HIGH HYDROSTATIC PRESSURE CURING OF FRESH MORTAR: ITS APPLICATION TO CONCRETE CURING

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WORKING PAPER NO. 25

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INTRODUCTION

Statement of Problem

Ocean engineering may be defined as the application of the engineering disciplines to the ocean. A serious problem which may be encountered when an engineering material is placed in the ocean, whether it is to be used for food production, navigation, defense, or tapping energy reserves, is the effect of the ocean environment on that material. In many cases the effect is detrimental.

An interesting question may be raised: can the ocean environment be utilized to produce beneficial effects on an ocean engineering material? The material of interest is concrete and the physical property of the ocean that may be used beneficially is hydrostatic pressure.

Motivation to Conduct Research

Normal concrete practice

Concrete with high compressive strength can withstand high compressive loads. If hydrostatic pressure could be utilized to increase the compressive strength of concrete, then its effect would be beneficial.

The conventional method for obtaining high-strength concrete is to reduce the water/cement ratio. This can be done in two ways. First, less water can be used although this produces a harsher, less workable mix which results in higher placement cost due to more labor requirements. The second way is to increase the cement content. This, however, also increases the cost.

A common method of increasing strength is to steam cure; however, this only produces ultimate strengths similar to those obtained after several months of curing at normal temperatures.

High-pressure autoclaving

Still another method of curing concrete is high-pressure autoclaving. In this process chemical reactions in addition to normal hydration occur between the concrete aggregates and/or cementitious materials and this produces permanent, extremely high, early compressive strengths of up to 152 N/mm^2 (22,000 psi).[1] These chemical reactions do not occur under normal steam curing conditions. To obtain these strengths, temperatures in the range of 163° and 191°C (325° to 375°F) and corresponding pressures

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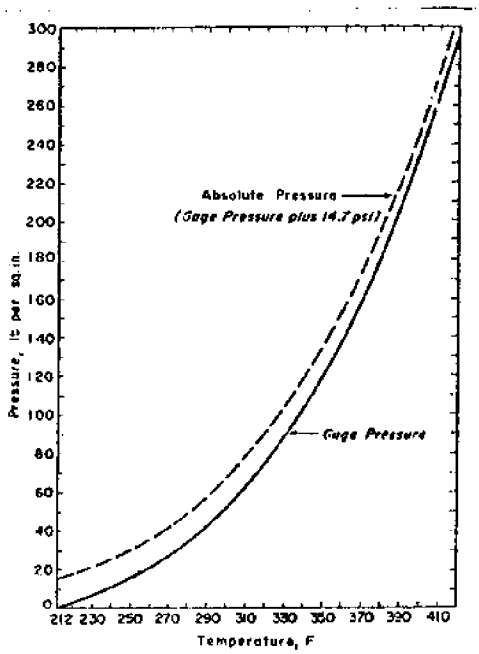
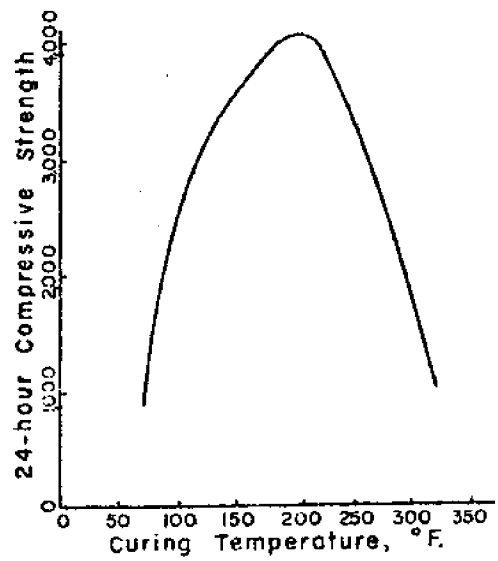
[1]American Concrete Institute Committee 516, 1965, "High Pressure Steam Curing: Modern Practice and Properties of Autoclaved Products," *Proceedings of the American Concrete Institute* 62:869-908.

of about 0.55 to 1.17 N/mm^2 (80 to 170 psig) are required. Figure 1 shows the well-known relationship between steam temperature and pressure. Hydration (and hence strength) is greatly accelerated by high temperature; however, as is seen in Figure 2, high temperature alone (177°C or 350°F) is not beneficial. Corresponding high pressures are also required if beneficial chemical reactions between the aggregates and/or cementitious materials are to occur.



*From: Washa, G.W., 1965, "High pressure steam curing: modern practice, and properties of autoclaved products," ACI Committee 516 Report in *Proceedings, American Concrete Institute*, figure 1, p. 870.

Figure 1. Relationship between temperature and pressure of saturated steam



*From: A.W. McCray and F.W. Cole, 1958, *Oil Well Drilling Technology*, University of Oklahoma Press, figure 20-2, p. 449.

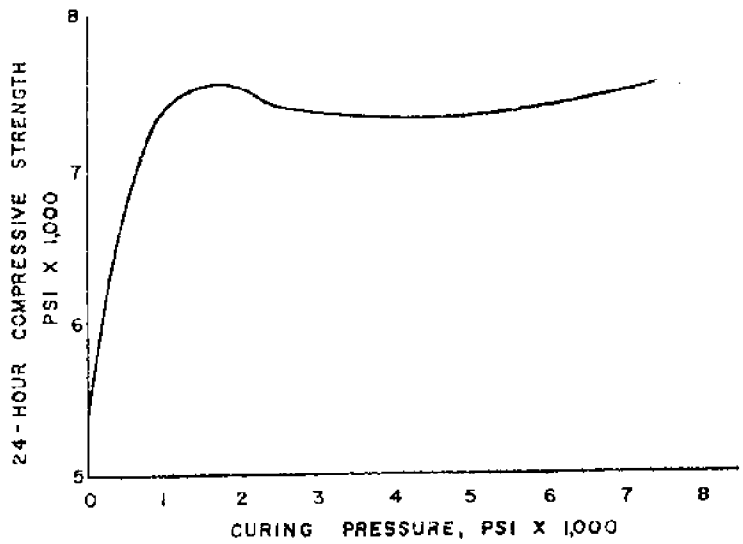
Figure 2. Relationship between 24-hour compressive strength and curing temperature for portland cement

Oil well cementing

High autoclaving pressures, 0.55 to 1.17 N/mm^2 (80 to 170 psig) do not appear high when compared with oil well cementing pressures. For example, in the oil well industry, cementing operations take place with pressures of up to 152 N/mm^2 (22,000 psi).

The cementing of casing in oil wells is almost a universal practice. It is done for a number of reasons such as to prevent drilling fluid from circulating outside the casing or to provide an anchor for blowout-preventer equipment.

With a few notable exceptions, portland cement is the principal constituent of most oil well cementing materials. Deep well casing conditions (171°C @ 151 N/mm^2 @ 6,096-m depth, or 340°F @ 21,970 psi @ 20,000-ft depth) decrease thickening time (pumpability time) for most oil well cements. Since thickening time is important in the oil well industry, some effects of high pressures and temperatures on cement properties have been examined.[2,3,4,5,6,7] These studies have shown that increasing the pressure under isothermal conditions will increase the compressive strength of oil well cement (Figure 3).



*From: A.W. McCray and F.W. Cole, 1958, *Oil Well Drilling Technology*, University of Oklahoma Press, figure 20-3, p. 450.

Figure 3. Relationship between curing pressure and compressive strength for portland cement

[2]Canada Cement Lafarge Ltd., 1973, *Canada Oil-Well Cements Laboratory Data Book*, 4th edition.

[3]M.A. Swayze, 1954, *Effects of High Temperatures and Pressures on Oil-Well Cements*, prepared for Mid-Continent District Study Committee on Cementing Practices, Drilling and Production Practice, Vol. 72.

[4]J.E. O'Neal and H.W. Benischek, 1954, "The Effects of High Temperature and Pressures on the Setting Time of Oil-Well Cements," paper presented at the spring meeting of the Rocky Mountain District, Division of Production, Casper, Wyoming.

[5]W.G. Bearden, 1959, "Effect of Temperature and Pressure on Physical Properties of Cements," in *Oil-Well Cementing Practices in the United States*, Vol 49.

[6]American Petroleum Institute correspondence (unpublished).

[7]A.W. McCray and F.W. Cole, 1958, *Oil Well Drilling Technology*, University of Oklahoma Press, Ch. 20.

It has also been shown that small increases in pressure, as well as high pressure, can significantly increase the strength of oil well cement slurries.[8]

NCEL studies

Naval Civil Engineering Laboratory (NCEL) studies on the in situ strength of subaqueous concrete concluded that hydrostatic pressure is detrimental.[9,10] Spurious data from that study [11] may be reinterpreted to show that there is a possible mechanism or a set of pressure conditions that will produce an increase in strength with pressure.

Mechanical compaction studies

Portland cement pastes can be compacted using mechanical pressures. One study[12] indicated that if a cement paste with a low water/cement ratio is compacted under high compressive loads (672 N/mm^2 or 97,500 psi), then very high compressive strength samples can be produced. The highest compressive strength reported is 375 N/mm^2 (54,389 psi).[13] This is stronger than mild steel.

State-of-the-Art of Pressure-Cured Concrete

Normal concrete practice

A review of the state-of-the-art of concrete curing is included in the Sea Grant publication about reinforced concrete.[14] Generally, little

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[8]API correspondence (unpublished).

[9]W.R. Lorman, 1970, *In-situ Strength of Subaqueous Concrete*, Technical Report R673, Naval Civil Engineering Laboratory, Port Hueneme, California.

[10]W. Lorman, 1971, *Supplement to In-situ Strength of Subaqueous Concrete*, Technical Report R673S, NCEL, Port Hueneme, California.

[11]*Supplement to In-situ Strength of Subaqueous Concrete*, 1971, Technical Report 673S, p. 11, fig. 9(a). (The highest 28-day strength plotted is that produced by one sample that was pressure cured at 47°F and 269 psi.)

[12]A.W. McCray and F.W. Cole, 1958, *Oil Well Drilling Technology*, University of Oklahoma Press.

[13]C.D. Lawrence, 1969, *The Properties of Cement Paste Compacted Under High Pressure*, Research Report 19, Cement and Concrete Association, London.

[14]D.C. Wilson, 1974, *Hawaii's Floating City Development Program: Concrete for Large Floating Structures*, UNIHI-SEAGRANT-CR-74-02, Sea Grant College Program, University of Hawaii, Honolulu. Also Technical Report No. 4, Oceanic Institute, Waimanalo, Hawaii.

is known about high hydrostatic pressure curing of concrete. This is because standard concrete practice emphasizes atmospheric pressure curing. Figure 4 summarizes the numerical relationship of the area of this research to that of standard concrete practice.

High pressure autoclaving

The state-of-the-art of high pressure autoclaving is considered advanced although the method is expensive. Generally, special concrete mixes with high silica content are required. The expense, however, comes mainly from the cost of the fuel required to produce the steam. Today, especially with the present "energy crisis," this is a very important limiting factor preventing wide use of the technique. Another limiting factor is the high cost of a pressure vessel large enough for a day's concrete production.

Oil well cementing

The oil well cementing industry is not in the concrete business. Thus, knowledge about the effects of high pressures and temperatures on cement properties has not been applied to the pressure curing of concrete.

Other factors also make the direct application of oil well cementing techniques to concrete curing difficult. For example, thickening time, not strength, is most important because it determines the length of time that the slurry can be pumped. Strength is important only to the extent that the cement must perform its required functions satisfactorily.

Farris,[15] in research work directed toward the determination of minimum strength requirements for oil well cements, found that a tensile strength of only 0.055 N/mm^2 or 8 psi (approximately 0.689 N/mm^2 or 100 psi compressive strength) is satisfactory. Based on this finding and other data, there is general agreement in the industry that the development of compressive strengths of only 1 or 2 N/mm^2, or a few hundred psi, is satisfactory.

Thus, although the state-of-the-art of oil well cementing is advanced ("oil well cements" were first used in oil well cementing operations in 1917) and the effect of pressure is generally understood, there are still major differences between construction applications and oil well cements. These differences are: (1) no aggregate is added to the oil well cements (in other words, a "neat" slurry is used); (2) large volumes of water are used in oil well cements in order to permit slurry to be pumped; and (3) high sulfate resistance is generally required in oil well cements.

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[15] R.F. Farris, 1941, "A Practical Evaluation of Cements for Oil Wells," *API Drilling and Production Practice*, p. 283.

PRESSURE		TEMPERATURE 0-10°C 32-50°F	10- 49°C 50-120°F	49-100°C 120-212°F	100-204°C 212-400°F	EQUIVALENT DEPTH OF WATER	
21-207 N/mm²	3000-30000 psi	unexplored	$ AREA OF PROPOSED STUDY	# DEEP OIL WELL CEMENTING	# VERY DEEP OIL WELL CEMENTING	6818-68182 feet	2078-20782 meters
2-21 N/mm²	300-3000 psi	* experimental deep water concrete	# (USUAL OIL WELL CEMENTING)		unexplored	682-6818 feet	208-2978 meters
0-2 N/mm²	0-300 psi	* standard shallow water placement	# (SHALLOW OIL WELL CEMENTING)		* standard autoclaving practice	0-682 feet	0-208 meters
atmospheric		* standard winter concreting practice	* standard summer concreting	* standard steam curing practice	* unused	surface	

*	STANDARD OR EXPERIMENTAL CONCRETE PRACTICE
#	STANDARD OIL WELL CEMENTING PRACTICE
$	AREA OF STUDY

Figure 4. Numerical relationship of area of study to standard concrete practice

NCEL studies

The method of curing concrete in the ocean at high pressures is new. NCEL has conducted only one study series[16,17] and this was at relatively low pressures (1.85 N/mm^2 or 269 psi).

Mechanical compaction studies

Mechanical compaction of neat cements is relatively new. Special hydraulic presses and molds are required and to date only laboratory samples have been made.

Objective of Research

The objective of the research is to determine the effects of curing mortar at high hydrostatic pressures with the hope of developing a high pressure curing technique for concrete that will produce beneficial results.

The following properties will be examined:

1. Compressive strength
2. Mass
3. Volume
4. Bulk density
5. Air entrainment
6. Permeable voids
7. Absorption rate

The steps of research to be performed are:

1. Examination of physical properties of pressure-cured mortar
2. Identification of beneficial and detrimental effects of pressure curing fresh mortar
3. Theoretical explanation of observations
4. Development of a concrete pressure curing technique

Analysis of the four pressure curing studies (autoclaving, oil well cementing, NCEL, and cement paste compaction) has led to the discovery of a new technique and curing process thay may be used to produce high-strength concrete building materials. The technique is based on the following hypothesis: high hydrostatic pressure compaction and curing of concrete at moderate temperatures will produce higher compressive strengths than curing at atmospheric pressure. As will be seen from the results of the experiments conducted for this study, the duration of curing is an important parameter.

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[16]W.R. Lorman, 1970, *In-situ Strength of Subaqueous Concrete*, Technical Report R673, Naval Civil Engineering Laboratory, Port Hueneme, CA.

[17]W.R. Lorman, 1971, *Supplement to In-situ Strength of Subaqueous Concrete*, Technical Report R673S, NCEL. Port Hueneme, CA.

MORTAR TESTING PROGRAM

The mortar testing program consisted of four series of experiments. The first series, which was coded by a single letter such as A, B, and C, was practice experiments. The second series, which was coded by double letters such as AA, BB, and CC, was used to select a batch design. The third series, which was coded A1, A2, A3, etc., was used to test various pressure curing techniques and equipment. The fourth and final series, which was coded J1, J2, J3, etc., was used to draw final conclusions about the effect of high hydrostatic pressure curing on mortar and to infer its effect on concrete.

Materials

Portland cement

The portland cement used in the tests came from one bag of type 1 Kaiser cement obtained from the Kaiser Cement & Gypsum Corp. Table 1 lists the chemical and physical properties of the cement as indicated by a batch certificate for that cement. Once the bag of cement was opened, the cement was stored in a dry airconditioned room in four 2-gallon water tight and air tight plastic poly pails made by Industrial Container Corp. (Los Angeles, California 90058).

C-109 silica sand

The aggregate (sand) used in the mortar was graded Ottawa sand, ASTM (American Society for Testing and Materials) designation C-109, furnished by Ottawa Silica Company, Ottawa, Illinois. This is the standard sand used in industrial cement testing. The sizes of the sand are listed in Table 2. Three 50-lb bags of C-109 sand were obtained through the Cyprus Hawaiian Cement Corp. They were stored in a cool dry place next to the cement in their original bags (duotex type bags made by Bemis Laminated Textiles).

Course aggregate was not used in the mortar tested due to the small size of the molds and because C-109 sand is a standard cement testing sand. The results of the experiments, however, can be applied to concrete if it is considered that a concrete with only fine aggregate is equivalent to mortar. It is noted that no aggregate was used in the oil well cement tests.

Mixing water

City tap water, which was drinkable and had no pronounced taste or odor, was used as mixing water for making the mortar. The City and County of Honolulu's water supply is from a natural underground source and has few impurities in it.

TABLE 1. CHEMICAL AND PHYSICAL PROPERTIES OF TYPE 1 KAISER CEMENT

Chemical Analysis for Sacked Cement from Silo 4

Chemical Compound	%	
SiO_2	21.82	
Fe_2O_3	3.22	
Al_2O_3	5.18	
CaO	65.13	
MgO	1.63	
SO_3	1.99	
LOI	0.12	(loss on ignition)
IR	0.12	(insoluble residue)
Free CaO	0.72	
	99.93	
C_3S	54.16	
C_2S	21.79	
C_3A	8.29	
C_4AF	9.79	
SiO_2/R_2O_3	2.60	(R_2O_3 where R = Fe_2O_3 + Al_2O_3)
	96.63	

Physical Test Results

False set = 73.6%
% H_2O for normal consistency = 23.6%

% H_2O for cubes = 48.5%

BSS (fineness) = 3,500

Per Mix = 500 gm cement
1,375 gm C-109 sand

Compressive Strength

1 day = 1,340 psi or 9.24 N/mm^2
3 days = 2,650 psi or 18.27 N/mm^2
7 days = 3,660 psi or 25.23 N/mm^2
28 days = 4,970 psi or 34.27 N/mm^2

Initial set = 2:50
Final set = 5:50
Autoclave expansion = +.026
Pack set = 8

TABLE 2. GRADED OTTAWA SAND, ASTM DESIGNATION C-109

Sieve (No.)	Percentage Retained
100	98 ± 2
50	75 ± 5
40	30 ± 5
30	2 ± 2
16	None

Molds

Six-ounce juice cans, commercially used to contain frozen concentrated orange juice, were used as molds to form and cure the mortar. Cardboard tubing of a similar size which is made for mortar testing was unavailable.

The juice cans were deemed to be acceptable for the following reasons:

1. The cans were all identical in size within measurable tolerances.
2. The weight of the fresh sample in the can could be obtained. (Bronze gang molds were not used because they did not allow individual weights to be obtained.)
3. The cans had lids to prevent spillage of mortar during placement of the samples into the pressure vessel.
4. The cans had flexible cardboard walls which allowed three-dimensional compaction of the sample.
5. The cans could be easily removed from the sample following pressure curing.

Impermeable flexible bags

"Meals-in-minutes" bags--boilable, freezable, waterproof, and vapor proof food storage bags--were used to package the concrete samples. These boilable cooking pouches, 8 in. x 6 in. with a capacity of 8 fluid ounces or ½ pint, were chosen because they are flexible, waterproof, and heat sealable. However, pinhole leaks did develop following compression in some of the bags; dry paper towels were placed between triple-bagged samples to test for such leaks.

Equipment

Mixing machine

The mixing machine used looked similar to that described for cement mixing in ASTM specification C305-65, but had a large mixing bowl 11½ in. deep and 12½ in. in diameter. It was a Univex mixer manufactured by Universal Industries, serial no. 2-8919-FM, 115 volts, 60 cy., 5.6 amps AC, State of Hawaii, University of Hawaii code F-275 BJ, manual speed control.

Miscellaneous mixing tools

A spoon, tamper, straight-edged trowel, rubber scrapers, and cleaning brushes were either purchased or borrowed from the Civil Engineering Department, University of Hawaii.

Weighing scales

The weights of cement and sand were obtained using a Sartorius-werke GMBH Gottingen scale which had a precision of .01 gm up to a maximum load of 1,000.00 gm. It was made in Germany (type 2254, Fabr. Nr. 76603, State of Hawaii, University of Hawaii code F-857 FK). A Mettler P1200 scale was used to weigh the cans and cured mortar. It also had a precision of .01 gm but had a maximum load capacity of 1,200.00 gm. It was made in Switzerland for Mettler Instrument Corp., Hightstown, New Jersey (110 volts, 60 cps, 15 w, no. 560100).

Graduated cylinder

A 250-ml graduated cylinder with scale markings 2 ml apart was used to measure out the quantity (and hence mass) of mixing water.

Flow table

An old flow table was bolted to a concrete floor. It was operated manually by turning a crank to drop the table.

Heat sealer

An electric heat sealing food packaging appliance specifically designed to heat seal "meals-in-minutes" bags was used to seal the bags and thus waterproof the samples. The heat sealer is commercially available from Sears, Roebuck and Co. (model 259-656500, 200 w, 120 volts, 60 cps, AC only).

Pressure vessel

A 16-inch diameter artillery shell was converted by Benthos Corp. into a pressure vessel for testing oceanographic instruments. It has the

internal dimensions as shown in Figure 5 and was rated to 68.95 N/mm^2 (10,000 psi).

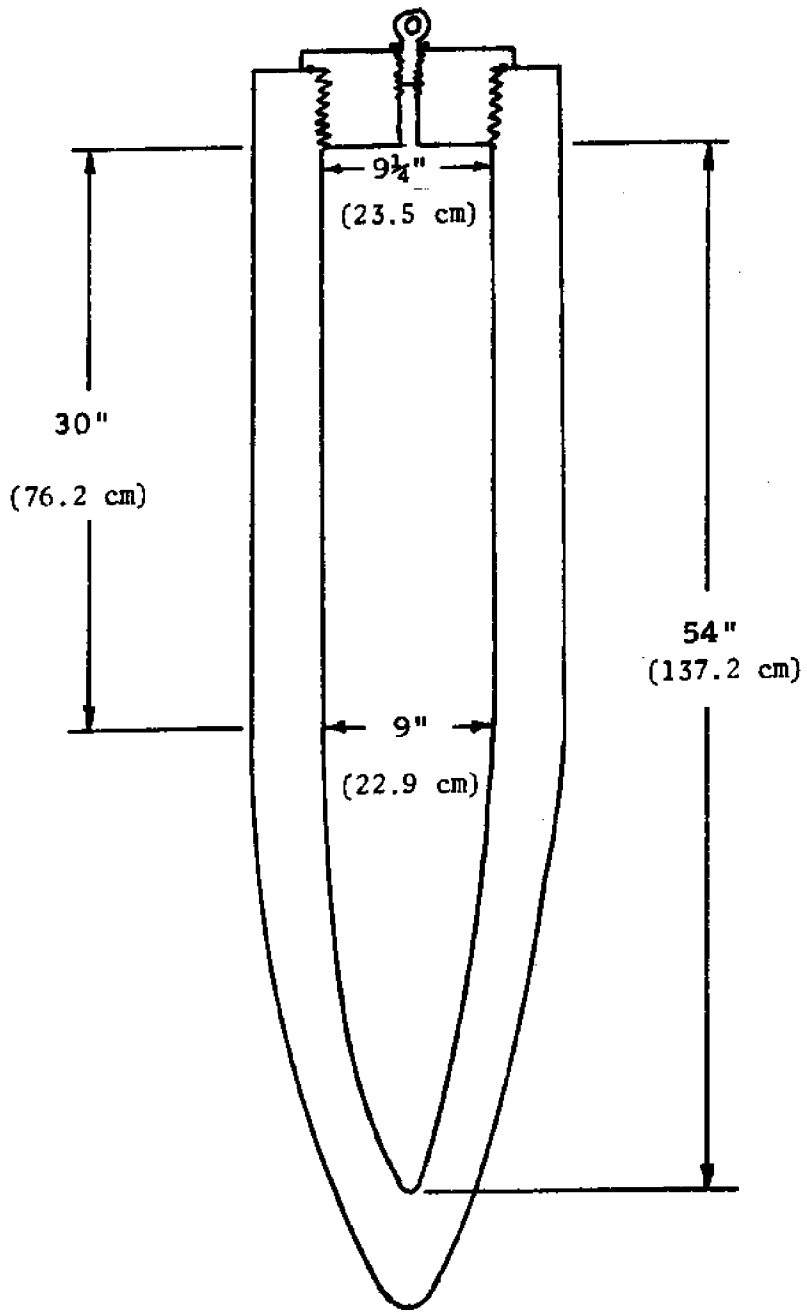

Figure 5. Internal dimensions of a pressure vessel

Sulfur capping pot and sample capping mold

A sulfur capping compound melting pot and sample capping mold belonging to the University of Hawaii Civil Engineering Department were used to cap the ends of the test specimens.

Compression strength testing machine

A Versa-tester compression strength testing machine (model AP-1000 series manufactured by Soiltest Inc., Evanston, Illinois 60202) was used to measure the maximum load capacity of the test specimens. This is a hydraulically operated tension-compression testing machine for soils, concrete, rock, bituminous materials, industrial products, material-fabrications; accuracy: ½ of 1% full scale in accordance with American Gauge Design Committee's gauge calibration standard, 3,000-lb capacity.

This machine was calibrated against a proving ring (Tinius-Olson proving ring number 15091) which was last calibrated in 1957.

Drying oven

A Sargent-Welch analytical drying oven was used to dry concrete specimens for the permeable voids tests. It was designed and manufactured by Sargent-Welch Scientific Co., State of Hawaii, University code F-634FR.

Facility

A curing room on the University of Hawaii Manoa campus was used to water cure the samples following pressure curing. It was maintained at 70 ± 2°F and 50 ± 2% relative humidity. Since a saturated environment was needed for curing, the samples were submerged in a watertight container placed in the curing room.

Experimental Procedures

Mixing

The mixing procedure used was that suggested by ASTM C-109 as follows:

1. Mix 30 sec slow speed after all cement in
2. Mix 30 sec slow speed while pouring all sand
3. Change to medium speed for 30 sec
4. Scrape 15 sec
5. Cover and stand for 75 sec
6. Mix medium speed for 60 sec
7. Scrape sides and stand for 90 sec
8. Mix 15 sec at medium speed

Pressure curing

The third series of experiments, the modified experimental tests, was used to test various pressure curing techniques and equipment. The hydrostatic pressure cure method, using a juice can as a mold, was selected as the pressure curing technique for the fourth series of experiments. The following is an outline of the procedure followed:

1. Weigh empty juice cans
2. Weigh portland cement
3. Weigh C-109 sand
4. Measure water in graduated cylinder
5. Mix batch
6. Fill cans
7. Weigh cans with samples in them
8. Cap cans with metal lids
9. Wipe up water bled off
10. Tape cap to can with masking tape
11. Attach rubber "can end" protector
12. Place samples in "meals-in-minutes" bags
13. Evacuate bag and heat seal
14. Weigh sample packaged in one bag
15. Wrap sample in dry paper towel, place in bag, and heat seal
16. Wrap sample again in dry paper towel, place in bag, and heat seal
17. Place samples in bucket of water
18. Transport samples to Pier 18
19. Place test samples in green plastic garbage bag inside gunny sack and suspend sack inside pressure vessel
20. Pressurize vessel to 5,000 psi in 5 minutes
21. Store control samples in pail of water right beside pressure vessel
22. Let sample cure for required length of time: 50 minutes, 19 hours, 67 hours, or 76+ hours
23. Depressurize samples according to decompression schedule developed
24. Remove samples from pressure vessel
25. Examine samples for leakage
26. Transport to curing room
27. De-bag until single bagged
28. Weigh single bag with sample in it
29. De-bag and de-cap
30. Weigh sample with can
31. De-can
32. Weigh sample
33. Weigh empty used can
34. Clean can and re-weigh empty used can
35. Measure diameter and length of samples
36. Cap samples with sulfur capping compound and test for compressive strength or submerge in water until ready to cap and test

EXPERIMENTAL DATA ANALYSIS

Measurements were made of the following properties: compressive strength, mass, volume, bulk density, air entrainment, permeable voids, and absorption rate. A statistical analysis of the data was done to determine the standard deviation of the mean. Photomicrographs were obtained but no statistical analyses of the size and number of voids were carried out.

Compressive Strength

All compressive strength measurements were made using a Versa-tester strength testing machine. The smallest cross-sectional area of the samples was measured and the maximum load at failure was recorded. Calibration of the testing machine indicated that observed loads needed to be corrected. These were corrected according to a table derived from calibration data (see Appendix A).

This corrected load was divided by the cross-sectional area to obtain compression strength in psi:

$$\frac{\text{corrected load, lb}}{\text{minimum cross-sectional area, in.}^2} = \text{compressive strength } \frac{\text{lb}}{\text{in.}^2}$$

These strengths were then converted to N/mm^2 by multiplying by .006894757 $N/mm^2/psi$.

Mass

The mass of a de-canned sample is the cylindrical piece of concrete that remains after the cardboard juice container in which the sample was cured has been removed. The mass of a dusted de-canned sample is the piece of mortar that remains after the loose sand grains have been brushed off.

There are several methods to obtain the mass of the hardened mortar sample:

1. Measure weight of de-canned sample
2. (Weight of can) + (cured sample) - (weight of empty used can)
3. (Weight of can) + (cured sample) - (weight of new can) - (weight of water absorbed by new can provided no leakage through bag)
4. (Weight of can) + (cured sample) - (weight of empty cleaned used can)
5. Measure weight of dusted de-canned sample

For each batch mixed, both the mass of the control sample and the mass of the test sample were obtained using the same method. Both methods 1 and 2 were used and the higher number of the two was selected as the mass.

Method 5 was used for the absorption and permeable voids tests.

Volume

Methods for measuring volume of cured mortar were as follows:

1. Measure diameter and length and calculate: $V = \pi(\frac{D}{2})(\frac{D}{2})h$
2. Measure weight of water displaced by sample
3. Measure loss in weight of saturated sample when submerged in water

Method 1 was used to calculate the volume since it was undesirable to submerge those samples that were to be tested on day 1.

Method 3 was used in the absorption and permeable voids tests.

Bulk Density

$$\text{Density} = \frac{\text{mass}}{\text{volume}}$$

Specific gravity is defined as the ratio of a weight or a mass of a given volume of a substance to that of an equal volume of water used as a standard.

The density of hardened concrete was calculated by dividing the mass by the calculated volume. Since the units are given in gm/cm^3, the value of the density is the same as the specific gravity.

Permeable Voids

There are two methods for measuring voids in hardened mortar:

1. C 642 (ASTM): Measure oven dry weight, saturated weight after immersion, saturated weight after boiling, and immersed weight; calculate volume of permeable pore space. These voids were not necessarily air voids; they may have originally been filled with water.
2. Photomicrograph: Measure size and number of voids.

The first method was used.

Absorption Rate

The method for obtaining absorption rate is as follows: measure weights of sample at successive times following oven drying and submersion in water.

The weight of water absorbed by a dried sample was obtained from measurements of submerged weight taken every 30 seconds for 15 minutes following submersion of a dried sample.

