SONIC TESTING OF STEEL REINFORCED CONCRETE

by

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ABSTRACT

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The effect that water-cement ratio, cement-aggregate ratio, reinforcing steel, and aggregate type have on pulse-velocity measurements in concrete is studied. Twenty-one concrete mix designs were developed and used to vary these parameters in plain concrete beams and cylinders and in reinforced beam specimens. A combination of sonic pulse-velocity testing and compressive strength testing was conducted for all mix designs as well as for six field core specimens removed from the deck of a bridge in service. An attempt to correlate laboratory specimen results with field specimen results is made with the ultimate goal of being able to predict the in-situ concrete properties of ultimate compressive strength and static modulus of elasticity by the use of pulse-velocity measurements. Results indicate that ultimate compressive strength and static modulus of elasticity as well as water-cement ratio, cement-aggregate ratio, aggregate type, weight density, percentage of reinforcement, and to a lesser extent, the proximity of reinforcement appear to be related to pulse velocity.

A correlation between "through" and "along" pulse-velocity measurement techniques is made, as well as a correlation between beam velocity measurements and cylinder velocity measurements. A relationship between dynamic and "initial tangent" static modulus of elasticity is made.

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CHAPTER I

INTRODUCTION

The Problem

There exist a great many bridge structures, of varying degree of importance, whose safety ratings cannot be accurately assessed because of uncertainty of the material strength, composition, or the internal condition of the structure. In light of recent failures, one of the most tragic being the Silver Bridge disaster of 1967, there has been an increased effort to maintain safe structures through regular inspection and analysis. Visual examination can be done quite readily. But, to analyze a structure, some knowledge of the material strength must be known. Many of the older structures are built of materials of which there is no material strength data available. Even when the original strength data can be obtained, it is not known how much the mechanical properties have changed since the time of building. It is also possible that the original specifications were not followed in the actual construction. Undetected flaws in construction materials may be present in a finished job. These are only a few of the reasons why the actual adequacy of a structure is not 100% certain.

A method to effectively determine the in situ condition of structural components is needed. To be economically feasible, such a method must not require the destruction of the structure tested. This would clearly defeat the purpose of testing a structure. This study is to explore the applicability of one of many non-destructive techniques of materials testing.

Non-destructive Testing of Concrete

The use of non-destructive methods of concrete testing found its first practical applications in Europe. Romania has had a standard for non-destructive testing of concrete since 1962.(1)* Non-destructive techniques have been used principally in Europe for routine construction inspection and quality control, while they have been used more for laboratory research in the United Kingdom. Research in these methods and in their applications to concrete has been carried on in the United States since the late 1930's, although they have not been adopted, to any great extent, in practical work.

In this country, the generally accepted method of testing the material properties of an existing concrete structure, or the quality of concrete in one under construction, involve testing a piece of the structure. Such testing assumes that samples from the structure are representative

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*Numbered superscripts in text denote references cited.

of the properties of the structure from which they are taken. There are many arguments against the likelihood of a sample of concrete being a representative one. When dealing with concrete, there are always variations in mixing conditions, variations in density due to improper distributions of fine and coarse aggregate in formwork, non-uniform compaction, and variations in curing conditions. These are variations within the structure itself. They are applicable to arguments against the dependability of samples cut from in situ concrete construction. When samples are taken from concrete being placed, the difference between them and the completed construction can be even more distinct. In general, the quality of a sample is better because it is more carefully made than the general construction, and is cured under more controlled conditions. Thus, it is apparent that non-destructive testing of the finished product will reduce or eliminate the sampling error associated with conventional means of concrete testing.

Purpose of the Study

In light of the difficulties encountered in determining the in situ properties of concrete by present sampling methods, it is the aim of this study to develop an alternate technique which is more applicable to the problem than present procedures.

The basic direction of this study is outlined by a research agreement, #2483, between the Ohio Department of Transportation and the Civil Engineering Department of Youngstown State University. The author, as a member of that research team, is using data taken in accordance with the research agreement in this report. Under this agreement, pulse-velocity testing of plain and reinforced concrete beams and cylinders was done. Although pulse-velocity testing is used in this study, it is not the only non-destructive test technique applicable to concrete.

The methods of non-destructive testing applicable to concrete fall into four major classifications. These are surface, vibration, radioactive, and electrical methods. Pulse-velocity techniques are part of the vibration class of methods. Vibration methods are generally of two types, resonant frequency and pulse propagation. Resonant frequency techniques are basically inapplicable here, because they require that a bridge or other large structure be vibrated at or near its resonant frequency. This is not only dangerous, but would require a great amount of power. For the properties of in situ concrete most useful for determining the adequacy of a structure, pulse propagation methods offer the most suitable method of investigation. The measurement of the velocity of a sonic pulse through a concrete structure is the key topic of this study.

The in situ properties of concrete which are essential to the determination of its value in a structure are principally its mechanical strength, and to a lesser extent, its elastic modulus. Only two methods are presently available to determine the mechanical strength non-destructively. They are surface hardness and vibrational methods. Surface hardness, as it implies, relates the hardness of the concrete to its strength. An obvious drawback to this method is that any surface in an older structure must be well preserved to give a valid strength indication of concrete throughout. Generally speaking, the concrete on the surface of a bridge structure is deteriorated and its hardness would be less than the interior mass of concrete. However, the pulse-velocity method offers a method to testing the entire mass of concrete. Pulse-velocity testing involves the passing of a sonic pulse through the entire mass, thus giving an indication of the overall concrete condition. The velocity of the sonic pulse can be related, in some cases, to the mechanical strength of the concrete. The relationship between pulse-velocity and concrete strength is empirical and in general can only be obtained with concretes of known composition. Pulse-velocity tests lend themselves most readily to applications on bridges, and may prove to be a valuable inspection technique, once correlated with the properties of the particular concrete being tested.

This study is concerned with the correlation between pulse-velocity measurements and the strength and elastic modulus of four aggregate types of concrete. The types are limestone, river gravel, glacial gravel and slag, as coarse aggregates, with natural sand as the fine aggregate. These are chosen because they occur commonly in bridge construction in Ohio. The parameters which can be controlled in the laboratory, that have an effect on pulse velocity, are varied to determine their relationship to pulse-velocity readings. Pulse-velocity readings through the concrete and along its surface are taken as an additional parameter of variation. A relationship between laboratory specimen test results and in situ material properties is attempted by the testing of core borings taken from an existing bridge deck.

State of the Art and Approach

Pulse-velocity testing of concrete is accomplished by the passing of a mechanical pulse, or soundwave, through the concrete. Although a true soundwave is a mechanical wave which falls within the normal audible frequency range of 30 to 17,000 cycles per second, pulse-velocity testing using frequencies higher than that range has been done, mainly on materials other than concrete.(2) "Sonic" testing is generally understood to include methods using vibrational frequencies in the ultrasonic region.

When a sonic pulse is induced into an object, its propagation through the object takes three basic waveforms. First, a wave in the longitudinal direction of the material is induced; this is called the longitudinal or compressional wave. The longitudinal wave travels fastest of the three waves. Secondly, a wave normal to the longitudinal wave is formed. This is the second fastest traveling wave and is called the shear wave. The third and slowest traveling wave is the Rayleigh wave which radiates on the surface of the object. Current pulse-velocity techniques involve only the measurement of the longitudinal wave, since it is easily distinguished and measured. The instrument which is used to measure the time of travel of the longitudinal wave over a given distance is the soniscope.

The development of the soniscope began in 1945 in an effort to develop a technique for examining cracks in dams.(3) The first soniscopes basically consisted of a pulse generator and a receiver which were connected to timing circuits that were activated by the sending and receiving of the sonic pulse. A visual trace of the sent and the received signals was displayed on a cathode ray tube which was calibrated so that the time between the two signals could be accurately measured. This required some judgement on the part of the operator. The early electronic units were much heavier than the present ones. Since the first units, the equipment has become more sophisticated, although basically still an electronic timing device. Some present day soniscopes have digital time readouts, accurate to within 0.1 microsecond, and weigh as little as seven pounds. Testing with a modern soniscope requires little human judgement and therefore the results are highly reproduceable.(4)

The efforts of past researchers show a divergence of opinion as to the ability to rate the strength of concrete by use of sonic tests. A better correlation between strength and pulse velocity seems to exist when the composition of the concrete is known. According to American Society for Testing and Materials (ASTM) Specification C597-71, the quality rating and uniformity of in situ concrete can be determined by use of pulse-velocity testing. The following table is recommended as a "rule of thumb" guide in judging concrete quality.$^{(5)}$

TABLE 1

RELATIONSHIP BETWEEN PULSE-VELOCITY AND CONCRETE QUALITY

Pulse Velocity (feet/sec.)	General Condition
Above 15,000	Excellent
12,000 - 15,000	Good
10,000 - 12,000	Questionable
7,000 - 10,000	Poor
Below 7,000	Very Poor

Many tables similar to the one above have been produced.

The theoretical relationship between compressional wave velocity and the dynamic modulus of elasticity has been established by Rayleigh to be

$$V = \sqrt{\frac{E_d}{\rho}}$$

where V = velocity of sound through the medium

E_d = dynamic modulus of elasticity

ρ = density of the medium

This formula is applicable to beam specimens and must be modified where slabs or mass concrete is being tested, where the effect of Poisson's ratio must be considered. It should be noted that the dynamic modulus of elasticity and that obtained by quasi-static stress-strain curves are different and are related only by empirical means.

The relationships between factors which have an effect on pulse velocity, and the relation between pulse velocity and the mechanical properties of strength and elastic modulus of concrete, are explored in this study. The pertinent factors which effect pulse velocity and which are used as variables in this study are:

1. Water-cement ratio
2. Aggregate-cement ratio
3. Aggregate type
4. Proximity of reinforcing steel

CHAPTER II

LABORATORY PREPARATIONS

Variation of Concrete Parameters

In order to investigate the effects of the water-cement ratio and the cement-aggregate ratio on the sonic pulse velocity, a method of concrete parameter variation and control had to be devised. This method had to yield concrete mixes that were widely varied but still within a practical range of workability. All mixes were designed to have an entrained air content of 5 to 7%, using Ohio Construction and Materials Specification's Number 57 coarse aggregate, and natural sand as fine aggregate. The 5 to 7% air content was obtained by the use of type 1A Portland Cement as required by the Ohio Department of Transportation.

The prime factor used to determine the range of parameter variation was the workability of the finished batch of concrete. This is because the batch had to be one which could be placed in forms and around reinforcing steel with a minimum of concrete "honeycombing" at the "stiff" end of the consistency range and one which would not suffer from aggregate segregation at the "wet" end of the range.

By the use of tables in the eleventh edition of "Design and Control of Concrete Mixtures", published by the Portland Cement Association, a range of workable concrete mixes was obtained.[6] The parameters of water-cement ratio (w/c), cement-aggregate ratio (c/a), and water-aggregate ratio (w/a) are related by the equation

$$(w/c) \times (c/a) = (w/a)$$

where these ratios are weight ratios. In Table 12 of the above-mentioned reference, the water-aggregate ratio remains fairly constant over the range of water-cement ratios given. This table is for air-entrained concrete of medium consistency, i.e., 3 to 4" slump. For the case of a moderate strength concrete with a 0.50 water-cement ratio and a 1" maximum aggregate size, for one cubic yard of concrete, the total water weight is 285 lbs. and the total aggregate weight is 2960 lbs. To vary the slump, which is a measure of workability, the water weight range was extended by 30 lbs. higher and lower than the case for concrete of medium consistency. This extension was estimated to give a slump range of about 1 to 6" by using information noted in the table. A slump of 1 to 6" is a practical range of concrete consistency. Using a constant total aggregate weight of 2960 lbs. and a water weight range of 255 to 315 lbs., the resulting water-aggregate ratio range is about 1/12 to 1/9. Thus, it was concluded that any concrete mix with a combination of water-cement and cement-aggregate ratios that yield a water-aggregate ratio in the range of 1/12 to 1/9 is a workable mix, provided that the ratio of fine to coarse aggregate is normal. For a 1" maximum aggregate size, a 1/2 fine to coarse aggregate ratio is about normal and was used in all concrete mixes fabricated for testing in this study. It was in this manner that the concrete mixes used in this study were derived. These mix combinations are shown in Table 2, with the "workable" mix combinations shown within the diagonal band.

In Table 2, the row of numbers just above the double line indicates the cement-aggregate ratio of the mix as noted by "c/a" to the left. The row of numbers above these corresponds to the cement aggregate ratios. The partial row of numbers above these (c/a numbers 3 through 6) are the group numbers for a group of at least three workable mixes of constant cement/aggregate ratio. These mixes have a water-aggregate ratio within the diagonal band. The numbers just to the left of the double line indicate the water-cement ratio as noted by "w/c" above. The column of letters to the left of these corresponds to the water/cement ratios. The numbers in the column to the extreme left are the group numbers for a group of at least four workable mixes of constant water-cement ratios.

To prove the validity of the mix workability by the use of the water-aggregate ratio method, test batches of mixes at the extremes of the range were made. In all cases, the consistency of the mix was satisfactory. With this established, the mix proportions of all concrete batches used in this study were chosen and used for four different aggregage types.

TABLE 2

COMBINATIONS OF WATER-CEMENT RATIOS AND CEMENT-AGGREGATE RATIOS YIELDING WATER-AGGREGATE RATIOS IN THE RANGE OF 1/12 TO 1/9, BY THEIR MULTIPLICATION

					CA-1	CA-2	CA-3	CA-4		
			1	2	3	4	5	6	7	8
		C/A W/C	$\frac{1}{7}$	$\frac{1}{6.5}$	$\frac{1}{6}$	$\frac{1}{5.5}$	$\frac{1}{5}$	$\frac{1}{4.5}$	$\frac{1}{4}$	$\frac{1}{3.5}$
WC-1	A	$\frac{4}{10}$	$\frac{4}{70}$	$\frac{4}{65}$	$\frac{4}{60}$	$\frac{4}{55}$	$\frac{4}{50}$	$\frac{4}{45}$	$\frac{4}{40}$	$\frac{4}{35}$
WC-2	B	$\frac{4.5}{10}$	$\frac{4.5}{70}$	$\frac{4.5}{65}$	$\frac{4.5}{60}$	$\frac{4.5}{55}$	$\frac{4.5}{50}$	$\frac{4.5}{45}$	$\frac{4.5}{40}$	$\frac{4.5}{35}$
WC-3	C	$\frac{5}{10}$	$\frac{5}{70}$	$\frac{5}{65}$	$\frac{5}{60}$	$\frac{5}{55}$	$\frac{5}{50}$	$\frac{5}{45}$	$\frac{5}{40}$	$\frac{5}{35}$
WC-4	D	$\frac{5.5}{10}$	$\frac{5.5}{70}$	$\frac{5.5}{65}$	$\frac{5.5}{60}$	$\frac{5.5}{55}$	$\frac{5.5}{50}$	$\frac{5.5}{45}$	$\frac{5.5}{40}$	$\frac{5.5}{35}$
WC-5	E	$\frac{6}{10}$	$\frac{6}{70}$	$\frac{6}{65}$	$\frac{6}{60}$	$\frac{6}{55}$	$\frac{6}{50}$	$\frac{6}{45}$	$\frac{6}{40}$	$\frac{6}{35}$

Variation of Reinforcing Steel Location

To test the effect of the proximity of reinforcing steel to the surface through which a sonic pulse is being passed, reinforced concrete beams were fabricated. The nominal beam dimensions were 4" wide × 4" high × 48" long. However, due to ease of building the steel forms to a slightly wider dimension and the use of steel end plates to support reinforcing steel, all beams were wider than 4" and reinforced beams were somewhat less than 48" long. Two reinforced beams were cast with three plain concrete beams as a control, for each mix design tested. With the two reinforced beams, three depths of steel could be obtained. Since the nominal beam depth was 4", a 2" distance from the center line of reinforcing steel to both the top and bottom beam surfaces could be obtained when the reinforcing steel was positioned at the center of a beam. When the center line of reinforcing steel was placed 1" from the top beam surface, a 3" depth from the bottom surface was obtained. Thus, by flipping the beam, two depths of reinforcing steel were yielded. The reinforcing for each reinforced beam consisted of two Number 5 deformed round steel bars, placed at the appropriate depth below the concrete surface and separated by a distance of 2" center-to-center. Figure 1 shows cross-sections of the reinforced beams.

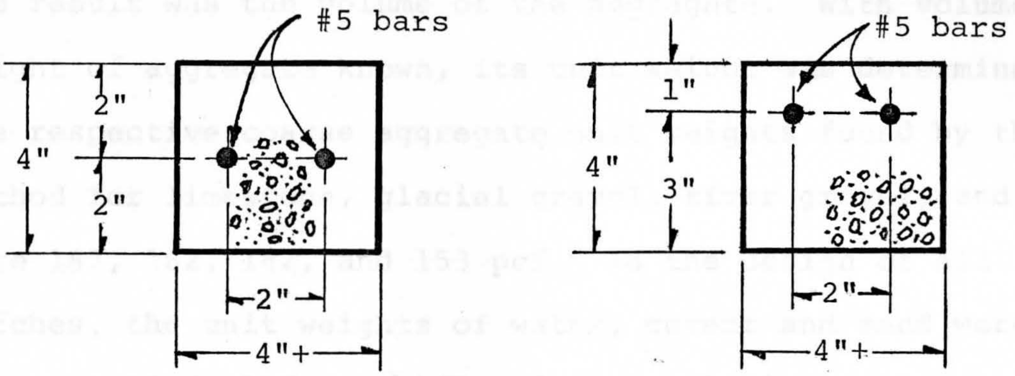


Figure 1. Beam Cross-section Showing Position of Reinforcing Steel.

Aggregate Testing and Mix Design

As all mix designs in this study are based on weight ratios, the absolute density, or unit weight, of the components of concrete, therefore, were necessary to relate these weights to the finished batch volume. A certain amount of aggregate testing was necessary to proceed with the design of a mix. Each coarse aggregate, limestone, river gravel, glacial gravel and slag, was tested for its unit weight, γ. The method of unit weight testing was by use of a 1/3 cubic foot bucket. The procedure was to weigh the bucket and then to note its weight increase after it was filled level with coarse aggregate. After that, the voids in the bucket were eliminated by filling the bucket to the top with water and recording the added water weight. Knowing the unit weight of water and the increased water weight, the void volume occupied by the water could be determined. When the void volume was subtracted from the known volume of the bucket, the result was the volume of the aggregate. With volume and weight of aggregate known, its unit weight was determined. The respective coarse aggregate unit weights found by this method for limestone, glacial gravel, river gravel, and slag were 167, 162, 162, and 153 pcf. In the design of all batches, the unit weights of water, cement and sand were taken at 62.4, 196, and 165 pcf respectively.

Since aggregates generally take some water away from the cement hydration process by absorption, it was thought necessary to determine the water correction factor needed to actually mix a batch of concrete to the desired final proportions. All concrete components were air-dry at the time of concrete mixing and assumed to absorb a certain amount of the water available during the mixing process. Thus, a lesser amount of water than added to the mix is available to participate in the cement hydration process. For all fine and coarse aggregates, with the exception of slag, the water absorption was taken to be 1% by weight.(7) The water absorption of slag was found to be 2.75% @ 1 hour in going from an air-dry state to a surface-moist state. Slag was the only aggregate tested for water absorption because it exhibited an unusually high affinity for water. The percentage absorption at 1 hour was used because the mixing and forming operations generally required about 1 hour to perform.

Sieve analyses of both fine and coarse aggregates were conducted on representative samples. The fineness modulus of the sand was determined and used as a means of controlling the usability of each batch of sand. In general, a fineness modulus of 2.5 was considered ideal. The sieve analysis of coarse aggregate was done to check the conformance to the State of Ohio specification for Number 57 coarse aggregate. The results of the sieve analyses are given in Appendix A.

As a prelude to the production of a great number of concrete specimens of varying composition, a method of batch and specimen identification was devised. As explained and as shown in Table 2, the cement-aggregate ratio of a mix is represented by a number given at the top of the column. A letter given at the left of the row represents the water-cement ratio of the mix. The coarse aggregate of a mix is represented by a second letter. These identification letters are as follows: "L" for limestone, "G" for glacial gravel, "R" for river gravel, and "S" for slag. These three basic qualities of water-cement ratio, cement-aggregate ratio, and aggregate type were used to identify concrete mixes and specimens made from those mixes. Referring to Table 2, a mix with a water-cement ratio of 4.5/10, a cement-aggregate ratio of 1/5, and limestone for coarse aggregate would be designated "B5L". Thus, all mix combinations can be designated by three characters.

In this study, mixes under group numbers WC-2 and CA-3, as shown in Table 2, were tested for various coarse aggregate types. This lead to a total of twenty-one different mix combinations as shown in Table 3.

TABLE 3

CONCRETE MIX COMBINATIONS

MIX GROUP	AGGREGATE TYPE Limestone	Glacial Gravel	River Gravel	Slag
CA-3	A5L B5L C5L D5L	A5G B5G C5G D5G	A5R B5R C5R D5R	A5S B5S C5S D5S
WC-2		B3G B4G B5G B6G		B3S B4S B5S

The actual mix design procedure was as follows. The absolute density, or unit weight, of each component of the concrete mix was listed. A total aggregate weight of 100 lbs. was chosen, and the fine and coarse aggregate weights proportioned accordingly. Based on the coarse aggregate weight and the cement-aggregate ratio, the cement weight was found. Knowing the cement weight and the water-cement ratio, the water weight was found. The weight of the air was taken as zero. Next, the chosen weight of each component was divided by its unit weight. This yielded a trial volume for each component of the mix except the air. The trial air volume was obtained by multiplying the sum of the trial weights of all the other components by 0.0638. This made the trial air volume 6% of the total volume. The volumes were then proportionately adjusted to a total volume of one cubic foot. These volumes were then converted back to component weights by multiplying them by their unit weights. The sum of these weights gave the theoretical unit weight of the final mix. Based on the final aggregate weights, an additional water weight adjustment was made. After completing and adjusting the mix proportions for one cubic foot of concrete, these amounts were increased as necessary to make a concrete batch large enough to fabricate five beam specimens plus at least two cylinder specimens. A sample mix design can be seen in Appendix B, along with a table of the material composition of all mix designs in this study.

Specimen Fabrication and Curing

After the concrete batch weights were measured, they were mixed in a 3-1/2 cubic foot tilting mixer which was powered electrically for laboratory work. The mixing process was allowed to continue until all mix ingredients were thoroughly interspersed. During the mixing process, the steel forms were prepared by coating all surfaces which would come into contact with the fresh concrete with an oil film. Steel end plates, designed to support the reinforcing steel were also coated and placed in the forms with reinforcing steel bars in place. Care was taken not to get any form oil on the reinforcing steel bars. Once the forms were prepared and the concrete completely mixed, the concrete was placed into a form by the use of hand scoops and periodically compacted with the scoop as it was placed. After the form was filled, the top surface was screeded level with the top of the form with a trowel. The sides of the beam were also troweled by slipping the blade of the trowel along the inside of the form. At this point the form was vibrated until all voids in the concrete were thought to be closed. The vibration of the form was accomplished by use of a small concrete vibrator of the type typically used in field construction. Next, the top surface was made as smooth as possible with the trowel. The beam was then placed in a moist-curing room. A similar procedure was followed until three plain concrete and two reinforced concrete beams were fabricated. With the remaining concrete, 12" × 6"-diameter cylinder specimens were made using the standard three layer method with 25 roddings per layer. These were also placed in the moist-curing room with the other fresh concrete specimens. All specimens were protected from contact with water droplets by a canopy of plastic sheeting until the initial concrete set. After at least two days curing time, the beam and cylinder specimens were carefully stripped from their forms and marked with their mixture designations by the use of an indelible fiber-tipped pen. The specimens were then placed back into the moist curing room until a 28-day curing time was obtained.

Field Specimen Preparation

As part of the research project, core samples from an existing bridge structure were taken. The purpose in taking the core samples was to measure the physical properties such as density, aggregate type and aggregate size so that pulse-velocity measurements and strength properties of these specimens could be compared to those of similar laboratory specimens. Because of state funding for the project, a state owned bridge in the vicinity of the university was chosen as a test structure. The structure, MAH-62-19.33, the McGuffey Bridge, is located in Mahoning County and is under the jurisdiction of Division 4 of the Ohio Department of Transportation. The facility is made up of twin bridges, each carrying a sidewalk and two of the four traffic lanes. A concrete median joins the two bridges at the center of the four traffic lanes. The five-span, continuous steel girder bridges have reinforced concrete decks, piers and abutments. The structure carries U. S. Route 62, and Ohio Route 7 over Crab Creek, in Youngstown, Ohio. The deck showed some signs of surface deterioration. Core samples were taken from the deck in the right hand lane of the northerly bridge by the Ohio Department of Transportation coring crew. Under the direction of Dr. Paul X. Bellini, a total of six specimens were extracted from various locations in the lane. At least one specimen was taken from each span. Four inch diameter cores were cut the full depth of the eight inch thick deck.

As each specimen was extracted from the deck it was numbered. Laminar cracking in the deck caused some samples to contain transverse cracks which completely separated the top few inches from the bottom. Of the six samples taken, four contained at least one piece of reinforcing steel embedded in it. One specimen had a longitudinal crack which penetrated about 2-1/2 inches in from the top surface. Only one core sample contained no cracks and no reinforcing steel. Common to all specimens was slag as the coarse aggregate. The maximum aggregate size used in the deck from which the cores were taken appeared to be one inch. (See Fig. 2.)

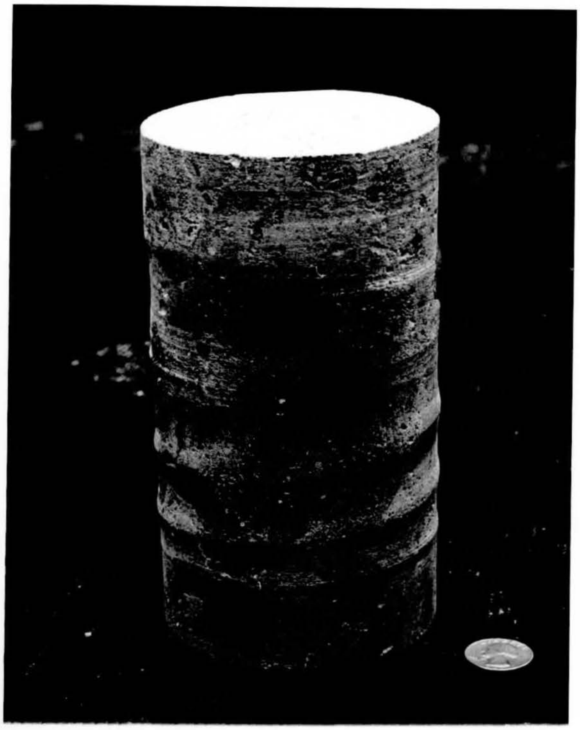


Figure 2. Close-up of Core Sample Showing Embedded Reinforcing Steel. Aggregate Size, and Aggregate Type.

Laboratory preparation of the core samples bagan with the sawing off of the ends of the specimens to provide a smooth, flat surface for sonic testing. This also eliminated the surface deterioration at the ends of the specimens. When possible, the specimen length, after the ends were removed, was 7 inches. However, when a considerable portion of the top surface was missing, the samples were cut to a height of 5 inches. Both the seven and five-inch heights are acceptable for testing for four-inch diameter cores, according to ASTM Specification C42-68. The six core specimens were then ready for sonic and strength testing in the laboratory. (See Fig. 3.)

Figure 3. Core Samples After Preparation for Sonic and Strength Tests.

CHAPTER III

DATA COLLECTION

Equipment and Instrumentation

In general, laboratory tests were performed to determine five basic parameters of each of the twenty-one concrete mixes tested. The same tests were performed on the field specimens when possible. Mix specimen tests consisted of determination of weight density, ρ, pulse velocity through, V_t, pulse velocity along, V_a, ultimate compressive strength, f'_c, and modulus of elasticity, E.

For weight density determination, the only items of equipment necessary were length measuring devices and weight measuring devices. The laboratory scale used to weigh concrete laboratory specimens was accurate to the nearest half pound and had a capacity great enough for any fabricated beam or cylinder specimen to be weighed. A smaller beam balance was used to weigh the field specimens with an accuracy to the nearest gram. For length measurement of the finished beam specimens, a steel surveyor's tape was used for measurements to the nearest hundredth of a foot. For the remainder of specimen measurements, a steel caliper rule capable of accuracy to one thousandth of an inch was used. These instruments were more than adequate for concrete density determination because surface irregularities and the lack of homogeneity in concrete offset much of this precision.

For pulse-velocity measurements, a velocity meter commercially available from the instrument division of James Electronics, Inc. was used. The meter is a lightweight, portable unit which can be operated on its internal, rechargable battery for up to five hours. The unit can also be run for longer periods by the use of an external, 12 volt storage battery, or an AC to DC convertor with a 12 volt output. These features make this an ideal device for field measurements of pulse velocities in concrete. The basic function of the velocity meter is to transmit, then receive, a pulse of energy and measure the transit time of this pulse through a given medium. This is achieved through the use of transducers which convert the electrical energy generated by the transmitter into a mechanical wave in the medium with which the transducer is in physical contact, and back to an electrical impulse when the mechanical wave excites the receiving transducer. The travel time of the wave between transducers is produced on a digital display by the meter. The time displayed is the time elapsed between pulse transmitted to pulse received, as measured by the high speed electronic clock within the velocity meter. Since the velocity meter does not truly measure velocity, but time, the distance between the centers of the transducers must be known to determine the true transit velocity of the sonic pulse. Also, since some losses do occur in the internal circuits between the pulse transmitter and the pulse receiver, a calibration bar is provided with the velocity meter so the device can be adjusted for circuit losses before each test. Another feature of the device is its ability to be used in conjunction with an oscilloscope to display the waveform of the sonic pulse after it has propagated through the specimen. The complete sonic testing setup can be seen in Figure 4, which shows the velocity meter being calibrated under the power of an external AC to DC convertor and the received pulse waveform being displayed on the oscilloscope.

