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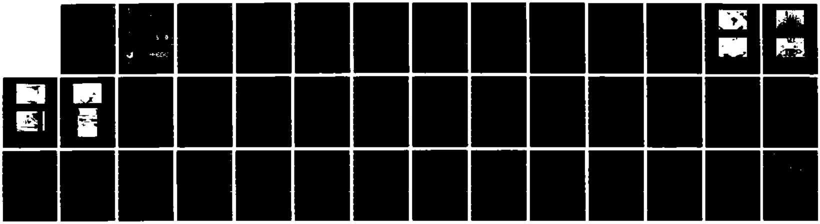

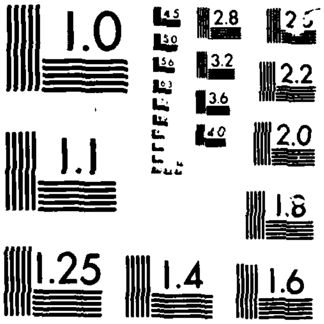

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ESL-TR-85-55

Feasibility of Producing Large–Sized, High–Strength Mortar & Concrete Cubes

W. B. LEDBETTER TEXAS A&M UNIVERSITY
MATTI RELIS CIVIL ENGINEERING DEPARTMENT
ROBERT DENSON COLLEGE STATION, TX 77843-3136

FINAL REPORT

JANUARY 1986

MAY 1984-AUGUST 1985

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This study was conducted to demonstrate the feasibility of producing relatively large mortar and concrete products (12-inch or 30 cm cubes) which possess ultrahigh strengths as a result of high-pressure compaction at pressures up to 16,000 psi (110 Mpa). Mortar and concrete cubes, possessing very high compressive strengths at very early ages, were produced, with high-pressure compaction. Mortar strengths in excess of 9,000 psi (60 Mpa) were produced at 1 day of age, although the mix designs were not optimized. The strengths continued to increase, although slowly, with continued curing.

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PREFACE

This report was prepared by the Civil Engineering Division, Texas Engineering Experiment Station, Texas A&M University System, College Station, Texas 77843-3136, and the Concrete Division, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, 39180, under Contract Number FO 8635-84-K-0053 for the Air Force Engineering and Services Center, Engineering and Services Laboratory (HQ AFESC/RD), Tyndall Air Force Base, Florida.

This report summarizes work done between May 1984 and August 1985, and discusses the feasibility of producing relatively large mortar and concrete products (12-inch or 30 cm cubes) which possess ultrahigh strengths as a result of high-pressure compaction at pressures up to 16,000 psi (110 MPA). The HQ AFESC/RDCS project officer was Thomas Hilferty, LCDR, CEC, USN.

This report has been reviewed by the public affairs office and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including Foreign Nationals.

This technical report has been reviewed and approved for publication.

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SECTION I

INTRODUCTION

A. STUDY OBJECTIVE

This study was conducted to demonstrate the feasibility of producing relatively large mortar and concrete products (12 inch or 30 cm cubes) which possess ultrahigh strengths as a result of high-pressure compaction at pressures up to 16,000 psi (110 Mpa).

B. BACKGROUND

In recent decades, the construction industry has placed increased reliance on concrete which develops compressive strengths on 10,000 to 12,000 psi (70 to 80 MPa) in relatively short times. The consistent production and usage of concrete with strengths significantly greater than this remains, however, more difficult to achieve. According to current practices and theory, for specialized uses, portland cement concrete material with strengths approaching 20,000 psi (140 MPa) may be produced by reducing the amount of porosity present in the microstructure of the paste-matrix material. To accomplish this, high-pressure compaction prior to hydration has provided excellent results. Reference 1, which is an early report on this same study, contains an extensive background of the state of the art in developing ultra-high-strength cements, mortars and concretes, and is not repeated here. This same reference also describes the research program which demonstrated that strengths in excess of 72,000 psi (500 MPa) can be achieved on 1 cm^3 cement compacts using an innovative die design which allows release of the compaction pressure without damaging the compact. (Reference 1).

The results of the literature survey and laboratory program reported in Reference 1 indicate that ultrahigh strengths can be achieved easily with small, 1 cm^3 cement compacts. No one has shown that ultrahigh strengths could be obtained with larger mortar and concrete products up to 12 inches (30 cm) in size. As sizes such as this are much more useful, it was necessary to explore methods to achieve ultrahigh strengths on large specimens of mortar and concrete.

C. SCOPE

This report describes (1) the construction of a die system capable of producing up to 12 inch (30 cm) cubes of mortars and concretes with compaction pressures of above 16,000 psi (110 Mpa) and (2) a feasibility evaluation of the die system to produce selected high-strength mortar and concrete cubes using the Corps of Engineers 2.4 million pound (1.1 million kgm) press at the Waterways Experiment Station in Vicksburg, Mississippi.

This is a followup to a previous report on this project titled "Properties of Miniature Cement - Fly Ash Compact Prepared by High-Pressure Compaction." (Reference 1)

SECTION II

DIE CONSTRUCTION

The design of the die system followed that given in the earlier report on this study (Reference 1) except that the size was scaled up to produce specimens 12 inches (30 cm) cubed and the design was optimized to use less costly materials whenever possible. Figures 1 through 8 depict photographs of the completed die assembly and loading ram. The die faces and loading ram face in contact with the specimen were constructed, utilizing AISI A-2 tool steel, which was case-hardened and highly polished, while the remainder of the die system used less expensive steels such as ASTM A514 and ASTM A108. The rods holding the assembly were made of ASTM 4340 steel. Tolerances of less than .001 inch (.03 mm) were maintained throughout.

The mortar and concrete mixtures were not optimized because of the high-compaction pressures involved. The ingredients included Types I and III portland cement, a commercially available Type C fly ash, and commercially available fine and coarse aggregates. A total of 12 specimens were produced, cured and tested with these ingredients. Two additional specimens were produced with steel fibers to see what compaction problems would result if steel fibers were introduced.

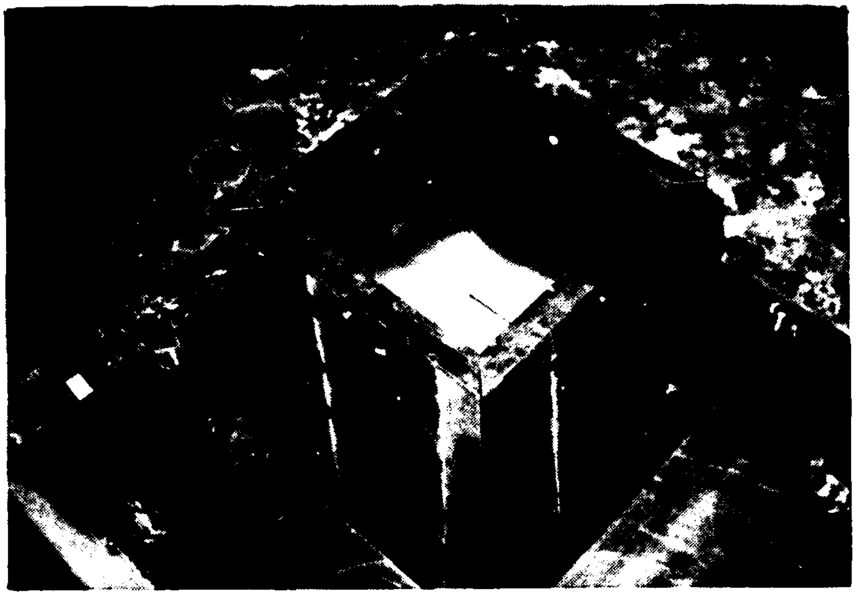

Figure 1. Die Faces on Baseplate.

