

Relation of Rebound-Hammer Test Results to Sonic Modulus and Compressive-Strength Data

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THIS presentation indicates the relationships, true or incidental, which exist between the amount of rebound on concrete of a light steel hammer and other particular properties of the concrete, such as compressive and flexural strength and sonic modulus of elasticity. The analysis is based on data obtained from 6-by-12-inch concrete cylinders and 6-by-6-by-24-inch prisms representing three different aggregates, three cement contents, three slumps, several variations of curing, and testing at ages of 7, 28, and 90 days and at 1 year. Under controlled laboratory conditions, there appeared to be a pronounced degree of correlation between hammer reading and compressive strength.

● IN 1951, the U. S. Naval Civil Engineering Research and Evaluation Laboratory began a systematic study into the physical properties of a series of Type I Portland cement concretes made with three different California aggregates (Table 1). With each aggregate, three cement contents were used, namely $3\frac{1}{2}$, $5\frac{1}{2}$, and $7\frac{1}{2}$ sacks per cubic yard of concrete, and with each of these there were three slumps represented 1, $3\frac{1}{2}$, and 6 inches. In addition, under carefully controlled laboratory conditions (at 73 F), different combinations of curing periods at 100 per cent RH and storage at 50 per cent RH were employed for specimens tested at 7, 28, and 90 days and at one year.

About sixteen 6- by 12-inch cylinders and four 6- by 6-inch beam specimens were cast from each of three separate batches of concrete representing any one given mix proportion; for each of the sixteen variables of curing and age of test, three cylinder specimens were employed, one from each of the three batches. Compressive strength, Poisson's ratio, static and sonic (in flexure) moduli of elasticity were obtained from the cylinders; moduli of rupture were determined from the flexural strength of continuously fog-cured specimens at ages up to one year.

During the initial stages of this broad program, several concrete test hammers were

TABLE 1
PHYSICAL PROPERTIES OF AGGREGATES

	Aggregate A		Aggregate B		Aggregate C	
	Fine	Coarse	Fine	Coarse	Fine	Coarse
Fineness modulus.....	3.12	6.86	2.92	6.82	2.79	6.72
Absorption, 24 hrs, percent...	1.7	3.1	1.8	1.6	1.5	0.7
Specific gravity	2.53	2.53	2.63	2.66	2.61	2.89
Los Angeles abrasion, 500 revolutions, "B" grading, percent loss....	—	28.1	—	33.0	—	13.5

made available to the Laboratory by the Bureau of Yards and Docks and it was decided with some interest to employ their use in the investigation. Hammer-reading determinations were made on all the aforementioned 6- by 12-inch cylinders immediately prior to their being capped for the regular compressive-strength tests. Each cylinder having been cast in a machined mold, the bottom 6-inch diameter face was smooth and uniform in appearance and was therefore chosen as the test surface; with this surface up, the hammer was used in the vertical position without exception.

It is to be noted that this arrangement eliminated much variation due to difference in shape or dimension of specimen, the method

of supporting or testing it, and the care and preparation of the impact surface.

In using the concrete test hammer, a light-weight steel plunger free to travel in a tubular frame, is drawn upward against the force of two tension springs. With the base of the instrument held firmly against the specimen

being tested, a trigger is pulled allowing the springs to drive the plunger against the concrete. The height of the first rebound is measured by a small indicating pointer sliding along a scale graduated 0 to 100; the higher the rebound, the harder the concrete.

It is this rebound number which will be used in the ensuing discussion. It is proposed to indicate the relationships which exist between this amount of rebound and the compressive strength, the modulus of rupture and the sonic modulus of elasticity. Some observations will also be made on the consistency of hammer readings as compared with the consistency of other observed properties.

Figure 1 shows the average curve of compressive strength versus rebound number for concretes made with aggregate A; included are two lines indicating plus or minus one standard deviation from this strength curve. Each point in the plot represents one cylinder; all aggregate A concretes are included regardless of cement content, slump, curing, or age of test up to and including 90 days. Similar plots were made for aggregates B and C and these were found to be almost identical to that for aggregate A.

The average curves for all of these aggregates are plotted in Figure 2, and it is interesting to note that each average curve does lie within plus or minus one standard deviation of any of the others. However, the standard deviation of plus or minus 750 or 800 psi noted in Figure 1 appears quite large when one is concerned with a 3,500 psi concrete. Therefore, separate plots were made for each of several combinations of curing and age of test.

Figure 3 indicates that for aggregate A concretes there is a difference in relationship of hammer reading to compressive strength due to method of curing. The more vertical of the two lines represents concrete fog-cured for only 3 or 7 days and then air-stored for the balance of 28 days, at which age they were tested. The other of the two curves is for the continuous fog-cured specimens, age 28 days. In general, air-dried concretes having low compressive strength, usually exhibited slightly higher rebound readings than did the continuous fog-cured concretes of similar strength. However, when the compressive strength of concrete reached 6,000 psi, the rebound numbers obtained on continuous fog-cured specimens were invariably greater than those for