Photomicrographs

There are four types of samples which may be photographed:

1. Broken section
2. Saw cut section
3. Saw cut and ground section
4. Thin section

All types of samples were examined with a microscope but only the saw cut and ground section was photomicrographed.

Air Entrainment

The general procedure described in the ASTM standard method of test for air content of hydraulic cement mortar, C185-71, was used. The juice can was used as the mold and it was assumed that all fresh mortar in the cans occupied 200.0 cm^3.

Standard Deviation

The formula used for the standard deviation was:

$$s = \sqrt{\frac{\sum_{i=1}^{h} x_i^2 - \frac{1}{n}\left(\sum_{i=1}^{h} x_i\right)^2}{n - 1}}$$

where:

s = standard deviation
x = sample value
h = number of class intervals in the frequency table
n = number of sample values obtained from the population

RESULTS

First Series of Experiments

The results of the first series of experiments, the practice tests, were somewhat disappointing. Consequently, many more practice batches were mixed than originally anticipated.

The practice tests did lead to improvements in the efficiency of batch mixing and clean up. Also, quality control was improved after the practice experiments since problem areas such as temperature control could be identified and corrected.

The experimental facilities available did not meet all ASTM specifications; therefore, quality control was a difficult problem. However, by the time the fourth series of experiments was performed, the following improvements had been made:

1. The compression testing machine was calibrated against a proving ring which itself was last calibrated in 1957.
2. A concrete curing room became available. The temperature and humidity were controlled at 70 ± 2°F and 50 ± 2%. Since a saturated environment was needed for curing, the samples were submerged in a watertight container placed in the curing room.
3. The flow table was bolted to a concrete floor.
4. The batch size was doubled since the mixing machine was larger than ASTM specifications.
5. Temperature variations were reduced during transport of samples to and from Pier 18 by carrying the samples in a pail of water.
6. All samples were tested for leakage.
7. The control and test samples were packaged, transported, and cured in the same manner except for the hydrostatic pressure difference. Thus both test and control samples experienced similar environmental changes.
8. The pressure curing experiment was repeated several times with an increased number of control samples. Results of similar experiments were then averaged.

Second Series of Experiments

The second series of experiments, the preliminary tests, was used to select a batch design. Although some batches produced very high compressive strengths following pressure curing, the variability within a batch was also very high. Rather than continue experiments to find an optimum pressure curing batch design, it was decided to use double the standard ASTM C-109 batch size. This new batch size, which was selected for the final series of experiments had the following components: 1,000 gm Kaiser

type 1 portland cement, 2,750 gm C-109 Ottawa silica sand, and 485 ml water. Thus the water/cement ratio was 0.485.

Third Series of Experiments

The third series of experiments, the modified experimental tests, was used to test various pressure curing techniques and equipment. The following is a list of the curing techniques that were tested:

1. Standard control cure:
   - cured at atmospheric pressure
   - used 2 in. x 2 in. x 2 in. bronze molds
   - cured in mold in saturated air for one day followed by removal of sample from mold
   - tested samples immediately or submerged in water until tested
2. Autoclaved following one day standard control cure:
   - removed from mold
   - autoclaved 63 hours at 127.5°C and approximately 15 psig
   - air dried or submerged in water until tested
3. Autoclaved fresh:
   - autoclaved fresh mortar in mold for 63 hours at 127.5°C and approximately 15 psig
   - air dried until tested
4. Compacted by mechanical press:
   - compacted sample for one day at 1,000 psi load
   - tested after removal from mold
5. Compacted by mechanical press:
   - compacted sample for one day at 3,000 psi load
   - removed from mold
   - cured in water until tested
6. Hydrostatic pressure cure, free flooded:
   - cured samples at 5,000 psi for 19 hours
   - tested following demolding
7. Hydrostatic pressure cure, free flooded:
   - cured samples at 9,000 psi for 67 hours
   - tested following demolding
8. Hydrostatic pressure cure, protective bag:
   - placed baggie around bronze mold (baggie leaked)
   - cured samples at 5,000 psi for 19 hours
   - tested following demolding
9. Hydrostatic pressure cure, wax coating:
   - painted wax coating on bronze mold
   - cured samples at 5,000 psi for 67 hours
   - tested following demolding

10. Hydrostatic pressure cure, wax coating:
    - painted wax coating on bronze mold
    - cured samples at 5,000 psi for 7 days
    - depressurized
    - repressurized
    - depressurized after 26 days from start
    - cured samples in molds 2 more days
    - tested on 28th day

11. Hydrostatic pressure cure, wax coating:
    - painted wax coating on 1.4-inch diameter metal tube
    - cured samples at 5,000 psi for 67 hours
    - tested sample following demolding

12. Hydrostatic pressure cure, rubber gasket:
    - used bronze molds
    - sealed with gasket glue and a rubber gasket
    - cured samples at 5,000 psi for 19 hours
    - tested following demolding or cured in water until tested

13. Standard control cure, rubber mold:
    - used 2-inch diameter triaxial soil test rubber membrane
    - removed aluminum mold after one day
    - submerged in water until tested

14. Hydrostatic pressure cure, copper tubes:
    - used 1-inch diameter copper tubes
    - placed steel plugs in ends
    - placed short piece of rubber tubing over copper-steel joint
    - cured samples at 5,000 psi for 19 hours and 67 hours
    - tested after demolding or submerged in water until tested

15. Hydrostatic pressure cure, rubber mold:
    - used 3/4-inch diameter rubber tube as mold
    - cured samples at 5,000 psi for 67 hours
    - tested following demolding

16. Standard control cure, rubber mold:
    - used 3/4-inch diameter rubber tube as mold
    - demolded after one day and tested

17. Hydrostatic pressure cure, pillow test:
    - used "meals-in-minutes" bags as mold
    - cured samples at 5,000 psi for 19 hours
    - cut and tested or water cured, cut, and tested sample

18. Hydrostatic pressure cure, dry cardboard tube:
    - used dry cardboard tube as mold inside "meals-in-minutes" bag
    - cured samples at 5,000 psi for 19 hours
    - demolded
    - water cured until tested

19. Hydrostatic pressure cure, juice can mold:
    - used juice can as mold
    - placed one "meals-in-minutes" bag around can
    - cured samples at 5,000 psi for 19 hours
    - demolded and tested

20. Hydrostatic pressure cure, juice can mold:
    - used juice can as mold
    - capped cans
    - triple-bagged in "meals-in-minutes" bags
    - used paper towel as leak detector
    - cured samples at 5,000 psi for 50 minutes, 19 hours, and 67 hours
    - tested after demolding or water cured until tested

Fourth Series of Experiments

The fourth and final series of tests, the "juice can tests," followed the pressure curing technique identified as curing technique 20 above.

The recorded observations and subsequent calculations of the fourth and final series of tests, the J series, are in Appendix B. The data are arranged in the order in which the batches were made.

There were five controllable variables in the final series of tests:

1. The control samples not pressure cured
2. The length of time from when the water and cement were first mixed until the beginning of the pressurization of the pressure vessel
3. The total length of time that the samples were pressurized above atmospheric pressure
4. The total length of time from the start of depressurization from the maximum curing pressure to achieving atmospheric pressure
5. The age of the samples when tested

An uncontrollable variable which was noticed following depressurization was leakage of the sample bags. Since all of the control bags did not leak, then initially, only those test samples that did not show signs of leakage were compared with the control samples.

As each batch was prepared and tested, a trend in the results became evident. This enabled similar test samples to be grouped as follows:

1. Those test samples that were pressurized within 3 hours after mixing, i.e., before "final set," and those test samples that were pressurized over 17 hours after mixing, i.e., after "final set." (Final set is defined in ASTM C191-74 as the time when the Vicat Apparatus needle does not sink visibly into the paste.)

2. These samples were then grouped according to the length of pressure cure:
   - 15 to 60 minutes
   - 17 to 21 hours
   - 65 to 70 hours
   - 72 to 168 hours
3. Each of these groups was then subdivided according to the length of decompression:
   - 5 to 10 minutes
   - 30 to 70 minutes
   - 7 to 100 hours

Control sample data

Table 3 lists the control sample data, organized according to age of sample when tested. All control samples showed no signs of leakage.

Figure 6 is a plot of the control sample data. Superimposed on the graph is a line for the mean compressive strength.

Figure 7 is a histogram showing the distribution of the control sample mass about its mean.

Figure 8 is a histogram showing the distribution of the control sample volume about its mean.

Figure 9 is a histogram showing the distribution of the control sample bulk density about its mean.

Test sample data

Table 4 lists the observed data obtained from the test samples.

Non-leaked (dry) test samples. The largest group of similar test samples are those that were pressurized in the pressure vessel from 17 to 21 hours and tested at various times following depressurization. These tests were called one-day pressure cures. Table 5 lists those samples that were pressure cured from 17 to 21 hours, decompressed from 30 to 70 minutes, and did not leak. Figure 10 is a plot of the test data. Superimposed on the graph is a line for the mean compressive strength of the control.

Tables 5, 6, and 7 group test data that had different lengths of pressure curing but similar lengths of decompression and all showed no signs of leakage.

Figure 11 is a plot showing the effect of different lengths of pressure curing.

Tables 5, 7, 8, and 9 group data that had lengths of pressure cures greater than 17 hours but different lengths of decompression and showed no signs of leakage.

TABLE 3. CONTROL SAMPLE DATA

Sample No.	Age When Tested (days)	Compressive Strength (psi)	Mass (gm)	Volume (cm^3)	Hardened Bulk Density $\left(\frac{mass}{volume}\right)$
1	1	1,377	424.25	190.42	2.23
4	1	1,281	422.60	192.55	2.20
7	1	1,184	425.07	189.93	2.24
20	1	1,098	422.45	189.93	2.22
31	1	1,199	422.00	194.68	2.17
53	1	1,349	423.94	194.68	2.18
56	1	1,457	427.78	195.01	2.19
71	1	1,422	427.26	194.68	2.19
74	1	1,392	424.08	194.68	2.18
Average		1,307	424.38	192.95	2.20
Standard Deviation		125	2.04	2.26	.02
No. of Samples		9	9	9	9
22	3	1,845	420.70	199.43	2.11
35	3	2,231	418.21	194.68	2.15
38	3	2,132	418.75	194.68	2.17
58	3	2,170	424.75	195.83	2.24
69	3	2,390	424.24	194.68	2.18
76	3	2,314	234.91	194.68	2.18
Average		2,180	421.76	195.66	2.17
Standard Deviation		189	2.92	1.90	.04
No. of Samples		6	6	6	6
78	5	2,844	421.81	193.37	2.18
11	7	2,859	422.77	194.68	2.17
24	7	2,922	422.18	189.93	2.22
33	7	3,226	421.12	192.06	2.19
40	7	3,482	423.21	194.68	2.17
47	7	3,560	424.36	194.68	2.18
49	7	3,288	423.63	194.68	2.18
60	7	3,568	426.11	194.68	2.19
65	7	3,617	424.17	196.97	2.15
85	7	3,389	427.29	194.68	2.19
Average		3,323	423.87	194.12	2.18
Standard Deviation		278	1.91	1.99	.02
No. of Samples		9	9	9	9
14	15	3,465	423.20	192.55	2.20
17	28	4,372	419.21	189.93	2.21
26	28	4,507	421.96	192.38	2.19
29	28	5,216	421.94	194.68	2.17
42	28	4,842	421.06	194.68	2.16
51	28	4,888	424.43	194.68	2.18
62	28	5,114	423.66	195.83	2.23
67	28	4,122	424.62	194.68	2.18
80	28	4,678	425.12	194.68	2.18
89	28	5,013	424.44	194.68	2.18
Average		4,861	422.94	194.02	2.19
Standard Deviation		292	2.00	1.78	.02
No. of Samples		9	9	9	9
44	--	--	423.81	194.68	2.18
TOTAL CONTROL AVERAGE			423.36	194.01	2.19
STANDARD DEVIATION			2.21	2.04	.03
NO. OF CONTROL SAMPLES			36	36	36

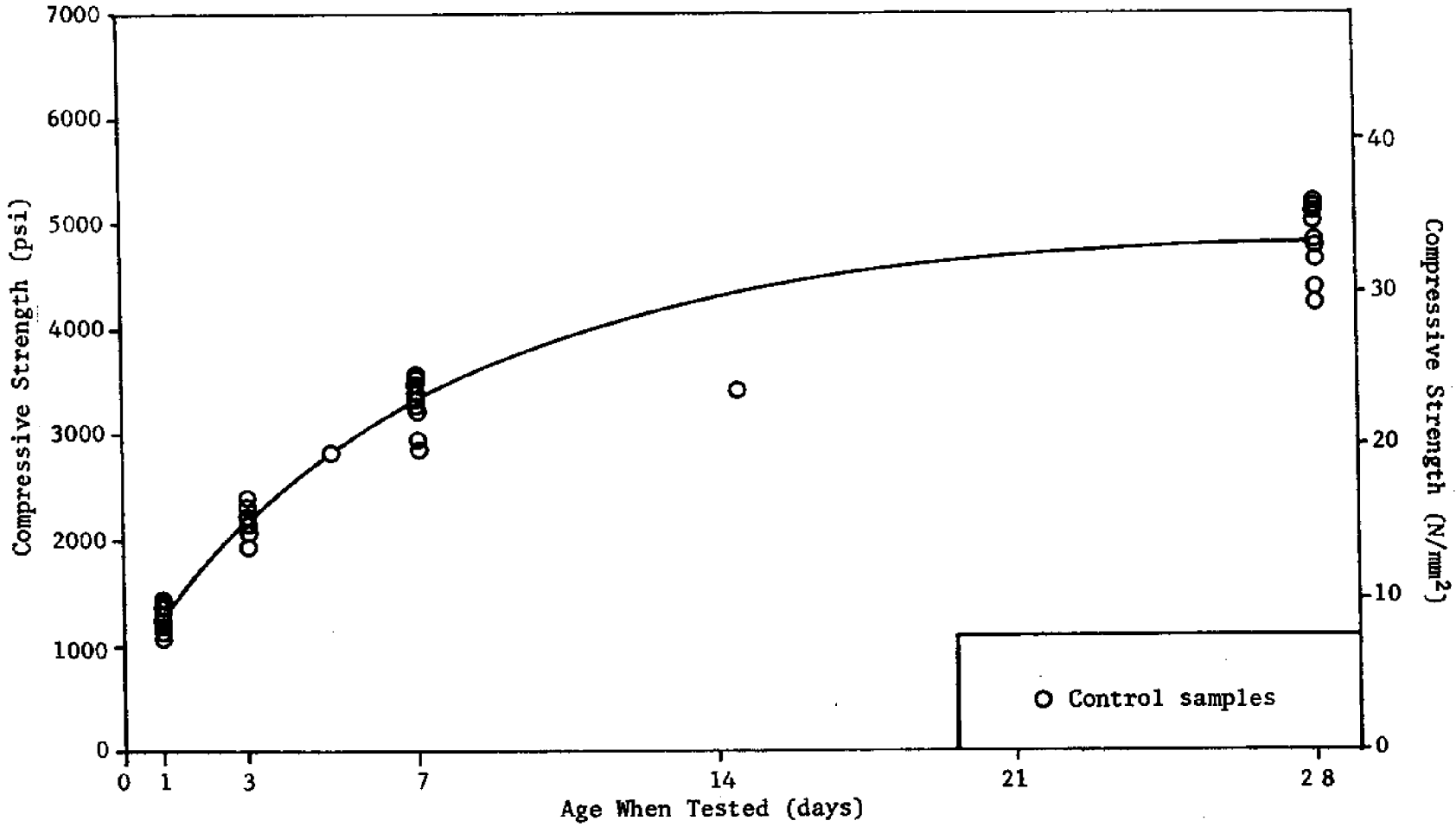

Figure 6. Strength of control samples versus age when tested

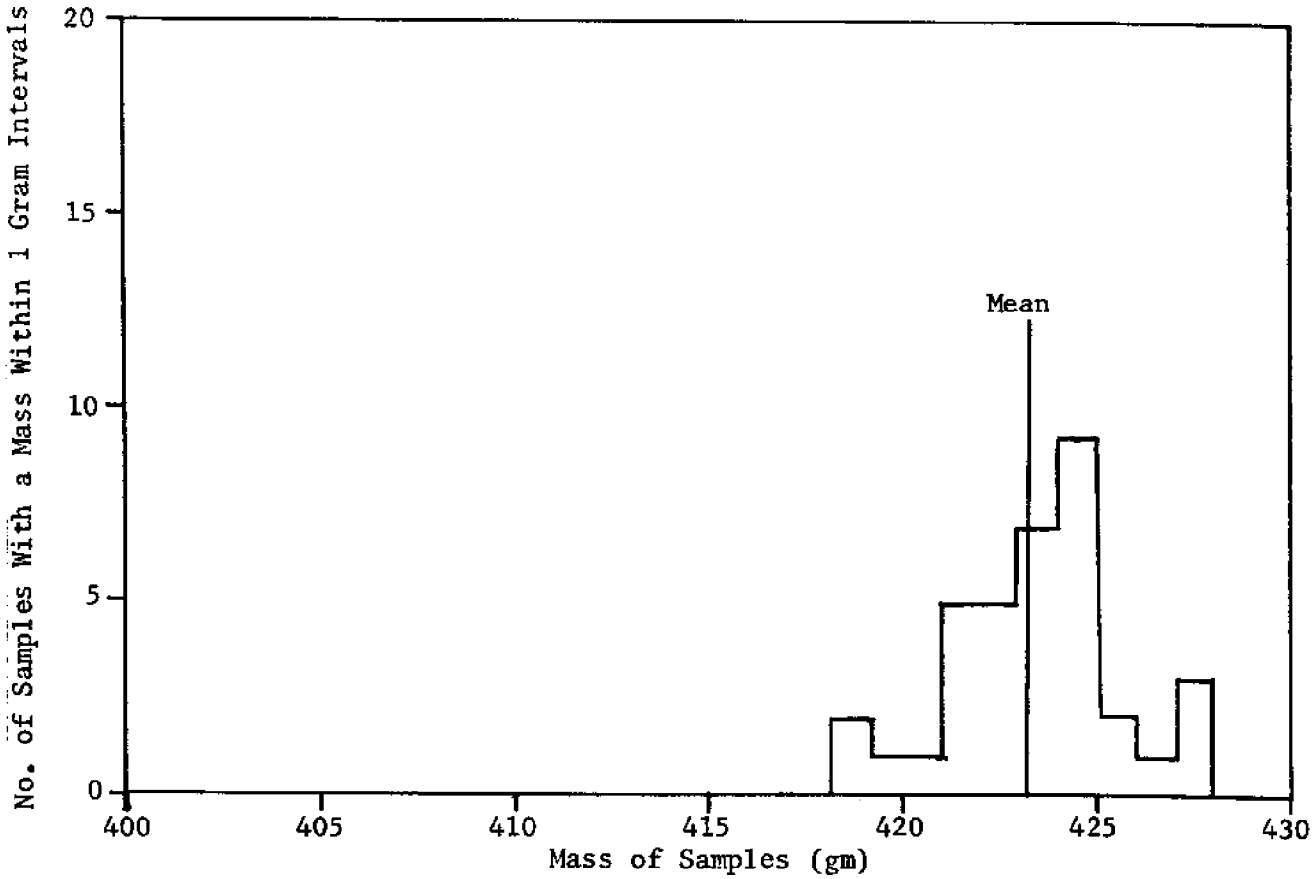

Figure 7. Distribution of control sample mass in relation to its mean

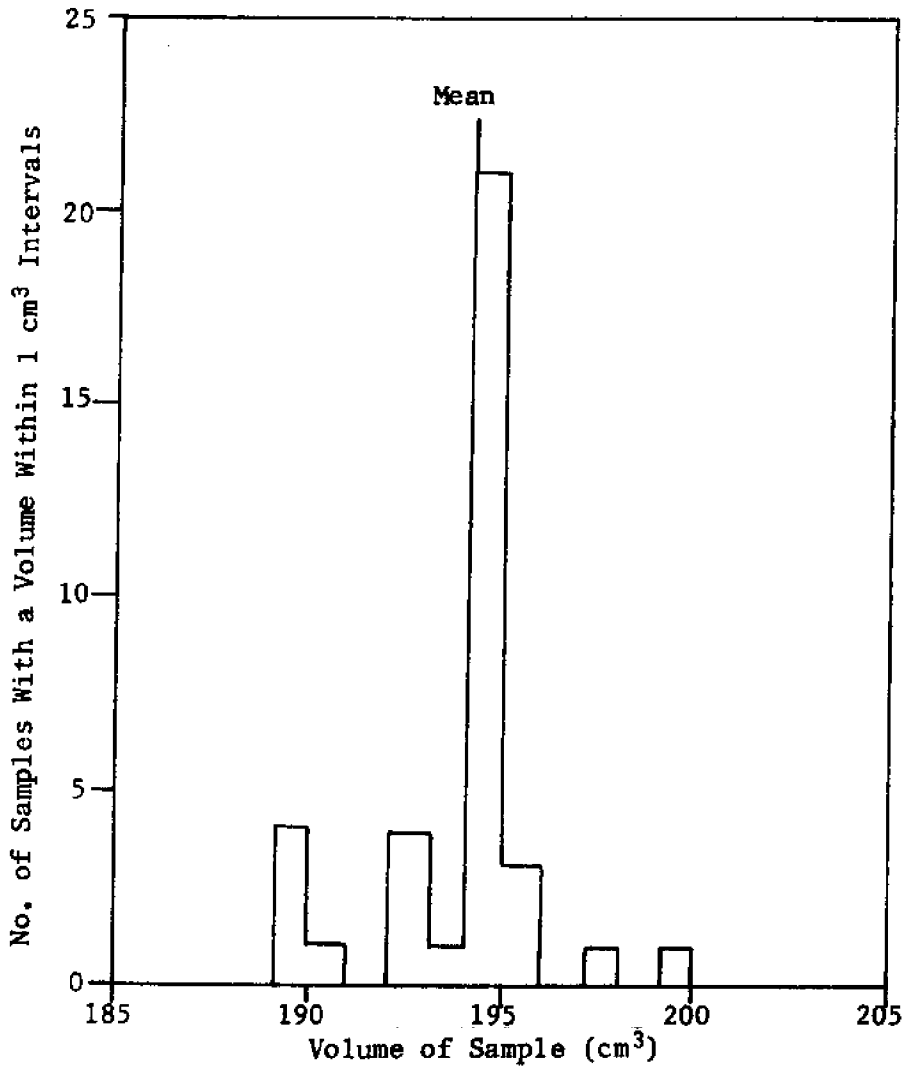

Figure 8. Distribution of control sample volume in relation to its mean

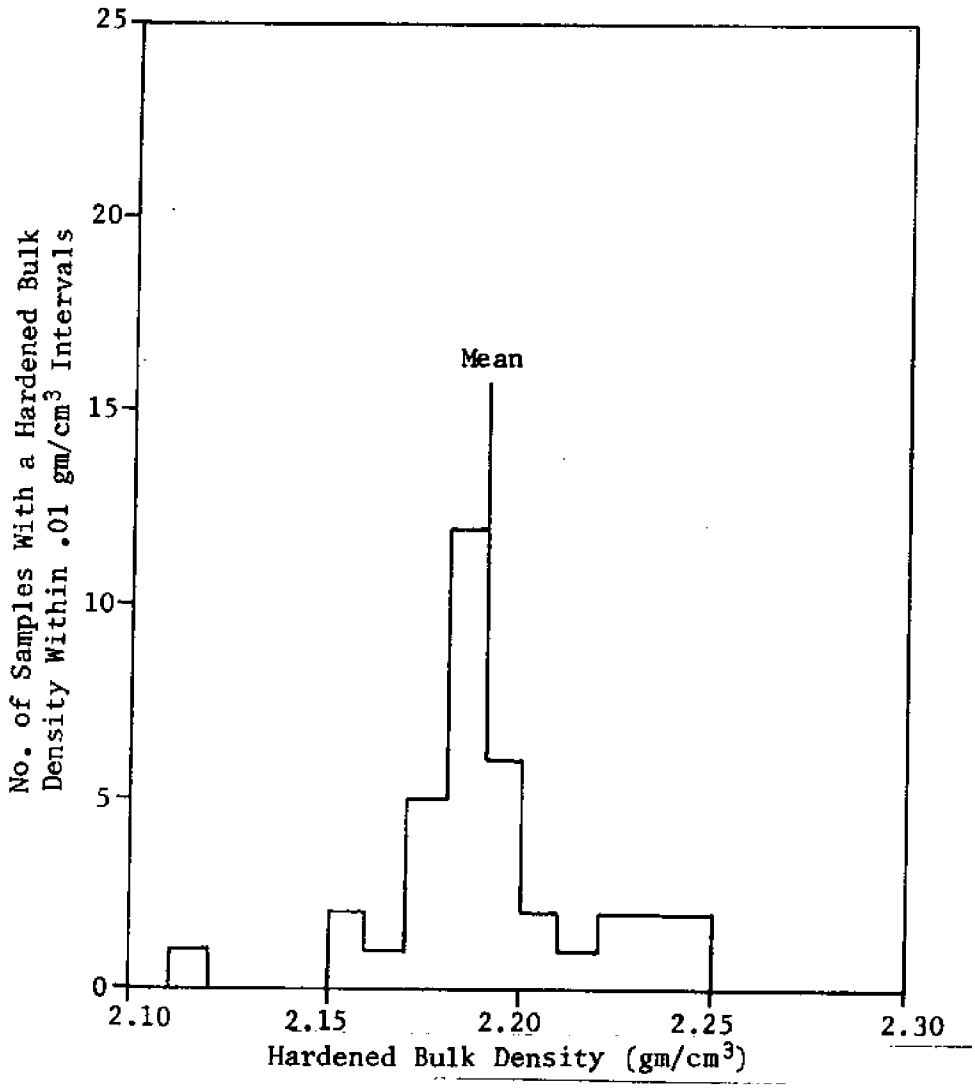

Figure 9. Distribution of control sample hardened bulk density in relation to its mean

TABLE 4. TEST SAMPLE DATA

Sample No.	Length of Time Between Mix and Pressure Curing (hr:min)	Length of Time at Pressure (hr:min)	Length of Decompression (hr:min)	Wet or Dry or Flooded	Age When Tested (day)	Compressive Strength (psi)	Mass (gm)	Volume (cm^3)	Hardened Bulk Density $\left(\frac{mass}{volume}\right)$
72	1:35	:50	:30	D	1	972	421.68	185.17	2.28
70	1:35	:50	:30	D	3	1,303	420.43	194.68	2.16
64	1:35	:50	:30	D	7	1,577	421.00	194.68	2.16
68	1:35	:50	:30	D	28	2,518	418.23	194.68	2.15
66	1:35	:50	:30	W	--	--	420.77	194.68	2.16
21	2:45	19:45	:05	D	1	1,312	414.85	184.68	2.25
23	2:45	19:45	:05	D	3	2,557	412.76	184.68	2.23
25	2:45	19:45	:05	D	7	2,922	409.09	184.68	2.22
27	2:45	19:45	:05	D	28	4,134	417.50	184.68	2.26
19	2:45	19:45	:05	W	--	--	420.13	182.72	2.30
3	2:11	19:15	:05	W	1	2,241	418.43	180.26	2.32
6	2:11	19:15	:05	W	1	2,708	416.43	175.67	2.37
9	2:11	19:15	:05	W	1	1,955	420.17	180.26	2.33
55	1:45	10:05	0:32	D	1	2,326	414.11	179.11	2.31
73	2:15	17:10	1:05	D	1	2,146	416.47	180.09	2.31
57	1:45	20:05	0:32	D	3	2,613	417.62	183.70	2.27
75	2:15	17:10	1:05	D	3	5,056*	413.94	180.09	2.30
79	2:15	17:10	1:05	D	5	4,386	418.99	180.09	2.33
59	1:45	20:05	0:32	D	7	4,194	414.82	177.80	2.33
46	2:55	10:00	1:10	D	7	4,826	415.65	180.09	2.31
48	2:55	20:00	1:10	D	7	4,226	417.17	185.01	2.25
63	1:45	20:05	:32	D	--	--	412.94	180.09	2.29
61	1:45	20:05	:32	D	28	6,489	415.45	180.09	2.31
81	2:15	17:10	1:05	D	28	5,473	420.16	181.40	2.32
50	2:55	20:00	1:10	D	28	6,120	412.61	180.09	2.29
30	2:10	19.05	1:05	W	1	2,761	412.26	177.80	2.32
52	2:55	20:00	1:10	W	1	1,732	416.68	180.09	2.31
34	2:10	19:05	1:05	W	3	3,635	415.75	180.26	2.31
32	2:10	19:05	1:05	W	7	5,375	414.25	180.26	2.30
28	2:10	19:05	1:05	W	28	6,186	411.31	180.26	2.28
36	2:10	19:05	1:05	W	29	5,318	413.27	182.72	2.26
77	2:15	17:10	1:05	W	--	--	420.71	181.40	2.32
54	2:55	10:00	1:10	W	--	--	413.18	180.09	2.29
39	2:45	66:55	1:05	D	7	4,484	419.34	177.80	2.36
37	2:45	66:55	1:05	W	3	3,292	415.32	180.09	2.31
41	2:45	66:55	1:05	W	28	5,924	412.40	180.09	2.29
43	2:45	66:55	1:05	W	--	--	416.36	180.09	2.31
45	2:45	66:55	1:05	W	--	--	414.75	180.09	2.30
84	2:10	76:35+	7:00+	D	7	4,957	419.82	180.09	2.33
90	2:10	76:35+	7:00+	D	28	6,039	424.25	180.09	2.36
86	2:10	76:35+	7:00+	W	--	--	427.41	181.40	2.36
10	17:02	:10	:05	W	7	2,402	416.79	189.93	2.19
13	17:02	:10	:05	W	15	3,760	418.80	187.30	2.24
16	17:02	:10	:05	W	28	4,402	420.13	185.34	2.21
12	18:10	5:15	:05	D	7	3,569	414.55	187.30	2.21
15	18:10	5:15	:05	D	15	4,221	420.00	187.30	2.24
18	18:10	5:15	:05	D	28	4,595	416.81	189.93	2.19
83	WET CONTROL		--	F	7	3,003	430.30	195.99	2.20
87	WET CONTROL		--	F	28	5,106	428.90	197.46	2.17
2	2:11	19:15	:05	F	1	1,082	421.07	187.96	2.24
5	2:11	19:15	:05	F	1	1,050	401.35	189.93	2.11
8	2:11	19:15	:05	F	1	1,110	406.65	195.17	2.08
82	2:10	76:35+	7:00+	F	7	3,513	438.49	194.68	2.25
88	2:10	76:35+	7:00+	F	28	4,227	438.17	194.68	2.25

*Figure is unreliable. Sample was accidently loaded until failure in one second; all other samples loaded slowed and failed between 20 and 80 seconds.