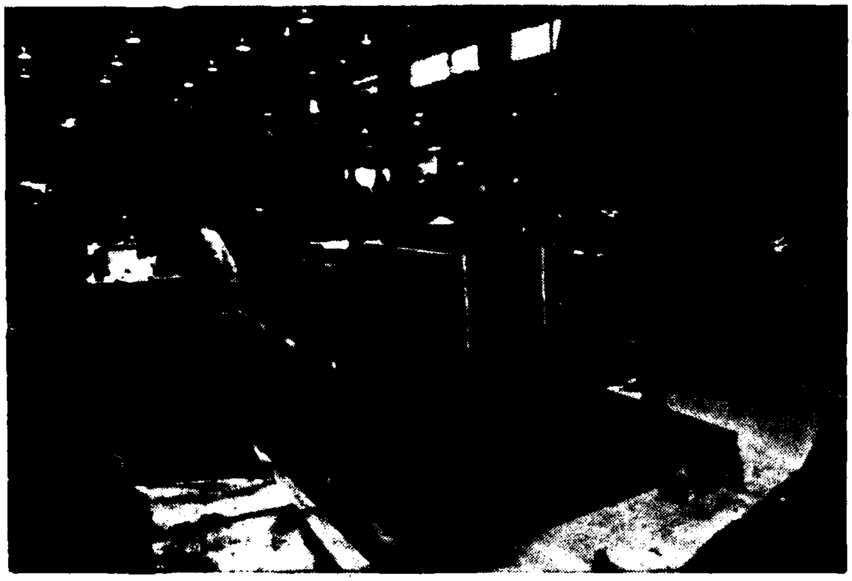

Figure 2. Die Faces and Hold-Down Bolts on Baseplates.

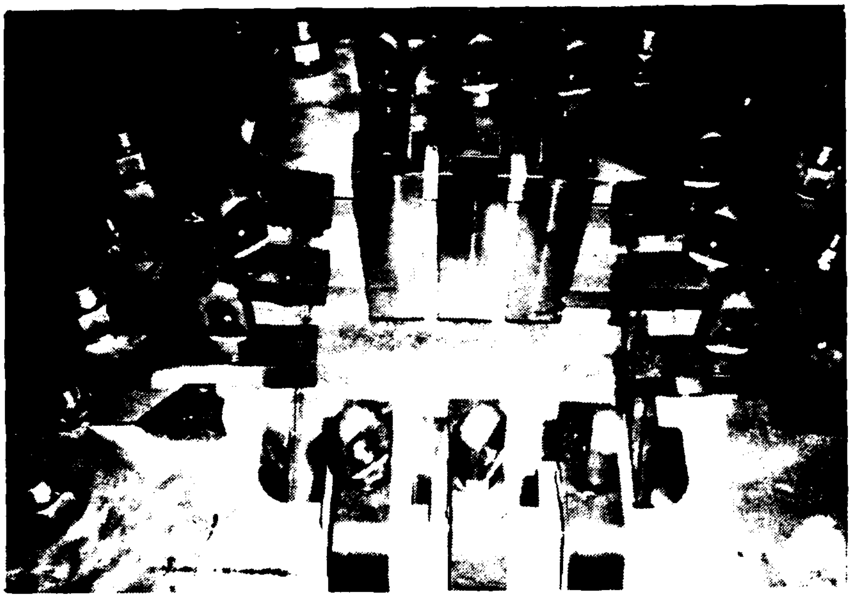

Figure 3. Restraining Assembly Without Die Faces.

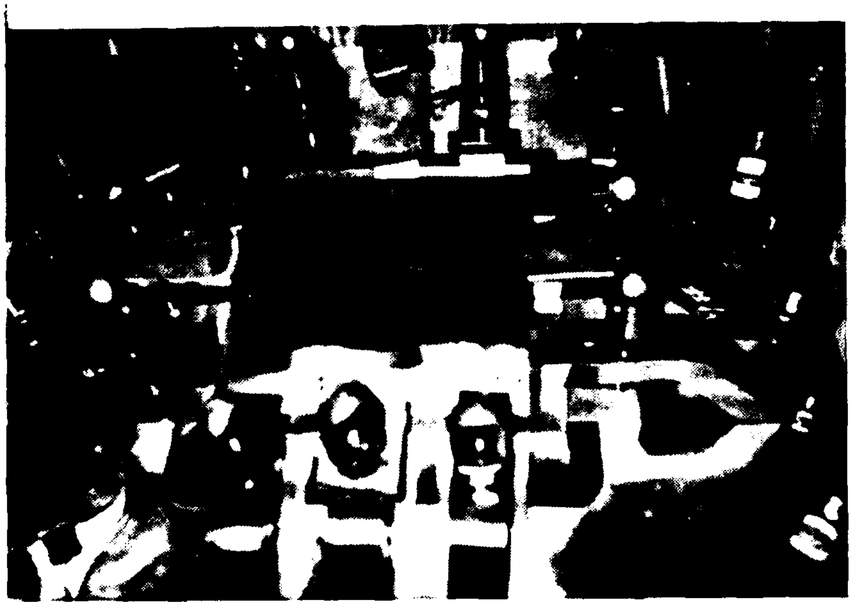

Figure 4. Restraining Assembly and Die Faces.

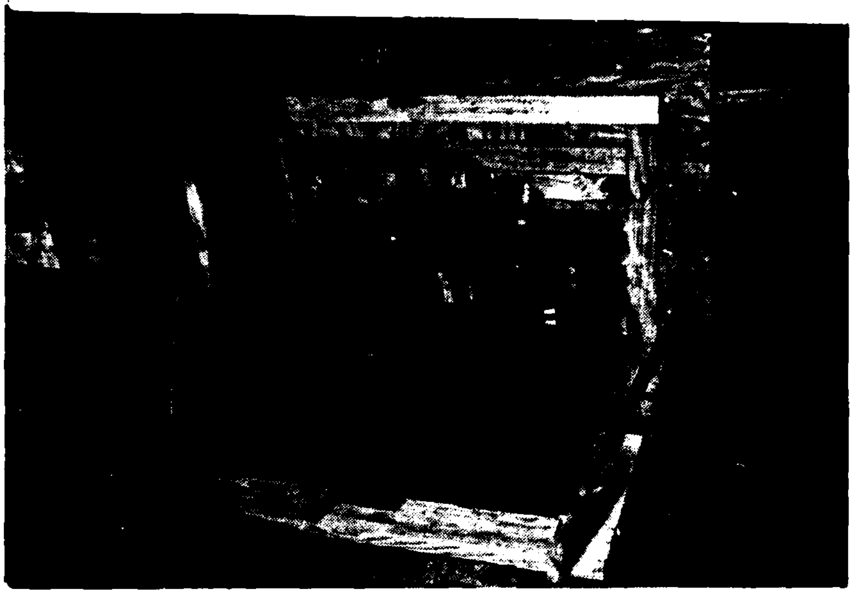

Figure 5. Restraining Assembly and Die Faces.

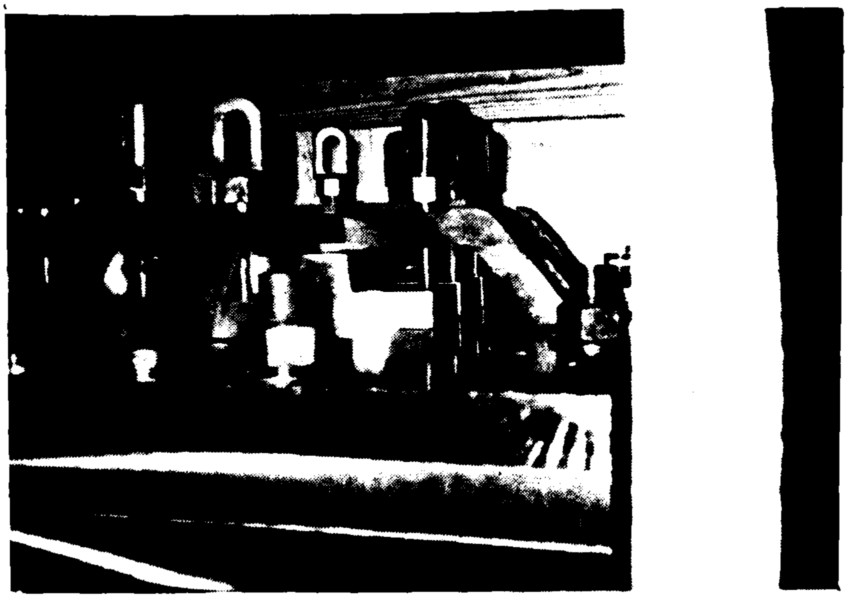

Figure 6. Closeup of Release Mechanism.

Figure 7. Die Plunger.