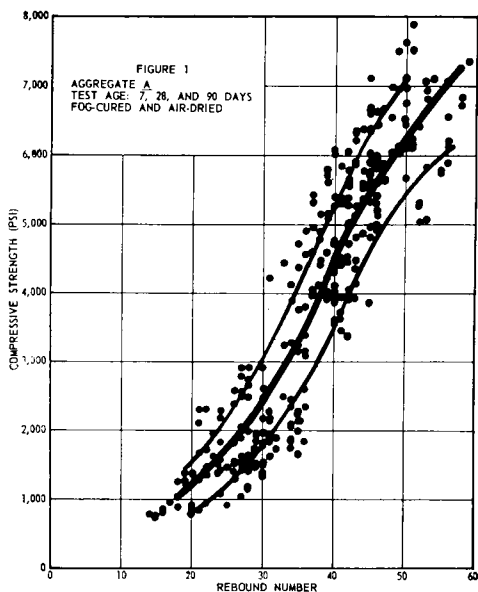


Figure 1

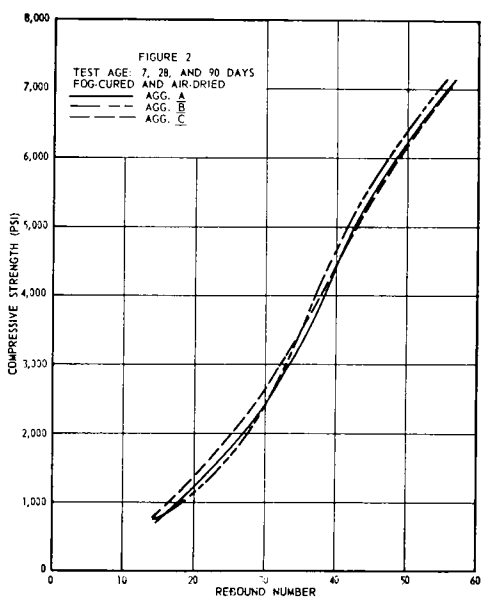


Figure 2

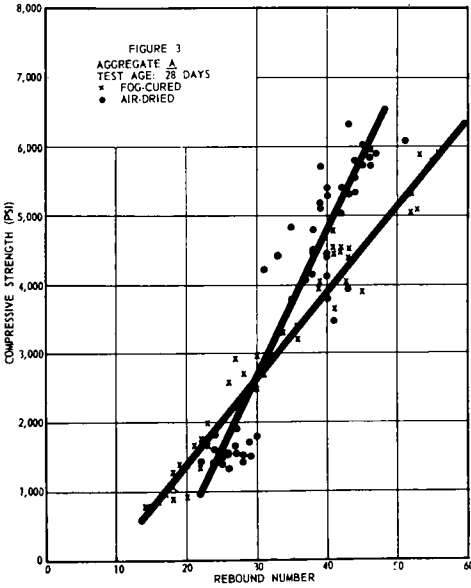


Figure 3

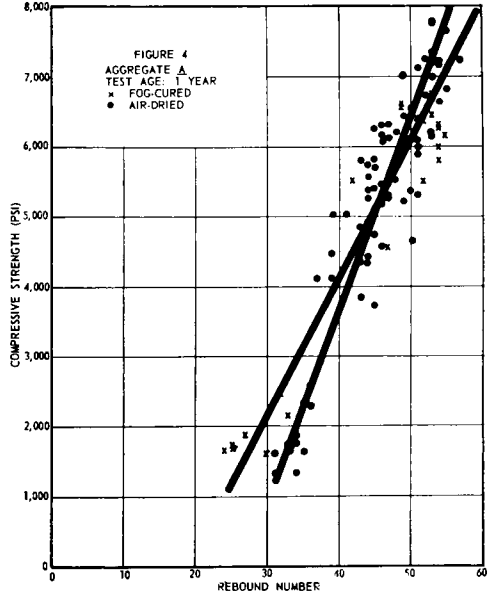


Figure 4

air-dried concretes of similar strength and composition.

This observation is also borne out by the plot in Figure 4 for concretes made of the same aggregate *A* but in this instance, the concretes tested had been aged 1 year instead of 28 days. The standard deviation of any of these single-factor plots appears to be much less in range than it was in the first plot mentioned above which included all the variables up to and including age at test of 90 days.

The more vertical of the two lines in Figure 4 represents only air-dried concretes since none of these was fog-cured for more than the first 28 days of the one year at age of test. Curves for the air-dried concretes of all these aggregates are shown in Figure 5. There appears to be great differences among the concretes that have been aged for one year whereas practically none for the concretes aged 90 days or less. Figure 5 indicates that hammer readings at age one year probably are as dependent upon aggregate (and possibly other variables) as upon the strength of the concrete.

Transverse strengths or moduli of rupture were determined at 7, 28, and 90 days, and at one year for continuous fog-cured beam specimens. These may be compared with hammer readings obtained from the 6- by 12-inch cylinders mentioned previously which were made from the same batches of concrete and were cured similar to the beams.

Figure 6 indicates the scatter of the individual points obtained with aggregate *A*; the variation from the mean curve increases greatly with increase in modulus of rupture or hammer reading. Similar plots were obtained for concretes made with aggregate *B* and aggregate *C*.

Figure 7 compares the average curve of Figure 6 with the averages obtained for the other two aggregates. It should again be noted that these values were obtained only for continuous fog-cured specimens that were fabricated and tested under carefully-controlled laboratory conditions.

In view of the scatter and the lack of coincidence among the curves for the three aggregates, it would be most difficult to predict this particular relationship even for the concretes which were studied. Also, there was little improvement in the character of individual curves that represented only one or two ages of test as opposed to character of the curves for the four which are covered in Figure 7.

Sonic moduli of elasticity were obtained on each cylinder by vibrating the specimen in flexure. It was anticipated that these values would have excellent correlation with the hammer readings since the view often has been expressed that impact-rebound is directly dependent upon the modulus of elasticity.