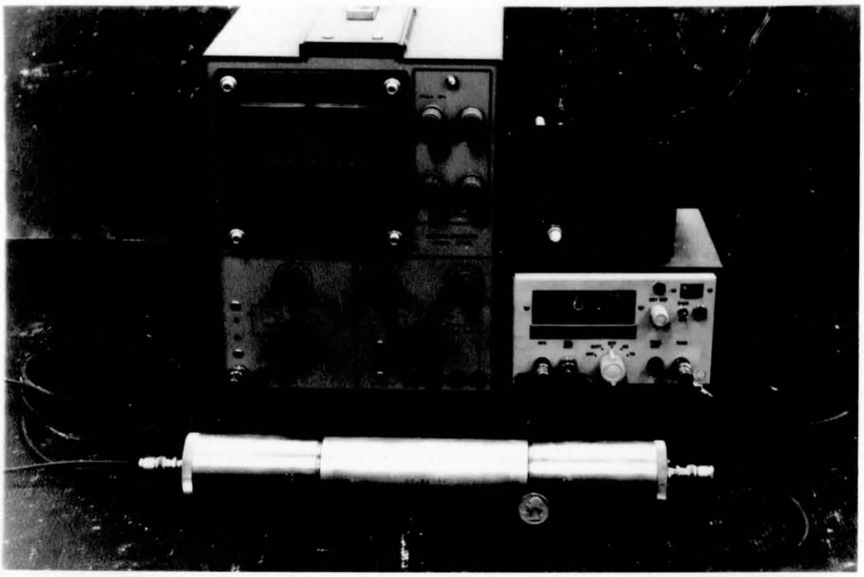


Figure 4. Complete Sonic Pulse Velocity Testing Setup.

The specifications for the C-4899 V-meter (velocity meter) as supplied by James Electronics, Inc. are as follows:

TIME MEASUREMENTS:	0.1 to 1000 microsecs range.
Units	Two ranges can be selected with units of either 0.1 or 1 microsec. Timing pulses derived from a 10 MHz crystal oscillator.
Accuracy	±0.1 microsec.
INPUT SENSITIVITY:	100 microvolt between 30 kHz and 100 kHz
Signal	Instrument may be used with input frequencies outside this range but with reduced sensitivity.
Impedance	Approx. 2MΩ
TRANSMITTER:	
Energising pulse	800 v peak, 2 microsec.
Pulse repetition frequency	10 pulses per sec. nominal.
POWER SUPPLY:	
Battery	Internal rechargeable Ni-Cd battery. Capacity for at least 5 hours continuous use.
Battery charger	Built-in constant current battery charger.
External	11 to 13 volts from a storage battery. Consumption 4W
Line	Line power supply unit available for delivering 12 v supply from 117 v, 60 Hz power line.
DISPLAY:	3 'in-line' numerical indicator tubes.
CIRCUIT:	Uses silicon semiconductors throughout. Decade and indicator boards use T.T.L. integrated circuits.
DIMENSIONS:	180 × 110 × 160 mm (7" × 4½" × 6½").
WEIGHT:	3.2 kg (7 lb) including battery.
AMBIENT TEMP. RANGE:	0°C to 40°C (in leather case).

For the determination of the ultimate compressive strength and elastic modulus of laboratory or field specimens, cylinders or core samples were loaded to failure in a hydraulic testing machine. The machine was equipped with a pen recorder to plot applied load against measured deflection. During a test, the machine automatically compresses the test specimen at a controlled rate while the load deflection curve is being plotted. The operating setup of the compression test for one of the field specimens can be seen in Figure 5.

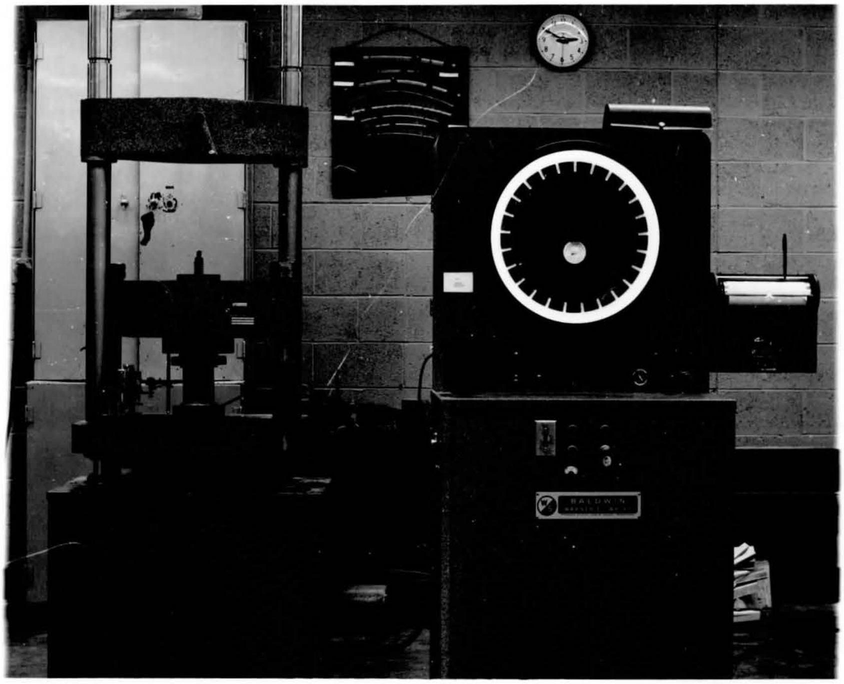


Figure 5. Complete Compression Test Setup.

Description of Tests

After a moist cure of at least twenty-eight days, a typical batch of laboratory test specimens was taken out of the moist-curing room to air dry. A typical set of two reinforced beams, three plain beams, and at least two cylinders was allowed to shed excess moisture by being placed in the normal atmospheric conditions of the laboratory for a minimum of forty-eight hours before any kind of tests were performed. Field specimens were prepared as described in Chapter II. At this point, the laboratory testing followed the sequence depicted in Figure 6. As each concrete mix design was tested, data was recorded on data sheets as presented in Appendix C.

In common practice, concrete mixes are designed to meet certain strength and durability requirements. To relate the strength of the mix designs of this study to those of a more conventional design, the breaking strength of a twenty-eight-day-old cylinder of each mix was determined. The standard cylinder size, six inches in diameter by twelve inches high, was used for consistency of results with industry-wide practice. Since the twenty-eight-day cylinder test was performed only to measure the ultimate compressive strength of the concrete mix design, no other tests were performed on the cylinder.

The procedure for the twenty-eight-day test for the ultimate cylinder compressive strength was simple. The cylinder, after having been moist-cured for twenty eight days,

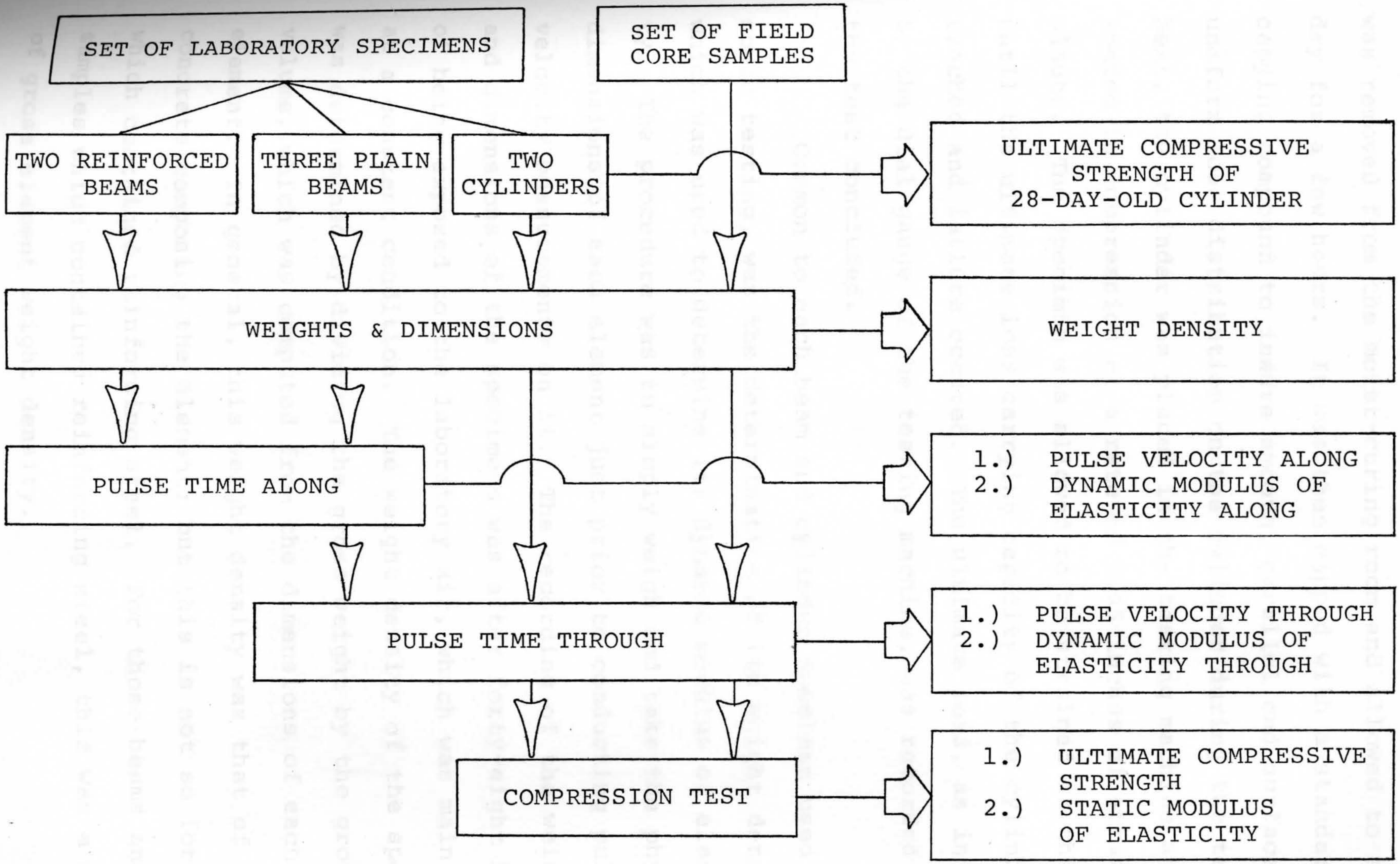


Figure 6. Flow Chart of Laboratory Tests Performed and Results Yielded.

was removed from the moist-curing room and allowed to surface dry for a few hours. It was then capped with a standard capping compound to insure smooth, parallel end surfaces for uniform load distribution on the cylinder during the test. Next, the cylinder was placed in the testing machine and loaded in compression at a rate of 0.05 inches of strain per minute. The specimen was allowed to be strained at this rate until the ultimate load carrying capacity of the cylinder was reached and failure occured. The ultimate load, as indicated by the dial gauge of the testing machine, was recorded and the test concluded.

Common to each beam and cylinder specimen used for sonic testing, was the determination of its weight density, which was used to determine its dynamic modulus of elasticity. The procedure was to simply weigh and take the physical dimensions of each element just prior to conducting pulse velocity measurements on it. The recording of the weight and dimensions of the specimens was after forty-eight hours of being exposed to the laboratory air, which was maintained at a constant condition. The weight density of the specimen was determined by dividing the gross weight by the gross volume, which was computed from the dimensions of each element. In general, this weight density was that of the concrete composing the element; but this is not so for those which contained reinforcing steel. For those beams and core samples which contained reinforcing steel, this was a measure of gross element weight density.

Two types of sonic testing were performed. Velocity-along tests, which were done only on the beams, is characterized by the fact that both transducers are coupled to the same flat concrete surface and are perpendicular to it. With this testing method, the sonic pulse is passed indirectly from one transducer to the other. This method is useful when testing concrete structures where only one surface is accessible, such as a bridge deck. Velocity-through tests are characterized by the passing of the sonic pulse directly through the medium by transducers placed on opposite faces of the element under test. (see Fig. 7)

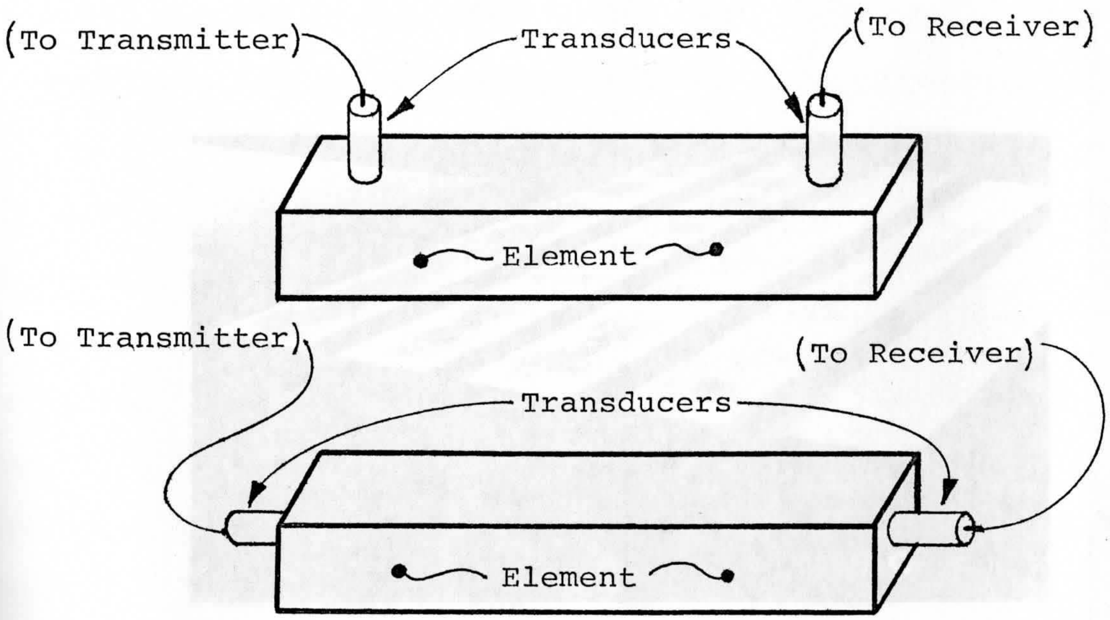


Figure 7. Difference between velocity along (top) and velocity through tests of an element.

For sonic testing, beams and cylinders were placed on a work table in the laboratory which was covered with an insulating material to acoustically isolate the specimens as much as possible. Beams were insulated by about one-half an inch of a material manufactured from recycled newspaper. This material also provided continuous support of the beams. Cylinders were similarly insulated and supported, for sonic testing, by an inch of expanded polystyrene foam. Attempts were made at passing a sonic pulse along these insulating materials, but they would not carry a pulse. A typical set of beam specimens ready for sonic testing can be seen in Figure 8.

Figure 8. Typical Set of Beam Specimens Ready for Sonic Testing.

Pulse velocity-along measurements were taken only on beam specimens. A total of seven different transducer positions were used to help "average" out any error of measurement. Each beam specimen was approximately four feet long, leaving the middle three and one-half feet to be tested at intervals of six inches. This was achieved by placing the receiving transducer in a stationary position near one end of the beam and moving the transmitting transducer towards it, from near the other end of the beam, in steps of six inches. A template made of thin plywood was used to position the transducers on the top surface of the beam under test. The template, which was of approximately the same dimension as the top surface of the beams, had holes of about the same diameter as the transducers drilled at six-inch intervals along the middle three and one half feet of its center line. This made the positioning of the transducers a fast and accurate procedure. It was found that the plywood template would transmit a sonic pulse. However, time measurements taken on a typical concrete beam showed no difference if the template was left in place during the test or removed before time measurements were taken. This is probably because the velocity of pulse propagation is significantly slower in the wood than in concrete and only the time of the first pulse to reach the receiving transducer is displayed. An acoustic coupling of the transducers to the concrete surfaces was accomplished by means of a thin film of water pump grease of a rather high viscosity. A supply of this came with the velocity meter and is the manufacturer's recommended couplant. It was used as a couplant for all operations involving the use or adjustment of the velocity meter.

A typical pulse velocity along test of a set of beams was as follows. The velocity meter was set up at one end of the table and calibrated to the velocity value indicated on the calibration bar provided with the velocity meter for this purpose. Grease was used to couple the transducers and the calibration bar which was supported on a pad of styrene foam during the process. A firm hand pressure was used to squeeze all but a very thin film from between the transducers and the surface with which they were in contact. The velocity meter was then adjusted until the reading was steady at the value indicated on the calibration bar. The velocity meter is shown adjusted to the bar valve in Figure 4. The first plain concrete beam was then cleaned with a brass-bristled brush to remove all loose material from the top surface of the beam, as were all specimens before they were sonically tested. The plywood template was then fitted on the top surface of the beam, and grease was applied to the beam area exposed through the holes in the template. Then, the receiving transducer was placed through the template to the concrete surface, on one end of the beam, and likewise with the transmitting transducer on the other end. During this process, the equipment was left on and undisturbed. With the aid of an assistant, the excess grease film was slowly pressed out between the faces of the transducers and the concrete. This was done by applying a firm downward pressure to the transducers and twisting slightly in a manner and magnitude similar to that used to calibrate the instrument. This process was continued until the digital display of the velocity meter was steady. This was a slow process which required a certain amount of judgement to know when the best reading was obtained. After the operators were satisfied with the digital readout, the value was recorded. At this point, the transducers were three and one-half feet apart. Then, the transmitting transducer was moved to the next hole in the template, six inches toward the receiver. This was done without disturbing the template or receiving transducer. Another digital readout of the time of pulse traverse between the transducers was recorded for that location. This process was repeated, in six-inch increments, until the transducers were six inches apart. A time through the beam was next taken and recorded. The same technique was used to test the remaining plain and reinforced beams with periodic calibration checks performed on the equipment. The time-through measurements were not taken on the reinforced beams because the projecting ends of reinforcing bars did not permit it. The process of measuring time along a beam can be seen in Figure 9 with the template removed for clarity.

Problems with a rough concrete surface on the reinforced concrete beams which were tested on both sides, to obtain a reading at two different reinforcing depths, necessitated grinding the surface smooth before testing.

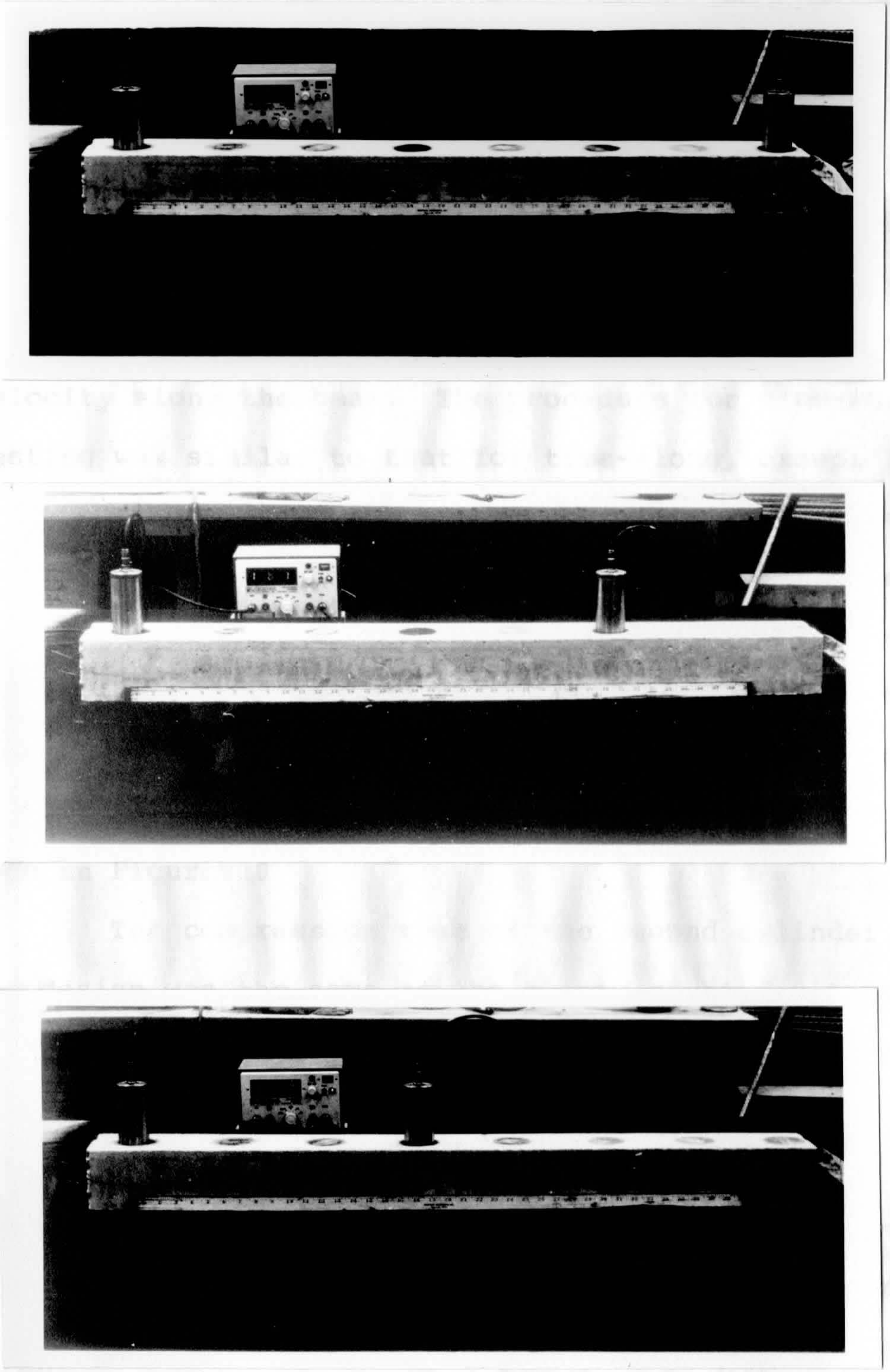


Figure 9. Measurement of Sonic Pulse Time Along a Beam.

This occured on the surface which was not cast against the steel form. All other time-along measurements were done on the smooth beam surface cast against the form.

Pulse time-through tests were performed on the three plain beams and one cylinder per mix design, and on the core samples. For the plain beams, the time-through tests were conducted as a means of comparing velocity through to velocity along the beam. The procedure for time-through testing was similar to that for time-along, except in the placement of the transducers. After surface preparation, the transducers were placed on the end faces of a beam or cylinder and pressed to remove excess couplant and to stabilize the reading on the velocity meter. The transducers were aligned visually, without the aid of a template. The measurement of sonic pulse time through a cylinder can be seen in Figure 10.

The compression test of the second cylinder of each mix design was the same as the twenty-eight-day test of the first, but this time, the load vs. deflection characteristics were recorded by the testing machine. These curves were later reduced to their form in Appendix D.

Field specimens were moisture conditioned and capped as per ASTM Specification C42-68, before their compression test. The compression testing of a typical field specimen can be seen in Figures 11 and 5.

Figure 10. Measurement of Sonic Pulse Time Through a Cylinder.

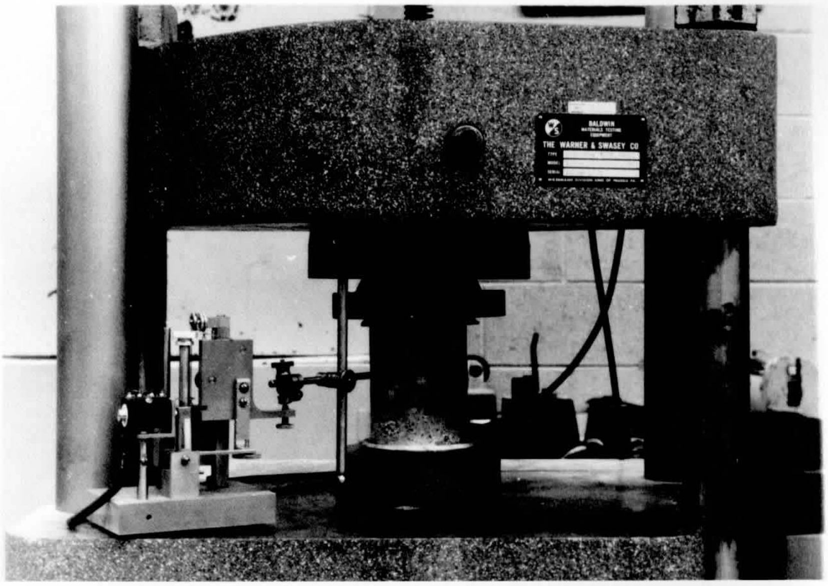


Figure 11. Compression Test of a Field Specimen.

CHAPTER IV

DATA ANALYSIS

Selection of Variables of Comparison

An attempt is now made to establish some useful relationships between the controlled input variables and the output variable of pulse velocity. The controlled input variables are the aggregate type, water-cement ratio, cement-aggregate ratio, and the proximity of reinforcing steel. The development of some relationship between pulse velocity and the strength and elasticity of concrete is also to be attempted, since such a relationship would be of great practical value.

Upon close examination of the data taken, it can be seen that several input variables were present but not controlled. These other input variables were not controlled because they were beyond the originally intended scope of this study or because they were simply uncontrollable, even though they could be measured. Although knowledge of the role that these uncontrolled input variables play was not a primary goal of this study, an accounting for their influence on pulse velocity is made.

Two important non-controlled input variables are mass density, ρ, and percentage of reinforcement. Enough elementary data was taken so that the effect of these two variables can be determined.

As stated in Chapter I, mass density is related to pulse velocity and dynamic modulus of elasticity by the relationship

$$V = \sqrt{\frac{E_d}{\rho}}$$

The mass density of the mixes varies enough so that some comparison between it and the pulse velocity can be made.

The other non-controlled input variable which will be accounted for, percentage of reinforcement, does not vary greatly. This is because the cross-sectional area of the reinforced beams was well controlled by the use of metal forms and two #5 longitudinal reinforcing bars as a standard for all reinforced beams. However, there is a possibility of relating the percentage of reinforcing to the pulse velocity. This can be done by evaluating the effect of the presence of reinforcing steel on the elasticity of the concrete beam and then relating the elasticity of this steel-concrete element to pulse velocity. This is possible since the static modulus of elasticity of the concrete, as a component of the steel-concrete element, varies from mix to mix.

Interpretation of Pulse-Velocity Test Data

Upon close examination of the techniques for pulse-velocity measurement, and giving consideration to the fact that the velocity of a propagated wave could be effected by the geometry of the object through which it is being passed, it becomes apparent that the effects of technique and geometry must be accounted for. In fact, for pulse-velocity data taken by use of one technique to be used in a manner consistent with data taken by another, it must be shown that the technique of measurement has no appreciable effect on pulse velocity. The same holds true for comparing pulse-velocity data taken on different geometric shapes.

The difference between test results obtained through measuring pulse velocity along a beam and pulse velocity measured by passing a pulse through the beam can be graphically compared quite effectively. By plotting the average through velocity for each concrete mix taken from plain concrete beams, against the average velocity for each mix taken along those same beams, the difference between the methods can be shown to be of no importance if the plot falls on a line through points of equal velocity relative to both velocity axes. As can be seen in Figure 12, there is apparently little difference in values of pulse velocity obtained by either method for a given beam. There is a tendency, however, for through velocity values to be slightly higher.

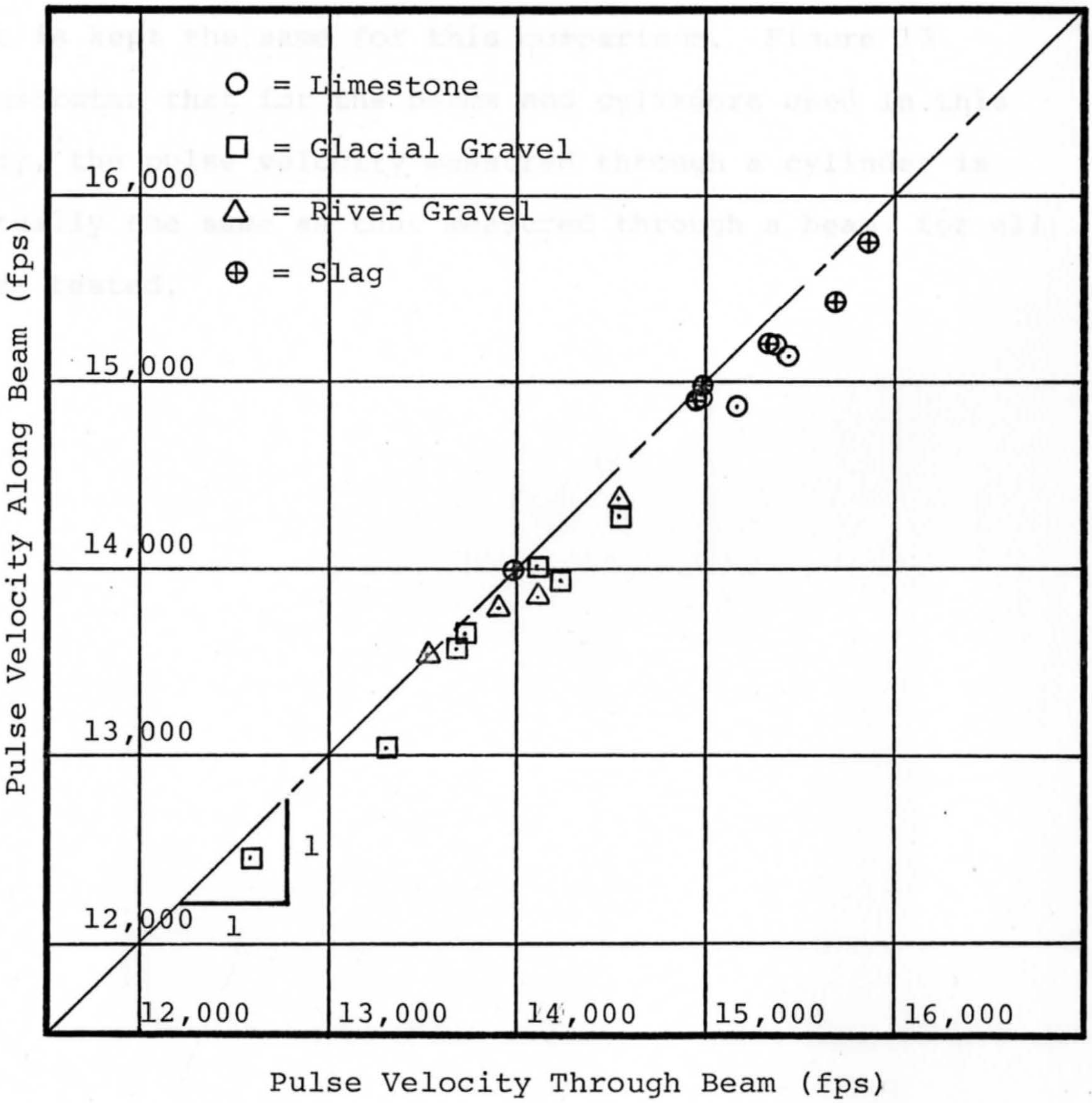


Figure 12. Velocity Along Beam vs. Velocity Through Beam, for All Mixes.

