

ACCELERATED TESTS OF THE CORROSION PROTECTION
OF THIN PRECAST CONCRETE SECTIONS


by

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III. INTRODUCTION

A method for specifying the depth of concrete cover for protection of reinforcing steel against corrosion has long been needed and sought after by the engineering profession. Such a method must be supported by a large body of quantitative data before it can be generally accepted. A half-life method has been proposed (1) which appears to be a satisfactory method, but the body of supporting evidence is still small. This method evaluates the protective ability of a specific depth of cover of a particular concrete mix by determining the half-life of the encased reinforcing steel. The half-life is defined as the length of time required for the cross-sectional area of the steel to be corroded to one-half its original area. The half-life is also dependent upon the shape of the reinforcing steel, thus the half-life determined for a thin steel ribbon would probably be different from the half-life for a round bar, even though the concrete cover was the same.

Research designed to supply quantitative data to support this method and to aid in understanding the problem of obtaining corrosion protection was started at V.P.I. in 1948 under the direction of Professor D. H. Pletta and sponsored by the Bureau of Yards and Docks, United States Navy. Funds were made available through the Office of Naval Research and a contract was entered into by the Bureau of Yards and Docks and the Virginia Polytechnic Institute Research Foundation. The work was carried out, on the fellowship plan, by

Mr. E. F. Massie in 1948, Mr. H. S. Robins in 1949, and Mr. J. P. Ferraci in 1950. The author was employed in September, 1951 to continue the research.

Some of the concrete test sections of Series I, (cast by Mr. Massie and Mr. Robins) principally those from lean and harsh mixes, showed evidence of corrosion. Most of the test sections from more plastic mixes still have not shown evidence of corrosion although some have been subjected to a moist atmosphere for as long as five years.

The object of the present research was to accelerate the rate of corrosion and there by obtain information about the corrosion protection offered by the more plastic mixes.

IV. EXPERIMENTAL INVESTIGATION

A. OBJECT OF THE INVESTIGATION

The primary objective of the investigation was to gain quantitative information about the ability of various concrete mixes to protect reinforcing steel against corrosion over long period of time. Previous research (1) (2) had shown that very harsh, porous concretes and wet concretes with low cement content provide inadequate protection. It was decided, therefore, that the present investigation should cover the range of concretes which previous tests have shown to provide protection for periods of time up to three to five years.

Secondary objectives were to investigate (1) effectiveness of several types of waterproofing with the various concrete mixes, and (2) the effect of fine flexural cracking of the concrete sections.

B. DESIGN OF THE EXPERIMENTS

General

The electrical resistance method was used to evaluate the protection given the reinforcing steel by the surrounding concrete. In this method a thin steel ribbon was cast in the thin concrete test sections to simulate the reinforcing steel. When corrosion of the steel occurred the cross-sectional area of the steel ribbon decreased and the electrical resistance of the ribbon increased. Hence, by periodic measurements of the electrical resistance of the ribbon the

progress of the corrosion was plotted and the half-life values for each test section found for various concrete mixes.

Design of the Experiments

The investigation was divided into four experiments for convenience in analysis. Experiments I and II were under exposure conditions which accelerated the corrosion tests. Because of economic and spatial limitations it was necessary to limit the number and size of the test sections, and factorial designs with single replication were used. The main effects and first order interactions only were to be calculated and the higher order interactions were to be used as estimates of experimental error. Two other experiments were run under more natural exposure conditions, one to "calibrate" the accelerating apparatus and one to investigate flexural cracking.

Experiment I

Experiment I was designed to investigate six concrete mix variables each at two levels (levels 0 and I). The symbols for the six variables are shown in table I. The number of test sections required was $2^6 = 64$; that is, every possible combination of the six variables at two levels. Each test section embodies a different "treatment" with a distinct treatment symbol. The treatment symbol contains only those letters representing the variables which were present in the test section at their higher level. For example: CAS is the treatment symbol for a test section made with a cement factor of 8, water /cement ratio by weight of .576, Aeolian limestone, depth of cover of 1/4 inch,

TABLE I: VARIABLES FOR EXPERIMENT NO. I

Symbol	Variable	Levels of Variable		Units
		0	1	
C	Cement Factor	7	8	Sacks/cu. yd.
W	Water/Cement Ratio	.576	.664	lb./lb.
A	Type of Aggregate	Dolomitic Limestone	Aeolian Limestone	- -
D	Depth of Cover	1/4	1/2	inches
S	Ratio of Maximum Size of Aggregate to Depth of Cover	1/2	3/4	in./in.
H	Type of Water	Fresh	Sea	- -

TABLE II: VARIABLES FOR EXPERIMENT NO. II

Symbol	Variable	Levels of Variable					Units
		0	1	2	3	4	
C	Cement Factor	7	8	-	-	-	sacks/cu. yd.
W	Water/Cement Ratio	.576	.664	-	-	-	lb./lb.
A	Type of Aggregate	Dolomitic	Aeolian	-	-	-	- -
P	Type of Water-proofing	No Water-Proofing	Slurry on Steel	Paint on Steel	Paint on concrete	Admixture	- -
Factors D, S and H held constant; D= 1/4 inch. S= 1/8", H= fresh water.							