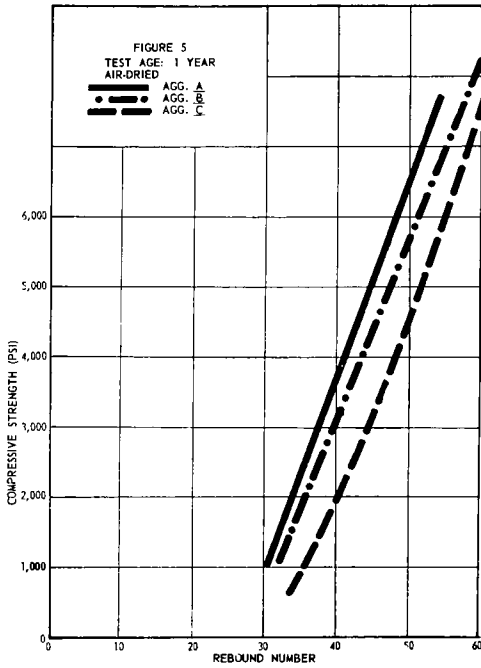


Figure 5

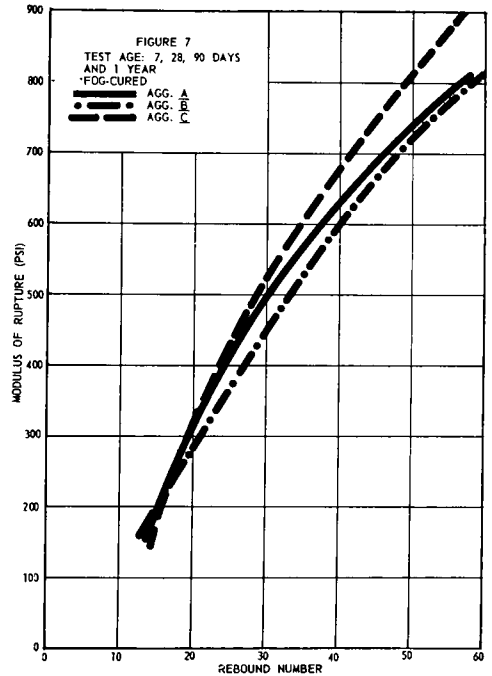


Figure 7

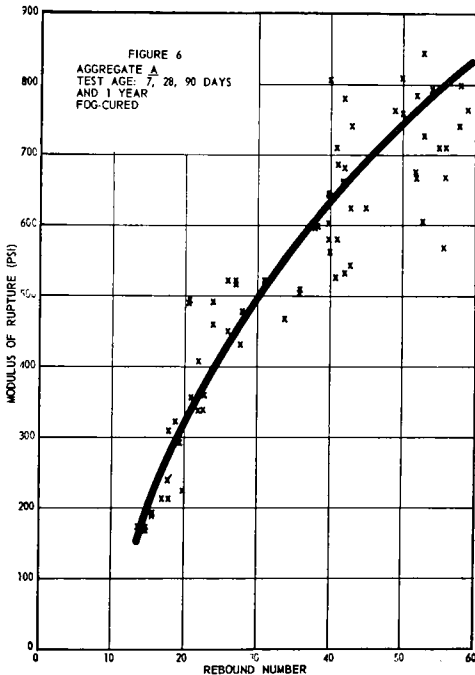


Figure 6

Figure 8 depicts the relationship between dynamic E and hammer rebound for specimens made with aggregate A that were

tested at age 28 days and either fog-cured or air-dried. Probably the most important conclusion is that for the same rebound number, wet-cured concrete seems to exhibit a much higher modulus of elasticity than does air-dried concrete. Secondly, the fog-cured concrete appears to reach its limit value of E when the hammer rebound value equals or exceeds 50; this may be quite important for dynamic studies of concrete structures.

Figure 9 illustrates again that for fog-cured concrete, the upper limit for E is reached with a corresponding hammer reading of 50. However, it is apparent that the E value is very much dependent upon the aggregate, and particularly so when the higher limits are being considered. Thus, no general rule can be given for the relationship of modulus of elasticity to rebound number.

The last plot to be presented, Figure 10, depicts the relationship of sonic E to hammer rebound for 1 year old concretes which have been either fog-cured or air-dried. The top line represents the fog-cured specimens and the lower, the air-dried; it is to be noted that for a hammer reading of 40, the E values are 5 million and 3 million psi, respectively. A structure in service made of this type of concrete

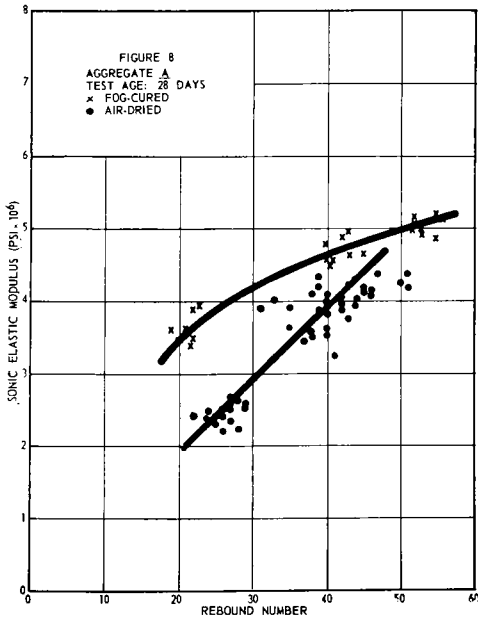


Figure 8

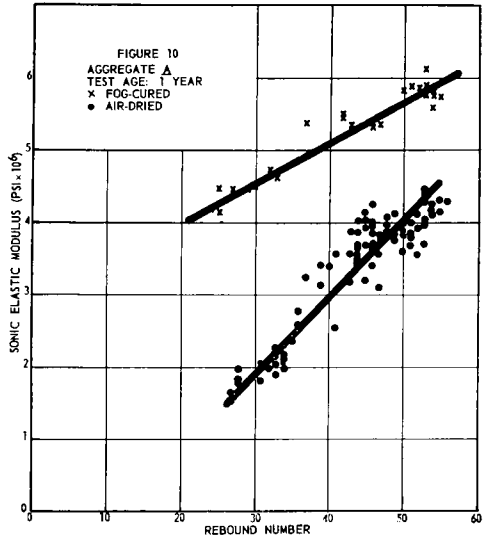


Figure 10

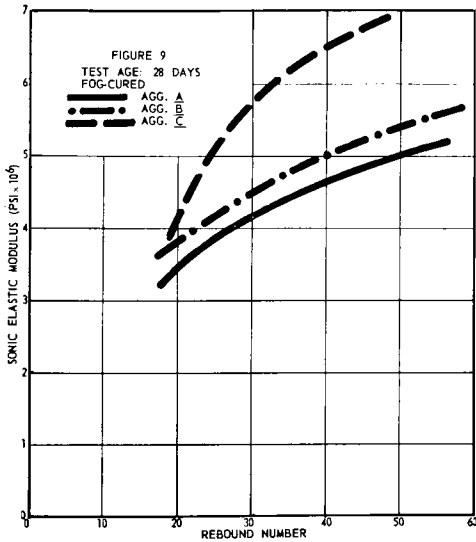


Figure 9

cretes at early ages regardless of aggregate or method of curing. As the data were studied, the deviation of hammer readings from batch-to-batch of concretes made with aggregate *A* appeared to be less than that observed with the other aggregates. In order to ascertain if this smaller deviation was indeed a function of the aggregate and not just a reflection of possibly better batch control of concretes made with aggregate *A* than with aggregates *B* and *C*, a statistical analysis was made involving hammer readings, compressive strength, and modulus of rupture.