To evaluate the effects of the geometry of the element being tested on pulse velocity, the same graphical technique can be used. The method of pulse-velocity measurement is kept the same for this comparison. Figure 13 illustrates that for the beams and cylinders used in this study, the pulse velocity measured through a cylinder is virtually the same as that measured through a beam, for all mixes tested.

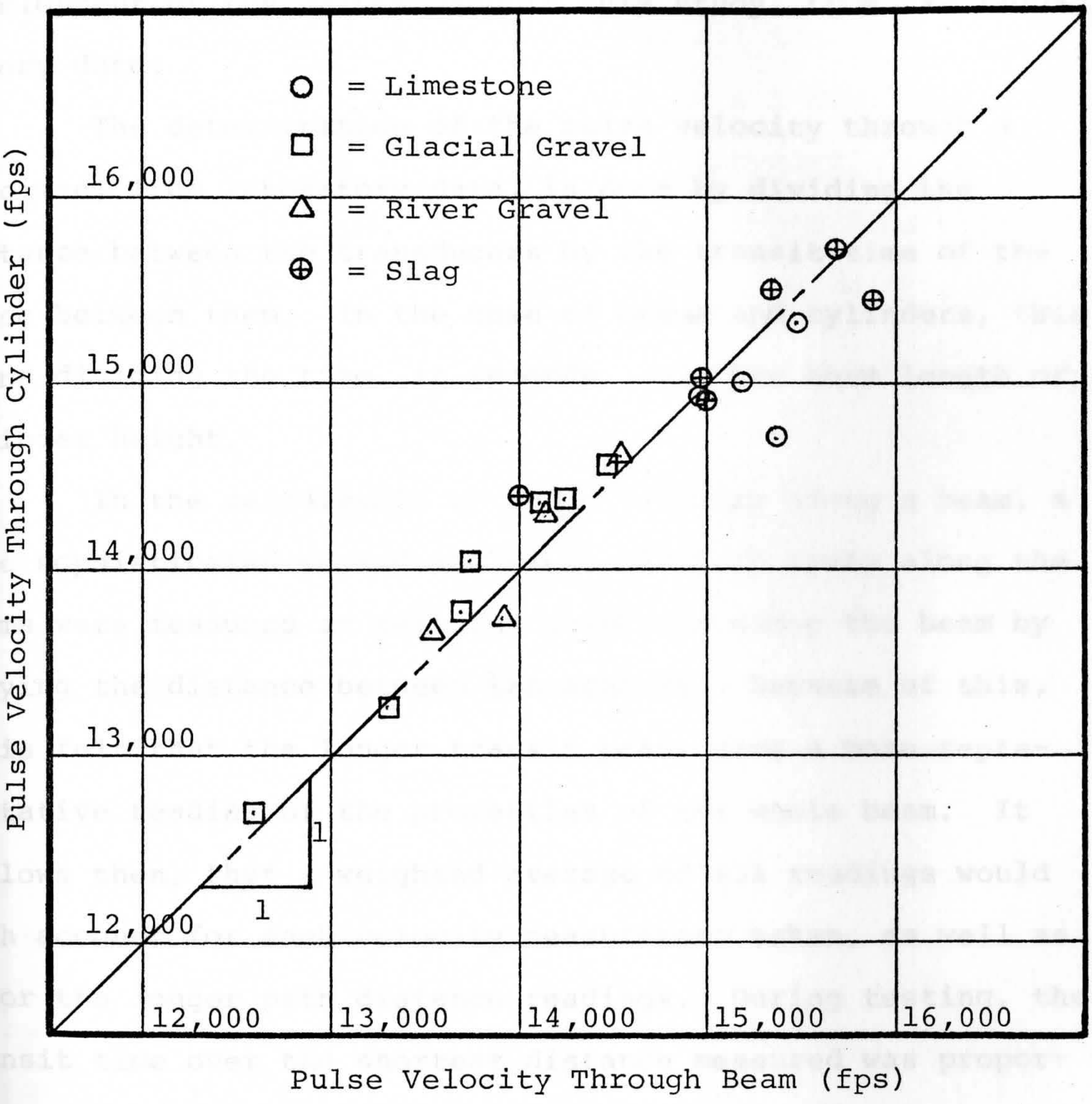


Figure 13. Velocity Through Cylinder vs. Velocity Through Beam, For All Mixes.

Method of Analysis

This section presents the methods and reasons for the development of the values used in this study, from raw laboratory data.

The determination of the pulse velocity through a specimen, from laboratory data, is done by dividing the distance between the transducers by the transit time of the pulse between them. In the case of beams and cylinders, this means dividing the time, in seconds, into the beam length or cylinder height.

In the calculation of pulse velocity along a beam, a more sophisticated method was used. Transit times along the beams were measured at selected intervals along the beam by varying the distance between transducers. Because of this, it is felt that the longer transit paths give a more representative reading of the properties of the whole beam. It follows then, that a weighted average of all readings would both account for each velocity measurement taken, as well as favor the longer path distance readings. During testing, the transit time over the shortest distance measured was proportionately less than longer distance readings, and in general, not very reproduceable. This could be due to the surface wave reaching the receiving transducer before the longitudinal wave with such a close proximity of the transducers. This fact lead to suspicion of close proximity readings taken with the transducers parallel and located on the same surface as was done in velocity-along measurements.

In weighting the velocity readings for each location along the beam, the velocity for each distance was calculated. This calculated velocity was then multiplied by the length of its path. These values were summed for all the readings taken along the beam. The path length of all readings taken is also summed to give the total length traveled. By dividing the sum of the velocity times its path length by the total length traveled, the weighted average velocity along is obtained. This yields the equation

$$V = \frac{\Sigma\, d^2/t}{\Sigma\, d}$$

where:

d = distance between transducers

t = transit time of the pulse

Using the above equation, all velocity-along values for beams were calculated and tabulated in the data analysis sheets in Appendix E.

The dynamic modulus of elasticity for all velocity measurement was calculated in accordance with the relationship

$$V = \sqrt{\frac{E_d}{\rho}}$$

After performing the mathematics with proper accounting for units and for the gravitational constant, the dynamic modulus of elasticity is given by

$$E_d = \frac{\gamma V^2}{4636.8}$$

where:

E_d = dynamic modulus of elasticity in p.s.i.

γ = weight density in p.c.f.

V = pulse velocity in f.p.s.

All calculated dynamic modulus of elasticity values are presented in Appendix E.

For the determination of the static modulus of elasticity of the cylinder specimens, the slope of the initial tangent of the load-deflection curves was calculated. The initial-tangent method was chosen because the strains caused by the mechanical pulse of the transducers are very small in relation to the magnitude of crushing strains. It is felt that a better correlation between static and dynamic elastic moduli can be obtained if they are studied over the same strain range.

The load-deflection curves for the concrete cylinders were also used to determine their ultimate compressive strength. This value is simply the maximum load carried by the cylinder divided by its area. The load-deflection curves are presented in Appendix D and the static modulus and ultimate strength values calculated from them are presented in Appendix E.

Graphic Results

Initially, data values were plotted as a method for studying the relationship between different variables. These early attempts did not even yield trends as to what relationships might exist between two variables. In many cases, the graph simply looked like a mass of points with no reasonable analytical evaluation possible. To eliminate the confusion and possibly make some relationships apparent, the average value for each property measured was calculated for each mix, using plain concrete specimens. There was a sufficient number of plain concrete specimens for each mix to make this average. For reinforced concrete specimens, the average velocity for each mix was also calculated, even though they were measured with three different proximities of reinforcement. This averaging of mix parameters eliminated many of the data points on the graphs, but still made no more sense of the data, in most cases.

Some relationships between variables do become apparent when these graphs are studied on an individual aggregate type basis. Many of these graphs, however, yield no more than trends between two variables. But, in most cases, some trend or tendency can be seen in these graphic results. The desired plots of variable relationships have been made using all mix values on each graph when possible and are delineated by the use of dashed lines connecting the data points of a particular aggregate type.

These dashed lines are connected between data points in order of increasing magnitude of the independent variable along the horizontal axis. This means that in some cases, the closest adjacent points are not connected. It should be noted when observing these plots, that in general, no apparent relationship exists except within a given aggregate type.

After the manipulating of the data so as to make some use of it, it is apparent that the number of data points for each relationship is small. Usually this number is three to four. While an equation fitting method could be used to determine an equation for these few data points, it is questionable as to the value of such a quantitative relationship. The true usefulness of these graphs appears to be the trends or effects of the variables they show, and to a lesser extent, the quantitative relationships.

The graphs of each of the original input variables of water-cement ratio, cement-aggregate ratio, proximity of reinforcement, and aggregate type vs. pulse velocity, are next presented. (See Figures 14 through 22.) It should be kept in mind that in these graphs, the data points are average values, except for the depth of reinforcement graphs. On the depth of reinforcement graphs, a table of the plain concrete velocity values for that mix are shown for reference. Both concrete strength and elasticity, versus pulse velocity are also included in this set of graphs. (See Figures 23 through 26.)

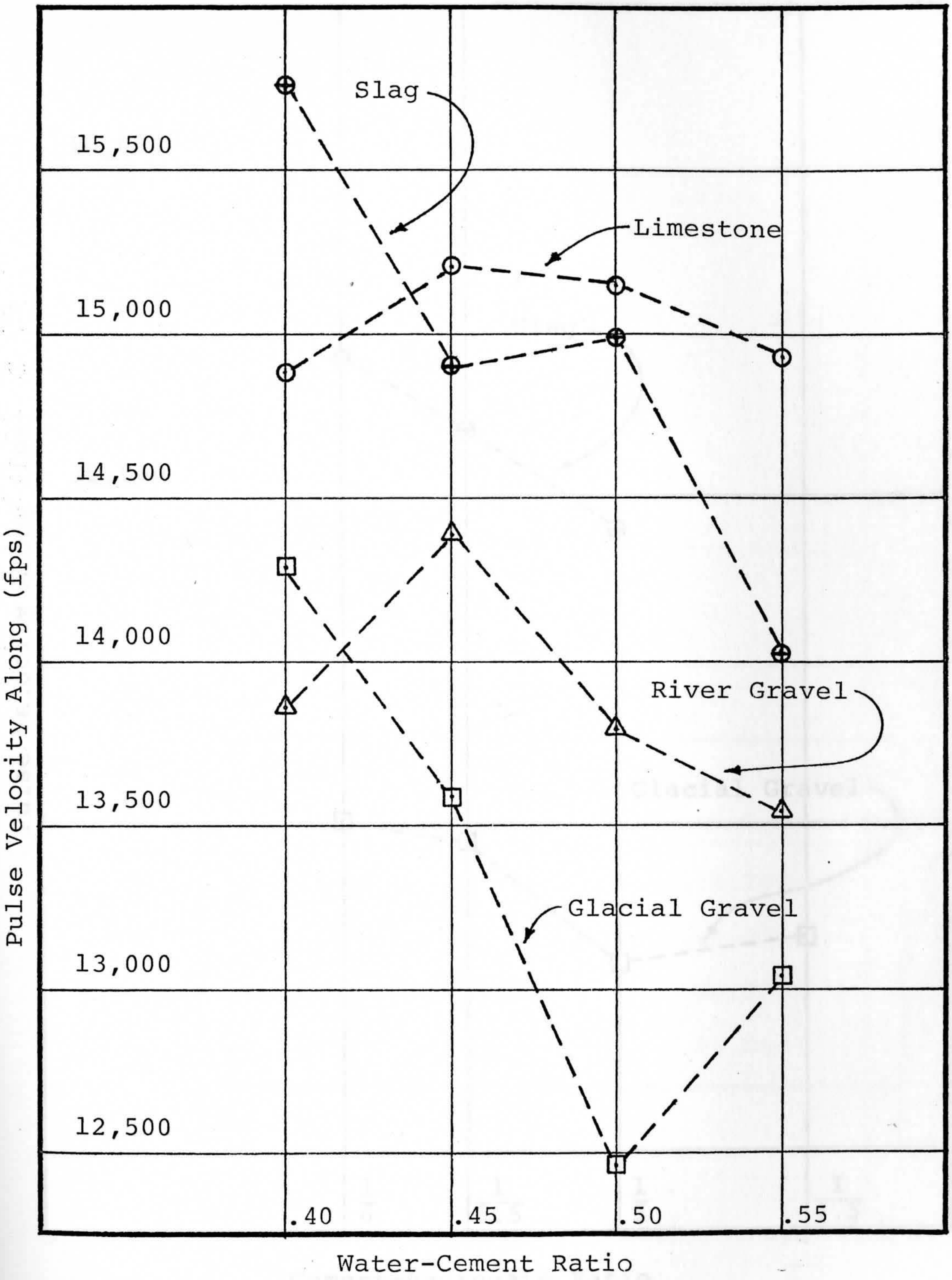


Figure 14. Velocity Along Beam vs. <u>Water-Cement</u> Ratio for a Constant C/A Ratio of 1/5.0.

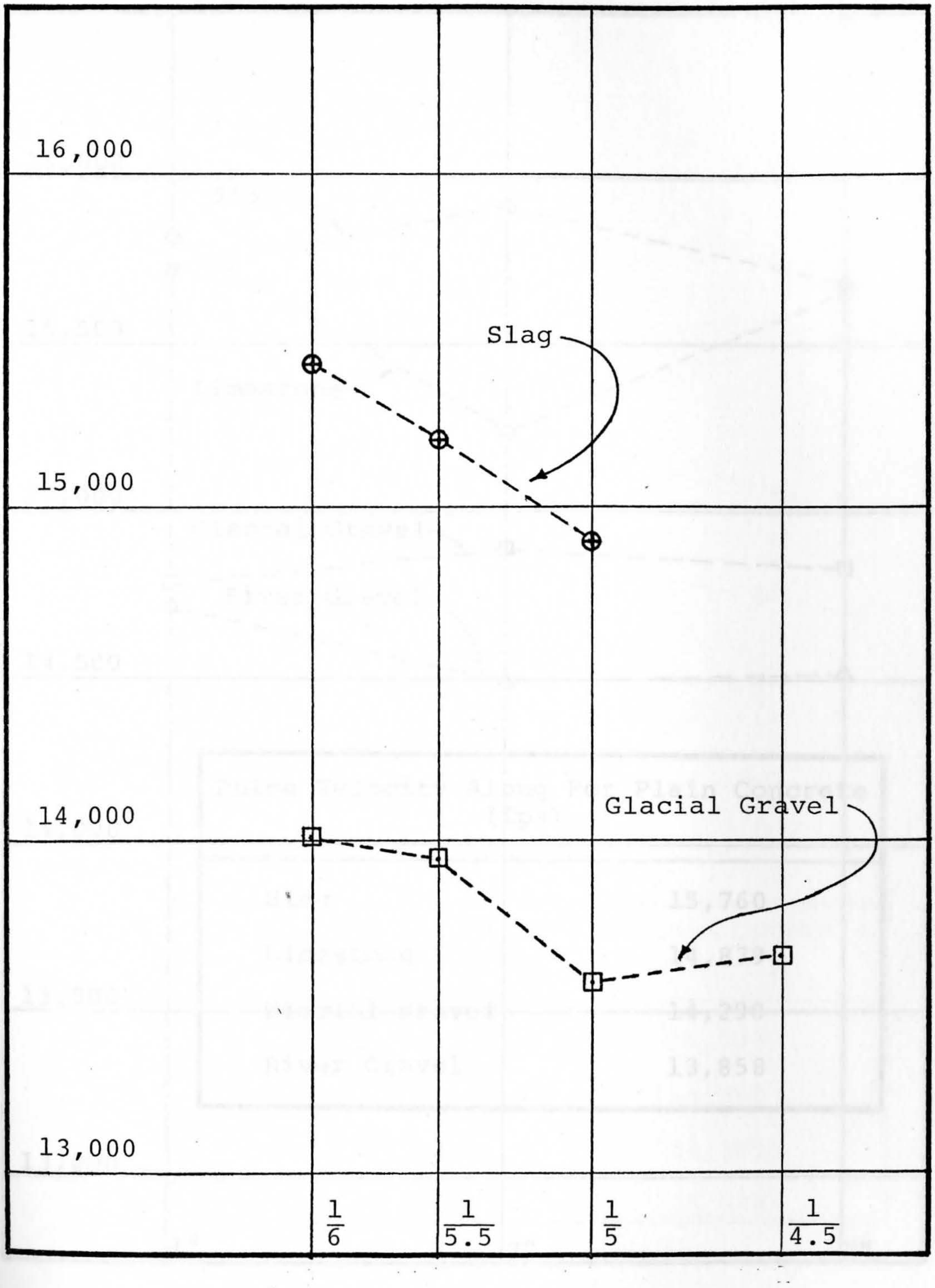


Figure 15. Velocity Along Beam vs. Cement-Aggregate Ratio for a Constant W/C Ratio of 4.5/10.

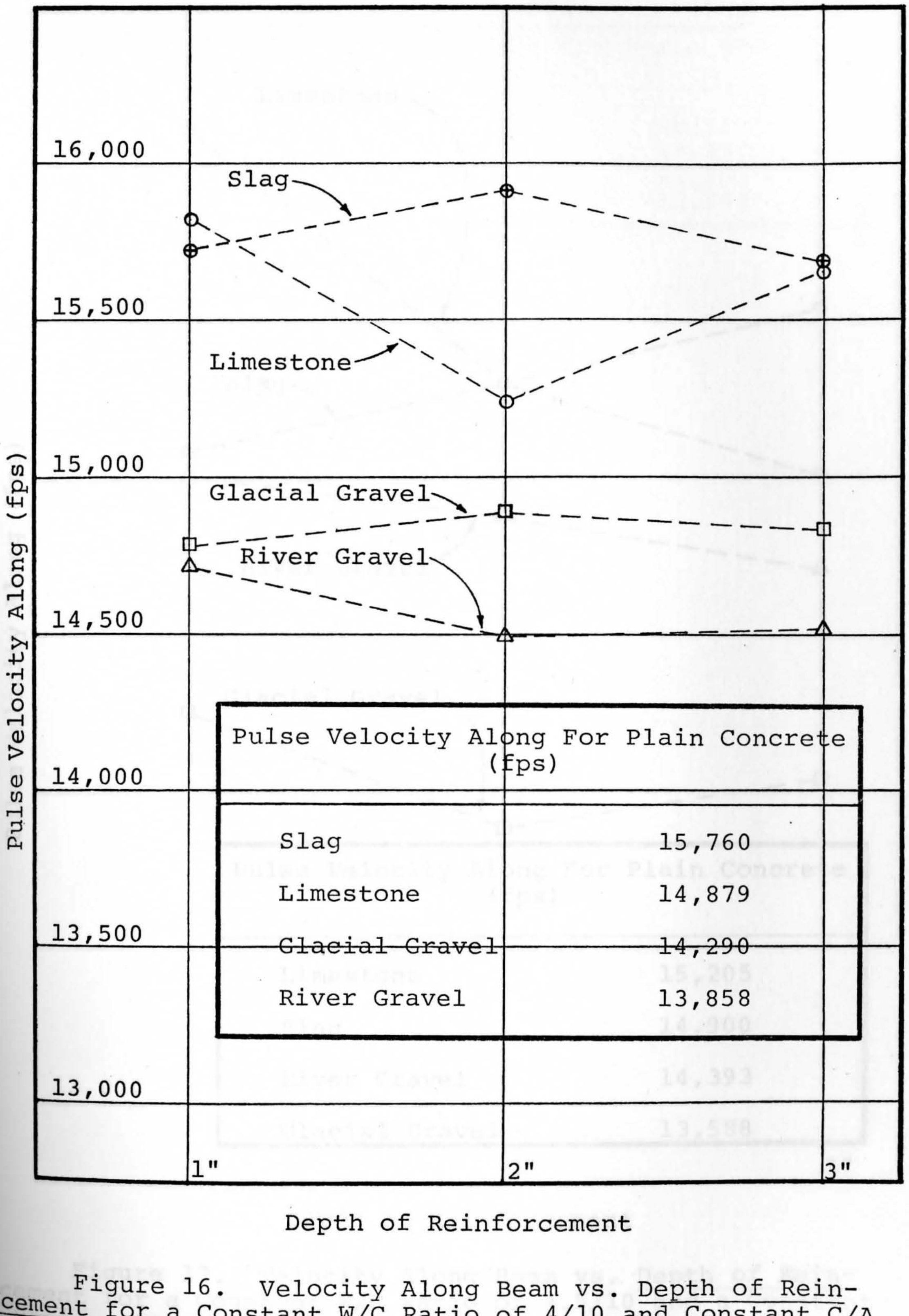
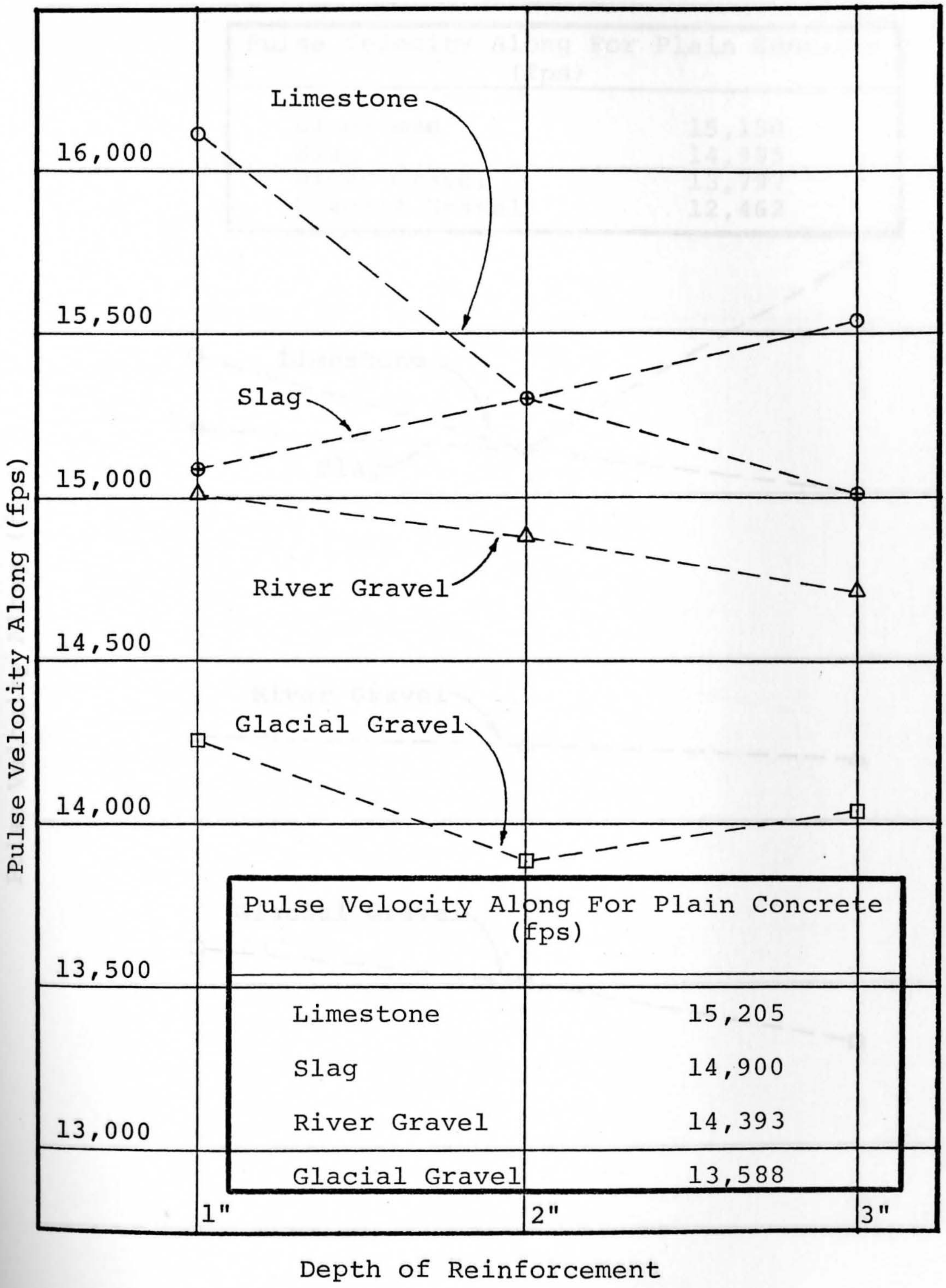


Figure 16. Velocity Along Beam vs. Depth of Reinforcement for a Constant W/C Ratio of 4/10 and Constant C/A Ratio of 1/5.0.



Pulse Velocity Along For Plain Concrete (fps)	
Limestone	15,205
Slag	14,900
River Gravel	14,393
Glacial Gravel	13,588

Figure 17. Velocity Along Beam vs. <u>Depth of Reinforcement</u> for a Constant W/C Ratio of 4.5/10 and a Constant <u>C/A Ratio</u> of 1/5.0.

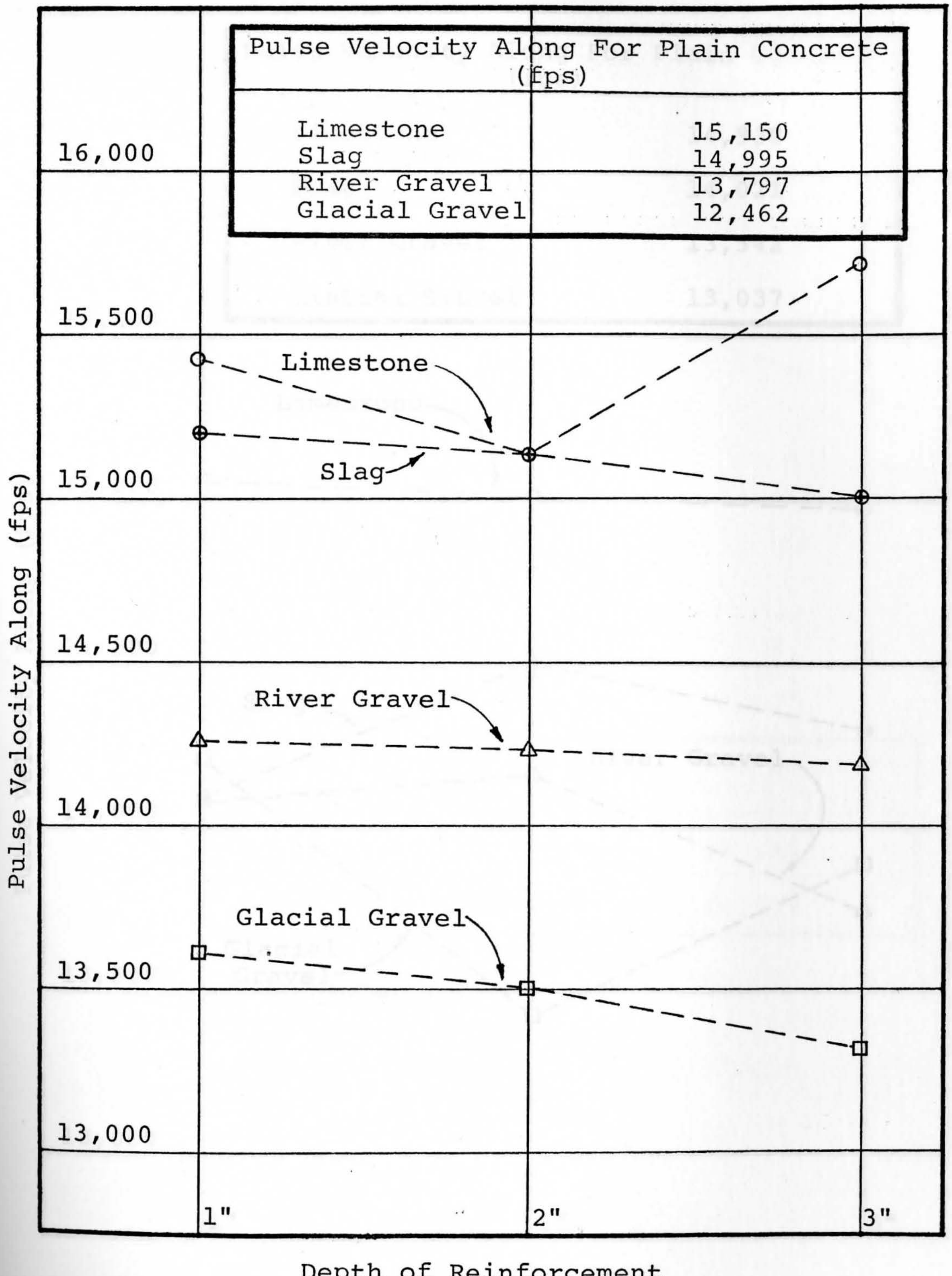


Figure 18. Velocity Along Beam vs. Depth of Reinforcement for a Constant W/C Ratio of 5/10 and a Constant C/A Ratio of 1/5.0.

