THE UNIVERSITY OF MANITOBA
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-- SONIC TESTING OF CONCRETE --

A CORRELATION OF PULSE VELOCITY TO THE MECHANICAL AND PHYSICAL PROPERTIES OF WINNIPEG CONCRETES

by

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ABSTRACT

This dissertation deals with the assessment of a non-destructive test method, namely the sonic pulse velocity method, as applied to concretes of known physical and mechanical properties.

Concrete produced by two Winnipeg concrete producers, Building Products and Supercrete, was investigated using three varying mix designs from each plant. Since the aggregate source of the two plants differ, the major difference between the two concretes tested was the properties of the respective aggregates. In hopes that the findings of this study could have a practical local application, mix designs actually used by the two producers in their daily production runs were incorporated into the test program.

While the three Supercrete mix designs closely matched the Building Products mixes, the pulse velocity measurements on the hardened concrete differed substantially between the two concretes. This showed the importance of the need to correlate pulse velocity readings to concretes of different properties before sonic methods could be used effectively. A relationship was developed for each of the mixes for pulse velocity versus strength and pulse velocity versus dynamic modulus of elasticity.

The test results from this study indicate that sonic tests could not be used as substitutes for other tests normally performed on concrete. Since they do provide a basis for evaluating

the uniformity and quality of a given concrete, they can be used as an extension of other methods of testing.

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NOTATION

SSD = Saturated Surface Dry

E = Static Modulus of Elasticity

E_D = Dynamic Modulus of Elasticity

μ = Poisson's ratio

K = Constant allowing for the inelastic, heterogeneous properties of different concrete mixes

ρ = Density of Concrete (unit weight)

f'_c = Ultimate Compressive Strength of Concrete

V = Pulse Velocity

G.F. = Gauge Factor

L = Physical Length of Cylinder

T = Time taken for pulse to travel length of cylinder

CHAPTER I

INTRODUCTION

1.1 Purpose of the Study

The purpose of this study is to apply a non-destructive test method, namely the sonic pulse-velocity method, to concrete of known physical and mechanical properties and correlate these properties to the recorded pulse velocity readings. By establishing a correlation, it could be possible to use sonic methods to determine the quality of "in-situ" concrete in the field providing the mix design and properties of the field concrete were known.

1.2 Statement of the Problem

For many years the standard test for determining the strength of concrete has been a destructive compressive test on specially prepared cylinders. Since the cylinders are laboratory cured they may not be representative of the concrete in the structure. A check may be made by testing a core from the "in-situ" concrete, however, this is not always possible since the appearance or performance of the member concerned may be affected.

The disadvantages of the standard test methods has encouraged various attempts to devise non-destructive test methods to be applied to "in-situ" concrete. One method where a considerable degree of success has been achieved is the ultrasonic pulse method. The application of the ultrasonic pulse method is based on the fact that the propagation velocity of the onset of a pulse of ultrasonic longitudinal waves, or pulse velocity, through a medium is proportional to its density. If a relationship can be determined between density and strength, it may be possible to determine one between pulse velocity and strength. Therefore, the objects of the ultrasonic pulse method are to establish:

a) the compressive strength of the concrete
b) the homogeneity of the concrete
c) defects in the concrete

The pulse method can be applied:

a) at precast concrete plants
b) at construction sites
c) to test structures in use
d) in research work

While pulse velocity research has been conducted in a number of areas throughout the world, no known attempt has been made to apply this research to local Winnipeg conditions. Since the properties of concrete materials may change appreciably from area to area and it is these properties that affect pulse velocity readings, it is necessary to correlate readings to known local concrete mixes before the pulse velocity method can be applied locally.

1.3 Scope

In hopes that the findings of this study could possibly be applied to actual concrete being placed in Winnipeg, and thereby be of some practical benefit, concrete producted by two local ready-mix companies was used throughout the investigation. The concrete was batched at two plants, namely Building Products and Supercrete. Actual mix designs used by the respective companies in their daily production runs were incorporated in the test program to further add to the practical benefits of the study.

Two seperate test programs, designed to measure the physical and mechanical properties of the concrete and the materials that make up the concrete, were run. These are designated as:

Test Series A

All test cylinders were cast with concrete produced at Building Products. The samples are identified in the report by the prefix "BP".

Test Series B

All test cylinders were cast with concrete produced at Supercrete. The samples are identified in the report by the prefix "S".

The basic difference between the two test series was the aggregate used. The respective mix designs were held relatively constant in regards to proportioning. The testing involved the determination of the density, air content, compressive strength, stress-strain relationship and pulse velocity of the individual concrete test specimens. A correlation was then established between the pulse velocity and the concrete properties of the respective mixes.

CHAPTER II

THEORY ON ULTRASONIC PULSE & REVIEW OF PREVIOUS RESEARCH

2.1 Theory on the Ultrasonic Pulse Test

The wave velocity of ultrasonic pulse in concrete is calculated from the time taken by a pulse to travel a measured distance. Mechanical energy in the form of a pulse or sound wave is transmitted between transmitting and receiving transducers. The transducers are in contact with the concrete so that the vibrations travel through it. The electrical signal generated by the transducer is fed through an amplifier to a plate of a cathode-ray tube. A second plate supplies timing marks at fixed intervals. Thus from the measurement of the displacement of the pulse signal relative to the position when the transducers are in direct contact with one another, the time taken by the pulse to travel through the concrete can be measured(1). The velocity can be calculated by dividing the distance between transducers by time. There are two methods of making the measurements:

a) by direct transmission through the concrete where the transducers are held on opposite faces of the member under test

b) by propagation along the surface when only one face of the concrete is accessible. Two disadvantages exists in this method. Since the maximum energy of the pulse is being directed into the concrete, the weaker signal received results in a less accurate reading. Also, measuring the pulse velocity at the surface only measures the surface properties and gives no indication about weaker concrete which may be below a stronger surface layer(2).

2.2 Review of Previous Research

Previous studies have been conducted in the classification of the quality of concrete on the basis of pulse velocity. Some figures suggested by Whitehurst(3) for concrete with a density of approximately 150 lbs./cu.ft. are given in Table 1.

Table 1

Classification of Concrete Quality

Longitudinal Pulse Velocity 10^3 ft./sec.	Quality of Concrete
15	excellent
12 - 15	good
10 - 12	doubtful
7 - 10	poor
7	very poor

According to Jones(4), however, the lower limit for good quality concrete is between 13,500 and 15,000 ft./sec.

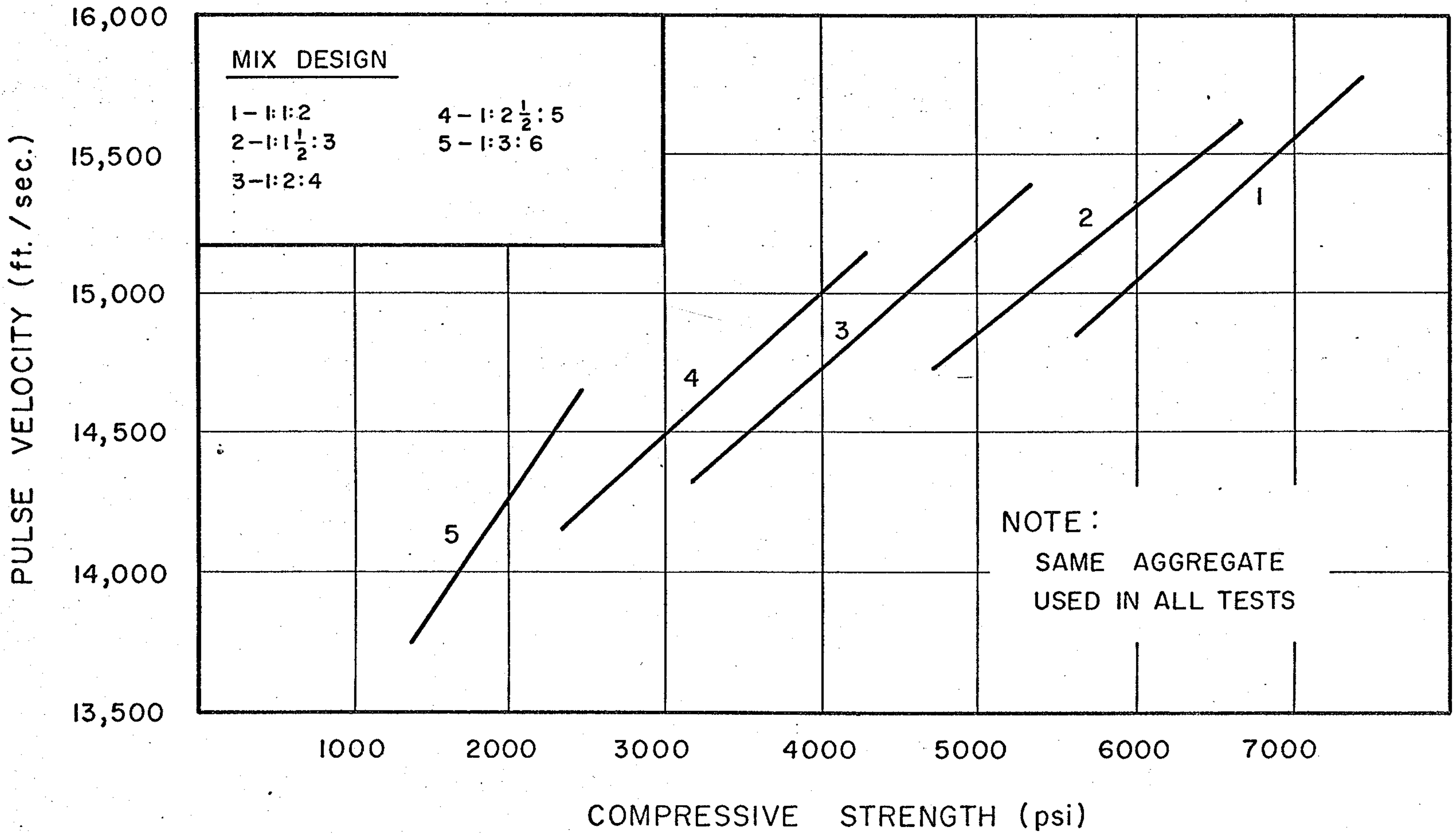
This discrepancy, and the generally wide variation in the pulse velocity of concretes are due to the influence of the coarse aggregate. Both its quantity and type affect the pulse velocity while, for a constant water-cement ratio, the influence of the coarse aggregate on strength is comparatively small(1).

It is Muenow's(5) opinion that the most accurate method of determining compressive strength is a correlation between destructive testing and velocity measurements. He suggests the relationship, shown in Figure 1, for velocity and compressive strength as a function of mix design.

From Figure 1 it can be observed that there is an overlap of readings between different mixes. Therefore, the mix design of the concrete to be tested must be known before a pulse velocity-compressive strength relationship can be applied.

FIGURE 1

GENERAL RELATIONSHIP
PULSE VELOCITY VS. STRENGTH



CHAPTER III

TESTING -- PROCEDURES AND RESULTS

IIIA TEST SERIES A

3A.1 Introduction

In this series, tests were carried out on the concrete materials and concrete as produced by Building Products and Concrete Supply, Winnipeg. Following is a breakdown on the various testing procedures and test results conducted on the test samples. All test samples in Test Series A are identified by the prefix "BP".

3A.2 Aggregates

3A.2a Gradation

It was decided to limit the maximum size of aggregate in the concrete mix to 3/4". Since the major applications utilizing sonic equipment would be in thin sections such as walls, slabs, and columns where 3/4" concrete is used, this was thought to be a valid limitation for test purposes.

Gradation tests were conducted on both the fine and coarse aggregates. Methods of sampling and grading were done in accordance with CSA Standard A23.1-1967. The gradation for the 3/4" aggregate is shown in Figure 2 while the sand gradation is shown in Figure 3.

Figure 2

Test Series A -- Sieve Analysis

Building Products 3/4" Coarse Aggregate

A.S.T.M. Standard Sieve Sizes	Total Passing each Sieve Percent by Weight	
	Test Aggregate	CSA Standard A23.1-1967 Specification
1 "	100.0	100
3/4"	98.1	90 - 100
3/8"	22.0	20 - 55
#4	3.5	0 - 10
#8	0.6	0 - 5

Figure 3

Test Series A -- Sieve Analysis

Building Products Fine Aggregate

A.S.T.M. Standard Sieve Sizes	Total Passing each Sieve Percent by Weight	
	Test Aggregate	CSA Standard A23.1-1967 Specification
3/8"	100.0	100
#4	96.4	95 - 100
#8	87.7	80 - 100
#16	75.8	50 - 85
#30	49.3	25 - 60
#50	21.3	10 - 30
#100	6.1	2 - 10
#200	2.9	

3A.2b Specific Gravity

Since the sonic pulse velocity is proportional to the density of the medium through which the pulse is transmitted, it is very important to know exactly what densities are being worked with. Therefore, specific gravities were determined on the aggregates in order to help explain the densities obtained in the final concrete mixes.

Typical calculations for the coarse specific gravity is shown in Sample Calculation 1. A dry bulk specific gravity of 2.638 was obtained.

Typical calculations for the fine specific gravity is shown in Sample Calculation 2. A dry bulk specific gravity of 2.602 was obtained.

3A.3 Cement

The cement used throughout the test program conformed to CSA Standard A5-1971 and was Type I Normal Portland Cement. However, this standard is only a minimum requirement. In actual fact, a given market may demand a higher quality cement with respect to minimum strengths. In order for a cement company to market its product in any given area it would be forced to meet these higher strength standards as set by competition. Also, these standards could vary from market area to market area. The Manitoba market compressive strength standard as compared to the CSA standard at the time of testing is shown in Table 2.

Sample Calculation 1

Test Series A -- Coarse Specific Gravity

Building Products 3/4" Coarse Aggregate

Wt. of Sample (S.S.D.) in Air (B)	2500 gms
Wt. of Sample (S.S.D.) in Water (C)	1573 gms
Wt. of Oven Dried Sample (A)	2447 gms

$$\text{Absorption} = \frac{B - A}{A} \times 100 = \frac{2500 - 2447}{2447} \times 100 = 2.168\%$$

$$\text{Bulk Specific Gravity} = \frac{B}{B - C} = \frac{2500}{2500 - 1573} = 2.695$$

$$\text{Apparent Specific Gravity} = \frac{A}{A - C} = \frac{2447}{2447 - 1573} = 2.799$$

$$\text{Bulk Specific Gravity}_{\text{(dry)}} = \frac{A}{B - C} = \frac{2447}{2500 - 1573} = 2.638$$

Sample Calculations 2

Test Series A -- Fine Specific Gravity

Building Products Fine Aggregate

Volume of flask at 20°C "V"	500 c.c.
Wt. of sand (S.S.D.) and flask	676.1 gms
Wt. of flask, sand (S.S.D.) and water at 20°C	987.0 gms
Wt. of flask	176.1 gms
Wt. of sand (S.S.D.) and water	810.9 gms
Wt. of sand (S.S.D.) "Wssd"	500.0 gms
Wt. of water added at 20°C "W"	310.9 gms
Wt. of sand (oven dried) and tare	874.8 gms
Wt. of tare	382.7 gms
Wt. of sand (oven dried) "A"	492.1 gms

$$\text{Absorption} = \frac{Wssd - A}{A} \times 100 = \frac{500 - 492.1}{492.1} = 1.608\%$$

$$\text{Bulk Specific Gravity (S.S.D.)} = \frac{Wssd}{V - W} = \frac{500}{500 - 310.9} = 2.645$$

$$\text{Apparent Specific Gravity} = \frac{A}{(V - W) - (Wssd - A)} =$$

$$\frac{492.1}{(500 - 310.9) - (500 - 492.1)} = 2.716$$

$$\text{Bulk Specific Gravity}_{\text{(dry)}} = \frac{A}{V - W} = \frac{492.1}{500 - 310.9} = 2.602$$

Table 2

Compressive Strength Comparison

of Normal Portland Cement

Age of Test (days)	CSA-A5-1971 Standard (psi)	Manitoba Market Standard at Time of Testing (psi)
3	1800	2600
7	2600	4200
28	3800	5700

It is critical that the compressive strength of the cement be known before sonic testing methods can be applied. Less cement per cubic yard could be used in a high cement standard market area in comparison to a lower standard market area, to obtain equivalent concrete strengths. However, the densities of the two concretes would be affected by the varying amounts of cement used. This would have to be taken into consideration when correlating pulse velocity to compressive strength for the concretes in question.

3A.4 Concrete Mixes

The decision to use concrete produced at a batch plant throughout the test program was based on two factors:

i) Better control in proportioning the materials could be accomplished with large volume batching. Control would be more difficult with a small laboratory mixer.

ii) Concrete produced at a batch plant during a normal days production would be a truer representation of the concrete going into the local market. This, therefore, would add to the practical benefits of the study.