The small number of specimens (three for each variable of age and curing) suggested the use of Tippet's method for estimating standard deviation, in which method the maximum range of each of a number of groups of data are used in the analysis. In this instance, 6 groups of 3 values each were employed in determining each standard deviation estimate shown in Table 2. The 6 groups are comprised of two cement contents ($5\frac{1}{2}$ and $7\frac{1}{2}$ sacks per cubic yard) with each of three slumps (1, $3\frac{1}{2}$, and 6 inches); the three cylinder strengths for each of these variables comprise the three values in each group. It is to be noted that these standard deviation estimates proved equal to those determined by a much more laborious method that was used in several trials for checking their validity.

As can be seen in Table 2, the hammer read-

and at age 1 year could be expected to be somewhere within this 2 million psi range providing a hammer reading of 40 was obtained. It would appear, therefore, that for actual concrete structures, the hammer reading would give but a poor indication of sonic modulus.

In summary, hammer rebound may indicate fairly well the compressive strength of con-

TABLE 2
ESTIMATED STANDARD DEVIATIONS

Test Age	Aggregate A			Aggregate B			Aggregate C		
	Hammer, unit	Comp. str., psi	Rupt. mod., psi	Hammer, unit	Comp. str., psi	Rupt. mod., psi	Hammer, unit	Comp. str., psi	Rupt. mod., psi
Fog-cured continuously									
7 days	1.28	189	20	2.16	322	34	2.36	381	44
28 days	1.40	322	47	2.45	247	35	2.06	323	29
90 days	1.08	251	41	1.18	260	31	2.36	661	47
1 year	1.24	309	44	2.26	255	33	2.66	445	32
Average.....	1.25	268	38	2.01	271	33	2.36	457	37
Fog-cured 7 days									
28 days	1.67	154		2.65	398		2.30	325	
90 days	1.56	384		1.77	358		1.60	440	
1 year	1.85	208		2.55	284		2.30	261	
Average.....	1.69	249		2.32	344		2.07	342	

ing standard deviation estimates for aggregate A are significantly less than for the other two aggregates. On the other hand, the differences in compressive strength deviation estimates for the three aggregates are small by comparison, and there is no apparent difference in modulus of rupture deviation due to aggregate. Since the deviation in hammer reading over a period of one year is fairly uniform for any aggregate and particular method of curing, one must conclude that aggregate is a primary factor in influencing the scatter of readings made with it; no effort was made to determine which characteristics of the aggregates are significant in this regard.

From the foregoing analysis, it may be stated that the use of the concrete test hammer may save much of the cost and time involved in the making of regular compressive strength tests if these are being made solely as a check on the constancy of quality of concrete; this is particularly true if the standard deviation of hammer readings for the particular concrete is equal to or less than the equivalent deviation of strength found in the standard compressive strength tests. Neither the Laboratory nor the Bureau of Yards and Docks² have accepted, approved, or endorsed the test hammer for use by the U. S. Navy or any of its components nor has the hammer been prohibited as such. The instrument should be quite useful in the hands of persons skilled in its use, application, and interpretation of results.

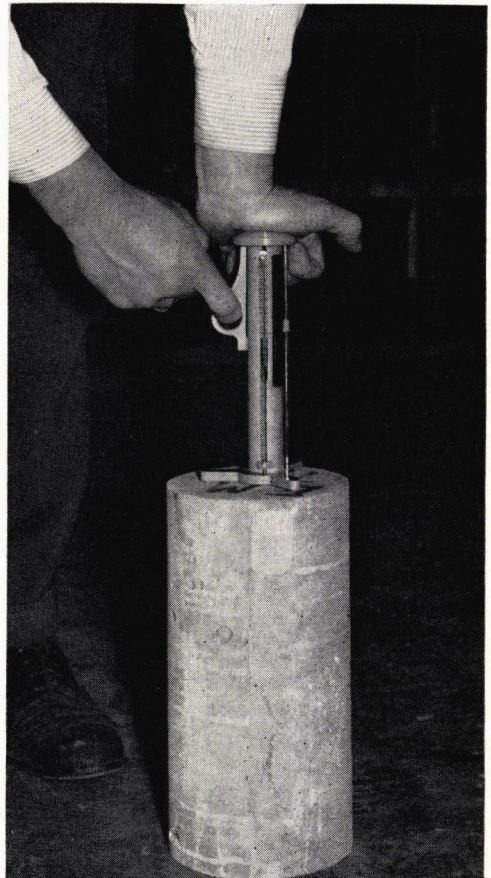


Figure 11. Rebound hammer in use.

DISCUSSION

PAUL KLIEMER, *Senior Research Engineer, Portland Cement Association*—The authors have presented a considerable amount of information concerning the possible usefulness of the concrete test hammer as a non-destructive testing technique. Rather wide interest is being evinced in the application of this equipment to the testing of concrete. Because of this interest, it is desirable that the results of careful evaluations of the potentialities of the equipment be made available so that there can be no misunderstanding as to the role of this test hammer in the field of concrete testing.

It is commendable that nowhere in their report do the authors state or imply that the rebound of the hammer is a direct measure of strength or elasticity. The writer has recently prepared a discussion of a paper¹ which stated that the test hammer utilizes the *principle* (writer's underline) that the rebound of a steel hammer is proportional to the strength of the concrete. Messrs. Petersen and Stoll do mention, however, that views have been expressed by others that "... impact-rebound is directly dependent upon the modulus of elasticity." A few words in this regard may not be amiss.

There appears to be no basis for assuming a fundamental relationship between the rebound of a steel hammer striking a material and the strength or elasticity of the material. However, what does the rebound of the hammer indicate? If the sample of the material being tested is large and the material is perfectly elastic, all of the energy imparted to it by virtue of the hammer striking it is returned to the hammer. Concrete, like almost all materials, is not perfectly elastic and therefore part of the energy imparted is dissipated as heat, the amount dissipated being dependent on the characteristic viscosity (damping) of the material. This characteristic viscosity, or internal friction, is probably a function of the elastic properties of the paste and aggregate, among other things, and will therefore differ for different concretes. In addition, the hammer blow does produce a permanent dent in the surface as the result of the impact, so part of the energy imparted by the hammer is required to produce this