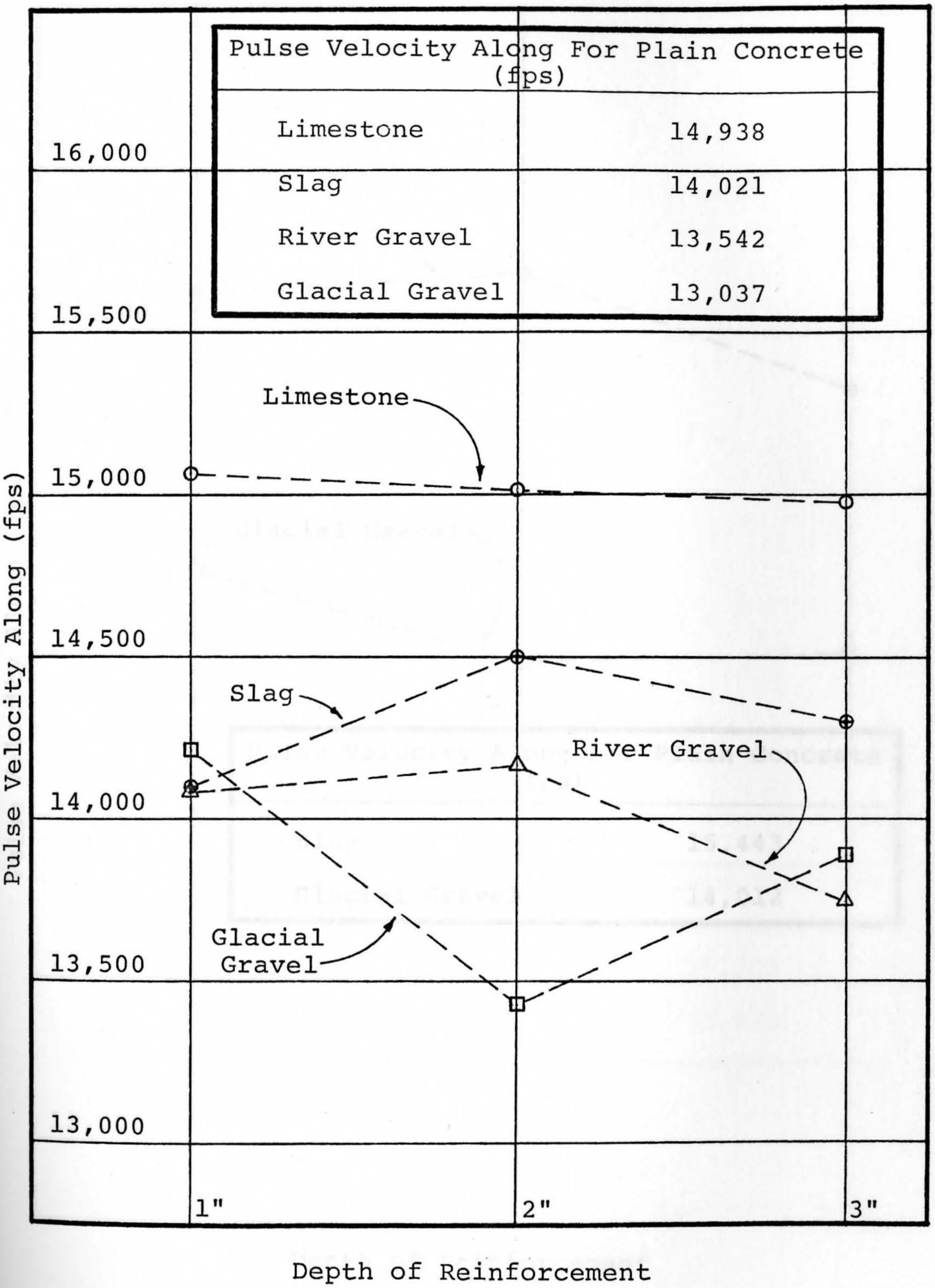
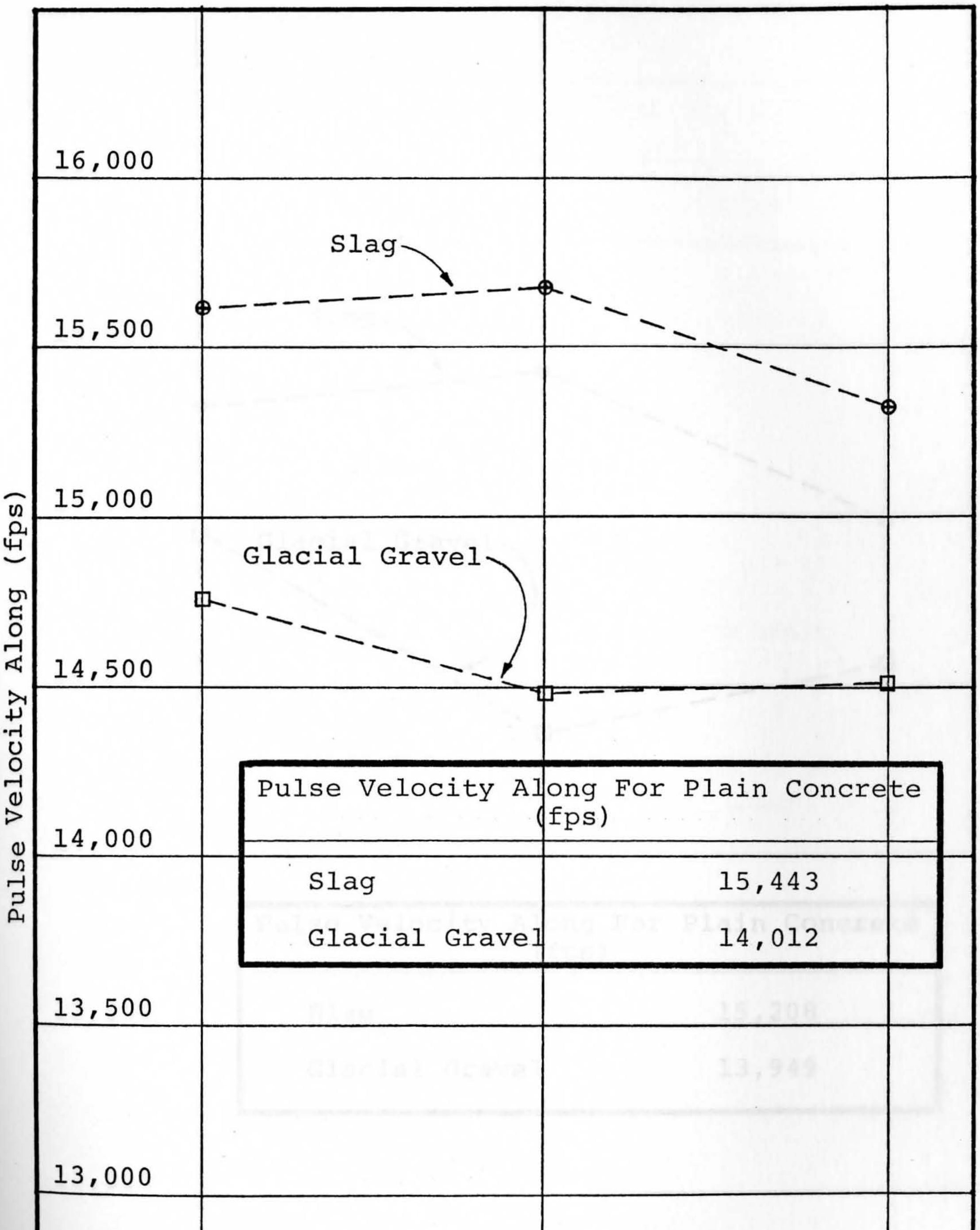
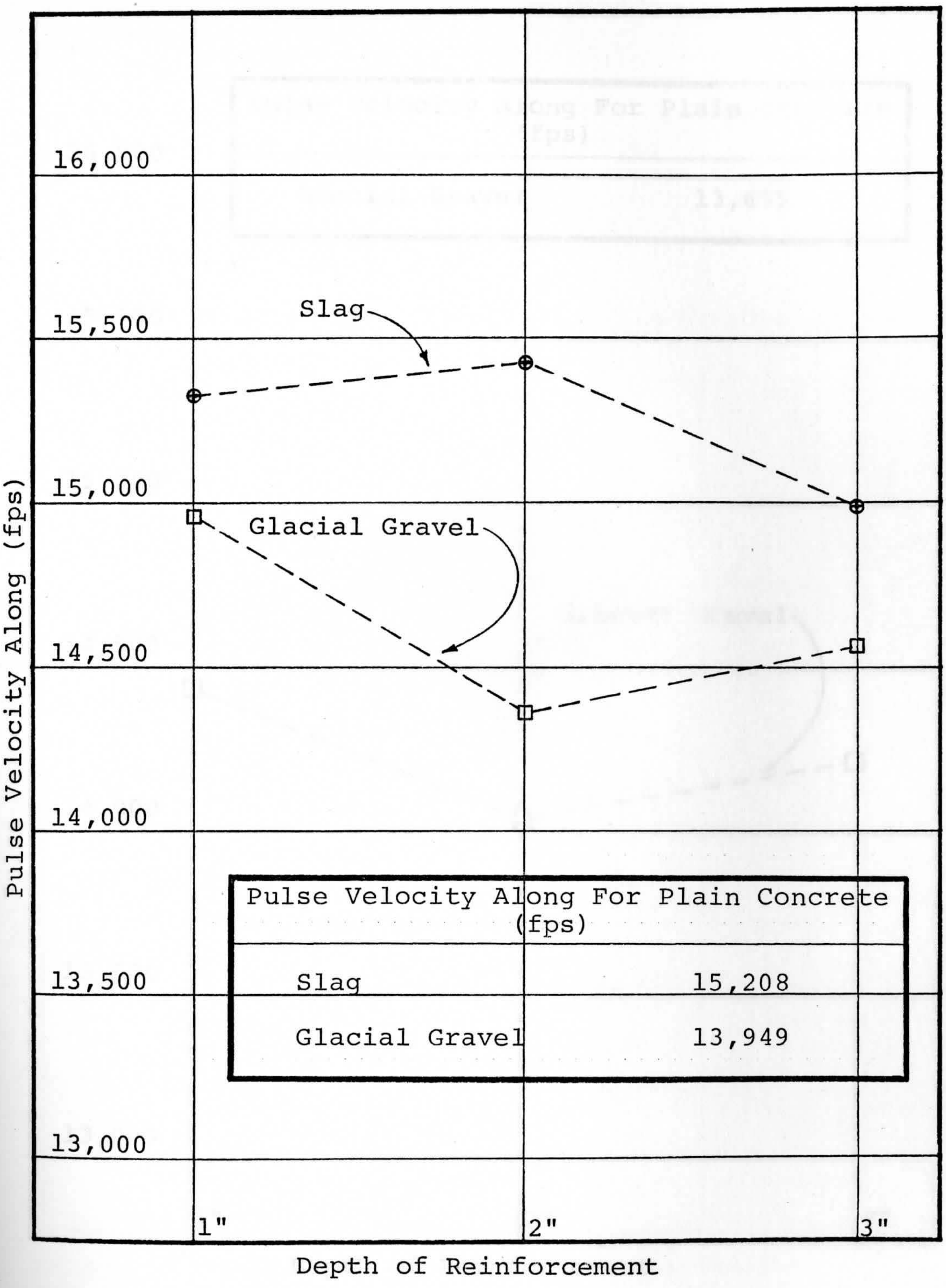


Figure 19. Velocity Along Beam vs. Depth of Reinforcement for a Constant W/C Ratio of 5.5/10 and a Constant C/A Ratio of 1/5.0.



Pulse Velocity Along For Plain Concrete (fps)	
Slag	15,443
Glacial Gravel	14,012

Figure 20. Velocity Along Beam vs. Depth of Reinforcement for a Constant W/C Ratio of 4.5/10 and a Constant C/A Ratio of 1/6.0.



Pulse Velocity Along For Plain Concrete (fps)	
Slag	15,208
Glacial Gravel	13,949

Figure 21. Velocity Along Beam vs. Depth of Reinforcement for a Constant W/C Ratio of 4.5/10 and a Constant C/A Ratio of 1/5.5.

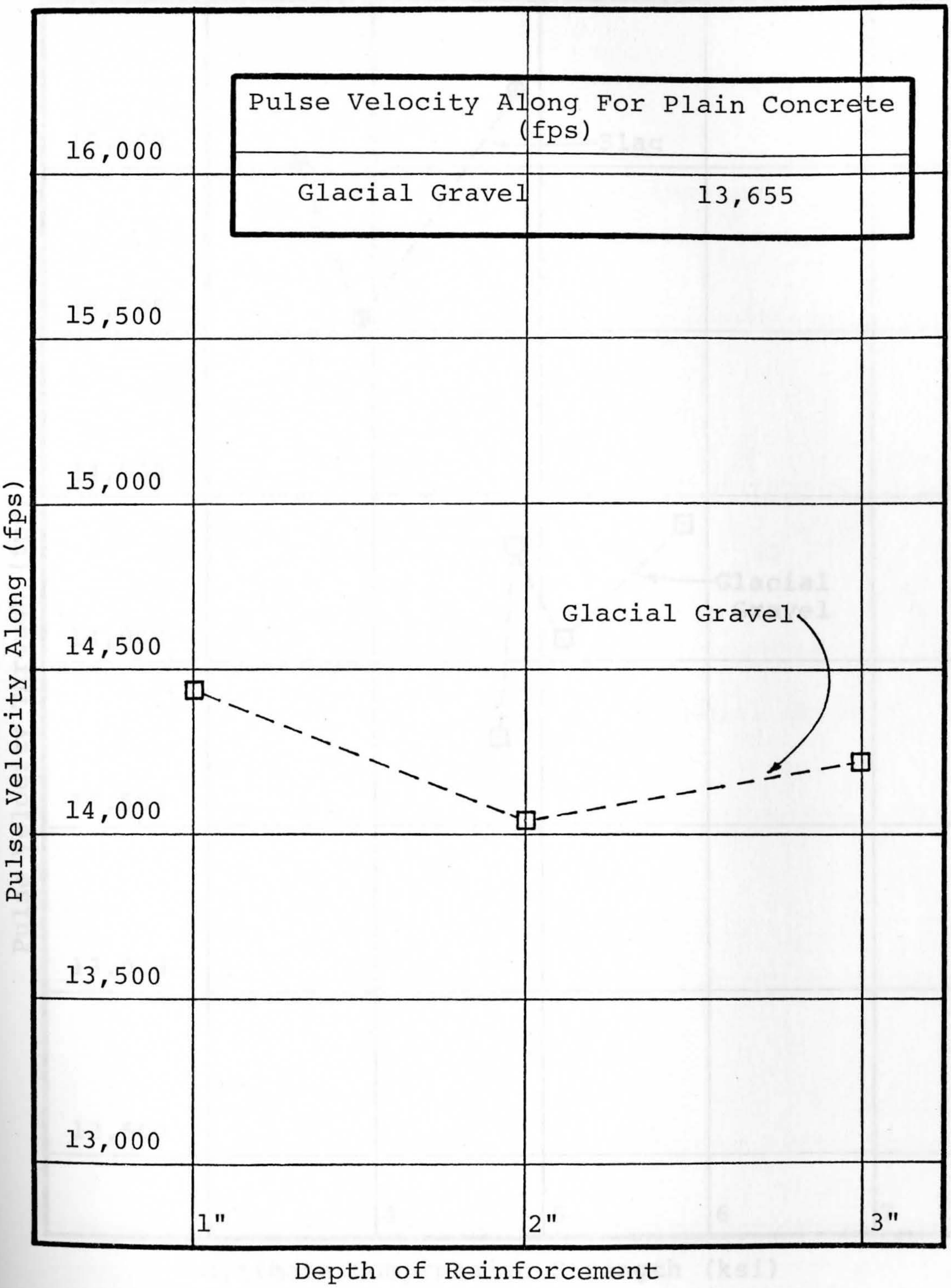
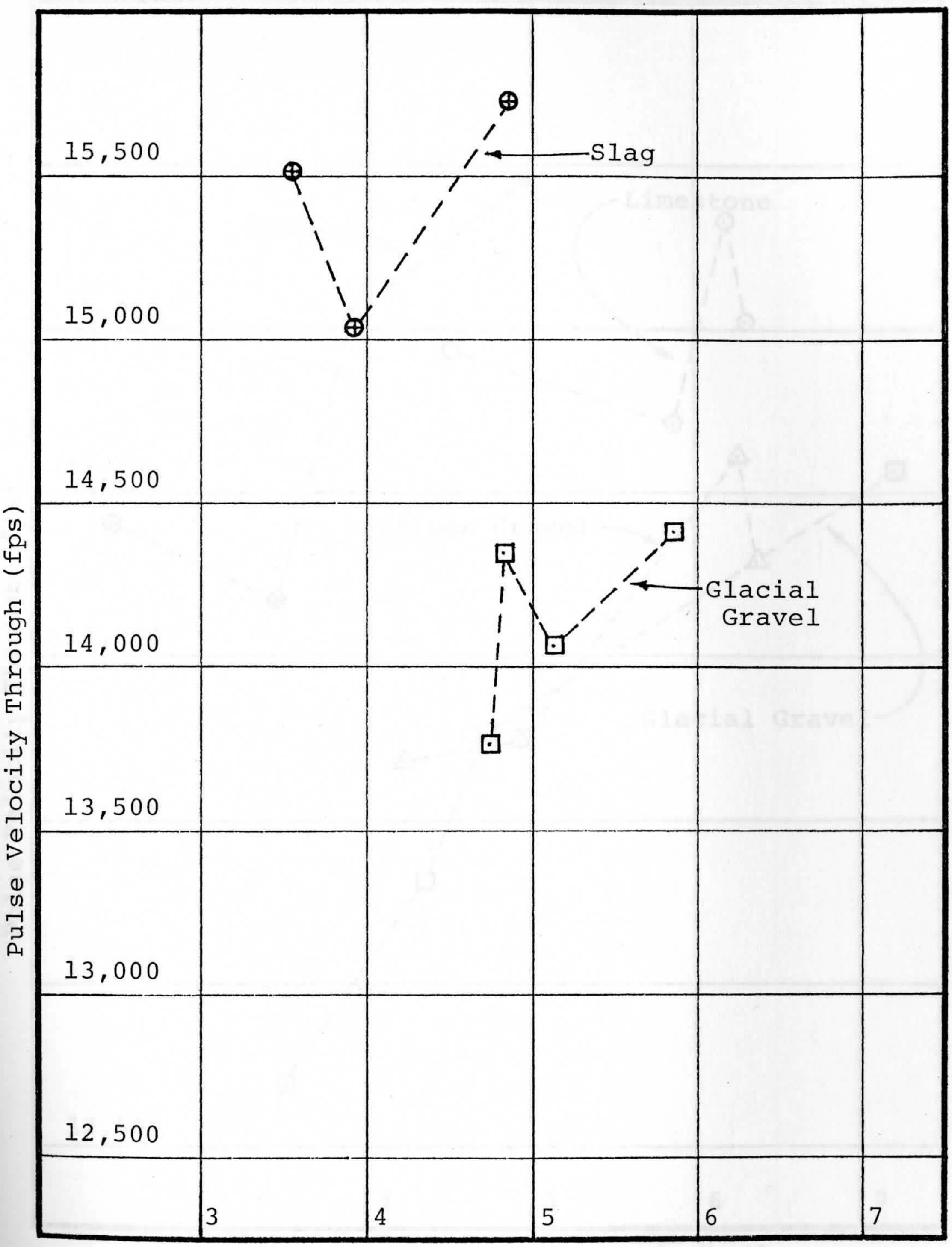


Figure 22. Velocity Along Beam vs. Depth of Reinforcement for a Constant W/C Ratio of 4.5/10 and a Constant C/A Ratio of 1/4.5.



Ultimate Compressive Strength (ksi)

Figure 23. Velocity Through Cylinder vs. Ultimate Compressive Strength for a Constant W/C Ratio of 4.5/10.

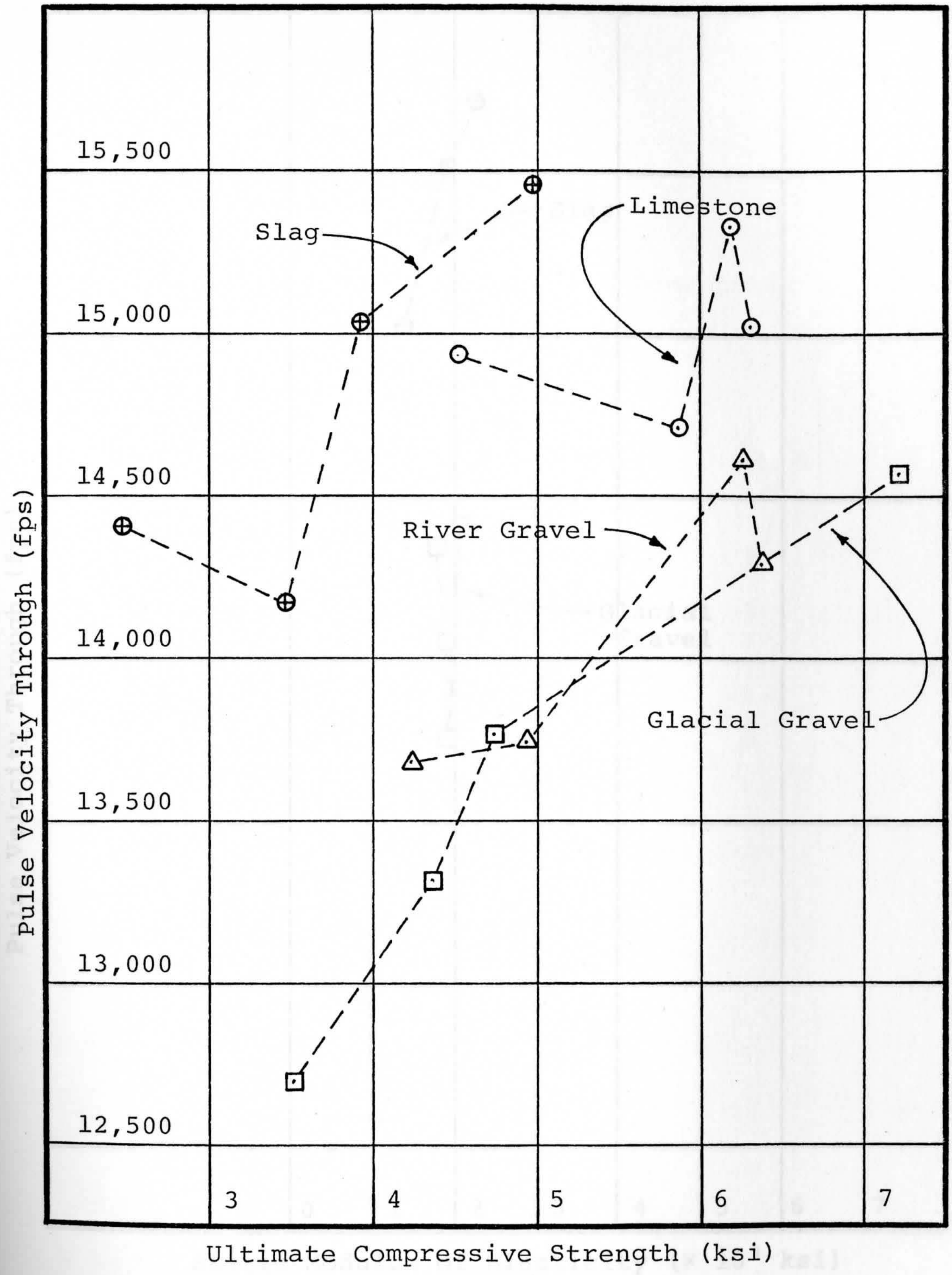


Figure 24. Velocity Through Cylinder vs. Ultimate Compressive Strength for a Constant C/A Ratio of 1/5.0.

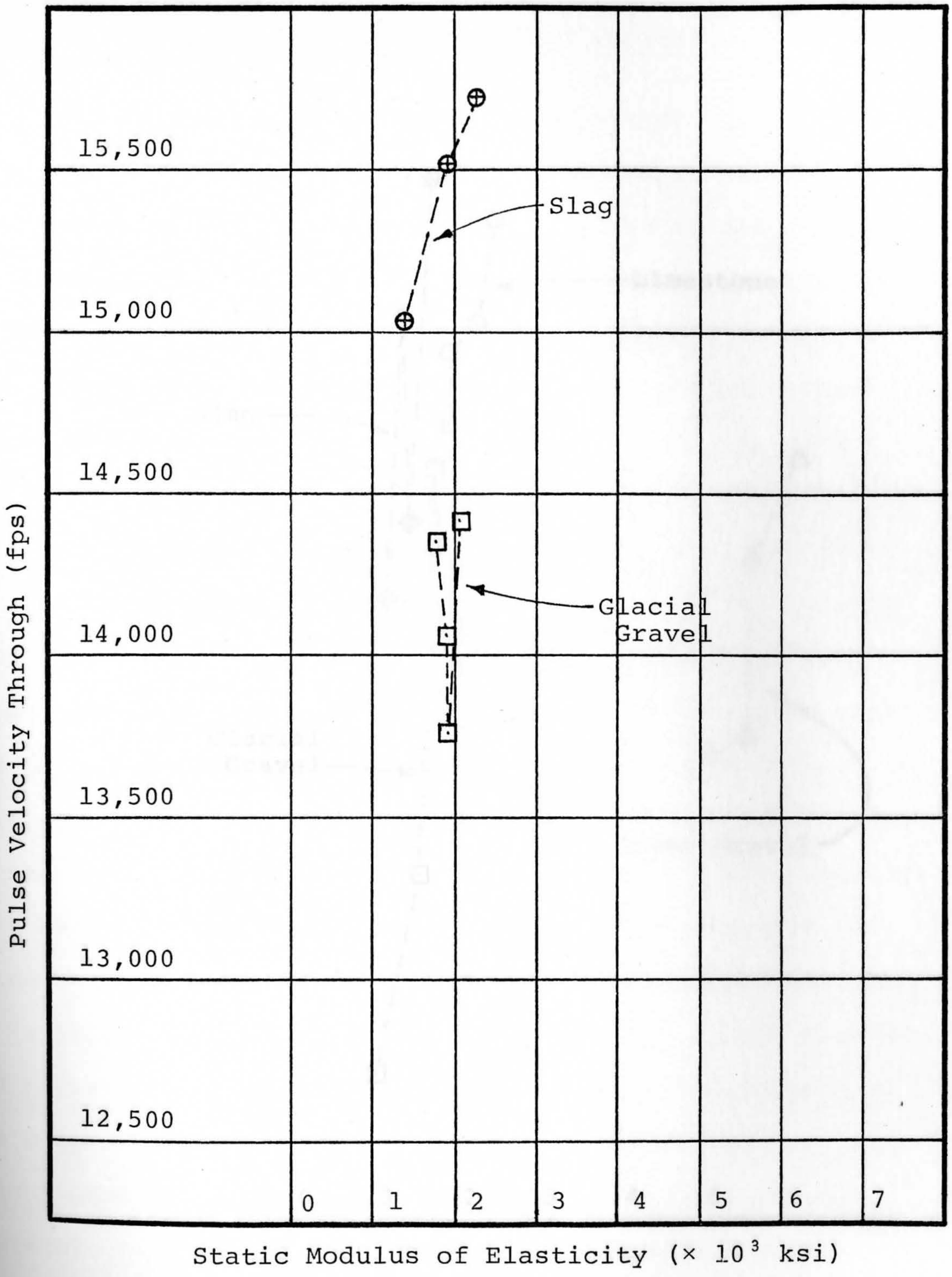


Figure 25. Velocity Through Cylinder vs. Static Modulus of Elasticity for a Constant W/C Ratio of 4.5/10.

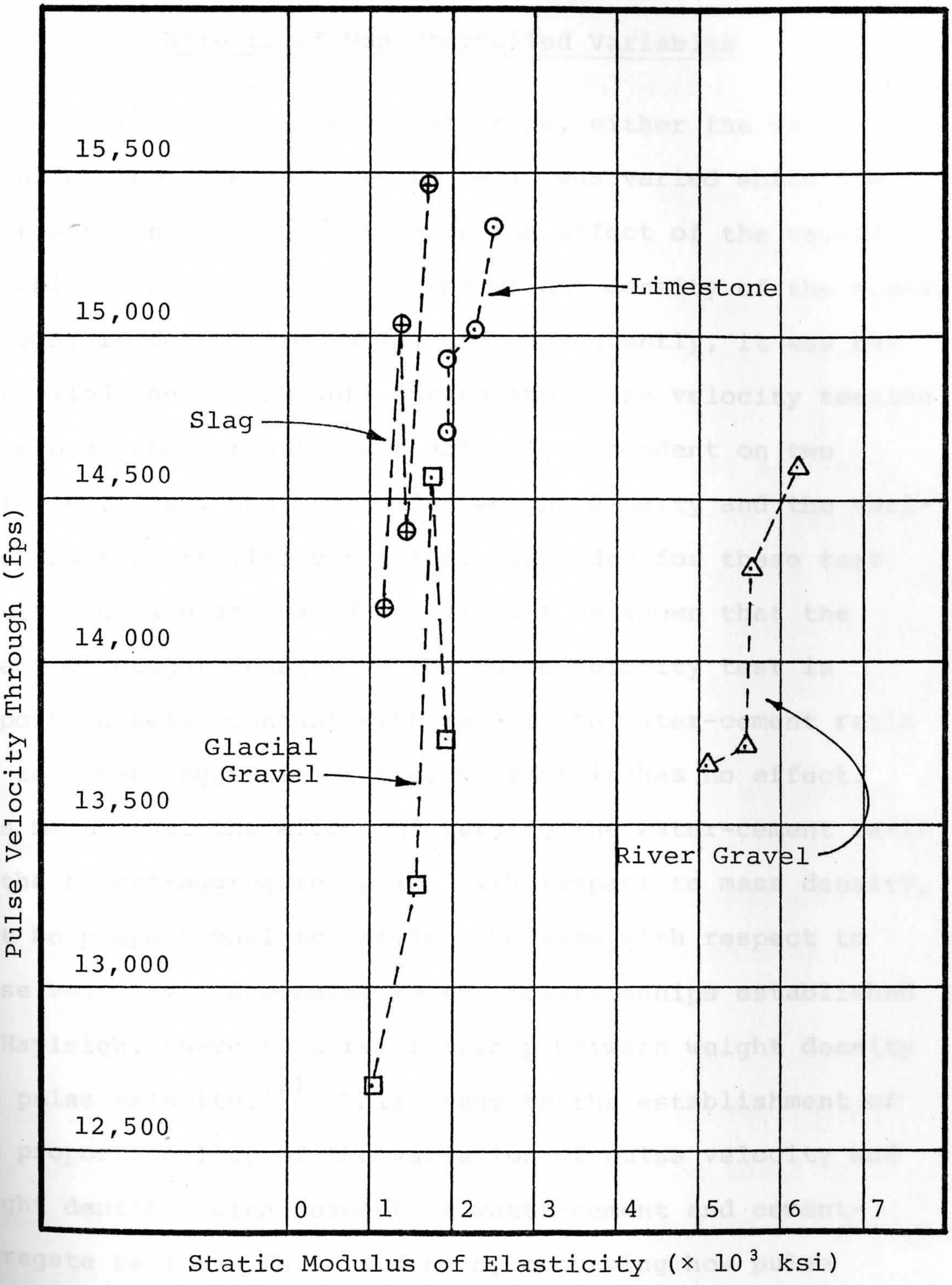


Figure 26. Velocity Through Cylinder vs. Static Modulus of Elasticity for a Constant C/A Ratio of 1/5.0.

