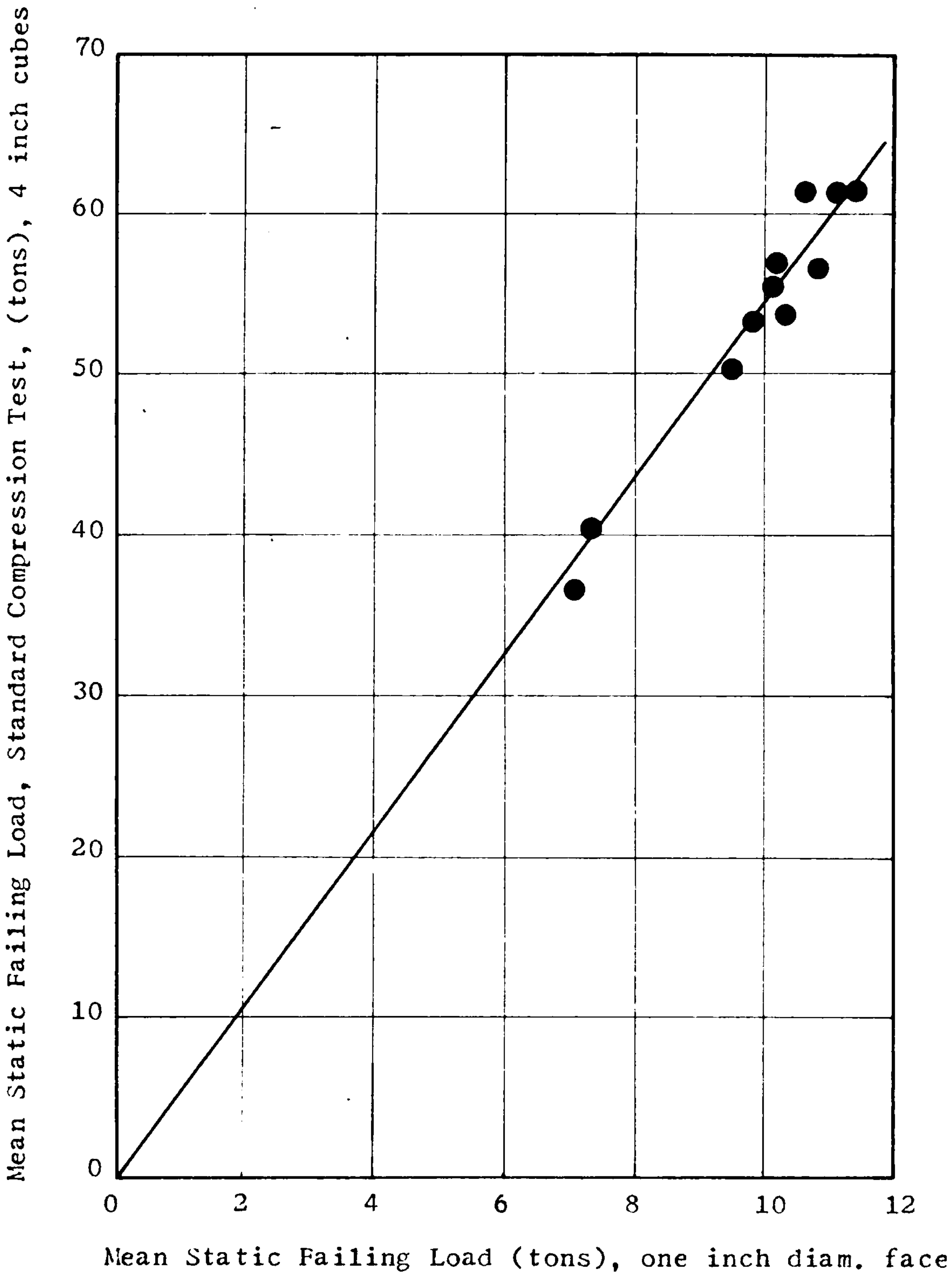

Fig. 2.1 - Relationship between failure load using one inch face and using standard test (Green (27))

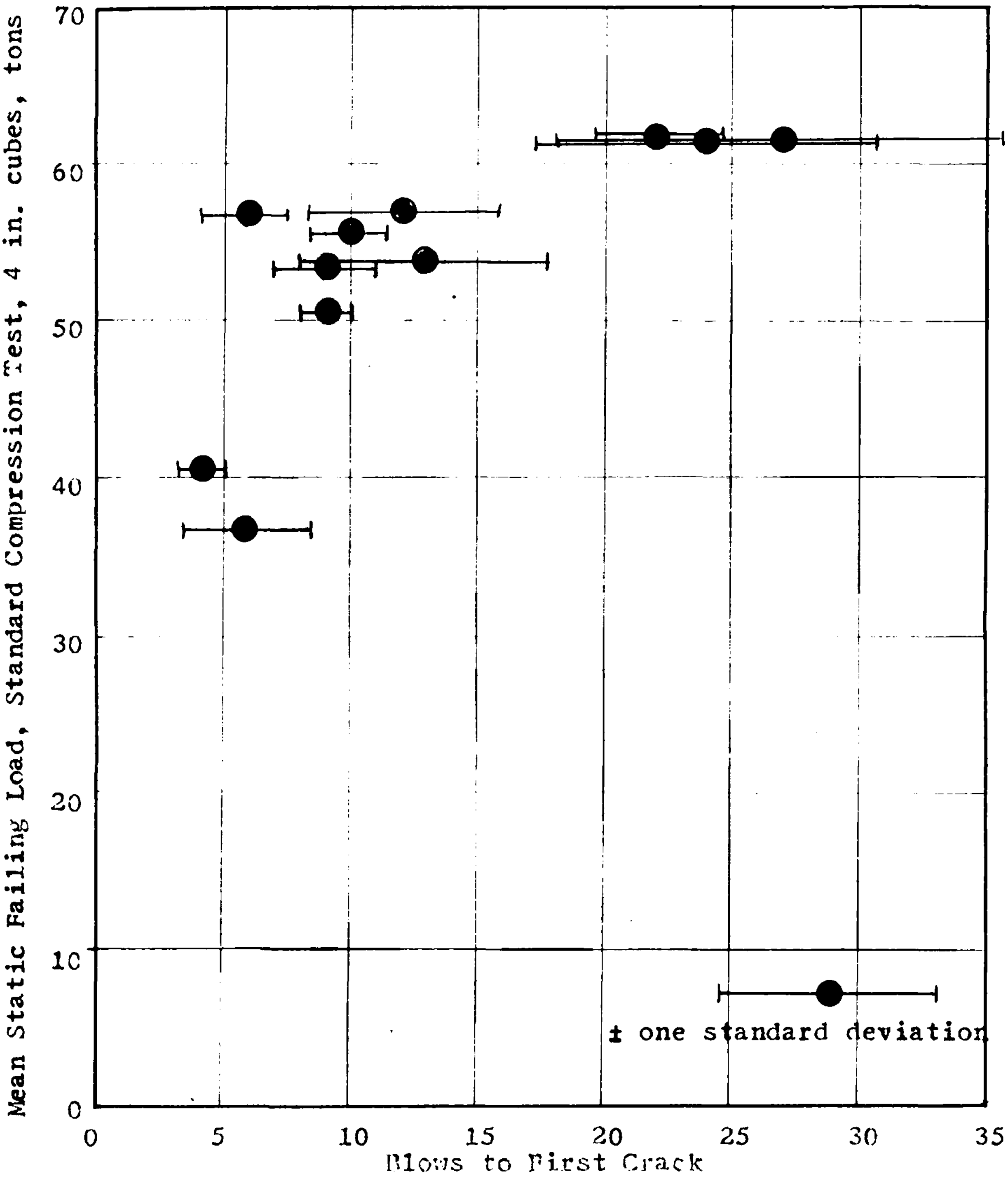

Fig. 2.2 - Relation between compressive strength and blows to first crack, (Green (27))

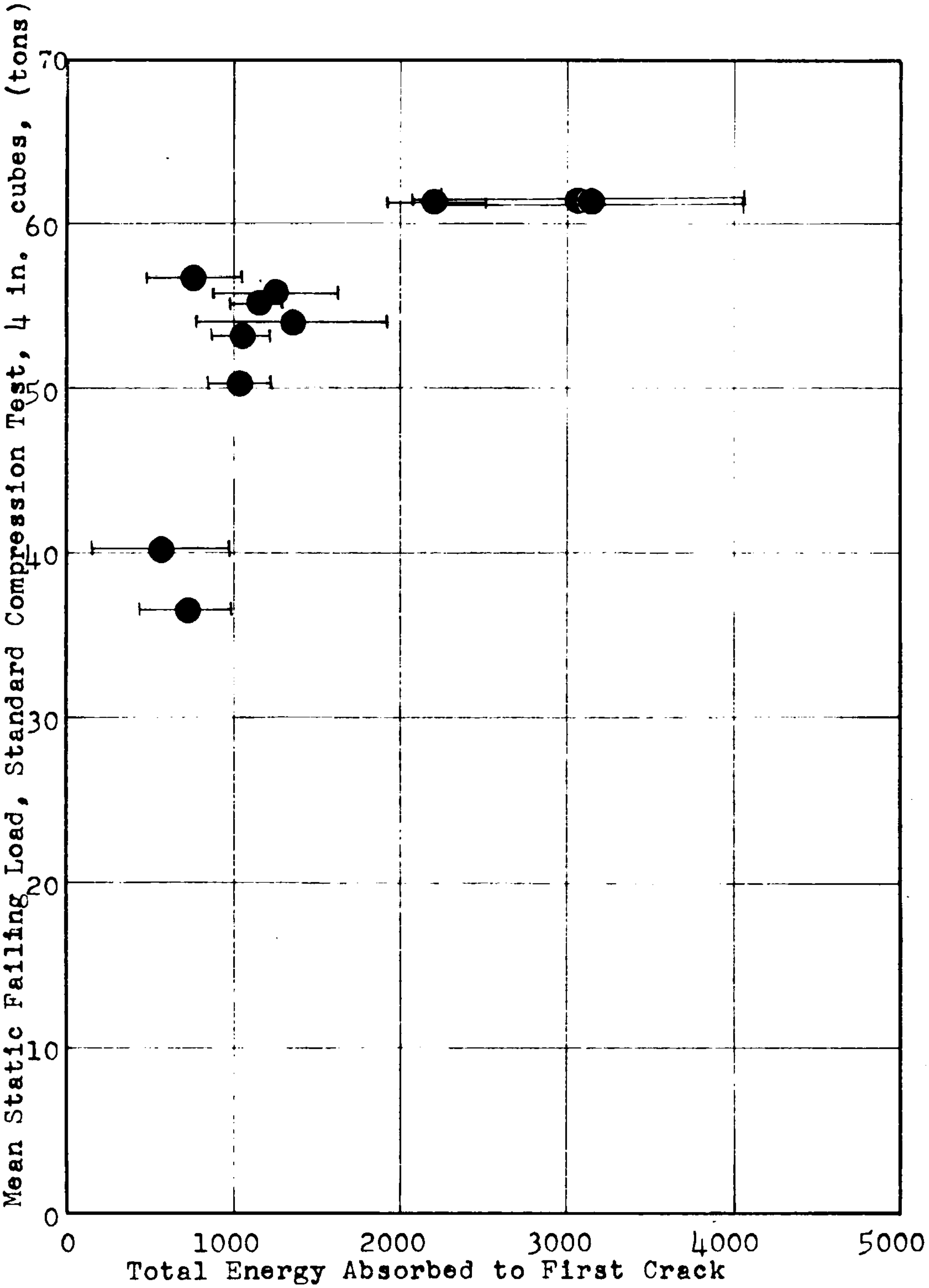

Fig. 2.3 - Relation between compressive strength and energy absorbed to first crack, (Green (27))

causes failure in many applications indicates that the concept of cumulative damage is applicable not only to tests in which the number of cycles is large (fatigue) but also to high rates of loading involving only a few cycles.

There have been numerous other tests to measure the resistance of concrete to particular types of impact, as for example, abrasion tests, explosive tests, projectile tests. These are all empirical in nature and yield information which is of value as an expedient practical measure but is of little value in the fundamental analysis of the behavior of the material.

The first systematic evaluation of the strength of concrete at varying rates of loading was done by Abrams (1) in 1917. He subjected six inch by twelve inch cylinders to compressive tests in a standard testing machine. Strengths were measured at various rates of straining over a range from 8 x 10^{-6} inches per inch per second to 2 x 10^{-4} inches per inch per second. A substantial increase in strength was noted with increased rate of straining. See Figure 2.4 and Table I of the Appendix. Three mixes, 1:9, 1:5, and 1:3 (cement:sand and aggregate) were tested. The greatest increase in strength was found for the richest mix and the smallest increase in strength for the leanest mix. The nominal

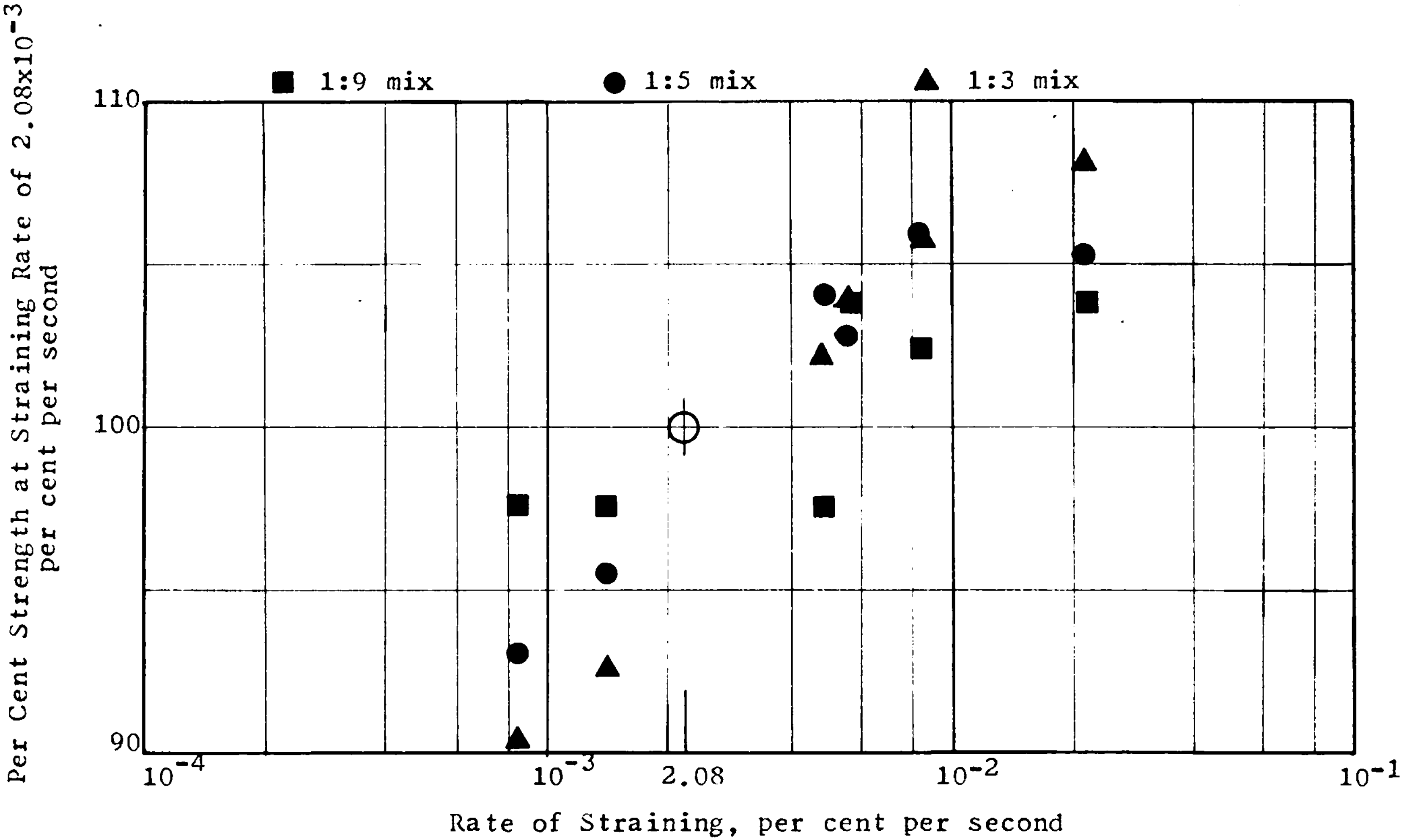

Fig. 2.4 - Effect of rate of straining on the compressive strength of 6 in. x 12 in. cylinders, (Abrams (1))

strengths were approximately 800 psi, 1900 psi, and 3100 psi. There also has been some doubt expressed by Evans (12) as to the ability of a lever testing machine to accurately determine the load values at the higher rates of straining.

In another series of tests conducted at the same time, Abrams found that the rate of application of the load up to at least 88 per cent of the ultimate strength had no effect on the ultimate strength.

In 1934 Moore (46) reported the results of a large number of tests carried out by ten different laboratories on two inch mortar cubes. Among these tests was a limited series of tests to investigate the effect of rate of loading on the compressive strength of mortar cubes. Three loading rates were used, 1000, 3000, and 6000 psi per minute. The results varied considerably, some cements showing an increase in strength with increased rate of straining and others showing a decrease in strength. The average of all the tests showed a slight increase in strength with increased rate of straining. In view of the wide range of results, this increase is not considered significant. See Figure 2.5 and Figure 2.6; also Table II in the Appendix.

Jones and Richart (36), 1936, reported an exten-

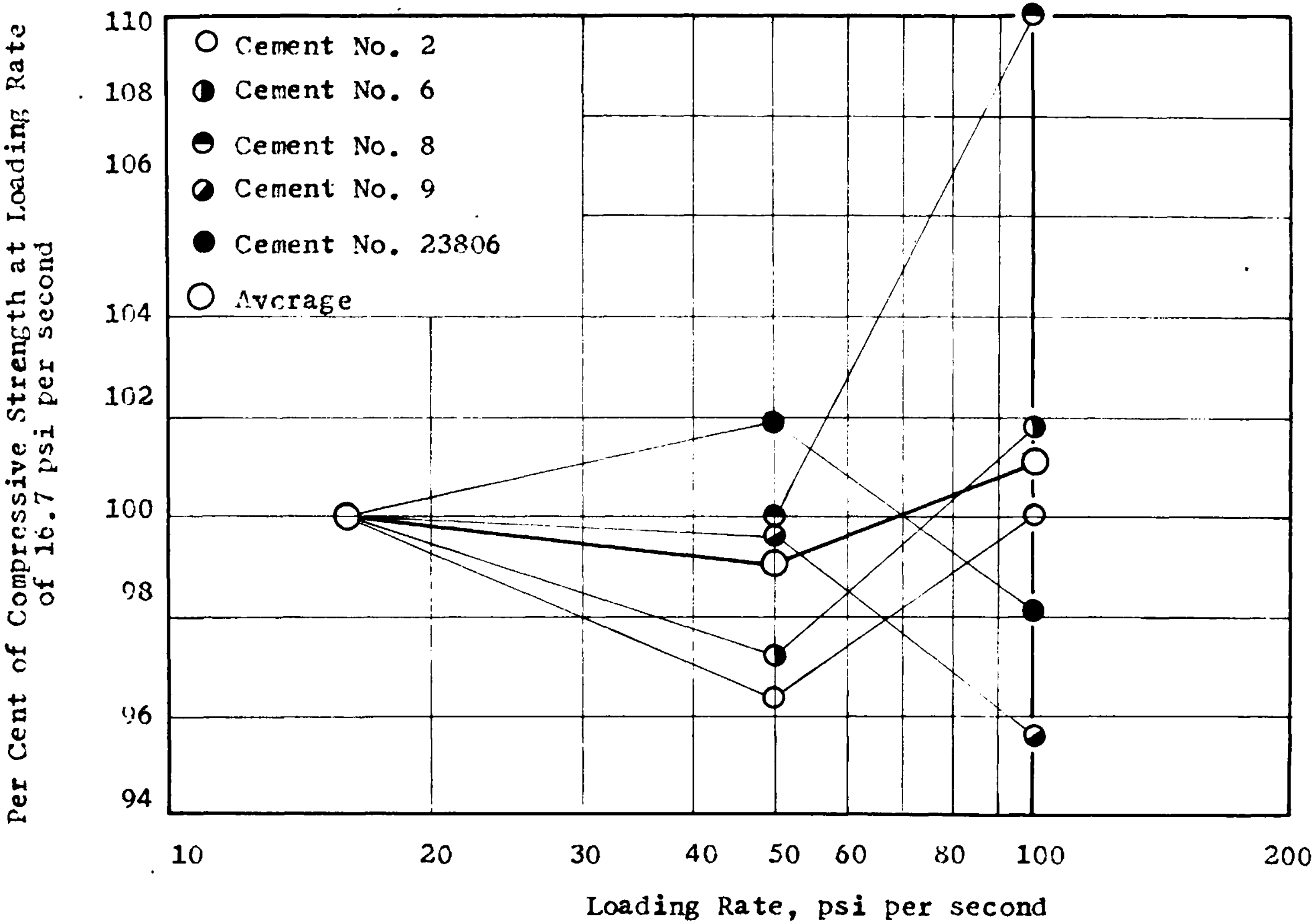

Fig. 2.5 - Effect of loading rate on the compressive strength of 2 in. cubes, age 3 days, (Moore (46))

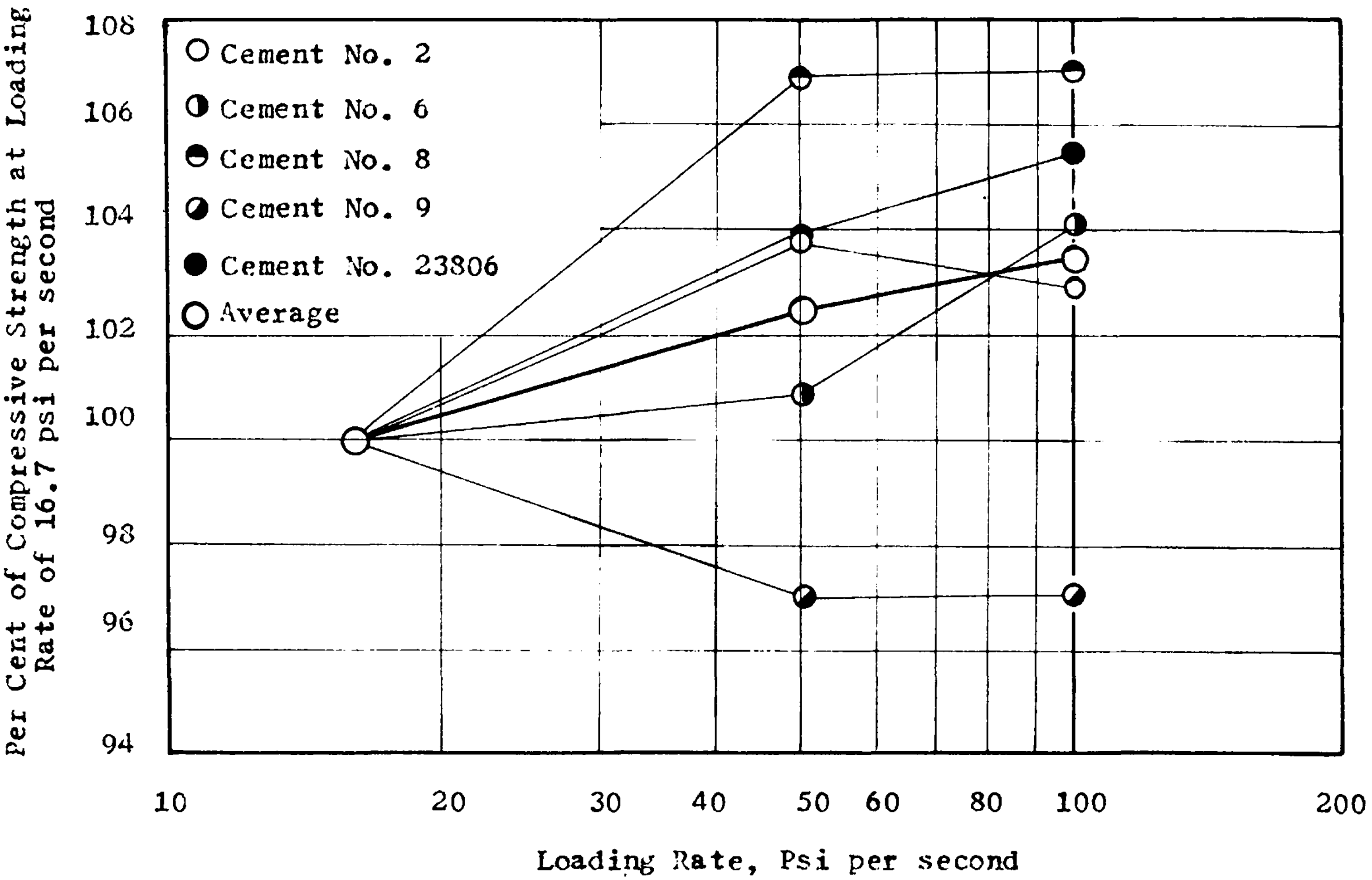

Fig. 2.6 - Effect of loading rate on the compressive strength of 2 in. cubes, age 7 days, (Moore (46))

sive series of tests, over a wide range of testing speeds, on the effect of rate of loading on the compressive strength of concrete. Using carbon resistor telemeter gages both load and strain were measured and recorded with an oscillograph. The test results showed a consistent increase in strength with increased rate of loading over a range of nine loading speeds from about 0.10 psi per second to about 4000 psi per second. The test specimens were standard six inch by twelve inch cylinders of nominal strengths of 2000, 3500, and 5000 psi. Three or more specimens were tested of each strength at each loading speed at ages of seven and twenty-eight days (See Figure 2.7 and Figure 2.8). The authors represented their results by straight lines on a plot of ultimate strength versus the logarithm of the rate of stressing. The percentage increase in strength with increased rate of straining was slightly greater for the twenty-eight day old concrete than for the seven day old concrete. The maximum increase in strength over the range of stressing rates investigated was approximately 30 per cent.