Three different mixes were batched and cylinders cast. The mix designs (BPA, BPB, and BPC), with respective water-cement ratios of 0.4, 0.6, and 0.8, are designs that are actually being used by Building Products in their daily production.

It should be noted that the coarse aggregate was held constant for the complete series of tests. Tests conducted by the research laboratories of James Electronics Inc., Chicago, Illinois, indicate that the coarse aggregate affects the wave velocity much more than the fine aggregate(5). The fine aggregate was considered to be part of the mortar along with the cement and water. Therefore, while the batch weight per cubic yard was held constant for the three sets, the various materials that made up the mortar were proportioned differently and the coarse aggregate was held constant.

WRDA (water-reducing admixture) was the only admixture used in the concrete mixes. It is an aqueous solution of highly purified metallic salts of lignin sulfonic acids, containing a catalyst which counteracts the normal hydration-retarding effect of other dispersing admixtures. As a dispersing agent it lessens the natural interparticle attraction between cement grains and water. It does this by colloidal action, which forms a coating on the cement particles. This reduces their tendency to clump together, and makes the mix more workable with less water.

The three mix designs in Test Series A, namely BPA, BPB, and BPC, are outlined in Figures 4, 5, and 6 respectively.

3A.5 Sampling of the Concrete

The batch plant at Building Products is a central mix operation. After the concrete was adequately mixed it was discharged into a transit-mixer truck. The truck was then backed to a platform where the concrete was thoroughly remixed in the transit mixer. Concrete was then sampled from the mixer with a shovel at intermittent periods. These samples were then hand mixed together on the platform in order to ensure a representative sample. Sets of twelve cylinders were then cast for each of the three mixes.

Three separate tests were then carried out on each mix while the concrete was in the plastic state. These were slump, air content, and unit weight determinations. The results of these tests for each of the three mixes are noted in Figures 4, 5, and 6 respectively.

All tests were carried out in accordance with CSA Standard A23.2-1967, Methods of Test for Concrete.

Figure 4

Test Series A -- Mix Design BPA

Materials	Saturated Surface Dry Design Wts. (lbs./cu.yd.)	Actual Design Wts. Allowing for Moisture Content of Sand (lbs./cu.yd.)	Total Actual Batch Weights (lbs.)
3/4" aggregate	1900	1900	10,450
sand	1180	1239	6,814
cement	700	700	3,845
water	280	221	1215 + 100= 1,315
WRDA (Water Reducing Agent)	40 fl. oz.		220 fl. oz.

Moisture Content of Sand = 5.0%

Design Water-Cement Ratio $= \frac{280}{700} = 0.40$

Actual Water-Cement Ratio $= \frac{1315 + 6814\ (.05)}{3845} = 0.43$

-Note-
Additional water was added to the final batch in order to obtain a more workable mix

Air Content	1.8%
Slump	2 1/4"
Unit Wt.	150.8 p.c.f.

Figure 5

Test Series A -- Mix Design BPB

Materials	Saturated Surface Dry Design Wts. (lbs./cu.yd.)	Actual Design Wts. Allowing for Moisture Content of Sand (lbs./cu.yd.)	Total Actual Batch Weights (lbs.)
3/4" aggregate	1900	1900	9,500
sand	1400	1470	7,400
cement	470	470	2,350
water	280	210	1,050
WRDA (Water Reducing Agent)	27 fl. oz.		135 fl. oz.

Moisture Content of Sand = 5.0%

Design Water-Cement Ratio $= \frac{280}{470} = 0.60$

Actual Water-Cement Ratio $= \frac{1050 + 7400\,(.05)}{2350} = 0.60$

Air Content 2.3%

Slump 3"

Unit Wt. 149.8 p.c.f.

Figure 6

Test Series A -- Mix Design BPC

Materials	Saturated Surface Dry Design Wts. (lbs./cu.yd.)	Actual Design Wts. Allowing for Moisture Content of Sand (lbs./cu.yd.)	Total Actual Batch Weights (lbs.)
3/4" aggregate	1900	1900	9,500
sand	1500	1575	7,775
cement	350	350	1,750
water	280	205	1,025
WRDA (Water Reducing Agent)	20 fl. oz.		100 fl. oz.

Moisture Content of Sand = 5.0%

Design Water-Cement Ratio $= \frac{280}{350} = 0.80$

Actual Water-Cement Ratio $= \frac{1025 + 7775\ (.05)}{1750} = 0.81$

Air Content	2.5%
Slump	2"
Unit Wt.	149.4 p.c.f.

3A.6 Curing

After the cylinders were cast, plastic covers were placed over them in order to prevent the water needed for hydration from evaporating. The cylinders were then set out of the sun and let stand for 24 hours before they were moved. The air temperature during this period ranged from 50 - 70 degrees. The next day the cylinders were carefully loaded into a van and rigidly supported while they were being transferred to the M. Block Testing Laboratory in Winnipeg. Extreme care was taken in handling the cylinders during the transportation and stripping operations in order to minimize any possibility of small fractures developing in the samples.

Cylinders from each of the three sets that were numbered from 1 through 6 were placed in a water bath for wet curing prior to testing. Cylinders numbered 7 through 12 were placed in a room for dry curing.

3A.7 Unit Weights

The unit weight of the concrete was determined at three different periods. The first measurement was taken while the concrete was in the plastic state. The second measurement was taken on four cylinders from each set at the age of one day. The third measurement was taken on the same four cylinders, two of which were wet cured and two of which were dry cured, at the age of 7 days.

The test used in determining the unit weight of the hardened concrete utilized the method in which the cylinder was weighed in air and then in water. Since the difference in the weights is equal to the volume of water displaced, the specific gravity of the concrete can be determined. From this, the unit weight can be calculated. The calculations are given in Sample Calculation 3.

A summary of the unit weights is given in Table 3.

Sample Calculation 3

Test Series A

Unit Weight of Hardened Concrete

Test Cylinder BPA1

Wt. of cylinder in air = W_A = 13,635 gms

Wt. of cylinder in water = W_W = 7,988 gms

Volume of cylinder = V = $W_A - W_W$ = 13,635 - 7,988 = 5647 c.c.

Specific gravity of cylinder = $\frac{W_A}{V} = \frac{13,635}{5,647}$ = 2.413

Since unit wt. of water = 62.4 p.c.f.

unit wt. of test cylinder BPA1 = 2.413 x 62.4 = 150.6 p.c.f.

Table 3

Test Series A

Concrete Unit Weights

Cylinder No.	Air Content (Plastic State) %	Method of Curing	Unit Weight (lbs./cu.ft.)		
			Plastic	Hardened	
				1-Day	7-Day
BPA1	1.8	Water bath	150.8	150.6	151.8
BPA2		"	"	151.9	154.0
BPA7		Air	"	150.6	150.2
BPA8		"	"	150.6	149.8
BPB1	2.3	Water bath	149.8	151.3	151.5
BPB2		"	"	151.3	152.8
BPB7		Air	"	150.6	150.0
BPB8		"	"	151.3	150.8
BPC1	2.5	Water bath	149.4	151.2	151.2
BPC2		"	"	151.2	152.0
BPC7		Air	"	150.6	150.9
BPC8		"	"	151.2	150.0

3A.8 Pulse Velocity Determination

3A.8a Operation of Equipment

The instrument used in determining the pulse velocities throughout the test program was the V-scope, Model No. C-4960 as manufactured by James Electronics Inc., Chicago, Illinois. A picture of the instrument is shown in Figure 7.

The operating frequency range of the instrument is 15-300 KC. The higher the frequency, the narrower the beam of pulse propagation but the greater the attenuation (or damping out) of the pulse vibrations. Metal testing requires high frequency pulses to provide a narrow beam of energy but such frequencies are unsuitable for use with heterogeneous materials such as concrete because of the considerable amount of attenuation which pulses undergo when they pass through these materials. The frequency found suitable and used throughout these tests was 50KC which corresponded to a wave length of about 130 mm. The instrument's pulse rate is 69 pulses per second.

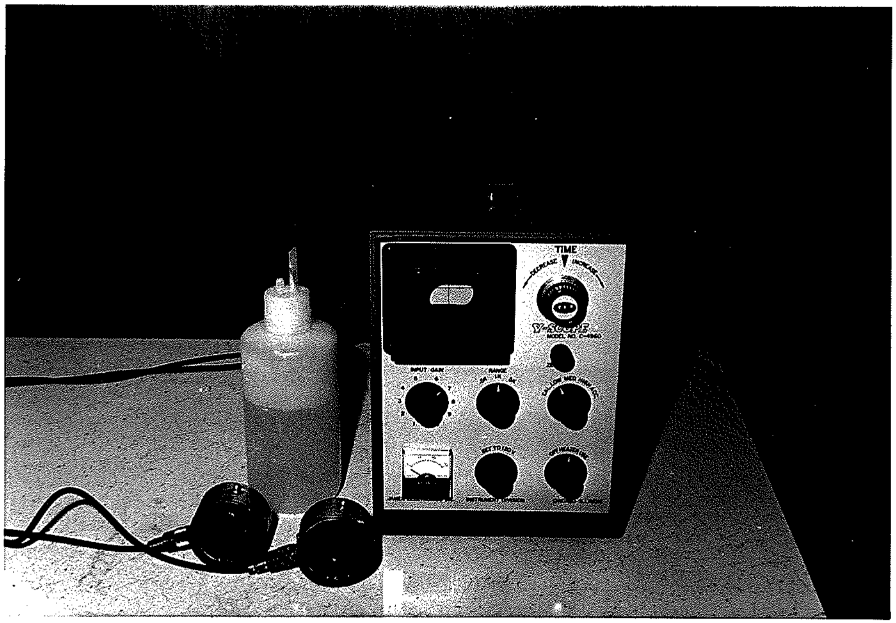
The basic operation of the James V-scope is outlined in Appendix A.

3A.8b Pulse Velocity Readings

Pulse velocity readings were taken on both wet cured and dry cured cylinders for each set at 7 and 28 days. Since

Figure 7

SONIC TESTING EQUIPMENT



the physical length of each cylinder varied slightly, each cylinder was measured in order that the pulse velocity could be calculated accurately. A typical calculation of pulse velocity is shown in Sample Calculation 4.

Tables 4, 5, and 6 outline the individual pulse velocities of the three mixes tested in Test Series A.

Sample Calculation 4

Test Series A

Sample Calculation of Pulse Velocity

Cylinder BPA1

Measured length of cylinder = L = 12.10"

Time taken for sonic wave to traverse length of cylinder = T = 63.0 microseconds

$$\text{Pulse Velocity} = \frac{L}{T} = \frac{12.10}{12} \times \frac{1}{63.0} =$$

.01605 ft./microsecond or 16,050 ft./sec.

Table 4

Test Series A -- BPA General Test Data

Cylinder No.	Method of Curing	Compressive Strength (psi)		Pulse Velocity (ft./sec. x 10^3)		E (psi x 10^6)	E_D (psi x 10^6)	Poisson's Ratio μ
		7-day	28-day	7-day	28-day			
BPA1	Water bath	5089		16.05		4.19	5.37	0.19
BPA2	"	5159		15.85				
BPA3	"	5000		16.05				
BPA4	"		6010		16.35	4.95	6.35	0.17
BPA5	"		6666		16.30			
BPA6	"		6117		16.2			
BPA7	Air	5018		15.7				
BPA8	"	5159		15.7				
BPA9	"	5408		15.9		4.10	5.26	0.18
BPA10	"		6206		15.7	5.04	6.46	0.17
BPA11	"		6081		15.75			
BPA12	"		6578		15.8			

Table 5

Test Series A -- BPB General Test Data

Cylinder No.	Method of Curing	Compressive Strength (psi)		Pulse Velocity (ft./sec. x 10^3)		E (psi x 10^6)	E_D (psi x 10^6)	Poisson's Ratio μ
		7-day	28-day	7-day	28-day			
BPB1	Water bath	3865		15.6		3.60	4.61	0.21
BPB2	"	4060		15.6				
BPB3	"	4113		15.65				
BPB4	"		4893		15.8	4.23	5.42	0.19
BPB5	"		5337		16.25			
BPB6	"		5230		16.1			
BPB7	Air	3830		15.35				
BPB8	"	3652		15.3				
BPB9	"	3865		15.3		3.91	5.01	0.21
BPB10	"		4823		15.3	4.23	5.42	0.19
BPB11	"		5159		15.5			
BPB12	"		4805		15.4			

Table 6

Test Series A -- BPC General Test Data

Cylinder No.	Method of Curing	Compressive Strength (psi)		Pulse Velocity (ft./sec. x 10^3)		E (psi x 10^6)	E_D (psi x 10^6)	Poisson's Ratio μ
		7-day	28-day	7-day	28-day			
BPC1	Water bath	2801		15.55		3.60	4.61	0.23
BPC2	"	2695		15.5				
BPC3	"	2695		15.4				
BPC4	"		3759		15.75	4.46	5.72	0.22
BPC5	"		3954		15.85			
BPC6	"		3635		15.85			
BPC7	Air	2553		14.55				
BPC8	"	2660		14.75				
BPC9	"	2411		14.75		2.02	2.59	0.24
BPC10	"		3191		15.05	2.96	3.79	0.23
BPC11	"		3493		15.05			
BPC12	"		3386		15.05			

3A.9 Compressive Strength Determination

The compressive strength was determined for each of the cylinders cast. The tests were conducted in accordance with CSA Standard A23.2.13 "Test for Compressive Strength of Moulded Concrete Cylinders". The equipment used in the test is shown in Figure 8. The compressive strengths of the test cylinders for each of the three mixes in Test Series A are given in Tables 4, 5, and 6 respectively.

3A.10 Strain Determination

The unit strain of the concrete under load was recorded at 5 kip load increments. Mechanical gauges (DEMEC) were used throughout the test. Initially the gauges were held in place by hand, however, the slightest hand movement would disrupt the readings. The gauges were then fastened securely to the cylinders by elastic bands as shown in Figure 9.

Strain readings were recorded for the following cylinders:

BPA1, BPB1, BPC1 - 7 day wet cured
BPA4, BPB4, BPC4 - 28 day wet cured
BPA9, BPB9, BPC9 - 7 day dry cured
BPA10, BPB10, BPC10 - 28 day dry cured

The strain readings on the above cylinders as well as the details of the gauges used are tabulated in Appendix B.

Figure 8

EQUIPMENT USED FOR COMPRESSIVE

STRENGTH DETERMINATION

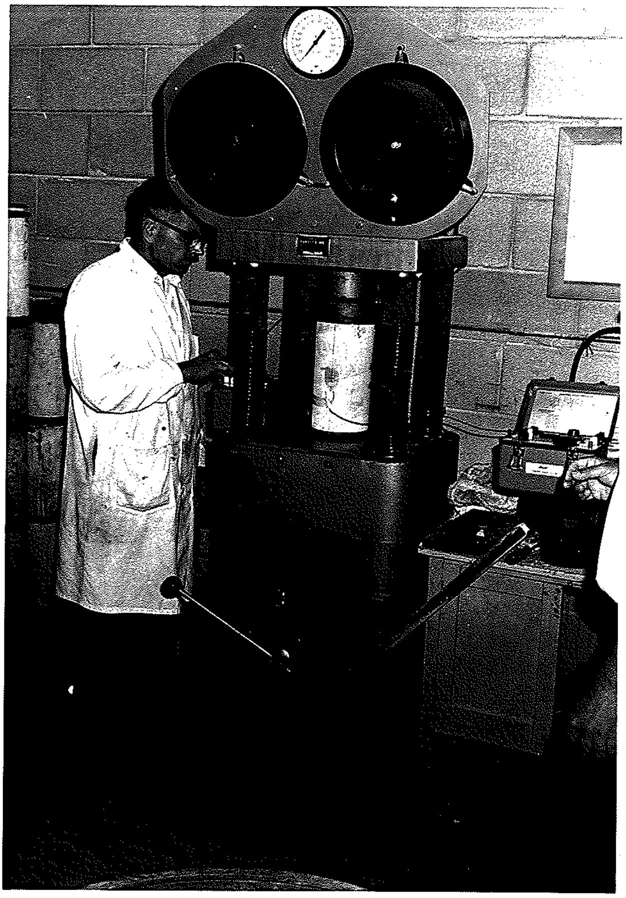
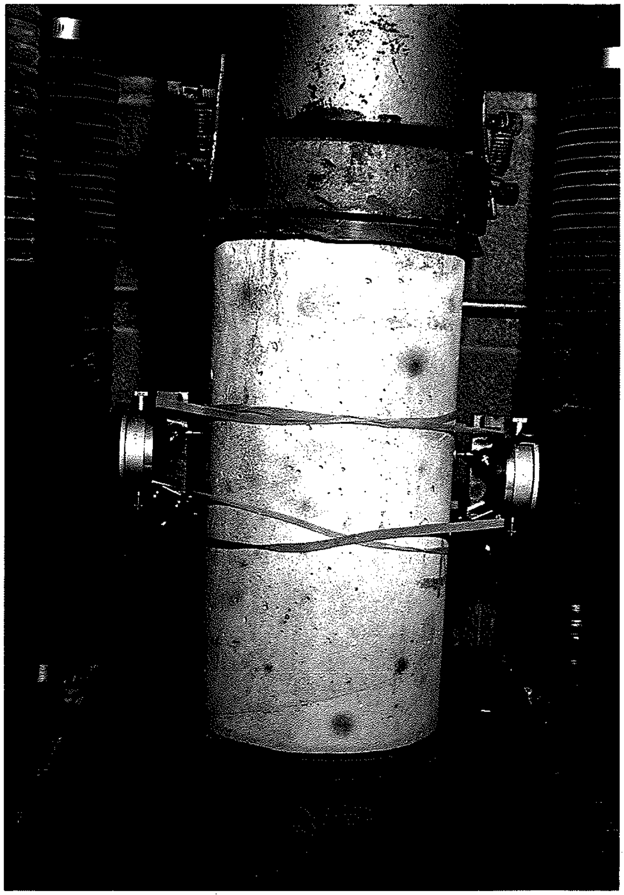


Figure 9

MECHANICAL GAUGE SUPPORT



IIIB TEST SERIES B

3B.1 Introduction

In this series, tests were carried out on the concrete materials and concrete as produced by Supercrete in the City of Winnipeg. Following is a breakdown on the various testing procedures and test results conducted on the test samples. To avoid duplication, where the procedures are the same as followed in Test Series A, it shall be noted as such. All test samples in Test Series B are identified by the prefix "S".