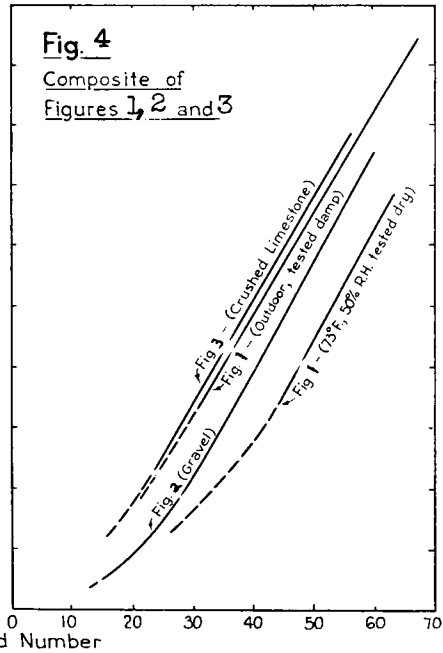
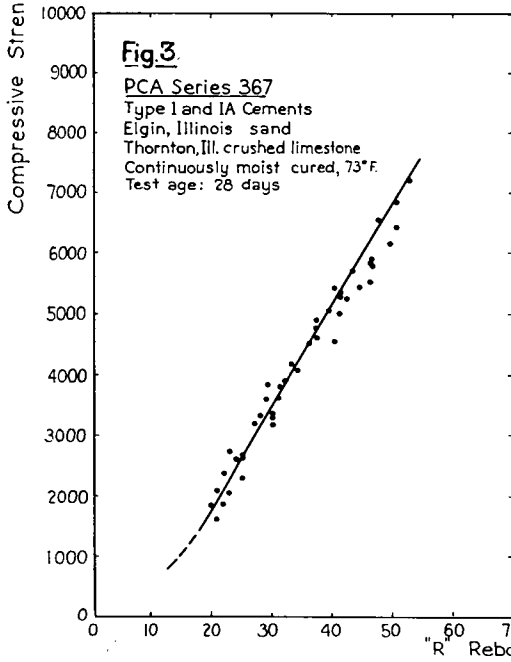
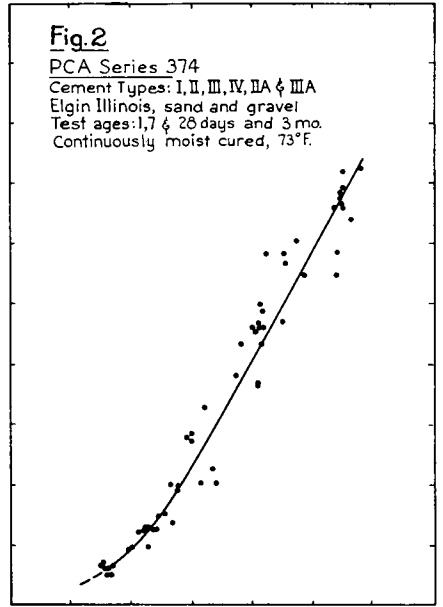
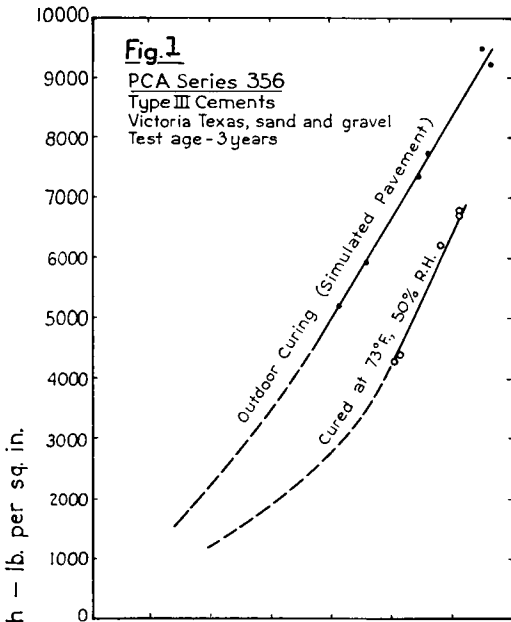
crushing. Therefore, neglecting friction in the device and the possible presence of loose grains on the surface tested, the energy loss involved is composed of two parts: that dissipated due to internal friction and to localized crushing.

Under proper conditions of testing, a good correlation of hammer rebound with compressive strength might be expected if the total energy loss is almost wholly due to localized crushing. In most concretes tested with the test hammer, the dent produced is rather small and the greater part of the energy loss might be due to the effect of viscosity or internal friction. If this is so, the correlation obtained might be poor unless the conditions affecting the viscosity remained constant. Concretes made with different types of aggregates might be expected to have different characteristic viscosities due to differences in elastic properties and bond of paste to aggregate. In addition, changes in the moisture content of the concrete might not only result in changes in viscosity of the paste phase and therefore of the concrete, but free water present in the voids would absorb part of the energy on impact. It should be recognized, also, that the effect of factors influencing only the surface region of the concrete specimen, such as carbonation, might be reflected to a larger degree in rebound hammer test results than in conventional strength tests of the gross specimen.

Despite these limitations, empirical relationships derived for a particular set of limiting conditions (such as constant curing condition and aggregate type) have proven useful and therein lies the greatest value of an instrument such as the concrete test hammer.