TABLE 5. HYDROSTATIC COMPACTION DATA OF TEST SAMPLES THAT WERE PRESSURE CURED FROM 17 TO 21 HOURS, DECOMPRESSED FROM 30 TO 70 MINUTES, AND DID NOT LEAK

Sample No.	Age When Tested (days)	Compressive Strength (psi)	Mass (gm)	Volume (cm^3)	Bulk Density $\left(\frac{mass}{volume}\right)$
55	1	2,326	414.11	179.11	2.31
73	1	2,146	416.47	180.09	2.31
Average		2,236			
57	3	2,613	417.62	183.70	2.27
79	5	4,386	418.99	180.09	2.33
59	7	4,194	414.82	177.80	2.33
46	7	4,826	415.65	180.09	2.31
48	7	4,226	417.17	185.01	2.25
Average		4,415			
50	28	6,120	412.61	180.09	2.29
61	28	6,489	415.45	180.09	2.31
63	--	--	412.94	180.09	2.29
81	28	5,473	420.16	181.40	2.32
Average		6,027			

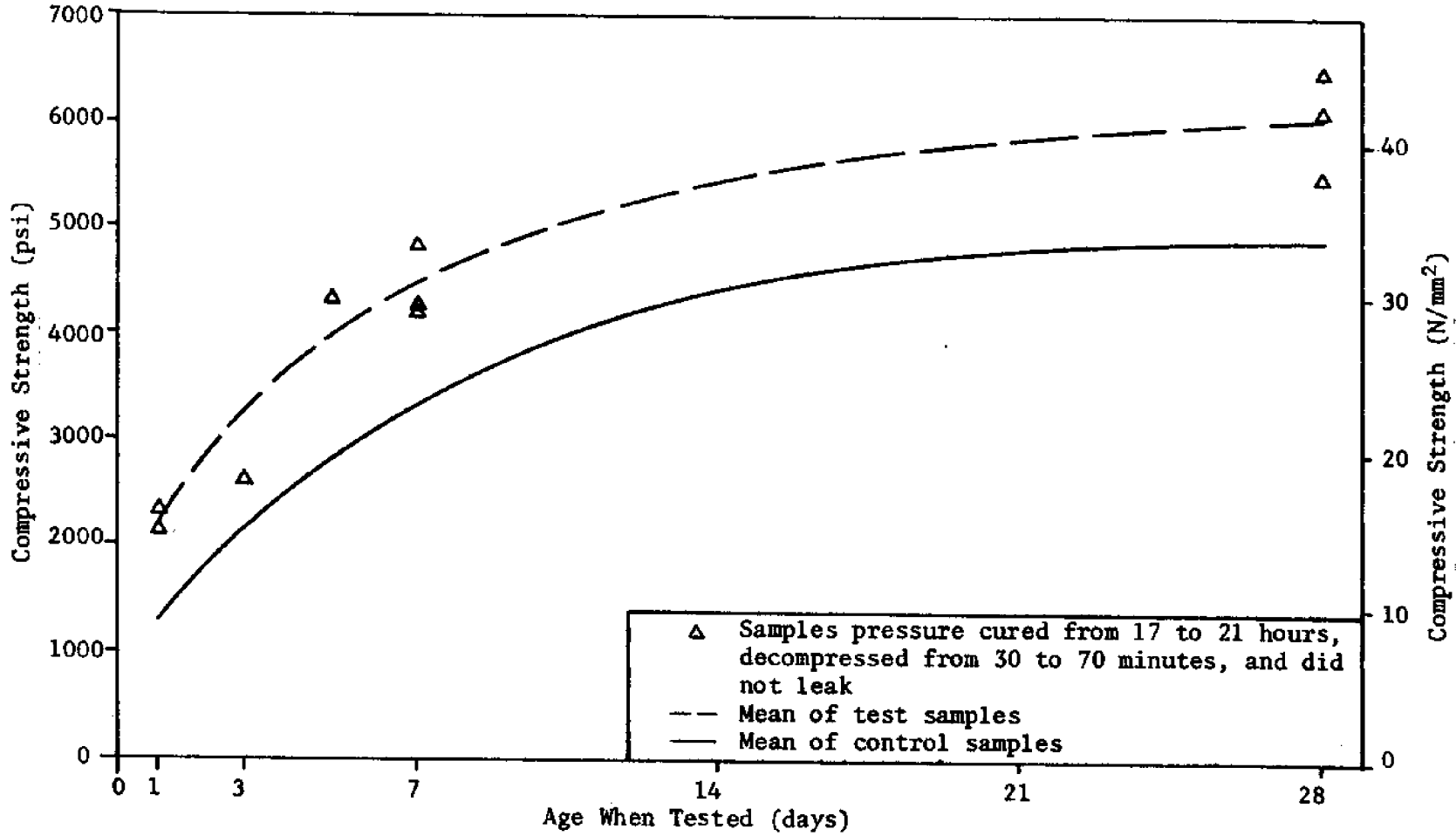

Figure 10. Test samples pressure cured from 17 to 21 hours, decompressed from 30 to 70 minutes, and did not leak

TABLE 6. HYDROSTATIC COMPACTION DATA OF TEST SAMPLES THAT WERE PRESSURE CURED FROM 15 TO 60 MINUTES, DECOMPRESSED FROM 30 TO 70 MINUTES, AND DID NOT LEAK

Sample No.	Age When Tested (days)	Compressive Strength (psi)	Mass (gm)	Volume (cm^3)	Bulk Density $\left(\frac{mass}{volume}\right)$
72	1	972	421.68	185.17	2.28
70	3	1,303	420.43	194.68	2.16
64	7	1,577	421.00	194.68	2.16
68	28	2,518	418.23	194.68	2.15

TABLE 7. HYDROSTATIC COMPACTION DATA OF TEST SAMPLES THAT WERE PRESSURE CURED FROM 65 TO 75 HOURS, DECOMPRESSED FROM 30 TO 70 MINUTES, AND DID NOT LEAK

Sample No.	Age When Tested (days)	Compressive Strength (psi)	Mass (gm)	Volume (cm^3)	Bulk Density $\left(\frac{mass}{volume}\right)$
39	7	4,484	419.34	177.80	2.36

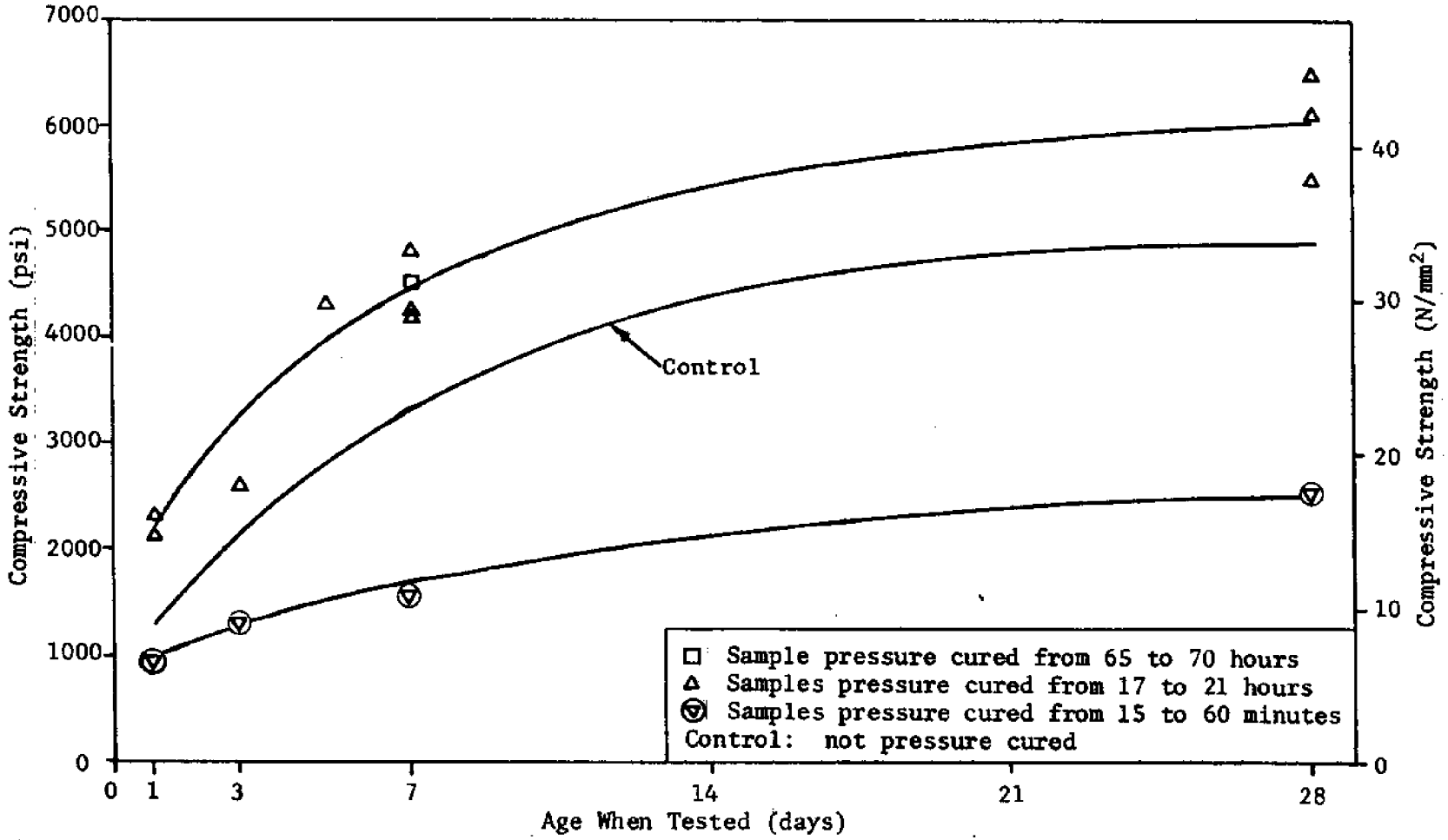

Figure 11. Various length of pressure curing for samples with 30 to 70 minutes decompression time and showing no signs of leakage

TABLE 8. HYDROSTATIC COMPACTION DATA OF TEST SAMPLES THAT WERE PRESSURE CURED FROM 17 TO 21 HOURS, DECOMPRESSED FROM 5 TO 10 MINUTES, AND DID NOT LEAK

Sample No.	Age When Tested (days)	Compressive Strength (psi)	Mass (gm)	Volume (cm^3)	Bulk Density $\left(\frac{mass}{volume}\right)$
21	1	1,312	414.85	184.68	2.25
23	3	2,557	412.76	184.68	2.23
25	7	2,922	409.09	184.68	2.22
27	28	4,134	417.50	184.68	2.26

TABLE 9. HYDROSTATIC COMPACTION DATA OF TEST SAMPLES THAT WERE PRESSURE CURED FROM 72 TO 168 HOURS, DECOMPRESSED FROM 7 TO 100 HOURS, AND DID NOT LEAK

Sample No.	Age When Tested (days)	Compressive Strength (psi)	Mass (gm)	Volume (cm^3)	Bulk Density $\left(\frac{mass}{volume}\right)$
84	7	4,957	419.82	180.09	2.33
90	28	6,039	424.25	180.09	2.31

Figure 12 is a plot showing the effect of different lengths of decompression.

Leaked (wet) test samples. Tables 10, 11, 12, 13, and 14 group test samples that were pressure cured and depressurized and showed signs of leakage.

Table 15 groups test samples that were "flooded" prior to pressure curing.

Figure 13 is a plot of data in Table 10 and shows the relationship of the compressive strength of leaked versus non-leaked samples that were pressure cured from 17 to 21 hours and decompressed from 5 to 10 minutes.

Figure 14 is a plot of data in Table 11 and shows the relationship of the compressive strength of leaked versus non-leaked samples that were pressure cured from 17 to 21 hours and decompressed from 30 to 70 minutes.

Figure 15 a plot of data in Tables 7, 9, and 12 and shows the relationship of the compressive strength of leaked versus non-leaked samples that were pressure cured for longer than 65 hours and were decompressed over a time interval greater than 30 minutes.

Control and test sample data

Table 16 summarizes the means and standard deviations of flooded, leaked, non-leaked, and control samples for mass, volume, and hardened bulk density.

Permeable voids

The results of the permeable voids study are listed in Table 17. Seven samples were used, each to represent a slightly different pressure curing condition:

1. Control: sample 44
2. 15 to 60-minute cure: sample 66
3. 17 to 21-hour cure, fast decompression: sample 19
4. 17 to 21-hour cure, slow decompression, non-leaked: sample 63
5. 17 to 21-hour cure, slow decompression, leaked: sample 77
6. 65 to 70-hour cure: sample 43
7. 72 to 168-hour cure, very slow decompression: sample 86

Absorption rate

Tables indicating the amount of saturation of samples 19, 43, 44, 63, 66, 77, and 86 following immersion in water after being oven dried are in Appendix C. Figure 16 is a plot of the amount of saturation versus time for all seven samples.

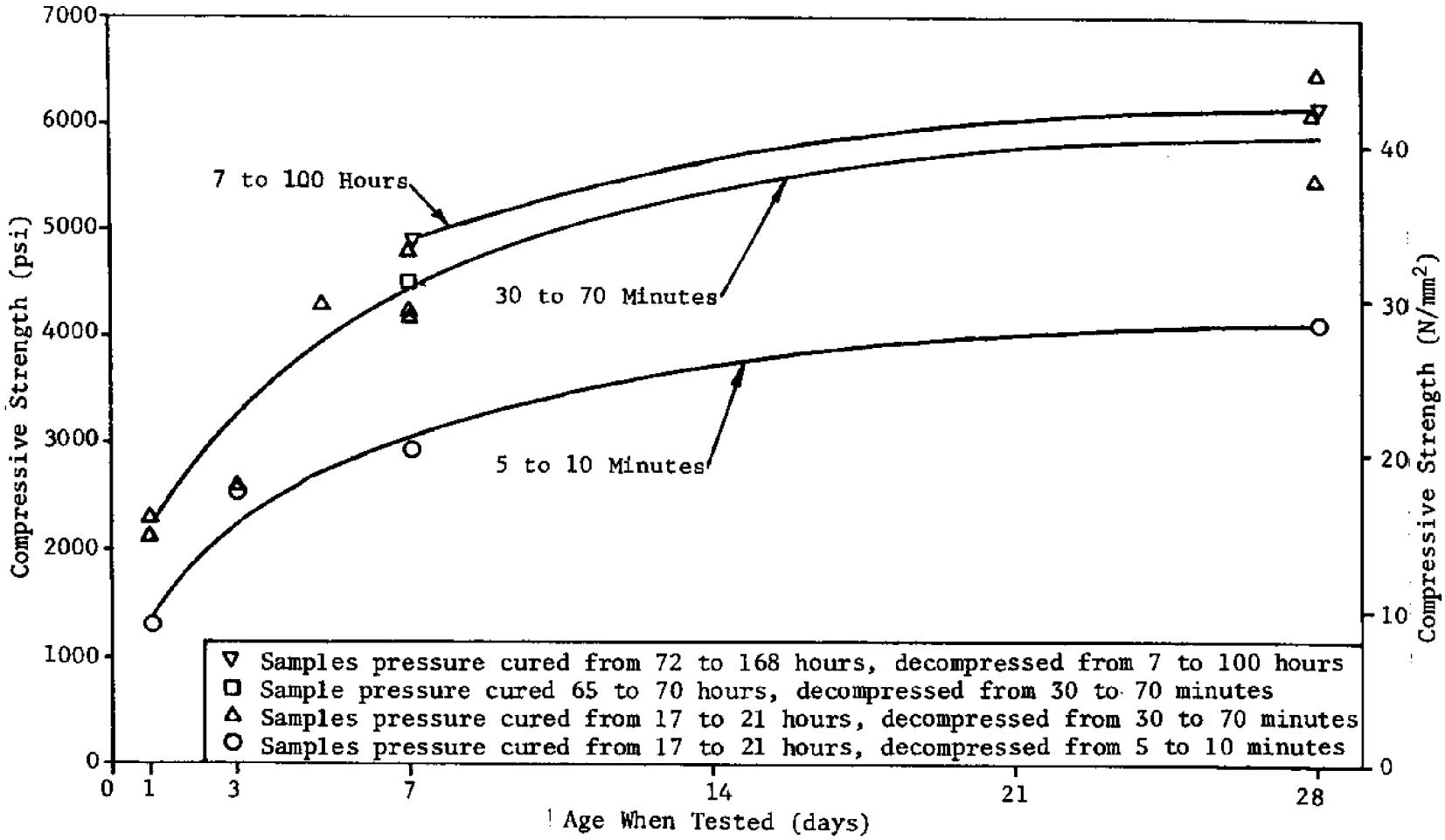

Figure 12. Various length of decompression for samples pressure cured greater than 17 hours and showing no signs of leakage

TABLE 10. HYDROSTATIC COMPACTION DATA OF TEST SAMPLES THAT WERE PRESSURE CURED FROM 17 TO 21 HOURS, DECOMPRESSED FROM 5 TO 10 MINUTES, AND LEAKED

Sample No.	Age When Tested (days)	Compressive Strength (psi)	Mass (gm)	Volume (cm^3)	Bulk Density $\left(\frac{mass}{volume}\right)$
3	1	2,241	418.43	180.26	2.32
6	1	2,708	416.43	175.67	2.37
9	1	1,955	420.17	180.26	2.33
	Average = 1,792				
19	--	--	420.13	182.72	2.30

TABLE 11. HYDROSTATIC COMPACTION DATA OF TEST SAMPLES THAT WERE PRESSURE CURED FROM 17 TO 21 HOURS, DECOMPRESSED FROM 30 TO 70 MINUTES, AND LEAKED

Sample No.	Age When Tested (days)	Compressive Strength (psi)	Mass (gm)	Volume (cm^3)	Bulk Density $\left(\frac{mass}{volume}\right)$
30	1	2,761	412.29	177.80	2.32
52	1	1,732	416.68	180.09	2.31
	Average = 2,247				
34	3	3,635	415.75	180.26	2.31
32	7	5,375	414.25	180.26	2.30
28	28	6,186	411.31	180.26	2.28
36	--	--	413.27	182.72	2.26
54	--	--	413.18	180.09	2.29
77	--	--	420.71	181.40	2.32

TABLE 12. HYDROSTATIC COMPACTION DATA OF TEST SAMPLES THAT WERE PRESSURE CURED FROM 65 TO 70 HOURS, DECOMPRESSED FROM 30 TO 70 MINUTES, AND LEAKED

Sample No.	Age When Tested (days)	Compressive Strength (psi)	Mass (gm)	Volume (cm^3)	Bulk Density $\left(\frac{mass}{volume}\right)$
37	3	3,292	415.32	180.09	2.31
41	28	5,924	412.40	180.09	2.29
43	--	--	416.36	180.09	2.31
45	--	--	414.75	180.09	2.30

TABLE 13. HYDROSTATIC COMPACTION DATA OF TEST SAMPLES THAT WERE PRESSURE CURED FROM 15 TO 60 MINUTES, DECOMPRESSED FROM 30 TO 70 MINUTES, AND LEAKED

Sample No.	Age When Tested (days)	Compressive Strength (psi)	Mass (gm)	Volume (cm^3)	Bulk Density $\left(\frac{mass}{volume}\right)$
66	--	--	420.77	194.68	2.16

TABLE 14. HYDROSTATIC COMPACTION DATA OF TEST SAMPLES THAT WERE PRESSURE CURED FROM 72 TO 168 HOURS, DECOMPRESSED FROM 7 TO 100 HOURS, AND LEAKED

Sample No.	Age When Tested (days)	Compressive Strength (psi)	Mass (gm)	Volume (cm^3)	Bulk Density $\left(\frac{mass}{volume}\right)$
86	--	--	427.41	181.40	2.36

TABLE 15. FLOODED TEST SAMPLES

Sample No.	Length Pressure Cure (hr:min)	Age When Tested (days)	Compressive Strength (psi)	Mass (gm)	Volume (cm^3)	Hardened Bulk Density $\left(\frac{mass}{volume}\right)$
83	Control	7	3,003	430.30	195.99	2.20
87	Control	28	5,106	428.90	197.46	2.17
2	19:15	1	1,082	421.07	187.96	2.24
5	19:15	1	1,050	401.35	189.93	2.11
8	19:15	1	1,110	406.65	195.17	2.08
82	76:35+	7	3,513	438.49	194.68	2.25
88	76:35+	28	4,227	438.17	194.68	2.25
Mean				423.17	193.70	2.19
Standard Deviation				14.70	3.43	.07
No. of Samples				7	7	7

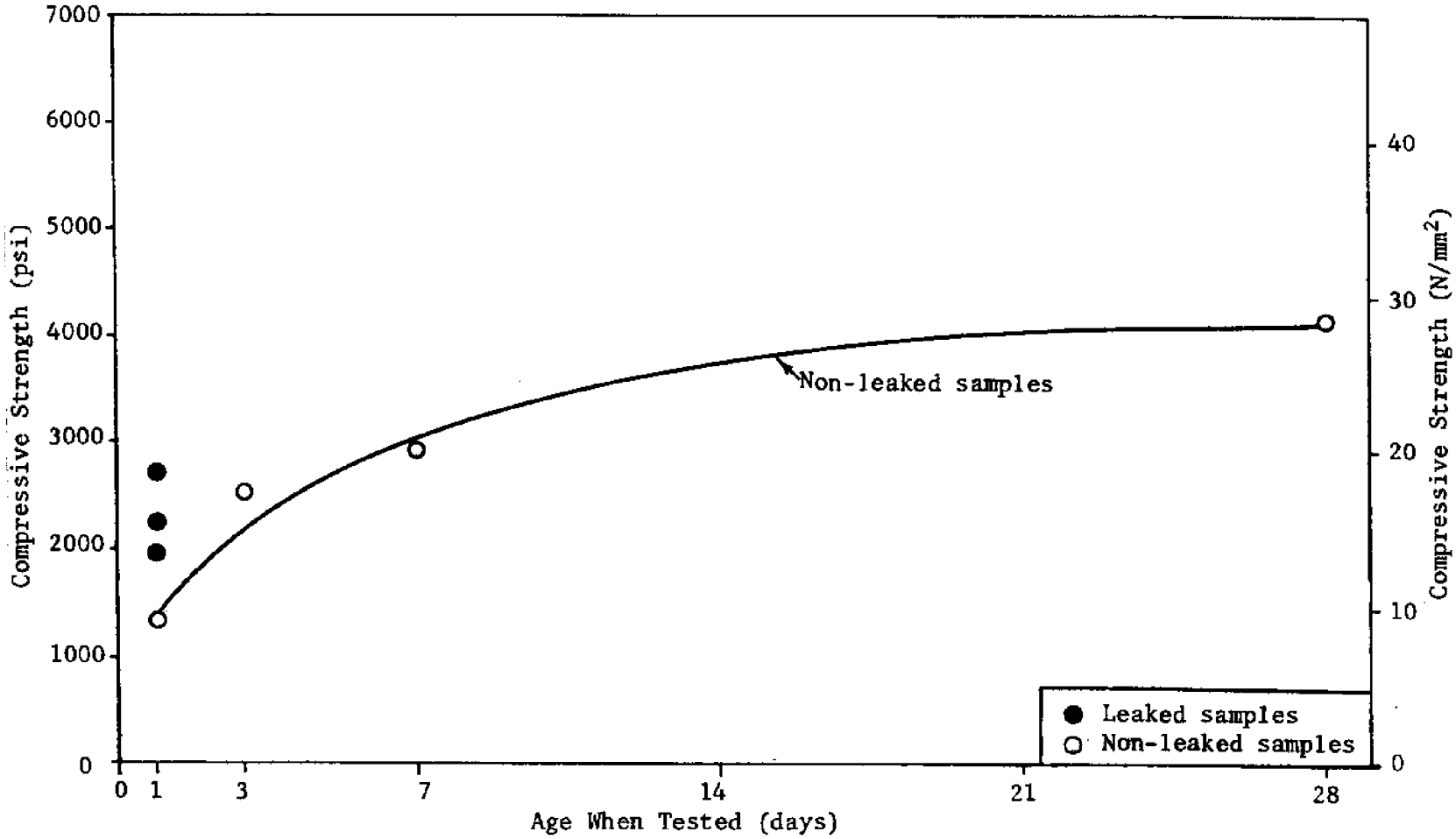

Figure 13. Leaked versus non-leaked samples pressure cured from 17 to 21 hours and decompressed from 5 to 10 minutes

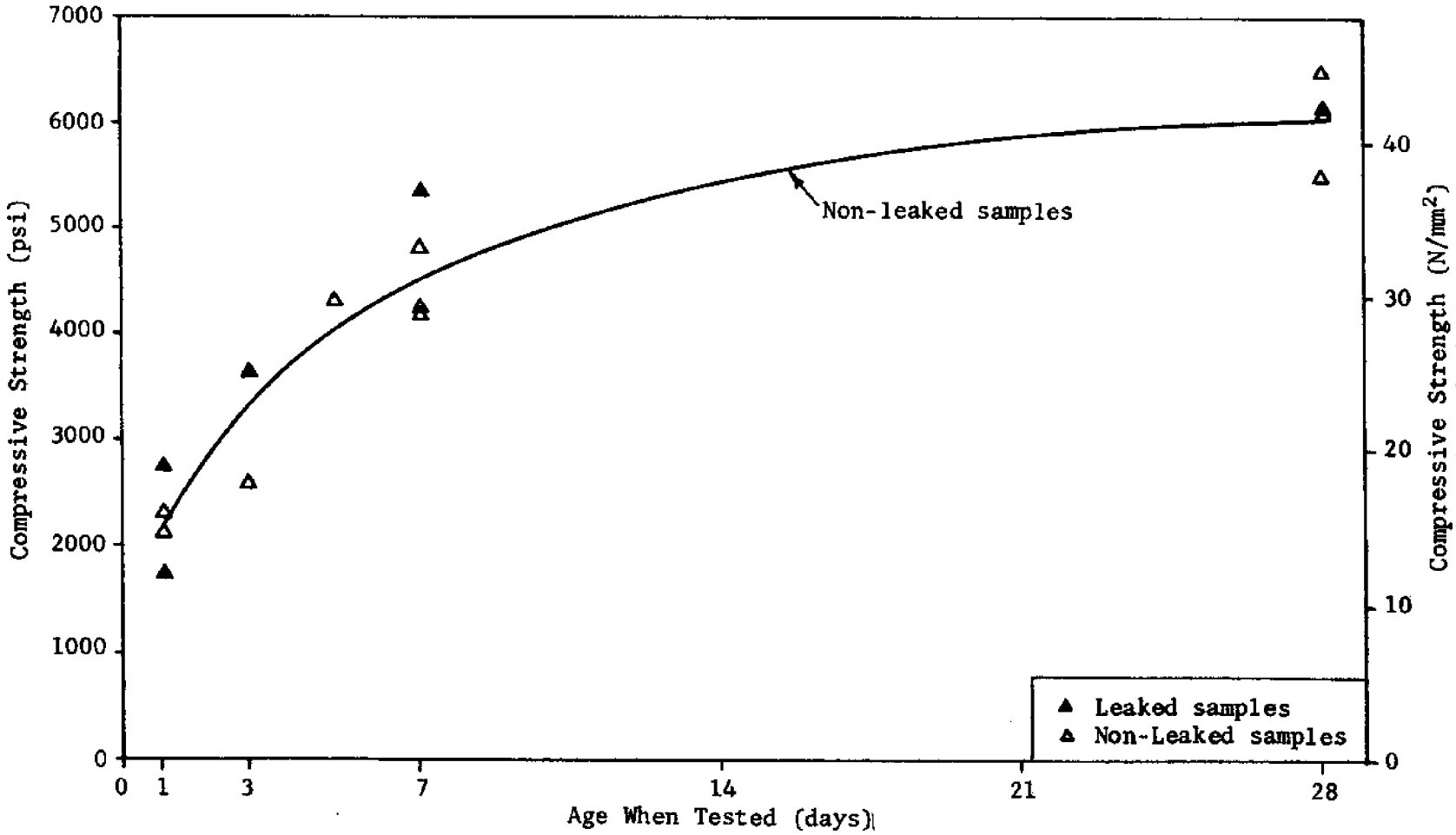

Figure 14. Leaked versus non-leaked samples pressure cured from 17 to 21 hours and decompressed from 30 to 70 minutes

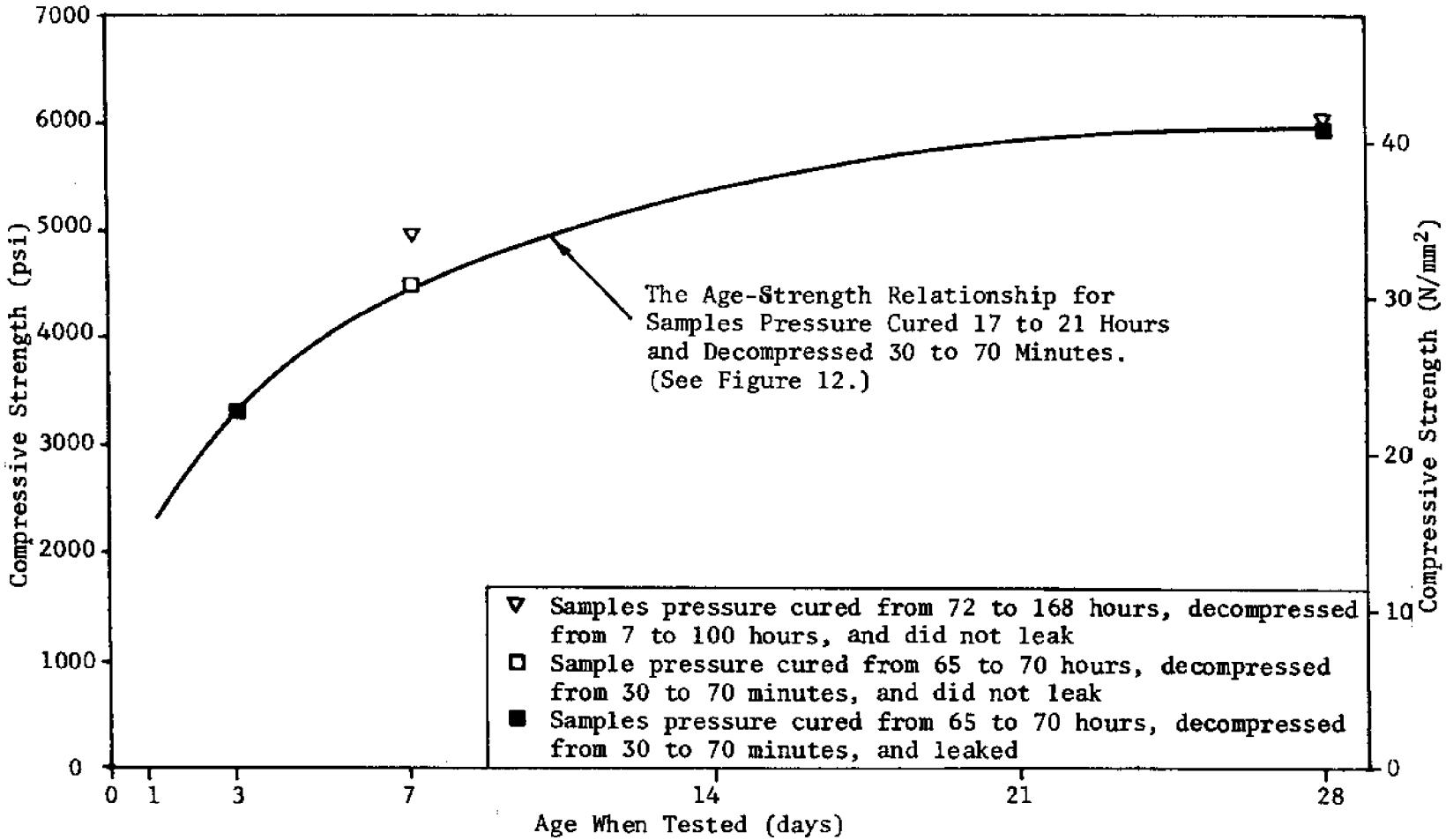

Figure 15. Leaked versus non-leaked samples pressure cured for longer than 65 hours and decompressed over a time interval greater than 30 minutes