Effects of Non-Controlled Variables

Within a given aggregate type, either the water-cement or the cement-aggregate ratio was varied while the other was constant, to determine the effect of the varied variable on pulse velocity. The weight density of the mixes, however, is not controllable, and consequently, it was not controlled (held constant) during the pulse velocity testing. Therefore, these results are actually dependent on two variables, i.e., non-controlled weight density and the variable under controlled variation. In order for these test results to have any validity, it must be shown that the effect of weight density on the pulse-velocity test is proportionately constant with respect to water-cement ratio and to cement-aggregate ratio, or, that it has no effect. This means that the effect of varying the water-cement ratio or the cement-aggregate ratio, with respect to mass density, must be proportional to varying the same with respect to pulse velocity. According to the relationships established by Rayleigh, there is a relationship between weight density and pulse velocity.(8) This leads to the establishment of the proportionality of the variation of pulse velocity and weight density, with respect to water-cement and cement-aggregate ratios. This is done by observing how pulse velocity and weight density vary while varying the water-cement ratio and holding the cement-aggregate ratio constant. The same process is then repeated for a varying cement-aggregate ratio and constant water-cement ratio.

As part of this comparison, the graphs of weight density vs. water-cement ratio and weight density vs. cement-aggregate ratio are shown in Figures 27 and 28.

By comparing these graphs to those using velocity along the beam as the dependent variable and the same independent variables, (Figures 14 and 15), it can be seen that within the aggregate type, the variation of weight density and pulse velocity is proportional, in most cases. By observing the characteristic shape of individual aggregate plots, this relationship is quite apparent. There exists a very good correlation between the two sets of graphs for both a varying water-cement ratio and for a varying cement-aggregate ratio. This fact leads to the possibility of the pulse velocity's being only a function of weight density. To investigate this possibility, pulse velocity as a function of weight density was plotted in Figure 29. As can be seen, the plot of pulse velocity versus weight density shows some relationship between these variables exists within each aggregate group only.

Another non-controlled variable present in the reinforced beam specimens is the percentage of reinforcement. This parameter was not varied by design in the tests performed, however, if this percentage is dealt with on the basis of its effect on the elasticity of the reinforced beam, some useful relationships can be brought to light.

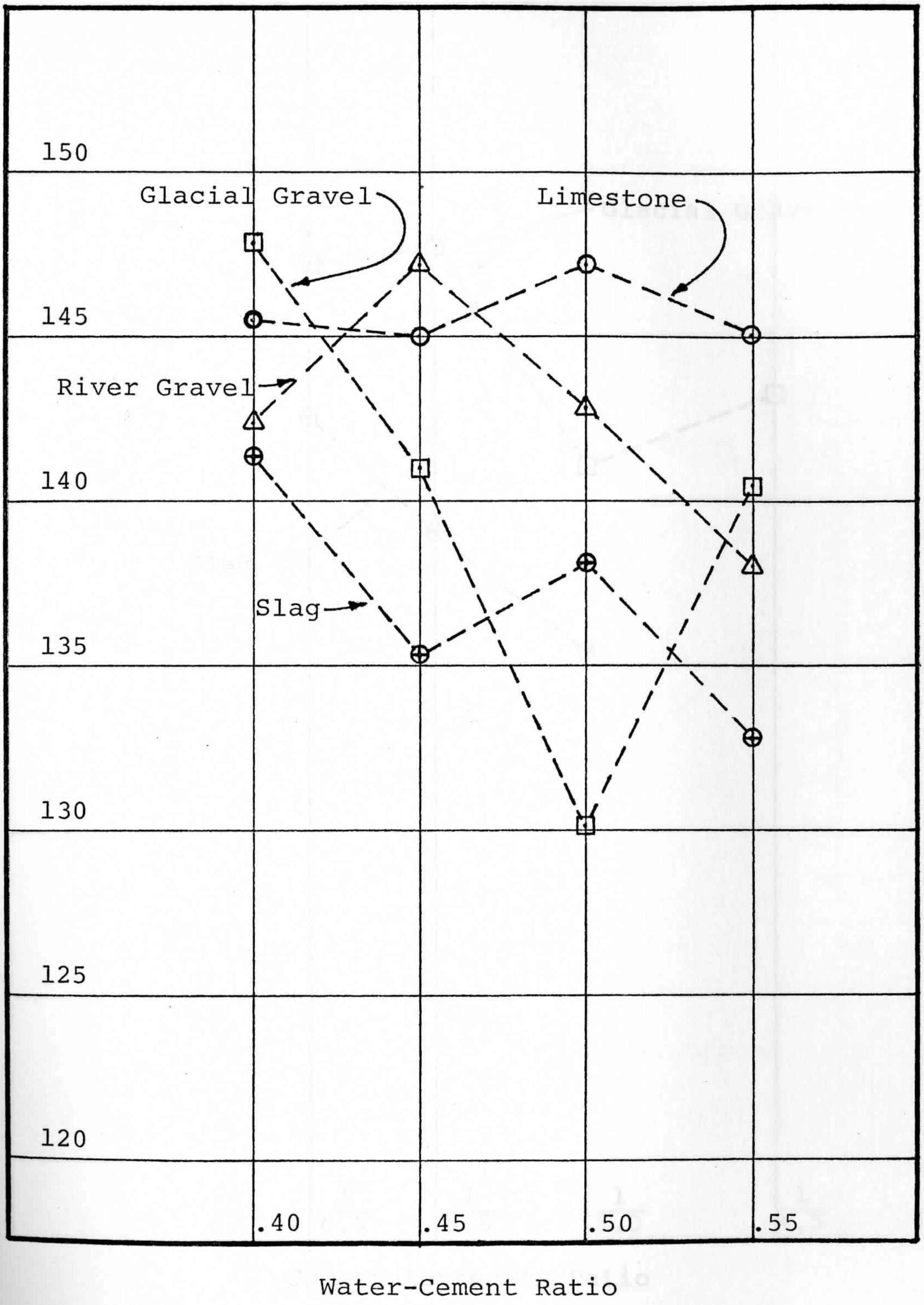


Figure 27. Weight Density vs. Water-Cement Ratio for a Constant Cement-Aggregate Ratio of 1/5.0.

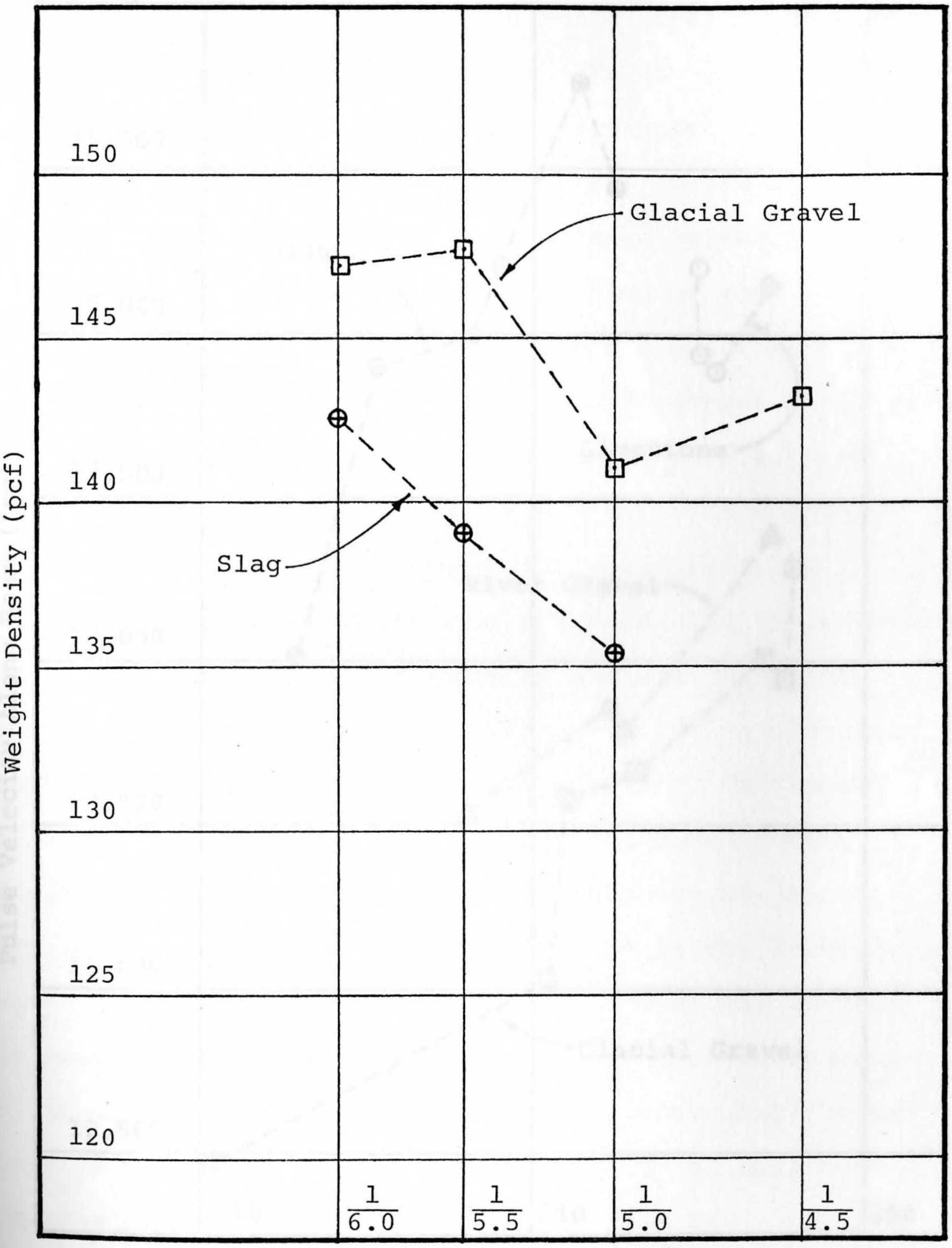


Figure 28. Weight Density vs. Cement Aggregate Ratio for a Constant Water-Cement Ratio of 4.5/10.

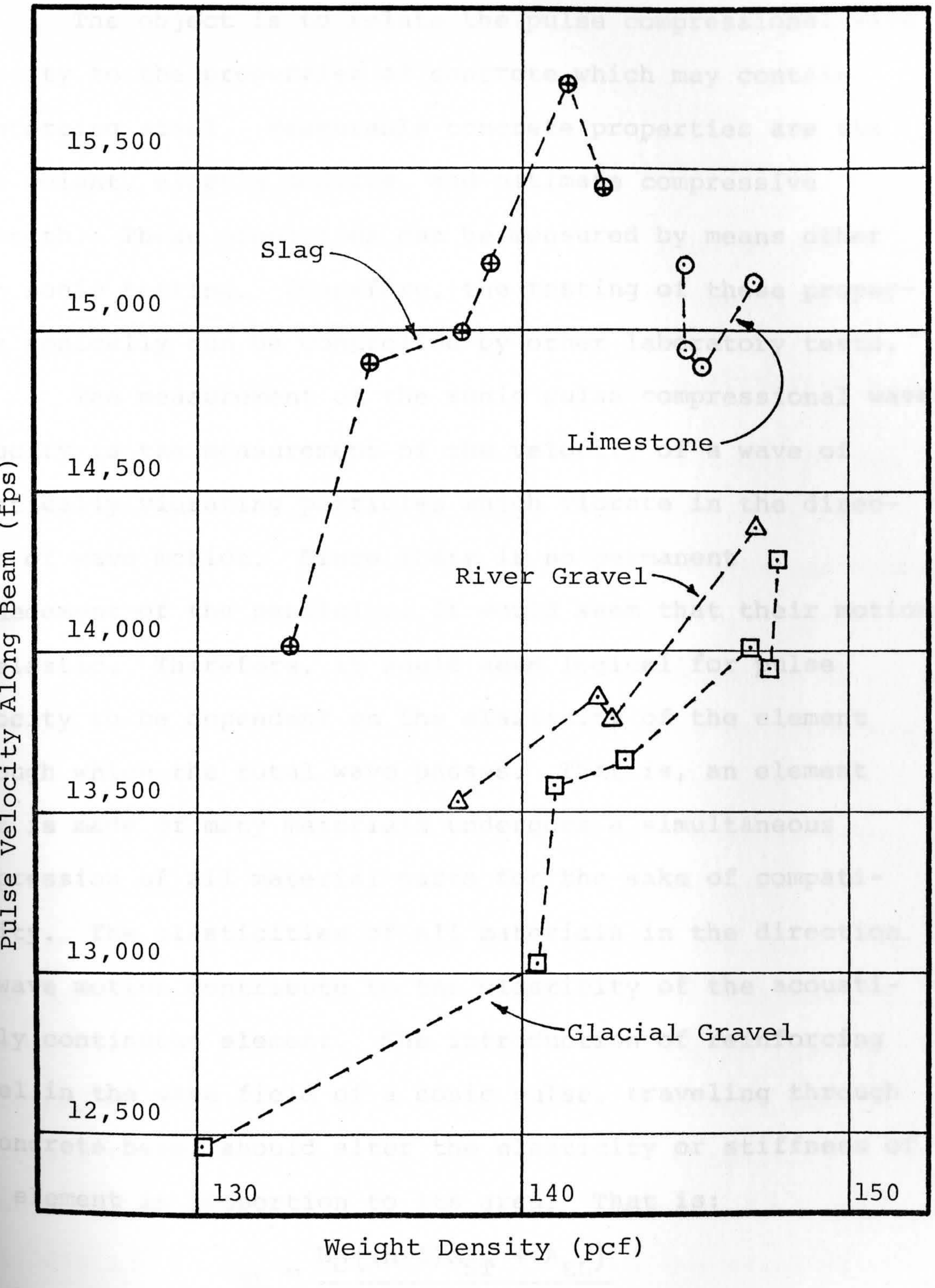


Figure 29. Velocity Along the Beam vs. Weight Density for All Mixes, Grouped by Aggregate Type.

The object is to relate the pulse compressional wave velocity to the properties of concrete which may contain reinforcing steel. Measurable concrete properties are its unit weight, elastic modulus, and ultimate compressive strength. These properties can be measured by means other than sonic testing. Therefore, the testing of these properties sonically can be controlled by other laboratory tests.

The measurement of the sonic pulse compressional wave velocity is the measurement of the velocity of a wave of elastically vibrating particles which vibrate in the direction of wave motion. Since there is no permanent displacement of the particles, it would seem that their motion is elastic. Therefore, it would seem logical for pulse velocity to be dependent on the elasticity of the element through which the total wave passes. That is, an element that is made of many materials undergoes a simultaneous compression of all material parts for the sake of compatibility. The elasticities of all materials in the direction of wave motion contribute to the elasticity of the acoustically continuous element. The introduction of reinforcing steel in the wave field of a sonic pulse, traveling through a concrete beam, should alter the elasticity or stiffness of the element in proportion to its area. That is:

$$E_{EL} = \frac{E_C\left((n-1)A_{ST} + A_{EL}\right)}{A_{EL}}$$

where:

E_{EL} = composite modulus of elasticity of the element under test, in the direction of the test.

E_C = modulus of elasticity of the concrete in the element.

n = the modular ratio of steel to element concrete.

A_{ST} = area of steel in the element in the direction of test.

A_{EL} = gross area of the element in the direction of test.

Of course, many things affect the elasticity of the concrete and they must be considered. The elasticity of reinforcing steel is, for the most part, a constant and known value.

It should be noted that since particle motion is involved, mass, and hence, mass density, must also be considered in the study of pulse velocities.

To investigate the relationship between pulse velocity and element elasticity, the results of cylinder compression tests and velocity-along readings for reinforced beams were used. To increase the confidence in the results, only mix designs which had two or more compression tests performed on them were used. This resulted in only two aggregate types having more than one element elasticity value to plot, slag and glacial gravel. The standard area of 0.3068 in^2 for a #5 reinforcing bar, and the usual value of 29×10^6 psi for the modulus of elasticity of steel was used to calculate the element elasticity modulus for the mix designations shown in Table 4.

ther values needed to calculate the element elasticity are isted in the appendices.

TABLE 4

MODULUS OF ELASTICITY OF BEAM ELEMENTS FOR VARIOUS MIX DESIGNS

Mix	E_{EL} ($\times 10^6$ psi)
D5G	2.47
D3G	2.70
B4G	2.95
B6G	2.74
D5S	2.36
B5S	3.12
B4S	2.76

The plot of these element moduli against the pulse velocity through them, shows some correlation, but again, only by aggregate type, as can be seen in Figure 30. When observing the relationship between pulse velocity and composite element modulus of elasticity, it should be noted that the pulse velocity in an element with a reinforcement ratio of 1.0, (i.e., pure steel), is 17,070 fps. This value was obtained by averaging the results of measuring the velocity through several samples of the reinforcing steel used in the beams.

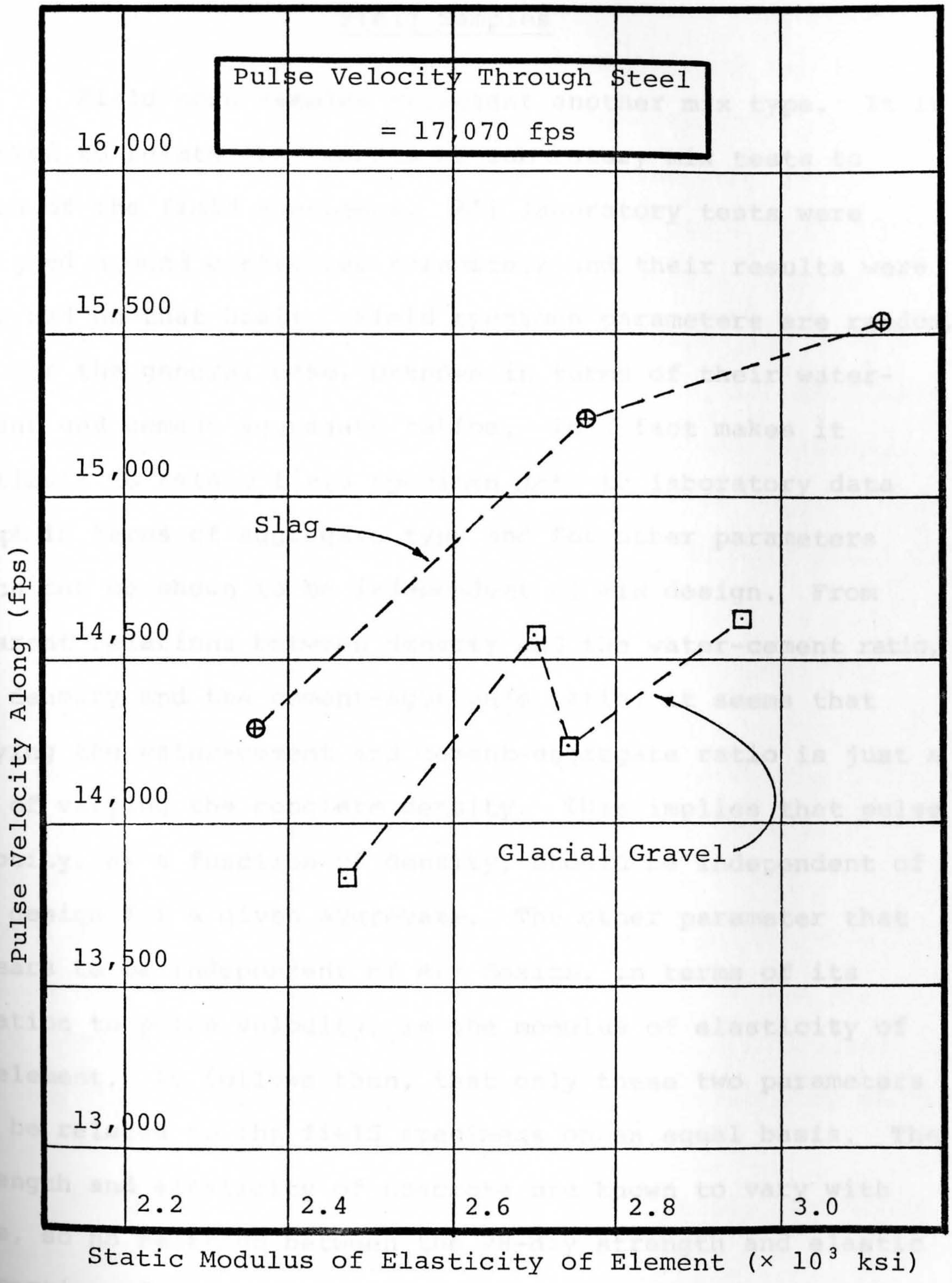


Figure 30. Velocity Along Beam vs. the Composite Beam Element Modulus of Elasticity.

Field Samples

Field core samples represent another mix type. It is desired to relate the results of laboratory mix tests to tests of the field specimens. All laboratory tests were designed around controlled parameters and their results were analyzed on that basis. Field specimen parameters are random, and for the general case, unknown in terms of their water-cement and cement-aggregate ratios. This fact makes it difficult to relate field specimen data to laboratory data except in terms of aggregate type and for other parameters which can be shown to be independent of mix design. From apparent relations between density and the water-cement ratio, and density and the cement-aggregate ratio, it seems that varying the water-cement and cement-aggregate ratio is just a way of varying the concrete density. This implies that pulse velocity, as a function of density, should be independent of mix design for a given aggregate. The other parameter that appears to be independent of mix design, in terms of its relation to pulse velocity, is the modulus of elasticity of an element. It follows then, that only these two parameters can be related to the field specimens on an equal basis. The strength and elasticity of concrete are known to vary with time, so no relation between the 28-day strength and elastic properties of the laboratory specimens can be justly compared to the much older field specimens.

Six field specimens were taken. Four contained reinforcing in a direction transverse to their axes and two contained no reinforcing. Weights and measurements taken on the two plain field specimens resulted in the same weight density of 125.3 pcf. It was found by inspection that the specimens contained slag aggregate. The average velocity through the two specimens was 14,082 fps. Since the modulus of elasticity of the element is time-dependent, no comparison can be made between field and laboratory specimen results. This time dependence may explain why the average modulus of elasticity of the two plain field specimens was only 8.681 × 10^5 psi.

The straight-line analytical relationship between weight density and pulse velocity for slag is

$$V\ (\text{fps}) = -5{,}764.20 + 150.66\gamma\ (\text{pcf})$$

as determined by the method of least squares. This is computed solely for the sake of comparison to the field specimens and not for its validity. Six data points were used in the calculation. If the weigh density of the two field specimens is used in the above equation, a calculated velocity of 13,131 fps is obtained. This is reasonably close to the actual value of 14,082 fps.

Calculating the straight-line relationship for pulse velocity versus E_{EL} in slag yields

$$V\ (\text{fps}) = 10{,}508.21 + 1645.07E_{EL}\ (\times 10^6\ \text{psi})$$

Using data for the two plain concrete specimens, and neglecting time dependent effects, this equation predicts a field specimen pulse velocity of 11,936 fps, and for plain concrete, $E_{EL} = E_C$.

Dynamic Modulus of Elasticity

The dynamic modulus of elasticity is related to pulse velocity by definition. This fact leads to the questioning of the relationship between the static modulus of elasticity and the dynamic modulus of elasticity, since the static modulus of elasticity appears to have some relation to pulse velocity also. This relationship, by aggregate type, has been plotted in Figure 31. There appears to be some correlation between the static and dynamic moduli of elasticity, but the practical value of the dynamic modulus of elasticity is not apparent. In general, the dynamic modulus has a much higher numerical value than the static modulus of elasticity for any given mix design.

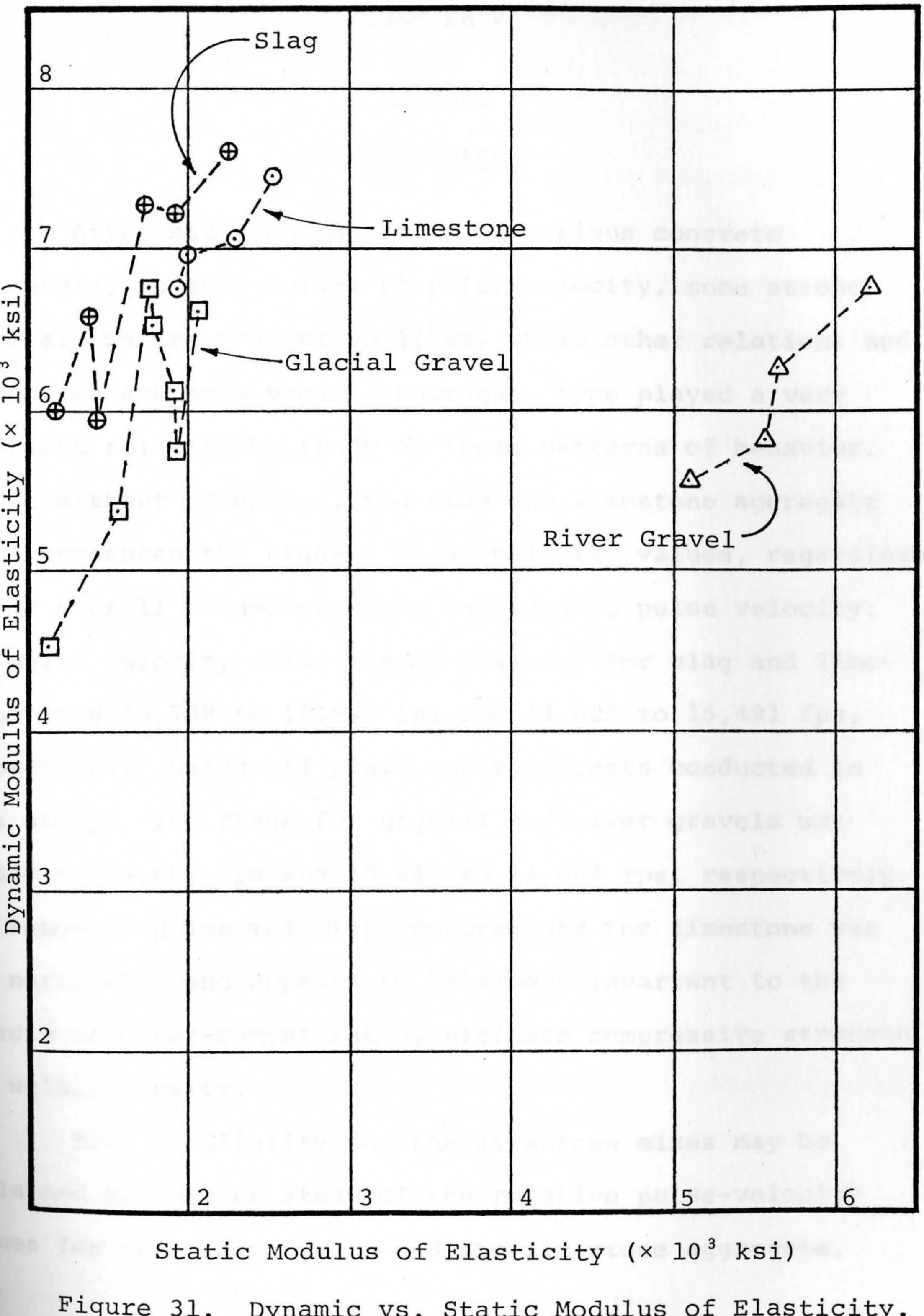


Figure 31. Dynamic vs. Static Modulus of Elasticity.

CHAPTER V

SUMMARY

Discussion

After studying the plots of various concrete parameters, as they relate to pulse velocity, some strong correlations are brought to light, while other relations and tendencies are more vague. Aggregate type played a very important role in the study of these patterns of behavior. Almost without exception, the slag and limestone aggregate mixes presented the highest pulse-velocity values, regardless of the overall parameter being compared to pulse velocity. The pulse velocity value ranges measured for slag and limestone were 13,738 to 15,977 fps and 14,629 to 15,491 fps, respectively, using all plain concrete tests conducted in this study. The range for glacial and river gravels was 12,449 to 14,607 fps and 13,442 to 14,604 fps, respectively. The range of pulse velocity measurements for limestone was the narrowest, and appears to be almost invariant to the effects of water-cement ratio, ultimate compressive strength, and weight density.

This peculiarity for the limestone mixes may be explained by further study of the relative pulse-velocity values for the cement paste and the limestone aggregate.

If their values are close, then the sonic pulse may be travelling through a medium which appears to be homogeneous in its acoustic properties when limestone is the aggregate being tested. Aggregate type appears to be the major determining factor in comparing various parameters to pulse velocity. No variation of the cement-aggregate ratio for the limestone mixes was done, nor was any accounting for of the effect of aggregate gradation made.

The only true effect that varying the water-cement ratio and the cement-aggregate ratio has on pulse velocity appears to be that it varies the weight density of the mix which in turn is consistent in its variation with pulse velocity. This is brought out in the comparison of plots of pulse velocity to water-cement ratio and weight density to water-cement ratio. The same applies to plots of pulse velocity to cement-aggregate ratio and weight density to cement-aggregate ratio. Individual plots of pulse velocity to water-cement ratio show that as the water content is increased, the pulse velocity tends to decrease. Likewise, an increase in the cement-aggregate ratio tends to decrease pulse velocity. Both of these tendencies are consistent in the way that weight density varies with changes in the water-cement and cement-aggregate ratios.

Plots of the effect of the proximity of reinforcing show a slight tendency for pulse velocity to decrease with an increase in the distance between the reinforcing steel and the transducers.

This is not a very strong tendency, but it is apparent in most plots, using the three proximities tested. The pulse velocity in reinforced concrete was consistently higher than for plain concrete of the same mix design. No pulse velocity measured in a reinforced beam exceeded that measured in the reinforcing steel alone. The percentage of longitudinal reinforcing steel appears to be the most important reinforcement effect for relatively slender beams, such as the ones tested. The effect of the proximity of reinforcement to the transducers is logically less for long distance pulse-velocity measurements, if pulse velocity gives a representative reading for the entire element in which it travels. It is apparent that the static modulus of elasticity of an element is directly proportional to the pulse velocity through it. This is related to the percentage of longitudinal reinforcing steel.