In 1942 Evans reported the results of a great number of tests over a wide range of loading rates from extremely slow (time to fracture, 90 minutes) to very fast (time to fracture, 0.001 seconds). Crushing tests

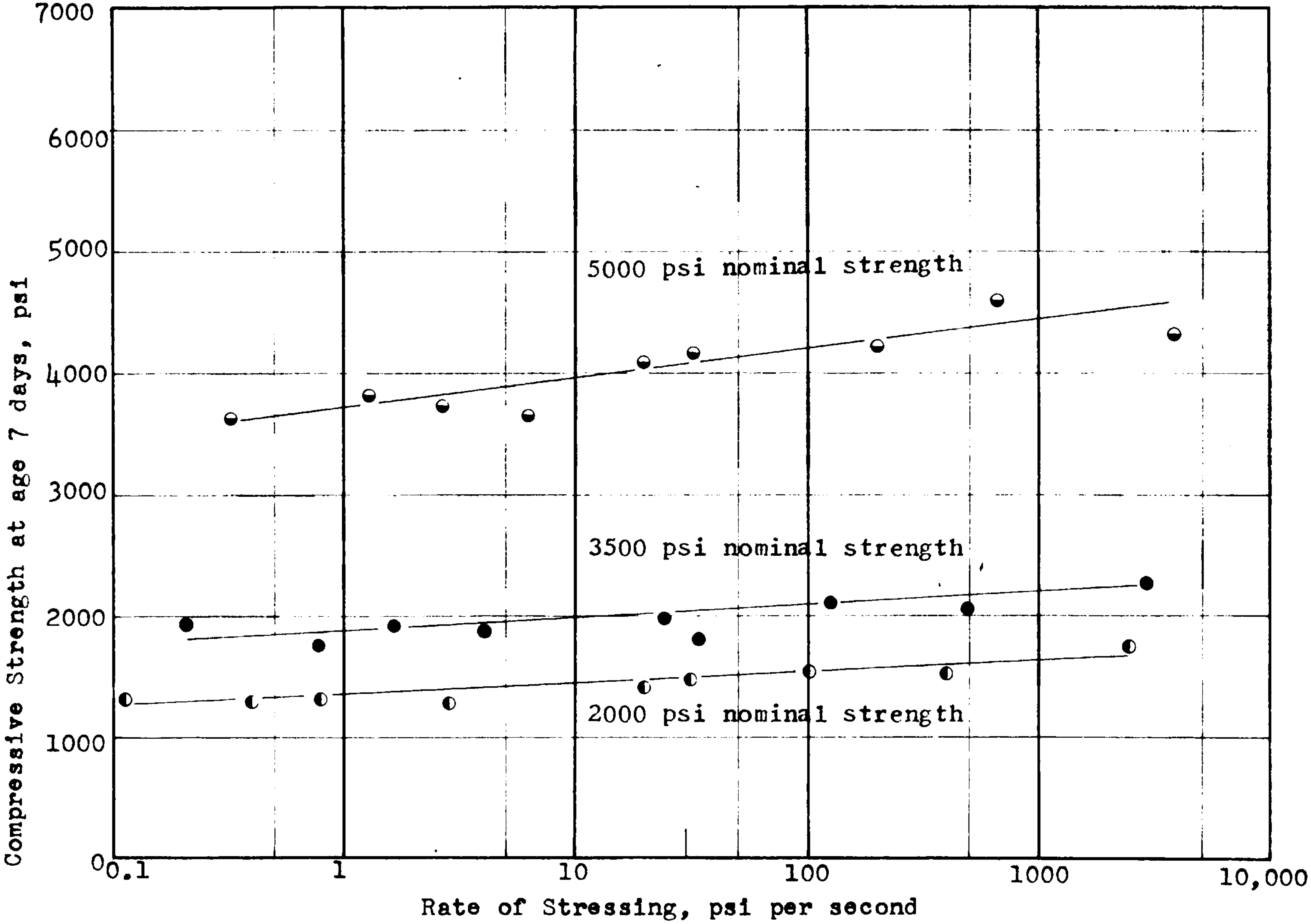

Fig. 2.7 - Effect of rate of stressing on the compressive strength of 6 in. x 12 in. cylinders, (Jones and Richart (36))

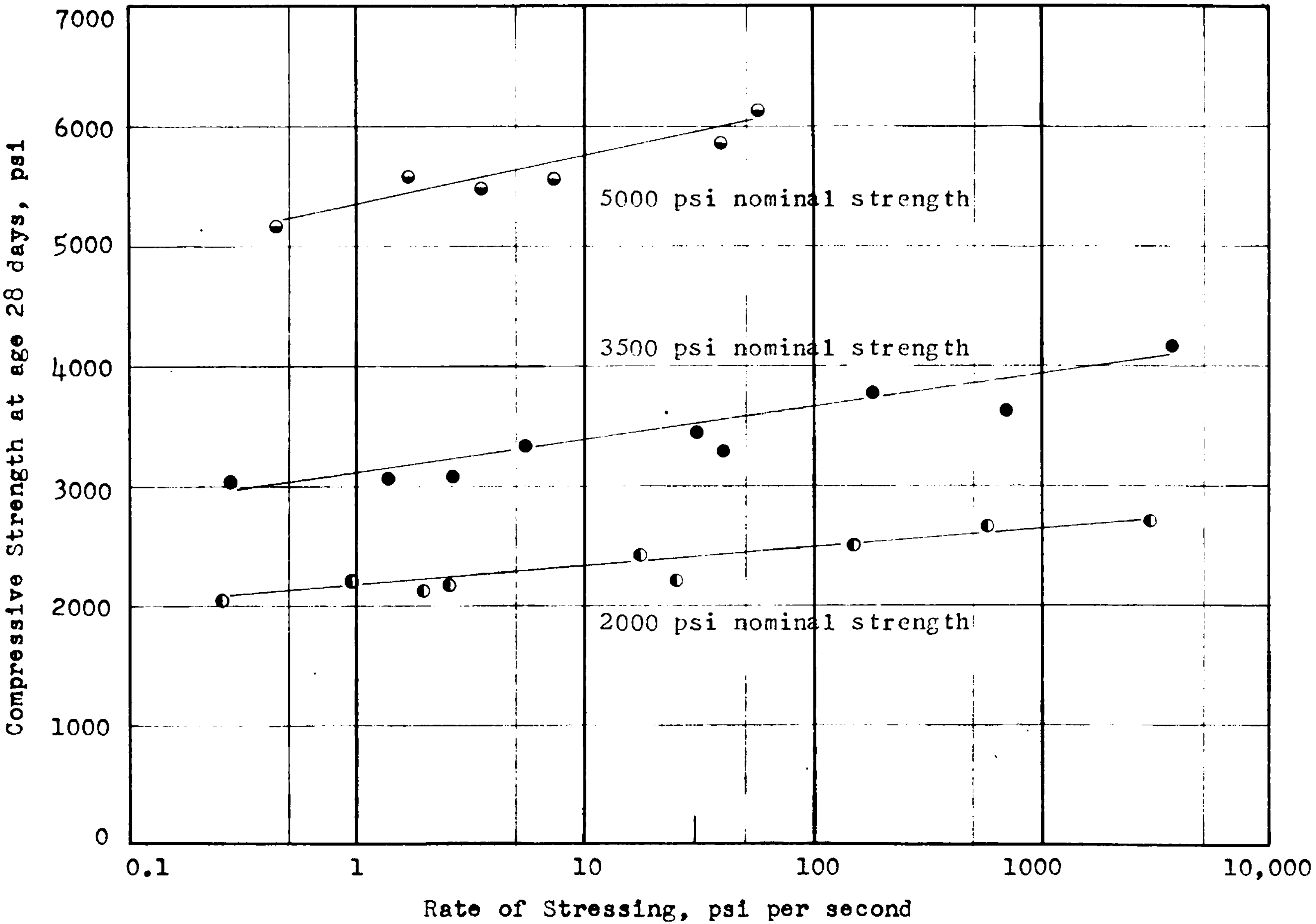

Fig. 2.8 - Effect of rate of stressing on the compressive strength of 6 in. x 12 in. cylinders, (Jones and Richart (36))

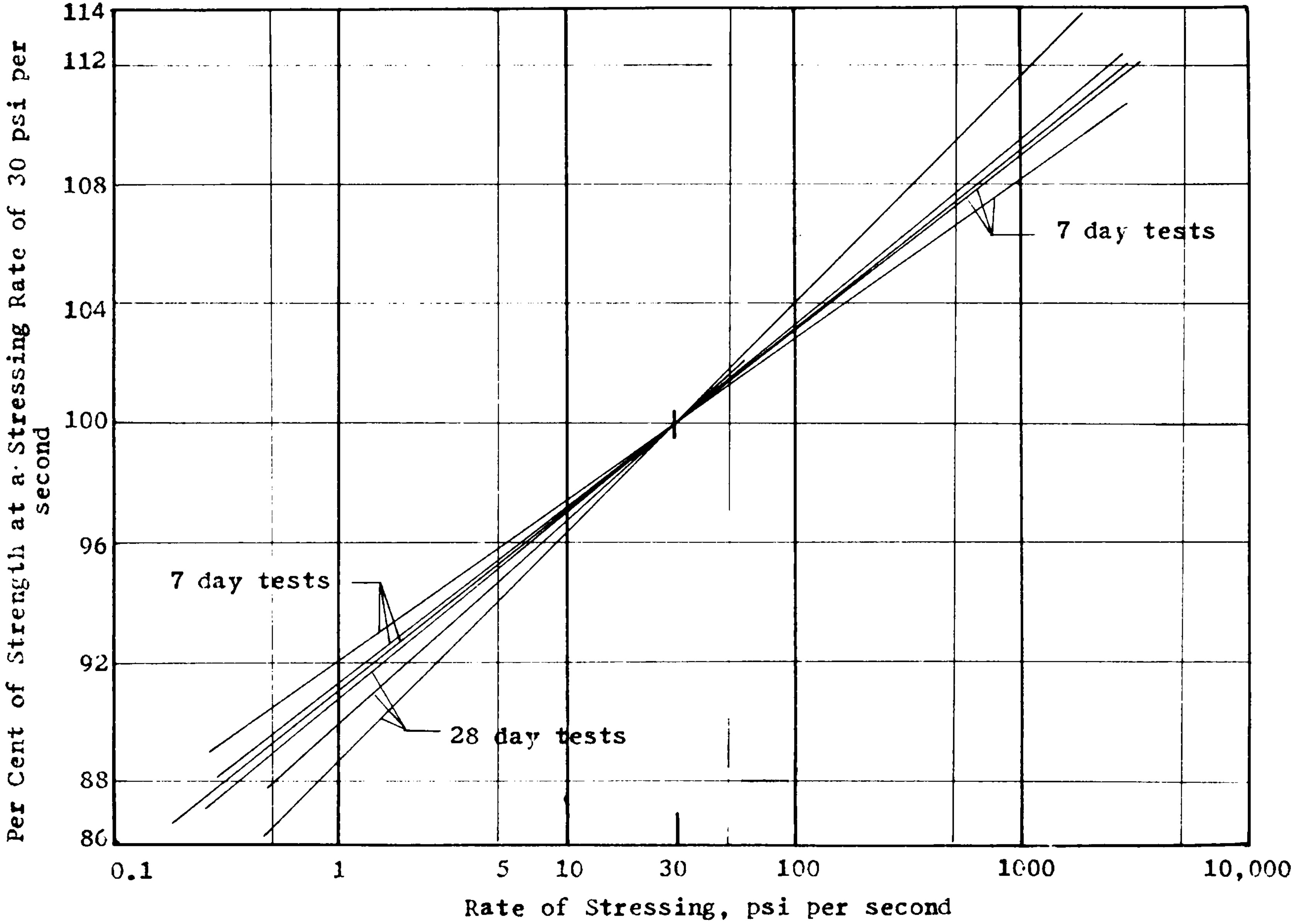

Fig. 2.9 - Effect of rate of stressing on the compressive strength of 6 in. x 12 in. cylinders, (Jones and Richart (36))

were made on two inch cubes of nominal strengths of 3200, 4600, and 6200 psi, and on three inch cubes of nominal ultimate strength of 1600 psi. A hand operated valve control on a pneumatic ram controlled the speed of loading. The ram was capable of exerting a force of 15 tons. Load was measured by means of an extensometer employing an optical lever to project a spot of light onto a revolving photographic drum. No substantial increase in strength was noted at loading speeds slower than about 0.05 second (time to fracture) but substantial increases in strength were noted at faster loading speeds. A 50 per cent increase in strength was noted for the lowest strength concrete at the highest rate of loading used. See Figure 2.10 and Figure 2.11. With increased straining rate the weaker concretes showed a greater increase in strength than did the stronger concretes. In lever machine tests at very slow speeds (time to fracture ranging from 90 minutes to 0.5 second) there was no significant difference in strength.

At the same time Evans made tests to determine the effect of rate of loading on mild steel, duralumin, brass and cast iron, all in tension.

The Bureau of Reclamation, as part of the Boulder Canyon Project, conducted a great number of tests to determine the effect of a number of variables on the strength of concrete. A summary of the investigations

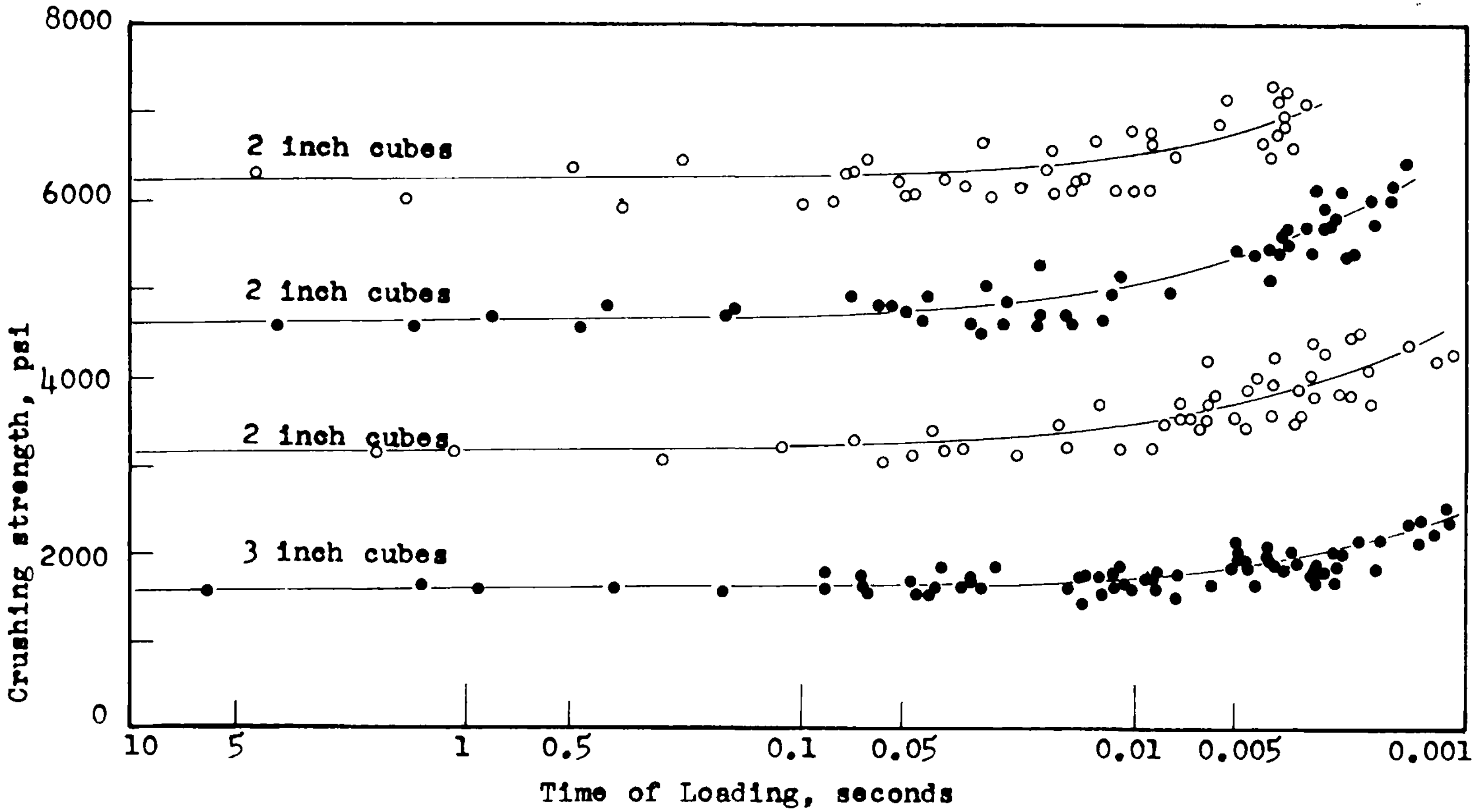

Fig. 2.10 - Effect of time of loading to fracture on the crushing strength of 2 in. and 3 in. cubes, (Evans(12))

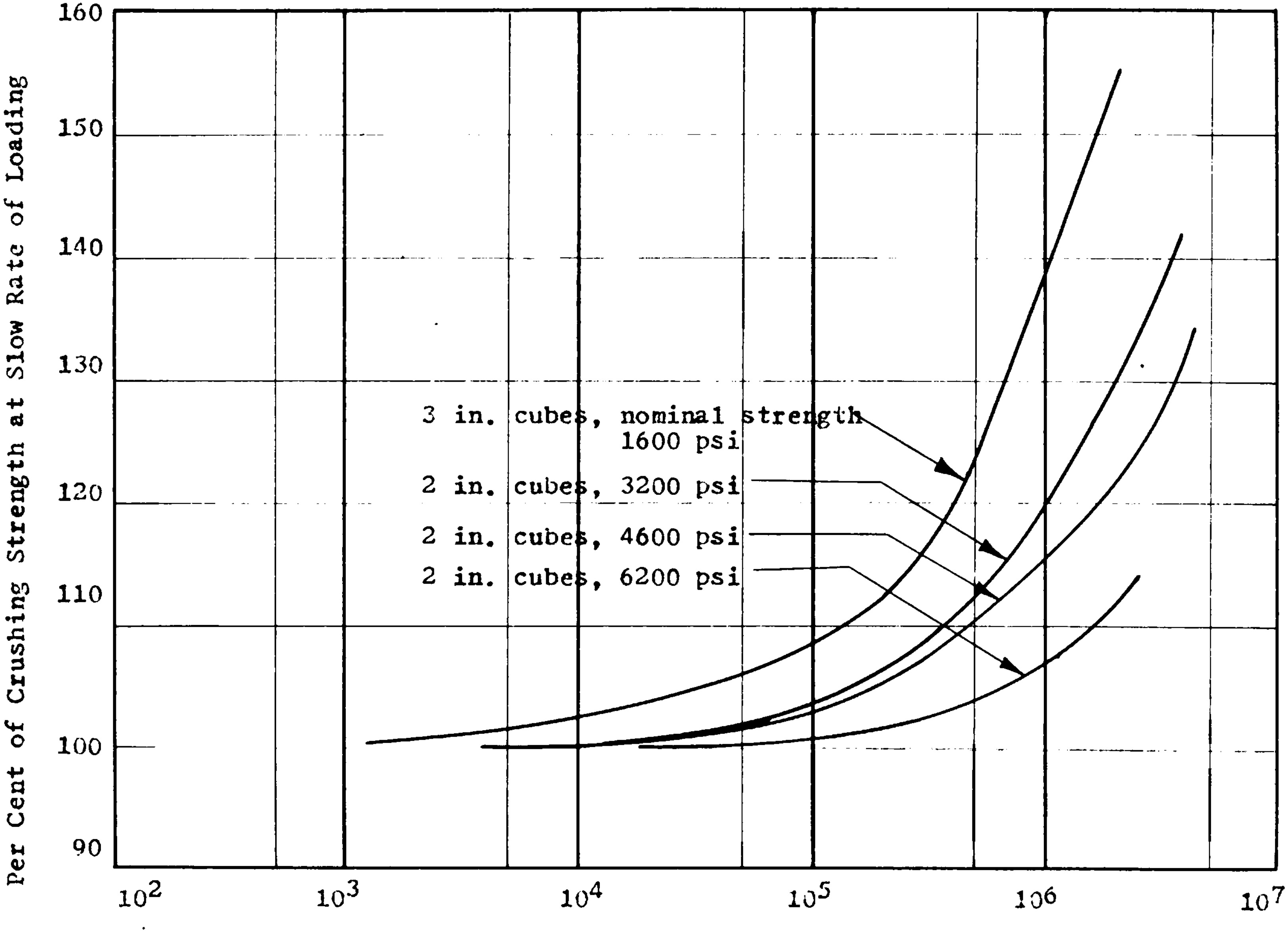

Fig. 2.11 - Effect of rate of stressing on the compressive strength of 2 in. and 3 in. cubes, (Evans (12))

carried out to investigate the effect of rate of loading on the compressive strength of concrete was published in 1949 as part of the Final Reports (78). Tests were made on both eight inch by sixteen inch cylinders add six inch by twelve inch cylinders. The rate of loading was varied from very slow to a maximum of 99.5 psi per second. A strength increase was noted with increased stressing rate with a maximum observed increase of 17 per cent of the strength at the slowest rate of loading. See Figure 2.12; also Tables III and IV in the Appendix.

In 1952 Gaede (20) reported the results of tests made on ten-centimeter (3.94 inches) cubes at two different loading rates, 2.44 kilograms per square centimeter per second and 40.4 kilograms per square centimeter per second (about 7.2 and 118 psi per second, respectively). The corresponding strengths were 322 kilograms per square centimeter and 327 kilograms per square centimeter (about 944 and 960 psi, respectively). The increase is not significant in comparison with the scatter of results. See Figure 2.13; also Table V in the Appendix.