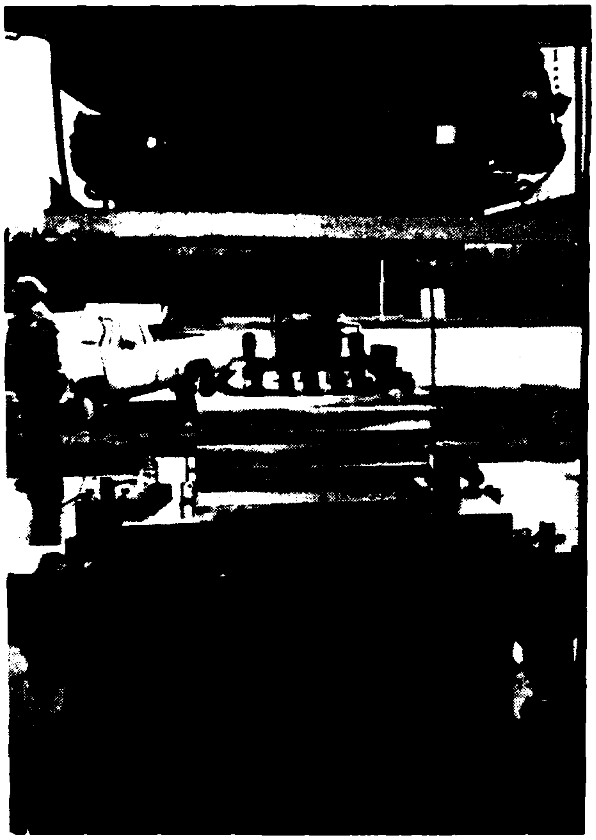

Figure 8. Complete Die System Being Loaded.

SECTION III

LABORATORY PROGRAM

A. MATERIALS AND MIXTURES

The materials used in this investigation were all obtained from commercial sources. Relevant properties are given in Appendix A. Type I and Type III portland cements meeting the requirements of ASTM C150 were obtained from the Midlothian, Texas Cement Plant, of Texas Industries, Inc. A Class C fly ash, meeting the requirements of ASTM C618 was obtained from Gifford-Hill & Company, Dallas, Texas (from the Welch Power Plant at Cason, Texas). Fine aggregate of pure silica sand, meeting the requirements of ASTM C33 was obtained from the Colorado Silica Sand Corporation, Colorado Springs, Colorado. The coarse aggregate used was a trap rock (1/2-inch or 13 mm top size) obtained from Lone Star Industries, Montvale, New Jersey. Three-quarter inch (20 mm) long steel fibers, used in two mixes, were obtained from the Fibercon Company, Pittsburgh, Pennsylvania. No other additives or admixtures were used.

The mix designs for the mortar and concrete cubes are summarized in Table 1. All mixes were designed to be approximately 12 inches (30 cm) cubed when high-pressure compacted. Four mortar cubes (labeled M in the mix numbers) and 10 concrete cubes (labeled C in the mix numbers) were prepared. Two of the concrete cubes had steel fibers added (labeled F in the mix numbers).

B. EXPERIMENTAL DESIGN

All experiments were conducted at the Structures Laboratory of the Corps of Engineers, Waterways Experiment Station (WES), Vicksburg, Mississippi. Each mixture was prepared in a standard 3 ft^3 (0.08 m^3) revolving-drum concrete mixer. The mixtures were all very stiff (almost zero slump). But, when they were high-pressure compacted, water was ejected through the die system. Following mixing, the mixtures were placed in the die, vibrated, and statically compacted by increasing the pressure to 2.4 million pounds (1.1 million kg), as fast as the press could be safely loaded (in about 5 minutes). The maximum loading was maintained for about 1 minute and then released as fast as possible. The die was then dismantled and a sound, highly compacted, relatively large cube was produced (12 inches or 30 cm cubed). This was a major result of this program because the largest previously reported specimens had been cylinders about 1 cm in diameter. (Reference 2)

A slightly different procedure was followed on four concrete cubes (those marked with an L in the mix numbers in Table 1).

TABLE 1. MORTAR AND CONCRETE CUBE MIXES (APPROXIMATELY 12 INCHES (30 CM) CUBED - EACH (.028 M^3) WHEN HIGHLY COMPACTED)

Mix No.[a]	Cement (lb)		Fly Ash (lb)	Fine Agg. (lb)	Coarse Agg. (lb)	Water (lb)	Remarks
	Type 1	Type 3					
Mortar							
1 (M1R)	74.3			49.5		18.6	
2 (M1A)	74.3			49.5		18.6	
3 (M2R)		74.3		49.5		18.6	
4 (M2A)		74.3		49.5		18.6	
Concrete							
5 (C1R)	48.8			29.1	58.1	14.6	
6 (C1A)	48.8			29.1	58.1	14.6	
7 (C2R)		48.8		29.1	58.1	14.6	
8 (C2A)		48.8		29.1	58.1	14.6	
9 (C2LR)		48.8		29.1	58.1	14.6	
10 (C2LA)		48.8		29.1	58.1	14.6	
11 (C3R)		33.3	14.3	29.1	58.1	14.3	
12 (C4R)		48.8		29.1	58.1	16.1	excess water
Concrete with steel fibers							
13 (C4F1R)		48.8		29.1	58.1	16.1	1.0% fiber[b]
14 (C4F2R)		48.8		29.1	58.1	16.1	1.5% fiber

[a] R = Regular cure in saturated lime water @ 73°F (23°C) until testing.

A = Accelerated cure - 5 hours @ 140°F (60°C) followed by regular cure in saturated lime water @ 73°F (23°C) until testing.

[b] By volume

Note: 1 lb = 0.454 kg

One half of these mixes were mixed, placed and pressure-compacted. Then the second half of each mix was mixed and placed, and the entire cube was compacted. This was to create two-layered cubes to observe the effects of this procedure on the completed specimens.

Two curing conditions were employed. As shown in Table 1, those specimens with an R in their mix numbers were placed in saturated lime water at room temperature (77 F or 25 C) and tested at periodic intervals. Those specimens with an A in their mix numbers were placed in a hot water bath at 140 F (60 C) immediately after casting and kept there for 5 hours, then placed in saturated lime water at room temperature and tested at periodic intervals.

Two series of tests were performed on all specimens. Non-destructive compressional ultrasonic pulse velocities (ASTM C597) were periodically measured at seven locations on each cube (see Figure 9). The data from these measurements are given in Table 2 for the mortar cubes and in Table 3 for the concrete cubes. Also, two standard 2 1/8 inch (50 mm) diameter cores were cut from each cube at three different ages, with one core in the vertical direction (the direction of high-pressure compaction) and the other in the horizontal direction (see Figure 9). Upon removal, the cores were cut into three smaller cores and the following tests were performed on each:

specific gravity
compressional wave pulse velocity
Poisson's ratio
dynamic modulus of elasticity
compressive strength

The data from these measurements are given in Tables 4 (mortar) and 5 (concrete).

Because of the amount of work involved, the tests to be done when the specimens were at different ages. The intent was to obtain measurements at ages of about 3 days, 28 days, and 90 days, but some deviations occurred.

On those concrete specimens incorporating steel fibers, it was decided to change the experimental program to substitute a flexural test of prisms cut from the cubes when ages exceeded 90 days. Thus, some of the cores were omitted on these cubes and the flexural data, using ASTM C1018, are given in Table 6.

C. ANALYSIS OF RESULTS

First, no difficulty was experienced in the production of these large specimens. Every cube was totally intact, with extremely smooth surfaces, and contained no cracks or crazing from releasing the high compaction pressure. Second, the two-layered cubes appeared sound, with no discernible layer effect.