Ratio of Max. agg. size to depth of cover of $3/4$ and fresh water. The symbol used for the treatment with all variables at the lower level is 1.

The levels of the water/cement ratio are equivalent to $6\ 1/2$ and $7\ 1/2$ gallons per sack of cement for fresh water, but slightly less for the sea water which is more dense.

In choosing the levels of variables D and S (See Table I) particular consideration was given to "Proposed Specifications for Minimum Bar Spacing and Protective Cover in Precast Concrete Framing Members" by Arshon Amirikian (3). The reader should note that since variable S was the ratio of the maximum size of aggregate to the depth of cover there were actually four maximum sizes of aggregate; i.e., with the $1/4$ depth of cover maximum sizes of aggregate were $1/4$ inch and $3/8$ inch.

The levels of variables C & W were chosen so that the treatments covered the range of plastic, workable mixes.

Experiment II

Experiment II was designed to investigate three concrete mix variables, each at two levels, and five different types of waterproofing as shown in Table II. This design includes no waterproofing as the zero level of waterproofing to provide a basis for evaluating the four actual methods of waterproofing that were used. The number of treatments, was $2^3 \times 5 = 40$, but eight of these treatments, those with the zero level of waterproofing, were identical with eight treatments in Experiment I so only 32 additional test sections

were needed for this experiment. The treatment symbols for this experiment follow the rule for Experiment I except that the "levels" of waterproofing are represented by number instead of letter. For example CWA3 is the symbol for the treatment with C, W, and A at their higher level and waterproofing at level three; paint on the concrete.

Experiment III

Calibrating of the accelerating apparatus was deemed necessary. Calibration in this case meant finding some means of translating the data from Experiments I and II in terms of time expressed as number of cycles of wetting and drying in the accelerating apparatus into time expressed as years of natural exposure conditions. Twenty-four of the treatments used in Experiment I were chosen to be duplicated for Experiment III, to be made from the same mixes and at the same time as the treatments of Experiment I. The twenty-four treatments were:

I	W	C	CW	D	CD
H	WH	CH	CWH	DS	CDS
S	WS	CS	CWS	SD	CSD
A	WA	CA	CWA	WDS	CWDS

In order to differentiate the treatments of Experiment III from others the treatment symbol is used with the figure 3 prefixed to it.(e.g. 3CWA).

The calibration factor for Experiment I was to be determined by a regression of results from Experiment III on results from Experiment I. It was realized that the results from Experiments III would not be available until several years after completion of Experiment I, hence, the calibration factor and long time effects can not be reported herein.

The exposure condition for Experiment III referred to above as natural and more natural, was to be a continued exposure to moist air (95 to 98% R.H.) at a temperature of 75°F. \pm 5°F. (Such an exposure is admittedly more severe than that encountered in most climates but possibly less severe than sea shore exposure.)

Experiment IV

Experiment IV was designed to investigate the effect of fine flexural cracking on the corrosion protection offered by concrete. The treatments for this experiment were duplicates of the twenty-four made for Experiment III, made from the same mixes and at the same time. The same treatment symbols were used, with a prefixed figure 4.

The flexural cracking was produced by bending with a central load (See Section D, Experimental Procedures). The test section was bent until the deflection at the center reached the value given by:

$$D = L^2/12,000t$$

where: D = deflection of test section, in inches,

L = span of the section, in inches,

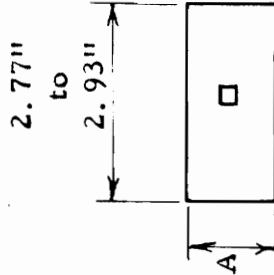
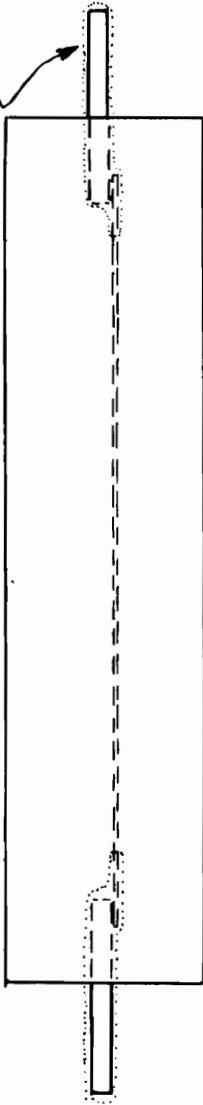
t = thickness of the section, in inches.

This formula is the same as that for the allowable deflection under a load test as specified by the building code of the American Concrete Institute.