In 1953 Watstein reported (65,66,67,68,69) the results of a study of the "effect of strain rate on the compressive strength and elastic properties of concrete." He subjected three inch by six inch cylinders of two

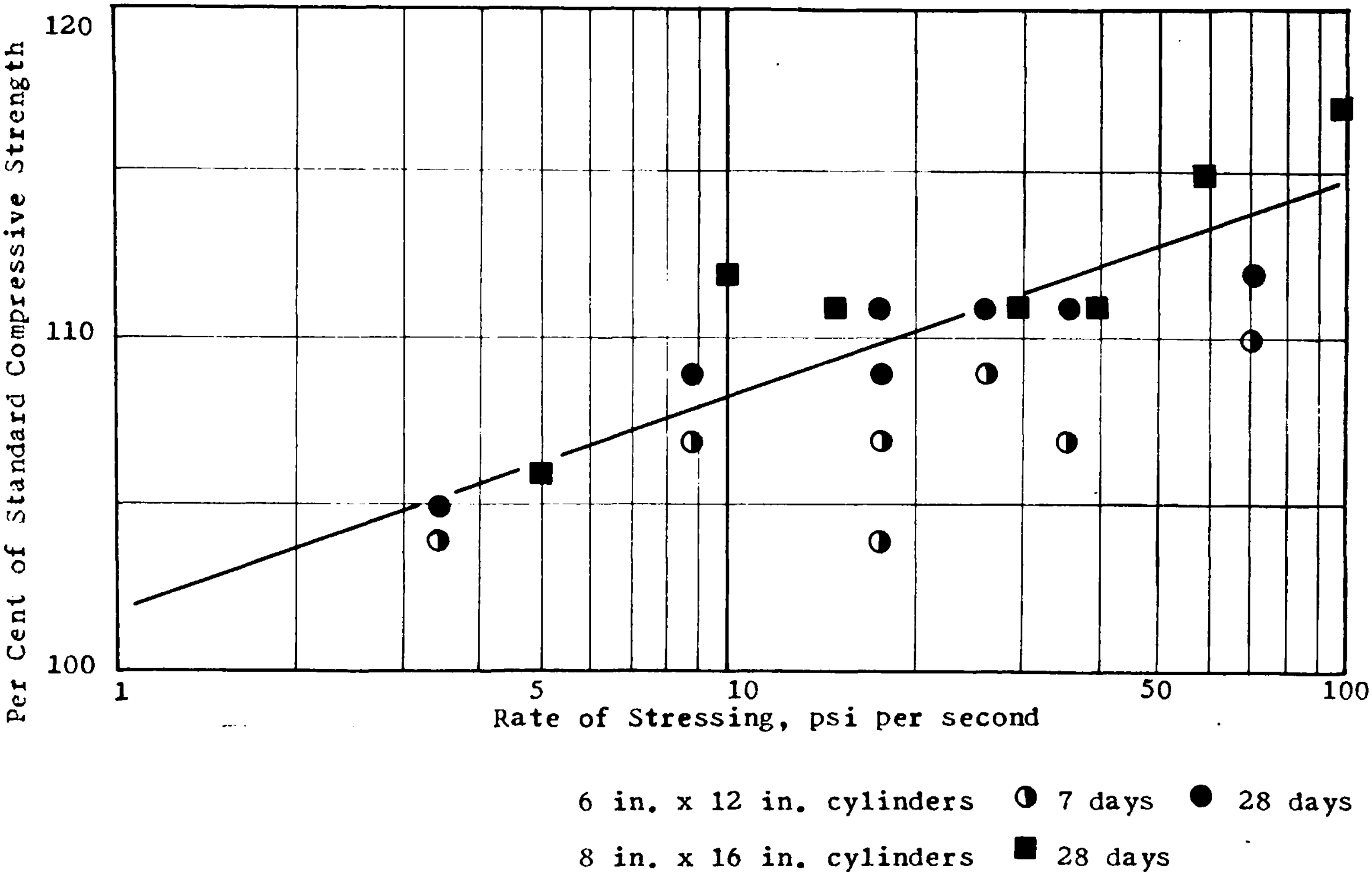

Figure 2.12 - Effect of Rate of Stressing on Strength of 6 in. x 12 in. and 8 in. x 16 in. cylinders, (Bureau of Reclamation (78))

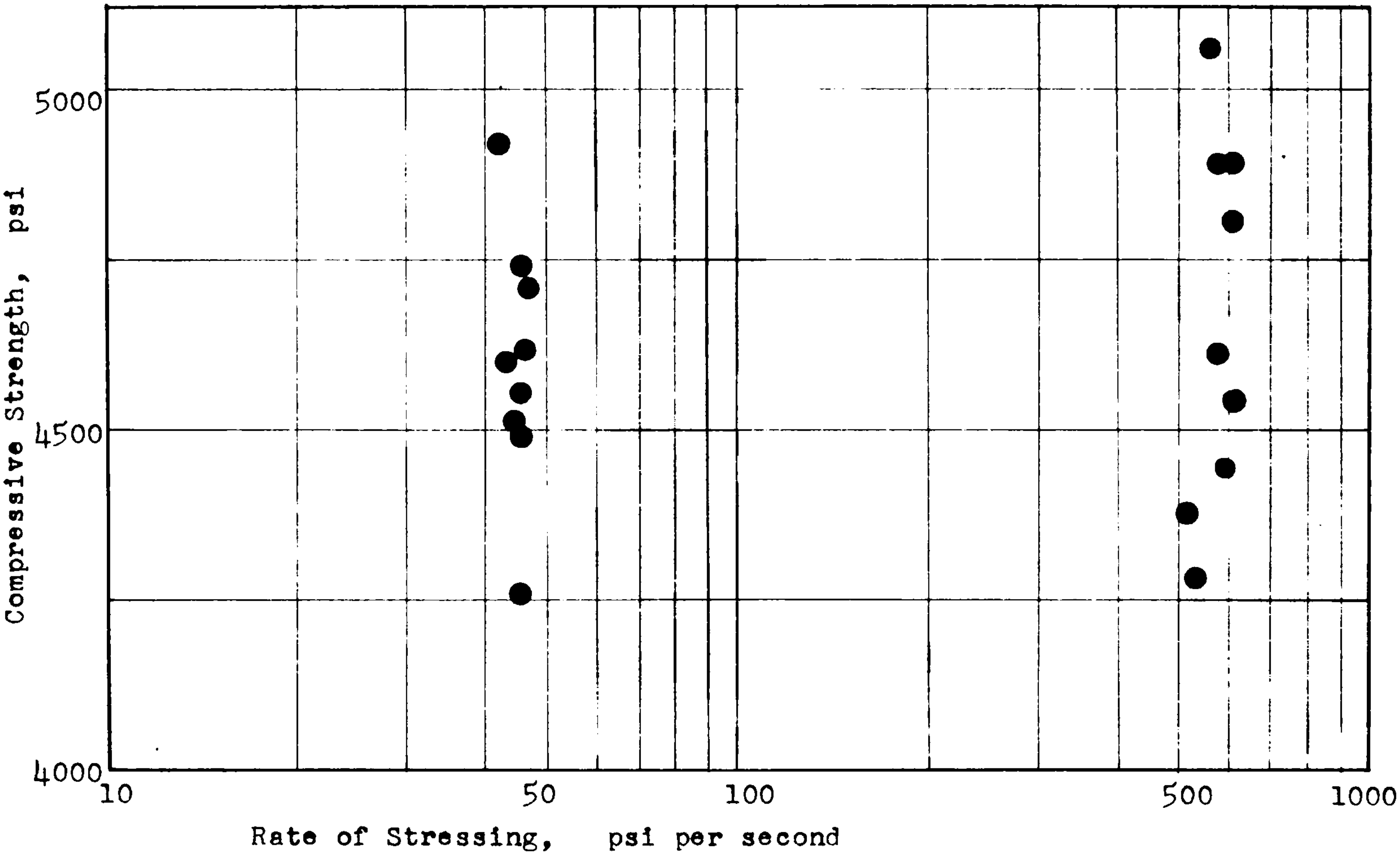

Fig. 2.13 - Effect of Rate of Stressing on the Compressive Strength of 10 centimeter cubes, (Gaede (20))

different strengths ("strong" and "weak" concretes of nominal ultimate strengths of 6500 and 2500 psi, respectively) to a series of tests over a range of stressing rates from approximately 6.0 psi per second to approximately 5 x 10^7 psi per second. The specimens were tested at the lower rates of stressing in a standard testing machine. To obtain the higher rates of stressing, cushioned drop tests were used. The rate of straining was also measured and the test results were plotted against the rate of straining (See Figure 2.14 and Figure 2.15).

Loads were determined by the use of bonded wire strain gages attached to a cylindrical dynamometer in series with the specimen. Strains were determined by the use of strain gages cemented to the test specimens. During a test the load and strain were recorded by photographing the traces on a dual-channel oscilloscope. Six tests were made at each speed of testing for both the weak and the strong concrete specimens. For each testing speed the static strength was determined by testing three inch by six inch control cylinders at a slow rate of loading (about 6.0 psi per second which is a somewhat slower rate of loading than recommended by the American Society for Testing Materials; see also Chapter 1 of this thesis). Control six inch by twelve inch cylinders were also tested and gave

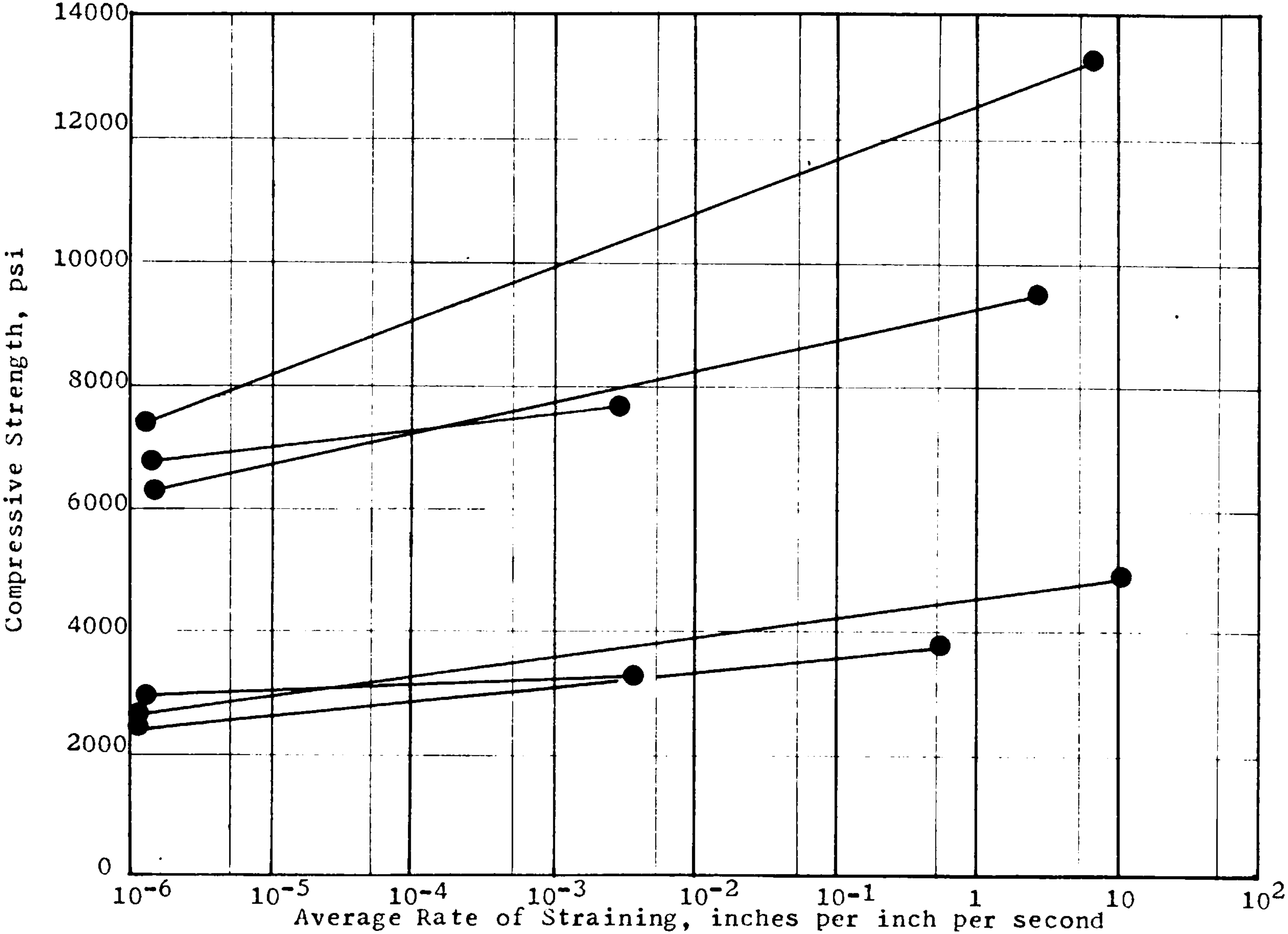

Fig. 2.14 - Effect of rate of straining on the compressive strength of 3 in. x 6 in. cylinders, (Watstein (65))

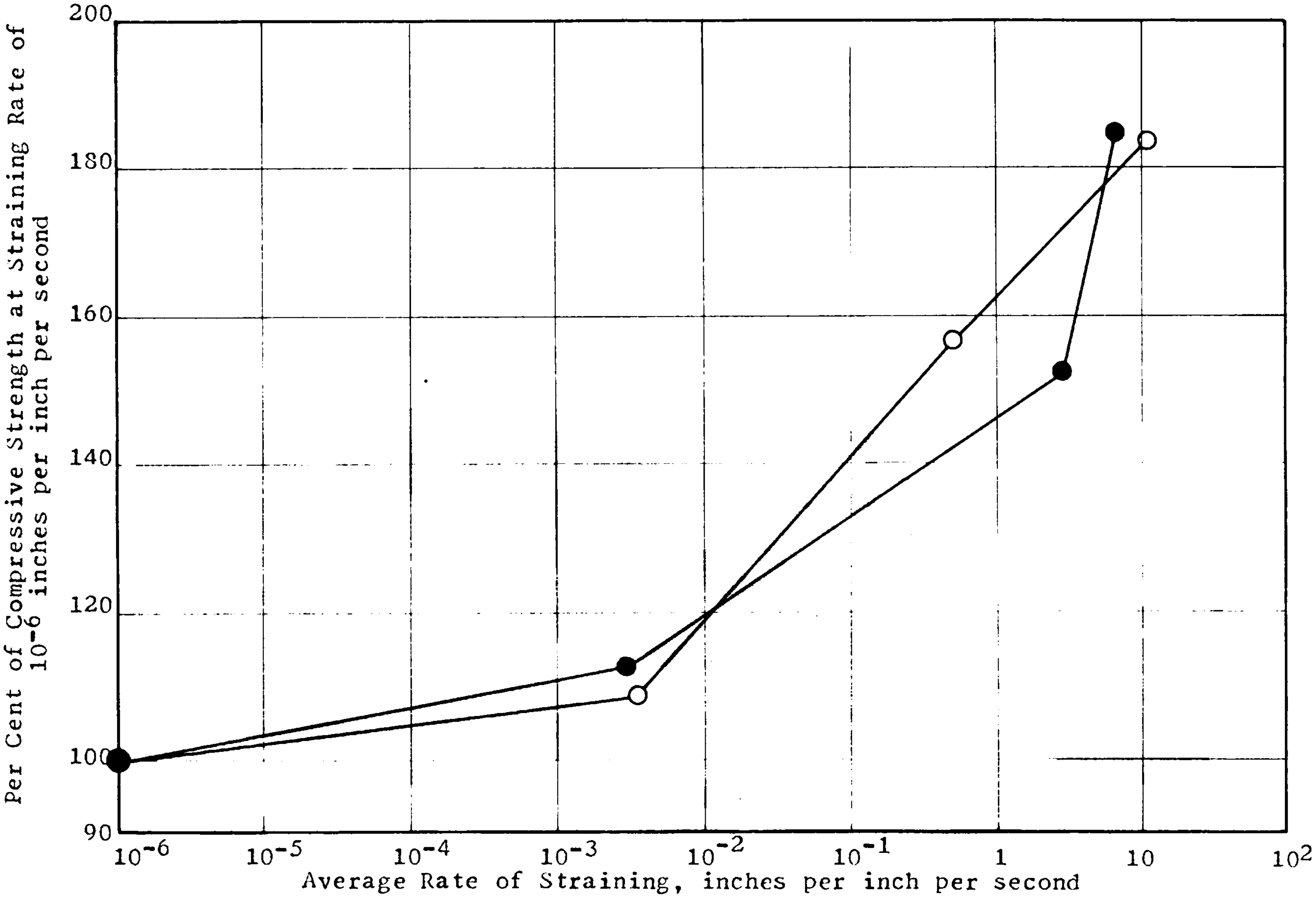

Fig. 2.15 - Effect of rate of straining on the compressive strength of 3 in. x 6 in. cylinders, (Watstein (65))

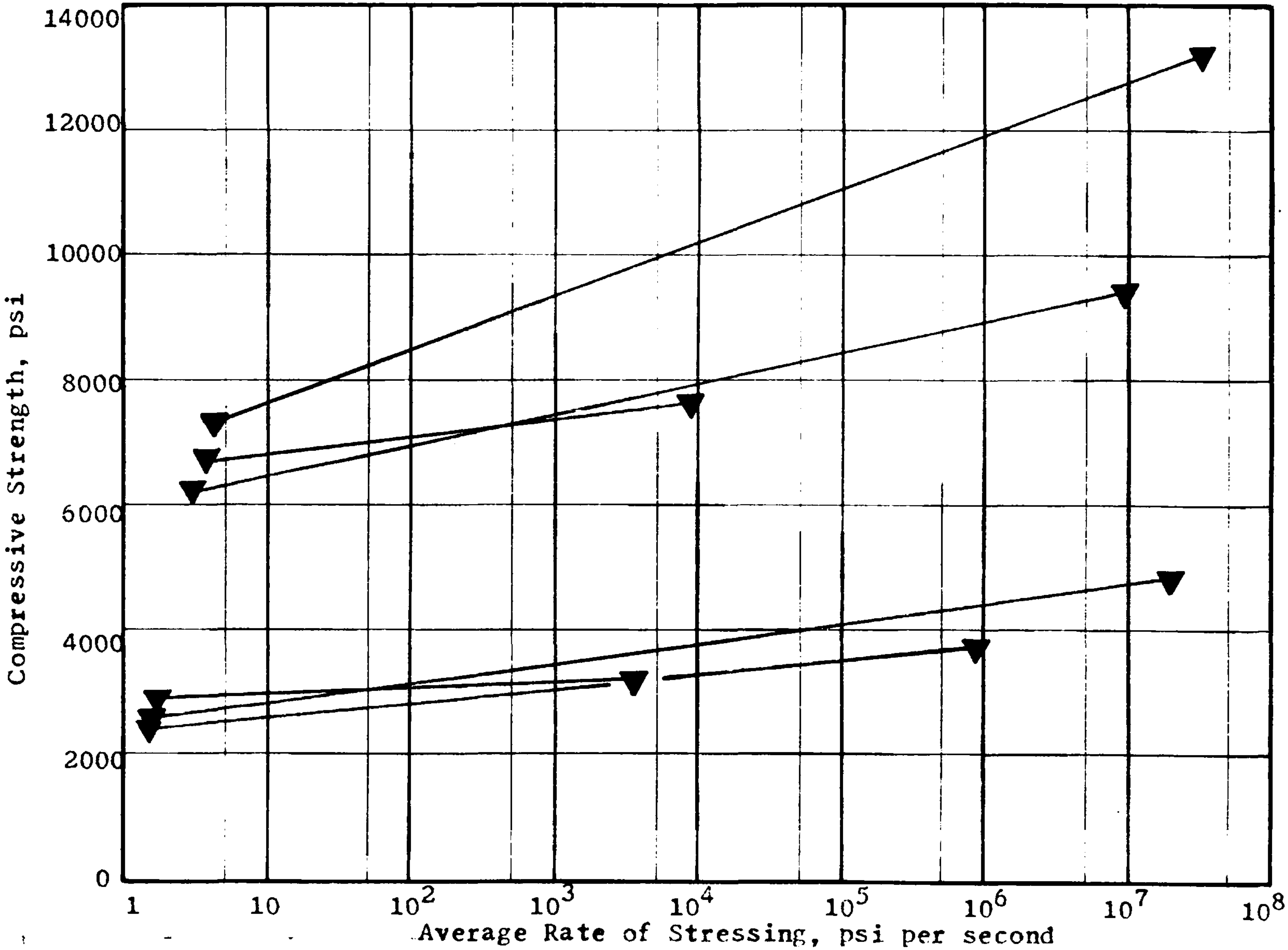

Fig. 2.16 - Effect of rate of stressing on the compressive strength of 3 in. x 6 in. cylinders, (Watstein (65))

slightly lower values of ultimate strength, as was expected.

A plot of the percentage increase in strength versus the log of the rate of stressing (or straining) shows a gradual increase in strength at testing speeds approximating ordinary testing speeds and a sharp increase in strength at the higher rates of stressing (or straining)(See Figure 2.15 and Figure 2.17). The maximum increase in strength was about 85 per cent at a stressing rate of 5 x 10^7 psi per second. Failure at even the highest rates of stressing was the conventional shear cone type of fracture.

There was extensive strain data obtained by Watstein. The secant modulus of elasticity was found to increase with increasing rates of loading. The strain energy absorbed also increased and, in general, greater values of strain at failure were obtained at the higher rates of loading. The information on the elastic properties of concrete obtained by Watstein (and others) is a subject in itself and no attempt will be made in this paper to evaluate and compare his findings on this subject. It should be noted, however, that Watstein's work was extremely detailed and stress-strain curves were obtained even at the highest rates of loading.

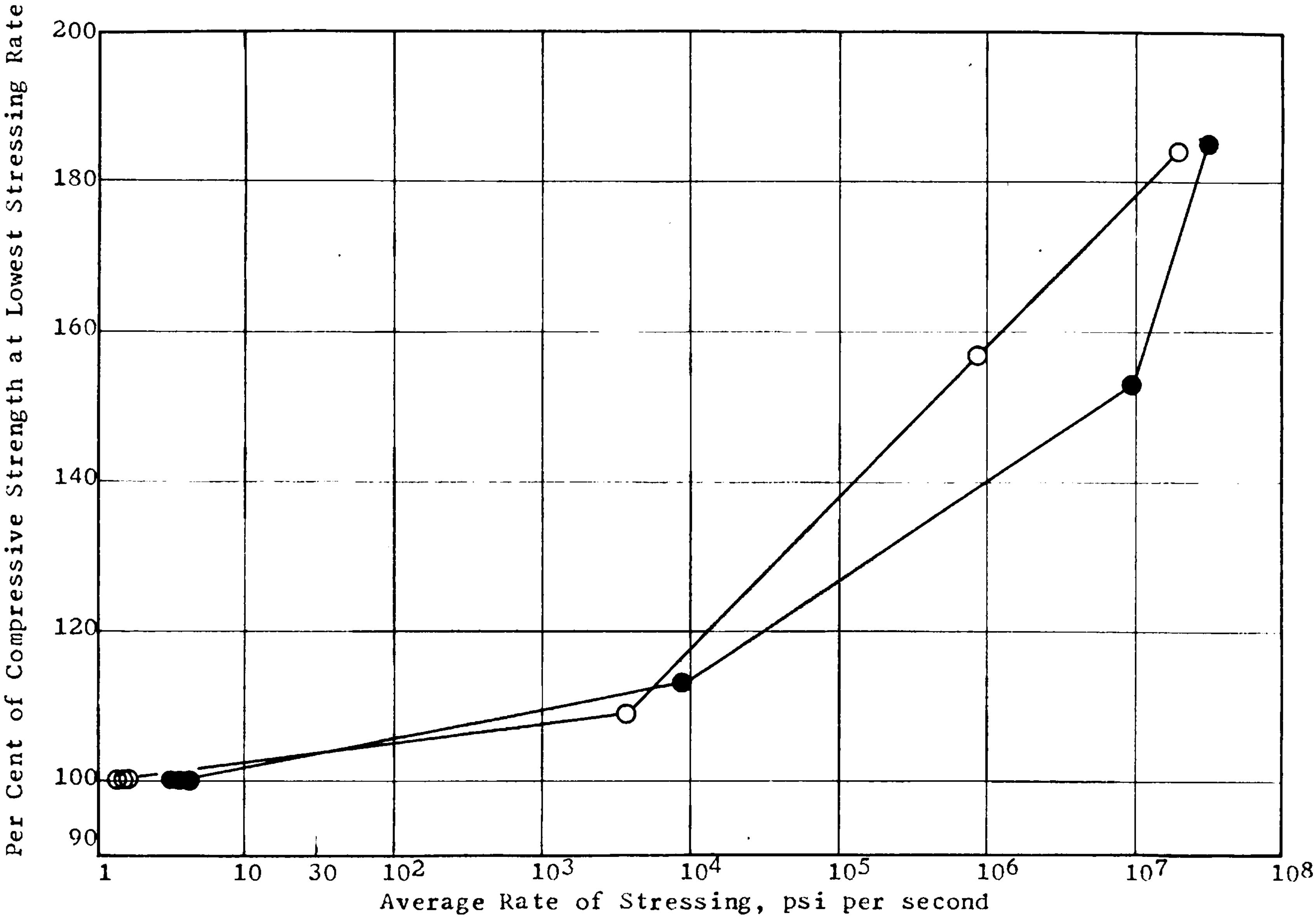

Fig. 2.17 - Effect of rate of stressing on the compressive strength of 3 in. x 6 in. cylinders, (Watstein (65))

2.2 Comparison of Investigations

It is of interest to compare the results of the various investigations described in the previous section. These investigations were conducted at widely spaced times on concretes differing in age, strength, type of aggregate, water-cement ratio, specimen type and numerous other characteristics. In spite of these many differences there is believed to be a basis for comparison since the failure process is believed to be fundamentally the same in all of the investigations.