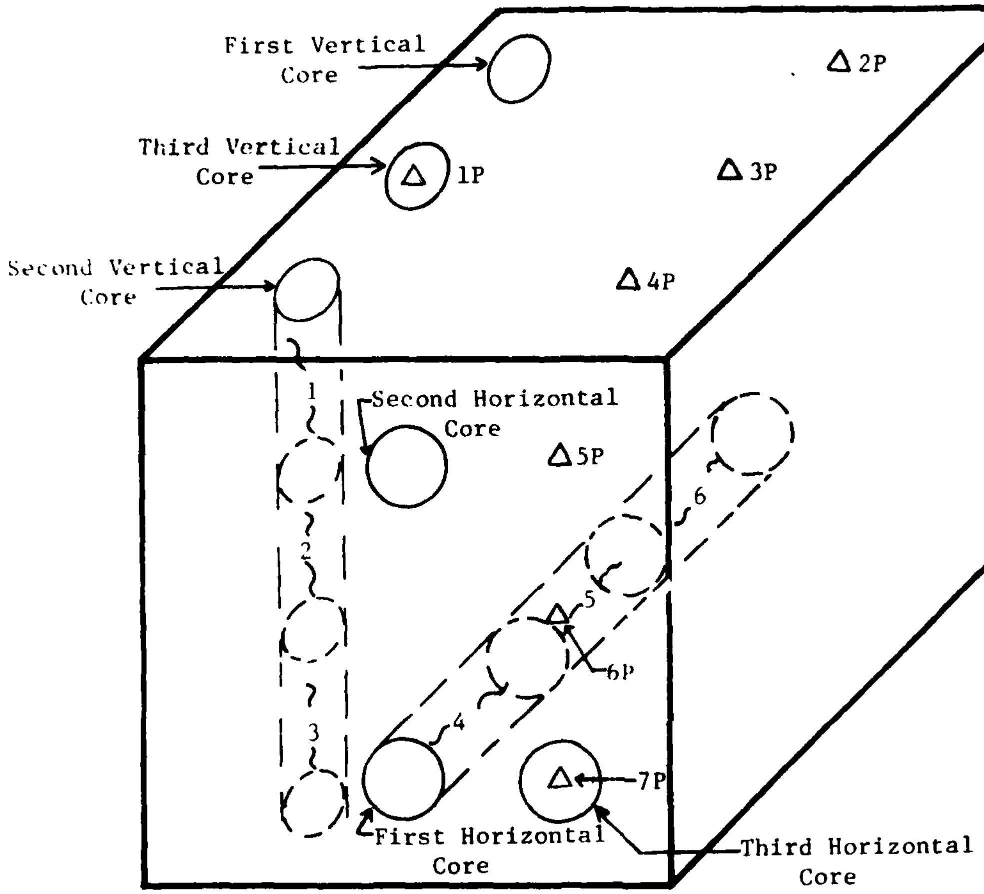

Figure 9. Isometric View of Block Showing Location of Cores and Pulse Velocities

Note: Two cores taken at each of three ages. Seven pulse velocities taken at several different ages.

Δ 1P - pulse velocity location 1

1 - core cylinder 1

TABLE 2. PULSE VELOCITY DATA FOR MORTAR CUBES (FT/S)

MIX	AGE (d)	V1	V2	V3	V4	V5	V6	V7	AVGV
4	3	14320	14120	13560	14120	15730	15730	15980	14794
4	30	15400	15400	15170	15170	16500	16500	16500	15806
4	99	15450	15130	14650	15020	16290	16480	16610	15661
2	1	15050	14840	15480	14840	16240	16500	16240	15599
2	3	15480	15950	15950	15710	16780	17360	17060	16327
2	30	15950	15950	16190	15950	17060	16780	17060	16420
2	100	16040	15730	15900	15970	16700	16830	16640	16259
1	1	14770	14770	14770	14770	16500	15980	15980	15363
1	3	14770	14770	14510	14030	15490	15730	15730	15004
1	28	15880	15880	15880	16190	17060	16780	16780	16350
1	88	16160	15850	15800	15900	17240	16890	16800	16377
3	1	14780	15000	15000	14780	16240	15980	15980	15394
3	2	15230	15710	15230	15470	16780	15980	15980	15769
3	37	15230	15230	15230	15710	16240	16240	16240	15731
3	87	15280	15490	15370	15660	16690	16450	16610	15936

1 ft/s = 0.309 m/s

TABLE 3. PULSE VELOCITY DATA FOR CONCRETE CUBES (FT/S)

MIX	AGE	V1	V2	V3	V4	V5	V6	V7	AVGV
5	3	14830	14830	14400	14830	15030	15030	15250	14886
5	32	16260	15760	15760	16010	16780	16780	17060	16344
5	91	16450	15580	15580	15830	16320	16160	16190	16016
6	3	14820	14820	14610	15020	15980	15730	16240	15317
6	32	16410	16670	16670	16670	17060	17060	17360	16843
6	91	16930	17040	16850	17200	17070	16620	16700	16916
7	3	14660	14270	14270	14660	16240	16240	16240	15226
7	31	16230	15520	15300	15750	16780	16500	16500	16083
7	90	15960	15540	15700	15910	16980	16450	16650	16170
8	1	14100	14870	13750	14290	14800	14380	14590	14397
8	3	14290	14870	14670	14670	15250	15730	15490	14996
8	31	15450	15490	15490	15490	16240	16240	16500	15843
8	100	16300	15800	15780	16470	17000	16580	16670	16371
11	3	13990	13990	13180	13990	15250	14590	14380	14196
11	28	15950	15410	15410	15410	16500	16240	16240	15880
11	91	16530	16240	16240	16350	16890	16560	16750	16509
12	3	14090	15010	14540	14310	15490	15250	15730	14917
12	28	16070	15010	15260	15010	16240	15980	16240	15687
12	91	15980	16010	15740	15950	16610	16610	16690	16227
9	3	14670	14850	14490	14490	15980	15980	16240	15243
9	31	16300	15640	15640	15640	16780	17060	17060	16303
9	90	16620	16430	16430	16390	17220	17100	17010	16743
10	1	9640	10150	14060	14060	15030	15030	15250	13317
10	3	13570	13890	13730	13730	14800	15250	14800	14253
10	31	15560	15150	15150	15350	15980	16240	15980	15630
10	100	15870	15810	15470	16030	16130	16830	15850	15999
13	3	14170	14170	13980	14170	15250	15250	15490	14640
13	27	15860	15180	15180	15630	15730	16240	16240	15723
13	90	15950	15670	15240	15290	16320	15680	15930	15726
14	3	13870	14460	14060	14460	15250	15250	15250	14657
14	27	15120	15580	14890	15340	15980	15980	15730	15553
14	90	15050	14910	14930	14820	15930	15700	15540	15269

1 ft/s = 0.309 m/s

TABLE 4. CORE DATA FROM MORTAR CUBES

MIX	AGE (d)	LOC	SG	CV	PR	E	STR
1	5	1	2.61	14570	0.10	7.29	15960
1	5	1	2.60	15030	0.12	7.64	14800
1	5	1	2.58	15010	0.18	7.20	14000
1	5	1	2.59	15780	0.14	8.30	16210
1	5	1	2.60	15420	0.14	7.93	15220
1	5	1	2.60	15410	0.10	8.16	9400
1	28	2	2.58	14860	0.11	7.46	19580
1	28	2	2.58	14800	0.12	7.34	21070
1	28	2	2.57	14720	0.14	7.14	18140
1	28	2	2.58	15600	0.15	8.00	22570
1	28	2	2.57	15610	0.17	7.85	19860
1	28	2	2.58	15390	0.15	7.81	21330
1	122	3	2.62	14920	0.10	7.68	10630
1	122	3	2.62	14290	0.05	7.18	8030
1	122	3	2.61	14560	0.13	7.18	11880
1	122	3	2.61	15940	0.06	8.88	14900
1	122	3	2.63	15770	0.09	8.65	16660
1	122	3	2.63	15390	0.15	7.97	16500
2	8	1	2.60	15580	0.09	8.34	20800
2	8	1	2.59	15110	0.13	7.62	18500
2	8	1	2.59	14630	0.10	7.32	10000
2	8	1	2.57	15700	0.17	7.97	--
2	8	1	2.57	15700	0.15	8.06	18000
2	8	1	2.59	16150	0.20	8.24	20900
2	39	2	2.61	14810	0.11	7.48	15690
2	39	2	2.61	14680	0.07	7.49	13870
2	39	2	2.59	15510	0.16	7.87	15000
2	39	2	2.61	15810	0.20	7.95	11930
2	39	2	2.62	15860	0.15	8.40	19020
2	39	2	2.62	15950	0.16	8.44	19690
2	116	3	2.63	15480	0.11	8.26	9700
2	116	3	2.62	15460	0.10	8.27	14600
2	116	3	2.62	15250	0.11	8.00	8710
2	116	3	2.64	15040	0.13	7.75	8760
2	116	3	2.63	15110	0.11	7.88	12100
2	116	3	2.62	14890	0.12	7.58	18180
3	4	1	2.55	15290	0.23	6.91	10300
3	4	1	2.56	15920	0.25	7.30	17360
3	4	1	2.55	15740	0.25	7.15	--
3	4	1	2.56	16940	0.28	7.74	7600
3	4	1	2.56	17080	0.31	7.30	14720
3	4	1	2.55	16890	0.30	7.21	9920
3	42	2	2.57	14510	0.13	7.03	12100
3	42	2	2.57	15090	0.17	7.34	17260
3	42	2	2.57	14840	0.11	7.40	15760
3	42	2	2.57	15700	0.12	8.27	10190
3	42	2	2.58	15750	0.20	7.81	7330
3	42	2	2.58	15890	0.18	8.07	9080
3	121	3	2.59	14810	0.17	7.10	10020
3	121	3	2.59	12400	0.17	5.01	6890