3B.2 Aggregates

3B.2a Gradation

The maximum aggregate size was again limited to 3/4". Gradation tests were conducted on both the fine and coarse aggregate as in Test Series A. The gradation of the coarse aggregate is shown in Figure 10 while the sand gradation is shown in Figure 11.

3B.2b Specific Gravity

The specific gravity of the coarse aggregate was determined as in Test Series A. A dry bulk specific gravity of 2.580 was calculated as shown in Sample Calculation 5.

Figure 10

Test Series B -- Sieve Analysis

Supercrete 3/4" Coarse Aggregate

A.S.T.M. Standard Sieve Sizes	Total Passing each Sieve Percent by Weight	
	Test Aggregate	CSA Standard A23.1-1967 Specification
1 "	100.0	100
3/4"	88.3	90 - 100
3/8"	22.0	20 - 55
#4	2.5	0 - 10
#8	0.9	0 - 5

Figure 11

Test Series B -- Sieve Analysis

Supercrete Fine Aggregate

A.S.T.M. Standard Sieve Sizes	Total Passing each Sieve Percent by Weight	
	Test Aggregate	CSA Standard A23.1-1967 Specification
3/8"	100.0	100
#4	99.7	95 - 100
#8	90.5	80 - 100
#16	69.4	50 - 85
#30	43.3	25 - 60
#50	17.9	10 - 30
#100	4.2	2 - 10
#200	1.9	

Sample Calculation 5

Test Series B -- Coarse Specific Gravity

Supercrete 3/4" Coarse Aggregate

Wt. of Sample (S.S.D.) in Air (B)	2500 gms
Wt. of Sample (S.S.D.) in Water (C)	1552 gms
Wt. of Oven Dried Sample (A)	2448 gms

$$\text{Absorption} = \frac{B - A}{A} \times 100 = \frac{2500 - 2448}{2448} \times 100 = 2.122\%$$

$$\text{Bulk Specific Gravity} = \frac{B}{B - C} = \frac{2500}{2500 - 1552} = 2.635$$

$$\text{Apparent Specific Gravity} = \frac{A}{A - C} = \frac{2448}{2448 - 1552} = 2.732$$

$$\text{Bulk Specific Gravity}_{\text{(dry)}} = \frac{A}{B - C} = \frac{2448}{2500 - 1552} = 2.580$$

3B.3 Cement

The cement used in Test Series B again far exceeded CSA Standard A5-1971 strength requirement. The comparison between the CSA standard and the Manitoba market area standard is outlined in Test Series A

3B.4 Concrete Mixes

Three different mixes were batched at Supercrete and the cylinders cast. The designed mixes (SA, SB, and SC), with respective water-cement ratios of 0.40, 0.62, and 0.82, are designs actually being used by Supercrete in their daily production.

A water-reducing admixture, as discussed in Test Series A, was also used in Test Series B.

The comparisons between the design and actual mixes tested, namely SA, SB, and SC, are given in Figures 12, 13, and 14 respectively.

3B.5 Sampling of the Concrete

The batch plant at Supercrete is a central mix operation. Unlike at Building Products where the concrete had to be sampled from the transit-mixer truck, the concrete was sampled directly from the central mixing drum. As the concrete was being discharged from the drum, samples were taken with a shovel and placed in a

Figure 12

Test Series A -- Mix Design SA

Materials	Saturated Surface Dry Design Wts. (lbs./cu.yd.)	Actual Design Wts. Allowing for Moisture Content of Sand (lbs./cu.yd.)	Total Actual Batch Weights (lbs.)
3/4" aggregate	1900	1900	7,600
sand	1260	1329	5,356
cement	700	700	2,800
water	280	211	799
WRDA (Water Reducing Agent)	39.8 fl. oz.		160 fl. oz.

Moisture Content of Sand = 5.5%

Design Water-Cement Ratio $= \frac{280}{700} = 0.40$

Actual Water-Cement Ratio $= \frac{799 + (5356)\ .055}{2800} = .039$

-Note-

Less water was used than called for in the mix design since a workable mix was obtained with a reduced water content

Air Content	2.3%
Slump	3 1/2"
Unit Wt.	148.0 p.c.f.
Concrete Temp.	75°F

Figure 13

Test Series B -- Mix Design SB

Materials	Saturated Surface Dry Design Wts. (lbs./cu.yd.)	Actual Design Wts. Allowing for Moisture Content of Sand (lbs./cu.yd.)	Total Actual Batch Weights (lbs.)
3/4" aggregate	1900	1900	7,600
sand	1368	1470	5,920
cement	445	445	1,780
water	275	173	686
WRDA (Water Reducing Agent)	26.8 fl. oz.		108 fl. oz.

Moisture Content of Sand = 7.5%

$$\text{Design Water-Cement Ratio} = \frac{275}{445} = 0.62$$

$$\text{Actual Water-Cement Ratio} = \frac{686 + (5920)\ .075}{1780} = 0.64$$

Air Content	3.2%
Slump	4 1/4"
Unit Wt.	146.4 p.c.f.
Concrete Temp.	71°F

Figure 14

Test Series B -- Mix Design SC

Materials	Saturated Surface Dry Design Wts. (lbs./cu.yd.)	Actual Design Wts. Allowing for Moisture Content of Sand (lbs./cu.yd.)	Total Actual Batch Weights (lbs.)
3/4" aggregate	1900	1900	7,600
sand	1441	1542	6,212
cement	340	340	1,360
water	280	179	672
WRDA (Water Reducing Agent)	20 fl. oz.		80 fl. oz.

Moisture Content of Sand = 7.0%

Design Water-Cement Ratio $= \frac{280}{340} = 0.82$

Actual Water-Cement Ratio $= \frac{672 + (6212)\ .070}{1360} = 0.81$

Air Content	3.0%
Slump	5 3/4"
Unit Wt.	146.6 p.c.f.
Concrete Temp.	69°F

small buggy. Since samples were taken intermittently as the concrete was being discharged, a good representative sample was obtained. The sample was then dumped from the buggy onto a platform and mixed with a small shovel. Sets of twelve cylinders were then cast for each of the three mixes.

As in Test Series A, slump, air content, and unit weight tests were conducted on each mix. The results of these tests are indicated in Figures 12, 13, and 14 for the respective mixes.

3B.6 Curing

The same techniques as discussed in Test Series A were employed in the curing and transportation operation in Test Series B.

3B.7 Unit Weights

The unit weight of the concrete was determined in both the plastic and hardened state as in Test Series A and a typical calculation is shown in Sample Calculation 6. A summary of the unit weights is shown in Table 7.

3B.8 Pulse Velocity Determination

3B.8a Test Procedure

The instrument used in determining the pulse velocity

Sample Calculation 6

Test Series B

Unit Weight of Hardened Concrete

Test Cylinder SA8

Wt. of cylinder in air = W_A = 13,340 gms

Wt. of cylinder in water = Ww = 7,750 gms

Volume of cylinder = V = $W_A - W_W$ = 13,340 - 7,750 = 5590 c.c.

Specific gravity of cylinder = $\frac{W_A}{V} = \frac{13,340}{5,590}$ = 2.39

Since unit wt. of water = 62.4 p.c.f.

$\therefore$ unit wt. of test cylinder SA8 = 2.39 x 62.4 = 149.0 p.c.f.

Table 7

Test Series B

Concrete Unit Weights

Cylinder No.	Air Content (Plastic State) %	Method of Curing	Unit Weight (lbs./cu.ft.) Plastic	Hardened 7-Day
SA1	2.3	Water bath	148.0	150.0
SA2		"	"	150.5
SA7		Air	"	149.0
SA8		"	"	149.0
SB1	3.2	Water bath	146.4	149.5
SB2		"	"	149.5
SB7		Air	"	147.0
SB8		"	"	147.5
SC1	3.0	Water bath	146.6	150.0
SC2		"	"	150.0
SC7		Air	"	147.0
SC8		"	"	146.5

of the test samples in Series B was the same as in Series A. The operation of the equipment is outlined in Appendix A.

3B.8b Pulse Velocity Readings

A typical calculation of pulse velocity is shown in Sample Calculation 7. Tables 8, 9, and 10 outline the individual pulse velocities of the three mixes tested in Test Series B.

Sample Calculation 7

Test Series B

Sample Calculation of Pulse Velocity

Cylinder SA4

Measured length of cylinder = L = 12.15"

Time taken for sonic wave to traverse length of cylinder = T = 64.5 microseconds

$$\text{Pulse Velocity} = \frac{L}{T} = \frac{12.15}{12} \times \frac{1}{64.5} =$$

.01570 ft./microsecond or 15,700 ft./sec.

Table 8

Test Series B -- SA General Test Data

Cylinder No.	Method of Curing	Compressive Strength (psi)		Pulse Velocity (ft./sec. x 10^3)		E (psi x 10^6)	E (elec. ck.) (psi x 10^6)	E_D (psi x 10^6)	Poisson's Ratio μ
		7-day	28-day	7-day	28-day				
SA1	Water bath	5727		15.55		3.82		4.90	.18
SA2	"	5780		15.55					
SA3	"	5762		15.45					
SA4	"		6879		15.7	4.25		5.45	.15
SA5	"		6737		15.9				
SA6	"		6879		16.1				
SA7	Air	5443		15.05					
SA8	"	5549		15.05					
SA9	"	5869		15.0		3.85		4.94	.18
SA10	"		6312		15.4	4.28	4.08	5.59	.16
SA11	"		6276		15.4				
SA12	"		6844		15.6				

Table 9

Test Series B -- SB General Test Data

Cylinder No.	Method of Curing	Compressive Strength (psi)		Pulse Velocity (ft./sec. x 10^3)		E (psi x 10^6)	E (elec. ck.) (psi x 10^6)	E_D (psi x 10^6)	Poisson's Ratio μ
		7-day	28-day	7-day	28-day				
SB1	Water bath	3954		14.35		3.26		4.18	0.21
SB2	"	3847		14.40					
SB3	"	3918		14.60					
SB4	"		4663		15.45	3.34		4.28	0.20
SB5	"		5106		15.45				
SB6	"		4929		15.50				
SB7	Air	3635		14.00					
SB8	"	3830		13.90					
SB9	"	3706		13.85		3.14		4.03	0.21
SB10	"		4911		14.40	3.68	4.77	4.72	0.19
SB11	"		4840		14.45				
SB12	"		4716		14.45				

Table 10

Test Series B -- SC General Test Data

Cylinder No.	Method of Curing	Compressive Strength (psi)		Pulse Velocity (ft./sec. x 10^3)		E (psi x 10^6)	E (elec. ck.) (psi x 10^6)	E_D (psi x 10^6)	Poisson's Ratio μ
		7-day	28-day	7-day	28-day				
SC1	Water bath	2004		13.90		2.92		3.74	0.25
SC2	"	2110		13.80					
SC3	"	2234		13.80					
SC4	"		3000		14.60	3.23		4.14	0.23
SC5	"		3289		15.10				
SC6	"		3121		15.10				
SC7	Air	2145		13.15					
SC8	"	2145		13.15					
SC9	"	2199		13.15		2.61		3.35	0.25
SC10	"		3280		13.80	3.14	3.26	4.03	0.23
SC11	"		3050		13.65				
SC12	"		3156		13.80				

3B.9 Compressive Strength Determination

The test procedure followed in Test Series B was the same as in Test Series A. The compressive strengths of the test cylinders for each of the three mixes in Test Series B are given in Tables 8, 9, and 10 respectively.

3B.10 Strain Determination

The unit strain of the concrete under load was determined as in Test Series A. In addition to the mechanical (DEMEC) gauge readings, checks were conducted electrically using SR-4 strain gauges. The cylinders that these checks were made on were SA10, SB10, and SC10 - the 28-day air-cured cylinders from each of the three mixes. The gauges were glued to the cylinders as shown in Figure 15. The gauges were then wired to Budd strain indicators (Figure 16) and the strain readings taken directly.

A tabulation of both the mechanical and electrical strain readings is recorded in Appendix B.

Figure 15

SECURING ELECTRICAL STRAIN GAUGES

Figure 16

BUDD ELECTRICAL STRAIN INDICATORS

CHAPTER IV

ANALYSIS OF TEST RESULTS AND CORRELATION OF THESE RESULTS TO PULSE VELOCITY

4.1 Introduction

This chapter will initially deal with an analysis of the physical and mechanical properties of the concretes tested in the individual test series. The discussion will then be enlarged upon to correlate the pulse velocity readings to these properties.

IVA ANALYSIS OF TEST SERIES A

4A.1 Aggregates

The gradation of both the coarse and fine aggregate as shown separately in Figure 2 and Figure 3 - Chapter III, met the requirements as specified in CSA Standard A23.1-1967.

4A.2 Concrete Mix Designs

While the mixes were designed for absolute water-cement ratios of 0.4, 0.6, and 0.8, some of the actual mixes were found too dry at these ratios. For this reason water was added to the batch and actual water-cement ratios were calculated and are as follows:

Table 11

	Designed Water-Cement Ratio	Actual Water-Cement Ratio
BPA	0.40	0.43
BPB	0.60	0.60
BPC	0.80	0.81

It can be seen that the ratios did not change appreciably and still gave a good range of concrete mixes to be tested.

4A.3 Unit Weights

The unit weight results as outlined in Table 3 - Chapter III, were predictable. In the plastic state the concrete with the lower water-cement ratio was more dense because of the higher cement content. This was verified in the test results where the densities were 150.8, 149.8, and 149.4 pounds per cubic foot for water-cement ratios of 0.43, 0.60, and 0.81 respectively.

After one day, tests on the hardened concrete generally showed that the unit weights increased slightly. This was due to volume changes resulting from the densification of the concrete. The densification or shrinkage of the concrete was observed physically upon investigation of the cylinder. During casting, the concrete was struck off level with the top of the cylinder.

However, during the dissipation of the bleed water, the concrete surface was being slowly depressed and the higher the degree of bleeding, the larger the volume changes. From the test results it can be seen that there was very little difference between the plastic and one-day unit weights of the BPA mix. However, the BPB and BPC mixes showed a larger unit-weight change. This can be explained in that the BPA mix had very little bleeding when compared to the BPB and BPC mixes.

The 7-day unit weight checks again showed changes. However, while the wet cured cylinders showed increases in unit weights, the dry cured cylinders generally showed decreases. Since the voids in the wet cured cylinders would naturally be filled with water, an increase in unit weight would be expected. However, in the case of the dry cured cylinders, the increasing loss of moisture due to the drying out of the cylinder resulted in a general decrease in the unit weights.

4A.4 Strength Results

The results of the compression tests were predictable and are given in Tables 4, 5, and 6 - Chapter III, for the respective mixes. Cylinders with the lower water-cement ratios tested higher than those with higher ratios. Also, the wet cured cylinders generally tested higher than the dry cured. The method of curing, however, did not have as much affect on the BPA mixes as on the weaker mixes. There was no appreciable difference in the strengths of the wet and dry cured cylinders for both the 7 and 28 day tests. An explanation for this could be that since hydration is a slow and continuing process as long as water is available, higher cement contents take longer to completely hydrate. After short duration curing there might be no appreciable difference in strength between high cement content mixes cured under different conditions. However, after long duration curing, three months to a year, high strength concrete cured under wet conditions would show higher strength gains in comparison to dry cured concrete.