The two most important investigations are those by Watstein and Evans. Both investigations covered substantially the same range of loading rates and both investigators obtained sufficient test results to provide a means of comparison. Their results, together with the results of others are shown in Figure 2.18. The ultimate strength obtained at a loading rate of 30 psi per second was used as a reference in the comparison. This rate of loading was chosen for two reasons. First, it lies approximately in the middle of the allowable range of loading rates permissible in the standard compression test used in the United States (ASTM (1958) C 116-49). Second, it is the reference used by McHenry and Shideler in their review published in 1955 (45).

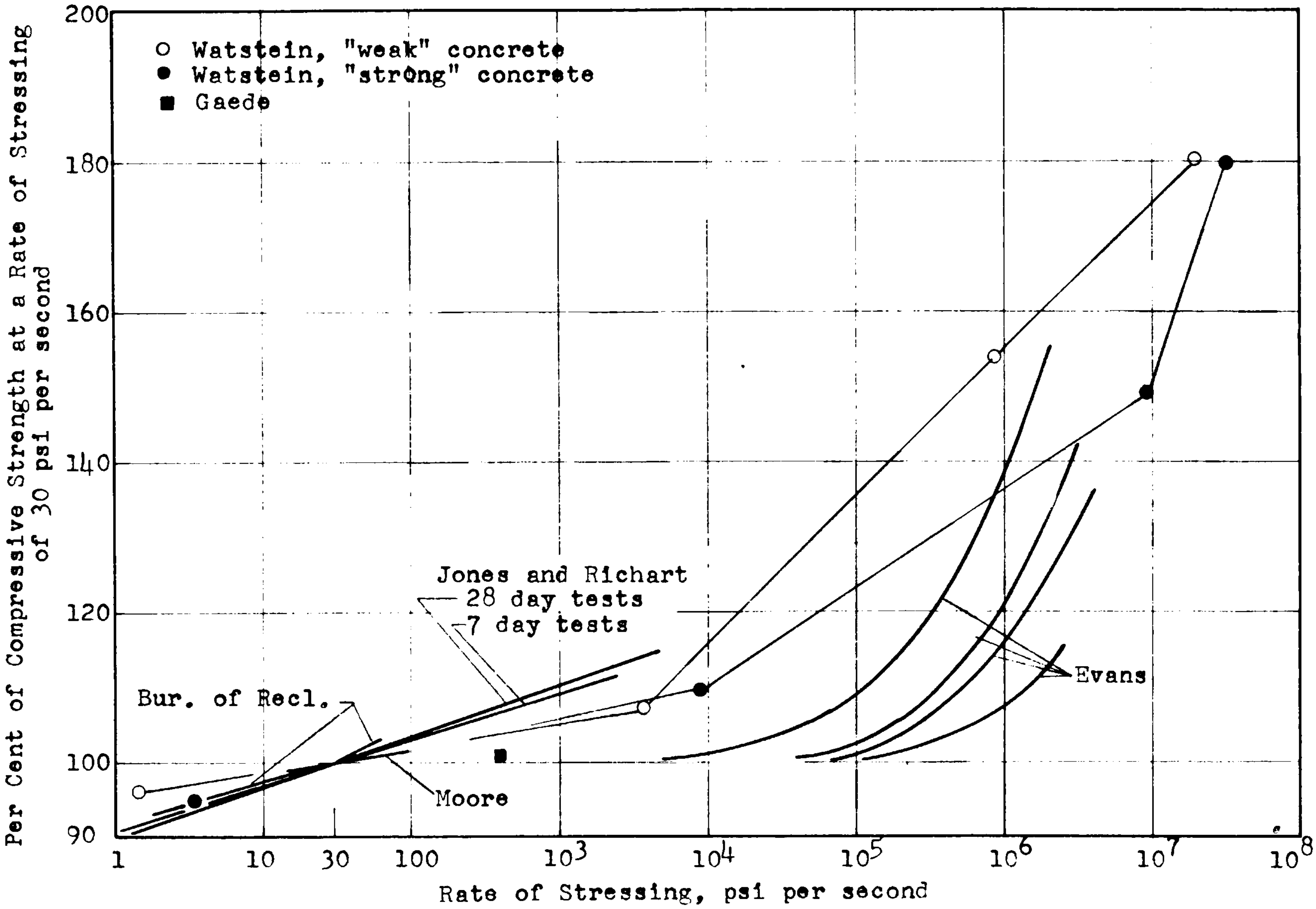

Fig. 2.18 - Comparison of the results of investigations of the strength of plain concrete at fast rates of loading in compression

From Figure 2.18 it can be seen that Watstein found a continuous increase over the entire range of loading rates with a sharp increase in strength beginning at a loading rate of about 10^4 psi per second. Evans found no increase until a loading rate of about 5 x 10^4 psi per second and then a sharp increase in strength, although not as great an increase as Watstein noted. Watstein found little difference between weak and strong concretes in the percentage increase in strength at the highest rate of stressing used but found that at intermediate rates of stressing the weaker concretes showed a greater percentage increase in strength. Evans found that the weaker concretes showed a greater percentage increase in strength than the stronger concretes as long as the rate of loading was greater than about 5 x 10^4 psi per second. The differences between the results found by Evans and Watstein may be chiefly due to the effect of the differences in specimen type. This will be discussed in greater detail in the next section.

Jones and Richart found a substantial increase in strength over a limited range of loading rates. They represented their results by straight lines on a plot of ultimate strength versus the log of the rate of loading. The results were remarkably uniform for all the concretes with various ultimate strengths tested. The average for specimens of ages seven and twenty-eight days are shown in Figure 2.18. It is seen that the increase is greater than that noted by Watstein, Evans, Gaede, and Moore. Inspection of Jones and Richart's data (see Figure 2.7 and Figure 2.8) also shows the results, on the same type of plot, to have a tendency to be concave upward in agreement with the results reported by Watstein and Evans. (It should be noted that Jones and Richart thought the straight line approximation to be incidental.)

Moore noted a percentage increase in strength even less than that noted by Jones and Richart. Gaede found a negligible increase in strength with increased loading rate. Jones and Richart tested cylinders while Moore and Gaede tested cubes.

The results of the Bureau of Reclamation's tests show a substantial increase in strength with increasing loading rates and agree quite closely with the results found by Jones and Richart.

2.3 Reasons for Differences in Results

To understand why concrete should show an increase in strength with increased loading rate one must consider the failure process. Ordinarily "failure" of concrete refers to an inability to carry a load. It is generally recognized that the mere occurrence of cracks does not mean that the concrete has failed in a gross sense. Jones (38), using an ultrasonic pulse technique, claims to have detected cracks in concrete at stress levels as low as 35 per cent of the ultimate compressive strength. Others, Berg (4), Blakey (6), Evans (15), have detected cracks prior to gross failure. Oppel (50) in a photoelastic study found strain concentrations as high as five times the average strain and these strain concentrations were generally at the edges of the aggregate pieces. It is apparent, then, that not only has cracking been detected prior to failure but it should be expected. When this cracking becomes extensive failure occurs.

It has further been hypothesized by Jones (37) that failure of cylinders of concrete results when the "pyramids" of uncracked concrete (under a triaxial compression due to friction between the ends of the specimen and the testing machine) force themselves into the cracked surrounding concrete, resulting in the well known cone of fracture.

It is seen from both Evans' and Watstein's results that low strength concretes show a greater percentage increase in strength than do the higher strength concretes. A close examination of Evans' data shows that the absolute increase in strength was approximately constant for concretes of all strengths at any given rate of loading. Watstein's results show a greater absolute increase in strength for the stronger concrete. The findings of Watstein support the idea that the percentage increase in strength with increased loading rate is, in part, dependent upon the strength. Evans' results support the idea that the actual increase in strength at any given loading rate is independent of the strength. It is probable that the increase in strength at any given loading rate is in part a constant value and in part a value dependent upon the strength of the concrete. The constant part of the increase is due to such factors as inertia forces, limiting velocities of cracking, effects of specimen configuration and corresponding modes of failure. The variable part of the increase which is dependent upon the strength is probably a result of the fact that increased strength is due not to an inherently greater strength of the component materials, but to the greater frequency of bonds of the constituent materials by the cement. The amount of each part of the increase in relation to the total increase will vary with the loading rate. This is shown by Watstein's tests in that the total increase is different for the strong and weak concretes but the percentage increase is the same (approximately) at one loading rate and different at another.

Over the range of loading rates involved in this study the cause of failure probably varies. At the lower rates of loading the cause of failure is probably related to volumetric strain phenomenon while at the highest rates it is probably due to failure by crack propagation. At low rates of loading considerable creep occurs. In long-time tests Shank (55) has shown that failure may occur at approximately 90 per cent of the standard compressive strength. Using plastic flow tests, Shank also found that the highest stress level that could be obtained was about 0.90 of the standard compressive ultimate strength. The close agreement seems more than incidental.

At the highest rates of loading considerable creep still occurs. The actual rate of loading required to force fracture of all surfaces simultaneously is extremely high and well beyond the range of loading rates used by the investigators whose work is described in this paper. Failure by crack propagation is possible at extremely short durations of load provided the stress is sufficient to initiate growth of cracks. The limiting velocity of cracks in a material has been shown to be, for a wide variety of materials, approximately $0.38\sqrt{E/\rho}$, where E is the modulus of elasticity and ρ is the density (Gilman (21)). If we assume E to be 4×10^6 psi and ρ to be 150 pounds per cubic foot, them the limiting velocity of a crack in concrete is given approximately by 4×10^3 inches per second. If crack origins are spaced, on the average, at one-half inch and all cracks originate simultaneously, the duration of time for failure is approximately 6×10^{-5} seconds. These values must be regarded as approximate until we have a greater knowledge of crack behavior in concrete.

Probably the most important difference between Watstein's and Evans' tests was the difference in specimen type. In tests of cylinders the failure mode is a shear fracture resulting in the formation of the well known "cone of fracture". In cube tests this cone cannot form freely and failure is more of a crushing nature.

Tests by Gonnerman (26), Hutchinson (34), Johnson (35), and Mather (43) have shown that cube tests invariably record higher strengths when subjected to static loading than do cylinder tests of the same concrete. This is due in large part to the difference in the length to diameter ratio. At l:d ratios less than about 1.5 the failure mode is of a restrained nature. At l:d ratios greater than about 1.5 the failure mode is the conventional cone failure and the strength is not greatly dependent upon the l:d ratio.

Watstein tested cylinders with an l:d ratio of 2.0 while Evans' cubes had an l:d ratio of 1.0. The correction factor to be applied to strengths obtained with specimens of l:d ratio of 2.0 to obtain the strength recorded by a specimen with l:d ratio of 1.0 is estimated to be between 1.03 and 1.35 with the majority of the investigators agreeing on an estimate of about 1.18. Hutchinson (34) has further found the factor to depend upon the strength of the concrete and to be greater for lower strength concretes (Figure 2.19).

The effect of using a cube specimen, then, is to make the observed percentage increase in strength less than the "true" percentage increase in strength that would be observed were failure not of a restrained nature. This effect tends to make Evans' tests more in agreement with Watstein's results. Using Hutchinson's correction factors, Evans' data has been plotted and compared with Watstein's results in Figure 2.20.

There have been objections to measuring strain at high rates of straining by strain gages on the grounds that only average strain is measured, and not the peak strain of a pulse wave. This is a valid argument. In the

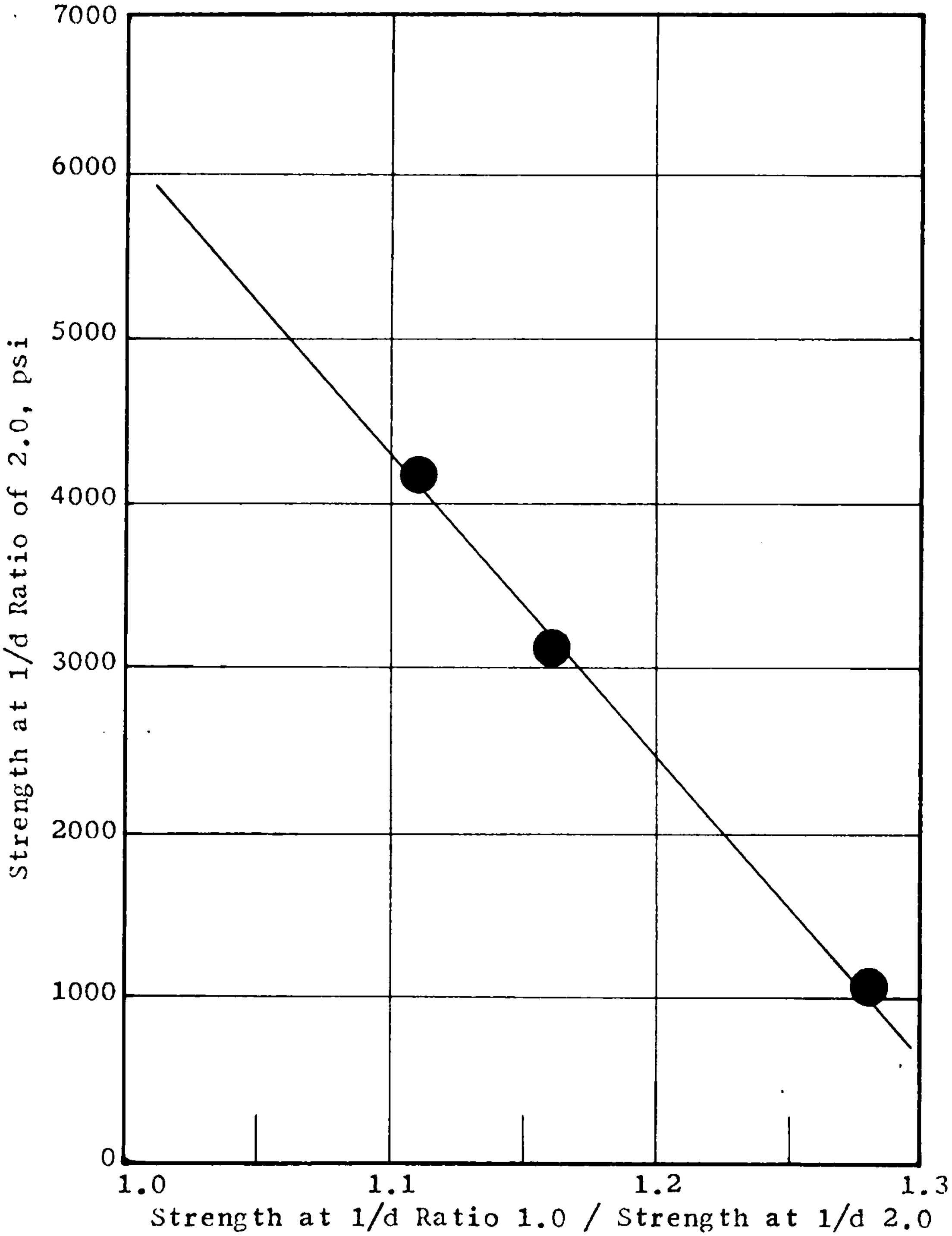

Fig. 2.19 - Effect of strength on correction factor for specimens with l/d ratio of 1.0, Hutchinson (34)

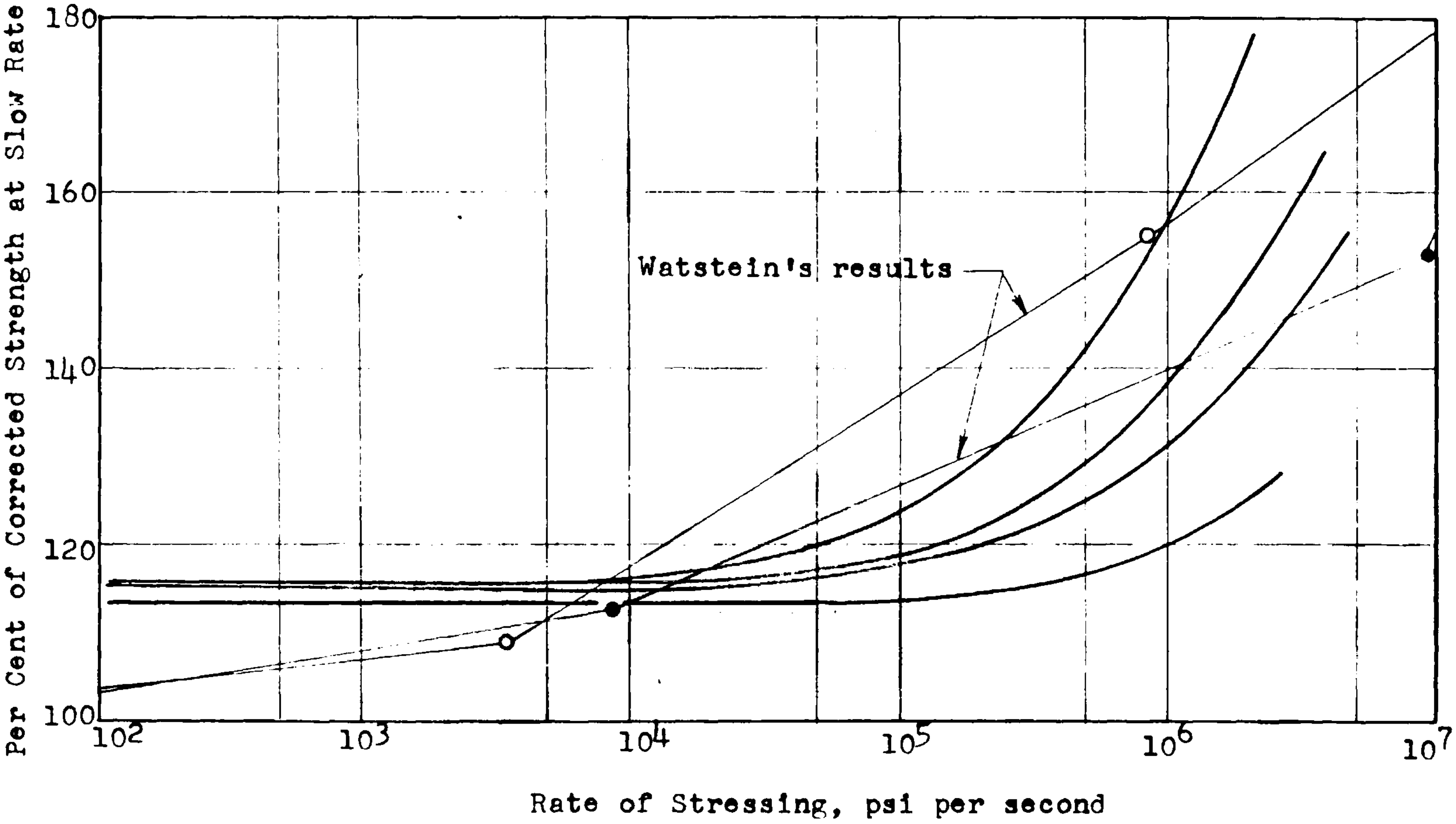

Fig. 2.20 - Effect of Rate of Stressing on Crushing Strength of Cubes, Corrected for Effect of Specimen Configuration, (Evans (12))

tests reported throughout this paper the strain rates were not high enough for wave effects to have a substantial effect. Further, Cunningham and Goldsmith (9) have shown that strain gages do accurately measure the intensities of pulses with durations as short a 24 microseconds. They concluded that strain gages can be used with accuracy if the length of the wave is at least ten times the length of the gage.

CHAPTER 3 - EFFECT OF FAST RATES OF LOADING ON SHEAR STRENGTH

3.1 Introduction

Concrete is not usually used to resist pure shear. Concrete fails in pure shear only when it is constrained so as to prevent a tension failure, the "diagonal tension" behavior well known in beam failures. This chapter will be concerned only with the strength behavior in pure shear. Little attention has been devoted to the study of concrete in pure shear and almost no work has been concerned with the shear strength of concrete at high loading rates.

3.2 Description of Investigations

The only investigation known of the behavior of concrete in shear at high loading rates is by Hansen, Nawy, and Shah (31, 48). They tested twelve specimens dynamically and of these only eight were without reinforcement. The eight tests on plain concrete specimens were divided into two series of four dynamically tested specimens. The specimens in all series were concrete blocks ten inches by twelve inches by twenty inches with two shear keys on each of the twelve inch by twenty inch sides. The shear keys were 2-5/8 inches by seven inches with the long axis perpendicular to the direction of the load application. The block, supported only by the shear keys, was enclosed in a housing frame. Cardboard was placed between the test blocks and the housing frame. The dynamic load was a pulse with a very short rise time and a long decay time. Two control specimens were tested in a similar manner with a total duration of load to failure of ten to fifteen minutes.

The first series of four tests was on plain keys with no transverse compression applied. The rise time varied between 25 and 50 milliseconds. In Figure 3.1 the ratio of the failure load in the dynamic tests to the failure load in the static tests is plotted against the log of the rate of loading. Watstein's results of compression tests are plotted for comparison.

The second series of tests was conducted with a transverse compression of 150 psi and 300 psi applied in each of two series of tests of two specimens each. Results of these tests are also shown in Figure 3.1. The increase in strength with rapid loading for the specimens under transverse compression was larger than for the specimens with no transverse compression applied.