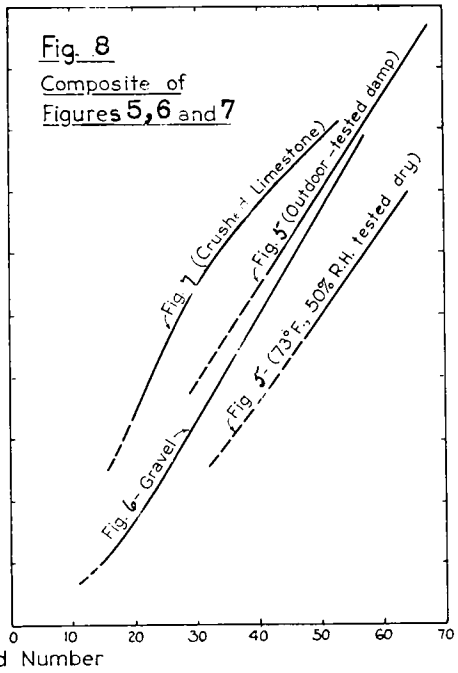
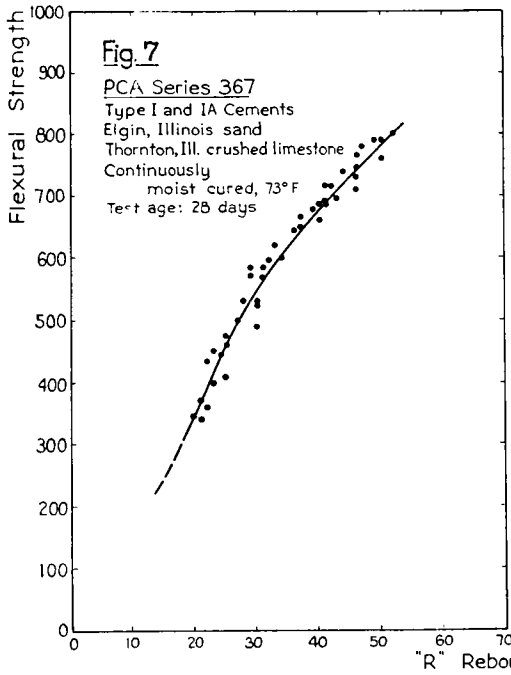
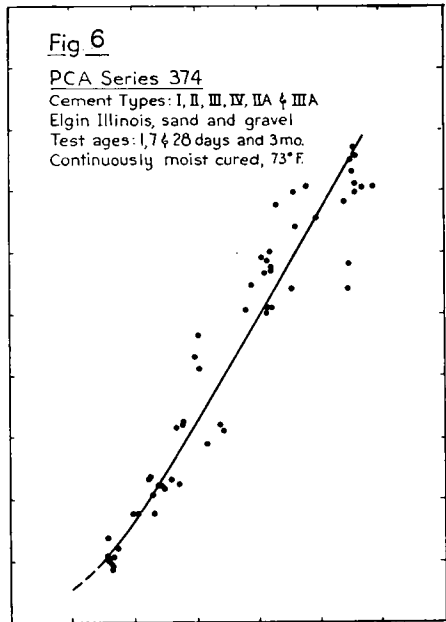
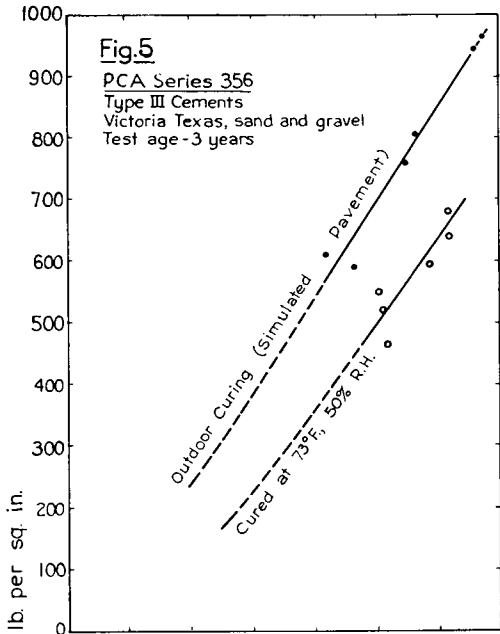
A considerable amount of data have been obtained by this laboratory using concretes prepared for various other purposes, that were being tested for strength and modulus of elasticity. The specimens were 6 x 6 x 30-in. concrete beams. The beams were tested in flexure with the load applied at the third-points of an 18-in. span, two breaks being obtained for each beam. Beam ends were tested in compression as 6-in. modified cubes, while the central portion was used for rebound determinations with the concrete test hammer. Hammer rebounds were determined for the three molded surfaces of the beam: the two sides and the bottom.

¹ "Test Hammer Provides New Method of Evaluating Hardened Concrete," Gordon W. Greene, ACI Proc., Vol. 51, p. 249.



Relationship Between Rebound Number and Compressive Strength

Figures 1-4



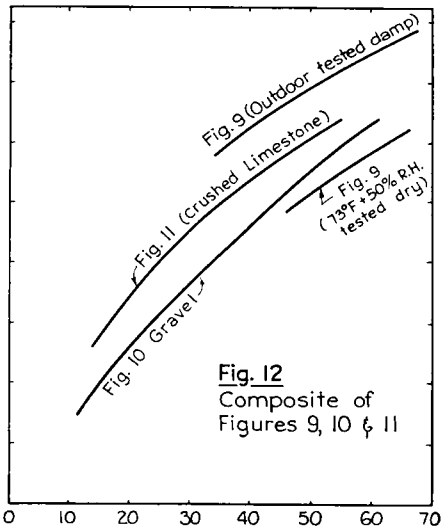
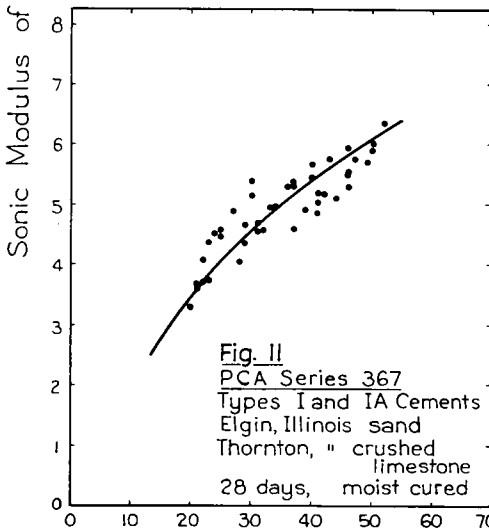
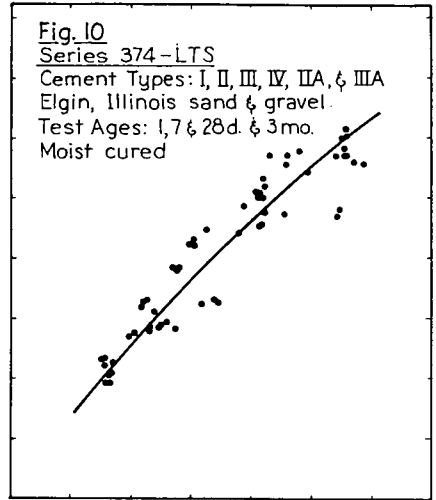
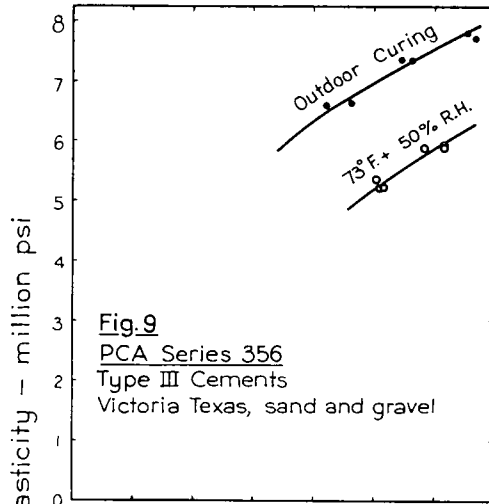
Relationship Between Rebound Number and Flexural Strength