4A.5 Determination of Young's Modulus of Elasticity

Concrete is not a truly elastic material, and the graphic stress-strain relationship for continuously increasing loading is generally in the form of a curved line. However, for concrete that has hardened thoroughly and has been moderately preloaded, the stress-strain curve is, for all practical purposes, a straight line within the range of usual working stresses. The stress-strain ratio determined from the virtually straight portion of the stress-strain curve is called the "modulus of elasticity". Usually, concretes of higher strength have higher elastic values, although modulus of elasticity is not directly proportional to strength(6).

The stress-strain readings are tabulated in Appendix B.

The stress-strain relationship was graphed for two cylinders, namely BPA4 and BPC10, and are shown in Figure 17. The calculations to determine "E" for BPA4 and BPC10 are given in Sample Calculation 8. E values were determined for the other cylinders in a similar manner and a complete tabulation of E values is shown in Tables 4, 5, and 6 - Chapter III, for the three separate mixes.

A satisfactory range in E values was obtained with a value of approximately 5.0×10^6 psi calculated for the BPA higher strength concrete as compared to approximately 3.7×10^6 psi for the BPC lower strength concrete. These results fall in the range of elastic moduli for ordinary concretes which range from 2.0×10^6 psi to 6.0×10^6 psi (6).

A check was made on the graphed E values using the following empirical equation developed by Adrian Pauw of the University of Illinois.

$$E = 33\sqrt{\rho^3 f'_c} \qquad - - - - - - -$$

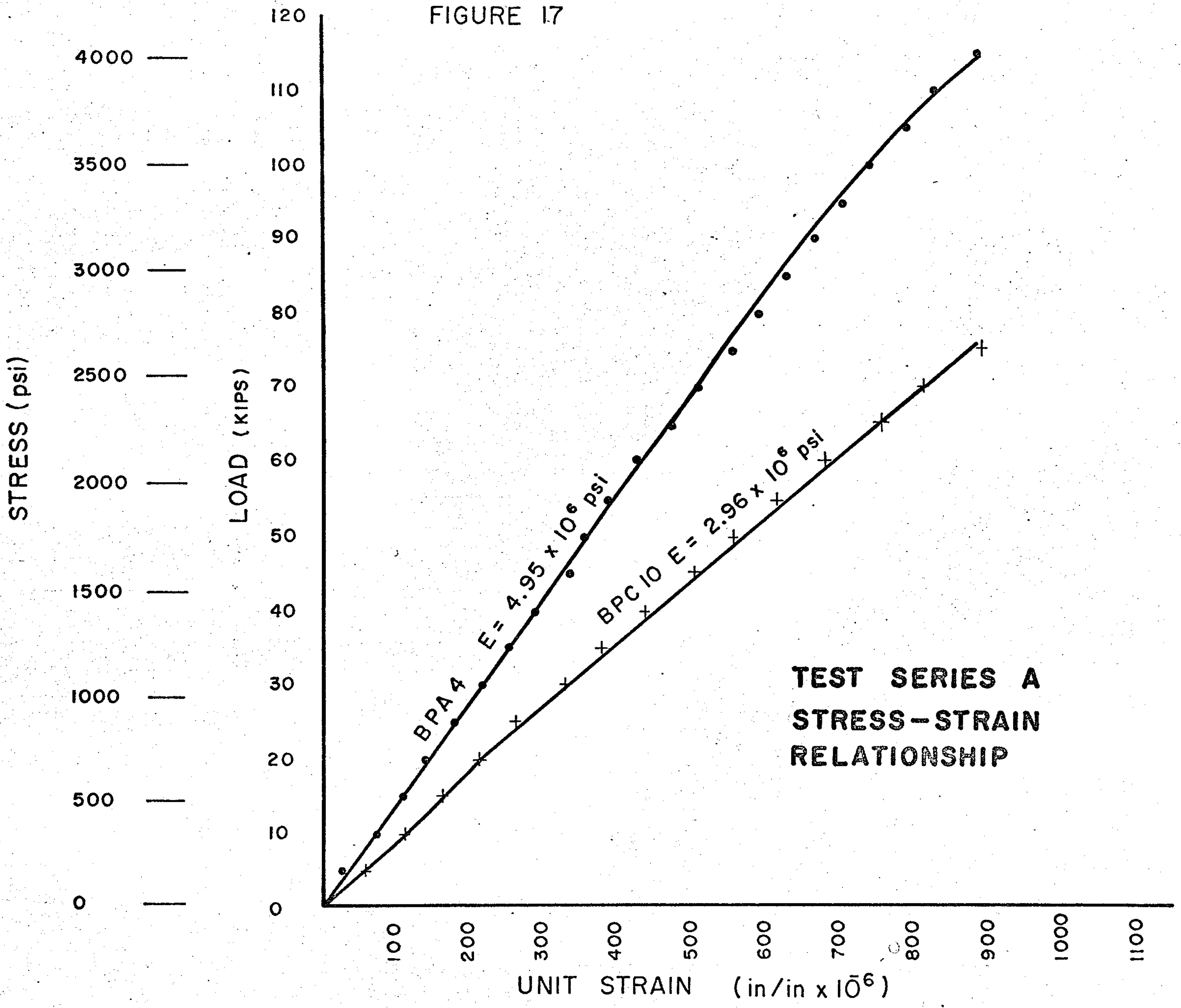
where E = static modulus of elasticity of concrete (psi)

ρ = unit weight of concrete (p.c.f.)

f'_c = ultimate strength of concrete (psi)

A typical calculation is shown in Sample Calculation 9 and a comparison of the check values to the graphed values is shown

FIGURE 17



TEST SERIES A
STRESS-STRAIN
RELATIONSHIP

Sample Calculation 8

Typical Calculations in Determining Modulus of Elasticity

Modulus of Elasticity is defined as the slope of the straight portion of the stress-strain curve. Therefore, two points on the straight portion of the curves in Figure 17 were used as follows:

Test Cylinder BPA4

Stress (psi)	Strain (in./in. x 10^{-6})
0	0
2123	430

$$\text{Modulus of Elasticity} = E = \frac{2123}{430 \times 10^{-6}} = 4.95 \times 10^{6} \text{ psi}$$

Test Cylinder BPC10

Stress (psi)	Strain (in./in. x 10^{-6})
708	216
2300	756

$$E = \frac{\text{Stress}}{\text{Strain}} = \frac{2300 - 708}{(756 - 216) \times 10^{-6}} = 2.96 \times 10^{6} \text{ psi}$$

in Table 12. While there is some discrepency in a couple of the values, the comparisons are generally within acceptable limits.

Sample Calculation 9

Check on Modulus of Elasticity Values

Cylinder BPA1

From the equation $E = 33\sqrt{\rho^3 f'_c}$

For cylinder BPA1 ρ = 151.8 p.c.f.

f'_c = 5089 psi

$$\therefore \quad E = 33\sqrt{151.8^3 (5089)} = 4.39 \times 10^6 \text{ psi}$$

Table 12

Comparison of Modulus of Elasticity Values

Cylinder No.	Measured E (x 10^6 psi)	Checked E (x 10^6 psi)
BPA1	4.19	4.39
BPA4	4.95	4.80
BPA9	4.10	4.46
BPA10	5.04	4.79
BPB1	3.60	3.83
BPB4	4.23	4.29
BPB9	3.91	3.76
BPB10	4.23	4.22
BPC1	3.60	3.24
BPC4	4.46	3.77
BPC9	2.02	2.98
BPC10	2.96	3.42

IVB ANALYSIS OF TEST SERIES B

4B.1 Aggregates

The gradation of both the coarse and fine aggregate as shown respectively in Figures 10 and 11 - Chapter III, met the requirements as specified in CSA Standard A23.1-1967. The dry bulk specific gravity of the coarse aggregate in Series B was somewhat lower than that of Series A. (2.638 as compared to 2.580)

4B.2 Concrete Mix Designs

In all the three mixes (SA, SB, and SC) the water contents in the final batch weights were adjusted slightly. These adjustments were made in order to produce a more workable mix. A comparison between the design and actual water-cement ratios is as follows:

Table 13

Comparison of Water-Cement Ratios

Mix	Design W/C	Actual W/C
SA	0.40	0.39
SB	0.62	0.64
SC	0.82	0.81

As in Test Series A, the slight change in water-cement ratios did not deter from the over-all range of mixes tested.

4B.3 Unit Weights

The unit weights of the concrete in Test Series B, as outlined in Table 7 - Chapter III, in both the plastic and hardened states were somewhat lower than those of Test Series A. This can be attributed to two factors:

i) The specific gravity of the coarse aggregate used in Series B was lower.

ii) The air contents of the plastic concrete were slightly higher in Series B.

In general, the lower the water-cement ratio the denser the concrete. This is attributed to the densifying effect of the higher cement contents. However, in Test Series B there was one slight reversal. Mix SC, with a water-cement ratio of 0.81, had a plastic unit weight of 146.6 p.c.f. while mix SB, with a water-cement ratio of 0.64, had a plastic unit weight of 146.4. Since this is only a slight difference, it could be attributed to the testing. However, upon further investigation, it was noted that the air content of mix SB was higher than that of mix SC (3.2% as compared to 3.0%). This higher air content contributed to the lower unit weight of mix SB.

The unit weights of the hardened concrete proved interesting also. While the values, as tabulated in Table 7 - Chapter III, did not fluctuate appreciably between the various mixes, the air cured cylinder densities were lower than the wet cured. This difference was due to the voids in the concrete being filled with water in the wet cured cylinders while the air cured cylinders were slowly losing moisture through drying. The effect of cement content on unit weight was brought out in the dry cured cylinders with SA8 having a higher unit weight than SC8 (149.0 p.c.f. as compared to 146.5 p.c.f.)

4B.4 Strength Results

The results of the compression tests are given in Tables 8, 9, and 10 - Chapter III, for the respective mixes. As expected, cylinders with the lower water-cement ratios tested higher than those with higher ratios. A good range of strengths was obtained with the SA, SB, and SC 28-day wet cured strengths approximately 6700, 4900, and 3200 psi respectively.

4B.5 Determination of Young's Modulus of Elasticity

The modulus of elasticity was determined for the various concrete mixes in Test Series B. The stress-strain readings are tabulated in Appendix B. The stress-strain relationship was graphed for two cylinders, namely SA10 and SB9. These are shown in Figure 18. E values of 4.28×10^6 psi and 3.14×10^6 psi respectively were calculated. In addition, the stress-strain relationship obtained by electrical methods was plotted as a check for cylinder SA10. The E value checked very closely at 4.08×10^6 psi. Calculations for the above values are shown in Sample Calculation 10.

E values were determined for the other cylinders in a similar manner and a complete tabulation of E values is shown in Tables 8, 9, and 10 - Chapter III, for the respective mixes.

Additionally, a check was made on the graphed E values using the following equation developed by Adrian Pauw of the University of Illinois.

$$E = 33 \sqrt{\rho^3 f'_c}$$

Where E = static modulus of elasticity of concrete (psi)

ρ = unit weight of concrete (p.c.f.)

f'_c = ultimate compressive strength of concrete (psi)

A typical calculation is given in Sample Calculation 11 and a comparison of the check values to the graphed values is shown in Table 14. The comparisons are, in general, within acceptable limits.

Sample Calculation 10

Typical Calculations in Determining Modulus of Elasticity

Modulus of Elasticity is defined as the slope of the straight portion of the stress-strain curve. Therefore, two points on the straight portion of the curves in Figure 18 were used as follows:

Test Cylinder SA10

Stress (psi)	Strain (in./in. x 10^{-6})
0	0
3185	746

$$E = \frac{3185}{746 \times 10^{-6}} = 4.28 \times 10^{6} \text{ psi}$$

Test Cylinder SA10 (SR-4 strain gauge check)

Stress (psi)	Strain (in./in. x 10^{-6})
354	125
3539	909

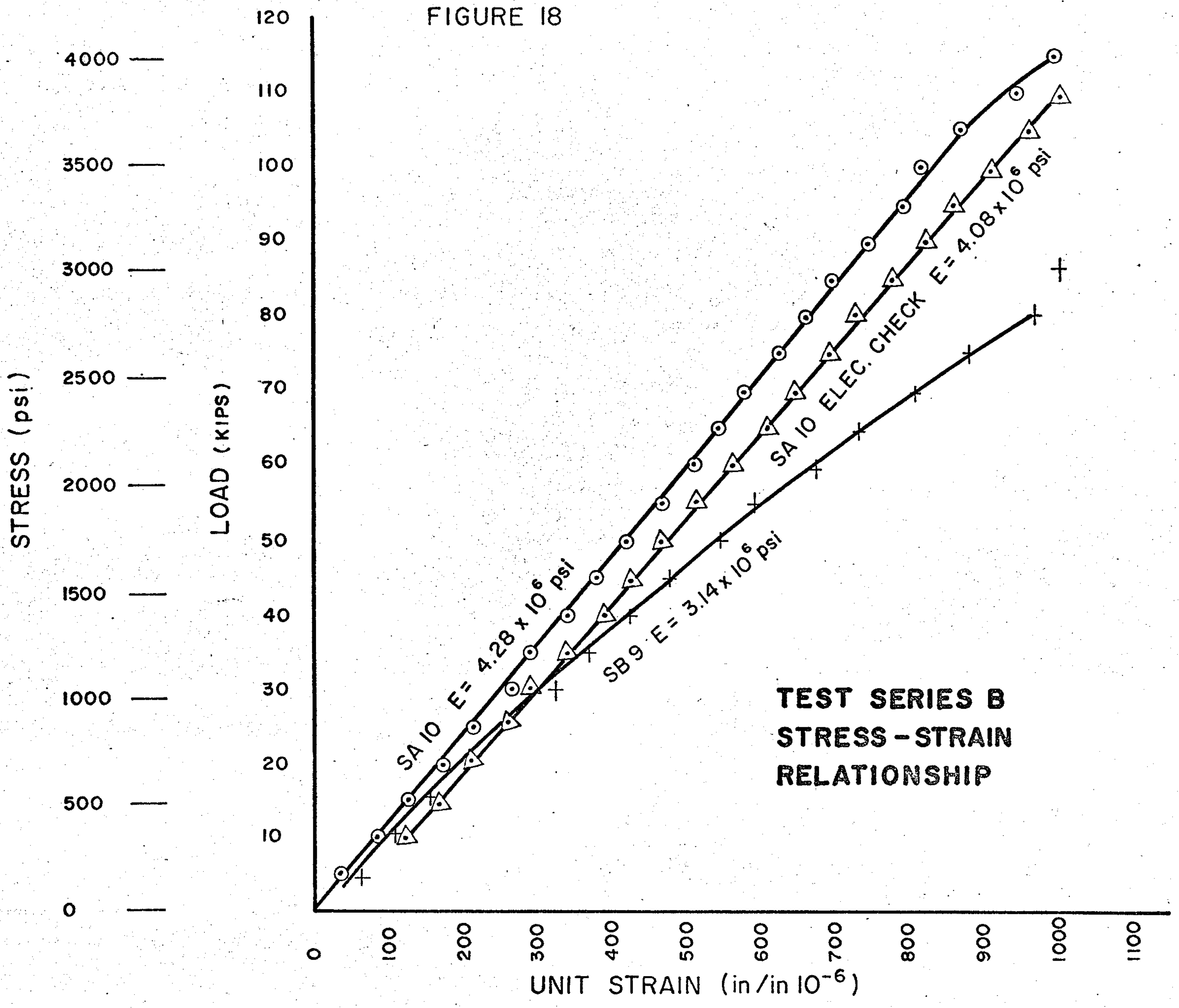
$$E = \frac{3539 - 354}{(909 - 125) \times 10^{-6}} = 4.08 \times 10^{6} \text{ psi}$$

Test Cylinder SB9

Stress (psi)	Strain (in./in. x 10^{-6})
0	0
2123	672

$$E = \frac{2123}{672 \times 10^{-6}} = 3.14 \times 10^{6} \text{ psi}$$

FIGURE 18



TEST SERIES B
STRESS - STRAIN
RELATIONSHIP

Table 14

Comparison of Modulus of Elasticity Values

Cylinder No.	Measured E (x 10^6 psi)	Checked E (x 10^6 psi)
SA1	3.82	4.61
SA4	4.25	5.04
SA9	3.85	4.60
SA10	4.28	4.77
SB1	3.26	3.79
SB4	3.34	4.13
SB9	3.14	3.62
SB10	3.68	4.17
SC1	2.92	2.72
SC4	3.23	3.33
SC9	2.61	2.77
SC10	3.14	3.38

Sample Calculation 11

Check on Modulus of Elasticity Values

Cylinder SA1

From the equation $E = 33\sqrt{\rho^3 f'_c}$

For cylinder BPA1 $\rho = 150.5$ p.c.f.