TABLE 16. SUMMARY OF MEAN AND STANDARD DEVIATION VALUES FOR MASS, VOLUME, AND HARDENED BULK DENSITY

Type of Sample	No. of Samples	Mass		Volume		Hardened Bulk Density	
		Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Control	36	423.36	2.21	194.01	2.04	2.19	.03
Flooded (test)	7	423.56	14.70	193.70	3.43	2.19	.07
Leaked (test)	21	416.92	3.83	181.94	4.24	2.29	.05
Non-leaked (test)	26	416.93	3.43	183.77	5.09	2.27	.06

TABLE 17. SPECIFIC GRAVITY, ABSORPTION, AND VOIDS IN HARDENED MORTAR

Sample No.	Length of Pressure Cure (hr:min)	Length of Decompression (hr:min)	Leaked (W) or Non-Leaked (D)	Oven Dry Weight (gm)	Saturated Weight After Immersion (gm)	Saturated Weight After Boiling (gm)	Immersed Weight of 100% Saturated Sample (gm)	Volume of Sample (ml)	Absorption After Immersion (%)	Absorption After Immersion and Boiling (%)	Bulk Specific Gravity Dry	Bulk Specific Gravity After Immersion	Bulk Specific Gravity After Immersion and Boiling	Apparent Specific Gravity	Volume of Permeable Voids Method A (%)	Volume of Permeable Voids Method B (%)	Average Volume of Permeable Voids (%)	Volume of Permeable Voids Sample Average to Control Sample (%)
19	19:45	0:05	W	395.40	421.72	422.30	238.70	183.60	6.66	6.77	2.15	2.30	2.30	2.52	14.68	14.65	14.67	102
43	66:55	1:05	W	388.62	412.75	413.53	235.65	177.88	6.21	6.39	2.18	2.32	2.32	2.54	14.17	14.00	14.09	98
44	Control		D	395.35	423.14	423.63	228.44	195.19	7.03	7.13	2.03	2.17	2.17	2.37	14.35	14.49	14.42	100
63	20:05	0:32	D	388.25	410.42	410.94	233.27	177.67	5.71	5.83	2.19	2.31	2.31	2.51	12.75	12.77	12.76	88
66	0:50	0:30	W	391.23	417.90	422.37	234.09	188.28	6.82	7.93	2.08	2.22	2.24	2.49	16.47	16.54	16.51	114
77	17:10	1:05	W	394.51	417.67	418.23	237.90	180.33	5.87	5.99	2.19	2.32	2.32	2.52	13.10	13.15	13.13	91
86	76:35+	7:00+	W	396.62	418.51	418.78	238.68	180.10	5.52	5.57	2.20	2.32	2.33	2.51	12.35	12.30	12.33	86

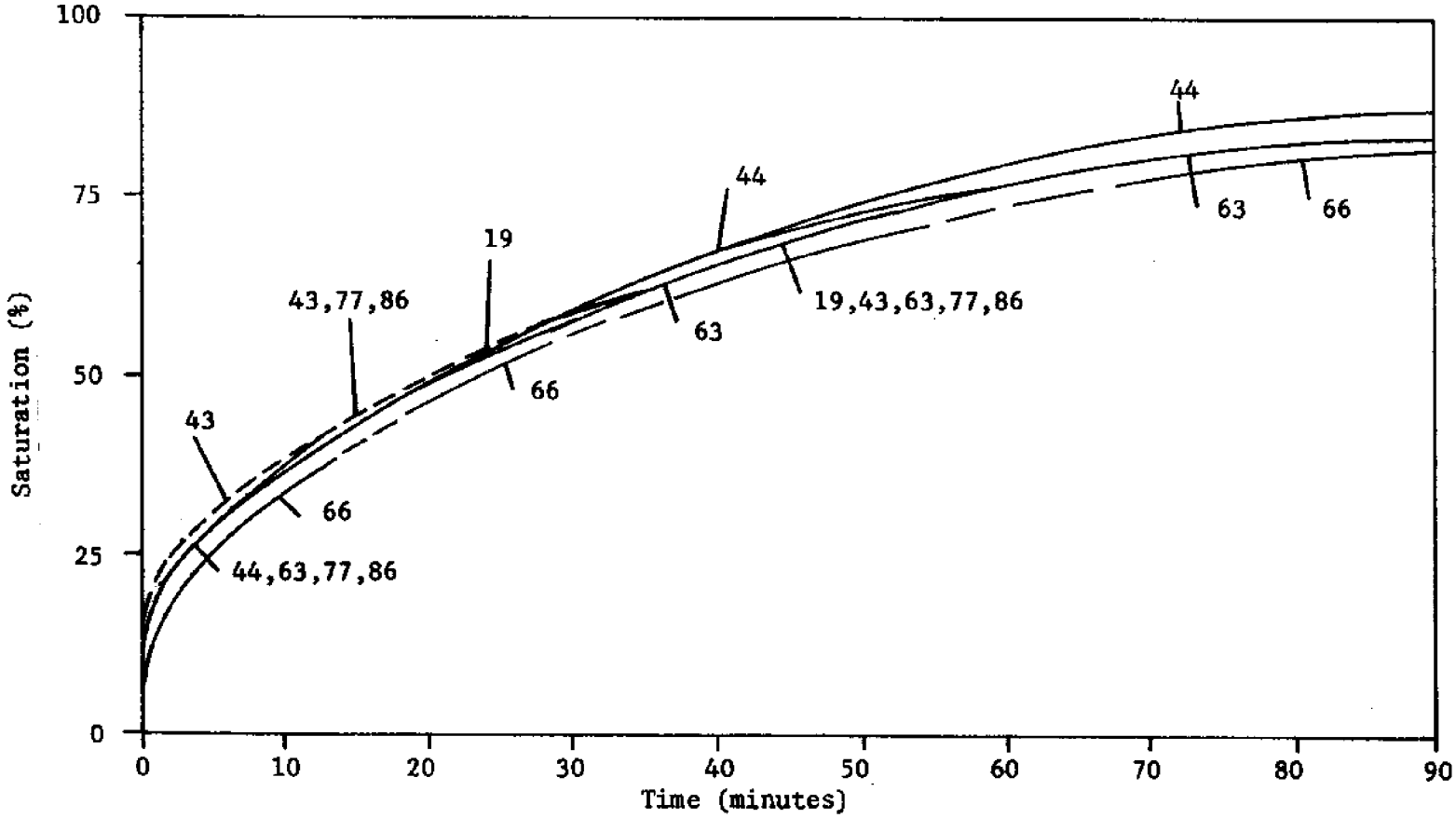

Figure 16. Percentage of saturation of dry samples versus time following immersion in water (Sample numbers listed in Table 17.)

Photomicrographs

After the tests, each of the seven samples used in the permeable voids test were cut in half with a rock saw, polished, and examined with a microscope. In addition, some other samples (those not in the permeable voids test) were examined. For example, remaining portions of both samples tested for compressive strength and samples not tested at all were taken; they showed nothing.

Air entrainment and standard deviation

The percentage of entrained air in the fresh concrete was 6.63 with a standard deviation of 0.58.

DISCUSSION

Experimental Methods

In the past, the use of pressure during the curing of portland cement products has largely been of secondary importance or at least a consequence of selecting some other parameter as the major curing method. For example, in high pressure autoclaving, the steam must be pressurized in order to obtain high temperatures.

As pointed out in the review of the state-of-the-art of methods for curing portland cement products, each discipline has independently acquired certain knowledge and practices suitable to meet its own needs. The discovery of a technique and curing process utilizing high hydrostatic pressure was thus due to an interdisciplinary approach; that is, data and methods of different curing procedures were combined and modified to produce a new method. Similarly, this research was conducted using an interdisciplinary approach, drawing upon civil engineering, geology, geophysics, and oil well cementing technologies to test the hypothesis; that is, concrete, a common ocean engineering material, was treated as if it were (geologically) an artificial metamorphic conglomerate rock. High pressure geophysical experimental equipment was used to hydrostatically compact and cure the test concrete. Civil engineering methods were used to analyze the test results.

It must be noted that, from a geological metamorphic point of view, it is assumed that the observed changes in physical properties are not due to chemical metamorphism (other than hydration) but instead are due to lithification, where lithification is that complex of processes that converts a newly deposited sediment into an indurated rock. An indurated rock is a rock that has been rendered hard by pressure and cementation in addition to heat. In other words, a high hydrostatic pressure-cured concrete may also be called an indurated conglomerate rock formed by lithification.

The modified experimental tests--the third series of experiments--were used to test various pressure curing techniques and equipment. As a result of those tests it was decided that one desirable parameter for pressure curing of concrete was "non-flooding." This means that the water surrounding the fresh concrete must not come into direct contact with the concrete until after the concrete has hardened. One reason for wanting a non-flooding condition is to prevent erosion of the fresh concrete. Test samples 2, 5, and 8 were flooded prior to pressurization and were not very well protected from the surrounding water. As a result, part of each sample was washed away. This fact is reflected in the reduced mass of the samples as compared with other test samples.

Control Samples

Nine samples were made from each batch of mortar that was mixed. Four of these, the 2nd, 4th, 6th, and 8th formed, were selected to be control samples. Each control sample was placed, tamped, vibrated, and packaged in the same manner as the test samples. They were even transported to Pier 18 and submerged in a pail of water during the time that the test samples were being pressure cured in the pressure vessel. In this way both the test and control samples underwent identical curing conditions, except for the pressure.

The control samples had two functions. One was to act as a standard against which the results of the pressure curing test could be compared. The other was to test and to demonstrate that each batch made was identical or similar to the others since any slight deviations between batches would be reflected both in the control and test samples; that is, a deviation in a control batch would indicate that the test results from that batch might not be valid also. In addition, the mean of the control samples was selected as the standard against which the test samples were compared.

The variation in compressive strength between samples of concrete is generally expected to be quite high. In industry for example, a variation of ±10% is quite common between successive batches. As can be seen in Table 4, the control samples were uniform in strength. All control samples were within two standard deviations of the mean. This indicates that the control samples had little variation. Similarly the control sample masses were grouped within a narrow band. This means that all the control samples were similar in size.

Analyses of the volumes of the control samples indicate that the accuracy of the calculated volume was limited by the accuracy of the original measurements. The bulk density of the hardened control concrete samples was based upon the mass and volume calculations. Therefore its accuracy was limited by the accuracy of the mass and volume calculations.

In all cases of comparison, it is the mean of all the control samples that is used as the standard, not the values for individual control samples.

Test Samples

Non-leaked (dry)

Analyses of the test results and comparison with the mean of the control samples indicate that pressure curing does indeed affect compressive strength, mass, volume, and hardened bulk density.

The analyses were done by grouping only similar test samples.

The first samples to be compared with the control samples were those samples pressure cured from 17 to 21 hours, decompressed from 30 to 70 minutes, and showed no signs of leakage. On the average these samples were about 905 psi stronger than the mean of the control sample. There was about a 5% change in volume with a resulting increase in bulk density.

Leaked (wet)

Some samples that were originally dry and packaged with a dry paper towel between triple bagging showed signs of leakage following depressurization. In most cases the paper towel was only damp and compressed against the side of the can. In some cases the towels were soaked with water and pinholes could be seen in the bag, usually at spots where the bag had wrinkled and pinched around the end of the can.

Initially, these samples were not compared with the control samples because the control samples had remained non-leaked or dry. However, the leaked samples looked similar to the non-leaked test samples; that is, they were the same size, weight, and density as the non-leaked samples and were a darker color than the control samples, just as the non-leaked samples were a darker color. Due to this similarity between leaked and non-leaked samples, it was suspected that the leaking occurred after compaction.

In general, samples which were deliberately flooded prior to pressure curing were similar to the control samples with respect to volume and compressive strength (e.g., samples 82 and 88). They were, however, higher in mass and bulk density because they were weighed in a saturated condition; the control samples were weighed prior to submersion or testing and thus were not completely saturated. On the other hand, flooded samples that were not packaged very well were leached and eroded, losing mass and volume with a subsequent reduction in bulk density and compressive strength (e.g., samples 2, 5, and 8). Finally, flooded samples that were packaged adequately but not pressure cured (flooded control samples) were similar to the control samples (e.g., samples 83 and 87).

A comparison among the dry test samples, the leaked test samples, and the flooded test samples indicates that in general, the leaked test samples are similar to the dry test samples but different from the flooded test samples. It is therefore concluded that in most cases, the leaking occurred after hydrostatic compaction had occurred.

Effect of Length of Pressure Cure

Analysis of the length of pressure cure indicates that if the mortar is depressurized before final set, the entrained air which was compressed during pressurization will expand and rupture the concrete. The concrete essentially will become unglued and uncompressed. The sample expands back to its original volume and becomes similar to the control volume.

If the mortar is pressure cured well beyond final set, which occurs in five hours, the sample will remain permanently compacted and will have a permanent increase in strength (at least for 28 days). Increasing the length of pressure curing may slightly increase the strength, but from the few long-term curing samples tested, no significant statistical difference from the one-day cures could be established.

Effect of Length of Decompression

Analysis of the effect of length of decompression indicates that quick decompression causes mechanical damage which reduces the strength gained due to pressure compaction. If the mortar is decompressed slowly, the amount of mechanical damage will be less and most of the strength gain retained.

The decompression procedure used was similar to decompression of humans who have been exposed to high pressure environments; that is, the rate of ascent was highest at the beginning and slower as the samples approached atmospheric pressure.

Humans require approximately one week of decompression from 500 ft or 220 psi above atmospheric pressure. The mortar, however, was decompressed much faster: from 1,000 psi/minute to 50 psi/hour or 5/6 psi/minute. The slowest rate of decompression produced the highest strengths.

The requirement for decompression is an important factor in the pressure curing process. The second commandment of deep ocean engineering states: "Thou shalt not use cables, or connectors, or free flooded devices which are filled with gas lest the gas migrate to strange and unknown locations and simulate the 'bends' when coming to the surface."[18] It was therefore realized that entrained air in concrete plays a very important role in the explanation of the observations and that a decompression schedule for pressure-cured concrete would have to be derived.

The fresh mortar had a calculated entrained air content of an average of 6.63%. This is considered to be air-entrained mortar since non-air-entrained concrete has about 1% air entrainment. No additives were used to achieve the air entrainment, but it occurred due to the fine aggregate size.

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[18] J.P. Craven, 1970, personal communication, "Ten commandments of deep ocean engineering." Marine Programs, University of Hawaii, Honolulu.

From Figure 16 it was observed that all samples had similar absorption rates. Samples initially oven dried became 25% saturated in 5 minutes following immersion in water, 50% saturated in about 20 minutes, 75% saturated in about 1 hour, and over 90% saturated in 2 hours. If it is assumed that desaturation rates are similar to saturation rates, then a concrete decompression schedule can be calculated (Table 18). A further assumption required to construct the decompression schedule is as follows: a sudden fall in ambient pressure to one-half its previous value can be tolerated provided a de-absorption adjustment period equal to that required for 25% desaturation follows. This assumption is based on the observation that a 5-minute decompression period was inadequate, but a 1-hour decompression period might be considered adequate. Also, 25% saturation occurred in 5 minutes. A minimum decompression schedule was set up so that a fall in ambient pressure to one-half its previous value occurred in 5 minutes.

TABLE 18. MINIMUM DECOMPRESSION SCHEDULE FOR PRESSURE-CURED CONCRETE

Pressure		Time From Start of Decompression to Reaching 1 Atmosphere Pressure (minutes)
psi	Atmosphere	
14.7	1	0
29.4	2	5
58.8	4	10
117.6	8	15
235.2	16	20
470.4	32	25
940.8	64	30
1,881.6	128	35
3,763.2	256	40
7,526.4	512	45
15,052.8	1,024	50
30,105.6	2,048	55
60,211.2	4,096	60

In actual practice a continuous decompression schedule was used; that is, the pressure gradually dropped during the 5-minute interval. A comparison between the calculated decompression schedule and that obtained for batch J6 is presented in Table 19.

TABLE 19. COMPARISON OF THE DECOMPRESSION SCHEDULE FOR BATCH J6 WITH THE MINIMUM DECOMPRESSION SCHEDULE

Batch J6		Minimum Decompression Schedule Pressure (psig)
Time From Start of Decompression (min)	Actual Pressure (psig)	
0	4,750	7,526.4
5	4,000	3,763.2
10	3,300	1,881.6
15	2,600	940.8
20	2,000	470.4
25	1,600	235.2
30	1,300	117.6
35	1,000	58.8
40	700	29.4
45	500	14.7
50	300	0
55	200	--
60	100	--
65	50	--
70	0	--

As can be seen in Table 19, at first batch J6 was decompressed slower than called for in the minimum decompression schedule and faster at the end of the decompression period. This occurred for two reasons. First, the proposed minimum concrete decompression schedule for pressure-cured concrete was calculated after all tests were done and results analyzed. Thus a "seat of the pants" decompression schedule was used. Secondly, the pressure gage did not indicate pressures below 50 psig so that the rate of final decompression was unknown.

Permeable Voids and Bridging Theory

The permeable voids study indicated that the control sample, 44, had 14.42% permeable voids and the pressure-cured mortar had less than this--down to 12.33% for sample 86. Since the entrained air in fresh mortar was an average of 6.63%, it can be assumed that the remaining voids not filled with air must have originally been filled with water.

It is conceivable that, for the mix design used, there is a minimum limit for the reduction of permeable voids due to pressure curing. This limit is hypothesized by a bridging theory which says that the central core of a material composed of aggregates will not become compacted as surrounding 3-D compacting pressure is applied. This occurs because the grains come in contact and form a "bridge" or boundary preventing further compaction.

Observations Explained Theoretically

To explain the physical properties of the pressure-cured mortar, it is first necessary to review what occurs in a non-pressure-cured control test, followed by an explanation of a flooded pressure-cured test, and then finally by an explanation of the non-flooded pressure-cured test.

In the non-pressure-cured control test, all samples were mixed and formed in the same way. The use of a fine aggregate caused high air entrainment. However, vibration during placement was able to get rid of some of the air. This was necessary in order to prevent honeycombing. Evacuation of air inside the bag surrounding the sample was not long enough or of sufficient vacuum pressure to remove the entrained air from the samples.

Some shrinkage is expected during normal curing due to the formation of denser hydration products. Thus, the hardened control volume is slightly less than the fresh volume. Water in excess of that required for hydration simply remains in the sample causing voids in addition to those initially containing air to occur.

In the flooded pressure-cured test, the mortar contained entrained air just as the control sample did. As the samples were pressurized, the volume of entrained air decreased. According to Boyles Law:

$$\text{Final Volume} = \frac{(\text{Initial Pressure})(\text{Final Volume})}{(\text{Final Pressure})}$$

The samples which were flooded did not change volume (shrink in size) as the samples were pressurized. Instead, as the entrained air became compressed, water from outside flowed into the voids in the samples. At high pressures the flooded sample probably does shrink in size due to the compaction of water, but such a compaction is small and cannot be distinguished from normal shrinkage during curing.

Upon depressurization, the compressed entrained air expands forcing some of the water out of the permeable voids. If decompression is fast, some mechanical damage may occur, such as cracking.

In the non-flooded pressure-cured test, the mortar contained entrained air just as the control and flooded samples did. However, these non-flooded pressure-cured test specimens do change in volume. As the hydrostatic pressure is increased, the entrained air is compressed. However, since there is an impermeable bag surrounding the sample, water does not flow in to fill the space originally occupied by air. Instead, the hydrostatic pressure, which is acting from all sides, compacts the sample; the aggregate is packed closer together and the cement paste is squeezed in to fill the voids. As pressure is increased, the reduction in air void size becomes minimal; hence, any further reduction in volume must be accounted for by a compression of the water in the cement paste.

The observed increase in strength can be accounted for by a reduction in the volume of entrained air since non-air-entrained concrete is stronger than air-entrained concrete (see Figure 17).

Another possible explanation might be that during pressurization, further compaction occurred by some of the water in the voids being squeezed out into the dry cardboard can surrounding the sample.

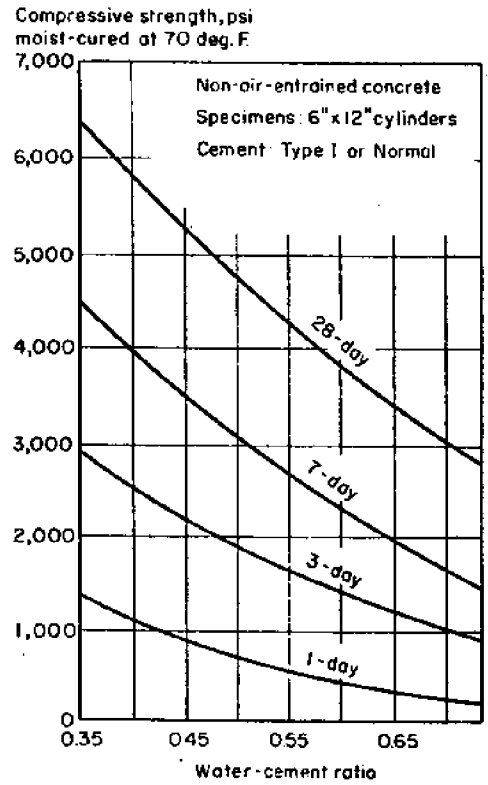
According to the permeable voids study, about 12 to 14% of the volume of the sample is voids. Water in these voids likewise becomes compressed. For example, 1 ml of water at the surface would occupy .98 ml at 5,000 psi.

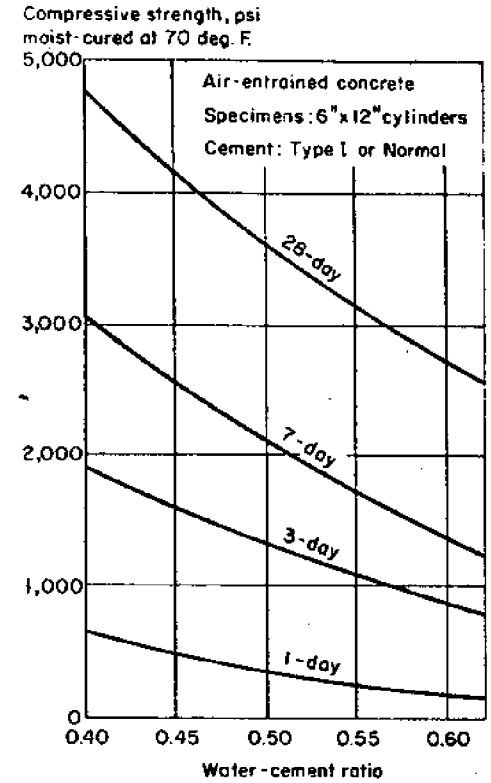
Under these conditions, the hydration of the portland cement takes place. As the samples are depressurized, the entrained air expands. Likewise the compressed water expands. If decompression is fast, mechanical damage occurs as the air and water escape from the sample. This water is mostly absorbed by the cardboard can as it also expands, acting like a sponge.

Process Design: Concrete Pressure Curing Technique

The incentive to develop any new technique into a commercial process is based on economics. Such is the case for the pressure curing of concrete. The application of the pressure curing technique to concrete might enable the Hawaiian concrete industry to commercialize the process. If so, three basic steps in the process must be carried out properly in order to obtain the desired results. These basic steps are: (1) placement, (2) curing, and (3) decompression. The placement of the concrete includes the batch design, the forms used, and the workability of the fresh concrete. The curing covers evacuation of the concrete, hydrostatic pressure compaction (depth and time), temperature control (if any), and further curing after decompression (if any). The decompression of the pressure-cured concrete concerns the rate at which the concrete is depressurized.

A proposed process utilizing the pressure curing technique is as follows. The batch design would be one of air entrainment. It is known





*From: Portland Cement Association, 1968, *Design and Control of Concrete Mixtures*, 11th edition, figure 8, p. 10.

Figure 17. Typical age-strength relationships based on compressive strength tests of 6 x 12-inch concrete cylinders.

that non-air-entrained concrete is stronger than air-entrained concrete; however, air-entrained concrete is more workable. Because of this workability, the water and sand content can be reduced significantly. Less water is required to make a cubic yard of air-entrained concrete than that of non-air-entrained concrete having the same consistency and maximum size of aggregate. Freshly mixed concrete containing entrained air is cohesive, looks and feels "fatty" or "workable," and may be handled and finished with ease.

The billions of disconnected air voids reduce segregation and bleeding of freshly mixed concrete. The primary function of air entrainment is normally for freeze-thaw resistance. While freeze-thaw resistance is not required in Hawaii, air entrainment could be used to increase workability of fresh concrete and reduce the water content.

The pressure curing technique could be applied to either concrete placed in the ocean and left there permanently or to precast members that are to be used on land in normal construction projects. If the concrete member is to be used on land, then decompression is required. Initially, only members required to resist compressive loads will be produced (such as columns or piles). As experience is gained, however, composite precast members containing steel reinforcement, prestressed members, polymer impregnated concrete or combinations thereof might be employed. The first beam structure might be a T-beam. In general, the process might be applied to any of the typical precast concrete members where compressive strength, weight, or permeability are important factors.

The forms used must be air tight and partly flexible. Air tightness is necessary if evacuation of the concrete following placement is to be carried out. In addition, internal or form vibrators should be employed during evacuation and initial hydrostatic pressurization, so that all entrapped air (air voids due to aggregate characteristics) and most of the intentionally entrained air bubbles can be removed. This is desirable primarily to reduce decompression hazards and also to convert the air-entrained concrete into a non-air-entrained concrete. A limited investigation of the frost resistance of pressure-compacted paste[19] indicates that it can withstand thermal shock. It is probable that further studies will show similar results for hydrostatic pressure-cured concrete.

The requirement of flexibility of the forms refers to the use of the form itself as a vibrator and to the ability of the form to adjust to shrinkage of the concrete during pressure curing. This shrinkage will occur both from normal shrinkage during curing (formation of denser hydration products) and from compression of both any remaining entrained air and water in the concrete--providing high hydrostatic curing pressures are employed. Thus, steel, fiberglass, or aluminum forms might be used.

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[19] I.A. Bajza, 1970, *Physical Properties of Cement, Cement Paste and Mortar Compacted by High Pressure: Influence of Compacting and Curing Procedure*, Technical Report 42.446, Cement and Concrete Association, 52 Crosvenor Gardens, London SW_I, p. 8.

Strategically placed rubber sheeting properly sealed for air tightness might also be used. For example, these could be placed on the ends of a cylindrical form as shown in Figure 18.

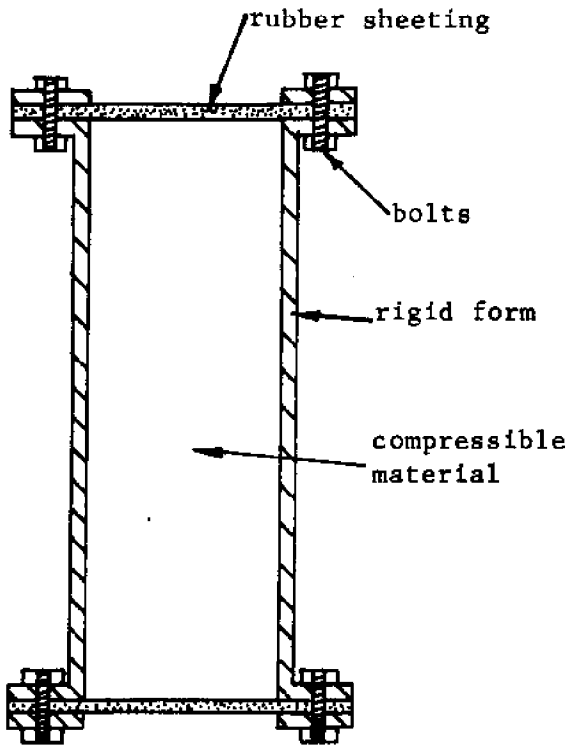


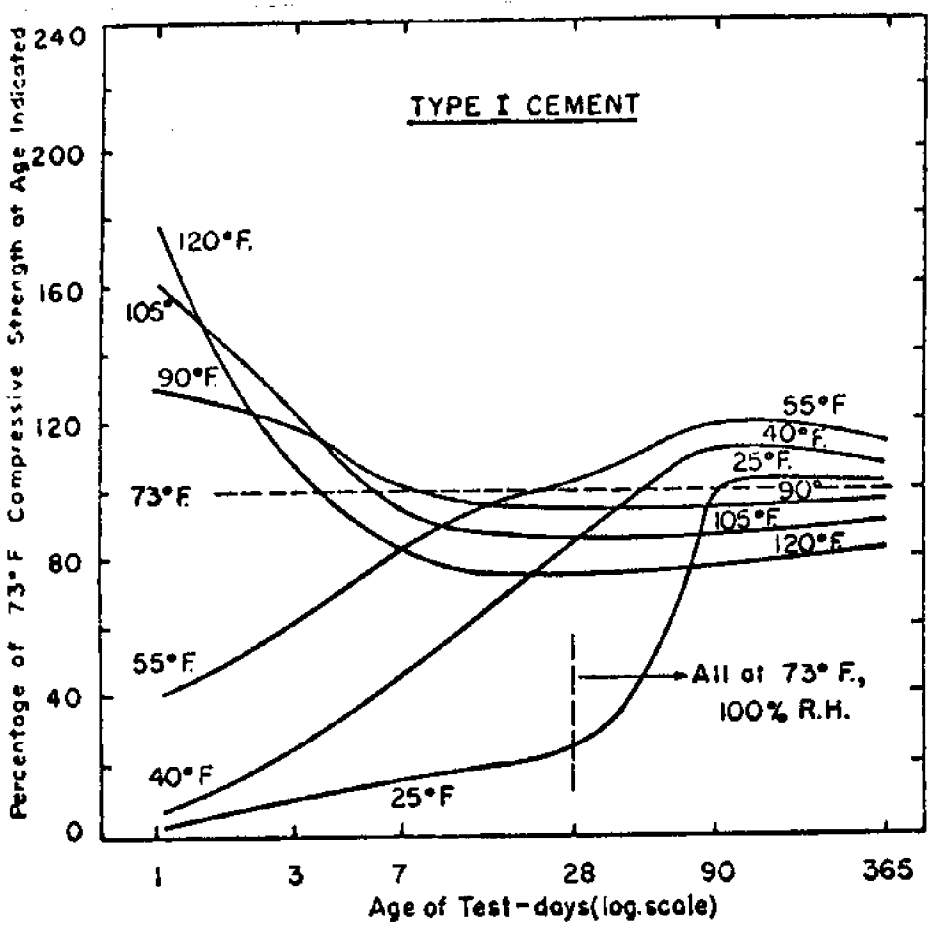
Figure 18. Proposed typical cross-section of a cylindrical form to be used in the pressure curing process

Once the concrete is placed in the form, evacuation begins and vibration continues. The next step is the submersion of the form. It could be lowered by a cable from a platform on the surface of the ocean or a submersible barge with the forms lashed to its deck could submerge. During submersion external vibration and evacuation would continue if this is shown to be of benefit. The depth of submersion and hence the hydrostatic pressure compaction obtained would be controlled by the economic advantage gained by deeper submersion.