As few tests were made in the test series no

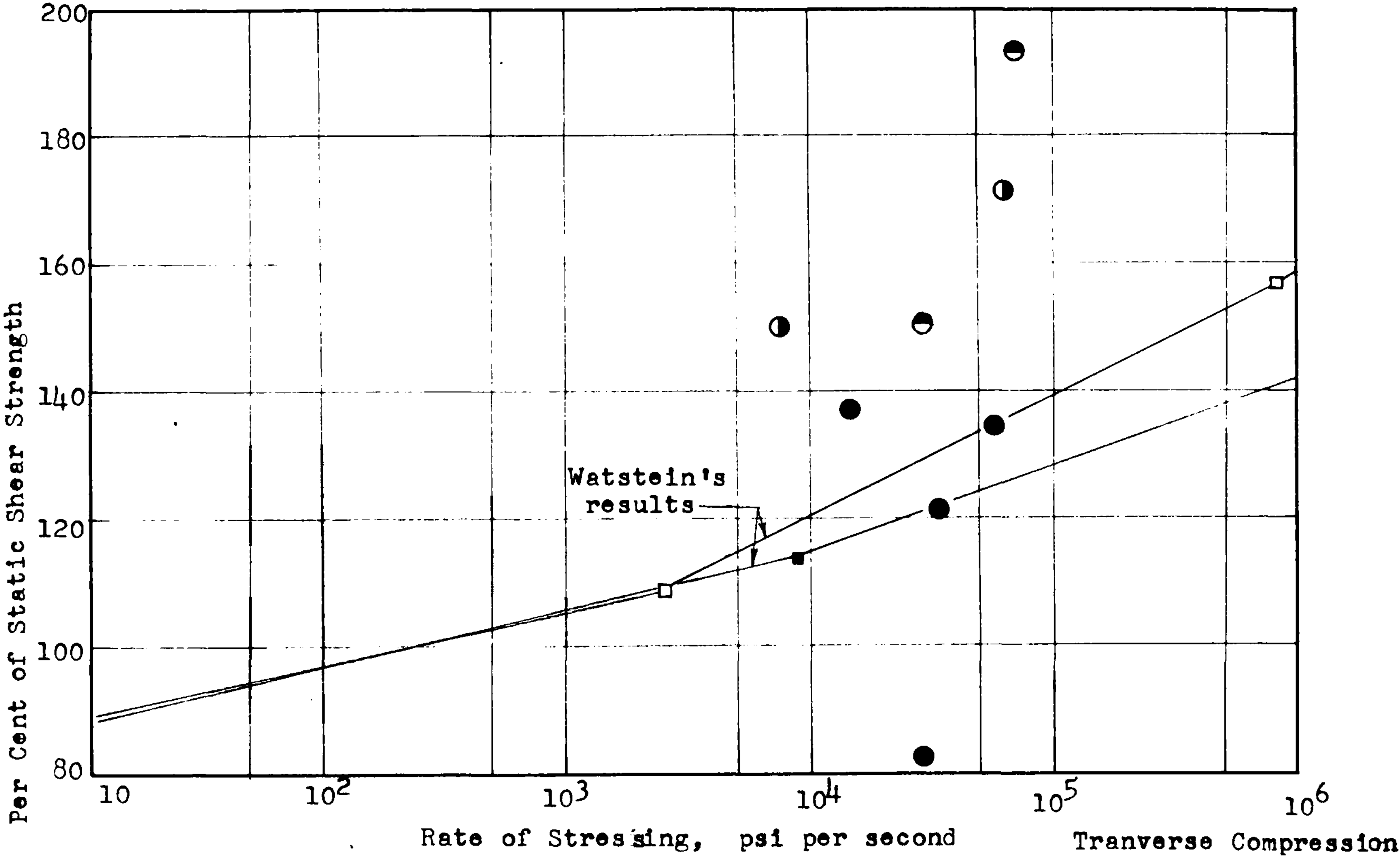

Fig. 3.1 - Effect of rate of stressing on the strength of plain concrete in pure shear, (Hansen et al. (31))

conclusions should be drawn as yet. It is expected, however, that concrete will show an increase in shear strength at high rates of loading. For a partial summary of results reported by Hansen, Nawy, and Shah, see Table VI in the Appendix.

CHAPTER 4 - EFFECT OF HIGH RATES OF LOADING ON THE TENSILE STRENGTH

4.1 Description of Investigations

Concrete is extensively used to resist flexural stresses. There is some data on the effect of high rates of loading on the flexural strength of concrete, but the experimental data is restricted to a rather narrow range of loading rates. Most of the data reported in this chapter are the results of investigations of the effect of methods of testing rather than investigations of the fundamental strength properties of concrete at high rates of loading. All tests involved flexure of plain concrete beams. This is not a serious difficulty, however, as the flexural strength (as computed using a straight-line stress distribution) has been shown to be closely related to the tensile strength (Moore (46)). Generally the flexural strength as defined by the modulus of rupture of plain concrete is between 1.5 and 2.0 times the tensile strength. It should be noted that the modulus of rupture is affected by a great number of variables such as the size of the specimen, aggregate characteristics, and the geometrical method of loading (e.g., third-point or central loading).

In 1927, Teller (61) presented data from a few tests showing an increase in the modulus of rupture with increased rate of loading. The rates of loading were not given but it is believed, from the description of the tests, that the rates varied from about 1.4 psi per second to 5.6 psi per second. An increase of eleven per cent in the modulus of rupture was noted over this range of loading rates. The results reported by Teller are presented in Table VII of the Appendix.

In 1933, Klettke, Webster, and White, working under the direction of Professor M. O. Withey, reported the results of a large number of tests of the effect of testing speed upon the modulus of rupture of plain concrete beams. At the time of writing the original has not been obtained by the writer and it has been necessary to use the data as reported by McHenry and Shideler (45). They showed a straight-line increase in modulus of rupture with increased loading rate on a plot of modulus of rupture versus the log of the loading rate. Both seven and twenty-eight day tests were reported. The percentage increase for the seven day tests was approximately twice the percentage increase for the twenty-eight day tests. The results are shown in Figure 4.1 and the numerical values are found in Table VIII of the Appendix. It should be noted that there

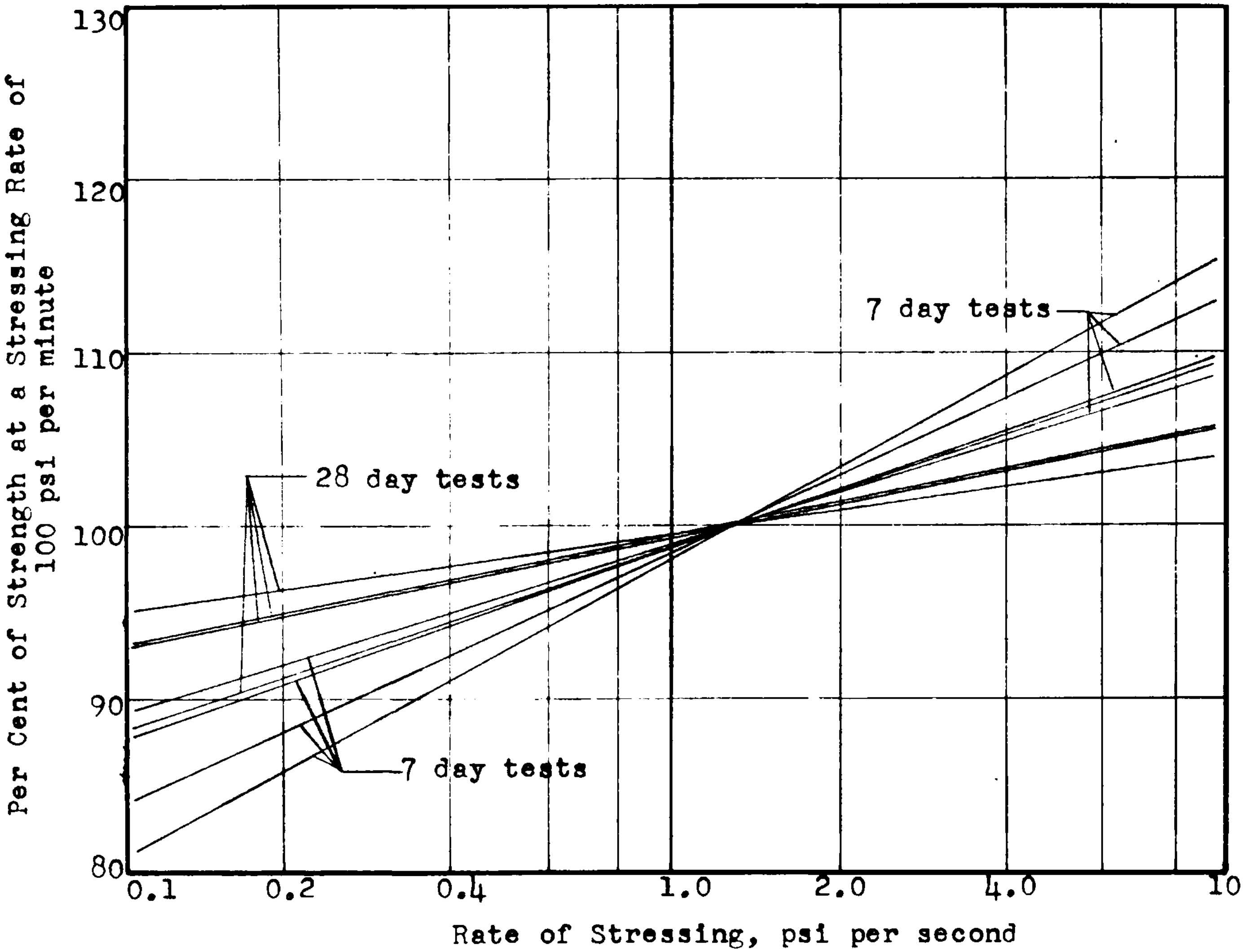

Fig. 4.1 - Effect of rate of stressing on the modulus of rupture of plain concrete beams, (Klettke, Webster, and White (41))

were other variables in this series of tests including the size, the span, and the age of the beam.

In 1943 Goldbeck (25) reported tests by the Illinois Division of Highways' Laboratory which showed an increase in the modulus of rupture from 500 psi to 600 psi when the loading rate was increased from 2.0 psi per second to 9.0 psi per second.

In 1952 Wright (71), as part of an extensive investigation of the effect of method of test on the flexural strength of concrete, investigated the effect of rate of application of the load on the modulus of rupture. The rate of increase of stress was varied between 0.33 psi per second and 19 psi per second. An increase of 15 per cent in the modulus of rupture was found over this range of loading rates. The results are shown in Figure 4.2. Wright concluded there was a linear relationship between the logarithm of the rate of loading and the modulus of rupture.

Fox (16), in 1958, applied trapezoidal load-time pulses to 18 inches by 2½ inches by 2½ inches plain concrete beams, using an approximate third-point loading. Failure occurred at various phases of the loading. Fourteen specimens failed in the increasing load phase of the loading cycle. The rate of loading of all the fourteen specimens was between 67,400 psi per second and 558,000 psi per second. All specimens

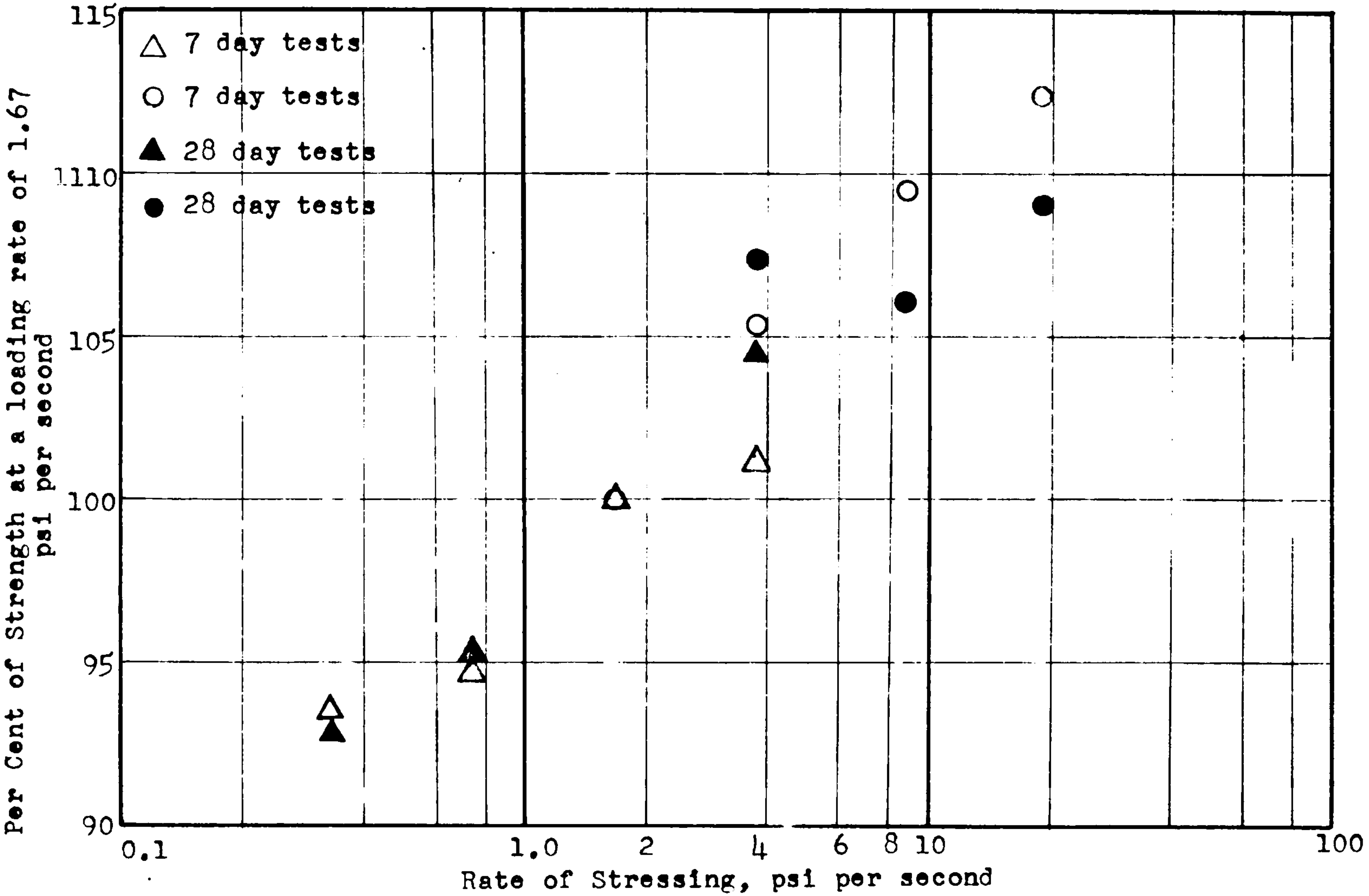

Fig. 4.2 - Effect of rate of stressing on the modulus of rupture of plain concrete beams, (Wright (71))

showed an increase in strength with reference to a static failure strength. The increase was not uniform, however, but ranged from 26 per cent to 90 per cent. The results of all 46 tests reported by Fox are found in Table IX of the Appendix. The results of the fourteen tests described above are shown in Figure 4.3.

Kesler reported (40) in 1953 the results of a series of tests made to investigate the effect of rate of loading on the fatigue resistance of concrete in flexure. Three loading speeds were used, 70 cpm, 230 cpm, and 400 cpm. The load-time cycle was sinusoidal. No significant difference was noted in the fatigue strength in the range of loading speeds investigated.

McHenry and Shideler (45) in 1955 briefly reviewed the work of Wright; of Klettke, Webster, and White; of the tests reported by Goldbeck; and of the fatigue tests reported by Kesler.

4.3 Comparison of Investigations

The results reported up to this time definitely indicate an increased strength in tension with increased rate of loading. Nevertheless, the results are scant in the higher ranges of loading rates. For this reason no useful comparison can be made between the results of the different investigators. It is hoped that work will be done in the future to supplement that which Fox

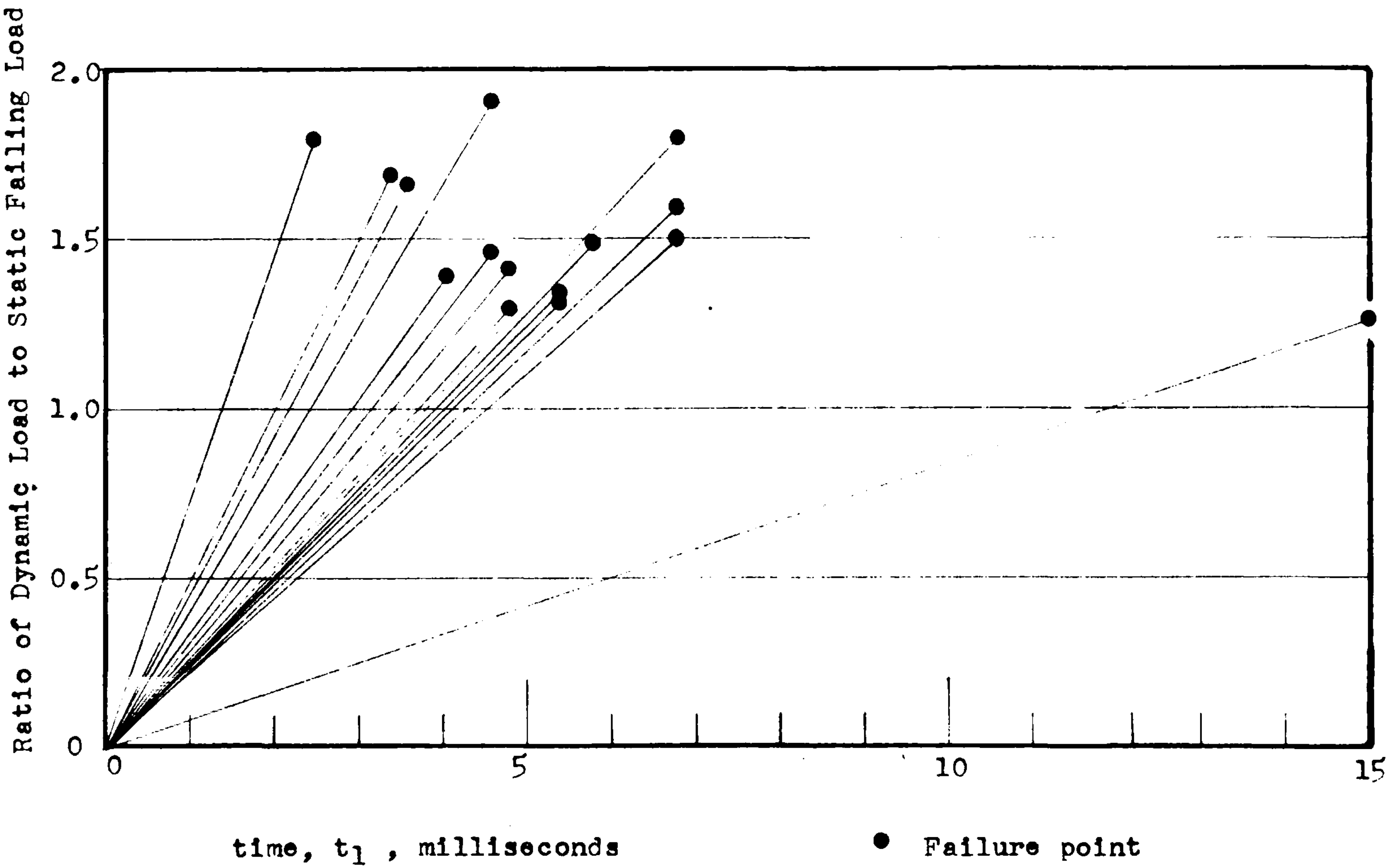

Figure 4.3 - Load-time curves for beams failing during initial application of load, (Fox (16))

started. As will be discussed in a later chapter, tensile strength characteristics are important.

CHAPTER 5 - COMPARISON WITH SIMILAR MATERIALS

5.1 Introduction

It is of interest to compare the effect of high rates of loading on concrete with the effect of high rates of loading on the strength of similar materials. In this chapter the effect of high straining rates on the strength of concrete will be compared with the effect of high straining rates on the strength of three rocks, a limestone, a sandstone, and a gabbro.

In the search for investigations of the effect of high rates of loadings on the strength of materials it was considered necessary that the investigated material be brittle. The failure process is believed by the writer to be the same in one brittle material as another. It was further desired that the investigations involve compression loading since concrete is most used in compression. There is little information available of the effect of straining rate on the strength of brittle materials in compression. The only investigation over a wide range of testing speeds that has been found is that by Serdengecti and Boozer (54).

Serdengecti and Boozer made tests on three different rocks, Pala gabbro, Solenhofen limestone, and

Berea sandstone. Triaxial compression tests were made over a range of straining rates from 10^{-5} inches per inch per second to one inch per inch per second. Temperature was also varied with tests made at temperatures of 78°F, 200°F, and 300°F. The data that was obtained not only provide a basis of comparison with the concrete compression tests described in Chapter 2 but also provide information on the nature of the increase in strength of a brittle material at high rates of loading.

5.2 Tests of Gabbro

Consider first the tests reported of gabbro. Gabbro is a coarse grained igneous rock. In all tests a brittle failure was observed with comparatively little strain prior to failure. The effect of temperature was found to be slight. Results were reported for confining pressures of atmospheric, 10,000 psi, and 20,000 psi. The results of the tests are tabulated in Table X in the Appendix. A plot of percentage increase in strength with increased straining rates for the three confining pressures is compared with the results obtained of concrete by Watstein. See Figure 5.1. Although the reference straining rate was not the same, good agreement is noted between the unconfined (atmospheric confining pressure) tests of gabbro and the results obtained by Watstein of concrete. The percentage increase in strength noted at

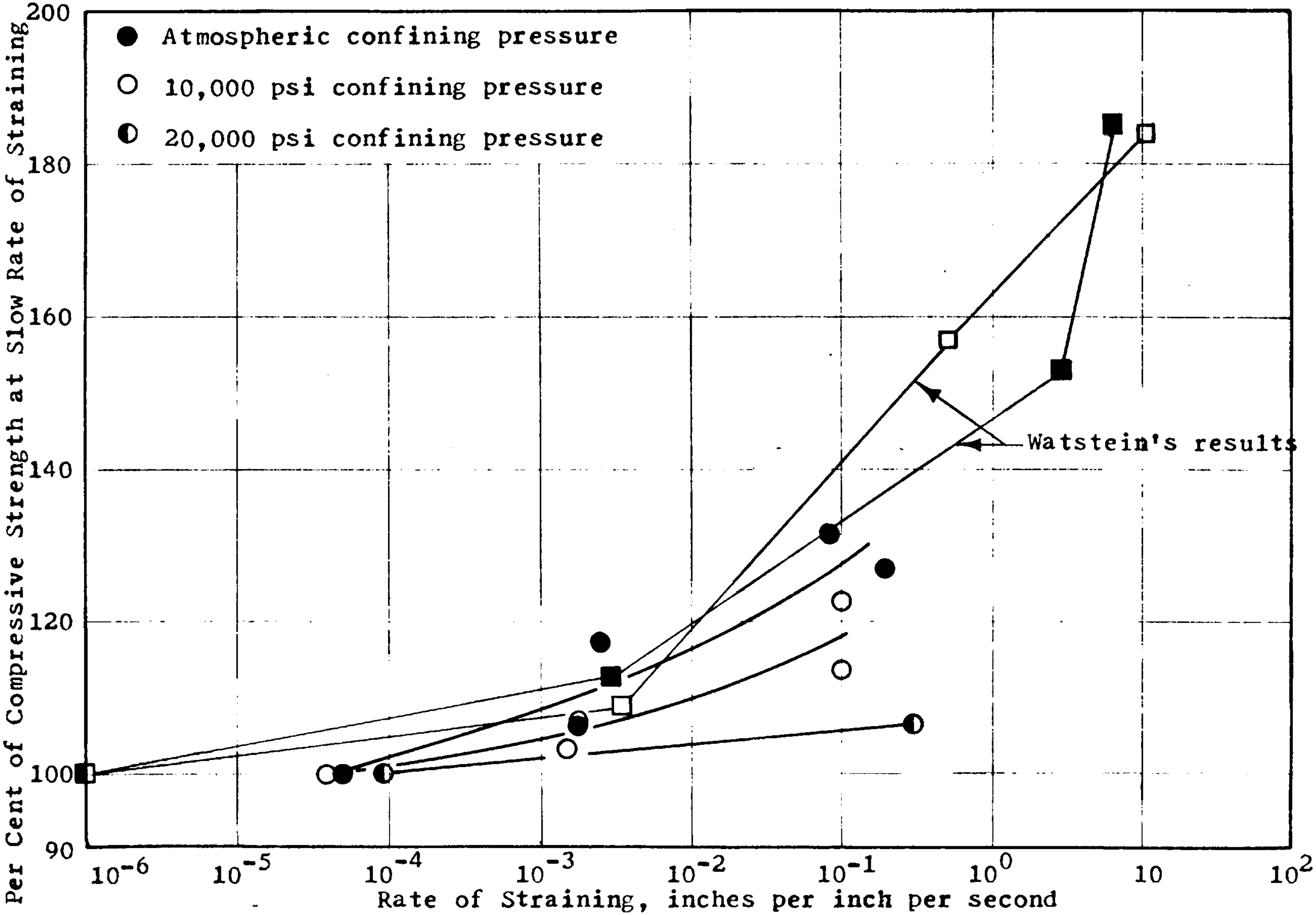

Fig. 5.1 - Effect of rate of straining on the compressive strength of Pala gabbro, (Serdengecti and Boozer (54))

a confining pressure of 10,000 psi is considerably less than that of the unconfined tests, and the percentage increase at 20,000 psi confining pressure is even less. These curves are somewhat misleading as one may see by examining the tabulation of the tests in Table X. The absolute increase in strength with increased straining rate is not significantly affected by the confining pressure and compared with the scatter of results the effect of different confining pressure is insignificant. In Figure 5.2 percentage increase in strength, using as reference the strength at the lowest straining rate in the unconfined series of compression tests, is compared with Watstein's results referred to an interpolated reference strength. The validity of this comparison rests on the assumption that the increase in strength at a high straining rate is independent of the magnitude of the confining pressure. This is found to be approximately true in the other tests reported for sandstone and limestone. These show a tendency towards a greater percentage increase with increased confining pressures. This will be discussed later in somewhat greater detail.