$f'_c = 5720$ psi

$$E = 33\sqrt{150.5^3\ (5720)} = 4.61 \times 10^6 \text{ psi}$$

IVC CORRELATION OF TEST RESULTS TO PULSE VELOCITY

4C.1 Introduction

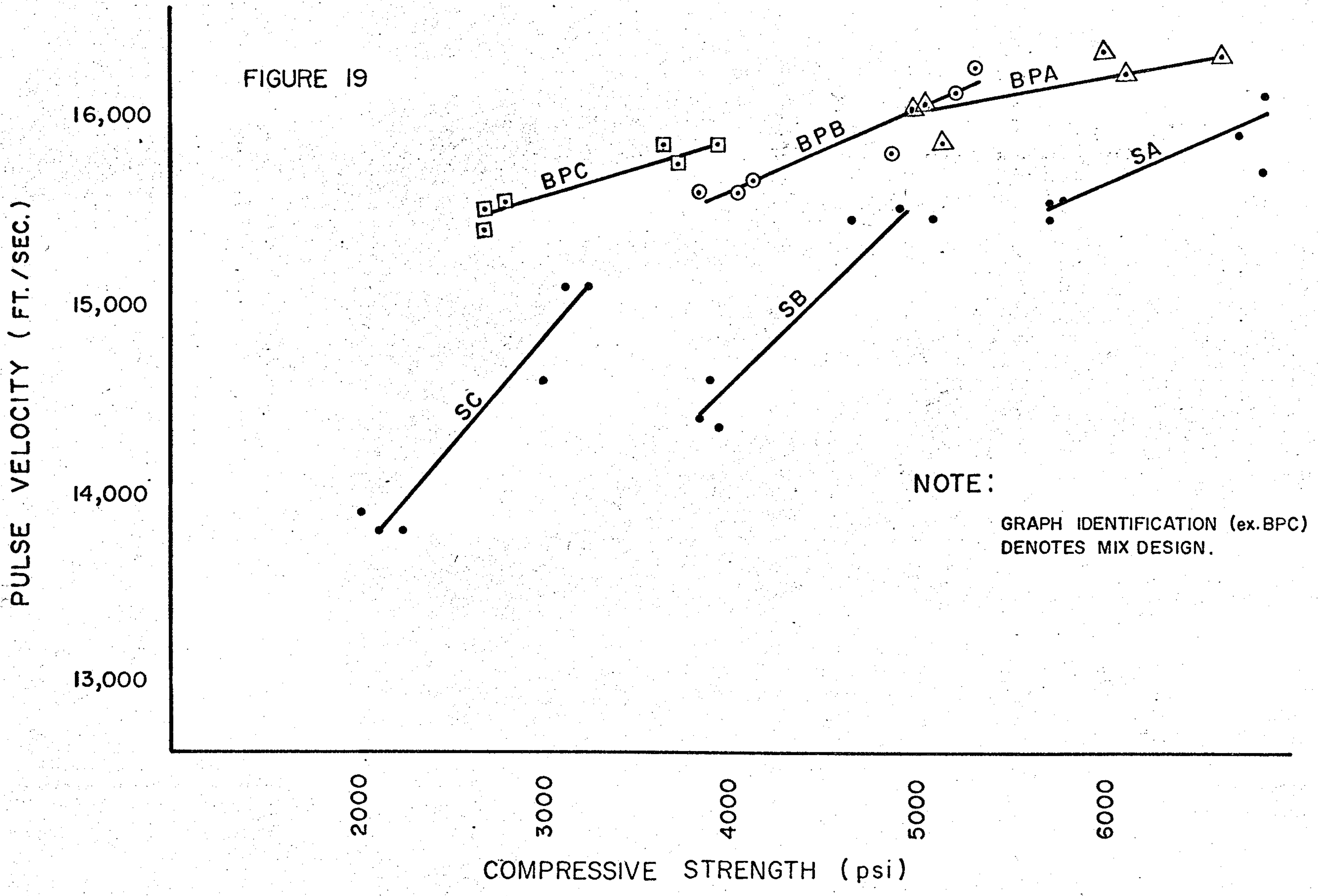
While the first two segments of this chapter dealt with an analysis of the physical and mechanical properties of the respective concretes tested, the discussion will now be enlarged upon to correlate the pulse velocity readings to these properties.

4C.2 Pulse Velocity Vs. Strength

A relationship of pulse velocity to compressive stength for the two test series is shown in Figure 19 and Figure 20 for the wet and dry cylinders respectively. While there is a tendency for concretes of higher strengths to have higher pulse velocities, no overall relationship can be established. One distinct observation

RELATIONSHIP OF PULSE VELOCITY TO COMPRESSIVE STRENGTH FOR SATURATED CONCRETE SPECIMENS

FIGURE 19

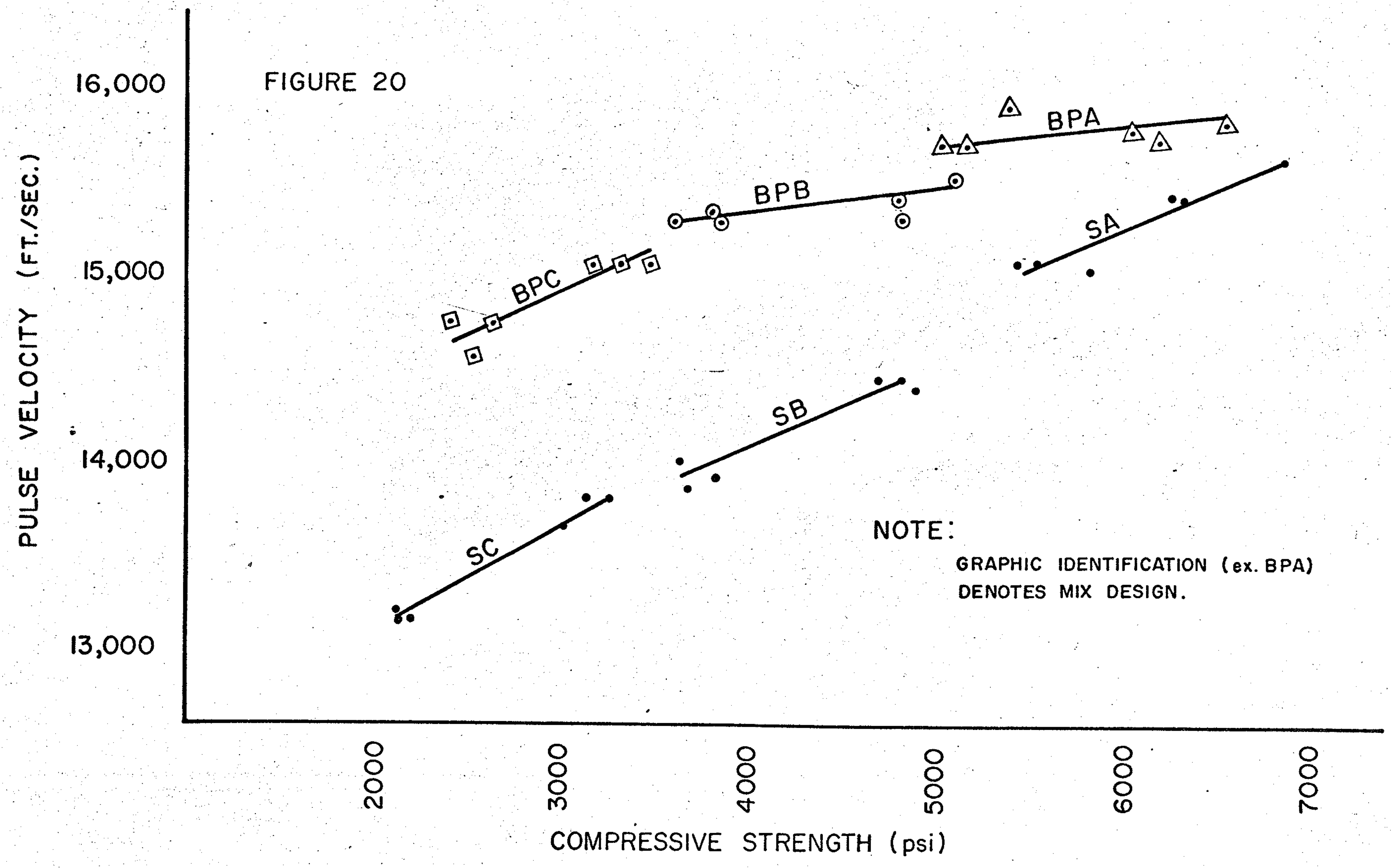


NOTE:

GRAPH IDENTIFICATION (ex. BPC) DENOTES MIX DESIGN.

RELATIONSHIP OF PULSE VELOCITY TO COMPRESSIVE STRENGTH FOR DRY CONCRETE SPECIMENS

FIGURE 20



NOTE:
GRAPHIC IDENTIFICATION (ex. BPA)
DENOTES MIX DESIGN.

was made in that the "S" concretes had lower pulse velocities that the "BP" concretes. The differences ranged from as low as 200 ft./sec. for the "A" mixes to as high as 1400 ft./sec. for the "C" mixes.

A relationship was established for the various mixes, but this relationship was dependant on the heterogeneous, inelastic properties of the concrete. However, a general relationship could not be established for the mixes as a whole. This would indicate that the mix design of a concrete must be known before a pulse velocity-strength relationship can be applied.

4C.3 Pulse Velocity Vs. Density

Concrete, being a heterogeneous material, is made up of coarse aggregate, a cement-sand mortar, and an air void structure. The density of the concrete is naturally dependant on the proportioning of the above. However, if the aggregate is held constant, lower densities are usually related to the air void structure and water-cement ratio of the concrete. In other-words, an increase in air content will decrease the density. In the sonic test method, pulses are not transmitted through air voids and if such a void lies in the pulse path, the instrument will indicate the time taken by the pulse to circumvent the void. Therefore, the higher the void structure the longer the time taken by the pulse to travel through the concrete specimen and the lower the pulse velocity.

Differences in densities can be attributed to the following factors:

i) Coarse Aggregate

Research has shown that both the amount of coarse aggregate used in any mix as well as the specific gravity of the coarse aggregate have an affect on the pulse velocity (5). Aggregates with lower specific gravities have shown to contribute to lower pulse velocities. This was borne out in this investigation since the "S" coarse aggregate did have a lower specific gravity then the "BP" coarse aggregate and the "S" pulse velocities were lower.

However, probably more important than the specific gravity of the coarse aggregate would be the gradation of the coarse aggregate. Both the amount and gradation of the coarse aggregate would affect the amount of cement-sand mortar used. The volume of mortar would determine the air void structure which in turn would have an affect on the density and pulse velocity of the concrete. Therefore, while the amount of the coarse aggregate was held constant throughout Test Series A and Test Series B, differences in gradation between aggregate "S" and aggregate "BP" could change the volume of mortar and thereby affect the void structure and pulse velocity. Also, variations in specific gravity between aggregates is usually associated with the void structure within the aggregate. Therefore, an aggregate with a lower specific gravity, such as the "S" aggregate, could have a higher void structure which, in turn, would contribute to lower pulse velocity readings.

ii) Air Content

As already explained, an increase in air content usually results in a decrease in density. In comparing the unit weights in the plastic state of Test Series A (Table 3 - Chapter III) to Test Series B (Table 7 - Chapter III), it can be observed that the "S" mixes have slightly lower densities. However, the air contents of the "S" mixes were slightly higher than those of the "BP" mixes. The increased air contents partially contributed to the lower densities in Test Series B and the increased air void structure, in turn, contributed to the reduced pulse velocity readings.

iii) Moisture Content

A comparison between Figure 19, the relationship of pulse velocity to compressive strength for saturated concrete specimens, and Figure 20, the same relationship for dry concrete specimens, shows that the pulse velocity readings on the dry cylinders were generally lower. This can be explained in that the saturated specimens offered less resistance to the pulse wave being transmitted through the concrete. Since the air voids were filled with water, the pulse wave did not have to circumvent the void but could pass right through it. The shorter transit time of the pulse resulted in higher pulse velocities. Jones has suggested that the dry readings can be from 10 to 15 percent lower (7). The results of this study showed a 5 - 10 percent difference in pulse velocity values between the wet and dry cylinders, but only for the B and C mixes of each series. The A mixes showed very little variation. Since the A mixes were richer in cement content, more of the mixing water could be used in the hydration process. Therefore, there would be less water available for bleeding and evaporation resulting in less voids. Because of the lesser void structure, variations in moisture content of the hardened concrete would have a lesser affect on the densities and pulse velocities since there would be fewer voids for the water to exist.

As occurred with compressive strength, no direct relationship could be developed between pulse velocity and density. In comparing the 7-day unit weights for Test Series A in Table 3 - Chapter III, and Test Series B in Table 7 - Chapter III, the only appreciable difference in unit weights is between the wet cured and dry cured cylinders. In fact, for all intents and purposes, the unit weights of the three wet cured mixes of the respective series are equal.

4C.5 Development of a Relationship Between Pulse Velocity, Modulus of Elasticity and Density

The classical formula for the velocity of a pulse travelling in an elastic solid is (5):

$$V = \sqrt{\frac{E}{\rho}} \qquad \text{- - - - - - - -} \quad (1)$$

Where V = pulse velocity

E = Young's modulus of elasticity

ρ = density of the material

The velocity of sound propagation through homogeneous elastic materials such as metals is usually considered a standard and will vary only with changes in the alloy. However, with a highly heterogeneous, inelastic material such as concrete, no set standard can be established and equation (1) would not necessarily apply. For example, equation (1) indicates that a reduction in density would result in an increase in pulse velocity providing E is held constant. However, both past research and the test results of this study show that a reduction in density of concrete usually brings about a reduction in pulse velocity. As discussed earlier, an increase in the air void struction of the concrete would reduce the density and also the pulse velocity. This fact was brought out in the difference in pulse velocities between the dry and wet cylinders. The dry cylinders naturally had more air voids and also recorded lower pulse velocities.

Equation (1) also indicates that the pulse velocity would be directly proportional to the square root of the modulus of elasticity. The tests results of this study indicated that while the concretes with the higher compressive strengths, and therefore the higher moduli of elasticities, generally produced higher pulse velocities, no general relationship could be established.

Since changes in strength and density were not reflected in pulse velocity changes in accordance with equation (1), modifications to the equation have been developed(8) resulting in the following equation:

$$E_D = V^2 \rho \frac{(1+\mu)(1-2\mu)}{(1-\mu)} \quad \text{- - - - - - - -} \quad (2)$$

Where

E_D = dynamic modulus of elasticity

V = pulse velocity

ρ = density of concrete

μ = Poisson's ratio

Two of the unkowns in equation (2) are the dynamic modulus of elasticity and poisson's ratio. The determination of these factors for each of the mixes in question was as follows:

Determination of Dynamic Modulus of Elasticity

The dynamic modulus of elasticity is normally determined on laboratory specimens subjected to longitudinal vibration at their natural frequency (1). However, research has been done on the comparison between static and dynamic modulus of elasticity. Takabayashi (9) has shown that the ratio of the static to dynamic modulus is higher the higher the strength of concrete. However, the degree of ratio change is more pronounced for concretes under 2000 psi. Once the concrete strengths exceed 2000 psi, the ratio of static to dynamic modulus is steady at 0.78. By applying this ratio to the measured static moduli, it was felt that the calculated dynamic moduli would provide an accuracy within the limitations of this study.

Therefore, the dynamic modulus of elasticity was calculated for each of the mixes tested using the following relationship:

$$E_D = \frac{E}{0.78}$$

Where

E_D = dynamic modulus of elasticity

E = static modulus of elasticity (measured)

The dynamic moduli for the respective cylinders in Test Series A are tabulated in Tables 4, 5, and 6 - Chapter III and for Test Series B in Tables 8, 9, and 10 - Chapter III.