Comparisons between pulse velocity and the ultimate compressive strength show some general correlation. This is to be expected, as the ultimate compressive strength is related to weight density and the modulus of elasticity by(9)

$$E_C = \omega^{1.5} \times 33\sqrt{f'_c}$$

where: values of ω are for concrete, between 90 and 155 pcf. Weight density and static modulus of elasticity in turn are related by test results to pulse velocity. The relationship between ω, E_C, and f'_c has been well documented for many aggregates including shale, slag, gravel, pumice, sand, perlite, and vermiculite.(10)

The general effects of the water-cement ratio, cement-aggregate ratio, aggregate type and percentage of reinforcing have been observed to be related to pulse velocity. These relationships are not well defined, but appear to be present. Some hope for developing a more definitive relationship might be found in work developed by the Technical Building Institute in Warsaw, Poland.(11) They have developed a nomograph relating pulse velocity to ultimate compressive strength if the water-cement ratio, total percentage of aggregate, quality of aggregate, aggregate gradation, cement type, age of concrete, moisture condition, and percentage of reinforcement are known. The results of the Polish work strengthen the results obtained in this study.

From the test results, it is strongly indicated that for the beams used, the difference in passing a sonic pulse through a beam as opposed to passing a pulse using the along-the-beam method is very small. Likewise, a pulse passed through a beam travels at the same rate when passed through a cylinder.

There is an apparent relationship between the static and the dynamic moduli of elasticity, as a result of tests conducted. No apparent use for the calculation of the dynamic modulus has been found.

Conclusions

The graphic results serve to show the characteristic tendencies and relationships between various parameters under study in this work. From the analysis of these results, it is felt that the following conclusions can be made:

1. Aggregate type is the most important factor for meaningful interpretation of pulse-velocity readings. Aggregate type must be identified in field specimens.
2. Pulse-velocity test results involving limestone aggregate must be interpreted with caution. Limestone concrete pulse-velocity readings exhibit little sensitivity to water-cement ratio, concrete strength, and weight density.
3. Weight density is an important factor affecting pulse velocity. The effect of the water-cement ratio, and the cement-aggregate ratio are secondary.
4. In relatively slender beams, the proximity of reinforcing has little effect on pulse velocity.
5. The percentage of reinforcement is related to pulse velocity through its effect on the composite modulus of elasticity of the element under test. The percentage of longitudinal reinforcing is the most important

factor affecting pulse velocity for slender beams.

6. The ultimate compressive strength of concrete is related to pulse velocity, but is affected by many variables, so as to cloud test results if proper accounting for these effects is not made.
7. Results of pulse-velocity testing along a beam can be compared to tests conducted through a beam, with a good degree of confidence.
8. The geometry of a beam as opposed to that of a cylinder has no effect on pulse-velocity measurements.
9. The dynamic modulus of elasticity is related to the static modulus of elasticity. The dynamic modulus is generally higher than the static modulus.

Recommendations

The recommendations made are made with practical reasons in mind. The ultimate goal is to determine nondestructively, or with the aid of a few core specimens, the in-situ concrete properties of ultimate compressive strength and static modulus of elasticity.

As aggregate type is the most important variable, some method of more accurately measuring and predicting the relationship between the individual aggregate type and pulse velocity should be pursued for common aggregates used in construction. This is especially needed in the case of limestone.

The effect of longitudinal reinforcing on pulse velocity has been observed, however, to make practical use of pulse-velocity testing, some accounting for the effects of transverse reinforcement on pulse velocity should be done in future work.

The many things that may affect a pulse-velocity reading and thus obscure its relationship to ultimate compressive strength must be defined. In addition to the ones brought out in this study, it is felt that some practical evaluation of aggregate gradation, concrete age, cement type, and moisture condition and the relationship of each to pulse velocity should be made.

Extension of this work should be limited to beam and cylinder specimens until a correlation has been made to test results for velocity measurements taken in slabs or some other geometric shape.

Many more specimens of each mix design and aggregate type are needed to develop analytical relations between pulse velocity and various parameters, over the range of practical concrete mix designs. Testing of a much greater number of specimens is urged in future work so as to make more accurate mathematical relationships possible. This may cause future studies to be limited to a reduced number of aggregate types for reasons of limited space.

APPENDIX A

Sieve Analyses

Batch No.	Sieve Size	Limestone % Passing Analysis No. 1	2	3	Glacial Gravel % Passing Analysis No. 1	2	3
	1"	100.0	100.0	100.0	100.0	100.0	100.0
	3/4"	84.1	93.9	94.1	93.9	93.1	91.8
1	1/2"	55.8	56.8	52.7	55.8	59.9	59.8
	3/8"	11.9	13.6	11.6	16.9	22.0	16.4
	#4	0.8	1.4	0.2	0.8	1.7	0.6
	1"	100.0	100.0		100.0	100.0	100.0
	3/4"	91.6	94.9		75.8	79.4	87.8
2	1/2"	43.5	55.1		23.6	27.4	56.1
	3/8"	17.1	13.9		9.6	6.7	13.3
	#4	0.8	0.7		0.2	0.4	0.5

		Limestone			Glacial Gravel		
Batch No.	Sieve Size	% Passing Analysis No.			% Passing Analysis No.		
		1	2	3	1	2	
1	1"	100.0	100.0	100.0	100.0	100.0	100.0
	3/4"	94.3	93.9	94.1	93.9	93.1	91.8
	1/2"	51.2	56.8	51.6	55.8	59.9	59.8
	3/8"	11.9	13.5	11.6	16.9	22.0	16.4
	#4	0.8	1.4	0.7	0.8	1.7	0.6
2	1"	100.0	100.0		100.0	100.0	100.0
	3/4"	91.6	94.9		71.8	75.4	87.8
	1/2"	43.5	53.1		23.6	27.4	56.1
	3/8"	11.1	11.7		2.8	4.7	13.3
	#4	0.8	0.7		0.2	0.4	0.5

Batch No.	Sieve Size	River Gravel % Passing Analysis No. 1	2	3	Slag % Passing Analysis No. 1	2	3
1	1"	100.0	100.0	100.0	100.0	100.0	100.0
	3/4"	85.9	85.7	82.5	15.3	75.7	85.3
	1/2"	44.4	37.8	47.7	36.2	28.9	30.1
	3/8"	17.3	11.9	23.5	9.4	8.9	8.7
	#4	0.5	0.3	0.6	0.3	0.8	0.4
2	1"				100.0	100.0	100.0
	3/4"				85.9	88.8	87.9
	1/2"				25.3	26.4	35.2
	3/8"				4.9	5.6	7.8
	#4				0.2	0.4	0.5

Sand

Sieve Size	Cumulative % Retained Trial Number 1	 2	 3
4	0.3	0.2	
8	11.2	10.4	
16	26.6	25.2	
30	48.3	45.7	
50	85.0	85.2	
100	98.1	97.5	
Total	269.5	264.2	
Fineness Modulus	2.69	2.64	
4	0.4	0.7	0.6
8	12.2	11.7	12.3
16	25.7	26.1	26.8
30	42.3	44.6	45.2
50	81.2	78.2	79.8
100	96.4	96.2	96.4
Total	258.2	257.5	261.1
Fineness Modulus	2.58	2.58	2.61

APPENDIX B

Mix Batching Procedure and Mix Compositions

SAMPLE MIX DESIGN

Mix Designation A5L:

Water-cement ratio = A5L

Cement-aggregate ratio = 4/10

Aggregate type = Limestone

Fines-coarse ratio = 1/2

Air content = ±6%

Design Procedure: (See Table)

1.) List absolute densities in Column 1.

2.) Using a total aggregate weight of 100 lbs., determine the sand and limestone trial weights by using the fine to coarse aggregate ratio. (1 part sand + 2 parts limestone = 100 lbs., therefore, sand weight = 33.33 lbs., and limestone weight = 66.67 lbs.)

3.) Determine the trial cement weight by multiplying the total aggregate weight by the cement-aggregate ratio. (100 lbs. x 1/5 = 20 lbs. of cement.)

4.) Determine the trial water weight by multiplying the trial cement weight by the water-cement ratio. (20 lbs. x 2/5 = 8 lbs. of water.)

5.) List the results of steps 2 through 4 in Column 2, using a trial air weight of zero.

6.) With the exception of air, divide the trial weight of each component by its absolute density and list the resulting trial volumes in Column 3. This summation is labeled "b".

7.) Multiply the summation, "b", by the ratio 6/94 to get the trial air volume "a".

8.) Divide the trial volumes by the summation of Column 3 ("a" + "b"), and list the results in Column 4. This yields the final component volumes which should sum to one cubic foot.

9.) Multiply the final volume of each component by its absolute density and list its final weight in Column 5. The summation of Column 5 yields the theoretical concrete weight per cubic foot.

Component	1 Absolute Density (lbs./ft.^{3})	2 Trial Weight (lbs.)	3 Trial Volume (ft.^{3})		4 Final Volume (ft.^{3})	5 Final Weight (lbs.)
Air	0.0	0.00	.053	= a	.060	0.00
Water	62.4	8.00	.128	b	.145	9.05
Cement	196.0	20.00	.102		.115	22.55
Sand	165.0	33.33	.202		.228	37.60
Limestone	167.0	66.67	.399		.452	75.50
Summation	——	——	.884		1.000	144.70

Mix Designation	COMPOSITION (For one cubic foot with 6% entrained air)									
	By Weight (pounds)					By Volume (cubic feet)				
	Water	Cement	Sand	Coarse Aggregate	Total	Air	Water	Cement	Sand	Coarse Aggregate
A5L	9.05	22.55	37.60	75.50	144.70	0.060	0.145	0.115	0.228	0.452
B5L	9.98	22.15	37.00	74.00	143.13	0.060	0.160	0.113	0.224	0.443
C5L	10.85	21.80	36.30	72.60	141.55	0.060	0.174	0.111	0.220	0.435
D5L	11.73	21.36	35.64	71.31	140.04	0.060	0.188	0.109	0.216	0.427
A5G	8.92	22.34	37.13	74.20	142.59	0.060	0.143	0.114	0.225	0.458
B5G	9.79	21.95	36.45	73.90	141.09	0.060	0.157	0.112	0.221	0.450
C5G	10.72	21.41	35.78	71.56	139.47	0.060	0.172	0.109	0.217	0.442
D5G	21.07	21.07	35.13	70.27	138.06	0.060	0.186	0.107	0.213	0.434
A5R	8.92	22.34	37.13	74.20	142.59	0.060	0.143	0.114	0.225	0.458
B5R	9.79	21.95	36.45	72.90	141.09	0.060	0.157	0.112	0.221	0.450
C5R	10.72	21.41	35.78	71.56	139.47	0.060	0.172	0.109	0.217	0.442
D5R	11.59	21.07	35.13	70.27	138.06	0.060	0.186	0.107	0.213	0.434
A5S	8.66	21.75	36.15	72.30	138.86	0.060	0.139	0.111	0.219	0.473
B5S	9.55	21.40	35.50	71.00	137.45	0.060	0.153	0.109	0.215	0.464
C5S	10.41	20.98	34.80	69.60	135.79	0.060	0.167	0.107	0.211	0.456
D5S	11.23	20.58	34.16	68.54	134.51	0.060	0.180	0.105	0.207	0.448
B3G	8.61	19.01	38.30	76.60	142.52	0.060	0.138	0.097	0.232	0.473
B4G	9.16	20.40	37.50	75.00	142.06	0.060	0.147	0.104	0.227	0.462
B6G	10.61	23.52	35.30	70.79	140.22	0.060	0.170	0.120	0.214	0.437
B3S	8.35	18.60	37.20	74.40	138.55	0.060	0.134	0.095	0.225	0.486
B4S	8.92	19.80	36.30	72.60	137.62	0.060	0.143	0.101	0.220	0.475

APPENDIX C

Laboratory Data

DATA SHEET

MIX DESIGN: A5L
DATE: 6-22-73

	BEAM TYPE	TRAVEL TIME ALONG - µ SEC.							TIME THROUGH µ SEC.	DIMENSIONS			WEIGHT LBS.
		DISTANCE BETWEEN TRANSDUCERS - FT.								LENGTH FT.	HEIGHT IN.	WIDTH IN.	
		0.5	1.0	1.5	2.0	2.5	3.0	3.5					
PLAIN	#1	30.4	65.3	99.0	132.9	166.6	201.9	235.6	259.3	3.930	4.06	4.64	74.75
	#2	31.2	66.8	101.2	135.5	169.1	203.3	239.1	259.1	3.935	4.07	4.47	71.60
	#3	32.0	67.2	100.9	135.4	169.6	202.9	237.7	258.3	3.935	4.02	4.61	74.50
REINFORCED	DEPTH OF STEEL												
	1"	30.5	62.0	94.0	125.6	158.2	190.7	224.0		3.890	4.05	4.59	78.25
	2"	31.9	64.8	97.1	129.6	162.8	197.9	234.5		3.880	4.03	4.67	78.90
	3"	29.7	62.6	95.5	127.8	160.6	192.9	225.6		3.890	4.05	4.59	78.25

CYLINDER	TIME THROUGH µ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	66.3	11.95	178.2
#2			
#3			
#4			

DATA SHEET

MIX DESIGN: B5L
DATE: 6-29-73

BEAM TYPE		TRAVEL TIME ALONG - µ SEC.							TIME THROUGH µ SEC.	DIMENSIONS			WEIGHT LBS.
		DISTANCE BETWEEN TRANSDUCERS - FT.								LENGTH FT.	HEIGHT IN.	WIDTH IN.	
		0.5	1.0	1.5	2.0	2.5	3.0	3.5					
PLAIN	#1	31.7	66.6	98.6	132.1	165.8	199.7	234.4	256.4	3.935	4.02	4.63	73.75
	#2	31.4	65.5	97.2	130.8	166.0	199.4	233.2	256.2	3.938	4.02	4.63	73.50
	#3	29.5	63.5	96.1	130.2	162.7	197.6	231.2	255.6	3.935	4.05	4.59	74.00
REINFORCED	DEPTH OF STEEL												
	1"	28.8	60.8	91.9	124.1	155.6	187.4	220.2		3.892	4.07	4.47	77.50
	2"	31.6	66.0	98.5	131.2	162.8	196.1	228.7		3.890	4.06	4.60	80.00
	3"	31.7	65.2	97.0	128.9	160.9	192.7	224.1		3.892	4.07	4.47	77.50

CYLINDER	TIME THROUGH µ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	67.9	11.980	166.0
#2			
#3			
#4			

DATA SHEET

MIX DESIGN: C5L
DATE: 6-27-73

BEAM TYPE		TRAVEL TIME ALONG - µ SEC.							TIME THROUGH µ SEC.	DIMENSIONS			WEIGHT LBS.
		DISTANCE BETWEEN TRANSDUCERS - FT.								LENGTH FT.	HEIGHT IN.	WIDTH IN.	
		0.5	1.0	1.5	2.0	2.5	3.0	3.5					
PLAIN	#1	31.4	66.4	102.1	138.3	170.8	206.2	242.2	254.3	3.927	4.05	4.63	74.00
	#2	28.8	64.9	96.7	128.5	161.8	194.2	230.8	253.5	3.927	4.02	4.63	75.50
	#3	30.2	64.8	97.6	128.9	162.9	196.5	231.2	255.7	3.927	3.97	4.62	74.00
REINFORCED	DEPTH OF STEEL												
	1"	31.8	65.1	96.2	127.8	162.3	195.1	229.3		3.885	4.00	4.64	78.50
	2"	33.7	66.5	98.4	132.3	166.0	196.3	321.2		3.885	4.05	4.46	77.00
	3"	29.6	62.1	94.8	127.2	159.4	192.1	225.5		3.885	4.00	4.64	78.50

CYLINDER	TIME THROUGH µ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	65.1	11.980	174.8
#2			
#3			
#4			

DATA SHEET

MIX DESIGN: D5L
DATE: 7-20-73

BEAM TYPE		TRAVEL TIME ALONG - μ SEC.							TIME THROUGH μ SEC.	DIMENSIONS			WEIGHT LBS.
		DISTANCE BETWEEN TRANSDUCERS - FT.								LENGTH FT.	HEIGHT IN.	WIDTH IN.	
		0.5	1.0	1.5	2.0	2.5	3.0	3.5					
PLAIN	#1	30.6	65.2	99.5	135.4	168.7	204.2	239.2	263.6	3.940	3.96	4.58	72.60
	#2	30.8	64.9	98.6	133.0	168.8	202.7	238.2	263.2	3.940	4.02	4.49	70.90
	#3	30.7	64.6	98.3	132.8	167.4	201.8	237.5	262.0	3.940	4.03	4.64	74.25
REINFORCED	DEPTH OF STEEL												
	1"	33.8	64.4	97.6	130.8	166.3	200.5	234.7		3.860	4.03	4.55	76.00
	2"	31.6	66.5	98.3	131.8	165.9	201.7	237.3		3.880	4.03	4.55	78.40
	3"	31.4	65.6	99.7	133.6	166.8	201.9	236.2		3.860	4.03	4.55	76.00

CYLINDER	TIME THROUGH μ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	66.4	11.900	127.5
#2			
#3			
#4			

DATA SHEET

MIX DESIGN: A5G
DATE: 6-29-73

BEAM TYPE		TRAVEL TIME ALONG - µ SEC.							TIME THROUGH µ SEC.	DIMENSIONS			WEIGHT LBS.
		DISTANCE BETWEEN TRANSDUCERS - FT.								LENGTH FT.	HEIGHT IN.	WIDTH IN.	
		0.5	1.0	1.5	2.0	2.5	3.0	3.5					
PLAIN	#1	33.0	69.4	105.4	141.2	178.0	211.5	245.9	271.4	3.945	4.10	4.46	74.00
	#2	32.8	68.8	104.3	140.2	174.8	210.5	246.4	269.6	3.938	4.08	4.56	75.50
	#3	32.4	67.5	102.7	140.4	176.2	211.9	246.5	271.8	3.942	4.05	4.64	75.75
REINFORCED	DEPTH OF STEEL												
	1"	34.5	68.0	100.7	135.2	168.6	202.6	237.5		3.893	4.08	4.61	80.50
	2"	32.1	67.4	100.0	133.1	167.7	202.5	237.1		3.895	4.11	4.64	81.00
	3"	32.1	68.0	101.4	134.9	168.3	202.4	236.1		3.893	4.08	4.61	80.50

CYLINDER	TIME THROUGH µ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	69.1	12.078	198.5
#2			
#3			
#4			

DATA SHEET

MIX DESIGN: B5G
DATE: 7-5-73

BEAM TYPE		TRAVEL TIME ALONG - μ SEC.							TIME THROUGH μ SEC.	DIMENSIONS			WEIGHT LBS.
		DISTANCE BETWEEN TRANSDUCERS - FT.								LENGTH FT.	HEIGHT IN.	WIDTH IN.	
		0.5	1.0	1.5	2.0	2.5	3.0	3.5					
PLAIN	#1	33.5	71.7	109.2	147.4	185.6	223.2	231.2	288.1	3.945	4.07	4.49	70.50
	#2	34.8	71.8	108.9	146.7	184.2	220.8	257.8	287.5	3.938	4.07	4.56	71.75
	#3	33.3	73.8	109.9	147.1	185.0	223.8	262.5	287.5	3.940	4.08	4.66	73.25
REINFORCED	DEPTH OF STEEL												
	1"	34.2	66.6	101.8	139.8	176.4	213.2	250.6		3.894	4.02	4.64	76.75
	2"	35.2	72.5	106.6	144.4	178.8	218.0	252.3		3.892	4.09	4.63	77.50
	3"	33.1	70.8	107.4	141.7	177.4	214.8	252.4		3.894	4.02	4.64	76.75

CYLINDER	TIME THROUGH μ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	72.7	12.008	134.0
#2			
#3			
#4			

DATA SHEET

MIX DESIGN: C5G
DATE: 7-9-73

BEAM TYPE		TRAVEL TIME ALONG - μ SEC. DISTANCE BETWEEN TRANSDUCERS - FT. 0.5	1.0	1.5	2.0	2.5	3.0	3.5	TIME THROUGH μ SEC.	DIMENSIONS LENGTH FT.	HEIGHT IN.	WIDTH IN.	WEIGHT LBS.
PLAIN	#1	36.6	77.2	118.5	161.2	202.4	242.9	284.6	314.6	3.950	4.05	4.47	64.50
	#2	37.9	78.4	119.4	161.0	202.2	242.7	283.2	311.6	3.940	4.12	4.57	66.50
	#3	36.2	78.8	119.2	160.2	202.1	242.8	284.1	312.7	3.940	4.05	4.68	68.05
REINFORCED	DEPTH OF STEEL												
	1"	37.4	69.7	104.1	145.6	186.2	222.4	263.8		3.890	4.03	4.69	72.70
	2"	35.1	75.3	107.2	144.9	184.6	225.8	264.5		3.885	4.05	4.63	72.50
	3"	35.1	76.0	113.3	148.9	187.5	226.4	264.1		3.890	4.03	4.69	72.70

CYLINDER	TIME THROUGH μ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	79.1	12.054	99.5
#2			
#3			
#4			

DATA SHEET

MIX DESIGN: D5G
DATE: 7-13-73

BEAM TYPE		TRAVEL TIME ALONG - μ SEC. DISTANCE BETWEEN TRANSDUCERS - FT. 0.5	1.0	1.5	2.0	2.5	3.0	3.5	TIME THROUGH μ SEC.	DIMENSIONS LENGTH FT.	HEIGHT IN.	WIDTH IN.	WEIGHT LBS.
PLAIN	#1	33.8	72.7	115.6	155.1	197.4	231.5	268.8	296.5	3.945	4.04	4.66	72.50
	#2		(TWO PLAIN BEAMS BROKEN)										
	#3												
REINFORCED	DEPTH OF STEEL												
	1"	34.3	68.0	102.4	140.0	176.4	213.8	250.8		3.885	4.03	4.67	75.60
	2"	33.8	73.6	108.3	146.6	185.7	223.4	262.5		3.890	4.00	4.61	75.30
	3"	33.3	72.8	108.0	144.0	179.9	217.0	254.2		3.885	4.03	4.67	75.60

CYLINDER	TIME THROUGH μ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	74.0	11.909	127.5
#2	75.1	11.910	119.4
#3			
#4			

DATA SHEET

MIX DESIGN: A5R
DATE: 7-18-73

BEAM TYPE		TRAVEL TIME ALONG - μ SEC.							TIME THROUGH μ SEC.	DIMENSIONS			WEIGHT LBS.
		DISTANCE BETWEEN TRANSDUCERS - FT.								LENGTH FT.	HEIGHT IN.	WIDTH IN.	
		0.5	1.0	1.5	2.0	2.5	3.0	3.5					
PLAIN	#1	35.9	71.5	108.3	144.6	181.2	217.3	253.4	279.5	3.925	4.06	4.97	77.90
	#2	32.7	70.8	107.0	144.1	181.0	217.5	254.7	277.7	3.930	4.06	4.96	78.25
	#3	33.8	71.1	107.5	143.8	181.0	217.6	256.5	277.1	3.930	4.04	4.89	77.25
REINFORCED	DEPTH OF STEEL												
	1"	33.6	66.6	100.9	135.1	170.1	205.1	240.6		3.885	4.05	4.95	82.25
	2"	32.9	68.8	102.2	136.3	172.8	208.6	244.3		3.880	4.05	4.90	81.25
	3"	32.6	68.0	104.3	137.8	172.7	206.4	243.4		3.885	4.05	4.95	82.25

CYLINDER	TIME THROUGH μ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	69.7	11.952	180.7
#2			
#3			
#4			

DATA SHEET

MIX DESIGN: B5R
DATE: 7-23-73

BEAM TYPE		TRAVEL TIME ALONG - μ SEC. DISTANCE BETWEEN TRANSDUCERS - FT. 0.5	1.0	1.5	2.0	2.5	3.0	3.5	TIME THROUGH μ SEC.	DIMENSIONS LENGTH FT.	HEIGHT IN.	WIDTH IN.	WEIGHT LBS.
PLAIN	#1	32.1	68.0	102.8	138.1	173.9	208.6	245.0	270.5	3.950	4.11	4.47	74.00
	#2	32.5	68.1	102.9	139.0	174.8	210.0	245.5	271.7	3.940	4.08	4.62	76.50
	#3	32.2	67.8	104.4	139.2	176.0	211.2	246.8	271.2	3.940	4.11	4.59	75.50
REINFORCED	DEPTH OF STEEL												
	1"	32.1	64.6	98.2	132.0	168.0	202.4	235.8		3.890	4.09	4.69	81.50
	2"	30.9	66.6	100.0	134.1	168.6	203.0	238.6		3.895	4.06	4.64	80.00
	3"	32.6	67.2	101.6	135.3	170.6	204.7	240.1		3.890	4.09	4.69	81.50

CYLINDER	TIME THROUGH μ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	68.6	12.022	176.4
#2			
#3			
#4			

DATA SHEET

MIX DESIGN: C5R
DATE: 7-24-73

BEAM TYPE		TRAVEL TIME ALONG - µ SEC. DISTANCE BETWEEN TRANSDUCERS - FT.							TIME THROUGH µ SEC.	DIMENSIONS			WEIGHT LBS.
		0.5	1.0	1.5	2.0	2.5	3.0	3.5		LENGTH FT.	HEIGHT IN.	WIDTH IN.	
PLAIN	#1	33.2	71.1	107.7	144.5	182.8	219.4	257.6	284.2	3.940	4.03	4.66	74.25
	#2	33.9	69.8	107.8	145.8	182.2	219.8	257.5	283.7	3.945	4.09	4.50	72.00
	#3	33.4	70.4	107.5	144.7	181.6	218.4	256.1	282.6	3.940	4.13	4.63	73.75
REINFORCED	DEPTH OF STEEL												
	1"	36.0	68.8	102.8	139.4	176.1	211.3	247.4		3.890	4.08	4.58	77.75
	2"	34.6	70.8	104.4	138.8	175.6	211.8	247.6		3.890	4.08	4.69	79.50
	3"	32.9	69.3	106.6	141.1	177.3	211.8	248.2		3.890	4.08	4.58	77.75

CYLINDER	TIME THROUGH µ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	72.4	11.938	139.5
#2			
#3			
#4			

DATA SHEET

MIX DESIGN: D5R
DATE: 7-26-73

BEAM TYPE		TRAVEL TIME ALONG – μ SEC. DISTANCE BETWEEN TRANSDUCERS – FT.							TIME THROUGH μ SEC.	DIMENSIONS			WEIGHT LBS.
		0.5	1.0	1.5	2.0	2.5	3.0	3.5		LENGTH FT.	HEIGHT IN.	WIDTH IN.	
PLAIN	#1	31.8	70.5	108.1	145.4	183.1	223.0	262.5	287.1	3.930	4.04	4.87	74.30
	#2	35.3	73.4	110.5	147.9	186.2	224.8	263.6	292.7	3.935	4.01	4.87	74.15
	#3	33.7	71.1	108.8	147.5	186.2	226.2	264.0	291.8	3.925	4.02	4.95	74.20
REINFORCED	DEPTH OF STEEL												
	1"	37.0	68.7	103.5	141.2	177.7	214.7	251.6		3.890	4.04	4.87	78.90
	2"	32.4	70.9	103.8	139.7	176.5	214.1	251.8		3.890	4.01	4.82	78.00
	3"	35.2	73.5	110.0	144.6	182.1	218.8	254.6		3.890	4.04	4.87	78.90

CYLINDER	TIME THROUGH μ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	72.8	11.948	119.8
#2			
#3			
#4			

DATA SHEET

MIX DESIGN: A5S
DATE: 7-30-73

BEAM TYPE		TRAVEL TIME ALONG - μ SEC. DISTANCE BETWEEN TRANSDUCERS - FT.							TIME THROUGH μ SEC.	DIMENSIONS			WEIGHT LBS.
		0.5	1.0	1.5	2.0	2.5	3.0	3.5		LENGTH FT.	HEIGHT IN.	WIDTH IN.	
PLAIN	#1	29.7	61.8	94.7	127.5	160.8	194.3	226.5	250.6	3.950	4.08	4.45	69.75
	#2	29.3	61.5	94.4	126.4	159.2	191.6	224.6	248.8	3.940	4.07	4.66	73.70
	#3	29.1	61.6	93.8	125.9	158.4	190.9	224.0	246.6	3.940	4.05	4.61	72.60
REINFORCED	DEPTH OF STEEL												
	1"	31.7	62.8	94.7	126.7	158.8	191.6	224.1		3.890	4.11	4.55	75.70
	2"	29.1	62.0	93.7	125.7	157.6	189.8	222.5		3.895	4.06	4.72	78.38
	3"	29.6	63.0	95.1	126.9	160.0	192.4	225.1		3.890	4.11	4.55	75.70

CYLINDER	TIME THROUGH μ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	64.3	11.930	140.9
#2			
#3			
#4			

DATA SHEET

MIX DESIGN: B5S
DATE: 8-1-73

BEAM TYPE		TRAVEL TIME ALONG - μ SEC. DISTANCE BETWEEN TRANSDUCERS - FT.							TIME THROUGH μ SEC.	DIMENSIONS			WEIGHT LBS.
		0.5	1.0	1.5	2.0	2.5	3.0	3.5		LENGTH FT.	HEIGHT IN.	WIDTH IN.	
PLAIN	#1	33.1	67.5	101.6	136.2	171.6	205.8	241.3	264.6	3.940	3.98	4.91	72.60
	#2	30.3	63.5	97.9	131.8	166.5	201.2	235.5	263.8	3.940	4.05	4.90	73.10
	#3	30.8	64.9	99.5	133.3	168.0	202.6	237.3	261.8	3.940	4.02	4.90	73.00
REINFORCED	DEPTH OF STEEL												
	1"	32.7	65.0	97.0	131.6	165.3	201.2	235.6		3.885	4.00	4.90	77.50
	2"	30.2	64.8	97.5	130.0	163.6	197.5	231.5		3.880	4.09	4.96	78.00
	3"	31.2	65.6	99.5	132.7	166.4	201.3	235.6		3.885	4.00	4.90	77.50

CYLINDER	TIME THROUGH μ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	63.6	11.476	110.7
#2			
#3			
#4			