Figures 5-8

REBOUND AND COMPRESSIVE STRENGTH

The relationship between rebound and compressive strength of 3-year old concretes made with Type III cements and a sand and gravel from Texas are shown in Fig. 1. These specimens were cured initially for 7 days in a moist-

room and then some were stored outdoors on a soil subgrade simulating a pavement exposure and the others in the laboratory at 73°F. and 50 percent relative humidity. The outdoor concretes were tested in their relatively damp condition as contrasted with the



Relationship Between Rebound Number and Sonic Modulus of Elasticity

Figures 9-12

companion laboratory specimens tested dry. These data show a more marked difference between the damp and dry condition than the data of Messrs. Petersen and Stoll in their Fig. 3 and 4. For these two curing conditions, at equal compressive strengths, the rebounds obtained for the concretes tested dry are generally 10 to 12 units higher than those for the concretes tested damp (outdoor storage). Approximately 2000 psi compressive strength is represented by this difference in rebound values.

Figures 2 and 3 show data for a variety of concretes made with the same fine aggregate but two different coarse aggregates: a gravel and a crushed limestone. These concretes were continuously moist cured until time for test. The scatter shown in Fig. 2 did not appear to be a function of type of cement. These data provide a fairly good example of the effect of aggregate type on data obtained with the concrete test hammer. For equal compressive strengths, the concretes made with the crushed limestone coarse aggregate showed rebound numbers about 7 units lower than those for the concretes made with the gravel coarse aggregate. This difference represents about 1,000 psi compressive strength.

Figure 4 is a composite of the three preceding figures and illustrates the effect of moisture condition and aggregate type on the observed relationships.

REBOUND AND FLEXURAL STRENGTH

Figures 5, 6, 7 and 8 show the relationships between the flexural strengths of these concretes and the hammer rebound numbers. The relationships are similar to those shown for compressive strength, the individual data, however, showing somewhat more scatter. The effects of moisture condition and aggregate type are similar to those found for the rebound number-compressive strength relationships. The effect of moisture condition supplements the data shown in Messrs. Petersen and Stoll's Fig. 6 and 7.

REBOUND AND SONIC MODULUS OF ELASTICITY

The relationships between sonic modulus of elasticity and rebound number are shown in Figs. 9, 10, 11 and 12. Here again, the relationships are affected by both moisture condition and aggregate type in the same manner as for

compressive and flexural strength. These data confirm the relationships shown by Messrs. Petersen and Stoll in their Figs. 8, 9 and 10. However, their statement that the upper limit of E is reached at rebound numbers of 50 or above is not borne out by the data obtained in this laboratory. For example, Fig. 9 shows rebound values over 65 with no apparent tendency of the curves to flatten out appreciably at these higher values.

SUMMARY

The data obtained by this laboratory provides an excellent confirmation of the data presented by Messrs. Petersen and Stoll. The indications are that empirical relationships between hammer rebound and strength or sonic modulus are affected by both the moisture condition of the concrete and the type of aggregate. These influences will limit the usefulness of the hammer to the preparation of an empirical "job curve" of hammer rebound vs. strength determined from test specimens made with the materials to be used and cured as prescribed. Indiscriminate use as a direct measure of concrete strength or modulus of elasticity would undoubtedly lead to misleading information.

ERNEST E. MCCOY, *Physicist, Concrete Division, Waterways Experiment Station, Corps of Engineers, U. S. Army, Jackson, Mississippi*—The authors have provided a report of some quite interesting tests and have presented a useful analysis of the results. Data such as these should be of considerable value to others who may be considering the procurement and evaluation of the "test hammer." The authors state that "the view has often been expressed that impact-rebound is directly dependent upon the modulus of elasticity" and then present their findings concerning the observed relationship. It is suggested that some elucidation may be provided from a consideration of what forces and properties may be presumed to be involved in a determination of "rebound number." It is the opinion of the writer that impact-rebound should be related to modulus of elasticity of concrete only in about the same loose way that modulus of elasticity is related to compressive strength. In a sense it may be that the impact-rebound measures strength of a thin surface layer of the concrete better than it measures modulus of elasticity.

The equations¹ describing the collision of two bodies for constant velocities are as follows: The first equation states the law of conservation of momentum; the second states the law of conservation of energy:

$$m_1v_1 + m_2v_2 = m_1V_1 + m_2V_2$$

$$\frac{1}{2}(m_1v_1^2 + m_2v_2^2) = \frac{1}{2}(m_1V_1^2 + m_2V_2^2)$$

where m and v (or V) are mass and velocity, the latter before and after collision. It will be noted that modulus of elasticity is not involved. These equations reduce to:

$$V_1 - V_2 = v_2 - v_1$$

for "perfect" masses. "Imperfect" masses obey:

$$V_1 - V_2 = e(v_2 - v_1)$$

where e is what has been called "recovery factor" or more properly "coefficient of restitution," but not modulus of elasticity; $e = 1$ for "perfect" bodies, $e = 0$ for completely inelastic materials that might adhere after collision so that $V_1 = V_2$. If two "perfect" bodies collide in frictionless space, each will proceed at a new velocity. When the plunger of the test hammer strikes the relatively large mass of concrete, the concrete may be considered to remain stationary; V_2 and v_2 are therefore zero, and

$$V_1 = -ev_1$$

The negative sign indicates that after impact the plunger velocity has changed direction. The amount that the test hammer rebounds depends on e , and the mechanical properties of the test hammer: springs, friction, etc. It is not known that a relation has been found between e and E . It is considered that e is related to the recoverable potential energy of the system and therefore inversely measures the damping capacity of the materials.² It would therefore be expected that any relations between rebound number and modulus of elasticity or rebound number and compressive strength would at least to a large extent be coincidental and not subject to generalization.

¹ Oldenburger, Rufus, "Mathematical Engineering Analysis", p. 17, The McMillan Co., 1950.