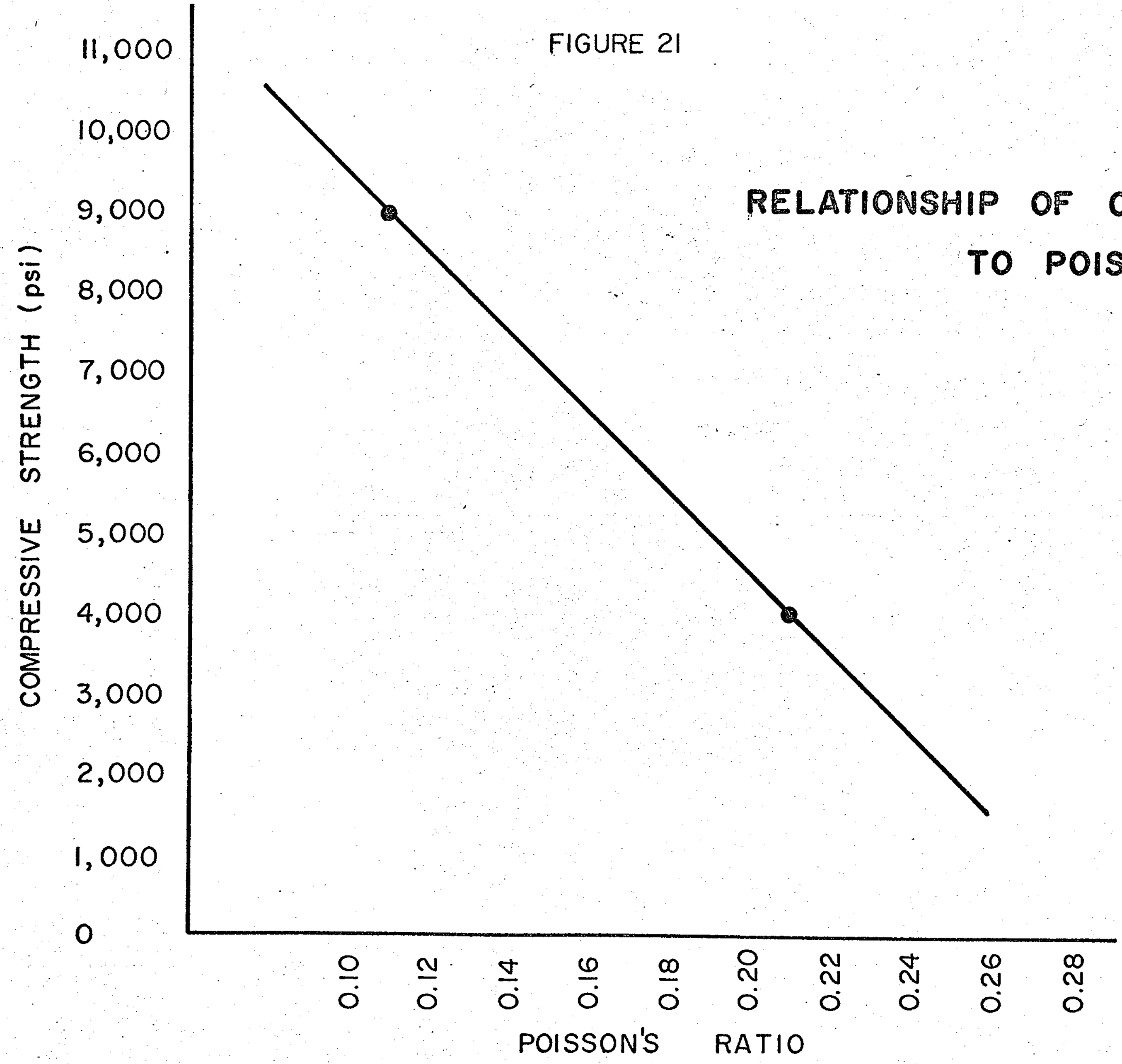
Determination of Poisson's Ratio

Poisson's ratio is defined as the ratio between the lateral strain accompanying an applied axial strain. Because lateral strains were not measured in this test program, it was felt that existing relationships between strength of concrete and poisson's ratio could be used without adversely affecting the accuracy of the findings. Neville states that poisson's ratio varies in the range 0.11 to 0.21 for ordinary concrete (1). Strength values of 9000 psi and 4000 psi were applied to the 0.11 and 0.21 ratios respectively. The relationship developed between poisson's ratio and compressive strength using the above values is shown in Figure 21.

From this graph, poisson's ratio was determined for each of the test cylinders in question in both Test Series A and Test Series B. The values are given in Tables 4, 5, and 6 - Chapter III for Test Series A, and Tables 8, 9, and 10 - Chapter III for Test Series B.

Once the dynamic modulus of elasticity and poisson's ratio were determined for the various mixes, there were no unknowns in equation (2). However, upon examination it was found that the equation could not be balanced. This was predictable since it has already been established that a direct relationship did not exist between pulse velocity, density and modulus of elasticity.

FIGURE 21



RELATIONSHIP OF COMPRESSIVE STRENGTH TO POISSON'S RATIO

4C.6 Introduction of K Factor

The fact that a relationship between pulse velocity and the properties of any given mix could be established while an overall relationship could not be established, emphasizes the importance of how changes in mix design can affect pulse velocity readings. It appears that by adjusting a mix, changes in the void structure take place. This change in void structure depends on the gradation of the coarse and fine aggregate and the amount of cement and water used. Since no general relationship could be established for a range of mix designs, a K factor was introduced into equation (2) to allow for the inelastic properties exhibited by concrete and how these properties can have different effects on different mixes.

By introducing a K factor, equation (2) becomes:

$$E_D = K \rho V^2 \frac{(1 + \mu)(1 - 2\mu)}{(1 - \mu)} \quad \text{- - - - - - - -} \quad (3)$$

Where

E_D = dynamic modulus of elasticity (psi)
ρ = unit weight (p.c.f.)
V = pulse velocity (fps)
μ = Poisson's ratio
K = constant

The K factor, as well as allowing for the inelastic properties of the concrete, also allows the equation to be balanced with respect to units.

4C.7 Determination of K Factors for Concretes Investigated

By substituting the known factors into equation (3), a K factor was calculated for each mix design under the various conditions tested in both Test Series A and Test Series B. Typical calculations are shown in Sample Calculation 12 and the K factors for the various mixes are tabulated in Table 15.

Sample Calculation 12

K Factor Determination

Test Series A - Cylinder BPA1

$$E_D = K\ V^2\ \rho\ \frac{(1+\mu)(1-2\mu)}{(1-\mu)}$$

$$5.37 \times 10^6 = K\ (16.05 \times 10^3)^2\ (151.8)\ \frac{(1+.19)(1-.38)}{(1-.19)}$$

$$K = \frac{5.37}{258\ (151.8)\ (0.91)}$$

$$K = 1.51 \times 10^{-4}$$

Test Series B - Cylinder SA1

$$E_D = K\ V^2\ \rho\ \frac{(1+\mu)(1-2\mu)}{(1-\mu)}$$

$$4.90 \times 10^6 = K\ (15.55 \times 10^3)^2\ (150.0)\ \frac{(1+.18)(1-.36)}{(1-.18)}$$

$$K = \frac{4.90}{242\ (150.0)\ (0.92)}$$

$$K = 1.47 \times 10^{-4}$$

Table 15

Tabulation of K Factors

Test Series	Cylinder No.	Age (Days)	Method of Curing	K Factor ($x\ 10^{-4}$)
A	BPA1	7	Wet	1.51
	BPA4	28	"	1.68
	BPA9	7	Dry	1.51
	BPA10	28	"	1.88
A	BPB1	7	Wet	1.41
	BPB4	28	"	1.55
	BPB9	7	Dry	1.60
	BPB10	28	"	1.69
A	BPC1	7	Wet	1.46
	BPC4	28	"	1.74
	BPC9	7	Dry	0.92
	BPC10	28	"	1.29
B	SA1	7	Wet	1.47
	SA4	28	"	1.54
	SA9	7	Dry	1.61
	SA10	28	"	1.67
B	SB1	7	Wet	1.53
	SB4	28	"	1.34
	SB9	7	Dry	1.59
	SB10	28	"	1.69
B	SC1	7	Wet	1.54
	SC4	28	"	1.51
	SC9	7	Dry	1.57
	SC10	28	"	1.67

4C.8 Analysis of K Factor Results

An analysis of the K factors as tabulated in Table 15 tend to indicate that no single K value could be applied to all mixes. Except for a couple of Test Series A readings, there is a general trend for the K factors for the dry concrete specimens to be higher than those for the wet specimens. Also, a pattern seems to have developed in the Test Series B results in that the K factors of the 28-day dry cylinders for each of the three mixes are approximately equal.

ie. SA10 = 1.67
SB10 = 1.69
SC10 = 1.67

This pattern is repeated in the 7-day dry cylinders

ie. SA9 = 1.61
SB9 = 1.59
SC9 = 1.57

and also in the 7-day wet cylinders

ie. SA1 = 1.47
SB1 = 1.53
SC1 = 1.54

However, this pattern did not occur in the 28-day wet cylinders in Test Series B or anywhere in Test Series A. Since the accuracy and methods of testing were the same in Series A as in Series B, no conclusions can be drawn as to the establishment of a single K factor over a range of mixes. Considerably more testing would have to be conducted in order to discover whether a relationship between K factors as occurred in Test Series B really does exist. However, the scope of this study indicates that a K factor must be established for each mix design. Also, the age and moisture content of the concrete must be known before applying a K factor.

IVD POSSIBLE SOURCE OF ERRORS IN TESTING

While extreme care was taken throughout the test program in order to ensure accurate test results, there was always the possibility, as in all test programs, that errors could have affected the results.

Since large volume batching (4 - 6 cu. yds./batch) was used for each concrete mix, it was felt that this diminished the possibility of the samples not being representative of the design. There was always the possibility that hairline cracks could have developed in the test cylinders while they were being transported and stripped after one-day's curing. However, this would have shown up in either the compression or pulse velocity tests. This was not obviously evident.

One possible source of error could have occurred in obtaining the pulse velocity readings. If there was not adequate acoustical coupling between the concrete and the face of each transducer, the signal curve displayed on the oscilloscope would not be as sharp in that it would be considerably flattened. Since the reading was taken when the trace leaves the horizontal, the flattened signal curve would make this point harder to detect. Most of the cylinder surfaces were sufficiently smooth to ensure good accoustical contact by the use of a coupling medium and by pressing the transducer against the concrete surface. The coupling medium used was simply a liquid soap. However, a few of the cylinders had one rough surface. This resulted in a flattened signal curve and made it difficult to determine an accurate pulse velocity.

Another source of error could have occurred in the strain readings obtained by means of the mechanical strain gauges. Since the gauges were meant to be held with the hand, this was the method used initially. However, it soon became apparent that the discrepancies in readings between the two gauges was mainly due to the firmness with which the respective gauges were being held. The slightest movement of the hand caused the gauge readings to jump. Before too long it was decided to fasten the gauges snugly to the cylinder by means of elastic bands (Figure 9 - Chapter III). This proved satisfactory since no more large jumps in gauge readings occurred. The affected readings were the BP-7 day tests. However, while these jumps did occur, this was taken into consideration in calculating E values for the cylinders in question.

CHAPTER V

CONCLUSIONS OF THE STUDY AND APPLICATIONS OF PULSE VELOCITY METHODS

5.1 Conclusions of Study Findings

While it was originally hoped to attain a single relationship between pulse velocity and concrete strength over a wide range of mix designs, this could not be clearly established. The classical formula for a pulse travelling in a homogeneous elastic solid (5),

$$V = \sqrt{\frac{E}{\rho}} \qquad \text{- - - - - - - -} \quad (1)$$

cannot be directly applied to concrete. The primary reason for this is that concrete, rather than being homogeneous and elastic is heterogeneous and inelastic. By using a developed modification (8) to equation (1) and including a K factor to allow for the inelastic properties of different mixes, the following equation was used:

$$E_D = K \, V^2 \, \rho \qquad \frac{(1 + \mu)\,(1 - 2\,\mu)}{(1 - \mu)}$$

Upon solving for K for the individual mixes, a wide range of K values was obtained (Table 15 - Chapter IV). Even though a certain degree of agreement exists between K factors for the various mixes in Test Series B, no definite conclusions can be drawn as to the establishment of a constant K factor over a range of mix designs. Until further research definitely proves otherwise, it is the author's opinion that a K factor must be determined for each concrete mix, taking into consideration the age and moisture content of the concrete, before pulse velocity methods can be appied.

The study has also shown the importance of knowing the moisture content of a concrete before pulse velocity methods can be applied. Pulse velocity readings on the wet cylinders ranged up to 10 percent higher than on the dry cylinders. Therefore, if the moisture content was disregarded, a wrong correlation between pulse velocity and concrete quality could be made.

While sonic testing methods do have a place in the evaluation of the quality of a concrete section, it is the author's opinion that the test should only be used in conjunction with existing methods of concrete evaluation. In some instances the use of sonic testing procedures may materially reduce the number of other tests, such as compressive strength tests, which might otherwise have to be performed. In other instances the use of sonic techniques may permit the testing of a great many more units or a much greater portion of a structure than would be possible or practicable by other techniques (10). As already stated, correlations between sonic test results and the concrete property to be evaluated must be established through tests on concrete as nearly identical to that under study as possible. If a section of concrete is found to be substandard by pulse velocity methods, established methods, such as coring, should be used to verify the pulse velocity findings.

In conclusion, it may be stated that sonic tests are not substitutes for other tests normally performed on concrete. The sonic tests do provide excellent tools for the extension of evaluations based on other tests of concrete to specimens or structures which are not themselves tested in another manner. They provide an unparalleled tool for evaluating the uniformity of concrete specimens or structures. They constitute no cure-all for the problems of the concrete testing engineer, but do constitute a valuable addition to the techniques available to him (10).

5.2 Recommended Applications of Pulse Velocity Methods

Following is a breakdown of a number of areas where pulse velocity methods can be effectively applied.

5.2a Quality Control in Precast Plants

Pulse velocity methods can be used for quality control in precast concrete plants. Sonic readings can first be correlated to the required mechanical and physical characteristics of the concrete by means of test specimens. This correlation can be a function of strength, moisture content, mix design, and setting characteristics of the concrete. Pulse velocity methods can then be used to effectively detect daily changes in the mix that may be caused by lack of compaction or change in water-cement ratio. The method can also be used as a tool for the determination of early age strength characteristics. Since the method is non-destructive, a number of tests can be conducted at various sections along a precast member. In this way, any changes and possible weaknesses in the quality of the concrete can be pinpointed.

5.2b "On-Site" Concrete Evaluation - New Construction

Applications where pulse velocity methods can be utilized for structural evaluation of concrete being placed on the job are unlimited. As in the precast plant, the desired physical and mechanical characteristics of the concrete must be correlated to the pulse velocity of the concrete supplied from the batch plant.

Some applications where pulse velocity methods can be used are as follows:

i) Cast-in-Place reinforced concrete beams and columns. Investigations could be made in areas of high deflection and at connections.

ii) Pilings and caissons above and below ground as well as below water.

iii) Wall and floor assemblies, which can be tested either with both transducers on the same surface or on opposing surfaces.

iv) All elements of bridge construction.

A practical application of the pulse velocity test could be to evaluate the action of either an accelerating admixture or a high early strength cement. This evaluation could enable the early removal of forms in jobs where repeated use of forms is desired. The soundness of the concrete could also be evaluated to determine whether future phases of construction, that depend on the soundness of the concrete under test, could proceed.

Another application for "on-site" concrete evaluation is the use of velocity measurements to determine that adequate consolidation and filling of deep forms has been accomplished(5). In this case, velocity can be measured directly through the forms. Common concrete discontinuities such as "honey-combing", segregation, inadequate compaction and voids can be detected by pulse velocity measurements. The use of the ultrasonic pulse technique for locating the above mentioned defects in concrete is based on the negligible transmission of ultrasonic energy across a concrete-air interface. Thus, any air-filled void lying immediately between two transducers will obstruct the direct ultrasonic beam and will produce lower pulse velocity readings. Completely filled forms with desired consolidation yield maximum velocity readings.

5.2c Evaluation of the Soundness of Existing Concrete Structures

While the findings of this study have indicated that the physical and mechanical characteristics of a concrete should be known before sonic pulse methods can be applied, there are limited uses for the test method for concrete of unknown properties. While strength determinations could not be made since this study has shown that minor or no changes in pulse velocity could be applied to a large range of strengths depending on the mix design, large discrepancies in "in-service" concrete quality and soundness could be located. For example, a number of readings could be taken along the face of a retaining wall. If the readings are uniform then a conclusion could be drawn that the concrete is sound. However, if any extremely low readings occur, this could be evaluated as a weak section in the wall. This weak section could be in the form of a crack or a void.

In addition to retaining walls, other evaluations on existing concrete structures could be made on:

i) Existing pilings and caissons.

ii) Roadways where tests could be made either across joints or in the middle of the slab.

iii) Water reservoir walls, both above and below ground.

iv) Hydroelectric structures such as dams, powerhouses, penstocks and gate structures.

v) Structures requiring evaluation after fires and earthquakes.

CHAPTER VI

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 Summary of Conclusions

A) Separate pulse velocity relationships exist for individual mixes, however, a general relationship encompassing a full range of mix designs cannot be established.

B) Because concrete is not an elastic, homogeneous solid, the classical formula for a pulse travelling in an elastic, homogeneous solid

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

must be modified by means of a K factor to allow for changes in the inelastic, heterogeneous properties of different concretes.

C) A correlation between pulse velocity readings and the mechanical and physical properties of a concrete must be known before pulse velocity methods can be applied.

D) The moisture content and age of the concrete to be tested must also be known before a pulse velocity analysis can be made.

E) Sonic testing methods should only be used as an extension of existing methods of concrete evaluation and not as a substitute.

F) Sonic methods could be most effectively used as a quality control tool. However, their results should never be used as a basis for rejecting work. Established test methods should be employed to verify sections of questionable quality until more confidence can be achieved with pulse velocity methods. This could be accomplished through more research into the interpretation of results.