TABLE 4. CORE DATA FROM MORTAR CUBES (CONCLUDED)

MIX	AGE (d)	LOC	SG	CV	PR	E	STR
3	121	3	2.58	15000	0.14	7.45	10020
3	121	3	2.58	15900	0.23	7.55	4500
3	121	3	2.59	15880	0.18	8.06	4690
3	121	3	2.59	15480	0.18	7.66	7120
3	149	3	2.57	15040	0.15	7.80	21260[a]
3	149	3	2.58	14900	0.16	7.25	22230[a]
3	149	3	2.58	15240	0.20	7.28	21090[a]
4	7	1	2.58	14420	0.08	7.11	13660
4	7	1	2.56	14240	0.18	6.46	16820
4	7	1	2.57	14800	0.13	7.28	19800
4	7	1	2.53	16110	0.15	8.40	13360
4	7	1	2.53	15610	0.13	7.99	11800
4	7	1	2.53	15500	0.27	6.55	11270
4	34	2	2.58	14460	0.08	7.15	10510
4	34	2	2.59	14540	0.08	7.27	15130
4	34	2	2.58	14820	0.15	7.22	16240
4	34	2	2.58	15660	0.14	8.15	20540
4	34	2	2.56	15620	0.12	8.14	14490
4	34	2	2.58	15660	0.18	7.84	15920
4	123	3	2.62	14100	0.10	6.87	9930
4	123	3	2.60	13960	0.06	6.78	9760
4	123	3	2.59	14840	0.12	7.42	9110
4	123	3	2.59	14670	0.15	7.09	18400
4	123	3	2.60	15690	0.14	8.24	16160
4	123	3	2.60	15040	0.15	7.49	17390

[a] = Ends lapped before testing

LOC = Core location (see Fig. 9)
SG = Specific Gravity
CV = Pulse Velocity in ft/s ft/s = 0.309 m/s)
PR = Poisson's Ratio
E = Dynamic modulus of elasticity in psi (1 psi = 0.006895 MPa)
STR = Compressive Strength in psi (1 psi = 0.006895 MPa)

TABLE 5. CORE DATA FROM CONCRETE CUBES

MIX	AGE (d)	LOC	SG	CV	PR	E	STR
5	4	1	2.71	14980	0.17	7.64	0
5	4	2	2.70	15590	0.18	8.17	11090
5	4	3	2.71	15380	0.19	7.90	11240
5	4	4	2.69	15740	0.19	8.19	11600
5	4	5	2.70	15780	0.20	8.18	10970
5	4	6	2.69	15670	0.20	8.02	12352
5	42	1	2.72	15460	0.16	8.21	10460
5	42	2	2.72	15600	0.14	8.48	10180
5	42	3	2.72	15500	0.17	8.23	10700
5	42	4	2.72	16420	0.21	8.82	10760
5	42	6	2.72	15860	0.14	8.82	6470
5	123	1	2.70	15480	0.06	8.65	8750
5	123	2	2.70	15420	0.09	8.50	8840
5	123	4	2.69	15420	0.09	8.48	7540
5	123	5	2.70	16130	0.17	8.85	9870
5	123	6	2.71	14790	0.16	7.48	12030
6	3	1	2.70	15010	0.17	7.62	9790
6	3	2	2.70	15190	0.16	7.91	9060
6	3	3	2.69	14920	0.14	7.71	9820
6	3	4	2.72	15040	0.26	6.82	9700
6	3	5	2.71	16090	0.25	7.81	12440
6	3	6	2.71	15170	0.27	6.75	10735
6	42	1	2.70	15320	0.15	8.09	4472
6	43	2	2.72	15800	0.16	8.61	10520
6	43	3	2.71	15580	0.14	8.49	8510
6	43	4	2.71	15830	0.15	8.69	9840
6	43	5	2.71	16160	0.20	8.58	12760
6	43	6	2.71	15590	0.15	8.39	10820
6	120	1	2.70	15540	0.01	8.79	4260
6	120	2	2.72	14880	0.00	8.07	7990
6	120	3	2.69	15170	0.11	8.12	7730
6	120	4	2.73	15530	0.18	8.21	9190
6	120	5	2.70	15160	0.16	7.88	8610
6	120	6	2.31	15090	0.23	6.08	8410
6	146	1	2.70	15300	0.07	8.44	11410[a]
6	146	3	2.69	15700	0.07	8.86	11520[a]
7	4	1	2.71	14440	0.18	7.01	8470
7	4	2	2.69	14200	0.08	7.23	7060
7	4	3	2.68	14580	0.18	7.10	8470
7	4	4	2.69	15160	0.14	7.93	10590
7	4	5	2.69	15240	0.13	8.09	10410
7	4	6	2.68	15430	0.11	8.35	10650
7	39	1	2.72	14810	0.16	7.57	7340
7	39	2	2.72	14900	0.12	7.88	9170
7	39	3	2.71	15140	0.13	8.07	8990
7	39	4	2.69	15750	0.16	8.47	11040
7	39	5	2.71	15710	0.19	8.16	9080
7	39	6	2.69	15200	0.18	7.76	7670
7	122	1	2.69	14350	0.13	7.17	7390
7	122	2	2.68	14500	0.05	7.56	9830

TABLE 5. CORE DATA FROM CONCRETE CUBES (CONTINUED)

MIX	AGE (d)	LOC	SG	CV	PR	E	STR
7	122	3	2.68	14630	0.12	7.48	11820
7	122	4	2.70	15730	0.14	8.59	9180
7	122	5	2.68	15400	0.17	7.99	6150
7	122	6	2.68	15340	0.18	7.83	8130
8	4	1	2.68	15050	0.15	7.73	7290
8	4	2	2.67	15220	0.21	7.42	--
8	4	3	2.67	15930	0.19	8.27	9510
8	4	4	2.69	15760	0.21	8.01	8340
8	4	5	2.66	15490	0.21	7.68	9940
8	4	6	2.68	15050	0.17	7.63	8910
8	37	1	2.65	14870	0.14	7.52	5570
8	37	2	2.68	15440	0.16	8.09	7320
8	37	3	2.68	15010	0.15	7.69	7640
8	37	2	2.71	16100	0.21	8.45	10340
8	37	2	2.69	15570	0.18	8.13	8960
8	37	2	2.71	16030	0.22	8.28	8590
8	117	1	2.70	14960	0.14	7.74	7480
8	117	2	2.71	14460	0.11	7.44	12320
8	117	3	2.71	15290	0.15	8.11	7320
8	117	4	2.71	14960	0.16	7.66	8620
8	117	5	2.71	15430	0.16	8.17	11600
8	117	6	2.72	15130	0.16	7.87	10500
9	5	1	2.69	14760	0.03	7.87	8530
9	5	3	2.69	14890	0.18	7.44	8590
9	4	4	2.69	15240	0.23	7.29	6940
9	4	5	2.69	14880	0.21	7.18	8940
9	4	6	2.68	13260	0.11	6.18	--
9	28	1	2.68	14820	0.14	7.55	7480
9	28	3	2.66	14820	0.15	7.48	8280
9	42	4	2.66	15480	0.17	7.99	9080
9	42	5	2.65	14850	0.16	7.43	9170
9	42	6	2.68	15690	0.18	8.21	9780
9	119	1	2.69	15230	0.05	8.37	8850
9	119	3	2.69	14960	0.06	8.03	8670
10	4	1	2.70	14250	0.25	6.21	7140
10	4	3	2.70	11800	0.02	5.03	--
10	4	4	2.70	15600	0.30	6.58	10110
10	4	5	2.69	14760	0.18	7.28	10310
10	4	6	2.69	14760	0.25	6.65	11000
10	35	1	2.67	14580	0.16	7.16	5890
10	35	3	2.69	15210	0.16	7.88	7640
10	35	4	2.65	15680	0.16	8.24	10350
10	35	5	2.65	15600	0.17	8.09	11620
10	35	6	2.66	15570	0.17	8.06	11470
10	120	1	2.70	14470	0.13	7.33	10500
10	120	3	2.70	14920	0.14	7.74	9830
11	5	3	2.59	14700	0.15	7.14	8760
11	5	2	2.58	14700	0.16	7.08	8180
11	5	3	2.58	15640	0.20	7.68	10320
11	5	4	2.58	15820	0.16	8.18	9590