Involved in all comparisons made in this chapter is the additional assumption that the absolute increase in strength at different confining pressures is proportional to the unconfined compressive strength. It was

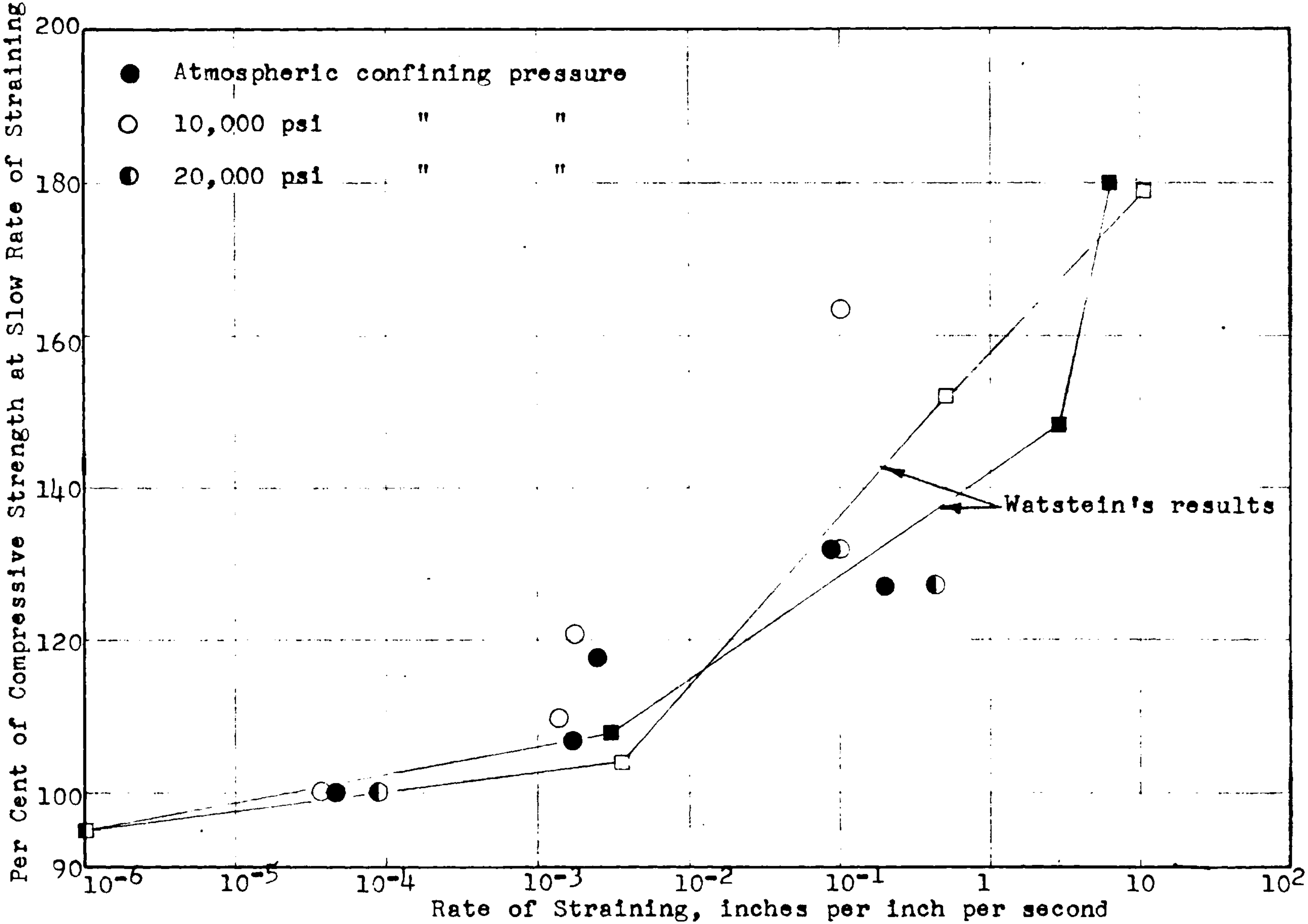

Fig. 5.2 - Effect of rate of straining on the compressive strength of Pala gabbro, (Serdengecti and Boozer (54))

noted in Chapter 2 that this was not found to be true for concrete at all rates of straining by either Watstein or Evans. As will be discussed in a later section, the absolute increase in strength is affected by the texture of the material as well as by the compressive strength.

5.3 Tests of Berea Sandstone

Serdengecti and Boozer also reported a series of tests at varying straining rates, temperatures, and confining pressures on Berea sandstone. Berea sandstone is composed of quartz grains cemented together with a clayey material. Failure was believed by Serdengecti and Boozer to be of two types, a failure of the clay cementing material or a fracture caused by contact of the individual grains. Brittle failures were observed in only two reported tests both at atmospheric confining pressure (See Table XI in the Appendix). At 10,000 psi confining pressure both ductile and transitional failures were observed. A transitional failure is characterized by an abrupt decrease in load resistance followed by a flow behavior. (For a pictorial representation of brittle, transitional, and ductile failures observed by Serdengecti and Boozer see Figure 5.3.) The flow resistance is attributed to friction between the broken segments of the specimen. At 20,000 psi confining

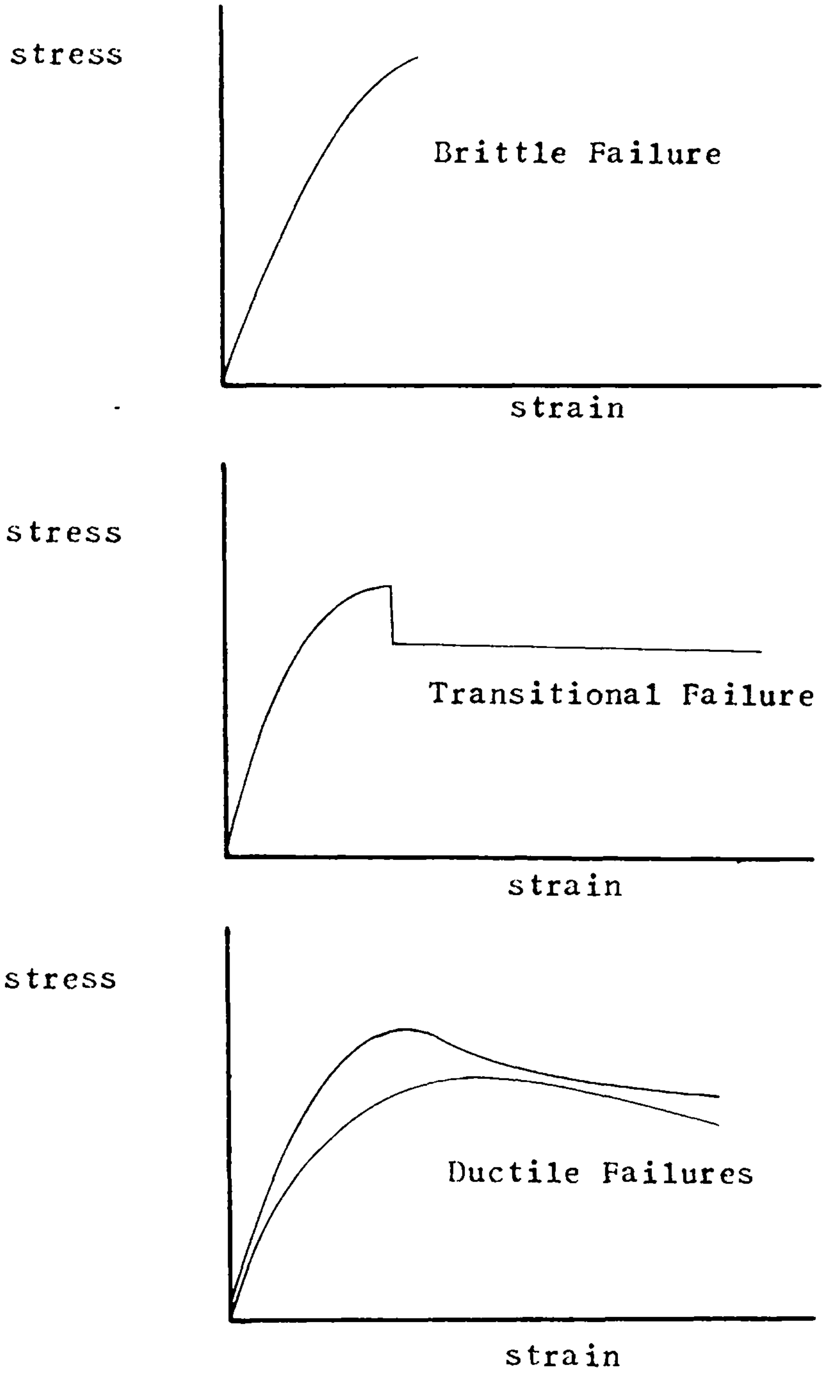

Fig. 5.3 - Pictorial representation of brittle, ductile, and transitional failures

pressure only ductile failures were observed.

The percentage increase in strength referred to the strength at the lowest rate of straining at atmospheric pressure is compared in Figure 5.4 with Watstein's results obtained for concrete. Considerable variation in results was found. In particular the results at a confining pressure of 20,000 psi are misleading. The absolute increase in strength used to compute the percentage increase is probably high. Table XI shows the absolute increase in strength at varying straining rates and temperatures. The results at a confining pressure of 20,000 psi are too inconsistent to justify a valid comparison. The inconsistency is believed to be due to the complex nature of the ductile failure. If the four "high" values are rejected the agreement with Watstein's results is good. However, because of the scatter of the results no conclusion is justified from the comparison.

5.4 Tests of Solenhofen Limestone

The most extensive series of tests reported by Serdengecti and Boozer were of Solenhofen limestone, a very fine grained strong limestone. Tests were made at confining pressures of 5000 psi, 10,000 psi, 15,000 psi, and 20,000 psi over a straining rate range from 2 x 10^{-5} inches per inch per second to 0.87 inches per inch per

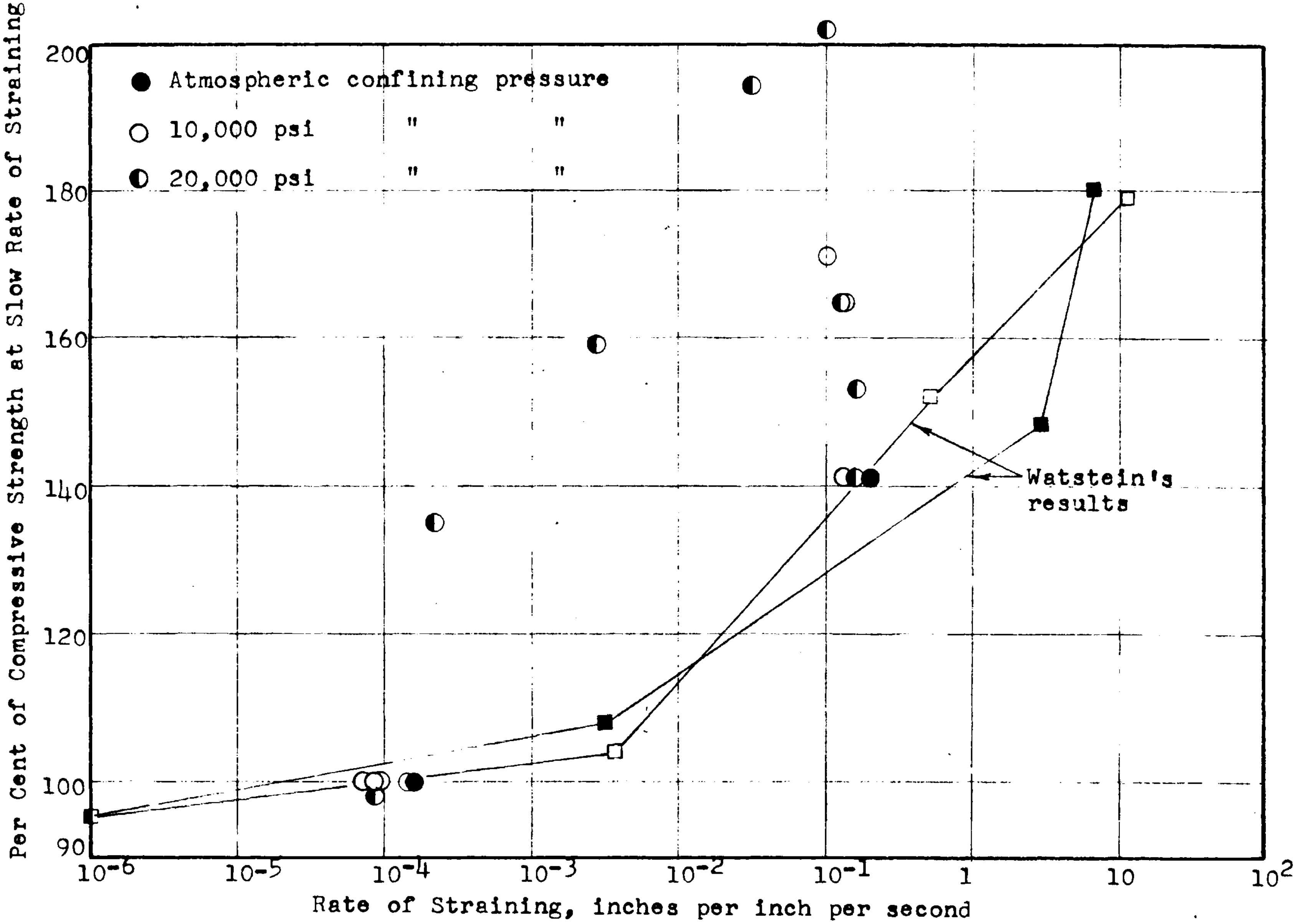

Fig. 5.4 - Effect of rate of straining on the compressive strength of Berea sandstone, (Serdengecti and Boozer (54))

second. The failure was brittle in all cases at 5000 psi confining pressure and ductile at all other confining pressures although a ductility bordering on the transitional type of failure was observed at the higher rates of straining at the other confining pressures. The absolute increase in strength with increasing rate of straining is tabulated in Table XII in the Appendix. A comparison similar to that described in the last section is shown in Figure 5.5. The strength was only a little affected by confining pressure. The absolute increase in strength tended to be greater for the higher confining pressures than for the lower confining pressures, at the high rates of straining.

The comparison with Watstein's results in Figure 5.5 shows a very slight increase in strength with increased straining rate, much less than that indicated for concrete by Watstein. The increase is reasonably consistent except for the results at 20,000 psi confining pressure.

5.5 Reasons for the Observed Differences

In the previous section it was seen that the effect of high rates of straining on the strength of Pala gabbro was approximately the same as the effect observed by Watstein on concrete. It was seen that the

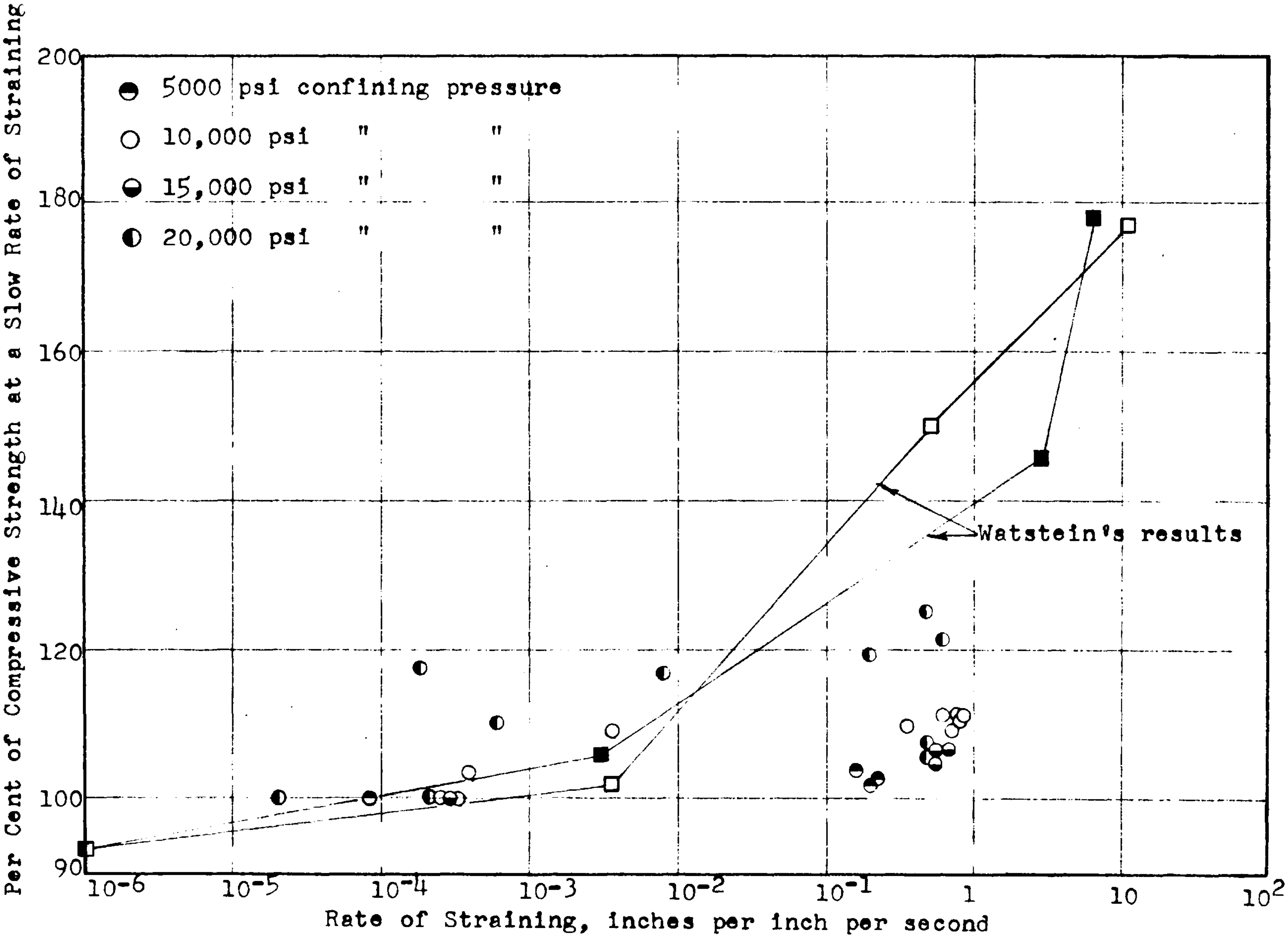

Fig. 5.5 - Effect of rate of straining on the compressive strength of Solenhofen limestone, (Serdengecti and Boozer (54))

effect of high straining rate on the strength of Solenhofen limestone was much less than the effect observed by Watstein on concrete. There are many influencing factors which affect the relative increase in strength. The factors thought to be of consequence will be discussed in this section.

The assumptions enabling a comparison to be made between rocks and concrete must first be stated. In section 5.2 it was assumed, first, that the absolute increase in strength of a given material at a given rate of straining in reference to a strength at a lower rate of straining is independent of the confining pressure, and second, that the <u>absolute</u> increase in strength at a given rate of straining is proportional to an intrinsic strength of a material. Neither assumption is valid under all conditions of loading. Within the ranges of loading conditions described in this paper, the assumptions are thought to be reasonably valid.

Consider the first assumption, that the absolute increase in strength is independent of the confining pressure. This would be true if the material were homogeneous, elastic, and if failure were dependent only upon the magnitude of the difference between the maximum and the minimum principal stresses (the so-called maximum shear stress theory of failure). In the tests reported the materials were neither homogeneous nor perfectly elastic. At large triaxial pressures there are two possible behaviors. The harder portions (in weak concrete, the aggregate) may be pushed together and cause fracture by contact of grains. On the other hand, high pressures may actually "close" cracks and, in effect, cause them to become critical factors in the failure process at a higher level of the differential stress.

The first behavior, fracture originating from contact of grains, would be expected of materials in which the constituents are considerably different in elastic properties, e.g., sandstone or concretes made with hard aggregates. According to the first hypothesis the maximum differential stress would be smaller at high triaxial confining pressures, other effects being the same.

Now consider the effect of high rate of straining on the behavior described in the above paragraph. If a material is elastic this behavior is independent of the straining rate, being primarily dependent upon the magnitude of the strain produced. If the material exhibits substantial creep effects, however, a high straining rate would tend to cause a higher maximum differential stress than at a lower straining rate. The rocks tested showed little creep within the ranges of straining rate involved in the investigations. Thus straining rate would not influence the magnitude of the differential stress at failure as a result of fracturing by contact of grains.

The second behavior, closing of cracks, would be expected of materials with relatively large cracks, or flaws. If flaw size is related to grain size, materials with large grains would show a higher maximum differential stress at high triaxial confining pressures than at low pressures. It is known that flaw size is related to the fracture strength, large-grained materials exhibiting lower strengths than smaller-grained materials (Brace (7)).

The effect of high straining rate on failure by crack propagation would be to decrease the time available for the propagation to failure thus increasing the maximum differential stress at fracture. If the material is large-grained the increase in strength would be greater than for a small-grained material since large cracks would be easier to close. Large cracks are capable of propagation at a lower stress level and thus, in an increasing loading situation, would have more time in which to fail.

Now consider the second assumption, that the absolute increase in strength is proportional to an intrinsic strength of a material. The work required to fracture a material is dependent on two factors, the energy stored as strain energy and the energy required to produce new surfaces. If a material exhibits little ductility (the usual definition of a brittle material) it is expected that the greater part of the energy required for fracture is proportional to the surface energy of the material. The surface energy of a material, in turn, is proportional to the tensile strength but is greatly affected by the size of the flaws existing in the material. Thus two different materials of different surface energies (or tensile strengths) having the same sizes of flaws (again, thought to be proportional to grain size) are expected to show the same percentage increase in strength with rapid straining rates.

Baker and Preston (2) reported a series of tests in tension on glass-like brittle rods in which the breaking stress was found as a function of duration of load. The percentage increase in strength at short durations of load referred to the strength at a duration of load of 1000 seconds was reasonably uniform from one material to another and appeared to be independent of the reference strength. The percentage increase in strength is plotted against the logarithm of the duration of the load in Figure 5.6. The results obtained by Baker and Preston are listed in Table XIII in the Appendix.

If these hypotheses are true, gabbro would be expected to show the same percentage increase in strength at high rates of straining as concrete since the two materials are both coarse grained. Limestone would be expected to show a lesser percentage increase in strength than concrete because it is much finer grained. Similarly mortars would be expected to show a lesser increase in strength at high rates of straining than would concrete made with large aggregate. Experiments reported in Chapter 2 tend to show this to be true.

In this paper the unconfined compression test has been used as the measure of the intrinsic strength. A more proper, but in the case of concrete impractical, intrinsic strength is the tensile strength of a material, especially if failure is thought to be the result of crack growth. Since the compressive strength of a material is theoretically eight times the tensile strength (Griffith (28), also Poncelet (52)), the percentage increase in strength referred to the compressive strength would differ only by a constant factor.