DATA SHEET

MIX DESIGN: C5S
DATE: 7-31-73

BEAM TYPE		TRAVEL TIME ALONG - μ SEC. DISTANCE BETWEEN TRANSDUCERS - FT. 0.5	1.0	1.5	2.0	2.5	3.0	3.5	TIME THROUGH μ SEC.	DIMENSIONS LENGTH FT.	HEIGHT IN.	WIDTH IN.	WEIGHT LBS.
PLAIN	#1	30.2	64.0	98.4	132.4	166.8	200.8	235.1	261.6	3.945	3.98	4.66	70.80
	#2	30.6	64.8	98.8	133.1	167.9	202.6	238.4	264.4	3.945	3.99	4.48	67.50
	#3	30.9	65.2	99.6	134.0	168.2	202.8	237.6	263.1	3.945	4.01	4.65	70.10
REINFORCED	DEPTH OF STEEL												
	1"	32.1	64.6	96.2	130.8	164.0	199.4	234.1		3.895	4.03	4.66	76.00
	2"	31.2	65.1	98.3	131.3	165.6	199.1	233.9		3.890	4.09	4.56	74.25
	3"	31.0	65.5	99.8	132.4	167.9	201.5	235.2		3.895	4.03	4.66	76.00

CYLINDER	TIME THROUGH μ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	66.1	11.236	98.0
#2			
#3			
#4			

DATA SHEET

MIX DESIGN: D5S
DATE: 8-2-73

	BEAM TYPE	TRAVEL TIME ALONG - µ SEC. DISTANCE BETWEEN TRANSDUCERS - FT.							TIME THROUGH µ SEC.	DIMENSIONS			WEIGHT LBS.
		0.5	1.0	1.5	2.0	2.5	3.0	3.5		LENGTH FT.	HEIGHT IN.	WIDTH IN.	
PLAIN	#1	31.6	67.7	104.3	140.2	176.9	214.0	249.7	276.6	3.940	4.03	4.54	67.10
	#2	32.1	68.6	104.8	142.4	179.6	216.6	254.7	281.6	3.945	4.00	4.51	65.50
	#3	32.0	69.2	105.6	144.7	182.6	221.5	259.6	286.8	3.940	3.96	4.69	67.00
REINFORCED	DEPTH OF STEEL												
	1"	35.3	68.9	104.0	141.1	177.2	217.3	249.7		3.895	3.94	4.64	71.10
	2"	31.8	68.5	101.7	135.9	172.6	208.9	246.7		3.890	3.99	4.66	72.35
	3"	31.8	68.7	104.1	138.6	175.6	210.8	250.0		3.895	3.94	4.64	71.10

CYLINDER	TIME THROUGH µ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	67.9	11.820	61.0
#2	68.2	11.810	76.0
#3	68.9	11.798	72.9
#4			

DATA SHEET

MIX DESIGN: B3G
DATE: 8-8-73

	BEAM TYPE	TRAVEL TIME ALONG - μ SEC. DISTANCE BETWEEN TRANSDUCERS - FT. 0.5	1.0	1.5	2.0	2.5	3.0	3.5	TIME THROUGH μ SEC.	DIMENSIONS LENGTH FT.	HEIGHT IN.	WIDTH IN.	WEIGHT LBS.
PLAIN	#1	32.0	69.5	104.6	141.7	179.1	214.6	252.5	278.6	3.950	4.09	4.50	73.80
	#2	32.0	68.4	105.1	143.0	179.4	216.0	252.6	279.6	3.940	4.09	4.67	76.75
	#3	34.6	70.0	107.1	142.9	180.2	217.8	255.7	280.0	3.940	4.06	4.66	76.50
REINFORCED	DEPTH OF STEEL												
	1"	33.7	66.5	99.4	134.6	169.9	204.3	240.6		3.890	4.08	4.54	78.30
	2"	33.6	69.4	102.2	137.2	172.2	207.8	244.8		3.890	4.02	4.64	79.40
	3"	32.5	68.4	103.2	137.8	172.6	207.9	243.1		3.890	4.08	4.54	78.30

CYLINDER	TIME THROUGH μ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	70.5	12.062	132.9
#2	69.3	12.038	137.0
#3	70.0	12.124	142.9
#4	70.4	12.023	133.4

DATA SHEET

MIX DESIGN: B4G
DATE: 8-10-73

BEAM TYPE		TRAVEL TIME ALONG - μ SEC.							TIME THROUGH μ SEC.	DIMENSIONS			WEIGHT LBS.
		DISTANCE BETWEEN TRANSDUCERS - FT.								LENGTH	HEIGHT	WIDTH	
		0.5	1.0	1.5	2.0	2.5	3.0	3.5		FT.	IN.	IN.	
PLAIN	#1	33.2	69.8	107.4	143.6	179.7	217.5	252.7	277.5	3.945	4.05	4.60	76.10
	#2	33.6	70.7	107.7	143.8	178.9	215.3	251.8	276.5	3.950	4.12	4.45	73.70
	#3	33.0	70.0	106.9	143.7	180.8	217.2	254.5	277.5	3.945	4.14	4.65	77.60
REINFORCED	DEPTH OF STEEL												
	1"	31.7	65.0	99.0	133.4	168.0	202.2	236.8		3.900	4.08	4.61	81.50
	2"	32.3	69.8	103.7	138.5	173.8	210.6	246.7		3.890	4.12	4.58	79.80
	3"	32.5	68.6	102.8	137.4	173.5	206.4	240.8		3.900	4.08	4.61	81.50

CYLINDER	TIME THROUGH μ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	69.2	11.967	166.7
#2	69.4	11.997	164.0
#3	69.5	12.028	171.5
#4	69.5	12.037	160.7

DATA SHEET

MIX DESIGN: B6G
DATE: 8-15-73

	BEAM TYPE	TRAVEL TIME ALONG - μ SEC.							TIME THROUGH μ SEC.	DIMENSIONS			WEIGHT LBS.
		DISTANCE BETWEEN TRANSDUCERS - FT.								LENGTH FT.	HEIGHT IN.	WIDTH IN.	
		0.5	1.0	1.5	2.0	2.5	3.0	3.5					
PLAIN	#1	34.3	71.2	107.7	145.2	184.4	221.9	260.0	287.8	3.925	4.06	4.97	78.30
	#2	33.5	70.3	107.3	144.4	183.0	220.0	259.3	284.3	3.925	4.02	4.88	76.70
	#3	34.8	73.0	109.6	146.7	186.4	223.5	260.4	285.5	3.930	4.07	4.85	77.40
REINFORCED	DEPTH OF STEEL												
	1"	34.3	67.2	101.0	137.5	174.4	209.0	246.0		3.890	4.04	4.89	82.00
	2"	34.8	71.3	105.4	141.3	177.8	214.5	251.4		3.890	4.05	4.91	82.30
	3"	32.6	69.6	105.5	140.6	176.2	212.0	248.5		3.890	4.04	4.89	82.00

CYLINDER	TIME THROUGH μ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	70.2	11.928	140.0
#2	71.8	11.922	148.4
#3	70.1	11.990	147.5
#4	71.0	11.936	143.9

DATA SHEET

MIX DESIGN: B3S
DATE: 8-24-73

BEAM TYPE		TRAVEL TIME ALONG - μ SEC. DISTANCE BETWEEN TRANSDUCERS - FT.							TIME THROUGH μ SEC.	DIMENSIONS			WEIGHT LBS.
		0.5	1.0	1.5	2.0	2.5	3.0	3.5		LENGTH FT.	HEIGHT IN.	WIDTH IN.	
PLAIN	#1	30.8	64.0	96.8	129.7	163.1	196.7	229.8	251.6	3.935	3.99	4.69	73.75
	#2	30.6	63.3	95.8	127.6	161.1	193.8	228.0	249.7	3.935	4.03	4.58	72.40
	#3	30.0	63.8	96.4	129.6	163.5	196.2	229.8	252.2	3.945	4.12	4.45	70.25
REINFORCED	DEPTH OF STEEL												
	1"	31.3	62.9	94.6	127.3	160.4	193.5	227.0		3.890	4.10	4.61	78.40
	2"	30.1	63.3	95.6	126.8	159.4	192.1	226.0		3.880	4.18	4.62	78.00
	3"	31.1	64.7	98.5	130.6	162.8	196.4	229.5		3.890	4.10	4.61	78.40

CYLINDER	TIME THROUGH μ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	64.0	11.986	117.7
#2	63.2	11.985	122.5
#3	63.1	11.948	149.5
#4	63.2	11.921	158.5

DATA SHEET

MIX DESIGN: B4S
DATE: 8-20-73

BEAM TYPE		TRAVEL TIME ALONG - µ SEC.							TIME THROUGH µ SEC.	DIMENSIONS			WEIGHT LBS.
		DISTANCE BETWEEN TRANSDUCERS - FT.								LENGTH FT.	HEIGHT IN.	WIDTH IN.	
		0.5	1.0	1.5	2.0	2.5	3.0	3.5					
PLAIN	#1	31.3	64.5	97.7	130.8	164.4	197.8	235.6	256.2	3.935	4.05	4.92	76.70
	#2	31.0	64.3	97.9	131.6	164.8	198.3	233.1	255.6	3.925	4.08	4.92	75.25
	#3	30.3	63.8	97.4	130.8	165.0	199.0	233.2	257.2	3.925	4.04	4.88	74.45
REINFORCED	DEPTH OF STEEL												
	1"	31.0	63.7	95.9	128.8	162.8	197.8	234.0		3.890	4.02	4.86	78.50
	2"	31.0	64.2	97.0	129.2	162.0	195.3	229.1		3.890	4.06	4.88	79.85
	3"	32.0	66.4	100.2	133.2	166.6	200.5	235.1		3.890	4.02	4.86	78.50

CYLINDER	TIME THROUGH µ SEC.	HEIGHT IN.	ULT. LOAD KIPS
#1	63.8	11.930	97.0
#2	64.5	12.043	95.3
#3	63.9	12.005	120.0
#4	65.4	11.966	89.0

MCGUFFEY BRIDGE

4" DIAMETER CORE DATA SHEET

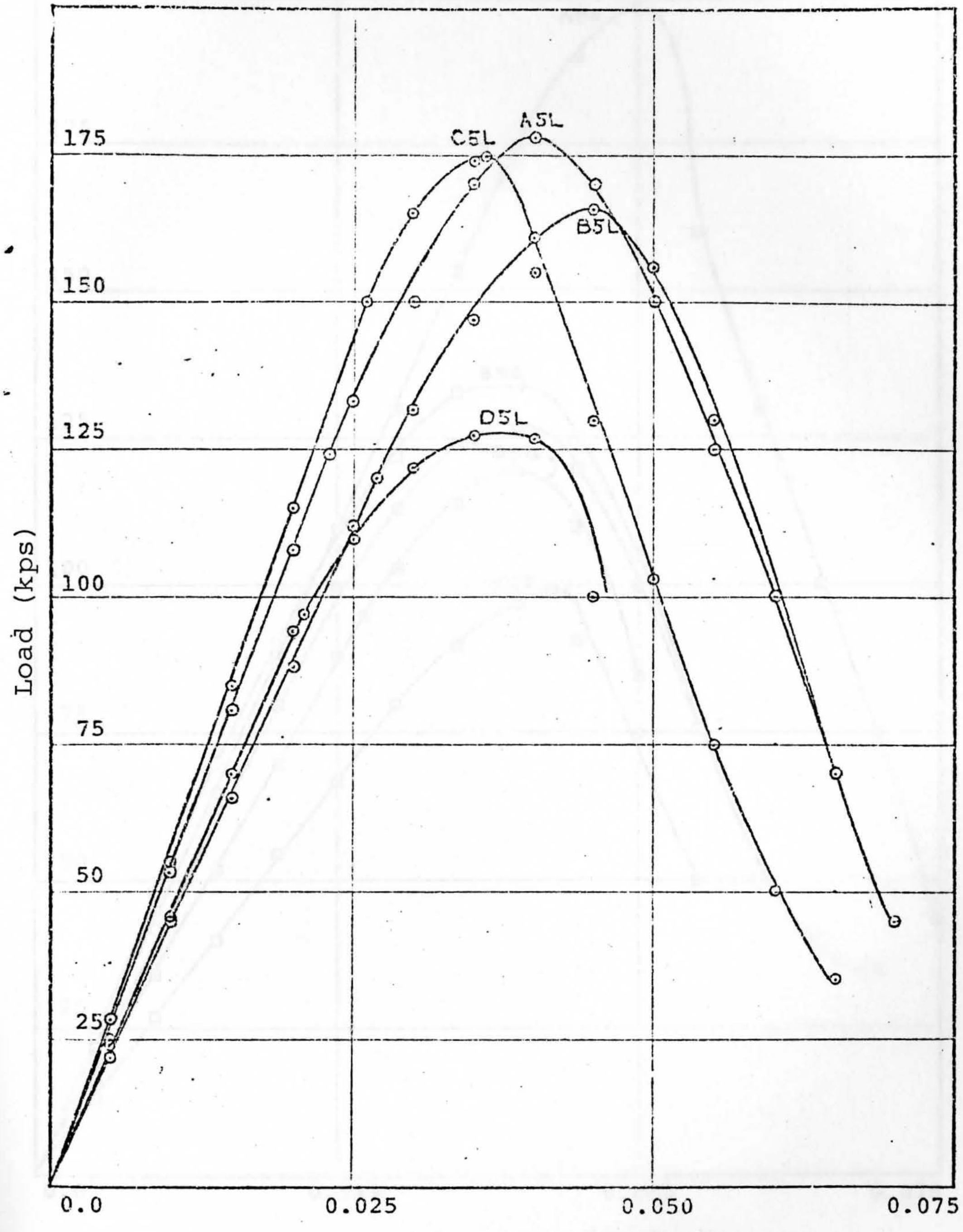
CORE SPECIMEN NO.	TIME THROUGH (μ sec.)	LENGTH (IN.)	ULTIMATE COMPRESSIVE LOAD (KIPS)	WEIGHT (GRAMS)
1	30.1	4.966	67.0	2224
2*	41.0	6.943	64.6	2891
3	42.3	6.970	65.6	3325
4	28.4	4.974	69.0	2348
5*†	41.6	7.015	57.5	2892
6	43.5	6.914	56.3	2896

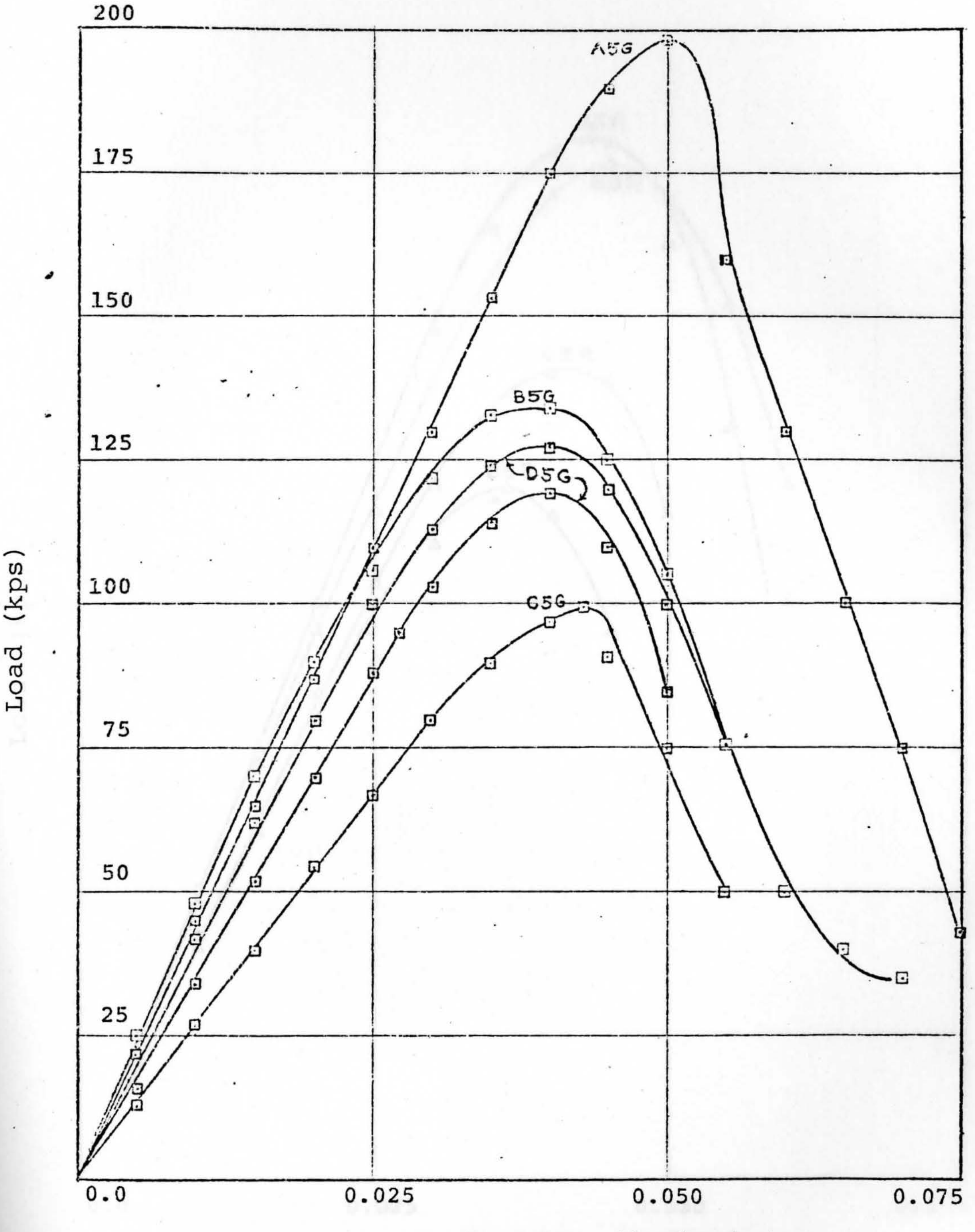
* No reinforcing steel present

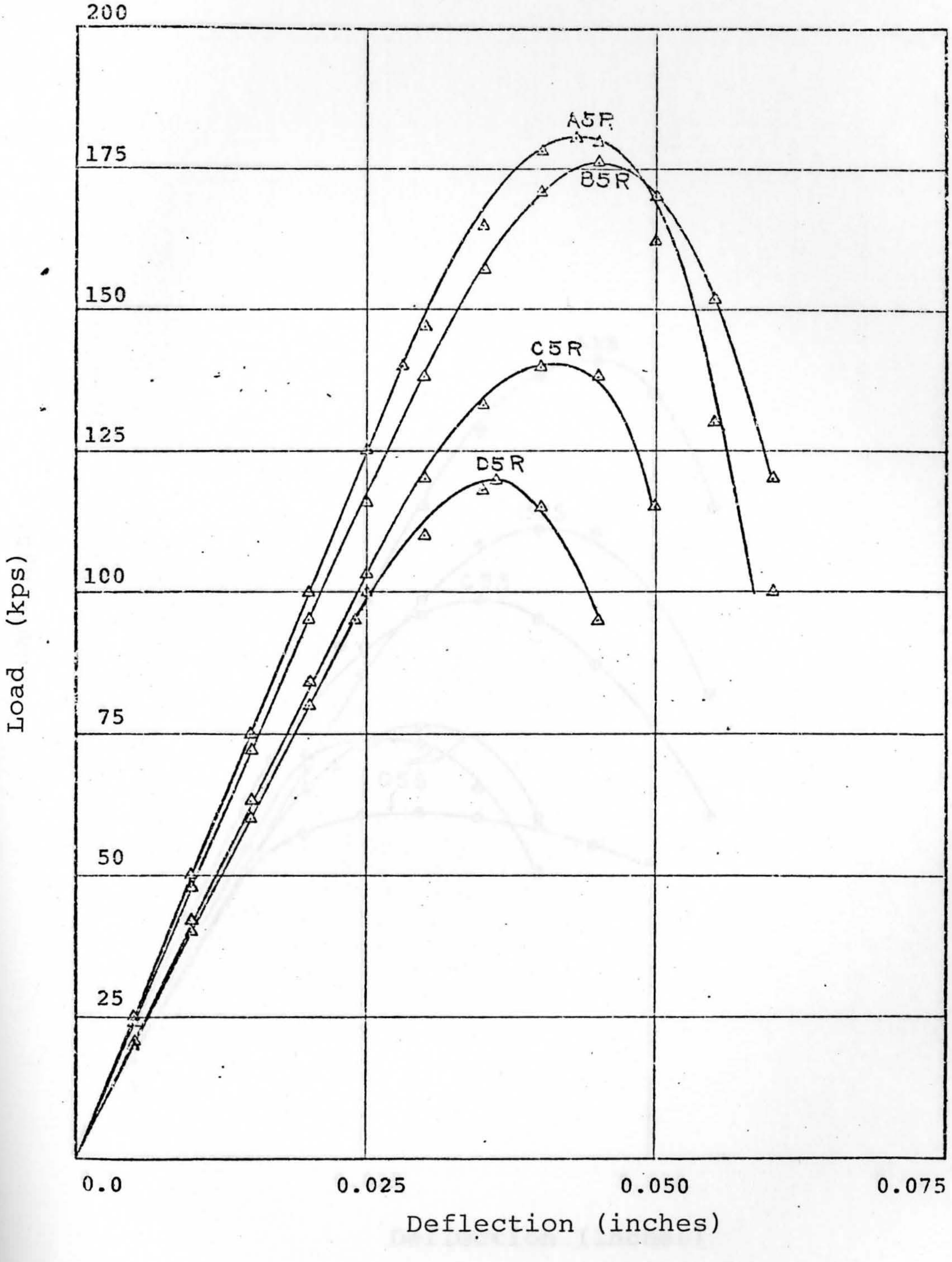
† Cracked longitudinally

APPENDIX D

Load Deflection Curves


200
175
150
125
100
75
50
25
A5L
C5L
B5L
D5L
Load (kps)
0.0
0.025
0.050
0.075
Deflection (inches)


200
175
150
125
100
75
50
25
Load (kps)
0.0
0.025
0.050
0.075
Deflection (inches)
A5G
B5G
D5G
C5G