TABLE 5. CORE DATA FROM CONCRETE CUBES (CONTINUED)

MIX	AGE (d)	LOC	SG	CV	PR	E	STR
11	5	5	2.58	15160	0.29	6.14	8820
11	5	6	2.59	15250	0.17	7.52	10600
11	28	1	2.64	15570	0.20	7.77	10630
11	28	2	2.65	15540	0.22	7.58	10130
11	28	3	2.64	15410	0.21	7.54	11270
11	28	4	2.65	15520	0.18	7.95	10320
11	28	5	2.66	14880	0.19	7.23	9050
11	28	6	2.67	16070	0.19	8.46	11120
11	127	1	2.67	15090	0.25	6.84	9740
11	127	2	2.66	14690	0.21	6.83	6540
11	127	3	2.67	14860	0.24	6.79	7600
11	127	4	2.69	15640	0.18	8.20	7830
11	127	5	2.68	16250	0.21	8.47	6710
11	127	6	2.69	15560	0.19	7.99	7150
12	4	1	2.67	14570	0.17	7.13	10770
12	4	2	2.63	14620	0.16	7.12	9110
12	4	3	2.63	14650	0.16	7.16	6720
12	4	4	2.62	14840	0.13	7.46	11110
12	4	5	2.61	14990	0.20	7.08	10890
12	4	6	2.64	14800	0.18	7.19	11150
12	28	1	2.68	15360	0.19	7.78	10410
12	28	2	2.69	15530	0.19	7.95	9170
12	28	3	2.68	15050	0.16	7.67	10700
12	28	4	2.69	15600	0.20	7.95	10480
12	28	5	2.65	15720	0.08	8.70	11720
12	28	6	2.68	15620	0.21	7.86	11050
12	127	1	2.70	15210	0.17	7.80	7820
12	127	2	2.71	14910	0.15	7.71	7930
12	127	3	2.69	15130	0.18	7.62	10850
12	127	4	2.70	15240	0.15	8.00	4960
12	127	5	2.72	15830	0.20	8.31	4430
12	127	6	2.71	15880	0.16	8.61	8420
13	4	1	2.73	13580	0.11	6.58	13240
13	4	2	2.71	13570	0.08	6.61	10760
13	4	3	2.73	14970	0.18	7.55	11010
13	4	4	2.73	14960	0.21	7.34	7700
13	4	5	2.73	14410	0.19	6.97	9520
13	4	6	2.73	14130	0.17	6.85	9900
13	99	1	2.72	14760	0.10	7.81	9720
13	99	2	2.75	14810	0.07	8.03	10950
13	99	3	2.72	13540	0.03	6.71	10580
13	99	4	2.73	14800	0.19	7.32	10540
13	99	5	2.74	15450	0.24	7.43	8500
13	99	6	2.72	15000	0.17	7.68	9930
14	5	1	2.78	14010	0.13	7.08	12160
14	5	2	2.78	14380	0.07	7.66	12000
14	5	3	2.78	14230	0.09	7.44	12350
14	5	4	2.76	15080	0.19	7.74	12160
14	5	5	2.76	14960	0.22	7.33	11110
14	5	6	2.75	14880	0.17	7.61	11240

TABLE 5. CORE DATA FROM CONCRETE CUBES (CONCLUDED)

MIX	AGE (d)	LOC	SG	CV	PR	E	STR
14	99	1	2.74	14290	0.15	7.14	10990
14	99	2	2.67	14090	0.16	6.70	10060
14	99	3	2.78	14440	0.08	7.72	10080
14	99	4	2.77	14550	0.12	7.64	10350
14	99	5	2.76	15280	0.18	8.03	8680
14	99	6	2.78	15080	0.10	8.34	9700
11	153	1	2.65	15380	0.19	7.71	10370
11	153	3	2.65	15570	0.20	7.78	11140
11	153	4	2.65	14440	0.15	7.04	10590
11	153	6	2.64	14170	0.10	6.98	10810
12	153	1	2.68	14410	0.10	7.33	12480
12	153	3	2.66	15000	0.15	7.61	10450
12	153	4	2.66	15510	0.19	7.86	12120
12	153	6	2.68	15790	0.18	8.32	13010

[a] = Ends lapped before testing

LOC = Core location (see Fig. 9)
SG = Specific Gravity
CV = Pulse Velocity in ft/s (1 ft/s = 0.309 m/s)
PR = Poisson's Ratio
E = Dynamic modulus of elasticity in psi (1 psi = 0.006895 MPa)
STR = Compressive Strength in psi (1 psi = 0.006895 MPa)

However, when cored in the vertical direction, a plane of weakness was discovered between the two layers, as all the cores broke along this plane. Third, the introduction of steel fibers did not damage the die nor the cubes. Finally, although very stiff mixtures were used, water was ejected from all mixes as they were compacted.

Compressional wave pulse velocities are an excellent means of determining the elastic properties of mortar and concrete (Reference 3). This means that the relative strength of the specimen can be reliably determined, as the velocity can be correlated with strength. Furthermore, pulse velocities can be used to indicate (1) whether the specimen is increasing in strength with time and (2) how uniform the strength of the specimen is - even if the strength itself cannot be reliably determined. With this in mind, an examination of Tables 2 and 3 reveal several important facts.

1. The pulse velocities were very high at very early ages (1-day values of over 14,000 ft/s or 4,300 m/s). This means very high strengths were achieved at very early ages.

2. The pulse velocities continued to increase with time, indicating that the specimens were continuing to gain in strength.

3. Although the strengths were increasing, the rate of increase with time was very low, suggesting that almost all of the strength was achieved very early (a further discussion of this point will be made later).

4. The pulse velocities from the seven positions in each cube were remarkably uniform, revealing that these large cubes were almost homogeneous in terms of their strengths. This is important because it demonstrates that uniformly high-strength mortar and concrete cubes can be produced in sizes up to at least 12 inches (0.3 meters) using this die system.

5. A comparison of the 1-day pulse velocities between the accelerated curing and the regular curing procedures indicate there no difference in the velocities (and hence strengths) as a result of accelerating the curing by the use of 140°F (60°C) water for 5 hours.

In examining the absolute values of the velocities in Tables 2 and 3, it would be wrong to conclude that because the velocities of the mortars and concretes were very similar their strengths would be similar. The relationship between velocity and strength is strongly influenced by the density and chemical makeup of the materials used, and both the densities and makeup of the mortars and concretes are significantly different.

Turning now to the core values, before examining Tables 4 and 5, it must be pointed out that the compressive strength values have almost no validity, because; (1) the core drill used at WES wobbled, resulting in nonstandard cores, (2) as the mortar and concrete cores possess very high strengths, the normal concrete preparation procedure of capping the ends would not yield correct values (the capping compound itself is too weak), forcing the personnel to grind and polish the ends of the cores before breaking, and (3) the technicians at WES did not lap the ends of most of the cores before breaking them, so that stress concentrations occurred which yielded not only variable results but undoubtedly low-strength results. Therefore, the measured strengths were less than the actual strengths of the mortars and concretes. After this problem was discovered, only a few additional cores could be drilled in a few of the cubes for correct testing. These additional results can be quickly identified in Tables 4 and 5 because their measured strengths were so much greater (see M2R at 149 days, C1A at 146 days, and C3R and C4R at 153 days). Measured mortar strengths of about 22,000 psi (150 Mpa) and concrete strengths of about 13,000 psi (90 Mpa) were achieved on the specimens whose ends were polished before testing. Keeping this in mind, an examination of Tables 4 and 5 indicates:

1. Specific gravities (densities) of the mortar cubes were significantly lower than the specific gravities of the concrete cubes (2.6 versus 2.7). This is expected because of the use of dense traprock coarse aggregate in the concrete cubes.