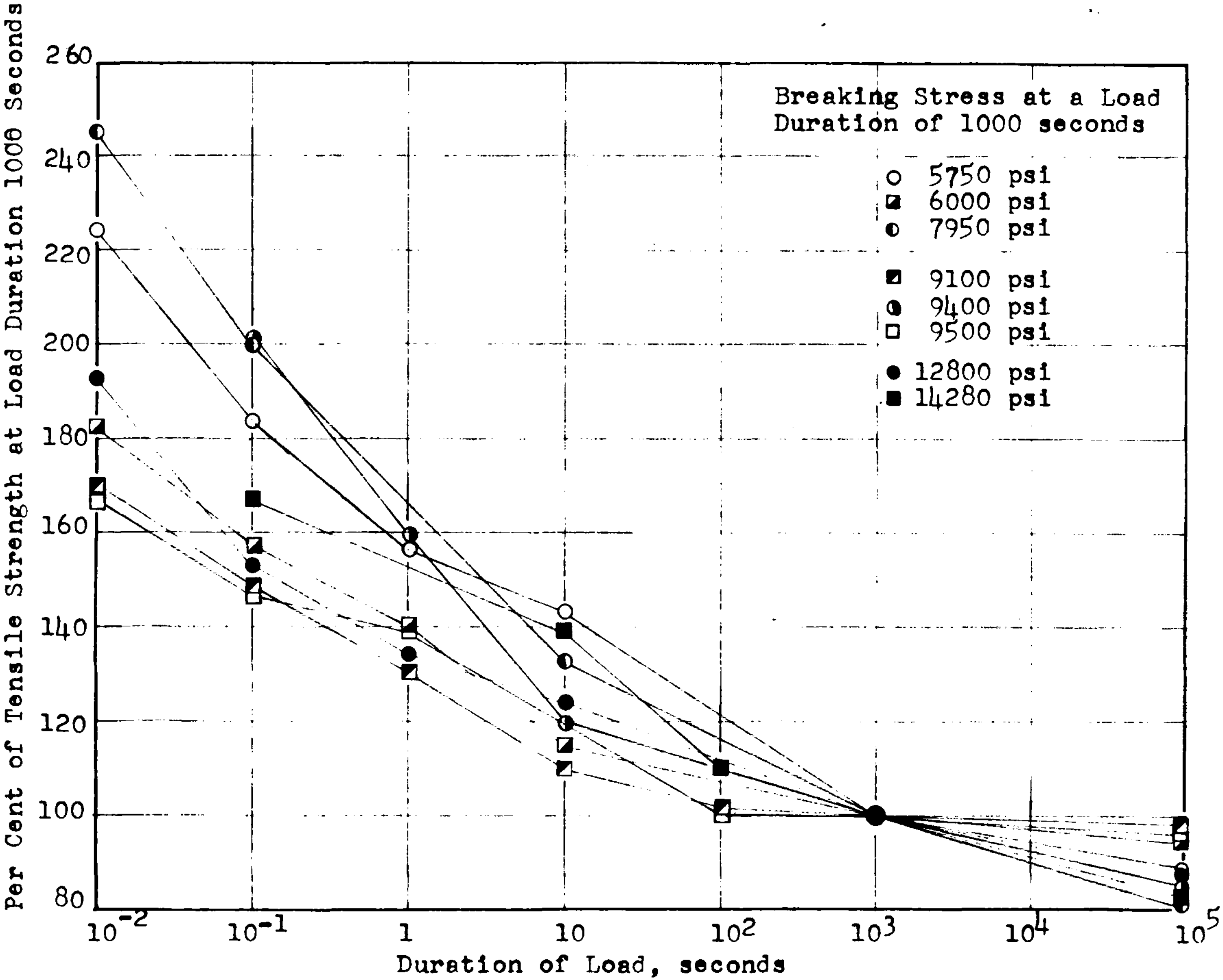

Fig. 5.6 - Effect of duration of load on the strength of glass-like brittle rods, (Baker and Preston (2))

It is regretted that the above discussion must be qualitative in nature rather than quantitative. There is much to be learned before an accurate prediction of the increase in strength at high rates of loading can be made. The most important characteristics necessary to implement the above hypotheses are the surface energy, modulus of elasticity, amount of creep at high rates of loading, and the critical flaw size.

5.6 Other Tests

Hollomon and Zener (33, 72, 73) have proposed for metals a "principal of equivalence" relating straining rate and temperature effects by a single parameter, p, of the form

$$p = \mathring{\epsilon} e^{Q/RT}$$

where $\mathring{\epsilon}$ is the straining rate, e is the natural base of logarithms, Q is a heat of activation, R is the gas constant, and T is the temperature. Further, the stress at failure, S, varies with the parameter p in an exponential relationship of the form

$$S \approx p^r$$

where r is some small number. This theory results in a straight line on a plot of stress at fracture versus the log of the rate of stressing. Such a relationship has not been shown to be true for concrete at very high rates of straining.

In connection wihh the work of Baker and Preston described in the last section, Taylor (60) has proposed a theory which relates time at load, t, to the temperature and constants of the material. He recommends the use of E/S versus logarithm of t plots ("S" for concrete would be the ultimate stress, usually denoted by f'_c), and obtained straight lines on such a plot for the data on glass obtained by Baker and Preston. Glathart and Preston (24) plotted the same results of Baker and Preston on a 1/S plot, and obtained straight lines which were, it was concluded, merely good approximations of the results.

CHAPTER 6 - SUMMARY AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 Summary

A comprehensive review of the literature on the effect of high rates of loading on concrete leads to the following conclusions. These conclusions should be accepted with a realization that only limited research has actually been carried out. In many cases the conclusion which is stated should be regarded only as a trend which undoubtedly will be modified upon completion of future research.

(1) A number of investigators have shown that at high rates of loading the compressive ultimate strength of concrete is greater than the ultimate strength at slow rates of loading. In some investigations the increase in strength was substantial, ranging as high as 85 per cent at a loading rate of 5×10^7 psi per second. In others the increase was slight. The different investigations have been difficult to correlate because of the differences in specimen type and in methods of testing.

(2) The increase in compressive strength with increased rate of loading is dependent, in part,

upon the strength of the concrete. The work of Evans and of Watstein indicate that a weaker concrete shows a greater percentage increase in strength at a high rate of loading than does a stronger concrete.

(3) The hypothesis that the increase in strength with high rate of loading is in part a constant value dependent upon limiting cracking velocity, inertia forces, and specimen configuration; and in part a variable value dependent upon the strength and nature of the cement bond appears to be valid.

(4) Previous loading history affects the failure strength under dynamic compressive loads. The concept of cumulative damage often used in fatigue analysis appears applicable.

(5) There is insufficient evidence to draw conclusions about the dynamic shear strength of concrete. There is, however, no reason to expect other than an increase in strength similar to the increase shown by concrete tested in compression.

(6) The dynamic tensile strength of concrete is definitely higher than the static tensile strength. Data is scant at the higher rates of loading.

(7) The dynamic compressive strength of brittle cement materials (concrete, gabbro, limestone,

sandstone) is dependent upon the grain size and structure. It is hypothesized that if a material is large-grained, a greater percentage increase in strength at high rates of loading will be observed than for a small-grained material. The difference in the increase is related to the relative size of flaws and the speed of crack propagation. Quantitative data is not available.

(8) Cube specimens tend to show little increase in strength with increasing rate of loading at the lower rates of stressing but show a substantial increase in strength at the higher rates of stressing. This is due in part to the restrained nature of the failure and in part to the grain structure of the small cubes tested.

(9) A comparison of investigations of the strength of rock at high rates of loading with similar investigations of concrete showed that a coarse-grained rock such as gabbro exhibited approximately the same percentage increase in strength with increased rate of straining as did concrete. Fine-grained rock exhibited a lesser percentage increase in strength at high rates of loading than did concrete.

6.2 Recommendations for Future Research

Nearly all the investigations described in this thesis involved loading to failure. The strength of concrete in an increasing loading situation is important to know but it is even more important to know the stress level that can be resisted for short durations of loading. There is an important distinction to be made between ductile metallic materials which retain a strength increase resulting from a high rate of stressing, and brittle materials such as concrete which in all probability cannot retain the apparent increase in strength resulting from a high rate of stressing. Tests should be made to investigate the ability of concrete to resist high stress levels for short durations of load. This is not a new recommendation. As early as 1932 Fox (17) suggested work should be done in this area. It seems long overdue.

The investigations of the strength in flexure at high rates of stressing is confined to the work of Green (27). A test program investigating the flexural strength of plain concrete at high rates of loading is needed.

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APPENDIX

Table I

Effect of Rate of Straining on the Compressive Strength of 6 in. x 12 in. Cylinders, (Abrams (1))

Rate of straining	Compressive strength		
per cent per sec*	1:9 mix psi	1:5 mix psi	1:3 mix psi
8.34×10^{-4}	800**	1740	2840
1.39×10^{-3}	800	1790	2910
2.08×10^{-3}	820	1870	3140
4.87×10^{-3}	800	1950	3210
5.56×10^{-3}	850	1920	3260
8.34×10^{-3}	840	1980	3320
2.08×10^{-2}	850	1970	3400

* Abrams recorded straining rate in inches per minute

** Each value is an average of 6 tests

Table II

Effect of Loading Rate on the Compressive Strength of 2 in. Cubes

Results Obtained by Committee C-1 (46)

Age of Cube	Loading Rate	Compressive Strength (2 in. cubes, Ottawa sand)				
	psi per minute	Cement No. 2 psi	Cement No. 6 psi	Cement No. 8 psi	Cement No. 9 psi	Cement No. 23806** psi
3 days	1000	1120*	1100	2600	2510	1060
	3000	1080	1070	2600	2500	1080
	6000	1120	1120	2860	2400	1040
7 days	1000	2120	2170	3620	3810	1800
	3000	2200	2190	3870	3700	1870
	6000	2180	2260	3840	3700	1900
28 days	1000					2910
	3000					2950
	6000					2990

* Each value is an average of 6 to 9 cubes **A normal Portland cement

Table III

Effect of Rate of Load Application on the Compressive Strength of 8 in. x 16 in. Cylinders, (Bureau of Recl. (78))

Rate of loading psi per second	Number of cylinders	Strength psi	Per Cent of standard*
5.0	14	3670	106
10.0	19	3880	112
14.9	24	3840	111
29.8	24	3840	111
39.8	14	3840	111
59.7	11	3980	115
99.5	11	4050	117

* Standard strength at a slow rate of testing was 3460 psi.

Table IV

Effect of Rate of Load Application on the Compressive Strength of 6 in. x 12 in. Cylinders, (Bureau of Reclamation (78))

Rate of loading psi per second	Number of cylinders	Strength psi	Per cent of standard*	Age at test
3.5	6	2610	104	7 days
8.8	12	2690	107	"
17.7	23	2690	107	"
17.7	9	2610	104	"
26.6	12	2740	109	"
35.4	12	2690	107	"
70.8	12	2760	110	"
3.5	23	3720	105	28 days
8.8	27	3860	109	"
17.7	38	3860	109	"
17.7	6	3930	111	"
26.6	16	3930	111	"
35.4	27	3930	111	"
70.8	22	3970	112	"

* Standard strength for the 7 day tests was 2510 psi; for the 28 day tests was 3540 psi.

Table V

Effect of Rate of Straining on the Compressive Strength of 10 centimeter cubes, (Gaede (20))

Speed of loading kg/cm^2/sec	Strength kg/cm^2		Speed of loading kg/cm^2/sec	Strength kg/cm^2
2.33	306		40.5	324
2.23	346		42.5	319
2.40	317		36.2	308
2.47	321		37.6	301
2.50	333		43.0	344
2.50	325		39.7	357
2.47	316		42.3	338
2.53	331		41.6	312
2.48	300		40.5	344
2.44	322	Average	40.4	327

Table VI

Effect of Rate of Loading on the Strength of Concrete in Pure Shear, (Hansen, Nawy, and Shah (31, 48))

Transverse compression psi	Shear strength psi	Time to failure millisec.	Rate of stressing psi per second	Per cent of strength at slow rate of loading*
None	1160	40	29,000	82
None	1290	30	43,000	121
None	1440	25	57,600	134
None	1510	100	15,100	137
150	1500	200	7490	136
150	1870	30	62,300	171
300	2070	30	69,000	193
300	2090	70	29,800	152

* The reference shear strength is the average of two tests at a slow rate of loading (time to failure about 10 to 15 minutes).

Table VII

Effect of Rate of Loading on the Modulus of Rupture of 6 in. x 6 in. Beams, (Teller (61))

Rate of stressing psi per second*	Rate of loading pounds per minute	Number of tests	Average modulus of rupture psi
1.39	50	6	426
2.78	100	6	436
5.56	200	6	474

* 60 inch moment arm assumed for the loading apparatus by the writer.

Table VIII

Effect of Rate of Loading on the Modulus of Rupture of Concrete, (Klettke, et al., (41)

Rate of stressing psi per minute	Modulus of rupture psi	Age	Per cent of strength at a stressing rate of 100 psi per minute
6	630*	28 days	93
500	710	"	105
6	670	"	93
500	755	"	105
6	700	"	95
500	765	"	104
6	700	"	88
500	860	"	109
6	455	7 days	81
500	640	"	114
6	500	"	88
500	620	"	109
6	545	"	89
500	660	"	108
6	545	"	84
500	725	"	112

* These values are obtained from the graphical representation of the results by McHenry and Shideler (45).

Table IX

Results of Pulse Tests on Plain Concrete

Beams, 18 in. x 2½ in. x 2½ in., (Fox (16))

Beam No.	Damage	W_1/W_s*	W_3/W_s	W_M/W_s	W_m/W_s	t_1	t_2	t_3
						milliseconds		
2	Unbroken	1.35	1.19	1.41	1.23	2.3	16.0	3.0
2	Broken	1.68	----	1.68	----	3.4	0	3.4
3	Broken	1.79	-----	1.79	----	2.5	0	3.5
4	Unbroken	1.44	1.38	1.64	1.31	2.3	16.8	3.4
4	Unbroken	1.34	1.20	1.37	1.27	2.0	15.8	3.1
5	Unbroken	1.29	1.27	1.36	1.27	3.3	23.0	4.0
5	Broken	1.51	1.51	1.56	1.42	3.7	3.6	4.0
8	Unbroken	1.28	1.26	1.46	1.22	5.6	68.4	13.8
8	Broken	1.79	----	1.79	----	6.8	0	3.8
9	Broken	1.46	1.48	1.54	1.41	7.0	46.6	3.2
10	Unbroken	1.58	1.57	1.67	1.52	2.2	12.6	3.0
10	Broken	1.59	----	1.59	----	6.8	0	3.8
32	Broken	1.27	1.25	1.28	1.24	15	34	5
33	Broken	1.26	----	1.26	----	15	0	8
34	Broken	1.28	1.22	1.28	1.24	14	24	5
35	Broken	1.27	1.25	1.27	1.25	15	7	6
38	Broken	1.90	----	1.90	----	4.6	0	4.8
39	Unbroken	1.33	1.34	1.59	1.25	4.0	68.2	12.0

* For key to symbols used in this table see last sheet

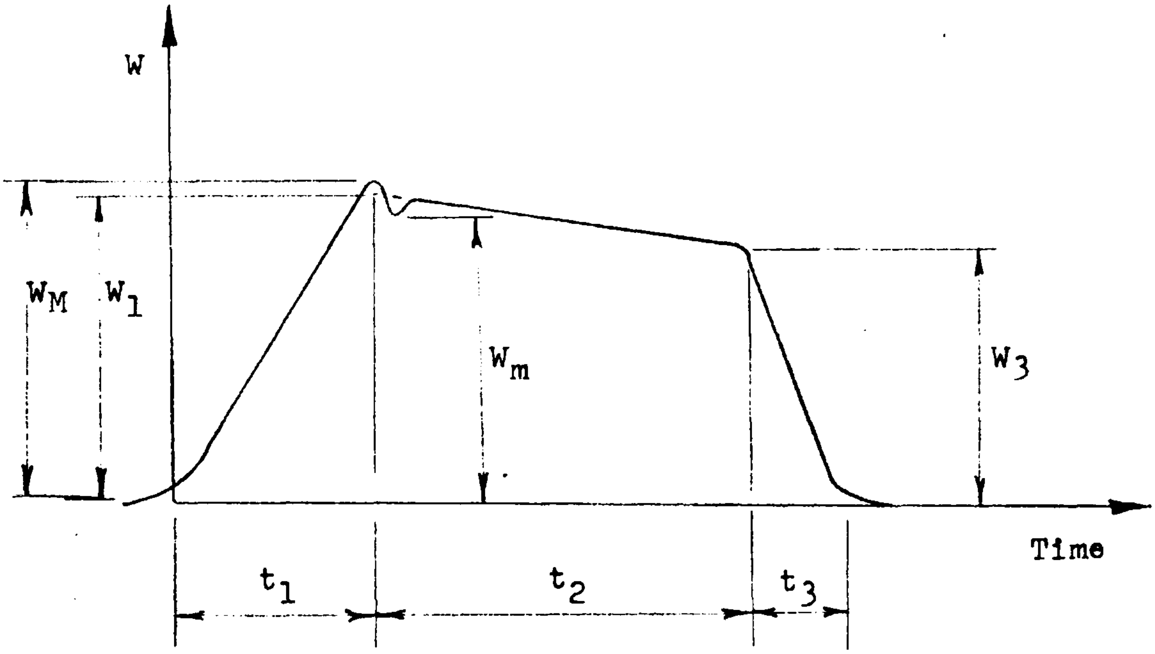
Table IX (continued)

Beam No.	Damage	W_1/W_s	W_3/W_s	W_M/W_s	W_m/W_s	t_1	t_2	t_3
						milliseconds		
39	Broken	1.66	----	1.66	----	3.6	0	4.0
40	Broken	1.67	1.41	1.81	1.49	4.6	11.6	4.6
44	Broken	1.39	1.39	1.42	1.32	4.0	32.4	4.2
45	Unbroken	1.50	1.47	1.56	1.48	5.2	21.4	9.4
45	Broken	1.42	----	1.42	----	4.8	0	5.2
46	Broken	1.35	1.21	1.36	1.26	4.0	4.6	3.6
51	Broken	1.45	----	1.45	----	5.8	0	3.8
52	Broken	1.49	----	1.49	----	5.8	0	3.8
53	Broken	1.40	1.23	1.46	1.28	4.6	9.6	3.6
68	Broken	1.30	1.35	1.34	1.30	12	82	4
69	Broken	1.12	1.15	1.15	1.10	15	70	4
71	Broken	1.09	1.15	1.09	1.06	15	104	4
75	Broken	1.38	1.22	1.47	1.21	4.6	5.0	3.6
77	Broken	1.39	----	1.39	----	4.2	0	4.8
78	Broken	1.22	1.23	1.32	1.16	4.2	35.6	3.8
80	Broken	1.31	----	1.31	----	5.4	0	3.8
81	Broken	1.23	1.23	1.29	1.17	4.2	5.2	3.9
82	Broken	1.22	1.22	1.27	1.17	4.2	14.7	3.2
83	Broken	1.29	----	1.29	----	4.8	0	4.5
98	Broken	1.50	----	1.50	----	6.8	0	5.2
99	Broken	1.46	----	1.46	----	4.6	0	4.6
100	Broken	1.35	1.29	1.44	1.23	4.2	4.6	3.8

Table IX (continued)

Beam No.	Damage	W_1/W_s	W_3/W_s	W_M/W_s	W_m/W_s	t_1	t_2	t_3
						milliseconds		
101	Broken	1.29	1.24	1.36	1.20	4.4	4.6	3,8
110	Unbroken	1.27	1.27	1.36	1.16	4.8	19.0	3.8
110	Broken	1.29	1.29	1.31	1.25	4.3	5.5	4.7
111	Unbroken	1.28	1.28	1.30	1.20	3.5	19.4	3.6
113	Unbroken	1.27	1.27	1.35	1.17	3.4	18.9	3.3
113	Broken	1.34	----	1.34	----	5.4	0	5.8

Note: W_s is the static load that failed control beams.



Key to Symbols Used in Table IX

Table X

Effect of Rate of Straining on the Strength of Pala Gabbro, (Serdengecti and Boozer (54))

Test No.	Confining pressure	Temperature	Failure type	Rate of straining	Differential stress	Increase
	psi	°F		seconds^{-1}	ksi	ksi*
437	Atm	78	Brittle	$4.8x10^{-5}$	31.5	0
438	"	"	"	$1.7x10^{-3}$	33.5	2.0
439	"	"	"	$2.4x10^{-3}$	37	5.5
442	"	"	"	$8.5x10^{-2}$	41.5	10.0
448	"	"	"	$2.0x10^{-1}$	40	8.5
452	10,000	"	"	$3.8x10^{-5}$	94.5	0
455	"	"	"	$1.4x10^{-3}$	97.5	3.0
454	"	"	"	$1.7x10^{-3}$	101	6.5
457	"	"	"	$1.0x10^{-1}$	107.5	13.0
458	"	"	"	$1.0x10^{-1}$	114.5	20.0
428	20,000	"	"	$9.1x10^{-5}$	137.5	0
417	"	"	"	$4.1x10^{-1}$	146	8.5

* The increase in stress is in reference to the lowest rate of straining at each confining pressure.

Note: The specimens were ½ inch in diameter and 1 inch long.

Table XI

Effect of Rate of Straining on the Strength of Berea Sandstone, (Serdengecti and Boozer (54))

Test No.	Confining pressure	Temperature	Failure type**	Rate of straining	Differential stress	Increase*
	psi	°F		seconds^{-1}	ksi	ksi
181	Atm	78	Brittle	1.3×10^{-4}	8.5	0
195	"	"	"	2.0×10^{-1}	12.0	3.5
222	10,000	78	Tran.	1.4×10^{-4}	36	0
174	"	"	"	1.0×10^{-1}	42	6.0
679	"	200	Ductile	7.0×10^{-5}	37	0
551	"	"	Tran.	1.2×10^{-1}	42.5	5.5
554	"	300	Ductile	8.6×10^{-5}	38.5	0
555	"	"	"	8.6×10^{-5}	38.5	0
552	"	"	Tran.	1.3×10^{-1}	42	3.5
665	20,000	78	Ductile	7.7×10^{-5}	44	-1.0
178	"	"	"	2.2×10^{-4}	48	3.0
146	"	"	"	2.8×10^{-3}	50	5.0
165	"	"	"	3.2×10^{-2}	53	8.0
166	"	"	Tran.	1.0×10^{-1}	55	10.0
662	"	"	"	1.2×10^{-1}	50.5	5.5
666	"	200	Ductile	8.0×10^{-5}	44.5	0
670	"	"	"	1.6×10^{-1}	49	4.5
667	"	300	"	9.7×10^{-5}	45	0
664	"	"	"	1.6×10^{-1}	48.5	3.5

* in reference to the lowest rate of straining at each temperature at each confining pressure

**For representation of failures see Figure 5.5.

Table XII

Effect of Rate of Straining on the Strength of Solenhofen Limestone, (Serdengecti and Boozer (54))

Test No.	Confining pressure	Temperature	Failure type**	Rate of straining	Differential stress	Increase*
	psi	°F		seconds^{-1}	ksi	ksi
639	5000	78	Brittle	8.6×10^{-5}	54	0
643	"	78	"	.15	56	2.0
640	"	200	"	8.4×10^{-5}	52	0
644	"	200	"	.22	53.5	1.5
641	"	300	"	8.9×10^{-5}	51	0
645	"	300	"	.20	52	1.0
371	10,000	78	Ductile	3.0×10^{-4}	55	0
587	"	78	"	3.7×10^{-4}	57	2.0
375	"	78	"	3.4×10^{-3}	60	5.0
383	"	78	"	.34	60.3	5.3
592	"	78	"	.61	61	6.0
387	"	78	"	.87	61	6.0
608	"	200	"	2.5×10^{-4}	55	0
609	"	200	"	.85	59	4.0
589	"	300	"	3.8×10^{-4}	52	0
594	"	300	"	.76	57	5.0
593	"	300	"	.80	56.5	4.5
652	15,000	78	"	2.6×10^{-4}	62	0
647	"	78	"	.52	65.5	3.5

(continued next sheet)

Table XII (continued)

Test No.	Confining pressure	Temperature	Failure type	Rate of straining	Differential stress	Increase
	psi	°F		seconds^{-1}	ksi	ksi
649	15,000	200	Ductile	3.4×10^{-4}	60	0
646	"	200	"	.53	62.5	2.5
651	"	300	"	2.8×10^{-4}	57	0
648	"	300	"	.65	60.5	3.5
522	20,000	78	"	2.0×10^{-5}	57.5	0
628	"	78	"	1.9×10^{-4}	67	9.5
390	"	78	"	6.0×10^{-4}	63	5.5
392	"	78	"	8.0×10^{-3}	66.5	9.0
397	"	78	"	.20	68	10.5
625	"	78	"	.47	71	13.5
402	"	78	"	.60	69	11.5
629	"	200	"	2.2×10^{-4}	64	0
626	"	200	"	.48	67	3.0
630	"	300	"	2.6×10^{-4}	60	0
627	"	300	"	.48	64	4.0

* The increase in stress is in reference to the lowest rate of straining at each temperature at each confining pressure.