The oil well cement studies (Figure 3) suggest that an optimum pressure would be 2,000 psi; however, just as the 24-hour strength versus temperature data may be misleading in terms of ultimate strength (Figure 19), so may be the 24-hour strength versus pressure data. Indeed, the pressure compaction studies[20] indicate that higher compacting pressures

[20]C.D. Lawrence, 1969, *The Properties of Cement Paste Compacted Under High Pressure*, Research Report 19, Cement and Concrete Association, London.

produce higher strength compacted cement pastes. It is believed that a similar relationship holds for hydrostatically pressure compacted concrete.



*From: Shideler, J.J., 1963, "Low pressure steam curing," ACI Committee 517 Report in *Proceedings, American Concrete Institute*, figure 1, p. 957.

Figure 19. Strength versus curing temperature for concrete cured at atmospheric pressure

The length of pressure curing required still needs further investigation. It must be beyond final set (5 hours and 50 minutes) and preferably no less than 12 hours. The few long-term tests conducted showed that the longer the pressure curing, the greater the strength. However, if thermal heat of compression is considered, this may simply be due to curing at a slightly higher temperature for a longer period of time. In fact, the heat produced from the compression of the entrained air during hydrostatic compaction may be used intentionally to initially speed up hydration. In the pressure-cured tests it was assumed that this heat was dissipated into the water; however, proper insulation around the concrete may not only keep the cold ocean temperatures from cooling the concrete but also keep in both thermal heat of compression and heat of hydration.

Once the concrete is compacted, additional curing, either steam curing or autoclaving, following decompression might produce even further significant increases in strength that might economically justify the complete pressure curing process.

The final basic step required in the pressure curing process is that of decompression. This is a critical step in that it may undo the improvement in concrete properties obtained thus far. The tests showed that decompression from 5,000 psi in 5 minutes produced detrimental results. The samples which were slowly decompressed from 5,000 psi to 100 psi over 7 hours, remaining there for 3 days and then decompressed from 100 psi to 0 in 15 minutes (batch J10), showed the highest strength and the lowest permeable voids.

In general, the slower the decompression, especially just as approaching the surface, the better. The proposed minimum decompression schedule for pressure-cured concrete is just that, a minimum. It is hoped and expected that in actual practice, decompression of an ocean pressure-cured concrete will be slow, perhaps lasting 2 or 3 days or more.

Once the pressure-cured concrete is ready to be used, one is concerned as to whether it has achieved the required strength. This may be done in the usual way by testing samples under compressive load until failure. The sample, however, is destroyed by this method. An alternate method of estimating compressive strength is to plot the hardened bulk density of the mortar control samples against their compressive strength (Figure 20). For the control samples, there appeared to be no relationship between strength and bulk density. However, when the compressive strengths of the test samples were plotted against their bulk densities (Figure 21), it was noted that, on the average, test samples with high bulk densities had higher strengths than low bulk density samples. It therefore appears that the determination of the bulk density of pressure-cured concrete is a good method of estimating its compressive strength. It might also be used as a quality control test to detect weak concrete.

A fairly simple method of determining the bulk density of a precast pressure-cured concrete member, since it is envisioned that the concrete will be unloaded by cranes, is to determine its weight in air and then to submerge it in water, still hanging from a cable, and to measure its submerged weight. The difference between the two weights should be equal to the weight of the water displaced; hence, the volume can be calculated. Its weight in air divided by its volume gives its bulk density. This bulk density in turn could be used to estimate the compressive strength of the concrete.

As mentioned in the discussion of the forms required, the process could be carried out from a platform on the surface or from a submersible barge (Figures 22 and 23).

If an offshore stable platform were used, cement and aggregates could be transported by barge to a site in deep water, say 3 miles off Honolulu. The concrete could be batched on the platform and then lowered over the side by cable. This would allow for good control of the

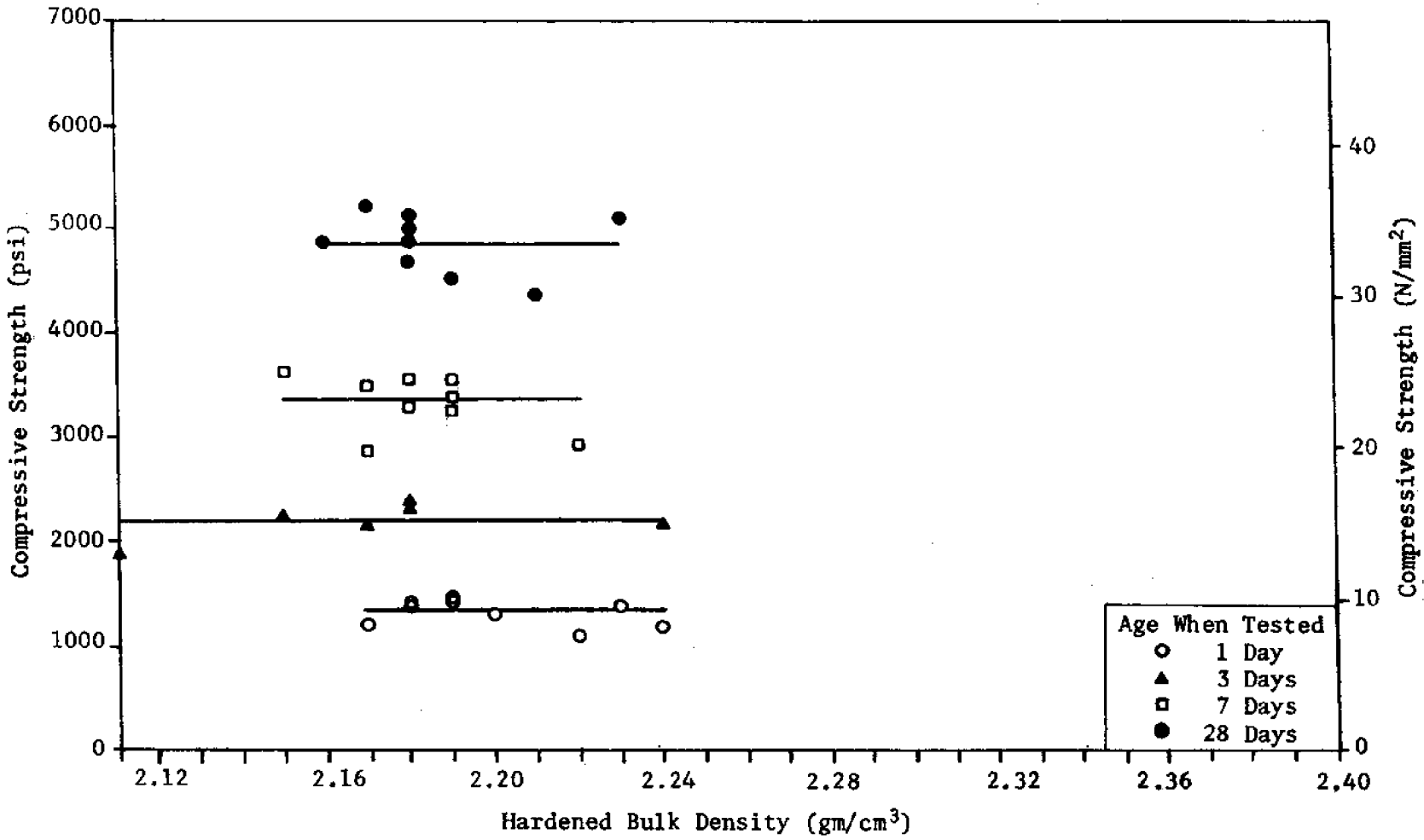


Figure 20. Strength versus density relationship for control samples

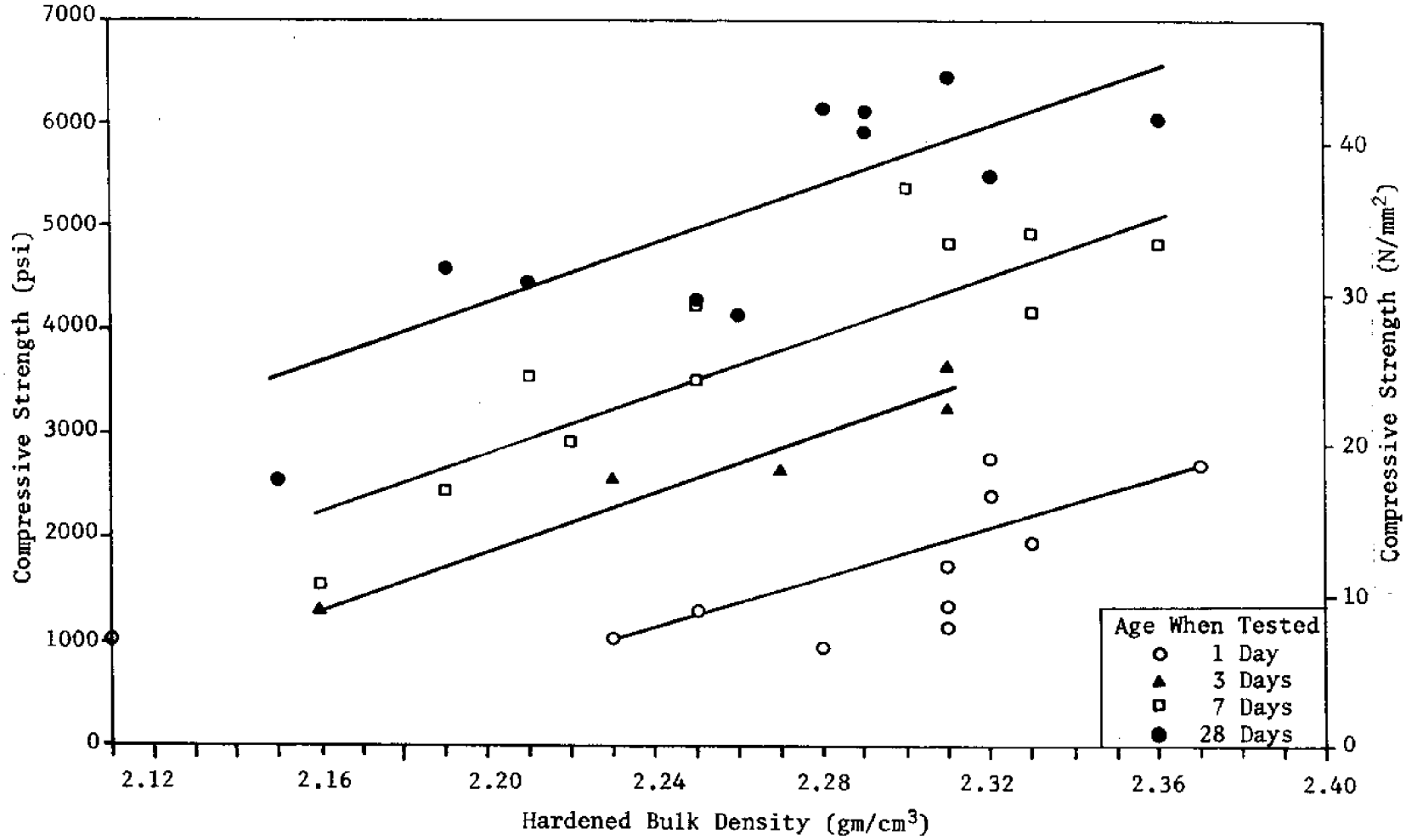


Figure 21. Strength versus density relationship for test samples

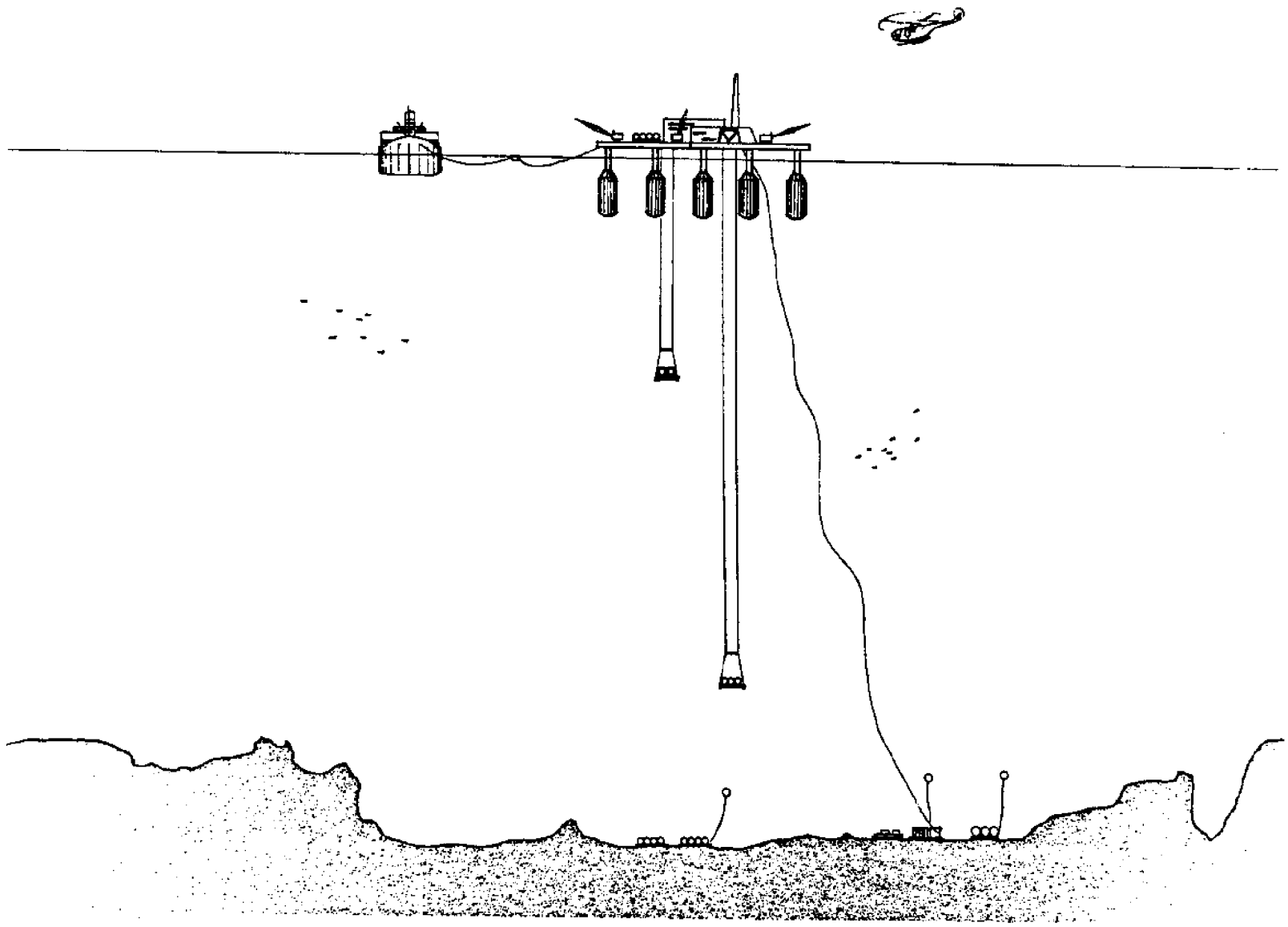


Figure 22. Hydrostatic pressure curing process based on a stable platform

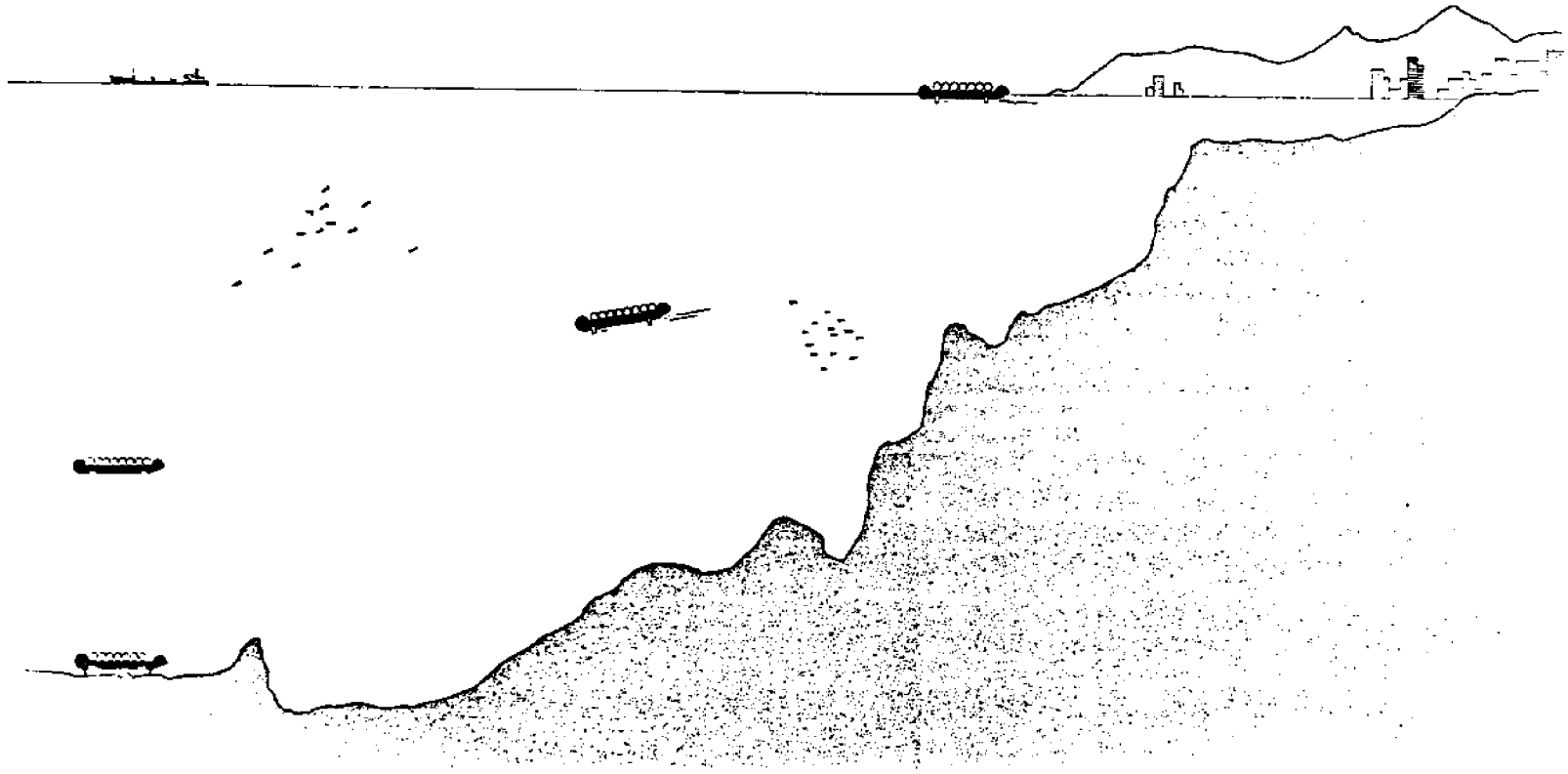


Figure 23. Hydrostatic pressure curing process based on a submersible barge

rate of lowering and decompression. If a week were selected as the length of time of pressure curing, a new batch could be mixed and lowered to the bottom each day and the previous week's concrete slowly raised during the remaining three-fourths of the day. Thus, only one winch per concrete curing platform would be needed.

Another alternative would be to use a submersible barge. The concrete forms would be lashed to the deck of the barge, which could then be towed out to sea or be self-propelled. It could then be submerged by taking on ballast. Then, if it were made just slightly negative, it would start to sink. If large planing wings were employed, the barge could glide out to sea into deeper and deeper water. The barge could be manned (using a pressure hull) or unmanned and operated by remote control. After remaining at the maximum depth, either hovering at a particular depth or resting on the bottom, the barge could be made slightly positive, either dropping ballast or using gas generation to expel water ballast. The submersible barge could then glide under control back to the surface, adjusting positive buoyancy as needed to follow the slowest decompression schedule economically justifiable. It could surface just outside the harbor and be towed or self-propelled to dock side where its cargo could be unloaded and a fresh concrete batch loaded for the next cycle of the process. A modification of this submersible barge process might be to employ a shuttle cycle, leaving a fresh batch on the bottom while picking up a day, week, or month-old batch.

SUMMARY

Physical Properties of Pressure-Cured Mortar

Mortar that was mixed at atmospheric pressure, packaged, and then hydrostatically compacted and cured had different physical properties from control samples which were not hydrostatically compacted and cured. In particular, the following was observed:

1. The volume was reduced by about 5%, primarily by a reduction in air void size.

2. The mass was reduced by about 2%, primarily by a loss of water into the cardboard form during depressurization.

3. The bulk density was increased by about 4%, primarily due to a reduction in volume.

4. The compressive strength was increased by about 6.24 N/mm^2 or 905 psi, primarily due to the increased quantity.

Beneficial Effects of Pressure Curing

The primary beneficial effect of pressure curing is an increase in compressive strength. This is an absolute increase or permanent set that

percentagewise is greater at one-day ages than at 28 days. In other words, the effect is similar to high, early strengths although the ultimate strength is also increased.

Another beneficial effect of pressure curing is the slight increase in density. Generally denser concretes are more durable. In addition, a means of non-destructive strength estimation based on the bulk density strength relationship was found; that is, the higher the bulk density, the higher the compressive strength.

Detrimental Effect of Pressure Curing

If the mortar is decompressed before final set, the entrained air re-expands and ruptures the mortar, resulting in an increase in permeable voids and a reduction in strength to about one-half the control. This effect can be reduced somewhat if the mortar is evacuated prior to pressurization.

If the hardened concrete is decompressed quickly, the entrained air expands and causes mechanical damage to the mortar, with a subsequent reduction in compressive strength and an increase in permeable voids.

Factors Affecting Age-Strength Relationship

Figure 24 is a composite plot of the results obtained. It summarizes the conclusions reached concerning the effect of various factors on the age-strength relationship of pressure-cured mortar. A short pressure cure, less than final set (5 hours and 50 minutes), reduces strength. Fast decompression also reduces strength. Long pressure cures with slow decompression produce increases in strength. The slower the decompression, the higher the ultimate strength.

CONCLUSIONS AND RECOMMENDATIONS

The ocean environment need not always have a detrimental effect on engineering materials placed in the ocean. Research indicates that high hydrostatic pressure, one parameter of the ocean environment, can be utilized to produce beneficial effects on an ocean engineering material. For example, when fresh cement mortar is packaged inside an impermeable flexible membrane and cured under high hydrostatic pressure its compressive strength increases.

This information can be used in two ways--either to produce a higher strength concrete or to reduce the cost of raw materials used in making concrete. For example, portland cement is the most expensive ingredient and a batch design with a smaller quantity of cement would

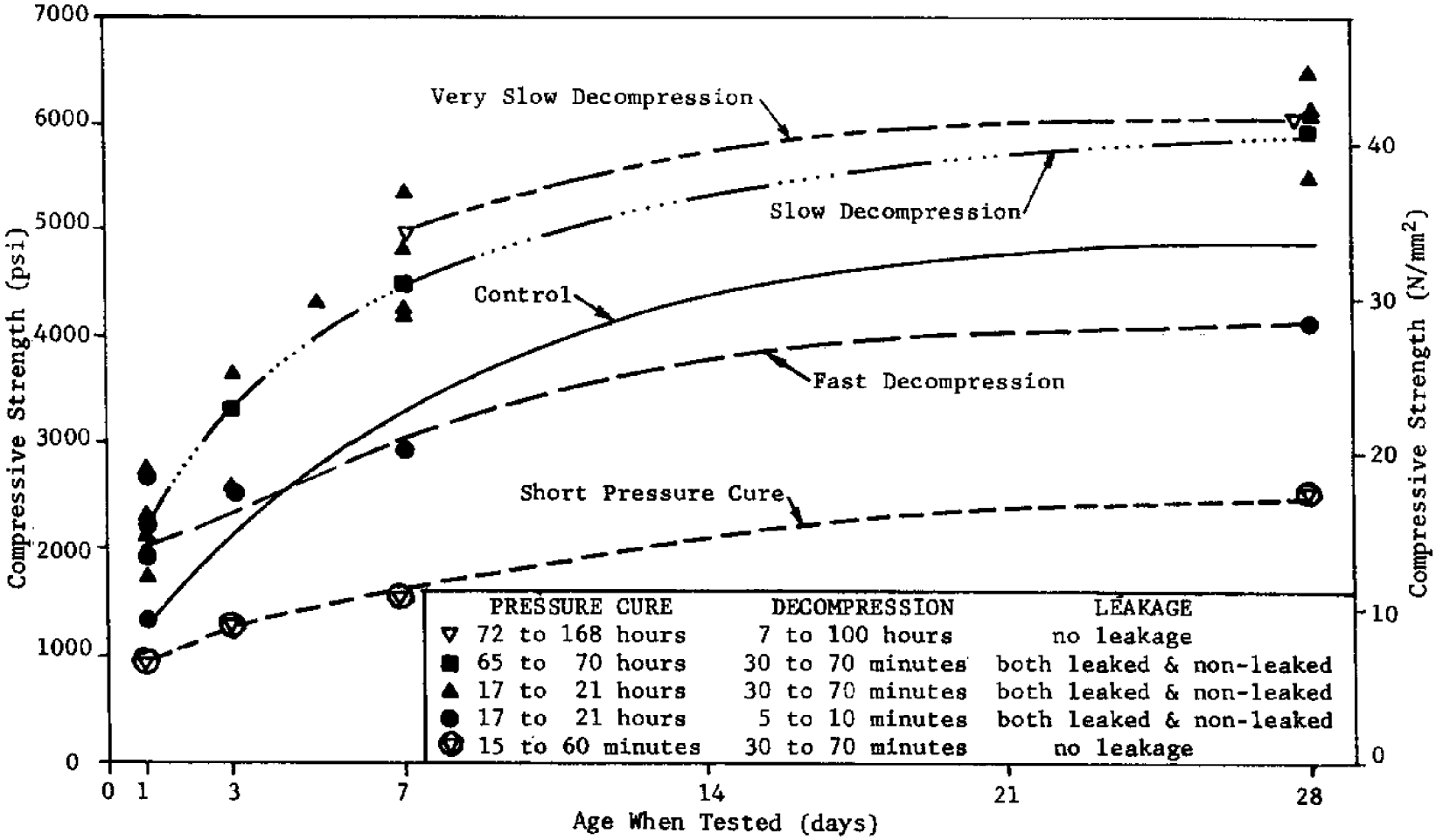


Figure 24. Composite plot to show effect of various factors on the age-strength relationship of pressure-cured mortar

normally have lower strength. However, if the concrete were pressure cured, the same strength as a normal batch could be obtained.

A proposed process utilizing the pressure curing technique was designed. This could utilize either an offshore floating stable platform or a submersible barge.

Further studies are required to refine the pressure curing technique into a commercial process suitable for the Hawaiian concrete industry. They include:

1. Optimization of the batch design
2. Selection of precast member to be manufactured
3. Selection of depth required for curing
4. Examination of applicability of using thermal heat of compression to increase strength
5. Testing of prototype in ocean

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APPENDICES

Appendix A. Compressive Strength Calibration Table

Appendix B. Recorded Observations and Subsequent Calculations of the Fourth Series of Tests: Batch Data, Strength Data, Weight Data, and Volume Data

Appendix C. Absorption Rate Data

APPENDIX A. COMPRESSIVE STRENGTH CALIBRATION TABLE

The compressive strength testing machine was calibrated with a proving ring and a table of corrected values was computed. The true loads and the corresponding observed loads are both listed in the following tables. The true loads were divided by the minimum cross-sectional area of the samples to obtain the compressive strength.

COMPRESSIVE STRENGTH CALIBRATION TABLE

```
      $JOB            C596WILSON PAGES=7
 1          Z=(163.-36.)/(900)
 2          Y=(133.-163.)/(6000)
 3          X=(133.-138.)/(5000)
 4          W=(256.-133.)/(5000)
 5          V=(401.-256.)/(5000)
 6          U=(478.-401.)/(5000)
 7          A=-10.
 8          B=1990
 9          C=3995.
10          D=4975.
11          E=9975.
12          F=14975.
13          G=19975.
14          H=24975.
15    8     WRITE(6,100)
16    100   FORMAT(1H1,'OBSERVED TRUE $ OBSERVED TRUE $ OBSERVED TRUE  $ OBSERVED TRUE
           1VED TRUE  $ OBSERVED TRUE  $ OBSERVED TRUE  $ OBSERVED TRUE  $ OBSERVED TR
           2SERVED TRUE  ')
17          WRITE(6,101)
18    101   FORMAT(1H ,'  LOAD   LOAD $  LOAD   LOAD $  LOAD   LOAD $  LOAD   LOAD $  LOAD   LOAD
           3D   LOAD  $  LOAD   LOAD $  LOAD   LOAD $  LOAD   LOAD $  LOAD   LOAD  LO
           4AD   LOAD  ')
19    5     A=A+10.
20          B=B+10.
21          C=C+5.
22          D=D+25
23          E=E+25
24          F=F+25
25          G=G+25
26          H=H+25
27          CA=A+36.5+(A-100.)*Z
28          IF(A.GE.1000.)GO TO 6
29          GO TO 7
30    6     CB=A+143.5+(A-1000.)*Y
31    7     CB=B+143.5+(B-1000.)*Y
32          CC=C+143.5+(C-1000.)*Y
33          CD=D+138.5+(D-5000.)*X
34          CE=E+133.5+(E-10000.)*W
35          CF=F+256.5+(F-15000.)*V
36          CG=G+401+(G-20000)*U
37          CH=H+478.5+(H-25000.)*U
38          IF(B.LT.100)CA=11111111111.
39          WRITE(6,102)A,CA,B,CB,C,CC,D,CD,E,CE,F,CF,G,CG,H,CH
40    102   FORMAT(F7.0,F7.0,' $',F7.0,F7.0,' $',F8.0,F7.0,' $',F8.0,F7.0,' $',F8.0,F7
           5F8.0,F7.0,' $',F8.0,F7.0,' $',F8.0,F7.0)
41          IF(D.EQ.10000.)GO TO 200
42          IF(A.EQ.590.)GO TO 8
43          IF(A.EQ.1190.)GO TO 8
44          IF(A.EQ.1790.)GO TO 8
45          GO TO 5
46    200   STOP
47          END
      $ENTRY
```

Note: Observed load and true load values given in pound units.