6.2 Recommendations for Future Research

This study has indicated that changes in either mix design or materials can have an effect on pulse velocity. Since the investigation was limited to two aggregate sources utilizing three mix designs with each, it is suggested that further research could be done on additional aggregates and by again varying the mix design. Both the aggregates and the mix designs should be confined to what is being used in the Winnipeg area. Only by restricting the research to local concretes until a good statistical correlation is developed, will it ever be possible to utilize sonic methods locally with confidence.

Future research could also include an investigation into an application of pulse velocity methods in determining the resistance of concretes to freeze-thaw. A method is already suggested in A.S.T.M. Specification C666 employing resonance methods using the following equation:

$$E_D = C N^2 \rho$$

Where

E_D = dynamic modulus of elasticity

C = constant factor

N = resonant frequency of concrete

ρ = density of concrete

The application of the above equation is discussed in A.S.T.M. Sepcification C215.

Basically the test correlates resonant frequency to dynamic modulus of elasticity of the concrete before the initial freeze-thaw cycle. The concrete is then subjected to freeze-thaw cylces and the resonant frequency is measured periodically. When the resonant frequency is such that the dynamic modulus is calculated at 60 percent of the initial, using the above equation, the test is terminated. It should be possible to correlate sonic pulse velocity readings to resonant frequency readings since they are both measuring the same concrete properties. By conducting a research program, it may be found possible to substitute pulse velocity methods into the forementioned freeze-thaw specification with positive results.

Another area where research could be applied would be in an actual quality control situation such as in a precast plant. For example, the required properties of a given mix could be correlated to pulse velocity. This could be accomplished by running sonic checks on the test cylinders that are normally taken during production. A good correlation to destructive testing could then be made and this correlation could be used in determining the quality of the concrete in the precast member. By periodically taking cores from the member when possible, a further check can be made. By continuously refining the correlation over a large number of tests, an extremely reliable method of rapid non-destructive testing could be achieved.

In conclusion, it is the author's considered opinion that further research into the correlation between pulse velocity and the various physical and mechanical properties of concretes will ultimately yield a reliable non-destructive test method of quickly evaluating the quality of these concretes.

ACKNOWLEDGMENTS

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He is most grateful to Building Products and Supercrete, the two ready-mix companies who made their facilities and staff available to provide test samples that were representative of concrete going into the local market.

Special consideration must be given to M. Block and Associates whose laboratory and test equipment was used throughout the program. Sincere thanks are especially extended to Mr. A. F. ("Paddy") McLellen, P. Eng., of this firm, whose comments and advice were very much appreciated.

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APPENDIX A

BASIC OPERATION OF THE JAMES V-SCOPE

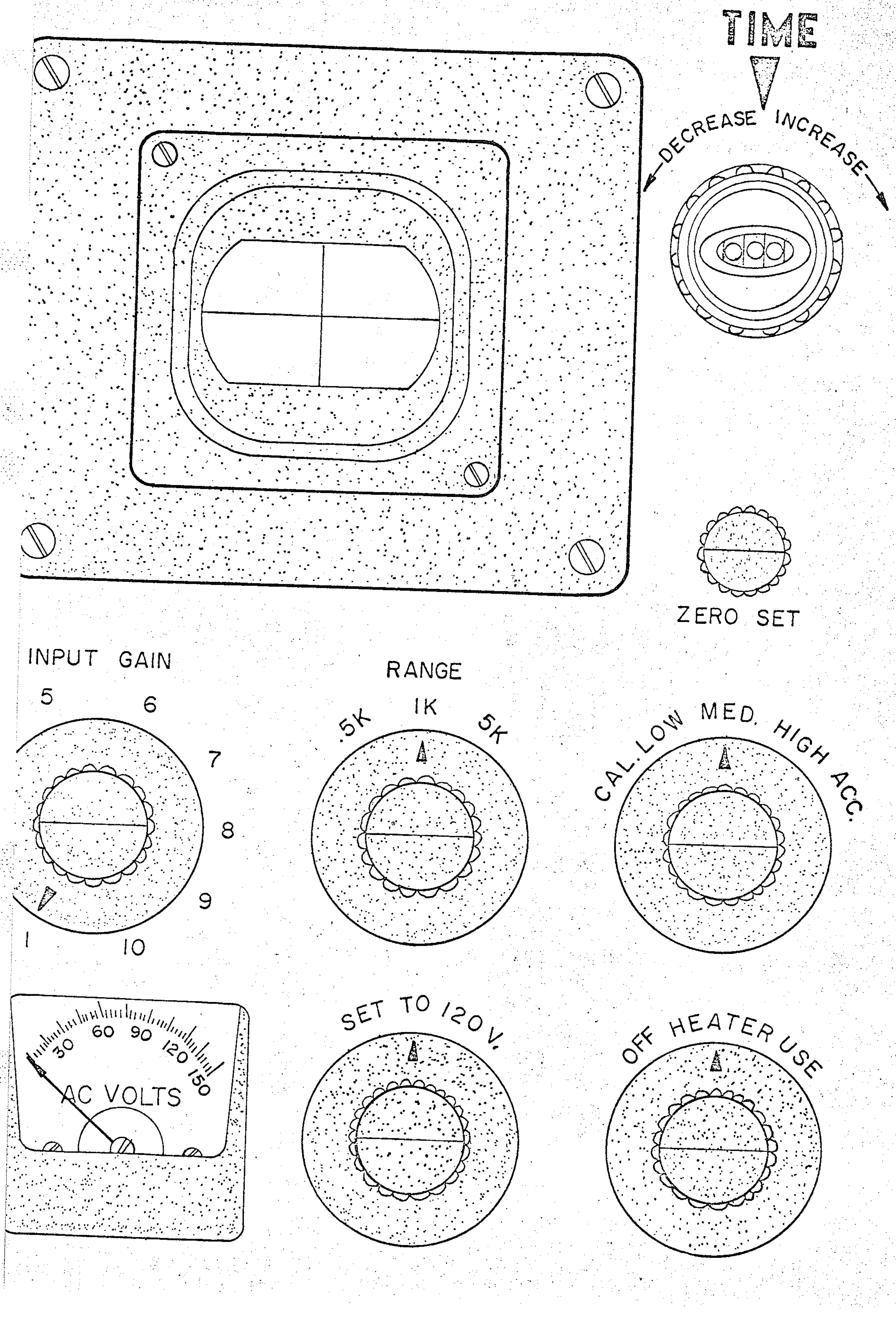
A diagram of the instrument panel is shown in Figure 22.

The start-up procedure for operating the V-scope is as follows:

1) Before plugging the instrument into the power source, the controls must be adjusted as follows:
    a) The TIME control is turned until digital counter reads zero.
    b) The INPUT GAIN control is turned to extreme counterclockwise position.
    c) The RANGE selector switch is turned to 1K position.
    d) The CAL-LOW-MED-HIGH-ACC power control is set to LOW position.
    e) The OFF-HEATER-USE selector is set to OFF position.
    f) The SET TO 120V control is turned completely counterclockwise.

2) The coaxial cables are attached to the transducers and then to the connectors on rear of V-scope.
3) The line cord is plugged into rear of instrument and into 120V power supply.
4) The OFF-HEATER-USE control is turned to HEATER position.

GURE 22 INSTRUMENT PANEL OF V-SCOPE

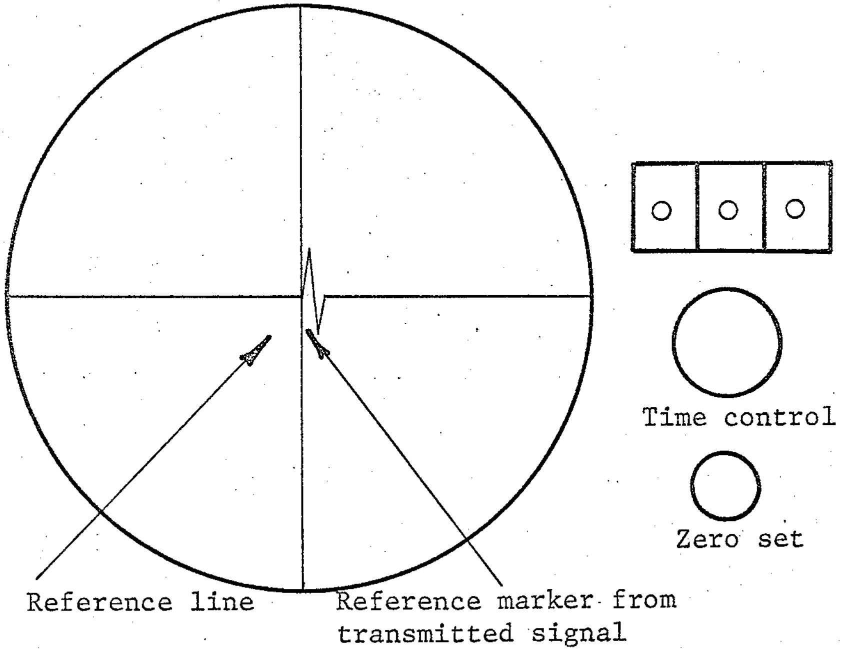


5) The SET TO 120V control is turned clockwise until voltmeter on front panel reads 120V.
6) A waiting period of approximately one minute is necessary for the V-scope to warm up.
7) The OFF-HEATER-USE control is set to USE position. At this time a trace will appear on the cathode ray tube and the transmitting transducer will begin emitting sound.
8) The ZERO SET control is adjusted so that the reference marker (see Figure 23) is lined up with the red vertical line on the face of the cathode ray tube.
9) It is necessary to wait approximately 5 minutes or until the reference stops drifting to the left. It can be determined when the drift has stopped by continually adjusting ZERO SET until no further adjustment is necessary.
10) A small amount of couplant fluid is placed on each of the rubber faces of the transducers and held tightly together.
11) The INPUT GAIN control is turned 1/4 turn clockwise.
12) The ZERO SET control is adjusted so that the point at which the trace leaves the horizontal is lined up with the red vertical reference line (see Figure 23).
13) To measure transit time the cylinder is now placed longitudinally between the transducers with couplant on each to assure a good bond. (Figure 24)

FIGURE 23

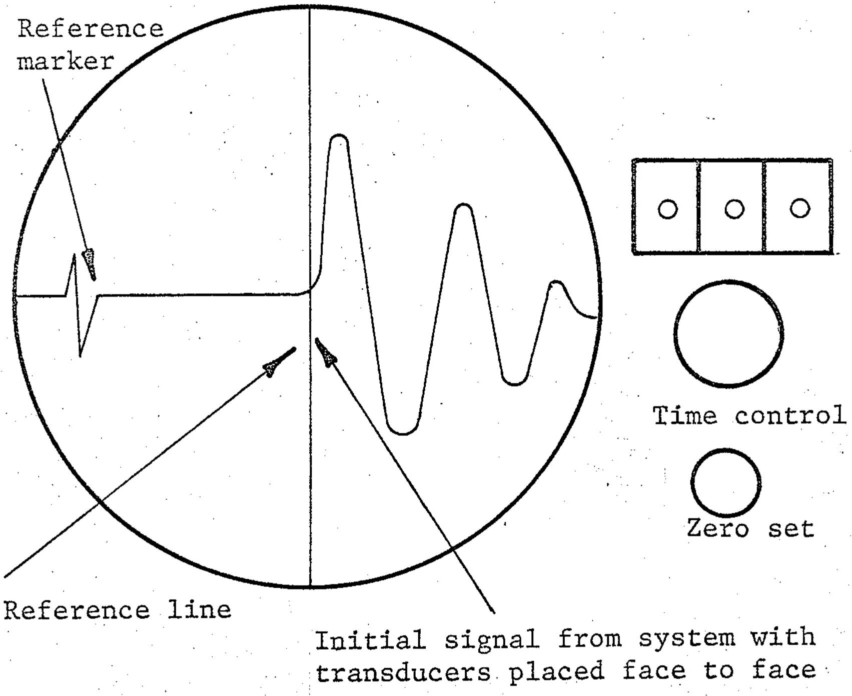
HOW TO ADJUST FOR ZERO DELAY

A. WARM UP CALIBRATION



1. Set TIME control to zero and dial.
2. Adjust ZERO set to place reference marker on vertical reference line at start of signal.
3. After 5 minute warm-up reset ZERO SET to line up marker with reference line.

B. TRANSDUCER CALIBRATION



1. Place transducers together with couplant liquid between them.
2. With TIME control still at zero, reset ZERO SET to first received signal. This is the t = 0 point for the instrument. This should be examined every 15 minutes for calibration stability.

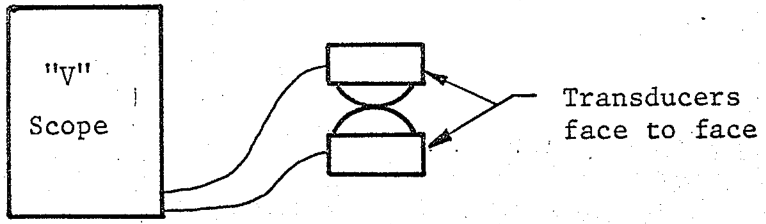


Figure 24

PLACING OF TRANSDUCERS.

14) The INPUT GAIN control is turned another 1/4 turn clockwise.

15) The TIME control is turned in INCREASE direction until the point at which the trace leaves the horizontal is directly lined up with the red vertical reference line.

16) The value is read from the counter. This value, with the RANGE selector in the 1K position, is the number of microseconds required to traverse the specimen. If the selector were in the 0.5K position, the value is divided in half for microseconds. With the selector in the 5K position, the value is multiplied by 5 for the number of microseconds.

APPENDIX B

STRESS-STRAIN RELATIONSHIPS

B1 Mechanical Gauge Data

Following is the data on the mechanical gauges used throughout the test program:

Gauge #1	Gauge #2
DEMEC No. 1271	DEMEC No. 1275
Gauge Factor = 2.49	Gauge Factor = 2.48

Because the gauge factors were so close, the total strain was determined by multiplying the average of the two gauge readings (corrected so that zero strain = zero load) by the average gauge factor.

$$\text{AV. G.F.} = \frac{2.48 + 2.49}{2} = 2.485$$

This considerably reduced the amount of calculations but had little or no affect on the final determination of elastic modulus.

B2 Test Series A

Following are the stress-strain readings taken on the various concrete mixes in Test Series A.

TEST SERIES A

CYLINDER NO. BPA1

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6}) Gauge #1	Gauge #2	Average	Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
0	0	0	0	0	0
5	177	18	18	18	44
10	354	36	36	36	89
15	531	56	56	56	139
20	708	76	76	76	188
25	885	93	78	86	213
30	1062	111	96	103	255
35	1238	129	106	118	293
40	1415	146	126	136	337
45	1592	161	140	150	372
50	1769	181	156	169	419
55	1946	199	174	187	464
60	2123	218	196	207	514
65	2300	227	216	222	551
70	2477	247	234	241	598
75	2654	272	251	262	651
80	2831	292	266	279	693
85	3008	317	288	303	752
90	3185	334	306	320	795
95	3362	352	321	337	837
100	3539	372	338	355	882
105	3715	392	356	374	929
110	3892	412	376	394	979
115	4069	427	401	414	1028
120	4246	462	431	447	1110

TEST SERIES A

CYLINDER NO. BPA4

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	15	15	15	37
10	354	30	30	30	75
15	531	45	45	45	112
20	708	55	60	57	142
25	885	70	75	72	179
30	1062	85	90	87	216
35	1238	100	105	102	254
40	1415	115	120	117	292
45	1592	140	135	137	341
50	1769	145	145	145	360
55	1946	155	165	160	398
60	2123	170	177	173	430
65	2300	185	195	190	474
70	2477	205	210	205	510
75	2654	220	225	222	554
80	2831	235	240	237	590
85	3008	255	255	255	634
90	3185	270	270	270	672
95	3362	285	285	285	710
100	3539	300	300	300	747
105	3715	320	315	317	789
110	3892	335	335	335	834
115	4069	355	355	355	884
120	4246				

TEST SERIES A

CYLINDER NO. BPA9

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6}) Gauge #1	Gauge #2	Average	Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
0	0	0	0	0	0
5	177	17	17	17	42
10	354	34	34	34	84
15	531	59	40	50	124
20	708	74	54	64	159
25	885	92	69	81	201
30	1062	111	84	98	243
35	1238	129	94	112	278
40	1415	144	104	124	308
45	1592	164	119	142	352
50	1769	209	135	172	427
55	1946	239	149	194	482
60	2123	252	164	208	516
65	2300	264	184	224	556
70	2477	274	198	236	586
75	2654	292	214	253	628
80	2831	314	229	272	675
85	3008	339	244	292	725
90	3185	359	259	309	767
95	3362	374	274	324	805
100	3539	401	294	348	864
105	3715	424	309	367	911
110	3892	439	324	382	949
115	4069	474	339	407	1011
120	4246	509	359	434	1078