**For representation of failures see Figure 5.5.

Note: The specimens were ½ inch in diameter and 1 inch long. All strength values have been obtained from plotted results in Tables X, XI, and XII.

Table XIII

Effect of Duration of Load on the Tensile Breaking Stress of Some Brittle Materials, (Baker and Preston (2))

Duration of stress	Average Breaking Stress* psi							
seconds	I**	II	III	IV	V	VI	VII	VIII
0.01	24600	12900	19900	-----	-----	15800	15400	10900
0.1	19600	10600	15900	19000	23880	13900	13500	9400
1.0	17100	9000	-----	14900	-----	12300	11900	8400
10	15900	8250	10500	11200	19800	-----	9900	6900
100	-----	-----	-----	-----	15660	9700	9400	-----
1000	12800	5750	7950	9400	14280	-----	9100	6000
86400	11300	5050	6450	7950	11740	9100	8900	5900

* Average of from 20 to 25 specimens 7/32" in diameter

** Eight different materials were tested:

I Disannealed Pyrex (tested dry)

II Disannealed scratched Pyrex (tested wet)

III Annealed soda-lime glass (tested wet)

IV Annealed lead glass (tested wet)

V Fused silica (tested wet)

VI Porcelain Type A (tested dry)

VII Porcelain Type B (tested dry)

VIII Porcelain Type C (tested dry)

ANNOTATED BIBLIOGRAPHY

STRENGTH OF CONCRETE AT HIGH RATES OF LOADING

This annotated bibliography is presented to enable future workers to readily determine which of the many published works are relevant to his study. Only investigations of plain concrete are covered. Annotation is of results reported on the strength properties of concrete, which in some cases is only part of the results obtained.

Investigations reporting results appearing in more than one source have been so annotated so as to lead the reader to the most complete description or the most readily available report. Only brief summaries of the ranges of loading rates and the strength differences are noted. The more significant works are described in somewhat greater detail in the text of the thesis.

The bibliography is in three parts: compression test investigations, shear test investigations, and tension test investigations. The investigations are listed in alphabetical order by author.

The foreign literature has not been completely searched but the more important works are believed to be included.

COMPRESSION TEST INVESTIGATIONS

1. Abrams, D. A., "Effect of Rate of Application of Load on the Compressive Strength of Concrete," *Proceedings, American Society for Testing Materials*, v. 17, part II, 1917, p. 364-377.

Tests were made to investigate the effect of rate of loading on compressive strength. Rate of shortening of six inches by twelve inches cylinders was varied from 0.006 to 0.150 inches per minute. An increase in strength was found of 6, 14, and 20 per cent for 1:9, 1:5, and 1:3 mixes, respectively. It was also found that the rate of loading up to at least 88 per cent of the ultimate strength had no effect on the ultimate strength, if the remainder of the load was applied at a slow speed.

2. Biron, F., "Les chocs en resistance des materiaux," *Technique des Travaux*, v. 12, n. 4, April 1936, p. 221-223.

A "theoretical study of effect of impact shocks on prismatic concrete blocks resting on two supports," (from Engineering Index, 1936, p. 263).

3. Covington, C., "Dynamic Energy-absorbing Characteristics of Lightweight Vermiculite Concrete," Structural Mechanics Research Laboratory, The University of Texas, Austin, Texas, June 1961.

Confined lightweight vermiculite concrete cylinders were subjected to impact tests using a dropped weight. Stress-strain curves were obtained and energy-absorption characteristics measured. Effect of impact velocity and impact mass weight were evaluated. Strains exceeded 30 per cent. Objective of tests was to measure the cushioning properties of lightweight vermiculite concrete.

4. Doanides, P. J., "Streamlined Vacuum Concrete Buntons for Mine Shafts," _Journal of the American Concrete Institute_, v. 48, December 1951, p. 309-320.

Steel missiles, weighing $2\frac{1}{4}$ or $3\frac{1}{4}$ pounds were used to simulate damage caused by spillage of ore down mine shafts onto vacuum concrete buntons. The missiles were cylindrical with a rounded conical point. The buntons were reinforced and in most cases the spalling did not penetrate the spiral reinforcement. First impact generally produced the heaviest damage with subsequent blows causing little additional damage. The spiral reinforcement proved effective in protecting the bunton.

5. Dutron, R., "La Composition des Betons de Route," Liege (1930).

A spherical weight of five kilograms was dropped from increasing heights onto ten centimeter concrete cubes and simply supported prisms. It was concluded that "concretes made with crushed aggregates offer higher resistance to impact than those made with gravel." (The annotation is derived from H. Green; see annotation.)

6. Evans, R. H., Effect of Rate of Loading on the Mechanical Properties of Some Materials," Institution of Civil Engineers, London, V. 18, n. 7-8, June 1942, p. 296-306.

Crushing tests were made on two inch cubes of nominal strengths of 3200, 4650, and 6250 psi and on three inch cubes of 1600 psi. The time to fracture was varied from 80 minutes to about 0.001 seconds. No significant increase was noted in strength at speeds slower than 0.05 seconds but substantial increases in strength were noted at higher speeds. Stronger concretes showed less percentage increase than did weaker concretes. Results are presented also for tests made on cast iron, steel, duralumin, and brass.

7. Evans, R. H., "Effect of Rate of Loading on Some Mechanical Properties of Concrete," Mechanical Properties of Non-Metallic Brittle Materials, Butterworths Scientific Publications, London, 1958, p. 175-192.

Previous investigations by Evans on the effect of rate of loading on the strength and elastic properties of concrete are described and results presented. Detailed description of results of tests on the effect of rate of loading on the modulus of elasticity is given. Results of crushing tests on two inch and three inch cubes are again presented. (See annotations 6 and 8.)

8. Evans, R. H., "Instantaneous Strains in Building Materials," Leeds Philosophical and Literary Society Proceedings, v. 3, July 1940, p. 584-592.

Tests were made on sandstone, granite, and concrete specimens to investigate the reduction of elastic time strain present in the immediate strain at high rates of loading. Three types of strain were distinguished: (1) instantaneous strain, (2) elastic time strain, (3) plastic time strain. A "short range integral strain curve" was obtained for the three materials investigated. No data is given on the ultimate strengths at fast rates of loading.

9. Fox, E. N., "Stress Phenomena Occurring in Pile Driving," Engineering, v. 134, September 1932, p. 263-265.

A theoretical investigation of the stresses occurring in pile-driving is presented based on wave theory. A discussion of the effects of repeated impact is presented. A cumulative damage phenomenon is hypothesized. No experimental data is presented.

10. Framm, F., "Uber Zerschmetterungsfestigkeit und ihre Beziehung zur Druckfestigkeit," Protocalle des Verein Deutscher, Portland-Zement Fabrikanten, 1920.

A conical two kilogram hammer was dropped from a height of 25 centimeters onto concrete specimens. Static and dynamic strengths were found to be not proportional. It was concluded that water-stored specimens show a higher impact resistance than do air-stored specimens. (The annotation is derived from H. Green; see annotation.)

11. Gaede, K., "Influence of the Rate of Loading upon the Compressive Strength of Concrete Cubes," Zement-Kalk-Gips, v. 5, June 1952, p. 195-196.

Tests made on ten centimeter cubes by different laboratories at two testing speeds showed little difference in strength. The slower rate of loading was approximately 2.44 kilograms per square centimeter per second and the faster rate was approximately 40.4 kilograms per square centimeter per second.

12. Glanville, W. H., Grime, G., Fox, E. N., and Davies, W. W., Building Research Technical Paper No. 20, (H, M. S. O., 1938).

Impact tests were made on cubes and prisms by means of drop tests. Stresses were measured by a piezoelectric gage. A large number of blows were delivered from successively increasing heights of drop. No consistent relationship was found between static compressive strength and impact strength. (The annotation is derived from H. Green; see annotation.)

13. Green, H., "The Impact Testing of Concrete," Mechanical Properties of Non-Metallic Brittle Materials, Butterworths Scientific Publications, London, 1958, p. 300-315.

Four inch concrete cubes were tested in a ballistic pendulum apparatus to measure the effect of impact upon concretes made with different types of aggregates. It was found that rough, angular aggregates offered the greatest resistance. A constant mass weight and a constant velocity of impact was used. Energy absorbed to first crack and to no rebound were the criteria of effectiveness.

Previous works on impact testing were reviewed. A number of the annotations in this bibliography are derived from Green's reviews.

14. Grime, G., "The Measurement of Impact Stresses in Concrete," Proceedings, Physical Society of London, v. 46, part 2, 1934, p. 196-204.

Measurement of strains in a reinforced concrete pile were made at the ends and mid-point by means of a quartz piezoelectric gage embedded in the concrete. Strain-time records were obtained by photographing an oscillograph trace. Stresses were inferred from a statically measured stress-strain relationship. A check on the accuracy of the results was made by calculating the momentum change of the dropped weight. No ultimate strength data is presented.

15. Guttman, A., and Seidel, K., "Ueber die Druckfestigkeit, Stossfestigkeit und Abnutzbarkeit von Beton," Zement, v. 25, n. 14, April 2, 1936, p. 233-240.

Drop tests were made onto concrete cubes. It was concluded that the impact strength increases with increased "static" strength, and that the impact strength of concretes made with crushed aggregate is higher than of concretes made with gravel aggregates. (The annotation is derived from H. Green; see annotation.)

16. Hodgson, G. H., "The Resistance of Concrete to High Explosives," Engineering, v. 147, 1939, p. 386.

An explosive charge was detonated under slabs of concrete two feet by two feet by six inches deep, simply supported at each corner. Photographs show damage to specimens. Slabs made with rough, angular granite aggregate sustained less damage than did slabs made with gravel aggregate.

17. Jones, P. G., and Richart, F. E., "The Effect of Testing Speed on Strength and Elastic Properties of Concrete," Proceedings, American Society for Testing Materials, v. XXXVI, part II, 1936, p. 380-392.

Tests were made on standard six inch by twelve inch cylinders of nominal strengths of 2000, 3500, and 5000 psi. Three or more were tested at nine different testing speeds at ages of seven and twenty-eight days. Time to failure varied from four hours to one second. Strains were measured by two carbon resistor telemeter gages of eight inch gage length. Loads were measured by a telemeter gage attached to a steel cylinder which transmitted the load. Results presented show an increase in strength with increasing stressing rate. The results were approximated by straight lines on a plot of the log of the stressing rate versus the strength.

18. Jones, R., "Elasticity and Rupture of Concrete and Stone at Constant Rates of Loading," Nature, v. 165. n. 4184, January 7, 1950, p. 39-40.

Compression tests were made on four inch cubes loaded to failure in a testing machine. The elastic modulus in the longitudinal direction was found to be constant up to failure while in the lateral direction there was a definite decrease beginning at about 35 per cent of the failing load. The load at which this decrease occurred was independent of the rate of loading in the range 600 psi per minute to 5000 psi per minute. The decrease was attributed to "internal rupture of the specimens along vertical planes." Similar tests were also made on basalt and York stone.

19. Mattimore, H. S., "Impact Test on Concrete to Regulate Coarse and Fine Aggregate Qualities and Mixes for Highways," Proceedings, American Society for Testing Materials, v. XX, part II, 1920, p. 266-277.

The test described consists of a striking head with eight striking points (non-slip horse calks) which is raised and released at the rate of 90 per minute until 5000 blows have been delivered to the specimen. An impact coefficient is then determined which is proportional to the weight loss in grams. No relation was found between compressive strength and the impact coefficient.

20. McHenry, D., and Shideler, J., "Review of Data on the Effect of Speed in Mechanical Testing of Concrete," Symposium on Speed of Testing of Non-Metallic Materials, American Society for Testing Materials Special Technical Publication No. 185, 1955.

Current specifications for concrete testing involving rate of loading are described. A review of the data on speed of testing effect on compressive strength, on flexural strength, and on modulus of elasticity is presented. An annotated bibliography is included. This is the only known review of the effect of speed of testing on the strength properties of concrete up to this time.

21. Moore, O. L., "Report of Working Committee of Committee C-1 on Plastic Mortar Tests for Portland Cement," Proceedings, American Society for Testing Materials, v. 34, part I, 1934, p.322-355.

The report presents in detail the results of a large number of tests on two inch cubes carried out by ten laboratories. Included among the results is the effect of rate of loading over a range of 1000 to 6000 psi per minute. Little increase in strength was noted and the results were not consistent.

22. Newmark, N. M., and Hansen, R. J., "Design of Blast-resistant Structures," Handbook of Shock and Vibration Control, Volume III, McGraw-Hill Book Co., New York, 1961.

A short discussion on the strength of materials under dynamic loading is presented. A table lists recommended design stresses for concrete and reinforcing steels used in structures to resist dynamic loads.

23. Passov, H., "Druckfestigkeit, Zugfestigkeit, Zerschmetterungsfestigkeit," Zement-Verlag, Charlottenburg, 1918.

Seven centimeter cubes of concrete were impacted by conical hammers of different weights and shapes. A "disintegration point" was obtained representing the product of the weight of the hammer and the height of drop at which cubes broke with a single blow. Impact and crushing strengths were found to be unrelated. (The annotation is derived from H. Green; see annotation.)

24. Shank, J. R., "Plastic Flow of Concrete at High Overload," Journal of the American Concrete Institute, v. 45, February 1949, p. 493-498.

The paper is primarily concerned with plastic flow of concrete at high loads. Data is presented indicating that a "true" ultimate strength under long-time loading is approximately 90 per cent of the ultimate strength. One series of tests recorded a "true" ultimate strength of 85 per cent of the ultimate strength. Data shows the "Effect of load holding on ultimate strength" as depending on the "Time of load holding." It was concluded that the "plastic flow curve is the same for short as well as long times, and for high loadings as well as for low."

25. Shield, R., "Shock Mitigation with Lightweight Vermiculite Concrete," Structural Mechanics Research Laboratory, The University of Texas, Austin, Texas, 1961.

Tests were made on confined cylinders of lightweight vermiculite concrete to investigate the cushioning properties of the material.

26. Slater, W. A. discussion by, of paper by Noble, P. M., "The Effect of Aggregate and Other Variables on the Elastic Properties of Concrete," Proceedings, American Society for Testing Materials, v. 31, 1931, p. 422-425.

Tests were made on 27 six inches by twelve inches cylinders to investigate the effect of time of application of load on the modulus of elasticity. Time for application of load was decreased from twenty minutes to one second.

27. Tatnall, F. G., "Speed of Testing," American Society for Testing Materials Bulletin, n. 161, October 1949, p. 23-28.

Under the sub-title "Cement and Concrete" is presented a summary, by J. R. Dwyer, of existing test requirements for speed of testing; a summary, by F. E. Richart, of the work reported in detail by Jones and Richart (see annotation); and a summary of data from the Bureau of Reclamation of work reported more extensively in Bulletin 4 (see annotation no. 35).

28. Thaulow, S., "Rate of Loading for Compressive Strength Tests," Betong., Stockholm, v. 38, 1953, p. 11.

Accepted test practice for several countries is presented. Data for rates of loading from 10 to 320 psi per second for four different strength concretes is given. An increase in strength with faster loading rate was found. (The annotation is derived from McHenry and Shideler; see annotation).

29. Watstein, D., "Effect of Strain Rate on the Compressive Strength and Elastic Properties of Concrete," Journal of the American Concrete Institute, v. 49, April 1953, p. 729-744.

The results of a thorough study of the effects of strain rate on the strength and elastic properties of concrete is presented. The stressing rates varied from about 5.0 psi per second to about 5 x 10^7 psi per second. Two concretes, a strong concrete of 6500 psi nominal strength and a weak concrete of 2500 psi nominal strength were tested. Bonded wire strain gages were used. Extensive data is presented on the elastic properties of concrete showing an increase in the work energy to failure with increasing straining rate. The strength increased with increased straining rate with a strength at the highest rate of straining 80 per cent higher than the strength at the lowest rate of straining.

30. Watstein, D., "Impact Resistance of Concrete," Concrete, v. 61, n. 5, 1953, p. 22, 24.

A condensed report of the results reported more extensively in the above cited work of Watstein. (See annotation no. 29.)

31. Watstein, D., "Investigation of the Properties of Plain Concrete under Impact," Progress Report, Building Technology Division, National Bureau of Standards, January 1949.

A progress report of the work cited above in annotation no. 29.

32. Watstein, D., "Properties of Concrete at High Rates of Loading," Symposium on Impact Testing, American Society for Testing Materials Special Technical Publication No. 176, 1955, p. 156-170.

Results of tests on "weak" concrete are presented. This data is part of the data presented in entirety in the work cited in annotation no. 29.

33. Watstein, D., and Boresi, A. P., "The Effect of Loading Rate on the Compressive Strength and Elastic Properties of Plain Concrete," Department of Commerce, National Bureau of Standards, Report 1523, Washington, March 1952.

This report covers the same results reported in a more readily available source cited in annotation no. 29.

34. Wenzel, F., "Beitrag zur Stossfestigkeit von Beton," Technische Hochschule, Aaechen, Dissertation (Leipzig: Frommhold und Wendler, 1934).

Using drop tests, it was concluded that increased compressive strength results in increased impact resistance. (The annotation is derived from H. Green; see annotation.)

35. ------. Bulletin 4, Mass Concrete Investigations, Boulder Canyon Project, Final Reports, Part VII, Cement and Concrete Investigations, p. 165-170.

A series of tests was made investigating the effect of rate of load application on the compressive strength of six inches by twelve inches and eight inches by sixteen inches cylinders. In general, a higher strength was noted with higher rate of loading.

36. ------, "Concrete Takes Greater Load If Suddenly Applied," Concrete, v. 44, n. 11, November 1936, p. 16.

A very short summary of the results of the study by Jones and Richart. (See annotation no. 17.)

37. -----, "Dynamic Stress-strain Characteristics of Lightweight Concretes," Quarterly Report No. 3, Isolation of Underground Structures from Dynamic Loads, February 13, 1961, Structural Mechanics Research Laboratory, The University of Texas, Austin, Texas.

Results of an investigation of the dynamic stress-strain and stress-time curves are presented for six lightweight aggregate concretes. The materials were of a crushable nature and strains were recorded to 30 percent.

38. -----, "Rate of Deformation of Concrete During Test in Compression," Roads and Streets, v. 68, June 1928, p. 289.

Rate of deformation and testing machine head speeds are compared for cylinders capped with plaster of Paris and with ground ends. In both cases there was a difference in the two rates and the difference was greatest for the capped specimens.

39. -----, "Shock Mitigation with Crushable Cushioning Materials," Quarterly Report No. 3, Isolation of Underground Structures from Dynamic Loads, February 13, 1961, Structural Mechanics Research Laboratory, The University of Texas, Austin, Texas.

Impact tests were made on confined lightweight aggregate concretes to determine their suitability as a cushioning material.

SHEAR INVESTIGATIONS

1. Hansen, R. J., Nawy, E. G., and Shah, J. M., "Response of Concrete Shear Keys to Dynamic Loading," Journal of the American Concrete Institute, v. 32, May 1961, p. 1475-1490.

Tests were conducted on shear keys 2-5/8 inches by seven inches using pulse loads having rise times between 25 and 40 milliseconds and a relatively long decay time. An increase in strength over the static failing strength was observed under the dynamic loading. Small transverse compressions (150 and 300 psi) not only raised the static shearing resistance but also the percentage increase in strength under the dynamic loading. There were twelve specimens tested dynamically in the entire series.

2. Nawy, E. G., and Shah, J. M., "The Response of Concrete Shear Keys to Dynamic Loading," Department of Civil and Sanitary Engineeering, Structural Division, Massachusetts Institute of Technology, January 1959.

A detailed description of the test results reported in a more readily available source cited in annotation no. 1 above.

3. Kesler, C. E., "Effect of Speed of Testing on Flexural Fatigue Strength of Plain Concrete," Proceedings, Highway Research Board, v. 32, 1953, p. 251-258.

Repeated sinusoidal loads were applied to six inches by six inches by 64 inches plain concrete beams at three loading speeds, 70 cycles per minute, 230 cycles per minute, and 440 cycles per minute, to investigate the effect of speed of loading on the flexural fatigue strength. No significant difference was noted in the fatigue strength at the speeds investigated.

4. Klettke, A. J., Webster, D. W., and White, F. P., "Effect of the Speed of Loading on the Modulus of Rupture of Plain Concrete," Thesis for B. S. degree, University of Wisconsin, 1933; directed by Professor M. O. Withey.

A large number of tests were made in flexure at ages of seven and twenty-eight days. The span and size of beam were varied. An increase in the modulus of rupture with increased loading rate was found in all cases but the increase was not of the same magnitude for all series of tests. (The results are reported also by McHenry and Shideler. This annotation is derived from McHenry and Shideler's description of the tests.)

5. McHenry, D., and Shideler, J. J., "Review of Data on Effect of Speed in Mechanical Testing of Concrete," Symposium on Speed of Testing of Non-Metallic Materials, American Society for Testing Materials Special Technical Publication No. 185, 1955, p. 72-82.

See annotation no. 20 of the compression tests.

TENSION TEST INVESTIGATIONS

1. Fox, E. N., "Some Exploratory Tests on the Strength of Concrete Beams under Pulse Loads," Mechanical Properties of Non-Metallic Brittle Materials, Butterworths Scientific Publications, London, 1958, p. 283-299.

Trapezoidal load-time pulses were applied to 18 inches by $2\frac{1}{2}$ inches by $2\frac{1}{2}$ inches plain concrete beams. Duration of load varied from six milliseconds to 87.8 milliseconds. Rise times varied from two milliseconds to fifteen milliseconds. Dynamic to static load ratios varied from 1.09 to 1.79. Failure occurred at different phases of the loading and data from 46 different tests is presented. Results indicate that strength under short durations of load is greater than under static loads.

2. Goldbeck, A. T., "Tensile and Flexural Strengths of Concrete," Report on Significance of Tests of Concrete and Concrete Aggregates, 2nd Edition, 1943, American Society for Testing Materials, p. 9-14.

A brief summary of the results of tests by the Illinois Division of Highways' Laboratory is presented. The range of loading rates was 120 psi per minute to 540 psi per minute. Over this range the modulus of rupture increased from 500 psi to 600 psi.

6. Teller, L. W., "Discussion on Transverse Testing of Concrete," *Proceedings, American Society for Testing Materials*, v. 27, part II, 1927, p. 418-420.

Data from a few tests is presented showing an increase in the modulus of rupture with increased rate of loading. Test beams were six inches by six inches by 30 inches, tested at twenty-eight days, and loaded as a cantilever. Insufficient data is given to determine the exact rate of stressing. With a fourfold increase in loading rate the modulus of rupture increased about eleven per cent.

7. Vironnaud, M., "Essais Mecaniques sur un Nouveau Type D'eprouvette en Mortier de Ciment," *Annales des Ponts et Chaussees*, v. 118, n. 2, 1948, p. 163-184.

Tests on a new type of mortar specimen are proposed. One of the tests was similar to the Charpy test used in the testing of metals.

8. Wright, P. J. F., and Garwood, F., "Effectof Method of Test on Flexural Strength of Concrete," *Magazine of Concrete Research*, n. 11, October 1952, p. 67-76.

Results of flexure tests over a range of stressing rates from 0.33 psi per second to 19 psi per second are reported. An increase in the modulus of rupture of fifteen per cent was found over this range.