COMPRESSIVE STRENGTH CALIBRATION TABLE

OBSERVED LOAD	TRUE LOAD	OBSERVED LOAD	TRUE LOAD	OBSERVED LOAD	TRUE LOAD	OBSERVED LOAD	TRUE LOAD	OBSERVED LOAD	TRUE LOAD	OBSERVED LOAD	TRUE LOAD	OBSERVED LOAD	TRUE LOAD	OBSERVED LOAD	TRUE LOAD
0.	*******	2000.	2157.	4000.	4145.	5000.	5139.	10000.	10134.	15000.	15257.	20000.	20401.	25000.	25479.
10.	*******	2010.	2167.	4005.	4150.	5025.	5163.	10025.	10159.	15025.	15282.	20025.	20426.	25025.	25504.
20.	*******	2020.	2177.	4010.	4155.	5050.	5188.	10050.	10185.	15050.	15308.	20050.	20452.	25050.	25529.
30.	*******	2030.	2187.	4015.	4160.	5075.	5213.	10075.	10210.	15075.	15334.	20075.	20477.	25075.	25555.
40.	*******	2040.	2197.	4020.	4165.	5100.	5238.	10100.	10236.	15100.	15359.	20100.	20503.	25100.	25580.
50.	*******	2050.	2207.	4025.	4170.	5125.	5263.	10125.	10262.	15125.	15385.	20125.	20528.	25125.	25605.
60.	*******	2060.	2217.	4030.	4175.	5150.	5288.	10150.	10287.	15150.	15411.	20150.	20553.	25150.	25631.
70.	*******	2070.	2227.	4035.	4180.	5175.	5313.	10175.	10313.	15175.	15437.	20175.	20579.	25175.	25656.
80.	*******	2080.	2237.	4040.	4185.	5200.	5338.	10200.	10338.	15200.	15462.	20200.	20604.	25200.	25682.
90.	*******	2090.	2247.	4045.	4189.	5225.	5363.	10225.	10364.	15225.	15488.	20225.	20629.	25225.	25707.
100.	137.	2100.	2257.	4050.	4194.	5250.	5388.	10250.	10389.	15250.	15514.	20250.	20655.	25250.	25732.
110.	148.	2110.	2267.	4055.	4199.	5275.	5413.	10275.	10415.	15275.	15539.	20275.	20680.	25275.	25758.
120.	159.	2120.	2277.	4060.	4204.	5300.	5438.	10300.	10441.	15300.	15565.	20300.	20706.	25300.	25783.
130.	171.	2130.	2286.	4065.	4209.	5325.	5463.	10325.	10466.	15325.	15591.	20325.	20731.	25325.	25809.
140.	182.	2140.	2296.	4070.	4214.	5350.	5488.	10350.	10492.	15350.	15617.	20350.	20756.	25350.	25834.
150.	194.	2150.	2306.	4075.	4219.	5375.	5513.	10375.	10518.	15375.	15642.	20375.	20782.	25375.	25860.
160.	205.	2160.	2316.	4080.	4224.	5400.	5538.	10400.	10543.	15400.	15668.	20400.	20807.	25400.	25885.
170.	216.	2170.	2326.	4085.	4229.	5425.	5563.	10425.	10569.	15425.	15694.	20425.	20833.	25425.	25911.
180.	228.	2180.	2336.	4090.	4234.	5450.	5588.	10450.	10595.	15450.	15720.	20450.	20858.	25450.	25936.
190.	239.	2190.	2346.	4095.	4239.	5475.	5613.	10475.	10620.	15475.	15745.	20475.	20883.	25475.	25962.
200.	251.	2200.	2356.	4100.	4244.	5500.	5638.	10500.	10646.	15500.	15771.	20500.	20909.	25500.	25988.
210.	262.	2210.	2366.	4105.	4249.	5525.	5663.	10525.	10671.	15525.	15797.	20525.	20934.	25525.	26012.
220.	273.	2220.	2376.	4110.	4254.	5550.	5688.	10550.	10697.	15550.	15822.	20550.	20959.	25550.	26037.
230.	285.	2230.	2386.	4115.	4259.	5575.	5713.	10575.	10723.	15575.	15848.	20575.	20985.	25575.	26063.
240.	296.	2240.	2396.	4120.	4264.	5600.	5738.	10600.	10748.	15600.	15874.	20600.	21010.	25600.	26088.
250.	308.	2250.	2406.	4125.	4269.	5625.	5763.	10625.	10774.	15625.	15900.	20625.	21036.	25625.	26114.
260.	319.	2260.	2416.	4130.	4274.	5650.	5788.	10650.	10799.	15650.	15925.	20650.	21061.	25650.	26139.
270.	330.	2270.	2426.	4135.	4279.	5675.	5813.	10675.	10825.	15675.	15951.	20675.	21086.	25675.	26164.
280.	342.	2280.	2436.	4140.	4284.	5700.	5838.	10700.	10851.	15700.	15977.	20700.	21112.	25700.	26190.
290.	353.	2290.	2446.	4145.	4289.	5725.	5863.	10725.	10876.	15725.	16003.	20725.	21137.	25725.	26215.
300.	365.	2300.	2455.	4150.	4294.	5750.	5888.	10750.	10902.	15750.	16028.	20750.	21163.	25750.	26241.
310.	376.	2310.	2465.	4155.	4299.	5775.	5913.	10775.	10928.	15775.	16054.	20775.	21188.	25775.	26266.
320.	388.	2320.	2475.	4160.	4304.	5800.	5938.	10800.	10953.	15800.	16080.	20800.	21213.	25800.	26291.
330.	399.	2330.	2485.	4165.	4309.	5825.	5963.	10825.	10979.	15825.	16105.	20825.	21239.	25825.	26316.
340.	410.	2340.	2495.	4170.	4314.	5850.	5988.	10850.	11004.	15850.	16131.	20850.	21264.	25850.	26342.
350.	422.	2350.	2505.	4175.	4319.	5875.	6013.	10875.	11030.	15875.	16157.	20875.	21289.	25875.	26367.
360.	433.	2360.	2515.	4180.	4324.	5900.	6038.	10900.	11056.	15900.	16183.	20900.	21315.	25900.	26392.
370.	445.	2370.	2525.	4185.	4329.	5925.	6063.	10925.	11081.	15925.	16209.	20925.	21340.	25925.	26418.
380.	456.	2380.	2535.	4190.	4334.	5950.	6088.	10950.	11107.	15950.	16234.	20950.	21364.	25950.	26443.
390.	467.	2390.	2545.	4195.	4339.	5975.	6113.	10975.	11132.	15975.	16260.	20975.	21391.	25975.	26469.
400.	479.	2400.	2555.	4200.	4344.	6000.	6138.	11000.	11158.	16000.	16285.	21000.	21416.	26000.	26494.
410.	490.	2410.	2565.	4205.	4348.	6025.	6162.	11025.	11184.	16025.	16311.	21025.	21442.	26025.	26519.
420.	502.	2420.	2575.	4210.	4353.	6050.	6187.	11050.	11209.	16050.	16337.	21050.	21467.	26050.	26545.
430.	513.	2430.	2585.	4215.	4358.	6075.	6212.	11075.	11235.	16075.	16363.	21075.	21493.	26075.	26570.
440.	524.	2440.	2595.	4220.	4363.	6100.	6237.	11100.	11261.	16100.	16388.	21100.	21518.	26100.	26596.
450.	536.	2450.	2604.	4225.	4368.	6125.	6262.	11125.	11286.	16125.	16414.	21125.	21543.	26125.	26621.
460.	547.	2460.	2614.	4230.	4373.	6150.	6287.	11150.	11312.	16150.	16440.	21150.	21569.	26150.	26646.
470.	559.	2470.	2624.	4235.	4378.	6175.	6312.	11175.	11337.	16175.	16465.	21175.	21594.	26175.	26672.
480.	570.	2480.	2634.	4240.	4383.	6200.	6337.	11200.	11363.	16200.	16491.	21200.	21619.	26200.	26697.
490.	582.	2490.	2644.	4245.	4388.	6225.	6362.	11225.	11388.	16225.	16517.	21225.	21645.	26225.	26723.
500.	593.	2500.	2654.	4250.	4393.	6250.	6387.	11250.	11414.	16250.	16543.	21250.	21670.	26250.	26748.
510.	604.	2510.	2664.	4255.	4398.	6275.	6412.	11275.	11440.	16275.	16568.	21275.	21696.	26275.	26773.
520.	616.	2520.	2674.	4260.	4403.	6300.	6437.	11300.	11465.	16300.	16594.	21300.	21721.	26300.	26799.
530.	627.	2530.	2684.	4265.	4408.	6325.	6462.	11325.	11491.	16325.	16620.	21325.	21746.	26325.	26824.
540.	639.	2540.	2694.	4270.	4413.	6350.	6487.	11350.	11517.	16350.	16646.	21350.	21772.	26350.	26849.
550.	650.	2550.	2704.	4275.	4418.	6375.	6512.	11375.	11542.	16375.	16671.	21375.	21797.	26375.	26875.
560.	661.	2560.	2714.	4280.	4423.	6400.	6537.	11400.	11568.	16400.	16697.	21400.	21823.	26400.	26900.
570.	673.	2570.	2724.	4285.	4428.	6425.	6562.	11425.	11594.	16425.	16723.	21425.	21848.	26425.	26925.
580.	684.	2580.	2734.	4290.	4433.	6450.	6587.	11450.	11619.	16450.	16749.	21450.	21873.	26450.	26951.
590.	696.	2590.	2744.	4295.	4438.	6475.	6612.	11475.	11645.	16475.	16774.	21475.	21899.	26475.	26976.

Note: Observed load and true load values given in pound units.

COMPRESSIVE STRENGTH CALIBRAITON TABLE (continued)

OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD
600.	707.	$	2600.	2754.	$	4300.	4443.	$	6500.	6637.	$	11500.	11670.	$	16500.	16800.	$	21500.	21924.	$	26500.	27021.
610.	718.	$	2610.	2763.	$	4305.	4448.	$	6525.	6662.	$	11525.	11696.	$	16525.	16826.	$	21525.	21949.	$	26525.	27047.
620.	730.	$	2620.	2773.	$	4310.	4453.	$	6550.	6687.	$	11550.	11722.	$	16550.	16851.	$	21550.	21975.	$	26550.	27073.
630.	741.	$	2630.	2783.	$	4315.	4458.	$	6575.	6712.	$	11575.	11747.	$	16575.	16877.	$	21575.	22000.	$	26575.	27099.
640.	753.	$	2640.	2793.	$	4320.	4463.	$	6600.	6737.	$	11600.	11773.	$	16600.	16903.	$	21600.	22026.	$	26600.	27103.
650.	764.	$	2650.	2803.	$	4325.	4468.	$	6625.	6762.	$	11625.	11798.	$	16625.	16929.	$	21625.	22051.	$	26625.	27129.
660.	776.	$	2660.	2813.	$	4330.	4473.	$	6650.	6787.	$	11650.	11824.	$	16650.	16954.	$	21650.	22076.	$	26650.	27154.
670.	787.	$	2670.	2823.	$	4335.	4478.	$	6675.	6812.	$	11675.	11850.	$	16675.	16980.	$	21675.	22102.	$	26675.	27179.
680.	798.	$	2680.	2833.	$	4340.	4483.	$	6700.	6837.	$	11700.	11875.	$	16700.	17006.	$	21700.	22127.	$	26700.	27205.
690.	810.	$	2690.	2843.	$	4345.	4488.	$	6725.	6862.	$	11725.	11901.	$	16725.	17032.	$	21725.	22153.	$	26725.	27230.
700.	821.	$	2700.	2853.	$	4350.	4493.	$	6750.	6887.	$	11750.	11927.	$	16750.	17057.	$	21750.	22178.	$	26750.	27255.
710.	833.	$	2710.	2863.	$	4355.	4498.	$	6775.	6912.	$	11775.	11952.	$	16775.	17083.	$	21775.	22203.	$	26775.	27281.
720.	844.	$	2720.	2873.	$	4360.	4503.	$	6800.	6937.	$	11800.	11978.	$	16800.	17109.	$	21800.	22229.	$	26800.	27306.
730.	855.	$	2730.	2883.	$	4365.	4507.	$	6825.	6962.	$	11825.	12003.	$	16825.	17134.	$	21825.	22254.	$	26825.	27332.
740.	867.	$	2740.	2893.	$	4370.	4512.	$	6850.	6987.	$	11850.	12029.	$	16850.	17160.	$	21850.	22279.	$	26850.	27357.
750.	878.	$	2750.	2903.	$	4375.	4517.	$	6875.	7012.	$	11875.	12055.	$	16875.	17185.	$	21875.	22305.	$	26875.	27382.
760.	890.	$	2760.	2913.	$	4380.	4522.	$	6900.	7037.	$	11900.	12080.	$	16900.	17212.	$	21900.	22330.	$	26900.	27409.
770.	901.	$	2770.	2922.	$	4385.	4527.	$	6925.	7062.	$	11925.	12106.	$	16925.	17237.	$	21925.	22355.	$	26925.	27435.
780.	912.	$	2780.	2932.	$	4390.	4532.	$	6950.	7087.	$	11950.	12131.	$	16950.	17263.	$	21950.	22381.	$	26950.	27460.
790.	924.	$	2790.	2942.	$	4395.	4537.	$	6975.	7112.	$	11975.	12157.	$	16975.	17289.	$	21975.	22406.	$	26975.	27484.
800.	935.	$	2800.	2952.	$	4400.	4542.	$	7000.	7137.	$	12000.	12183.	$	17000.	17314.	$	22000.	22432.	$	27000.	27509.
810.	947.	$	2810.	2962.	$	4405.	4547.	$	7025.	7161.	$	12025.	12208.	$	17025.	17340.	$	22025.	22457.	$	27025.	27535.
820.	958.	$	2820.	2972.	$	4410.	4552.	$	7050.	7186.	$	12050.	12234.	$	17050.	17366.	$	22050.	22483.	$	27050.	27560.
830.	970.	$	2830.	2982.	$	4415.	4557.	$	7075.	7211.	$	12075.	12260.	$	17075.	17392.	$	22075.	22508.	$	27075.	27585.
840.	981.	$	2840.	2992.	$	4420.	4562.	$	7100.	7236.	$	12100.	12285.	$	17100.	17417.	$	22100.	22533.	$	27100.	27611.
850.	992.	$	2850.	3002.	$	4425.	4567.	$	7125.	7261.	$	12125.	12311.	$	17125.	17443.	$	22125.	22559.	$	27125.	27636.
860.	1004.	$	2860.	3012.	$	4430.	4572.	$	7150.	7286.	$	12150.	12336.	$	17150.	17469.	$	22150.	22584.	$	27150.	27662.
870.	1015.	$	2870.	3022.	$	4435.	4577.	$	7175.	7311.	$	12175.	12362.	$	17175.	17495.	$	22175.	22609.	$	27175.	27687.
880.	1027.	$	2880.	3032.	$	4440.	4582.	$	7200.	7336.	$	12200.	12388.	$	17200.	17520.	$	22200.	22635.	$	27200.	27712.
890.	1038.	$	2890.	3042.	$	4445.	4587.	$	7225.	7361.	$	12225.	12413.	$	17225.	17546.	$	22225.	22660.	$	27225.	27738.
900.	1049.	$	2900.	3052.	$	4450.	4592.	$	7250.	7386.	$	12250.	12439.	$	17250.	17572.	$	22250.	22686.	$	27250.	27763.
910.	1061.	$	2910.	3062.	$	4455.	4597.	$	7275.	7411.	$	12275.	12464.	$	17275.	17597.	$	22275.	22711.	$	27275.	27789.
920.	1072.	$	2920.	3072.	$	4460.	4602.	$	7300.	7436.	$	12300.	12490.	$	17300.	17623.	$	22300.	22736.	$	27300.	27814.
930.	1084.	$	2930.	3081.	$	4465.	4607.	$	7325.	7461.	$	12325.	12516.	$	17325.	17649.	$	22325.	22762.	$	27325.	27839.
940.	1095.	$	2940.	3091.	$	4470.	4612.	$	7350.	7486.	$	12350.	12541.	$	17350.	17675.	$	22350.	22787.	$	27350.	27865.
950.	1106.	$	2950.	3101.	$	4475.	4617.	$	7375.	7511.	$	12375.	12567.	$	17375.	17700.	$	22375.	22813.	$	27375.	27890.
960.	1118.	$	2960.	3111.	$	4480.	4622.	$	7400.	7536.	$	12400.	12593.	$	17400.	17726.	$	22400.	22838.	$	27400.	27916.
970.	1129.	$	2970.	3121.	$	4485.	4627.	$	7425.	7561.	$	12425.	12619.	$	17425.	17752.	$	22425.	22863.	$	27425.	27941.
980.	1141.	$	2980.	3131.	$	4490.	4632.	$	7450.	7586.	$	12450.	12644.	$	17450.	17778.	$	22450.	22889.	$	27450.	27966.
990.	1152.	$	2990.	3141.	$	4495.	4637.	$	7475.	7611.	$	12475.	12669.	$	17475.	17803.	$	22475.	22914.	$	27475.	27992.
1000.	1164.	$	3000.	3151.	$	4500.	4642.	$	7500.	7636.	$	12500.	12695.	$	17500.	17829.	$	22500.	22939.	$	27500.	28017.
1010.	1175.	$	3010.	3161.	$	4505.	4647.	$	7525.	7661.	$	12525.	12721.	$	17525.	17855.	$	22525.	22965.	$	27525.	28042.
1020.	1187.	$	3020.	3171.	$	4510.	4652.	$	7550.	7686.	$	12550.	12746.	$	17550.	17880.	$	22550.	22990.	$	27550.	28068.
1030.	1198.	$	3030.	3181.	$	4515.	4657.	$	7575.	7711.	$	12575.	12772.	$	17575.	17906.	$	22575.	23016.	$	27575.	28093.
1040.	1209.	$	3040.	3191.	$	4520.	4662.	$	7600.	7736.	$	12600.	12797.	$	17600.	17932.	$	22600.	23041.	$	27600.	28119.
1050.	1221.	$	3050.	3201.	$	4525.	4666.	$	7625.	7761.	$	12625.	12823.	$	17625.	17958.	$	22625.	23066.	$	27625.	28144.
1060.	1232.	$	3060.	3211.	$	4530.	4671.	$	7650.	7786.	$	12650.	12849.	$	17650.	17983.	$	22650.	23092.	$	27650.	28169.
1070.	1233.	$	3070.	3221.	$	4535.	4676.	$	7675.	7811.	$	12675.	12874.	$	17675.	18009.	$	22675.	23117.	$	27675.	28195.
1080.	1243.	$	3080.	3231.	$	4540.	4681.	$	7700.	7836.	$	12700.	12900.	$	17700.	18035.	$	22700.	23143.	$	27700.	28220.
1090.	1253.	$	3090.	3240.	$	4545.	4686.	$	7725.	7861.	$	12725.	12926.	$	17725.	18061.	$	22725.	23168.	$	27725.	28245.
1100.	1263.	$	3100.	3250.	$	4550.	4691.	$	7750.	7886.	$	12750.	12951.	$	17750.	18086.	$	22750.	23193.	$	27750.	28271.
1110.	1273.	$	3110.	3260.	$	4555.	4696.	$	7775.	7911.	$	12775.	12977.	$	17775.	18112.	$	22775.	23219.	$	27775.	28296.
1120.	1283.	$	3120.	3270.	$	4560.	4701.	$	7800.	7936.	$	12800.	13002.	$	17800.	18138.	$	22800.	23244.	$	27800.	28322.
1130.	1293.	$	3130.	3280.	$	4565.	4706.	$	7825.	7961.	$	12825.	13028.	$	17825.	18163.	$	22825.	23270.	$	27825.	28347.
1140.	1303.	$	3140.	3290.	$	4570.	4711.	$	7850.	7986.	$	12850.	13054.	$	17850.	18189.	$	22850.	23295.	$	27850.	28372.
1150.	1313.	$	3150.	3300.	$	4575.	4716.	$	7875.	8011.	$	12875.	13079.	$	17875.	18215.	$	22875.	23320.	$	27875.	28398.
1160.	1323.	$	3160.	3310.	$	4580.	4721.	$	7900.	8036.	$	12900.	13105.	$	17900.	18241.	$	22900.	23346.	$	27900.	28423.
1170.	1332.	$	3170.	3320.	$	4585.	4726.	$	7925.	8061.	$	12925.	13130.	$	17925.	18266.	$	22925.	23371.	$	27925.	28449.
1180.	1342.	$	3180.	3330.	$	4590.	4731.	$	7950.	8086.	$	12950.	13156.	$	17950.	18292.	$	22950.	23396.	$	27950.	28474.
1190.	1352.	$	3190.	3340.	$	4595.	4736.	$	7975.	8111.	$	12975.	13182.	$	17975.	18318.	$	22975.	23422.	$	27975.	28499.

Note: Observed load and true load values given in pound units.

COMPRESSIVE STRENGTH CALIBRATION TABLE (continued)

OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD
1200.	1362.	$	3200.	3350.	$	4600.	4741.	$	8000.	8136.	$	13000.	13207.	$	18000.	18343.	$	23000.	23457.	$	28000.	28525.
1210.	1372.	$	3210.	3360.	$	4605.	4746.	$	8025.	8160.	$	13025.	13233.	$	18025.	18369.	$	23025.	23473.	$	28025.	28550.
1220.	1382.	$	3220.	3370.	$	4610.	4751.	$	8050.	8185.	$	13050.	13259.	$	18050.	18395.	$	23050.	23489.	$	28050.	28575.
1230.	1392.	$	3230.	3380.	$	4615.	4756.	$	8075.	8210.	$	13075.	13284.	$	18075.	18421.	$	23075.	23505.	$	28075.	28601.
1240.	1402.	$	3240.	3390.	$	4620.	4761.	$	8100.	8235.	$	13100.	13310.	$	18100.	18446.	$	23100.	23521.	$	28100.	28626.
1250.	1412.	$	3250.	3399.	$	4625.	4766.	$	8125.	8260.	$	13125.	13335.	$	18125.	18472.	$	23125.	23537.	$	28125.	28652.
1260.	1422.	$	3260.	3409.	$	4630.	4771.	$	8150.	8285.	$	13150.	13361.	$	18150.	18498.	$	23150.	23553.	$	28150.	28677.
1270.	1432.	$	3270.	3419.	$	4635.	4776.	$	8175.	8310.	$	13175.	13387.	$	18175.	18524.	$	23175.	23569.	$	28175.	28703.
1280.	1442.	$	3280.	3429.	$	4640.	4781.	$	8200.	8335.	$	13200.	13412.	$	18200.	18549.	$	23200.	23585.	$	28200.	28728.
1290.	1452.	$	3290.	3439.	$	4645.	4786.	$	8225.	8360.	$	13225.	13438.	$	18225.	18575.	$	23225.	23601.	$	28225.	28753.
1300.	1462.	$	3300.	3449.	$	4650.	4791.	$	8250.	8385.	$	13250.	13463.	$	18250.	18601.	$	23250.	23701.	$	28250.	28779.
1310.	1472.	$	3310.	3459.	$	4655.	4796.	$	8275.	8410.	$	13275.	13489.	$	18275.	18626.	$	23275.	23736.	$	28275.	28854.
1320.	1482.	$	3320.	3469.	$	4660.	4801.	$	8300.	8435.	$	13300.	13515.	$	18300.	18652.	$	23300.	23752.	$	28300.	28929.
1330.	1491.	$	3330.	3479.	$	4665.	4806.	$	8325.	8460.	$	13325.	13540.	$	18325.	18678.	$	23325.	23777.	$	28325.	28955.
1340.	1501.	$	3340.	3489.	$	4670.	4811.	$	8350.	8485.	$	13350.	13566.	$	18350.	18704.	$	23350.	23803.	$	28350.	28980.
1350.	1511.	$	3350.	3499.	$	4675.	4816.	$	8375.	8510.	$	13375.	13592.	$	18375.	18729.	$	23375.	23829.	$	28375.	29005.
1360.	1521.	$	3360.	3509.	$	4680.	4821.	$	8400.	8535.	$	13400.	13617.	$	18400.	18755.	$	23400.	23853.	$	28400.	29031.
1370.	1531.	$	3370.	3519.	$	4685.	4826.	$	8425.	8560.	$	13425.	13643.	$	18425.	18781.	$	23425.	23878.	$	28425.	29056.
1380.	1541.	$	3380.	3529.	$	4690.	4830.	$	8450.	8585.	$	13450.	13668.	$	18450.	18807.	$	23450.	23904.	$	28450.	29082.
1390.	1551.	$	3390.	3539.	$	4695.	4835.	$	8475.	8610.	$	13475.	13694.	$	18475.	18832.	$	23475.	23930.	$	28475.	29107.
1400.	1561.	$	3400.	3549.	$	4700.	4840.	$	8500.	8635.	$	13500.	13720.	$	18500.	18858.	$	23500.	23955.	$	28500.	29132.
1410.	1571.	$	3410.	3558.	$	4705.	4845.	$	8525.	8660.	$	13525.	13745.	$	18525.	18884.	$	23525.	23980.	$	28525.	29158.
1420.	1581.	$	3420.	3568.	$	4710.	4850.	$	8550.	8685.	$	13550.	13771.	$	18550.	18909.	$	23550.	24006.	$	28550.	29183.
1430.	1591.	$	3430.	3578.	$	4715.	4855.	$	8575.	8710.	$	13575.	13796.	$	18575.	18935.	$	23575.	24031.	$	28575.	29109.
1440.	1601.	$	3440.	3588.	$	4720.	4860.	$	8600.	8735.	$	13600.	13822.	$	18600.	18961.	$	23600.	24056.	$	28600.	29134.
1450.	1611.	$	3450.	3598.	$	4725.	4865.	$	8625.	8760.	$	13625.	13848.	$	18625.	18987.	$	23625.	24082.	$	28625.	29160.
1460.	1621.	$	3460.	3608.	$	4730.	4870.	$	8650.	8785.	$	13650.	13873.	$	18650.	19012.	$	23650.	24107.	$	28650.	29185.
1470.	1631.	$	3470.	3618.	$	4735.	4875.	$	8675.	8810.	$	13675.	13899.	$	18675.	19038.	$	23675.	24133.	$	28675.	29210.
1480.	1641.	$	3480.	3628.	$	4740.	4880.	$	8700.	8835.	$	13700.	13925.	$	18700.	19064.	$	23700.	24158.	$	28700.	29234.
1490.	1650.	$	3490.	3638.	$	4745.	4885.	$	8725.	8860.	$	13725.	13950.	$	18725.	19090.	$	23725.	24183.	$	28725.	29261.
1500.	1660.	$	3500.	3648.	$	4750.	4890.	$	8750.	8885.	$	13750.	13976.	$	18750.	19115.	$	23750.	24209.	$	28750.	29286.
1510.	1670.	$	3510.	3658.	$	4755.	4895.	$	8775.	8910.	$	13775.	14001.	$	18775.	19141.	$	23775.	24234.	$	28775.	29312.
1520.	1680.	$	3520.	3668.	$	4760.	4900.	$	8800.	8935.	$	13800.	14027.	$	18800.	19167.	$	23800.	24260.	$	28800.	29337.
1530.	1690.	$	3530.	3678.	$	4765.	4905.	$	8825.	8960.	$	13825.	14053.	$	18825.	19192.	$	23825.	24285.	$	28825.	29363.
1540.	1700.	$	3540.	3688.	$	4770.	4910.	$	8850.	8985.	$	13850.	14078.	$	18850.	19218.	$	23850.	24310.	$	28850.	29388.
1550.	1710.	$	3550.	3698.	$	4775.	4915.	$	8875.	9010.	$	13875.	14104.	$	18875.	19244.	$	23875.	24336.	$	28875.	29413.
1560.	1720.	$	3560.	3708.	$	4780.	4920.	$	8900.	9035.	$	13900.	14129.	$	18900.	19270.	$	23900.	24361.	$	28900.	29439.
1570.	1730.	$	3570.	3717.	$	4785.	4925.	$	8925.	9060.	$	13925.	14155.	$	18925.	19295.	$	23925.	24386.	$	28925.	29464.
1580.	1740.	$	3580.	3727.	$	4790.	4930.	$	8950.	9085.	$	13950.	14181.	$	18950.	19321.	$	23950.	24412.	$	28950.	29489.
1590.	1750.	$	3590.	3737.	$	4795.	4935.	$	8975.	9110.	$	13975.	14206.	$	18975.	19347.	$	23975.	24437.	$	28975.	29515.
1600.	1760.	$	3600.	3747.	$	4800.	4940.	$	9000.	9135.	$	14000.	14232.	$	19000.	19372.	$	24000.	24463.	$	29000.	29540.
1610.	1770.	$	3610.	3757.	$	4805.	4945.	$	9025.	9159.	$	14025.	14258.	$	19025.	19398.	$	24025.	24488.	$	29025.	29565.
1620.	1780.	$	3620.	3767.	$	4810.	4950.	$	9050.	9184.	$	14050.	14283.	$	19050.	19424.	$	24050.	24513.	$	29050.	29591.
1630.	1790.	$	3630.	3777.	$	4815.	4955.	$	9075.	9209.	$	14075.	14309.	$	19075.	19450.	$	24075.	24539.	$	29075.	29616.
1640.	1800.	$	3640.	3787.	$	4820.	4960.	$	9100.	9234.	$	14100.	14334.	$	19100.	19475.	$	24100.	24564.	$	29100.	29642.
1650.	1809.	$	3650.	3797.	$	4825.	4965.	$	9125.	9259.	$	14125.	14360.	$	19125.	19501.	$	24125.	24590.	$	29125.	29667.
1660.	1819.	$	3660.	3807.	$	4830.	4970.	$	9150.	9284.	$	14150.	14386.	$	19150.	19527.	$	24150.	24615.	$	29150.	29692.
1670.	1829.	$	3670.	3817.	$	4835.	4975.	$	9175.	9309.	$	14175.	14411.	$	19175.	19553.	$	24175.	24640.	$	29175.	29718.
1680.	1839.	$	3680.	3827.	$	4840.	4980.	$	9200.	9334.	$	14200.	14437.	$	19200.	19578.	$	24200.	24666.	$	29200.	29743.
1690.	1849.	$	3690.	3837.	$	4845.	4984.	$	9225.	9359.	$	14225.	14462.	$	19225.	19604.	$	24225.	24691.	$	29225.	29769.
1700.	1859.	$	3700.	3847.	$	4850.	4989.	$	9250.	9384.	$	14250.	14488.	$	19250.	19630.	$	24250.	24716.	$	29250.	29794.
1710.	1869.	$	3710.	3857.	$	4855.	4994.	$	9275.	9409.	$	14275.	14514.	$	19275.	19655.	$	24275.	24742.	$	29275.	29819.
1720.	1879.	$	3720.	3867.	$	4860.	4999.	$	9300.	9434.	$	14300.	14539.	$	19300.	19681.	$	24300.	24767.	$	29300.	29845.
1730.	1889.	$	3730.	3876.	$	4865.	5004.	$	9325.	9459.	$	14325.	14565.	$	19325.	19707.	$	24325.	24793.	$	29325.	29870.
1740.	1899.	$	3740.	3886.	$	4870.	5009.	$	9350.	9484.	$	14350.	14591.	$	19350.	19733.	$	24350.	24818.	$	29350.	29895.
1750.	1909.	$	3750.	3896.	$	4875.	5014.	$	9375.	9509.	$	14375.	14616.	$	19375.	19758.	$	24375.	24843.	$	29375.	29921.
1760.	1919.	$	3760.	3906.	$	4880.	5019.	$	9400.	9534.	$	14400.	14642.	$	19400.	19784.	$	24400.	24869.	$	29400.	29946.
1770.	1929.	$	3770.	3916.	$	4885.	5024.	$	9425.	9559.	$	14425.	14667.	$	19425.	19810.	$	24425.	24894.	$	29425.	29972.
1780.	1939.	$	3780.	3926.	$	4890.	5029.	$	9450.	9584.	$	14450.	14693.	$	19450.	19836.	$	24450.	24920.	$	29450.	29997.
1790.	1949.	$	3790.	3936.	$	4895.	5034.	$	9475.	9609.	$	14475.	14719.	$	19475.	19861.	$	24475.	24945.	$	29475.	30022.