² Fruedenthal, Albert M., "The Inelastic Behavior of Engineering Materials and Structures, p. 540, John Wiley and Sons, 1950.

The view has also been expressed that a ball-indentation test may also serve as a means of determining the modulus of elasticity of concrete. A recent reference to a paper by Hofmann³ states that his paper describes a "ball-indentation test for testing rigidity of concrete; results with three different test specimens." From the comment quoted, it would appear that Hofmann believes that indentation results provide a measure of modulus of elasticity.

P. H. PETERSEN and U. W. STOLL, *Closure*—The authors wish to thank McCoy and Klieger for their valuable discussion of the paper. The additional data presented by Klieger is especially welcome, since it amplifies the range of concretes considered, and forestalls a premature conclusion regarding the character of the rebound number-sonic modulus relationship.

Recurring statements by McCoy, Klieger, and in informal comments which have been received, emphasize that dampening (expressed as coefficient of restitution, hardness, and hysteresis) likely has a greater influence on relative hammer reading than does the sonic modulus of the concrete. In light of those suggestions, the authors re-examined the strength and elastic data contained in Figures 2, 3, 8, and 10 of the paper. Table A of this discussion lists the strengths, hammer readings, and elastic moduli obtained from the curves. Since the hammer rebound scale is linear and the hammer springs obey Hooke's Law, the square of the rebound number is presented and is considered an index of the energy recovered after impact. The ratio of this energy index and the compressive strength is also tabulated. These ratios are plotted versus the companion sonic moduli as shown in the figure below the table.

This analysis indicates that the ratio of recoverable energy (R^2) to strength (f_c) is surprisingly constant over a wide range of strengths. The plot does suggest that the energy-strength ratio decreases with increasing sonic moduli, at least for the dry concretes and the low strength fog cured specimens.

The following analysis is presented in explanation of the above relation. Let us consider the energy loss upon impact of the hammer as

³ Hofmann, R. W., "Die Kugelfallprobe als Mittel zur Steifeproofung des Betons", Bauingenieur 29:5, May 1954, pp. 160-3.

AVERAGE PROPERTY VALUES OF CONCRETE, AGGREGATE "A"

(See figures 3, 4, 8 and 10 of Paper)

Age and Type of Curing	Re-bound Number (R)	Strength f_u' (psi)	R^2	R^2/f_u'	Sonic Modulus ($\times 10^6$ psi)
1 year, air dry	55	7,900	3,020	2.62	4.5
fog	30	2,200	900	2.45	4.5
1 year, air dry	58	8,700	3,370	2.58	5.0
fog	38	3,500	1,450	2.62	5.0
28 day, air dry	35	3,700	1,230	3.00	3.5
fog	21	1,400	441	3.18	3.5
air dry	41	5,000	1,680	2.98	4.0
fog	27	2,200	730	3.01	4.0
air dry	46	6,100	2,110	2.80	4.5
fog	38	3,700	1,450	2.55	4.5

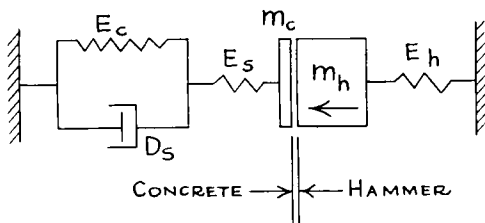


Figure 1. Phase 1, hammer moving to the left.

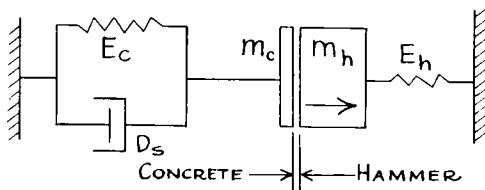
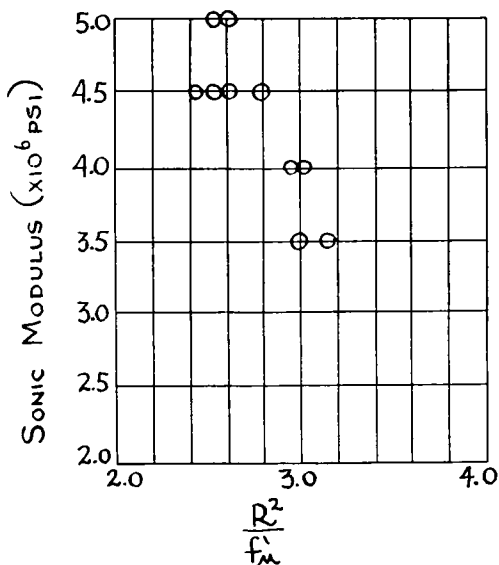


Figure 2. Phase 2, hammer moving to the right.



for wet concretes. Thus the greater the sonic modulus, the larger the decrease in hammer reading caused by dynamic dampening energy loss for dry concretes.

The authors feel that the decrease in energy index—strength ratio suggested by the plot at the end of this discussion roughly conforms with this analysis. The weaker, wet concretes (3.5 sacks per cubic yard) seem not to behave in the manner defined. The reason for this is not apparent at this time.

Figures 1 and 2 are a schematic representation of what has been indicated.

E_s = equivalent spring reaction of concrete being crushed = $f(f_u')$

E_c = f (sonic modulus of concrete)

D_s = f (dynamic dampening of concrete) = $f(f_u', E_c)$

$m_c \ll m_h$ = mass of hammer

E_h = loading springs constant for hammer

In addition to the above factors, there are others which will cause energy loss (friction, surface roughness, wind resistance, etc.) but these would, in effect, reduce the energy input a constant amount for given test conditions. The authors feel that the diagrams do indicate the most important variables involved in the concrete-hammer system.

REFERENCE

1. KESLER AND HIGUCHI: Compressive Strength of Concrete, A.S.T.M. Proceedings 1953, page 1050.

divided between two major causes: (1) dampening due to crushing of the concrete, and (2) dynamic dampening in the elastically deformed portion of the concrete, this value being related to the logarithmic decrement as measured by the sonic apparatus. Assume that the energy loss due to crushing (reduction in R^2) is inversely proportional to the compressive strength. If the strength is held constant, it follows that the hammer reading will be decreased as the dynamic dampening increases. Kesler and Higuchi (1) point out that for dry concretes at constant strength, the dynamic dampening *increases* as the sonic modulus increases, the opposite being true