TEST SERIES A

CYLINDER NO. BPA10

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	16	16	16	40
10	354	32	32	32	80
15	531	52	47	49	122
20	708	62	57	59	147
25	885	77	72	74	184
30	1062	92	87	89	222
35	1238	112	102	107	226
40	1415	137	112	124	309
45	1592	152	137	144	358
50	1769	162	147	154	384
55	1946	182	162	172	428
60	2123	202	177	189	470
65	2300	217	192	204	507
70	2477	237	207	222	553
75	2654	252	222	237	590
80	2831	262	257	259	644
85	3008	287	272	279	694
90	3185	302	287	286	713
95	3362	322	297	309	770
100	3539	342	317	329	820
105	3715	357	337	347	864
110	3892				
115	4069				
120	4246				

TEST SERIES A

CYLINDER NO. BPB1

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	18	18	18	44
10	354	36	36	36	89
15	531	61	46	54	134
20	708	81	50	66	164
25	885	101	62	82	203
30	1062	126	72	99	246
35	1238	146	85	116	288
40	1415	166	93	130	323
45	1592	191	111	151	375
50	1769	216	121	169	419
55	1946	241	139	190	472
60	2123	271	151	211	524
65	2300	296	161	229	569
70	2477	314	183	249	618
75	2654	356	203	280	695
80	2831	386	223	305	757
85	3008	411	241	326	810
90	3185	441	261	351	872
95	3362	481	291	386	959
100	3539	541	311	426	1058
105	3715	616	331	474	1177
110	3892				
115	4069				
120	4246				

TEST SERIES A

CYLINDER NO. BPB4

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	18	18	18	44
10	354	36	36	36	89
15	531	51	51	51	126
20	708	67	67	67	166
25	885	87	77	82	203
30	1062	107	92	99	246
35	1238	127	107	117	290
40	1415	147	117	132	328
45	1592	157	132	145	360
50	1769	187	147	167	414
55	1946	202	162	182	452
60	2123	227	177	202	501
65	2300	252	192	222	551
70	2477	262	212	237	588
75	2654	277	237	257	638
80	2831	307	242	275	683
85	3008	337	277	307	762
90	3185	357	292	325	807
95	3362	372	312	342	829
100	3539	392	332	362	877
105	3715				
110	3892				
115	4069				
120	4246				

TEST SERIES A

CYLINDER NO. BPB9

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	20	20	20	49
10	354	40	40	40	99
15	531	50	60	55	136
20	708	70	75	73	181
25	885	78	90	84	208
30	1062	96	110	103	255
35	1238	111	125	118	293
40	1415	131	145	138	342
45	1592	151	165	158	392
50	1769	170	185	178	442
55	1946	191	208	199	494
60	2123	217	232	224	556
65	2300	256	255	256	636
70	2477	271	280	276	685
75	2654	286	300	293	728
80	2831	316	330	323	802
85	3008	346	360	353	877
90	3185	376	400	388	964
95	3362	406	430	418	1038
100	3539	446	480	463	1150
105	3715	506	560	533	1324
110	3892				
115	4069				
120	4246				

TEST SERIES A

CYLINDER NO. BPB10

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	17	17	17	42
10	354	34	34	34	84
15	531	64	54	59	146
20	708	69	59	64	159
25	885	84	84	84	208
30	1062	104	99	102	253
35	1238	119	114	117	290
40	1415	134	124	129	320
45	1592	154	144	149	370
50	1769	169	154	162	402
55	1946	189	174	182	452
60	2123	209	194	202	501
65	2300	229	204	217	539
70	2477	249	224	237	588
75	2654	279	239	259	643
80	2831	289	254	272	675
85	3008	304	274	289	718
90	3185	314	284	299	743
95	3362				
100	3539				
105	3715				
110	3892				
115	4069				
120	4246				

TEST SERIES A

CYLINDER NO. BPC1

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	16	16	16	39
10	354	32	32	32	79
15	531	48	48	48	119
20	708	63	54	59	147
25	885	78	62	70	173
30	1062	93	71	82	204
35	1238	93	88	90	223
40	1415	108	103	106	263
45	1592	118	120	119	295
50	1769	138	138	138	342
55	1946	173	176	175	434
60	2123	203	208	206	512
65	2300	253	238	246	611
70	2477	303	283	293	728
75	2654	378	333	356	884
80	2831				
85	3008				
90	3185				
95	3362				
100	3539				
105	3715				
110	3892				
115	4069				
120	4246				

TEST SERIES A

CYLINDER NO. BPC4

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	16	16	16	39
10	354	33	33	33	82
15	531	38	48	43	107
20	708	58	58	58	144
25	885	73	73	73	181
30	1062	93	88	91	226
35	1238	108	103	106	263
40	1415	133	118	126	313
45	1592	143	138	141	350
50	1769	163	153	158	392
55	1946	188	168	178	442
60	2123	308	188	198	492
65	2300	233	208	221	549
70	2477	248	228	238	591
75	2654	293	243	268	665
80	2831				
85	3008				
90	3185				
95	3362				
100	3539				
105	3715				
110	3892				
115	4069				
120	4246				

TEST SERIES A

CYLINDER NO. BPC9

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	Meaningless Readings	0	0	0
5	177		28	28	69
10	354		56	56	139
15	531		85	85	211
20	708		115	115	285
25	885		140	140	347
30	1062		177	177	440
35	1238		204	204	507
40	1415		227	227	564
45	1592		257	257	638
50	1769		282	282	700
55	1946		314	314	780
60	2123		359	359	892
65	2300		459	459	1140
70	2477				
75	2654				
80	2831				
85	3008				
90	3185				
95	3362				
100	3539				
105	3715				
110	3892				
115	4069				
120	4246				

TEST SERIES A

CYLINDER NO. BPC10

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	23	23	23	57
10	354	46	46	46	115
15	531	71	61	66	164
20	708	96	81	87	216
25	885	121	96	108	268
30	1062	151	116	133	331
35	1238	181	136	158	384
40	1415	206	151	178	443
45	1592	241	167	204	507
50	1769	261	187	224	557
55	1946	291	207	249	619
60	2123	326	227	276	686
65	2300	361	247	304	756
70	2477	391	267	329	818
75	2654	436	287	361	897
80	2831				
85	3008				
90	3185				
95	3362				
100	3539				
105	3715				
110	3892				
115	4069				
120	4246				

B3 Test Series B

Following are the stress-strain readings taken on the various concrete mixes in Test Series B.

TEST SERIES B

CYLINDER NO. SA1

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	18	18	18	45
10	354	36	36	36	90
15	531	56	41	49	122
20	708	71	61	66	164
25	885	91	76	84	209
30	1062	121	91	106	264
35	1238	126	106	116	289
40	1415	141	121	131	326
45	1592	151	136	141	359
50	1769	176	151	163	405
55	1946	196	171	183	445
60	2123	216	191	203	505
65	2300	236	206	221	550
70	2477	251	221	236	558
75	2654	271	241	256	637
80	2831	291	261	276	687
85	3008	325	276	301	748
90	3185	330	291	311	774
95	3362	350	311	330	823
100	3539				
105	3715				
110	3892				
115	4069				
120	4246				

TEST SERIES B

CYLINDER NO. SA4

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	16	16	16	40
10	354	32	32	32	80
15	531	47	47	47	117
20	708	62	62	62	155
25	885	82	72	77	192
30	1062	87	92	89	222
35	1238	97	102	100	245
40	1415	112	107	109	272
45	1592	132	132	132	328
50	1769	152	142	147	366
55	1946	172	162	167	416
60	2123	202	167	185	461
65	2300	216	187	202	504
70	2477	237	202	220	548
75	2654	247	217	232	578
80	2831	262	232	247	615
85	3008	277	247	262	653
90	3185	307	262	285	710
95	3362	327	277	302	753
100	3539	337	292	315	785
105	3715				
110	3892				
115	4069				
120	4246				

TEST SERIES B

CYLINDER NO. SA9

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	18	18	18	45
10	354	36	36	36	90
15	531	51	46	49	122
20	708	76	61	69	172
25	885	91	76	84	209
30	1062	116	91	104	249
35	1238	141	106	124	309
40	1415	156	121	139	346
45	1592	181	136	158	394
50	1769	196	146	171	426
55	1946	221	166	194	483
60	2123	241	181	211	525
65	2300	266	196	231	575
70	2477	286	211	249	620
75	2654	315	226	271	675
80	2831	325	241	283	705
85	3008	355	256	306	760
90	3185	375	271	323	805
95	3362	395	286	341	850
100	3539	420	301	361	900
105	3715	440	321	381	954
110	3892	460	336	398	990
115	4069				
120	4246				

TEST SERIES B

CYLINDER NO. SA10

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	16	16	16	40
10	354	35	35	35	87
15	531	50	50	50	124
20	708	75	65	70	174
25	885	90	85	87	217
30	1062	110	100	105	262
35	1238	120	115	117	292
40	1415	140	135	137	342
45	1592	150	150	150	374
50	1769	175	160	167	416
55	1946	190	185	187	466
60	2123	205	205	205	510
65	2300	225	220	222	544
70	2477	235	235	235	578
75	2654	245	255	250	623
80	2831	255	270	263	656
85	3008	275	285	280	697
90	3185	295	305	300	746
95	3362	315	325	320	798
100	3539	325	330	327	815
105	3715	345	350	347	864
110	3892	380	380	380	946
115	4069	395	400	397	990
120	4246				

TEST SERIES B

CYLINDER NO. SA10

Total Compressive Load (Kips)	Stress (psi)	Electrical Total Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})		
		Gauge #1	Gauge #2	Average
0	0	0	0	0
5	177	56	38	47
10	354	176	75	125
15	531	230	110	170
20	708	279	148	213
25	885	330	190	260
30	1062	372	222	297
35	1238	430	265	348
40	1415	480	300	390
45	1592	515	342	428
50	1769	561	369	465
55	1946	606	418	512
60	2123	651	461	556
65	2300	713	505	609
70	2477	753	545	649
75	2654	811	575	693
80	2831	853	611	732
85	3008	905	646	776
90	3185	960	685	822
95	3362	1000	717	859
100	3539	1071	747	909
105	3715	1122	797	959
110	3892	1163	829	996
115	4069	1231	865	1048
120	4246	1238	898	1091

TEST SERIES B

CYLINDER NO. SB1

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	25	20	22	54
10	354	50	40	45	112
15	531	65	60	62	154
20	708	95	75	85	212
25	885	120	95	107	266
30	1062	140	115	127	316
35	1238	165	135	150	374
40	1415	190	155	172	429
45	1592	210	175	192	478
50	1769	245	190	220	548
55	1946	260	210	235	585
60	2123	290	235	263	654
65	2300	320	260	290	723
70	2477	345	285	315	784
75	2654	380	310	345	859
80	2831	415	335	375	934
85	3008	445	360	402	1000
90	3185	475	385	430	1070
95	3362				
100	3539				
105	3715				
110	3892				
115	4069				
120	4246				

TEST SERIES B

CYLINDER NO. SB4

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	20	20	20	50
10	354	40	40	40	100
15	531	50	60	55	137
20	708	75	75	75	187
25	885	100	95	97	241
30	1062	125	125	125	311
35	1238	135	140	137	341
40	1415	155	150	152	379
45	1592	175	165	170	424
50	1769	195	185	190	473
55	1946	220	205	212	528
60	2123	235	230	232	578
65	2300	265	245	255	635
70	2477	285	265	275	684
75	2654	295	285	290	722
80	2831	330	305	317	790
85	3008	345	330	337	840
90	3185	370	355	362	903
95	3362	400	370	385	960
100	3539	430	405	417	1035
105	3715				
110	3892				
115	4069				
120	4246				

TEST SERIES B

CYLINDER NO. SB9

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	25	20	22	55
10	354	55	35	45	112
15	531	75	55	65	162
20	708	100	70	85	212
25	885	120	95	107	266
30	1062	145	115	130	324
35	1238	165	130	147	367
40	1415	190	150	170	424
45	1592	215	170	192	478
50	1769	245	195	220	548
55	1946	260	210	235	585
60	2123	300	240	270	672
65	2300	325	265	295	735
70	2477	355	295	325	810
75	2654	385	320	352	878
80	2831	425	355	390	970
85	3008	460	385	422	1050
90	3185	510	440	475	1180
95	3362				
100	3539				
105	3715				
110	3892				
115	4069				
120	4246				

TEST SERIES B

CYLINDER NO. SB10

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	25	15	20	50
10	354	50	30	40	100
15	531	80	45	63	157
20	708	100	55	78	194
25	885	130	70	100	249
30	1062	150	80	115	286
35	1238	175	95	135	336
40	1415	200	105	153	382
45	1592	220	120	170	424
50	1769	245	135	190	474
55	1946	260	150	205	510
60	2123	300	165	233	580
65	2300	325	180	253	630
70	2477	345	195	270	672
75	2654	360	210	285	710
80	2831	395	225	310	770
85	3008	415	240	328	817
90	3185	445	250	348	866
95	3362	475	265	370	921
100	3539				
105	3715				
110	3892				
115	4069				
120	4246				

TEST SERIES B

CYLINDER NO. SB10

Total Compressive Load (Kips)	Stress (psi)	Electrical Total Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})		
		Gauge #1	Gauge #2	Average
0	0	0	0	0
5	177	30	45	38
10	354	60	90	75
15	531	87	127	107
20	708	118	176	147
25	885	140	217	179
30	1062	176	262	219
35	1238	207	312	259
40	1415	228	340	284
45	1592	260	393	326
50	1769	292	440	366
55	1946	323	495	409
60	2123	360	548	454
65	2300	390	600	495
70	2477	420	644	532
75	2654	458	698	578
80	2831	492	742	617
85	3008			
90	3185			
95	3362			
100	3539			
105	3715			
110	3892			
115	4069			
120	4246			

TEST SERIES B

CYLINDER NO. SC1

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	35	20	27	67
10	354	70	40	55	137
15	531	105	55	80	199
20	708	140	75	107	266
25	885	175	95	135	337
30	1062	210	115	162	404
35	1238	255	135	195	485
40	1415	285	155	220	549
45	1592	335	175	255	635
50	1769	415	205	310	773
55	1946	600	240	420	1045
60	2123				
65	2300				
70	2477				
75	2654				
80	2831				
85	3008				
90	3185				
95	3362				
100	3539				
105	3715				
110	3892				
115	4069				
120	4246				

TEST SERIES B

CYLINDER NO. SC4

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	20	30	25	62
10	354	40	60	50	124
15	531	50	80	65	162
20	708	60	100	80	199
25	885	80	130	105	262
30	1062	105	160	132	329
35	1238	130	210	170	423
40	1415	145	235	190	472
45	1592	175	270	227	564
50	1769	215	310	262	652
55	1946				
60	2123				
65	2300				
70	2477				
75	2654				
80	2831				
85	3008				
90	3185				
95	3362				
100	3539				
105	3715				
110	3892				
115	4069				
120	4246				

TEST SERIES B

CYLINDER NO. SC9

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	30	25	28	70
10	354	60	50	55	137
15	531	90	75	83	207
20	708	120	100	110	274
25	885	145	120	133	332
30	1062	180	145	163	406
35	1238	215	165	190	474
40	1415	260	190	225	560
45	1592	285	220	253	630
50	1769	345	255	300	748
55	1946	420	295	358	892
60	2123				
65	2300				
70	2477				
75	2654				
80	2831				
85	3008				
90	3185				
95	3362				
100	3539				
105	3715				
110	3892				
115	4069				
120	4246				

TEST SERIES B

CYLINDER NO. SC10

Total Compressive Load (Kips)	Stress (psi)	Mechanical Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})			Total Strain Avg. Rdg. x Avg. G.F. (in./in. x 10^{-6})
		Gauge #1	Gauge #2	Average	
0	0	0	0	0	0
5	177	25	25	25	62
10	354	55	45	50	125
15	531	80	60	70	174
20	708	90	90	90	224
25	885	115	110	113	282
30	1062	130	130	130	324
35	1238	155	175	165	412
40	1415	180	205	193	480
45	1592	210	225	218	543
50	1769	225	255	240	599
55	1946				
60	2123				
65	2300				
70	2477				
75	2654				
80	2831				
85	3008				
90	3185				
95	3362				
100	3539				
105	3715				
110	3892				
115	4069				
120	4246				

TEST SERIES B

CYLINDER NO. SC10

Total Compressive Load (Kips)	Stress (psi)	Electrical Total Strain Gauge Rdgs. (Adj. for Zero Load = Zero Strain) (in./in. x 10^{-6})		
		Gauge #1	Gauge #2	Average
0	0	0	0	0
5	177	60	50	55
10	354	120	100	110
15	531	181	138	159
20	708	238	179	209
25	885	288	227	258
30	1062	350	285	317
35	1238	409	341	375
40	1415	476	395	435
45	1592	550	455	503
50	1769	620	512	566
55	1946	708	573	640
60	2123	810	650	730
65	2300			
70	2477			
75	2654			
80	2831			
85	3008			
90	3185			
95	3362			
100	3539			
105	3715			
110	3892			
115	4069			
120	4246			