Note: Observed load and true load values given in pound units.

COMPRESSIVE STRENGTH CALIBRATION TABLE (continued)

OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD	$	OBSERVED LOAD	TRUE LOAD
1800.	1959.	$	3800.	3946.	$	4900.	5039.	$	9500.	9634.	$	14500.	14744.	$	19500.	19887.	$	24500.	24970.	$	29500.	30248.
1810.	1968.	$	3810.	3956.	$	4905.	5044.	$	9525.	9659.	$	14525.	14770.	$	19525.	19913.	$	24525.	24996.	$	29525.	30273.
1820.	1978.	$	3820.	3966.	$	4910.	5049.	$	9550.	9684.	$	14550.	14795.	$	19550.	19938.	$	24550.	25021.	$	29550.	30285.
1830.	1988.	$	3830.	3976.	$	4915.	5054.	$	9575.	9709.	$	14575.	14821.	$	19575.	19964.	$	24575.	25046.	$	29575.	30124.
1840.	1998.	$	3840.	3986.	$	4920.	5059.	$	9600.	9734.	$	14600.	14847.	$	19600.	19990.	$	24600.	25072.	$	29600.	30149.
1850.	2008.	$	3850.	3996.	$	4925.	5064.	$	9625.	9759.	$	14625.	14872.	$	19625.	20016.	$	24625.	25097.	$	29625.	30175.
1860.	2018.	$	3860.	4006.	$	4930.	5069.	$	9650.	9784.	$	14650.	14898.	$	19650.	20041.	$	24650.	25123.	$	29650.	30200.
1870.	2028.	$	3870.	4016.	$	4935.	5074.	$	9675.	9809.	$	14675.	14924.	$	19675.	20067.	$	24675.	25148.	$	29675.	30225.
1880.	2038.	$	3880.	4026.	$	4940.	5079.	$	9700.	9834.	$	14700.	14949.	$	19700.	20093.	$	24700.	25173.	$	29700.	30251.
1890.	2048.	$	3890.	4036.	$	4945.	5084.	$	9725.	9859.	$	14725.	14975.	$	19725.	20119.	$	24725.	25199.	$	29725.	30276.
1900.	2058.	$	3900.	4045.	$	4950.	5089.	$	9750.	9884.	$	14750.	15000.	$	19750.	20144.	$	24750.	25224.	$	29750.	30302.
1910.	2068.	$	3910.	4055.	$	4955.	5094.	$	9775.	9909.	$	14775.	15026.	$	19775.	20170.	$	24775.	25250.	$	29775.	30327.
1920.	2078.	$	3920.	4065.	$	4960.	5099.	$	9800.	9934.	$	14800.	15052.	$	19800.	20196.	$	24800.	25275.	$	29800.	30352.
1930.	2088.	$	3930.	4075.	$	4965.	5104.	$	9825.	9959.	$	14825.	15077.	$	19825.	20221.	$	24825.	25300.	$	29825.	30378.
1940.	2098.	$	3940.	4085.	$	4970.	5109.	$	9850.	9984.	$	14850.	15103.	$	19850.	20247.	$	24850.	25326.	$	29850.	30403.
1950.	2108.	$	3950.	4095.	$	4975.	5114.	$	9875.	10009.	$	14875.	15128.	$	19875.	20273.	$	24875.	25351.	$	29875.	30429.
1960.	2118.	$	3960.	4105.	$	4980.	5119.	$	9900.	10034.	$	14900.	15154.	$	19900.	20299.	$	24900.	25376.	$	29900.	30454.
1970.	2127.	$	3970.	4115.	$	4985.	5124.	$	9925.	10059.	$	14925.	15180.	$	19925.	20324.	$	24925.	25402.	$	29925.	30479.
1980.	2137.	$	3980.	4125.	$	4990.	5129.	$	9950.	10084.	$	14950.	15205.	$	19950.	20350.	$	24950.	25427.	$	29950.	30505.
1990.	2147.	$	3990.	4135.	$	4995.	5134.	$	9975.	10109.	$	14975.	15231.	$	19975.	20376.	$	24975.	25453.	$	29975.	30530.
2000.	2157.	$	4000.	4145.	$	5000.	5139.	$	10000.	10134.	$	15000.	15256.	$	20000.	20401.	$	25000.	25478.	$	30000.	30555.

```
CORE USAGE        OBJECT CODE=    2320 BYTES,ARRAY AREA=       0 BYTES,TOTAL AREA AVAILABLE=   59488  BYTES
DIAGNOSTICS         NUMBER OF ERRORS=       0, NUMBER OF WARNINGS=       0, NUMBER OF EXTENSIONS=       0
COMPILE TIME=     0.16 SEC,EXECUTION TIME=     0.85 SEC,  WATFIV - VERSION 1 LEVEL 3 MARCH  1971      DATE=  75/135
```

Note: Observed load and true load values given in pound units.

APPENDIX B. RECORDED OBSERVATIONS AND SUBSEQUENT CALCULATIONS OF THE FOURTH SERIES OF TESTS: BATCH DATA, STRENGTH DATA, WEIGHT DATA, AND VOLUME DATA

Appendix B contains the original observations, measurements, and calculations from the fourth series of experiments, the J series. The data are arranged in the order in which the batches were made and is subdivided into four sections: (1) batch data, (2) strength data, (3) weight data, and (4) volume data.

Many of these measurements are related or used in several calculations but for simplicity were only included once. Since this double use of data may make it confusing to follow how each calculation was made, an explanation precedes each table to help in clarifying what each data entry means and how it was derived.

BATCH DATA

Sample no.: Each sample was given a number from 1 through 90.

Batch code: There were 10 batches made; all had identical batch designs and mixing procedures. Each batch produced nine samples. The batches were coded J1, J2, J3,...J10, where "J" refers to the use of juice cans as molds.

Sample type: Some samples from each batch were used as controls; these were designated by the letter "C," meaning control sample. The samples that were pressure cured are designated by the letter "T," meaning test sample. Some samples were flooded prior to pressure testing and designated "T_f," meaning flooded test sample. Some samples were flooded but cured under water at atmospheric pressure as control samples and were designated "C_f," meaning flooded control sample.

Forming time: This is length of time from when the cement and water were first mixed to the start of the pressurization of the pressure vessel and hence the start of pressure curing.

Pressure curing time: The total length of time that the samples were in the pressure vessel and the pressure vessel was pressurized above atmospheric pressure was called pressure curing time.

Decompression: This is total length of time from the start of depressurization from the maximum curing pressure to achieving atmospheric pressure.

Sample leakage: The samples were triple-bagged with dry paper towels between the bags. Leakage was determined by the wet towels. Leaked samples are designated "W," meaning wet. The samples which were deliberately flooded prior to curing were designated "F," meaning flooded. Non-leaked samples are designated "D," meaning dry.

Date mixed: This refers to the day and month of 1975 that the batches were mixed.

Time mixed: The time was recorded using a 24-hour clock.

STRENGTH DATA

Sample no.: Each sample was given a number from 1 through 90.

Date tested: The day and month of 1975 that sample was tested for compressive strength are listed.

Time tested: The time that sample was tested for compressive strength was recorded using a 24-hour clock.

Age when tested: This was calculated as follows: (the date tested) - (the date mixed).

Time to break: This is the time required to fail the sample in compression, from when the sample was loaded to 100 lb until failure.

Observed load: All samples were loaded at an approximate constant rate of .0005 in./sec; that is, a loading rate was set by a dial on the testing machine and the loading rate was not manually changed during the test. Observed maximum loads less than 6,000 lb were read to the nearest 5 lb. Loads between 6,000 and 30,000 lb were read to the nearest 25 lb.

Corrected (true) load: The compression strength testing machine was calibrated with a proving ring and a table of true values was computed (see Appendix A). The true load corresponding to the observed load was obtained from that table. True load and corrected load mean the same thing.

Type of break: A diagram was used to indicate the physical appearance of the cross-section of the failure mode.

 means a triangular piece of the side fell away from the sample--conical failure on one side, tension crack on the other side occurring after initial failure.

 means generally high strength samples failed from top to bottom at an angle.

sp. br. indicates spectacular break--sample disintegrated into pieces after reaching maximum load.

Compressive strength: This was calculated by taking the corrected load and dividing the cross-sectional area (measured in pounds per square inch).

Air entrainment: The percentage of entrained air of fresh mortar (by volume) is recorded.

Fresh sample weight: This was calculated as follows: (weight of can filled with fresh mortar) - (weight of new empty can).

Fresh bulk density: This was calculated as follows: (fresh sample weight) ÷ (200 cm^3).

WEIGHT DATA

Sample no.: This refers to the number of the sample.

Calculated cured weight: This was calculated as follows: (cured weight in can) - (used can weight).

Measured cured weight: After the can was removed from the cured sample, the sample was placed on a scale and weighed.

Fresh weight in can: This is weight of can filled with fresh mortar.

Cured weight in can: This is weight of can filled with cured mortar.

Weight of sample lost: This was calculated as follows: (fresh weight in can) - (cured weight in can) = weight of sample lost during curing. (Most of this was due to loss of water and cement as lid was put on. This dripped down the side of the can and was wiped up with a paper towel.)

Cured bagged weight: This is the weight of cured sample in one bag after the outer bags and paper towel were removed.

Fresh bagged weight: This is the weight of fresh sample packaged in one bag before being wrapped in paper towel and triple bagged.

Weight of water gained: This was calculated as follows: (cured bagged weight) - (fresh bagged weight) = weight of water gained through the impermeable bag. (Both positive and negative weight gains were observed, with the highest positive gains in samples that leaked.)

Used weight in can: This is the weight of the can after it was removed from the cured sample.

New can weight: This is the weight of the new empty can.

Can weight gain: This was calculated as follows: (used can weight) - (new can weight).

VOLUME DATA

Sample no.: This is the number of the sample.

Short diameter: The smallest diameter of an elliptically shaped cross-section of the cured sample was recorded.

Long diameter: The largest diameter in the same plane as the short diameter and perpendicular to the sides was recorded.

Average length: This was calculated as follows: (short length)

+ (long length) ÷ (2.0).

Volume (cm^3): The volume in cubic inches was converted to cubic centimeters by multiplying volume ($in.^3$) by 16.3871.

Cured bulk density: This was calculated as follows: (weight of cured sample) ÷ (volume of sample). (Note: The calculated cured weight and the measured cured weight were compared and the highest weight of the two was used as the weight of the cured sample.)

BATCH DATA

Sample No.	Batch Code	Sample Type	Forming Time (hr:min)	Pressure Curing Time (hr:min)	Decompression Schedule (hr:min)	Sample Leakage	Date Mixed	Time Mixed
1	J1	C	--	--	--	D	20 Feb	14:14
2	J1	T_f	2:11	19:15	0:10	F	20 Feb	14:14
3	J1	T	2:11	19:15	0:10	W	20 Feb	14:14
4	J1	C	--	--	--	D	20 Feb	14:14
5	J1	T_f	2:11	19:15	0:10	F	20 Feb	14:14
6	J1	T	2:11	19:15	0:10	W	20 Feb	14:14
7	J1	C	--	--	--	D	20 Feb	14:14
8	J1	T_f	2:11	19:15	0:10	F	20 Feb	14:14
9	J1	T	2:11	19:15	0:10	W	20 Feb	14:14
10	J2	T	17:02	0:10	0:05	W	24 Feb	15:35
11	J2	C	--	--	--	D	24 Feb	15:35
12	J2	T	18:10	5:15	0:05	D	24 Feb	15:35
13	J2	T	17:02	0:10	0:05	W	24 Feb	15:35
14	J2	C	--	--	--	D	24 Feb	15:35
15	J2	T	18:10	5:15	0:05	W	24 Feb	15:35
16	J2	T	17:02	0:10	0:05	W	24 Feb	15:35
17	J2	C	--	--	--	D	24 Feb	15:35
18	J2	T	18:10	5:15	0:05	W	24 Feb	15:35
19	J3	T	2:45	19:45	0:05	W	25 Feb	13:00
20	J3	C	--	--	--	D	25 Feb	13:00
21	J3	T	2:45	19:45	0:05	D	25 Feb	13:00
22	J3	C	--	--	--	D	25 Feb	13:00
23	J3	T	2:45	19:45	0:05	D	25 Feb	13:00
24	J3	C	--	--	--	D	25 Feb	13:00
25	J3	T	2:45	19:45	0:05	D	25 Feb	13:00
26	J3	C	--	--	--	D	25 Feb	13:00
27	J3	T	2:45	19:45	0:05	D	25 Feb	13:00
28	J4	T	2:10	19:05	1:05	W	27 Feb	15:00
29	J4	C	--	--	--	D	27 Feb	15:00
30	J4	T	2:10	19:05	1:05	W	27 Feb	15:00
31	J4	C	--	--	--	D	27 Feb	15:00
32	J4	T	2:10	19:05	1:05	W	27 Feb	15:00
33	J4	C	--	--	--	D	27 Feb	15:00
34	J4	T	2:10	19:05	1:05	W	27 Feb	15:00
35	J4	C	--	--	--	D	27 Feb	15:00
36	J4	T	2:10	19:05	1:05	W	27 Feb	15:00
37	J5	T	2:45	66:55	1:05	W	28 Feb	14:00
38	J5	C	--	--	--	D	28 Feb	14:00
39	J5	T	2:45	66:55	1:05	D	28 Feb	14:00
40	J5	C	--	--	--	D	28 Feb	14:00
41	J5	T	2:45	66:55	1:05	W	28 Feb	14:00
42	J5	C	--	--	--	D	28 Feb	14:00
43	J5	T	2:45	66:55	1:05	W	28 Feb	14:00
44	J5	C	--	--	--	D	28 Feb	14:00
45	J5	T	2:45	66:55	1:05	W	28 Feb	14:00
46	J6	T	2:55	20:00	1:10	D	4 Mar	13:20
47	J6	C	--	--	--	D	4 Mar	13:20
48	J6	T	2:55	20:00	1:10	D	4 Mar	13:20
49	J6	C	--	--	--	D	4 Mar	13:20
50	J6	T	2:55	20:00	1:10	D	4 Mar	13:20
51	J6	C	--	--	--	D	4 Mar	13:20
52	J6	T	2:55	20:00	1:10	W	4 Mar	13:20
53	J6	C	--	--	--	D	4 Mar	13:20
54	J6	T	2:55	20:00	1:10	W	4 Mar	13:20
55	J7	T	1:45	20:05	0:32	D	6 Mar	14:40
56	J7	C	--	--	--	D	6 Mar	14:40
57	J7	T	1:45	20:05	0:32	D	6 Mar	14:40
58	J7	C	--	--	--	D	6 Mar	14:40
59	J7	T	1:45	20:05	0:32	D	6 Mar	14:40
60	J7	C	--	--	--	D	6 Mar	14:40
61	J7	T	1:45	20:05	0:32	D	6 Mar	14:40
62	J7	C	--	--	--	D	6 Mar	14:40
63	J7	T	1:45	20:05	0:32	D	6 Mar	14:40

BATCH DATA (continued)

Sample No.	Batch Code	Sample Type	Forming Time (hr:min)	Pressure Curing Time (hr:min)	Decompression Schedule (hr:min)	Sample Leakage	Date Mixed	Time Mixed
64	J8	T	1:35	0:50	0:30	D	10 Mar	13:15
65	J8	C	--	--	--	D	10 Mar	13:15
66	J8	T	1:35	0:50	0:30	W	10 Mar	13:15
67	J8	C	--	--	--	D	10 Mar	13:15
68	J8	T	1:35	0:50	0:30	D	10 Mar	13:15
69	J8	C	--	--	--	D	10 Mar	13:15
70	J8	T	1:35	0:50	0:30	D	10 Mar	13:15
71	J8	C	--	--	--	D	10 Mar	13:15
72	J8	T	1:35	0:50	0:30	D	10 Mar	13:15
73	J9	T	2:15	17:10	1:05	D	12 Mar	13:00
74	J9	C	--	--	--	D	12 Mar	13:00
75	J9	T	2:15	17:10	1:05	D	12 Mar	13:00
76	J9	C	--	--	--	D	12 Mar	13:00
77	J9	T	2:15	17:10	1:05	W	12 Mar	13:00
78	J9	C	--	--	--	D	12 Mar	13:00
79	J9	T	2:15	17:10	1:05	D	12 Mar	13:00
80	J9	C	--	--	--	D	12 Mar	13:00
81	J9	T	2:15	17:10	1:05	D	12 Mar	13:00
82	J10	T_f	2:10	76:35	7:00*	F	14 Mar	13:30
83	J10	C_f	--	--	--	F	14 Mar	13:30
84	J10	T	2:10	76:35	7:00*	D	14 Mar	13:30
85	J10	C	--	--	--	D	14 Mar	13:30
86	J10	T	2:10	76:35	7:00*	W	14 Mar	13:30
87	J10	C_f	--	--	--	F	14 Mar	13:30
88	J10	T_f	2:10	76:35	7:00*	F	14 Mar	13:30
89	J10	C	--	--	--	D	14 Mar	13:30
90	J10	T	2:10	76:35	7:00*	D	14 Mar	13:30

*Time until decompressed to 100 psi. The samples remained there for 3 days and then decompressed from 100 psi to 0 in 15 minutes.

STRENGTH DATA

Sample No.	Date Tested	Time Tested	Age When Tested (days)	Time to Break (sec)	Observed Load (lb)	Corrected Load (lb)	Type of Break	Compressive Strength (psi)	Air Entrain-ment (%)	Fresh Sample Weight (gm)	Fresh Bulk Density $\left(\frac{\text{mass}}{\text{volume}}\right)$
1	21 Feb	15:15	1	46	4,180	4,324	--	1377	--	--	--
2	21 Feb	15:19	1	40	3,250	3,399	--	1082	--	--	--
3	21 Feb	15:23	1	55	6,900	7,037	--	2241	--	--	--
4	21 Feb	15:27	1	41	3,980	4,125	--	1281	--	--	--
5	21 Feb	15:31	1	60	3,425	3,573	--	1050	--	--	--
6	21 Feb	15:35	1	52	8,150	8,285	--	2708	--	--	--
7	21 Feb	15:38	1	60	3,665	3,812	--	1184	--	--	--
8	21 Feb	15:41	1	60	3,425	3,573	--	1110	--	--	--
9	21 Feb	15:45	1	60	6,000	6,138	--	1955	--	--	--
10	3 Mar	15:20	7	70	7,600	7,736		2402	--	--	--
11	3 Mar	15:24	7	63	9,300	9,434		2859	--	--	--
12	3 Mar	15:28	7	65	11,325	11,491		3569	--	--	--
13	11 Mar	16:25	15	75	11,925	12,106		3760	--	--	--
14	11 Mar	16:29	15	75	11,000	11,158		3465	--	--	--
15	11 Mar	16:34	15	69	13,375	13,592		4221	--	--	--
16	24 Mar	15:30	28	69	13,600	13,822		4402	--	--	--
17	24 Mar	15:35	28	66	13,850	14,078		4372	--	--	--
18	24 Mar	15:37	28	72	14,550	14,795		4595	--	--	--
19	--	--	--	--	--	--	--	--	--	--	--
20	26 Feb	13:00	1	55	3,385	3,534	--	1098	--	--	--
21	26 Feb	13:04	1	65	4,080	4,224	--	1312	--	--	--
22	28 Feb	14:10	3	60	6,100	6,237		1845	--	--	--
23	28 Feb	14:15	3	67	8,100	8,235		2557	--	--	--
24	4 Mar	13:50	7	74	9,275	9,409		2922	--	--	--
25	4 Mar	13:54	7	75	9,275	9,409		2922	--	--	--
26	25 Mar	13:00	28	73	14,450	14,693		4507	--	--	--
27	25 Mar	13:04	28	76	13,100	13,310		4134	--	--	--
28	27 Mar	15:13	28	82	19,050	19,424		6186	7.88	425.11	2.12
29	27 Mar	15:18	28	71	16,900	17,212		5216	6.58	430.17	2.15
30	28 Feb	15:00	1	57	8,425	8,560		2761	7.45	426.23	2.13
31	28 Feb	15:04	1	48	3,810	3,956		1199	7.01	428.26	2.14
32	6 Mar	15:39	7	91	16,575	16,877		5375	7.45	427.06	2.13
33	6 Mar	15:35	7	75	10,500	10,646		3226	7.88	425.10	2.12
34	2 Mar	16:50	3	75	11,250	11,414		3635	6.58	430.06	2.15
35	2 Mar	16:54	3	70	7,225	7,361	--	2231	7.88	424.10	2.12
36	28 Mar	15:09	29	95	16,400	16,697		5318	7.45	426.77	2.13
37	3 Mar	15:04	3	75	10,200	10,338		3292	--	--	--
38	3 Mar	15:00	3	70	6,900	7,037		2132	--	--	--
39	7 Mar	17:24	7	80	13,675	13,899		4484	--	--	--
40	7 Mar	17:20	7	77	11,325	11,491		3482	--	--	--
41	28 Mar	15:14	28	85	18,250	18,601		5924	--	--	--
42	28 Mar	15:18	28	71	15,700	15,977		4842	--	--	--
43	--	--	--	--	--	--	--	--	--	--	--
44	--	--	--	--	--	--	--	--	--	--	--
45	--	--	--	--	--	--	--	--	--	--	--
46	11 Mar	16:38	7	72	14,900	15,154		4826	6.58	429.48	2.15
47	11 Mar	16:42	7	60	11,575	11,747		3560	6.58	429.58	2.15
48	11 Mar	16:46	7	64	13,225	13,438		4226	6.58	430.95	2.15
49	11 Mar	16:50	7	56	10,700	10,851		3288	7.01	429.13	2.14
50	1 Apr	13:30	28	96	18,850	19,218		6120	7.45	427.01	2.13
51	1 Apr	13:35	28	95	15,850	16,131		4888	6.58	430.83	2.15
52	5 Mar	13:20	1	45	5,300	5,438		1732	6.58	430.33	2.15
53	5 Mar	13:24	1	45	4,310	4,453		1349	6.58	429.94	2.15
54	--	--	--	--	--	--	--	--	7.01	428.57	2.14
55	7 Mar	18:18	1	64	7,075	7,211		2326	7.01	428.70	2.14
56	7 Mar	18:15	1	57	4,610	4,751		1457	5.71	433.65	2.17
57	9 Mar	16:54	3	65	8,175	8,310		2613	6.58	430.84	2.15
58	9 Mar	16:50	3	68	6,850	6,987		2170	6.14	431.95	2.16
59	13 Mar	15:20	7	74	12,800	13,002		4194	6.58	430.28	2.15
60	13 Mar	15:24	7	65	11,600	11,773		3568	5.71	433.40	2.17
61	3 Apr	14:40	28	91	19,975	20,376		6489	6.58	429.29	2.15
62	3 Apr	14:44	28	82	16,175	16,466		5114	6.58	431.22	2.15
63	--	--	--	--	--	--	--	--	7.45	426.82	2.13

STRENGTH DATA (continued)

Sample No.	Date Tested	Time Tested	Age When Tested (days)	Time to Break (sec)	Observed Load (lb)	Corrected Load (lb)	Type of Break	Compressive Strength (psi)	Air Entrain-ment (%)	Fresh Sample Weight (gm)	Fresh Bulk Density $\left(\frac{mass}{volume}\right)$
64	17 Mar	14:40	7	70	5,065	5,203		1577	6.58	429.80	2.15
65	17 Mar	14:43	7	78	11,900	12,080		3617	6.14	431.80	2.16
66	--	--	--	--	--	--	--	--	6.14	431.80	2.16
67	7 Apr	13:15	28	76	16,600	16,903		5122	6.58	430.74	2.15
68	7 Apr	13:19	28	60	3,175	8,310		2518	7.01	428.43	2.14
69	13 Mar	14:28	3	59	7,750	7,886		2390	6.58	429.89	2.15
70	13 Mar	14:32	3	70	4,155	4,299		1303	6.58	429.70	2.15
71	11 Mar	14:37	1	50	4,550	4,691	--	1422	5.71	434.57	2.17
72	11 Mar	14:40	1	50	2,900	3,052	--	972	5.71	433.85	2.17
73	13 Mar	14:20	1	63	6,600	6,737		2146	7.01	429.21	2.14
74	13 Mar	14:24	1	48	4,450	4,592		1392	6.58	430.31	2.15
75	15 Mar	13:00	3	1	15,600*	15,874		5056*	7.01	427.76	2.14
76	15 Mar	13:05	3	55	7,500	7,636		2314	6.58	429.39	2.15
77	--	--	--	--	--	--	--	--	5.27	435.36	2.18
78	17 Mar	13:50	5	75	9,250	9,384		2844	7.01	427.27	2.14
79	17 Mar	13:54	5	70	13,550	13,771		4386	6.14	432.27	2.16
80	9 Apr	13:00	28	85	15,175	15,437		4678	6.58	429.86	2.15
81	9 Apr	13:05	28	85	16,875	17,186		5473	5.71	433.78	2.17
82	21 Mar	18:00	7	75	11,425	11,594		3513	7.01	428.82	2.14
83	21 Mar	18:04	7	70	9,775	9,909		3003	6.14	432.12	2.16
84	21 Mar	18:12	7	75	15,300	15,565		4957	7.01	427.63	2.14
85	21 Mar	18:08	7	65	11,025	11,184		3389	6.14	432.53	2.16
86	--	--	--	--	--	--	--	--	6.14	433.09	2.16
87	11 Apr	15:10	28	85	16,550	16,851		5106	6.14	431.45	2.16
88	11 Apr	15:14	28	76	13,725	13,950		4227	6.14	431.31	2.16
89	11 Apr	15:18	28	75	16,250	16,543		5013	6.58	430.05	2.15
90	11 Apr	15:22	28	79	18,600	18,961		6039	6.58	431.14	2.15

*Loaded too fast (1 second) therefore strength higher than true strength.

WEIGHT DATA

Sample No.	Calculated Cured Weight (gm)	Measured Cured Weight (gm)	Fresh Weight in Can (gm)	Cured Weight in Can (gm)	Sample Weight Lost (gm)	Cured Bagged Weight (gm)	Fresh Bagged Weight (gm)	Water Weight Gained (gm)	Used Can Weight (gm)	New Can Weight (gm)	Can Weight Gained (gm)
1	--	424.25	--	--	--	--	--	--	--	--	--
2	--	421.07	--	--	--	--	--	--	--	--	--
3	--	418.43	--	--	--	--	--	--	--	--	--
4	--	422.60	--	--	--	--	--	--	--	--	--
5	--	401.35	--	--	--	--	--	--	--	--	--
6	--	416.43	--	--	--	--	--	--	--	--	--
7	--	425.07	--	--	--	--	--	--	--	--	--
8	--	406.65	--	--	--	--	--	--	--	--	--
9	--	420.17	--	--	--	--	--	--	--	--	--
10	--	416.79	--	444.23	--	452.50	--	--	--	--	--
11	--	422.77	--	439.38	--	--	--	--	--	--	--
12	--	414.55	--	435.28	--	442.72	--	--	--	--	--
13	--	418.80	--	446.48	--	461.87	--	--	--	--	--
14	--	423.20	--	440.32	--	--	--	--	--	--	--
15	--	420.00	--	446.00	--	--	--	--	--	--	--
16	--	420.13	--	445.25	--	460.47	--	--	--	--	--
17	--	419.21	--	435.54	--	--	--	--	--	--	--
18	--	416.81	--	437.64	--	--	--	--	--	--	--
19	--	420.13	--	444.85	--	448.80	--	--	--	--	--
20	--	422.45	--	443.38	--	449.08	--	--	--	--	--
21	--	414.85	--	444.65	--	450.19	--	--	--	--	--
22	--	420.70	--	441.29	--	446.59	--	--	--	--	--
23	--	412.76	--	439.00	--	446.13	--	--	--	--	--
24	--	422.18	--	443.80	--	448.71	--	--	--	--	--
25	--	409.09	--	440.47	--	446.34	--	--	--	--	--
26	--	421.96	--	442.47	--	448.24	--	--	--	--	--
27	--	417.50	--	444.42	--	451.28	--	--	--	--	--
28	--	411.31	436.21	431.03	5.18	--	--	--	19.06	11.10	7.96
29	--	421.94	441.32	435.51	5.81	--	--	--	13.33	11.15	2.18
30	--	412.26	437.27	432.32	4.95	--	--	--	--	11.04	--
31	--	422.00	440.07	436.74	3.33	--	--	--	--	11.81	--
32	--	414.25	438.37	431.50	6.87	--	--	--	18.00	11.31	6.69
33	--	421.12	436.10	433.14	2.96	--	--	--	13.27	11.00	2.27
34	--	415.75	441.37	435.65	5.72	--	--	--	19.27	11.31	7.96
35	--	418.21	435.13	431.18	3.95	--	--	--	12.63	11.03	1.60
36	--	413.27	442.18	441.59	0.59	--	--	--	27.48	15.41	12.07
37	415.32	414.65	--	442.51	--	--	--	--	27.19	Sunkist	--
38	418.75	418.43	--	436.04	--	--	--	--	17.29	Sunkist	--
39	419.34	417.38	--	441.23	--	--	--	--	21.89	Sunkist	--
40	423.21	424.47	--	441.07	--	--	--	--	17.86	Sunkist	--
41	412.40	411.80	--	439.79	--	--	--	--	27.39	Sunkist	--
42	421.06	420.58	--	438.11	--	--	--	--	17.05	Sunkist	--
43	416.36	415.96	--	441.21	--	--	--	--	24.85	Sunkist	--
44	423.81	423.65	--	441.85	--	--	--	--	18.04	Sunkist	--
45	414.75	414.06	--	443.02	--	--	--	--	28.27	Sunkist	--
46	415.65	414.91	441.60	435.67	5.93	468.15	468.14	+ .01	20.02	12.12	7.90
47	424.36	423.94	441.65	440.06	1.59	452.35	452.29	+ .06	15.70	12.07	3.63
48	417.17	416.55	443.06	435.61	7.45	468.00	468.03	- .03	18.44	12.11	6.33
49	423.63	423.14	441.23	438.24	2.99	450.63	450.66	- .03	14.61	12.10	2.51
50	412.61	411.76	439.11	432.63	6.48	464.70	464.73	- .03	20.02	12.10	7.92
51	424.43	423.88	442.83	439.33	3.50	451.60	451.61	- .01	14.90	12.00	2.90
52	416.68	416.37	442.50	441.46	1.04	467.90	467.82	+ .08	24.78	12.17	12.61
53	423.94	423.77	442.07	439.20	2.87	451.53	451.53	.00	15.26	12.13	3.13
54	413.18	412.52	440.66	433.60	7.06	464.60	464.36	+ .24	20.42	12.09	8.33
55	414.11	410.28	441.17	433.87	7.30	452.83	453.27	- .44	19.76	12.47	7.29
56	427.78	427.55	446.09	442.66	3.43	454.90	454.91	- .01	14.88	12.44	2.44
57	417.62	414.06	443.57	437.21	6.36	456.57	456.69	- .12	19.59	12.73	6.86
58	424.75	423.43	442.46	438.69	4.77	451.64	451.63	+ .01	13.94	11.51	2.43
59	414.82	410.47	442.81	434.06	8.75	455.04	454.98	+ .06	19.24	12.53	6.71
60	426.11	425.48	445.23	439.78	5.45	453.62	453.65	- .03	13.67	11.83	1.84
61	415.45	413.57	440.97	432.41	8.56	453.14	453.14	.00	16.96	11.68	5.28
62	423.66	422.71	442.72	437.37	5.35	451.28	451.32	- .04	13.71	11.50	2.21
63	412.94	410.87	439.25	431.54	7.71	448.84	452.13	- 3.29	18.60	12.43	6.17