200
175
150
125
100
75
50
25
Load (kps)
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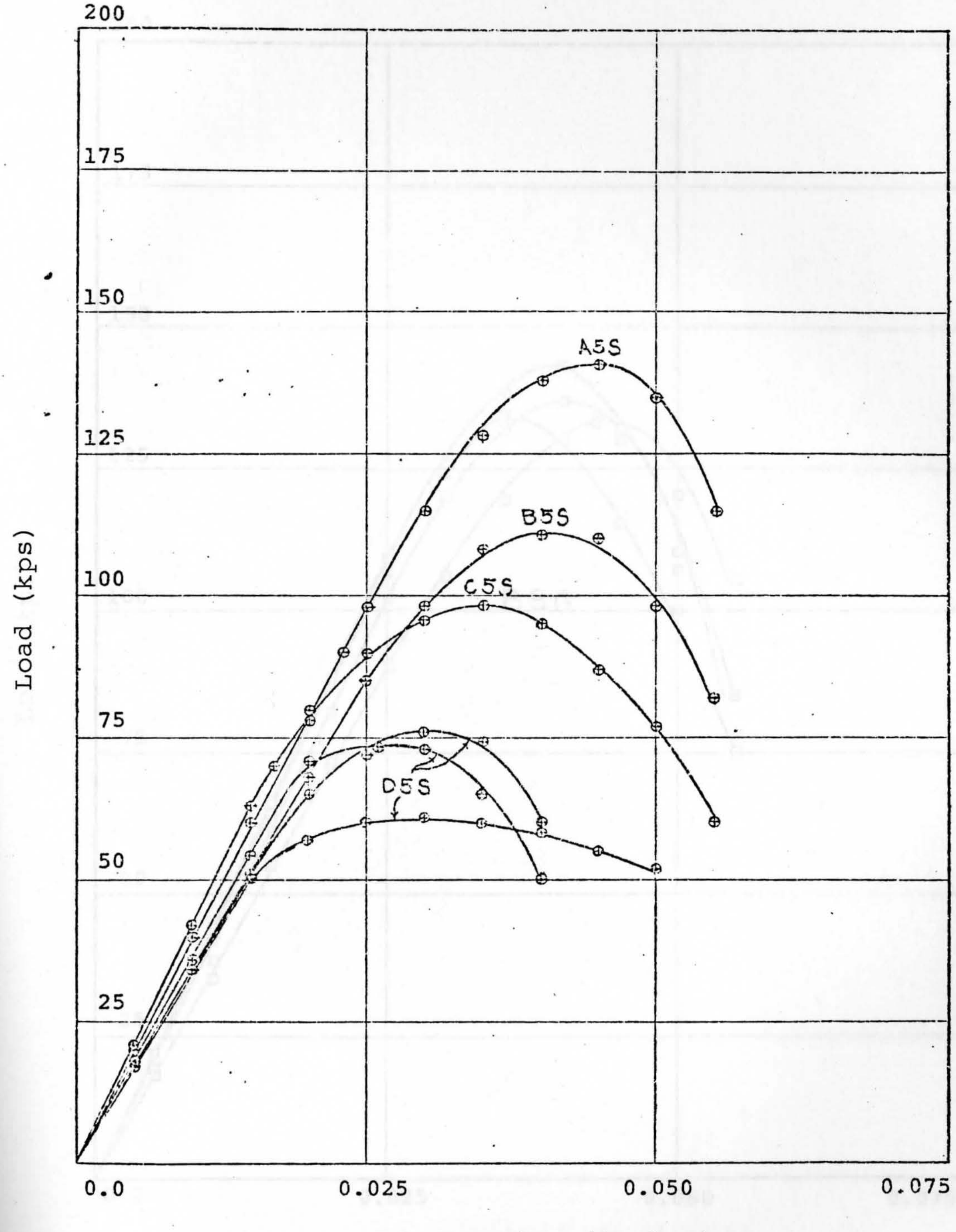
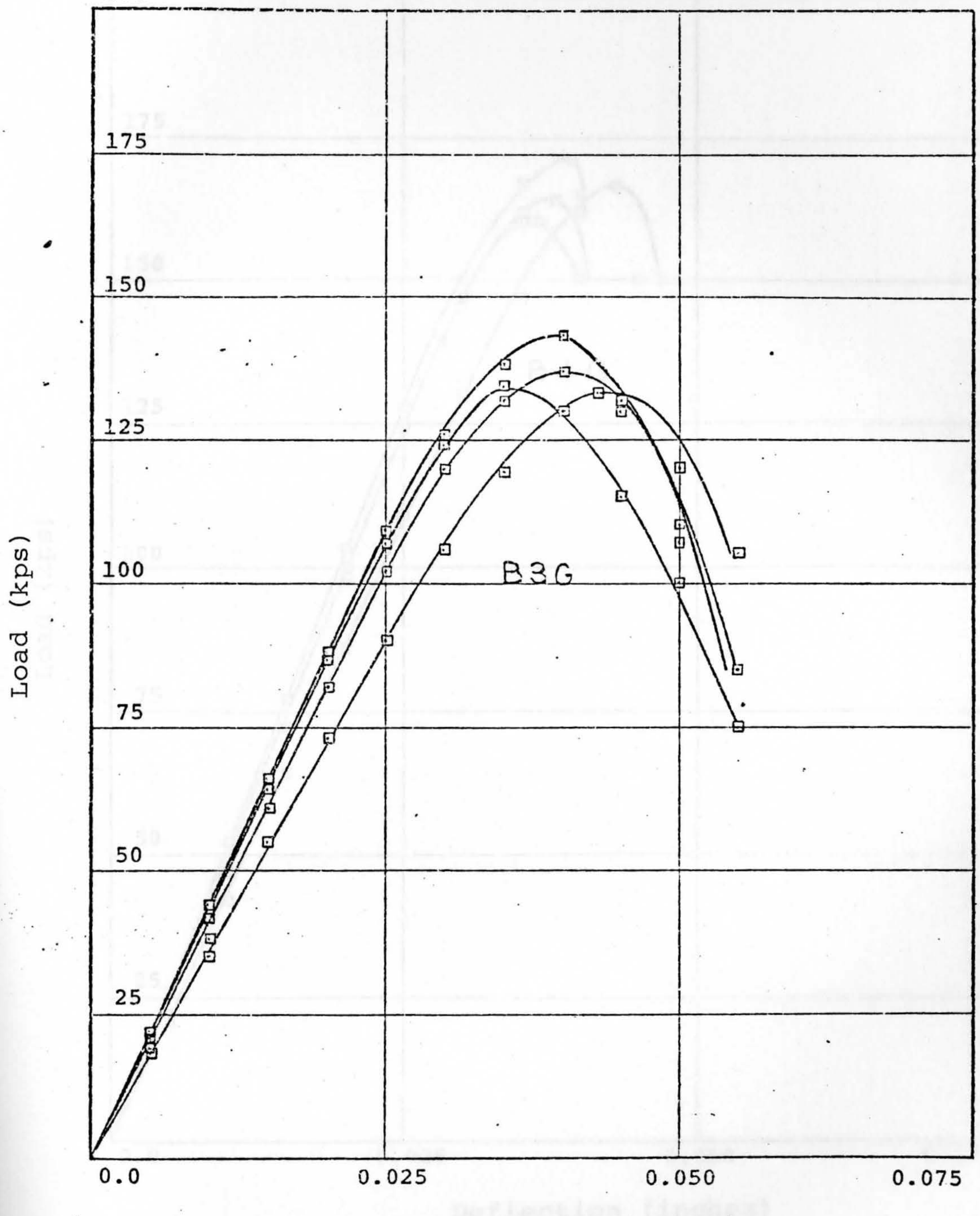
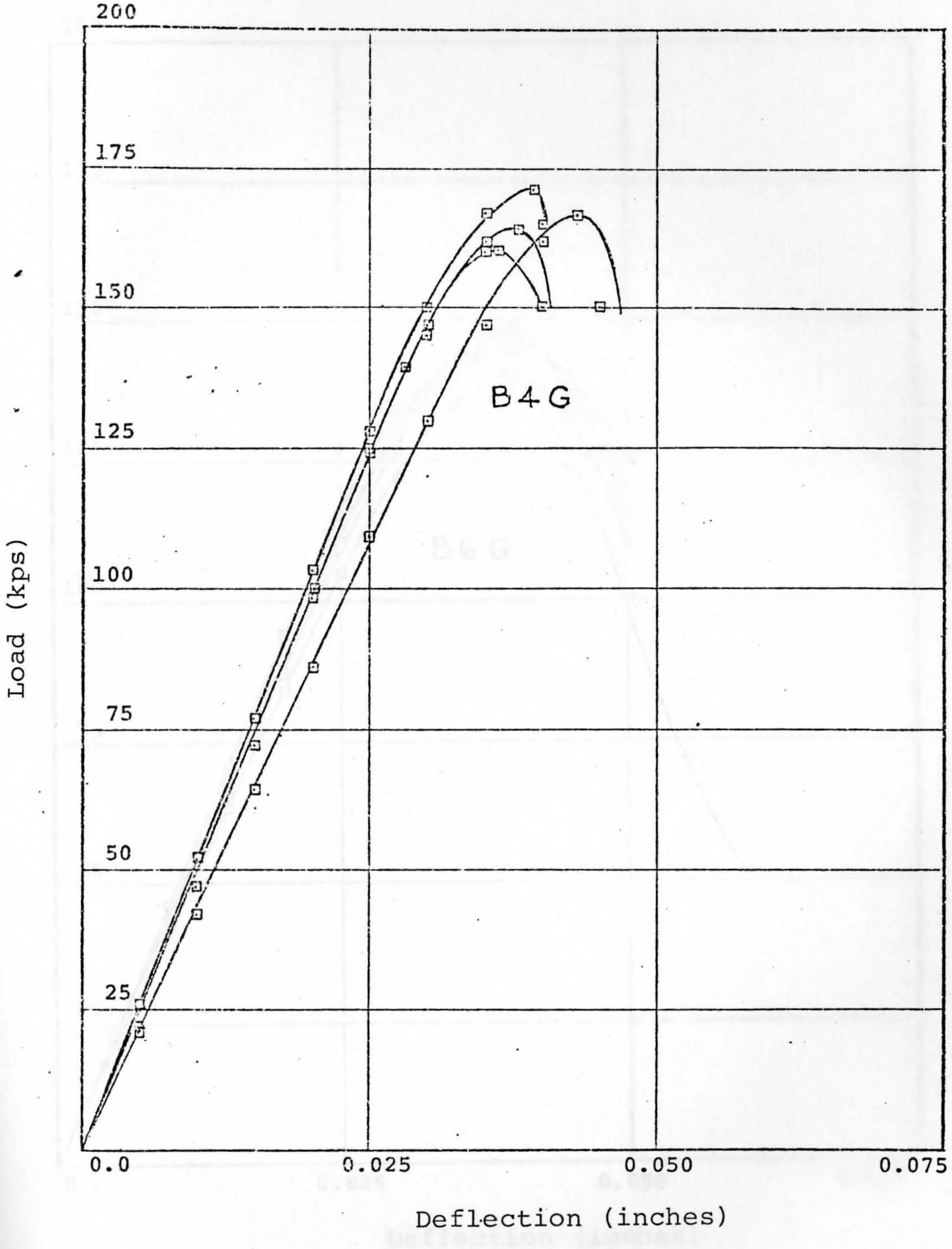
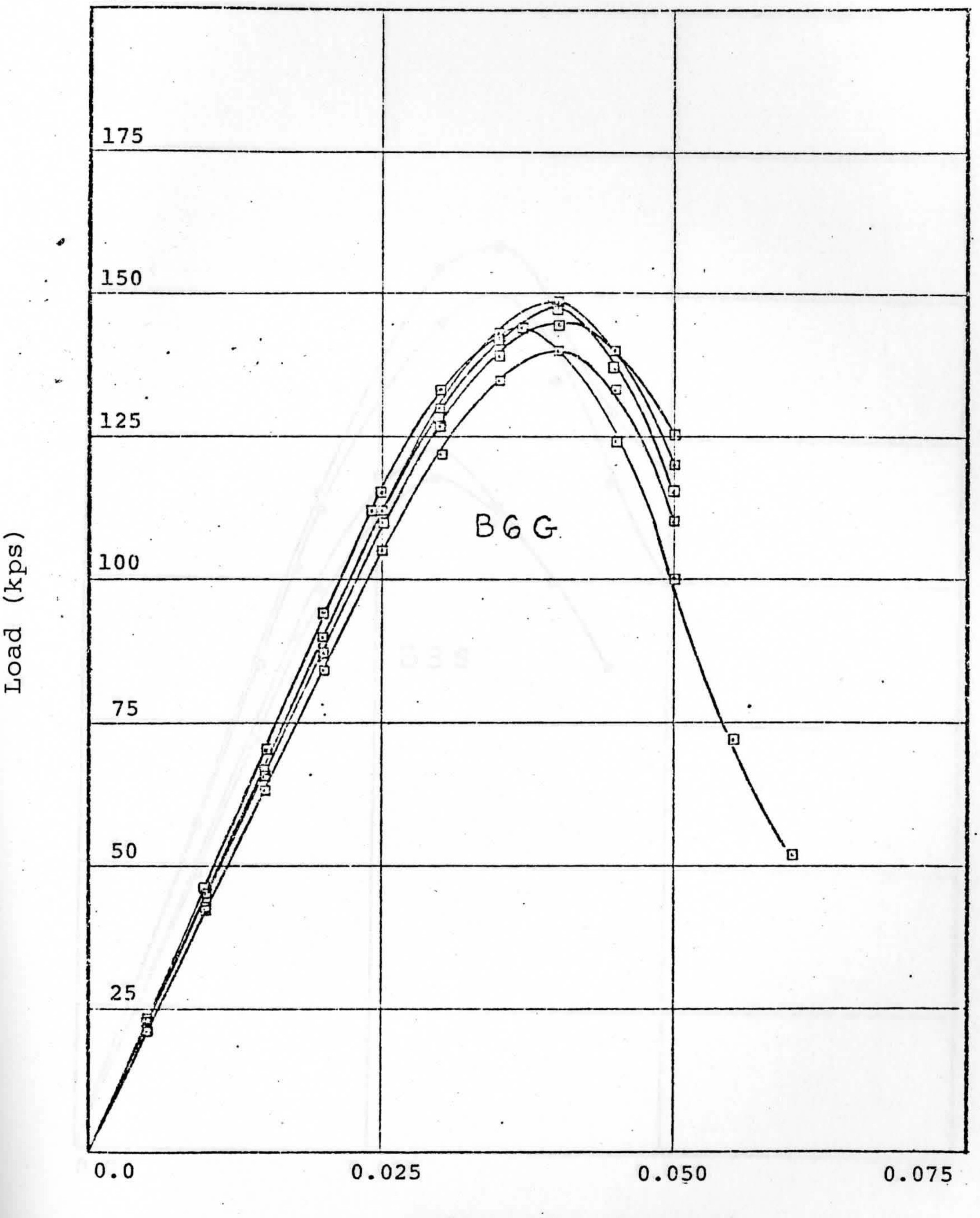
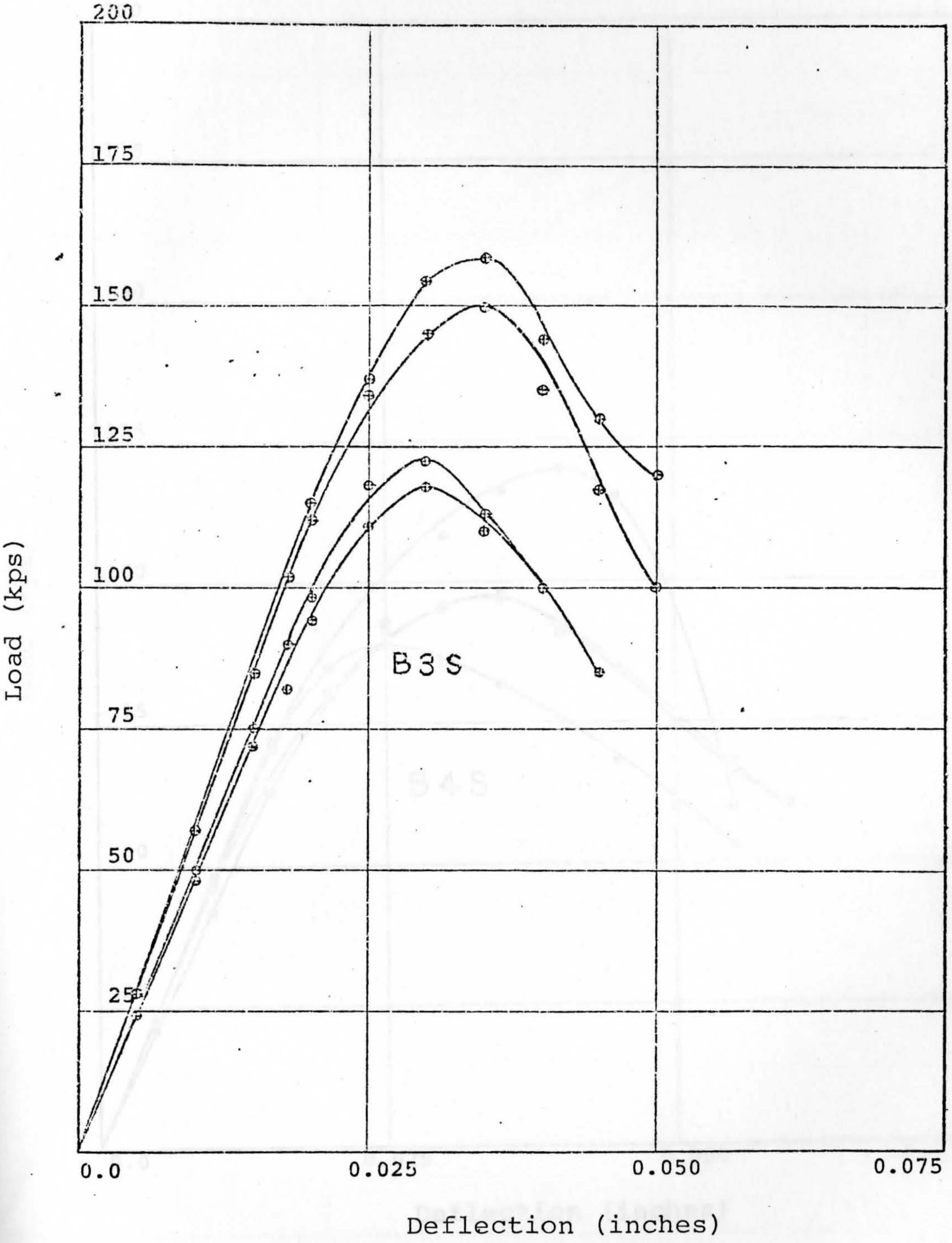
0.025
0.050
0.075
Deflection (inches)
A5R
B5R
C5R
D5R

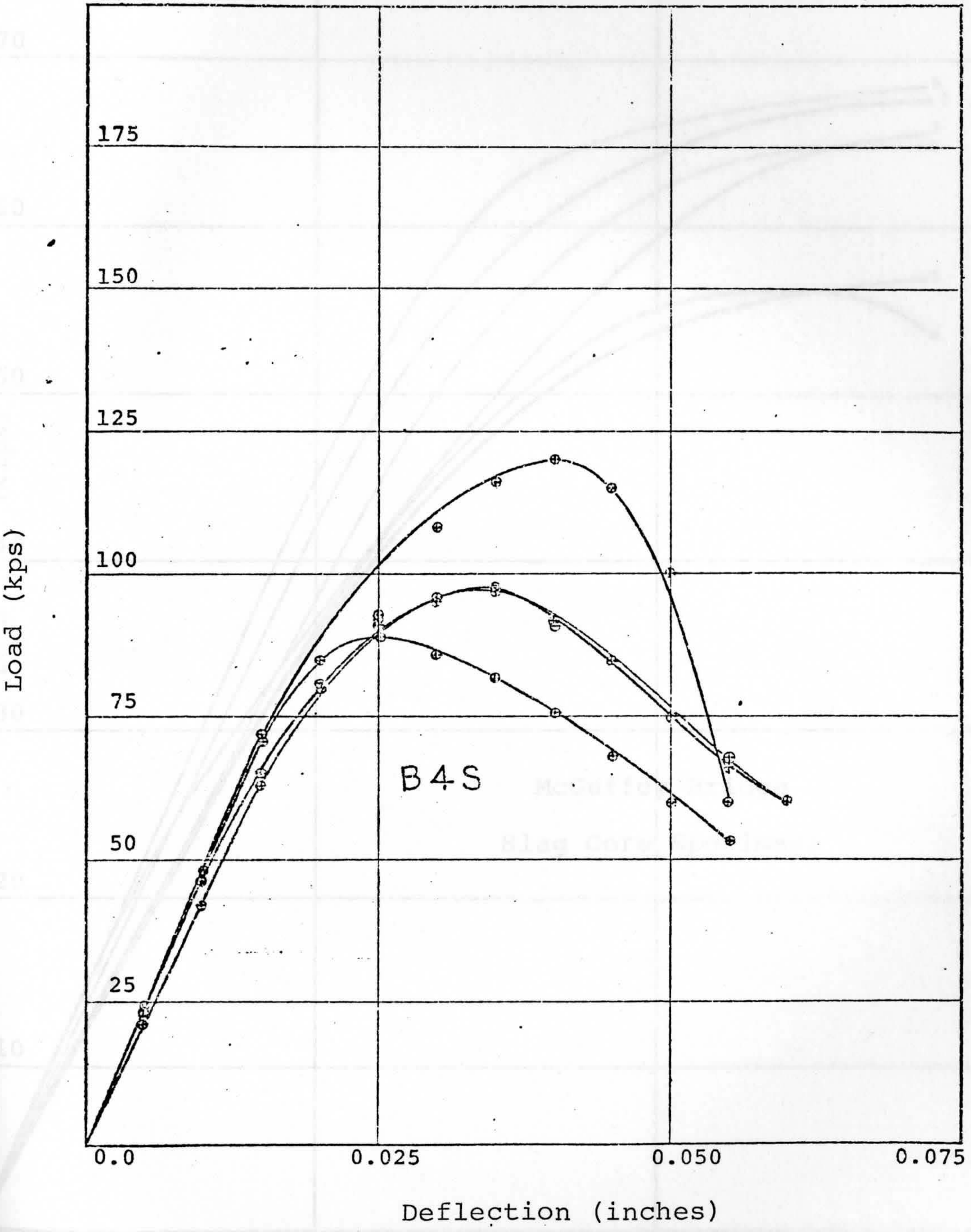

200
175
150
125
100
75
50
25
Load (kps)
0.0
0.025
0.050
0.075
Deflection (inches)
A5S
B5S
C5S
D5S

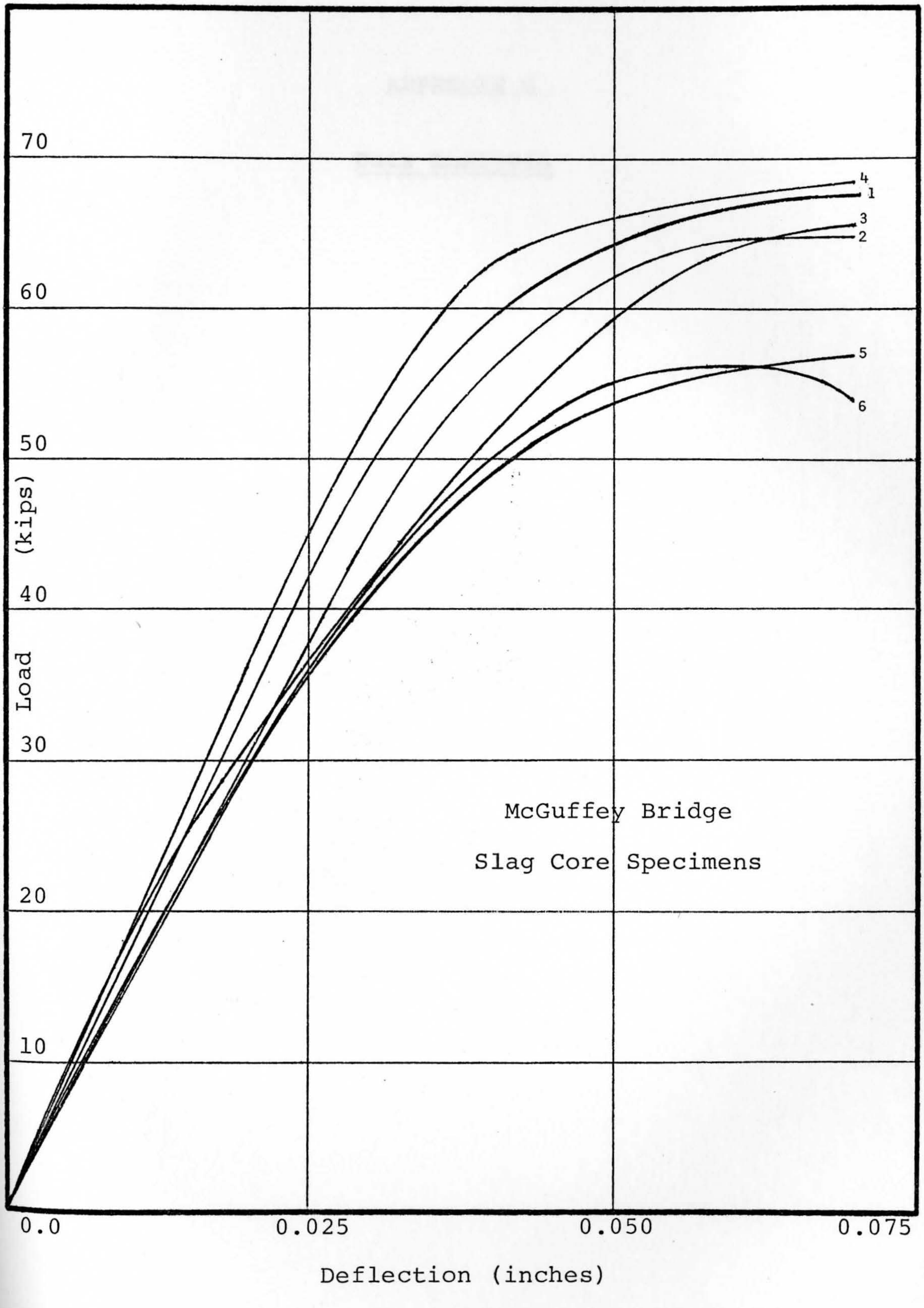

200
175
150
125
100
75
50
25
Load (kps)
B3G
0.0
0.025
0.050
0.075
Deflection (inches)


200
175
150
125
100
75
50
25
Load (kps)
B4G
0.0
0.025
0.050
0.075
Deflection (inches)


200
175
150
125
100
75
50
25
Load (kps)
B6G
0.0
0.025
0.050
0.075
Deflection (inches)


Load (kps)
200
175
150
125
100
75
50
25
0.0
0.025
0.050
0.075
Deflection (inches)
B3S


200
175
150
125
100
75
50
25
Load (kps)
0.0
0.025
0.050
0.075
Deflection (inches)
B4S


McGuffey Bridge
Slag Core Specimens
Load (kips)
70
60
50
40
30
20
10
0.0
0.025
0.050
0.075
Deflection (inches)
4
1
3
2
5
6

APPENDIX E

Data Analysis

PLAIN CONCRETE

Mix Designation	Spec. No.	BEAM SPECIMENS Weight Density pcf	Velocity Through fps	Velocity Along fps	DYNAMIC MODULUS Through (ksi×10³)	Along (ksi×10³)
A5L	1	145.4	15,156	15,032	7.203	7.086
	2	144.0	15,187	14,800	7.163	6.802
	3	147.1	15,234	14,806	7.362	6.955
	avg.	145.5	15,192	14,879	7.243	6.948
B5L	1	145.0	15,347	15,073	7.365	7.105
	2	144.4	15,371	15,162	7.358	7.159
	3	145.7	15,395	15,379	7.447	7.432
	avg.	145.0	15,371	15,205	7.390	7.232
C5L	1	144.7	15,442	14,629	7.441	6.679
	2	148.7	15,491	15,467	7.696	7.672
	3	147.9	15,358	15,353	7.523	7.519
	avg.	147.1	15,430	15,150	7.553	7.290
D5L	1	146.3	14,947	14,857	7.049	6.964
	2	143.6	14,970	14,948	6.940	6.920
	3	145.1	15,038	15,010	7.077	7.050
	avg.	145.0	14,985	14,938	7.022	6.978

CYLINDER SPECIMENS			
Velocity Through (fps)	Ultimate Comp. Stress (ksi)	Static Elas. Mod. ($ksi\times10^3$)	Dynamic Elas. Mod. ($ksi\times10^3$)
15,020	6.303	2.295	7.079
15,020	6.303	2.295	7.079
14,703	5.871	1.941	6.760
14,703	5.871	1.941	6.760
15,335	6.182	2.520	7.460
15,335	6.182	2.520	7.460
14,935	4.509	1.986	6.975
14,935	4.509	1.986	6.975

		BEAM SPECIMENS				
Mix Designation	Spec. No.	Weight Density pcf	Velocity Through fps	Velocity Through fps	DYNAMIC MODULUS	
					Through (ksi×10^3)	Along (ksi×10^3)
A5G	1	147.7	14,536	14,225	6.730	6.446
	2	148.4	14,607	14,320	6.829	6.563
	3	147.3	14,503	14,326	6.682	6.520
	avg.	147.8	14,549	14,290	6.747	6.510
B5G	1	140.8	13,693	13,575	5.694	5.596
	2	141.4	13,697	13,661	5.721	5.691
	3	140.8	13,704	13,528	5.703	5.557
	avg.	141.0	13,698	13,588	5.706	5.615
C5G	1	129.9	12,556	12,469	4.417	4.356
	2	129.1	12,644	12,449	4.451	4.315
	3	131.2	12,600	12,468	4.492	4.399
	avg.	130.1	12,600	12,462	4.453	4.357
D5G*	1	140.5	13,305	13,037	5.364	5.150
	2					
	avg.	140.5	13,305	13,037	5.364	5.150

*Two beams broken

Mix Designation	Spec. No.	BEAM SPECIMENS Weight Density pcf	Velocity Through fps	Velocity Along fps	DYNAMIC MODULUS Through (ksi×10^3)	Along (ksi×10^3)
A5R	1	141.3	14,043	13,831	6.010	5.829
	2	142.4	14,152	13,897	6.151	5.931
	3	143.3	14,183	13,847	6.217	5.926
	avg.	142.3	14,126	13,858	6.126	5.895
B5R	1	146.8	14,603	14,459	6.751	6.619
	2	148.3	14,501	14,395	6.725	6.627
	3	146.3	14,528	14,326	6.659	6.476
	avg.	147.1	14,544	14,393	6.712	6.574
C5R	1	144.5	13,863	13,781	5.989	5.918
	2	142.8	13,906	13,774	5.955	5.843
	3	141.0	13,942	13,837	5.911	5.822
	avg.	142.8	13,904	13,797	5.952	5.861
D5R	1	138.4	13,689	13,681	5.593	5.587
	2	138.9	13,444	13,442	5.414	5.413
	3	136.8	13,451	13,503	5.338	5.379
	avg.	138.0	13,528	13,542	5.448	5.460

CYLINDER SPECIMENS			
Velocity Through fps	Ultimate Comp. Stress ksi	Static Elas. Mod. (ksi×10^3)	Dynamic Elas. Mod. (ksi×10^3)
14,290	6.391	5.648	6.267
14,290	6.391	6.206	6.766
14,604	6.239	6.206	6.766
14,604	6.239	6.206	6.766
13,741	4.934	5.570	5.815
13,741	4.934	5.570	5.815
13,677	4.237	5.099	5.567
13,677	4.237	5.099	5.567

		BEAM SPECIMENS				
					DYNAMIC MODULUS	
Mix Designation	Spec. No.	Weight Density pcf	Velocity Through fps	Velocity Along fps	Through ($\text{ksi}\times 10^3$)	Along ($\text{ksi}\times 10^3$)
A5S	1	140.1	15,762	15,643	7.507	7.394
	2	142.0	15,836	15,789	7.680	7.634
	3	142.1	15,977	15,848	7.823	7.697
	avg.	141.4	15,858	15,760	7.670	7.575
B5S	1	135.8	14,890	14,629	6.493	6.268
	2	134.6	14,936	15,115	6.476	6.632
	3	135.4	15,050	14,957	6.614	6.533
	avg.	135.3	14,959	14,900	6.528	6.478
C5S	1	139.3	15,080	15,098	6.832	6.848
	2	137.8	14,921	14,961	6.616	6.652
	3	137.2	14,994	14,926	6.652	6.592
	avg.	138.1	14,998	14,995	6.700	6.697
D5S	1	134.0	14,244	14,231	5.863	5.853
	2	132.5	14,009	14,027	5.608	5.622
	3	131.8	13,738	13,804	5.365	5.416
	avg.	132.8	13,997	14,021	5.612	5.630

CYLINDER SPECIMENS

Velocity Through fps	Ultimate Comp. Stress ksi	Static Elas. Mod. (ksi×10³)	Dynamic Elas. Mod. (ksi×10³)
15,461	4.983	1.718	7.290
15.461	4.983	1.718	7.290
15,037	3.915	1.398	6.598
15,037	3.915	1.398	6.598
14,165	3.466	1.197	5.976
14,165	3.466	1.197	5.976
14,507	2.157	1.372	6.027
14.431	2.688	1.437	5.964
14,269	2.578	1.518	5.831
14,402	2.474	1.442	5.941

		BEAM SPECIMENS				
Mix Designation	Spec. No.	Weight Density pcf	Velocity Through fps	Velocity Along fps	DYNAMIC MODULUS Through ($\text{ksi}\times 10^3$)	DYNAMIC MODULUS Along ($\text{ksi}\times 10^3$)
B3G	1	146.2	14,178	14,092	6.338	6.261
	2	146.9	14,092	14,058	6.291	6.261
	3	148.1	14,071	13,887	6.324	6.160
	4					
	avg.	147.1	14,114	14,012	6.318	6.227
B4G	1	149.1	14,216	13,950	6.499	6.258
	2	146.5	14,286	13,977	6.448	6.172
	3	147.1	14,216	13,920	6.411	6.147
	4					
	avg.	147.6	14,239	13,949	6.453	6.192
B5G	1	140.8	13,693	13,575	5.694	5.596
	2	141.4	13,697	13,661	5.721	5.691
	3	140.8	13,704	13,528	5.703	5.557
	avg.	141.0	13,698	13,588	5.706	5.615
B6G	1	142.4	13,638	13,667	5.712	5.736
	2	143.4	13,806	13,762	5.895	5.857
	3	143.7	13,765	13,537	5.872	5.679
	4					
	avg.	143.2	13,736	13,655	5.826	5.757

CYLINDER SPECIMENS			
Velocity Through fps	Ultimate Comp. Stress ksi	Static Elas. Mod. (ksi$\times 10^3$)	Dynamic Elas. Mod. (ksi$\times 10^3$)
14,258	4.700	1.545	6.449
14,476	4.845	1.818	6.648
14,433	5.054	1.954	6.609
14,232	4.718	1.872	6.426
14,350	4.829	1.797	6.533
14,411	5.896	1.895	6.611
14,406	5.800	2.175	6.606
14,422	6.066	2.150	6.621
14,433	5.684	2.052	6.631
14,418	5.862	2.068	6.617
13,764	4.739	1.930	5.761
13,764	4.739	1.930	5.761
14,160	4.951	1.771	6.192
13,837	5.249	1.898	5.913
14,253	5.217	1.904	6.274
14,009	5.089	2.030	6.061
14,065	5.127	1.901	6.110

CYLINDER SPECIMENS			
Velocity Through fps	Ultimate Comp. Stress ksi	Static Elas. Mod. (ksi×10^3)	Dynamic Elas. Mod. (ksi×10^3)
15,607	4.163	2.034	7.486
15,803	4.333	2.120	7.675
15,779	5.287	2.418	7.652
15,719	5.606	2.476	7.594
15,727	4.847	2.262	7.602
15,583	3.431	1.826	7.279
15,559	3.371	1.787	7.257
15,656	4.244	2.028	7.348
15,247	3.148	1.994	6.969
15.511	3.549	1.909	7.213
15,037	3.915	1.398	6.598
15,037	3.915	1.398	6.598

REINFORCED CONCRETE

Mix Designation	[illegible]	[illegible]
ASL		
	avg.	
BSL	1	[illegible]
	2	15,302
	3	15,547
	avg.	15,656
CSL	1	15,427
	2	15,146
	3	15,722
	avg.	15,432
DSL	1	15,070
	2	15,007
	3	14,972
	avg.	15,017

Mix Designation	Depth of Reinforcement inches	Velocity Along fps
A5L	1	15,821
	2	15,244
	3	15,652
	avg.	15,572
B5L	1	16,119
	2	15,303
	3	15,547
	avg.	15,656
C5L	1	15,427
	2	15,146
	3	15,722
	avg.	15,432
D5L	1	15,070
	2	15,007
	3	14,973
	avg.	15,017

Mix Designation	Depth of Reinforcement inches	Velocity Along fps
A5G	1	14,782
	2	14,897
	3	14,844
	avg.	14,841
B5G	1	14,255
	2	13,891
	3	14,037
	avg.	14,061
C5G	1	13,613
	2	13,502
	3	13,319
	avg.	13,478
D5G	1	14,208
	2	13,423
	3	13,876
	avg.	13,836

Mix Designation	Depth of Reinforcement inches	Velocity Along fps
A5R	1	14,707
	2	14,497
	3	14,507
	avg.	14,570
B5R	1	15,007
	2	14,870
	3	14,706
	avg.	14,861
C5R	1	14,261
	2	14,234
	3	14,185
	avg.	14,227
D5R	1	14,083
	2	14,159
	3	13,742
	avg.	13,995

Mix Designation	Depth of Reinforcement inches	Velocity Along fps
A5S	1	15,724
	2	15,906
	3	15,697
	avg.	15,776
B5S	1	15,083
	2	15,303
	3	15,020
	avg.	15,135
C5S	1	15,201
	2	15,146
	3	15,004
	avg.	15,117
D5S	1	14,095
	2	14,498
	3	14,298
	avg.	14,297

Mix Designation	Depth of Reinforcement inches	Velocity Along fps
B3S	1	15,610
	2	15,675
	3	15,436
	avg.	15,537
B4S	1	15,323
	2	15,424
	3	14,990
	avg.	15,246
B5S	1	15,083
	2	15,303
	3	15,020
	avg.	15,135

Mix Designation	Depth of Reinforcement inches	Velocity Along fps
B3G	1	14,755
	2	14,476
	3	14,502
	avg.	14,578
B4G	1	14,959
	2	14,357
	3	14,555
	avg.	14,624
B5G	1	14,255
	2	13,891
	3	14,037
	avg.	14,061
B6G	1	14,445
	2	14,050
	3	14,217
	avg.	14,237

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