2. The measured strengths of the mortar cubes were significantly higher than the measured strengths of the concrete cubes. This also is expected. Since measured mortar strengths of about 22,000 psi (150 Mpa) were achieved, this indicates that actual mortar strengths well in excess of 22,000 psi (150 Mpa) were probably realized. The highest measured strength of a concrete specimen without steel fibers was about 13,000 psi (90 Mpa) so the actual strengths were probably significantly higher. Thus, when comparing strengths of normally compacted mortars and concretes with those achieved through the high-pressure compaction system employed, the findings demonstrate the feasibility of producing ultra-high-strength mortars and concrete, using this process.

3. The compressional-wave pulse velocities on the cores were very similar to the velocities taken on the entire cubes from which the cores were obtained.

4. The Poisson's ratios vary considerably, indicating that the method of measurement may not be accurate.

5. The dynamic moduli of elasticity are all high, indicating that high strength and relatively stiff mortars and concretes were produced.

6. Although there was considerable data scatter, no discernible difference in values would be attributed to either the type of cement or the curing imposed. The inclusion of fly ash as a partial replacement for the portland cement in the concrete cubes did not materially change their physical properties. Therefore, when analyzing the results, all the mortar cubes can be considered together and all the concrete cubes without steel fiber reinforcement can be considered together.

7. The last analysis concerns the steel fiber-reinforced concrete specimens. Pertinent data from these specimens are given in Table 6. Prisms numbered "1" from both cubes were taken from the top, while prisms numbered "2" were taken from the bottom of both cubes. The bottoms of the cubes exhibited significantly higher flexural strengths than the tops, which could mean that some fiber alignment might have been achieved in the lower portions of the cubes. All the measured flexural strengths are high, but not as high as one would expect, given the high compressive strength of the concrete, coupled with the presence of steel fibers. Furthermore, there appears to be little difference in strength from the two quantities of steel used. C4F1R had 1.0 percent steel, while C4F2R had 1.5 percent steel (by volume), which could mean that 1.0 percent fibers or less in this mix may have been the optimum amount. However, the results are not reliable because no replication was made and the mixes were not designed for the addition of fibers.

D. COMPARISON OF RESULTS BETWEEN THE LARGE DIE AND SMALL DIE

Although the strength values obtained in this investigation are highly suspect, it is still worthwhile to attempt to compare these results with those obtained in the first report on this project. (Reference 1) To make this comparison, several assumptions had to be made. They were:

1. Since compressional pulse velocities, specific gravities, and dynamic moduli of elasticity all generally increased with age, the actual strengths of the mortars and concretes must also have increased with age.

2. Compressional pulse velocity and compressive strengths are directly proportional to each other, with a constant depending upon the particular mix under investigation.

3. Since the measured strengths were always less than the actual strengths, it is reasonable to assume that the actual strength of any cylinder would be at least as high as the highest strength value of the three cylinders cut from the same core. Using this premise, the highest strength value can be compared with the median pulse velocities of the three cylinders cut from any one core. Furthermore, several of the highest measured strengths from any core were still more than 2000 psi (14 MPa) below the highest measured strengths at the earliest ages. Logically, these low strengths were the result of measurement errors and, thus, were removed from the data sets for these analyses.

4. Since the pulse velocities for the various mortar and concrete mixes did not vary as a function of cement type, curing procedure, or the presence of fly ash (in the concrete cubes), the mortar data could all be considered together and the concrete data could all be considered together (omitting only the steel fiber-reinforced concrete cube data).

Using these assumptions, linear regression analyses were run on the remaining core data for both the mortar and concrete cubes. The resulting equations, and correlation coefficients, were:

For mortar cylinders:

$$f'c = 2.494(V) - 20240 \qquad (1)$$

$$r = 0.38$$

For concrete cylinders:

$$f'c = 1.01(V) - 5113 \qquad (2)$$

$$r = 0.41$$

where: $f'c$ = predicted compressive strength (psi)
V = actual compressive wave pulse velocity (ft/s)

As you can see, the relationships do not exhibit strong correlations, but they do appear reasonable because strength increases with an increase in pulse velocity.

Continuing with the analysis, using the cube pulse velocities given in Tables 2 and 3 as better estimates of the cube properties as a function of age, the strength of each cube at each age for which measurements were taken was calculated using Equations (1) and (2). Predictive equations for compressive strength using the log age as the independent variable were then developed, using linear regression analyses.

The equations are:

For mortar:

$$f'c = 895(\log \text{age}) + 18201 \qquad (3)$$

$$r = 0.57$$

For concrete:

$$f'c = 1145(\log \text{age}) + 9234 \qquad (4)$$

$$r = 0.89$$

These two equations were developed from mortar and concrete cubes, subjected to compaction pressures of 16,700 psi (115 Mpa). We now can compare these results with the 1 cm^3 cement compacts prepared and evaluated in the first report on this project. (Reference 1) Very good predictive equations were developed using the 1 cm^3 compacts and the equation of interest in this analysis is:

$$f'c = -248.7(\text{FA}) + 5904.7(\log \text{age}) + 4552.8(\log \text{CP}) + 17329.9 \qquad (5)$$

$$r = 0.92$$

Using values of 0.0 for the percent fly ash (FA) and 16,700 psi for the compaction pressure (CP), Equation (5) becomes:

$$f'c = 5904.7(\log \text{age}) + 36555.1 \qquad (6)$$

Finally, using Equations (3), (4) and (6) for comparison, Fig. 10 results. This figure contains some very interesting information. The results indicate a linear relationship between compressive strength and the log of age, as would be expected. The highest strengths were produced with pure cement compacts, while the lowest strengths were produced with concrete. But, of perhaps greatest interest is the fact that the most of the strengths are achieved at very early ages. One-day pulse values were measured on the mortar and concrete cubes, which have been translated into the expected strength at 1 day. How much earlier than 1 day are these linear relationships valid? This is a point worth investigating further.

The differences in slopes between the three lines may not be too important at this stage, because of the tenuous nature of the assumptions that went into the development of the relationships for the mortar and concrete cubes. The data and relationship for the cement compacts taken from Reference 1 are statistically valid and meaningful, to include the rate of strength gain with time. It remains to be seen whether or not mortar and concrete cubes <u>really</u> have a slower rate of strength gain.