WEIGHT DATA (continued)

Sample No.	Calculated Cured Weight (gm)	Measured Cured Weight (gm)	Fresh Weight in Can (gm)	Cured Weight in Can (gm)	Sample Weight Lost (gm)	Cured Bagged Weight (gm)	Fresh Bagged Weight (gm)	Water Weight Gained (gm)	Used Can Weight (gm)	New Can Weight (gm)	Can Weight Gained (gm)
64	421.00	419.97	441.71	438.21	3.50	455.67	--	--	17.21	11.91	5.30
65	424.17	423.06	443.08	437.00	6.08	451.62	--	--	12.83	11.28	1.55
66	420.77	418.76	442.65	436.07	6.58	456.37	--	--	15.30	11.35	3.95
67	424.62	423.63	442.35	437.80	4.55	450.54	--	--	13.18	11.61	1.57
68	418.23	417.04	439.89	434.28	5.61	452.89	--	--	16.05	11.46	4.59
69	424.24	423.04	441.00	436.76	4.24	449.87	--	--	12.52	11.11	1.41
70	420.43	419.28	441.30	436.55	4.75	453.72	--	--	16.12	11.60	4.52
71	427.26	426.67	445.83	440.02	5.81	453.09	--	--	12.76	11.26	1.50
72	421.68	420.62	444.99	437.29	7.70	468.56	--	--	15.61	11.14	4.47
73	416.47	414.77	440.63	431.12	9.51	453.36	453.36	.00	14.65	11.42	3.23
74	424.08	423.24	441.31	436.32	4.99	449.00	448.98	+ .02	12.24	11.00	1.24
75	413.94	411.76	440.17	431.49	8.68	452.13	452.10	+ .03	17.55	12.41	5.14
76	423.91	423.36	441.00	437.19	3.81	449.69	449.73	- .04	13.28	11.61	1.67
77	420.71	418.36	447.33	437.50	9.83	467.69	457.24	+10.45	16.79	11.97	4.82
78	421.81	421.17	438.13	434.30	3.83	446.59	446.56	+ .03	12.49	10.86	1.63
79	418.99	416.65	444.17	435.00	9.17	456.57	456.56	+ .01	16.01	11.90	4.11
80	425.12	424.25	441.76	438.32	3.44	450.77	450.75	+ .02	13.20	11.90	1.30
81	420.16	417.08	446.28	436.39	9.89	459.60	459.59	+ .01	16.23	12.50	3.73
82	438.49	437.72	440.72	459.14	-18.42	--	--	--	20.65	11.90	8.75
83	430.30	428.90	444.59	446.41	- 1.82	--	--	--	16.11	12.47	3.64
84	419.82	418.79	439.05	435.53	3.52	451.22	451.17	+ .05	15.71	11.42	4.29
85	427.29	426.68	445.40	441.72	3.28	454.23	454.32	- .09	14.43	12.47	1.96
86	427.41	425.89	445.86	442.74	3.12	461.05	459.15	+ .90	15.33	12.77	2.56
87	428.90	427.97	442.99	444.83	- 1.84	--	--	--	14.93	11.54	4.39
88	438.17	437.33	443.97	460.30	-16.33	--	--	--	22.13	12.66	9.47
89	424.44	423.57	441.79	438.67	3.12	451.45	451.49	- .04	14.23	11.74	2.49
90	424.25	423.14	443.78	440.77	3.01	458.81	458.78	+ .03	16.52	12.64	3.88

VOLUME DATA

Sample No.	Short Diameter (in)	Long Diameter (in)	Cross-sectional Area (in^3)	Short Length (in)	Long Length (in)	Average Length (in)	Volume (in^3)	Volume (cm^3)	Cured Bulk Density $\left(\frac{mass}{volume}\right)$
1	1.95	2.05	3.14	--	--	3.70	11.62	190.42	2.23
2	2.00	2.00	3.14	--	--	3.65	11.47	187.96	2.24
3	1.95	2.05	3.14	--	--	3.50	11.00	180.26	2.32
4	2.00	2.05	3.22	--	--	3.65	11.75	192.55	2.20
5	2.00	2.05	3.22	--	--	3.60	11.59	189.93	2.11*
6	1.95	2.00	3.06	--	--	3.50	10.72	175.67	2.37
7	2.00	2.05	3.22	--	--	3.60	11.59	189.93	2.24
8	2.00	2.05	3.22	--	--	3.70	11.91	195.17	2.08
9	2.00	2.00	3.14	--	--	3.50	11.00	180.26	2.33
10	2.00	2.05	3.22	3.50	3.65	3.60	11.59	189.93	2.19
11	2.00	2.10	3.30	3.55	3.70	3.60	11.88	194.68	2.17
12	2.00	2.05	3.22	3.50	3.60	3.55	11.43	187.30	2.21
13	2.00	2.05	3.22	3.50	3.65	3.55	11.43	187.30	2.24
14	2.00	2.05	3.22	3.60	3.70	3.65	11.75	192.55	2.20
15	2.00	2.05	3.22	3.50	3.60	3.55	11.43	187.30	2.24
16	2.00	2.00	3.14	3.55	3.65	3.60	11.31	185.34	2.27
17	2.00	2.05	3.22	3.50	3.65	3.60	11.59	189.93	2.21
18	2.00	2.05	3.22	3.60	3.60	3.60	11.59	189.93	2.19
19	1.95	2.05	3.14	--	--	3.55	11.15	182.72	2.30
20	2.00	2.05	3.22	--	--	3.60	11.59	189.93	2.22
21	2.00	2.05	3.22	--	--	3.50	11.27	184.68	2.25
22	2.05	2.10	3.38	--	--	3.60	12.17	199.43	2.11
23	2.00	2.05	3.22	--	--	3.50	11.27	184.68	2.23
24	2.00	2.05	3.22	--	--	3.60	11.59	189.93	2.22
25	2.00	2.05	3.22	--	--	3.50	11.27	184.68	2.22
26	2.00	2.075	3.26	--	--	3.60	11.74	192.38	2.19
27	2.00	2.05	3.22	--	--	3.50	11.27	184.68	2.26
28	2.00	2.00	3.14	3.45	3.55	3.50	11.00	180.26	2.28
29	2.05	2.05	3.30	3.55	3.65	3.60	11.88	194.68	2.17
30	1.975	2.00	3.10	3.45	3.55	3.50	10.85	177.80	2.32
31	2.05	2.05	3.30	--	--	3.60	11.88	194.68	2.17
32	2.00	2.00	3.14	3.50	3.50	3.50	11.00	180.26	2.30
33	2.05	2.05	3.30	3.50	3.60	3.55	11.72	192.06	2.19
34	2.00	2.00	3.14	3.45	3.55	3.50	11.00	180.26	2.31
35	2.05	2.05	3.30	3.60	3.60	3.60	11.88	194.68	2.15
36	2.00	2.00	3.14	3.50	3.60	3.55	11.15	182.72	2.26
37	2.00	2.00	3.14	3.45	3.55	3.50	10.99	180.09	2.31
38	2.05	2.05	3.30	3.60	3.60	3.60	11.88	194.68	2.15
39	1.975	2.00	3.10	3.45	3.55	3.50	10.85	177.80	2.36
40	2.05	2.05	3.30	3.55	3.65	3.60	11.88	194.68	2.17
41	2.00	2.00	3.14	3.50	3.50	3.50	10.99	180.09	2.29
42	2.05	2.05	3.30	3.55	3.65	3.60	11.88	194.68	2.16
43	2.00	2.00	3.14	3.45	3.55	3.50	10.99	180.09	2.31
44	2.05	2.05	3.30	3.55	3.65	3.60	11.88	194.68	2.18
45	2.00	2.00	3.14	3.45	3.55	3.50	10.99	180.09	2.30
46	2.00	2.00	3.14	3.50	3.50	3.50	10.99	180.09	2.31
47	2.05	2.05	3.30	3.55	3.65	3.60	11.88	194.68	2.18
48	2.00	2.025	3.18	3.55	3.55	3.55	11.29	185.01	2.25
49	2.05	2.05	3.30	3.60	3.60	3.60	11.88	194.68	2.18
50	2.00	2.00	3.14	3.45	3.55	3.50	10.99	180.09	2.29
51	2.05	2.05	3.30	3.60	3.60	3.60	11.88	194.68	2.18
52	2.00	2.00	3.14	3.45	3.55	3.50	10.99	100.09	2.31
53	2.05	2.05	3.30	3.60	3.60	3.60	11.88	194.68	2.18
54	2.00	2.00	3.14	3.50	3.50	3.50	10.99	180.09	2.29
55	1.975	2.00	3.10	3.55	3.50	3.525	10.93	179.11	2.31
56	2.00	2.075	3.26	3.65	3.65	3.65	11.90	195.01	2.19
57	2.00	2.025	3.18	3.50	3.55	3.525	11.21	183.70	2.27
58	2.00	2.05	3.22	3.60	3.60	3.60	11.59	195.83	2.24
59	1.95	2.025	3.10	3.50	3.50	3.50	10.85	177.80	2.33
60	2.05	2.05	3.30	3.60	3.60	3.60	11.88	194.68	2.19
61	2.00	2.00	3.14	3.45	3.55	3.50	10.99	180.09	2.31
62	2.00	2.05	3.22	3.60	3.60	3.60	11.59	195.83	2.23
63	2.00	2.00	3.14	3.50	3.50	3.50	10.99	180.09	2.29

*This sample was damaged (pitted). Its measured volume was high because the volume of the pits was not subtracted; therefore the density measured is lower than the actual density.

VOLUME DATA (continued)

Sample No.	Short Diameter (in)	Long Diameter (in)	Cross-sectional Area (in^2)	Short Length (in)	Long Length (in)	Average Length (in)	Volume (in^3)	Volume (cm^3)	Cured Bulk Density ($\frac{mass}{volume}$)
64	2.05	2.05	3.30	3.60	3.60	3.60	11.88	194.68	2.16
65	2.05	2.075	3.34	3.60	3.60	3.60	12.02	196.97	2.15
66	2.05	2.05	3.30	3.60	3.60	3.60	11.88	194.68	2.16
67	2.05	2.05	3.30	3.60	3.60	3.60	11.88	194.68	2.18
68	2.05	2.05	3.30	3.60	3.60	3.60	11.88	194.68	2.15
69	2.05	2.05	3.30	3.5[illegible]	3.65	3.60	11.88	194.68	2.18
70	2.05	2.05	3.30	3.60	3.60	3.60	11.88	194.68	2.16
71	2.05	2.05	3.30	3.60	3.60	3.60	11.88	194.68	2.19
72	2.00	2.00	3.14	3.60	3.60	3.60	11.30	185.17	2.20
73	2.00	2.00	3.14	3.45	3.55	3.50	10.99	180.09	2.31
74	2.05	2.05	3.30	3.60	3.60	3.60	11.88	194.68	2.18
75	2.00	2.00	3.14	3.50	3.50	3.50	10.99	180.09	2.30
76	2.05	2.05	3.30	3.60	3.60	3.60	11.88	194.68	2.18
77	2.00	2.00	3.14	3.50	3.55	3.525	11.07	181.40	2.32
78	2.05	2.05	3.30	3.55	3.60	3.575	11.80	193.37	2.18
79	2.00	2.00	3.14	3.45	3.55	3.50	10.99	180.09	2.33
80	2.05	2.05	3.30	3.60	3.60	3.60	11.88	194.68	2.18
81	2.00	2.00	3.14	3.50	3.55	3.525	11.07	181.40	2.32
82	2.05	2.05	3.30	3.60	3.60	3.60	11.88	194.68	2.25
83	2.05	2.05	3.30	3.60	3.65	3.625	11.96	195.99	2.20
84	2.00	2.00	3.14	3.50	3.50	3.50	10.99	180.09	2.33
85	2.05	2.05	3.30	3.60	3.60	3.60	11.88	194.68	2.19
86	2.00	2.00	3.14	3.50	3.55	3.525	11.07	181.40	2.36
87	2.05	2.05	3.30	3.65	3.65	3.65	12.05	197.46	2.17
88	2.05	2.05	3.30	3.60	3.60	3.60	11.88	194.68	2.25
89	2.05	2.05	3.30	3.60	3.60	3.60	11.88	194.68	2.18
90	2.00	2.00	3.14	3.50	3.50	3.50	10.99	180.09	2.31

APPENDIX C. ABSORPTION RATE DATA

SATURATION DATA OF SAMPLE 19

Constants

Average Volume of Permeable Voids in Sample:	14.65%
Weight of Water in Saturated Permeable Voids:	26.90 gm
Weight in Water of 0% Saturated Sample:	211.80 gm
Weight in Water of 50% Saturated Sample:	225.25 gm
Weight in Water of 100% Saturated Sample:	238.70 gm

Time from Start of Immersion (hr:min:sec)	Weight in Water (gm)	Weight of Water Absorbed (gm)	Saturation (%)	Time from Start of Immersion (hr:min:sec)	Weight in Water (gm)	Weight of Water Absorbed (gm)	Saturation (%)
000:00:00	211.80	0.00	0.00	000:15:30	223.83	12.03	44.72
0:00:01	213.65	1.85	6.88	0:16:00	223.94	12.14	45.13
0:00:02	214.48	2.68	9.96	0:16:30	224.09	12.29	45.69
0:00:30	216.11	4.31	16.02	0:17:00	224.22	12.42	46.17
0:01:00	216.50	4.70	17.47	0:17:30	224.39	12.59	46.80
0:01:30	217.00	5.20	19.33	0:18:00	224.56	12.76	47.43
0:02:00	217.41	5.61	20.86				
0:02:30	217.82	6.02	22.38	0:20:00			50.00
0:03:00	218.13	6.33	23.53				
0:03:30	218.54	6.74	25.06	0:21:00	225.55	13.75	51.12
0:04:00	218.80	7.00	26.02				
0:04:30	219.07	7.27	27.03	0:46:30	230.78	18.98	70.56
0:05:00	219.39	7.59	28.22	0:47:00	230.85	19.05	70.82
0:05:30	219.70	7.90	29.37	0:47:30	230.92	19.12	71.08
0:06:00	219.96	8.16	30.33	0:48:00	230.99	19.19	71.34
0:06:30	220.17	8.37	31.12	0:48:30	231.05	19.25	71.56
0:07:00	220.42	8.62	32.04	0:49:00	231.12	19.32	71.82
0:07:30	220.67	8.87	32.97	0:49:30	231.19	19.39	72.08
0:08:00	220.92	9.12	33.90	0:50:00	231.26	19.46	72.34
0:08:30	221.12	9.32	34.65	0:50:30	231.32	19.52	72.57
0:09:00	221.31	9.51	35.35				
0:09:30	221.53	9.73	36.17	2:02:00	236.82	25.02	93.01
0:10:00	221.72	9.92	36.88	2:02:30	236.82	25.02	93.01
0:10:30	221.94	10.14	37.70	2:03:00	236.84	25.04	93.09
0:11:00	222 13	10.33	38.40				
0:11:30	222.32	10.52	39.11	3:23:30	237.35	25.55	94.98
0:12:00	222.53	10.73	39.89	3:24:00	237.35	25.55	94.98
0:12:30	222.69	10.89	40.48	3:24:30	237.35	25.55	94.98
0:13:00	222.89	11.09	41.23				
0:13:30	223.04	11.24	41.78	65:44:00	238.07	26.27	97.66
0:14:00	223.21	11.41	42.42				
0:14:30	223.38	11.58	43.05	102:53:00	238.16	26.36	97.99
0:15:00	223.65	11.85	44.05				
				BOILED	238.70	26.90	100.00

SATURATION DATA OF SAMPLE 43

Constants

Average Volume of Permeable Voids in Sample:	14.00%
Weight of Water in Saturated Permeable Voids:	24.91 gm
Weight in Water of 0% Saturated Sample:	210.74 gm
Weight in Water of 50% Saturated Sample:	223.20 gm
Weight in Water of 100% Saturated Sample:	235.65 gm

Time from Start of Immersion (hr:min:sec)	Weight in Water (gm)	Weight of Water Absorbed (gm)	Saturation (%)	Time from Start of Immersion (hr:min:sec)	Weight in Water (gm)	Weight of Water Absorbed (gm)	Saturation (%)
000:00:00	210.74	0.00	0.00	000:15:30	221.91	11.17	44.84
0:00:01	212.95	2.21	8.87	0:16:00	222.02	11.28	45.28
0:00:02	213.95	3.21	12.89	0:16:30	222.13	11.39	45.72
0:00:30	215.58	4.84	19.43	0:17:00	222.24	11.50	46.17
0:01:00	216.04	5.30	21.28	0:17:30	222.36	11.62	46.65
0:01:30	216.44	5.70	22.88	0:18:00	222.49	11.75	46.17
0:02:00	216.81	6.07	24.37	0:18:30			
0:02:30	217.11	6.37	25.57	0:19:00			
0:03:00	217.41	6.67	26.78	0:19:30			
0:03:30	217.70	6.96	27.94	0:20:00			
0:04:00	217.96	7.22	28.98	0:20:30	223.25	12.51	50.22
0:04:30	218.20	7.46	29.95	0:21:00	223.35	12.61	50.62
0:05:00	218.44	7.70	30.91	0:21:30	223.46	12.72	51.06
0:05:30	218.66	7.92	31.79	0:22:00	223.58	12.84	51.55
0:06:00	218.89	8.15	32.72				
0:06:30	219.06	8.32	33.40	1:30:30	231.29	20.55	82.50
0:07:00	219.24	8.50	34.12	1:31:00	231.30	20.56	82.54
0:07:30	219.45	8.71	34.97	1:31:30	231.32	20.58	82.62
0:08:00	219.62	8.88	35.65	1:32:00	231.34	20.60	82.70
0:08:30	219.83	9.09	36.49	1:32:30	231.35	20.61	82.74
0:09:00	219.99	9.25	37.13				
0:09:30	220.15	9.41	37.78	3:00:00	233.89	23.15	92.93
0:10:00	220.32	9.58	38.46	3:00:30	233.89	23.15	92.93
0:10:30	220.49	9.75	39.14	3:01:00	233.90	23.16	92.97
0:11:00	220.64	9.90	39.74	3:01:30	233.89	23.15	92.93
0:11:30	220.81	10.07	40.43	3:02:00	233.89	23.15	92.93
0:12:00	220.94	10.20	40.95				
0:12:30	221.08	10.34	41.51	65:22:00	234.72	23.98	96.27
0:13:00	221.20	10.46	41.99				
0:13:30	221.35	10.61	42.59	102:31:00	234.84	24.10	96.75
0:14:00	221.50	10.76	43.20				
0:14:30	221.63	10.89	43.72	BOILED	234.65	24.91	100.00
0:15:00	221.77	11.03	44.28				

SATURATION DATA OF SAMPLE 44

Constants

Average Volume of Permeable Voids in Sample:	14.49%
Weight of Water in Saturated Permeable Voids:	28.28 gm
Weight in Water of 0% Saturated Sample:	200.16 gm
Weight in Water of 50% Saturated Sample:	214.30 gm
Weight in Water of 100% Saturated Sample:	228.44 gm

Time from Start of Immersion (hr:min:sec)	Weight in Water (gm)	Weight of Water Absorbed (gm)	Saturation (%)	Time from Start of Immersion (hr:min:sec)	Weight in Water (gm)	Weight of Water Absorbed (gm)	Saturation (%)
000:00:00	200.16	0.00	0.00	000:15:30	212.62	12.46	44.06
0:00:01	202.28	2.12	7.50	0:16:00	212.79	12.63	44.66
0:00:02	203.17	3.01	10.64	0:16:30	212.94	12.78	45.19
0:00:30	203.77	3.61	12.77	0:17:00	213.07	12.91	45.65
0:01:00	204.48	4.32	15.28	0:17:30	213.25	13.09	46.29
0:01:30	205.02	4.86	17.19	0:18:00	213.41	13.25	46.85
0:02:00	205.56	5.40	19.09	0:18:30	213.57	13.41	47.42
0:02:30	205.92	5.76	20.37	0:19:00	213.70	13.54	47.88
0:03:00	206.30	6.14	21.71	0:19:30	213.85	13.69	48.41
0:03:30	206.65	6.49	22.95	0:20:00	213.98	13.82	48.87
0:04:00	206.96	6.80	24.05	0:20:30	214.11	13.95	49.33
0:04:30							
0:05:00	207.68	7.52	26.59	0:26:30	216.52	16.36	57.85
0:05:30	207.98	7.82	27.65				
0:06:00	208.25	8.09	28.61	1:01:30	222.78	22.62	79.99
0:06:30	208.50	8.34	29.49	1:02:00	222.83	22.65	80.16
0:07:00	208.79	8.63	30.52	1:02:30	222.88	22.72	80.34
0:07:30	209.02	8.86	31.33	1:03:00	222.94	22.78	80.55
0:08:00	209.27	9.11	32.21	1:03:30	222.99	22.83	80.73
0:08:30	209.52	9.36	33.10	1:04:00	223.04	22.88	80.91
0:09:00	209.77	9.61	33.98				
0:09:30	210.01	9.85	34.83	2:37:00	227.33	27.17	96.07
0:10:00	210.20	10.04	35.50	2:37:30	227:33	27.17	96.07
0:10:30	210.41	10.25	36.24	2:38:00	227.33	27.17	96.07
0:11:00	210.62	10.46	36.99	2:38:30	227.33	27.17	96.07
0:11:30	210.81	10.65	37.66	2:39:00	227.33	27.17	96.07
0:12:00	211.00	10.84	38.33				
0:12:30	211.20	11.04	39.04	64:50:00	228.11	27.95	98.83
0:13:00	211.39	11.23	39.71				
0:13:30	211.94	11.78	41.65	101:59:00	228.26	28.10	99.36
0:14:00	212.11	11.95	42.26				
0:14:30	212.27	12.11	42.82	BOILED	228.44	28.28	100.00
0:15:00	212.44	12.28	43.42				

SATURATION DATA OF SAMPLE 66

Constants

Average Volume of Permeable Voids in Sample:	16.54%
Weight of Water in Saturated Permeable Voids:	31.14 gm
Weight in Water of 0% Saturated Sample:	202.95 gm
Weight in Water of 50% Saturated Sample:	218.52 gm
Weight in Water of 100% Saturated Sample:	234.09 gm

Time from Start of Immersion (hr:min:sec)	Weight in Water (gm)	Weight of Water Absorbed (gm)	Saturation (%)	Time from Start of Immersion (hr:min:sec)	Weight in Water (gm)	Weight of Water Absorbed (gm)	Saturation (%)
000:00:00	202.95	0.00	0.00	000:14:00	214.72	11.77	37.80
0:00:15	206.01	3.06	9.83	0:14:30	214.87	11.92	38.28
0:00:30	206.66	3.71	11.91	0:15:00	215.00	12.05	38.70
				0:15:30	215.17	12.22	39.24
0:01:00	207.49	4.54	14.58	0:16:00	215.30	12.35	39.66
0:01:30	208.13	5.18	16.63	0:16:30	215.43	12.48	40.08
0:02:00	208.65	5.70	18.30	0:17:00	215.59	12.64	40.59
0:02:30	209.10	6.15	19.75	0:17:30	215.74	12.79	41.07
0:03:00	209.53	6.58	21.13	0:18:00	215.84	12.89	41.39
0:03:30	209.91	6.96	22.35	RUBBED OFF AIR BUBBLES			
0:04:00	210.26	7.31	23.47	0:18:30	216.80	13.85	44.48
0:04:30	210.63	7.68	24.66	0:19:00	216.91	13.96	44.83
0:05:00	210.91	7.96	25.56	0:19:30	217.05	14.10	45.28
0:05:30	211.18	8.23	26.43	0:20:00	217.17	14.22	45.66
0:06:00	211.45	8.50	27.30	0:20:30	217.30	14.35	46.08
0:06:30	211.73	8.78	28.20	0:21:00	217.44	14.49	46.53
0:07:00	211.94	8.99	28.87				
0:07:30	212.21	9.26	29.74	1:37:00	226.79	23.84	76.56
0:08:00	212.40	9.45	30.35	1:37:30	226.81	23.86	76.62
0:08:30	212.67	9.72	31.21	1:38:00	226.83	23.88	76.69
0:09:00	212.85	9.90	31.79	1:38:30	226.85	23.90	76.75
0:09:30	213.04	10.09	32.40	1:39:00	226.87	23.92	76.81
0:10:00	213.23	10.30	33.08				
0:10:30	213.44	10.49	33.69	63:41:00	229.50	26.55	85.26
0:11:00	213.65	10.70	34.36				
0:11:30	213.83	10.88	34.94	100:51:00	299.62	26.67	85.65
0:12:00	214.02	11.07	35.55				
0:12:30	214.14	11.19	35.93	BOILED	234.09	31.14	100.00
0:13:00	214.41	11.46	36.80				
0:13:30	214.55	11.60	37.25				

SATURATION DATA OF SAMPLE 77

Constants

Average Volume of Permeable Voids in Sample:	13.15%
Weight of Water in Saturated Permeable Voids:	23.72 gm
Weight in Water of 0% Saturated Sample:	214.18 gm
Weight in Water of 50% Saturated Sample:	226.04 gm
Weight in Water of 100% Saturated Sample:	237.90 gm

Time from Start of Immersion (hr:min:sec)	Weight in Water (gm)	Weight of Water Absorbed (gm)	Saturation (%)	Time from Start of Immersion (hr:min:sec)	Weight in Water (gm)	Weight of Water Absorbed (gm)	Saturation (%)
000:00:00	214.18	0.00	0.00	000:14:00	224.02	9.84	41.48
				0:14:30	224.16	9.98	42.07
0:00:30	217.15	2.97	12.52	0:15:00	224.29	10.11	42.62
0:01:00	217.94	3.76	15.85	0:15:30	224.42	10.24	43.17
0:01:30	218.47	4.29	18.09	0:16:00	224.55	10.37	43.72
0:02:00	218.94	4.76	20.07	0:16:30	224.68	10.50	44.27
0:02:30	219.36	5.18	21.84	0:17:00	224.78	10.60	44.69
0:03:00	219.67	5.49	23.15	0:17:30	224.92	10.74	45.28
0:03:30	219.98	5.80	24.45	0:18:00	225.02	10.84	45.70
0:04:00	220.26	6.08	25.63	RUBBED AIR BUBBLES OFF			
0:04:30	220.55	6.37	26.85	0:18:30	225.52	11.34	47.81
0:05:00	220.79	6.61	27.87	0:19:00	225.64	11.46	48.31
0:05:30	221.04	6.86	28.92	0:19:30	225.76	11.58	48.82
0:06:00	221.24	7.06	29.76	0:20:00	225.86	11.68	49.24
0:06:30	221.50	7.32	30.86	0:20:30	225.98	11.80	49.75
0:07:00				0:21:00	226.09	11.91	50.21
0:07:30	221.92	7.74	32.63				
0:08:00	222.11	7.93	33.43	1:11:30	232.66	18.48	77.91
0:08:30	222.29	8.11	34.19	1:12:00	232.71	18.53	78.12
0:09:00	222.49	8.31	35.03	1:12:30	232.73	18.55	78.20
0:09:30	222.64	8.46	35.67	1:13:00	232.78	18.60	78.41
0:10:00	222.82	8.64	36.42	1:13:30	232.81	18.63	78.54
0:10:30	223.00	8.82	37.18	1:14:00	232.85	18.67	78.71
0:11:00	223.15	8.97	37.82				
0:11:30	223.30	9.12	38.45	63:13:00	237.36	23.18	97.72
0:12:00	223.46	9.28	39.12				
0:12:30	223.60	9.42	39.71	100:22:00	237.44	23.26	98.06
0:13:00	223.76	9.58	40.39				
0:13:30	223.89	9.71	40.94	BOILED	237.90	23.72	100.00

SATURATION DATA OF SAMPLE 86

Constants

Average Volume of Permeable Voids in Sample:	12.30%
Weight of Water in Saturated Permeable Voids:	22.16 gm
Weight in Water of 0% Saturated Sample:	216.52 gm
Weight in Water of 50% Saturated Sample:	227.60 gm
Weight in Water of 100% Saturated Sample:	238.68 gm

Time from Start of Immersion (hr:min:sec)	Weight in Water (gm)	Weight of Water Absorbed (gm)	Saturation (%)	Time from Start of Immersion (hr:min:sec)	Weight in Water (gm)	Weight of Water Absorbed (gm)	Saturation (%)
000:00:00	216.52	0.00	0.00	000:13:30	225.39	8.87	40.03
0:00:15	218.45	1.93	8.71	0:14:00	225.56	9.04	40.79
0:00:30	218.92	2.40	10.83	0:14:30	225.67	9.15	41.29
0:00:45	219.29	2.77	12.50	0:15:00	225.80	9.28	41.88
0:01:00	219.65	3.13	14.12	0:15:30	225.93	9.41	42.46
0:01:30	220.04	3.52	15.88	0:16:00	226.04	9.52	42.96
0:01:45	220.28	3.76	16.97	0:16:30	226.15	9.63	43.46
0:02:00	220.50	3.98	17.96	0:17:00	226.29	9.77	44.09
0:02:30	220.88	4.36	19.68	RUBBED AIR BUBBLES OFF			
0:03:00	221.25	4.73	21.34	0:17:30	226.84	10.32	46.57
0:03:30	221.55	5.03	22.70	0:18:00	226.98	10.46	47.20
0:04:00	221.87	5.35	24.14	0:18:30	227.08	10.56	47.65
0:04:30	222.11	5.59	25.23	0:19:00	227.21	10.69	48.24
0:05:00	222.37	5.85	26.40	0:19:30	227.30	10.78	48.65
0:05:30	222.59	6.07	27.39	0:20:00	227.41	10.89	49.14
0:06:00	222.82	6.30	28.43	0:20:30	227.52	11.00	49.64
0:06:30	223.04	6.52	29.42	0:21:00	227.64	11.12	50.18
0:07:00	223.25	6.73	30.37				
0:07:30	223.45	6.93	31.27	0:51:30	232.17	15.65	70.62
0:08:00	223.65	7.13	32.18	0:52:00	232.21	15.69	70.80
0:08:30	223.86	7.34	33.12	0:52:30	232.26	15.74	71.03
0:09:00	224.01	7.49	33.80	0:53:00	232.30	15.78	71.21
0:09:30	224.16	7.64	34.48	0:53:30	232.37	15.85	71.53
0:10:00	224.32	7.80	35.20	0:54:00	232.40	15.88	71.66
0:10:30							
0:11:00	224.67	8.15	36.78	62:49:00	238.47	21.95	99.05
0:11:30	224.82	8.30	37.45				
0:12:00	224.97	8.45	38.13	99:58:00	238.55	23.03	99.41
0:12:30	225.10	8.58	38.72				
0:13:00	225.26	8.74	39.44	BOILED	238.68	22.16	100.00