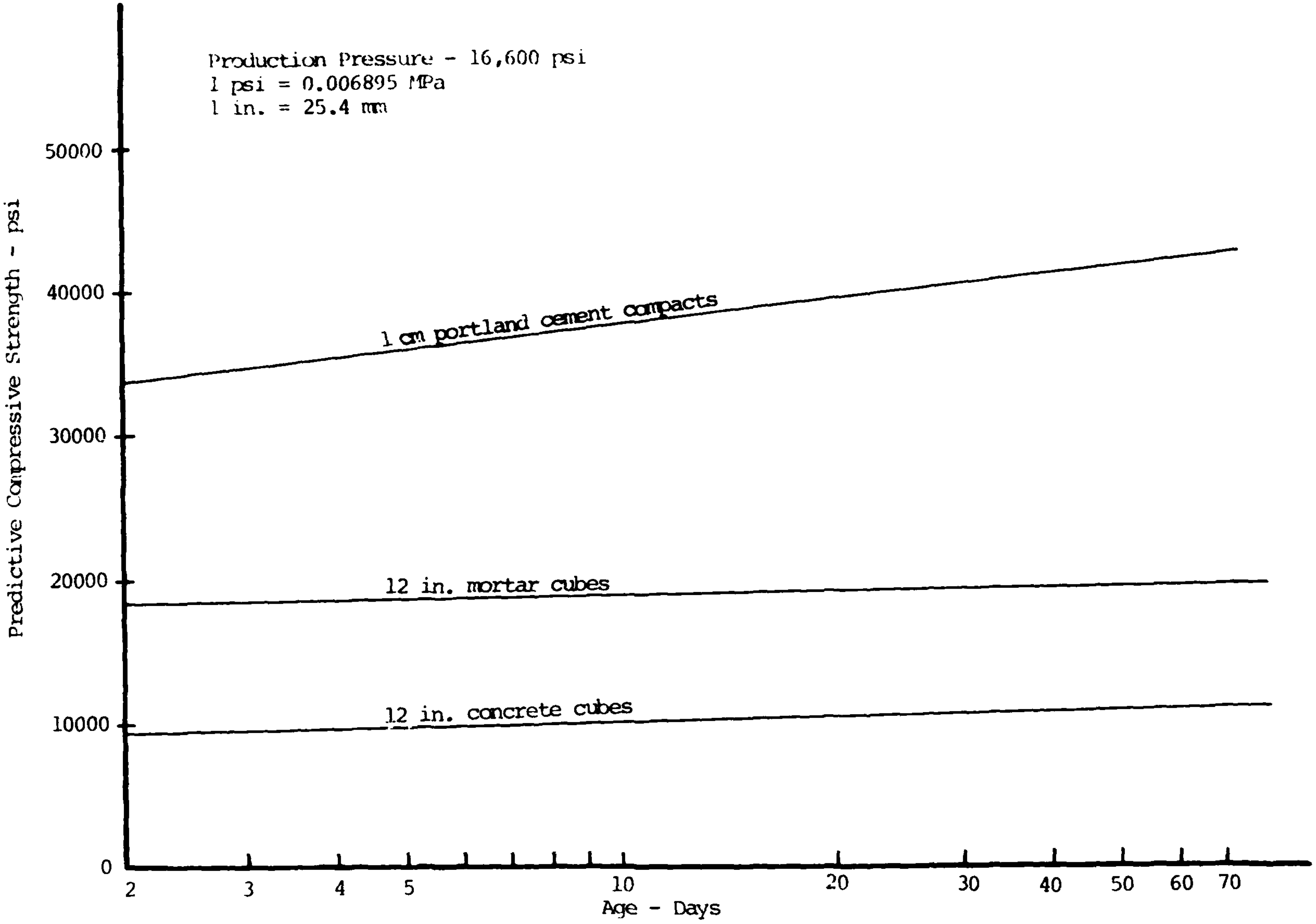

Figure 10. Predicted Compressive Strength vs. Age Relationships

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

From the research reported herein, the following conclusions can be drawn.

1. Relatively large mortar and concrete cubes can be produced by high-pressure compaction, using a die system developed at Texas A&M University. The resulting cubes are smooth, without blemishes or cracks, and of very precise dimensions.

2. Although improper lab procedures were used, mortar and concrete cubes, possessing very high compressive strengths at very early ages, were produced, using high-pressure compaction. Mortar strengths in excess of 18,000 psi (125 Mpa) and concrete strengths in excess of 9,000 psi (60 Mpa) were produced at 1 day of age, although the mix designs were not optimized.

3. The mortar and concrete cubes produced in this investigation achieved <u>in excess</u> of 90 percent of their 90-day strength in <u>1</u> day or less and then continued to increase in strength very slowly.

4. The use of a high quality Class C fly ash as a partial portland cement replacement (30 percent) did not "appear" to result in any decrease in concrete strength. This is different than experienced with the small cubes (1 cm), as reported in Reference 1, and may be not be correct because of improper lab procedures.

5. The use of steel fiber-reinforcement did not adversely affect the high-compaction process, as sound cubes were produced; however, the flexural strengths of these cubes were not as high as would be expected, from their high-compressive strengths. Not too much weight should be given to this finding because the mixes were not designed for steel fibers.

B. RECOMMENDATIONS

As the research produced the desired results, i.e., the production of very high-strength mortars and concretes through high-pressure compaction, additional research should be conducted to:

1. Explore the fundamental reasons for reaching these high strengths.

2. Verify the relationships between actual concrete strengths (in cores) and compressional wave pulse velocities for concretes of different types compacted to different pressures.

3. Strive to reach even higher strengths through such means as mix design optimization, employment of higher compaction pressures, use of high-temperature curing, and replacement of traditional ingredients with other materials.

4. Determine the performance characteristics of ultra-high-strength mortars and concretes.

5. Examine the economic benefits versus costs of producing ultra-high-strength concretes for use by the Air Force.

REFERENCES

1. Bormann, Jeffery R., W.B. Ledbetter, and M. Relis, Properties of Miniature Cement - Fly Ash Compacts Prepared by High Pressure Compaction, Report prepared for the Department of the Air Force, Armament Division, Elgin Air Force Base, Florida 32542, 1 August 1985, (pending publication).

2. Roy, D.M., and G.R. Goula, "Porosity - Strength Relation in Cementitious Materials with Very High Strengths," Journal of the American Ceramic Society, Vol 53, No. 10, 1973, pg 549-550.

3. Mindess, Sidney, and J. Francis Young, Concrete, Prentice-Hall, Inc., Englewood Cliffs, NJ 07632, 1981.

APPENDIX A

MATERIAL DATA

TABLE A1. CEMENT COMPOSITION AND PROPERTIES

Midlothian TXI Type III Cement	
Physical Test Results as reported by TXI	
NC	26.5
% H_2O Cubes	48.5
% Flow	112
% Air	9.0
% Passing #325 Sieve	98.6
Blaine (cm^2/gm)	5350
Wagner (cm^2/gm)	2550
Gilmore Setting Time Initial/Final (hrs:min)	2:35/4:15
Vicat Setting Time Initial/Final (hrs:min)	0:50/3:20
% Fed. False Set	7.1
Autoclave Expansion	
D.O.P. (mm)	
1	50
2	50
3	50
4	50
5	50
Compressive Strengths (2"x2" cubes)	
1 day	3592 psi
3 day	5425 psi
7 day	6242 psi
28 day	7575 psi
Specific Gravity	3.13

TABLE A1. CEMENT COMPOSITION AND PROPERTIES (CONCLUDED)

Chemical Analysis / X-Ray Analysis		
SiO_2	20.11	
Al_2O_3	4.38	
Fe_2O_3	3.52	
CaO	64.66	
MgO	0.78	
SO_3	3.34	
P_2O_5	0.23	
TiO_2	0.22	
Cr_2O_3	0.00	
Mn_2O_3	0.30	
Na_2O	0.29	
K_2O	0.38	
Total		98.20
C_3S	63.40	
C_2S	9.80	
C_3A	6.80	
C_4AF	10.70	

C_3A calculations include Al_2O_3, P_2O_5, and TiO_2

TABLE A2. FLY ASH COMPOSITION AND PROPERTIES

Gifford-Hill Class "C" Fly Ash

Physical properties

	Sample	Specification
Fineness, +325 Sieve, % Retained:	18.3	34.0 max.
PAI (28 days), % Control	101.4	75.0 min.
Water Requirement, % Control	90	105.0 max.
Autoclave Soundness, %	0.218	0.8 max.

	Sample	Specification
Specific Gravity: unsieved	2.71	....
sieved	2.75	....

Chemical Properties

	Sample	Specification
Silicon Dioxide	32.03	
Aluminum Oxide	17.10	
Ferric Oxide	7.25	
Total	56.38	50.0 min.
Calcium Oxide	29.88	
Magnesium Oxide	6.34	
Sulfur Trioxide	3.61	5.0 max.
Sodium Oxide	2.08	
Potassium Oxide	0.26	
Loss on Ignition	0.88	6.0 max.
Moisture Content	0.07	3.0 max.
Total	99.50	
Sodium Oxide Equivalent	2.25	

TABLE A3. AGGREGATE DATA

Item	Fine Aggregate	Coarse Aggregate
Sieve Analysis (% Retained) as per ASTM C33		
3/4 in.		
1/2 in.		0.1
3/8 in.		3.8
No. 4	0.0	84.4
No. 8	0.7	96.3
No. 16	39.3	97.3
No. 30	64.0	
No. 50	80.0	
No. 100	93.5	
No. 200	99.4	
Dry loose unit wt (lb/ft^3)	-	101.0
S.G. (Dry Bulk)	2.60	2.91
Absorptions (%)	0.56	0.96

END

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