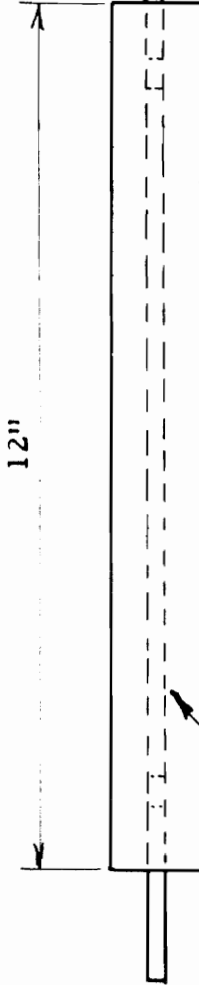
Size of Test Section

The thickness of the test sections was set when 1/4 inch and 1/2 inch were chosen for depths of cover (see variable D, table I). Previous investigators at VPI had used test sections six inches wide and twelve inches long. Space limitations of the specimen chamber for the present research required that the width of the panels be reduced considerably. A width of 2-1/2 inches was thought to be the practical minimum for representing 3/4 inch and 1-1/4 inch precast concrete sections. This width was changed to 2-3/4" in order to make economical use of existing molds. The length was set at 12 inches since this was a convenient length to handle and allowed sufficient extent of concrete for a reasonable sample. Details and dimensions of the test sections are shown in Figure I.

Dotted lines indicate the extent of the coating of Seal-Glo.



0.008" x 0.25" Steel ribbon soldered to 1/4" x 1/4" copper terminals.



Dimension 'A' Varies:
0.70"-0.90" for D₀
1.20"-1.33" for D₁

Figure 1.
DETAILS AND DIMENSIONS OF TEST SECTIONS

C. CYCLIC APPARATUS

Requirements

A special cyclic apparatus was needed to produce a severe exposure condition to accelerate corrosion of the steel ribbon for Experiments I and II. Previous investigators (4) (5) had found that repeated cycles of two days in moist air and two days in dry air produced more rapid corrosion than did a continued exposure to moist air. This can be explained* as follows: The corrosion (rusting) process requires the presence of both water and oxygen. Under continually moist conditions a blanket of iron oxide builds up around the steel and inhibits the corrosion process by slowing down the rate of infiltration of oxygen. However, with alternate wetting and drying the blanket of iron oxide is dehydrated, at least partially, during the drying period and if fine shrinkage cracks form, more oxygen and water will be allowed to reach the steel during the subsequent wetting period.

Accepting this explanation it seemed that it would be necessary to get the moisture, and dissolved oxygen, to the steel more quickly and also to remove the moisture more quickly in order to accelerate the corrosion of the steel. It was decided to do this by exposing the test sections to water under pressure for the wetting period and then to a stream of warm dry air for the drying period.

* This explanation is due to Dr. N. F. Murphy, Department of Chemical Engineering, V.P.I.

To establish the length of the wetting period, absorption tests were made on eight concrete blocks 1-1/8" x 2" x 4" and four blocks 1-1/2" x 2" x 4". The concrete mix for all 12 blocks used seven sacks of cement per cubic yard and six gallons of water per sack of cement. The fine aggregate was Petersburg Sand, coarse aggregate was 1/4" maximum dolomite limestone from Ellet, Virginia. The blocks absorbed an average of 4.75 percent of moisture, based on oven dry weight, during 70 minutes under a water pressure of 65 psig. Ninety-four percent of this moisture was absorbed in the first 15 minutes of the test and the increase after 30 minutes was less than 0.2 percent. It seemed, for this concrete, that 30 minute wetting period would be sufficient. Since some of the concretes which were to be investigated would be somewhat more dense than this one, a wetting period of one hour, with a pressure of 60 psig, was chosen.

Equipment for performing drying tests, using a flow of dry air, was not available, hence the length of the drying period had to be decided after the apparatus had been constructed.

A further requirement was that the cyclic apparatus be fully automatic so that the periods of wetting and drying would be repeated uniformly without requiring constant attention.

Description of the Apparatus

A schematic flow diagram of the cyclic apparatus is shown in Figure 2. To start the wetting period, valve V2 opens to allow 70°F. water from the tempering tank to enter the test chamber. The check valve, V5, and valve V3 close so that the pressure builds up in the test chamber. At the end of the wetting period valve V2 closes and V3 opens to drain the water from the tank. After a short time the compressor is switched on and blows air through the test chamber to dry the specimens. The compressor is switched off at the end of the drying period and after 3 minutes the cycle is repeated.

The Nash Hytor compressor is a centrifugal displacement type of pump using water as a compressant. This "seal water" also takes up the heat of compression of the air so that the temperature of the air leaving the compressor is not more than 10°F. greater than the temperature of the seal water. A small amount of seal water is continuously supplied to the compressor, exits with the compressed air and is removed in a simple baffle separator. Since the seal water temperature averages approximately 60°F, the air leaving the separator is at about 70°F, saturated.

The air is cooled to about 50°F. as it passes through the cooler, its excess moisture condenses and is removed through a condensate trap to the drain. The air is then heated to test temperature, the relative humidity decreasing as the temperature is increased. This final temperature of the air can be varied from 50°F. to about 130°F by various combinations of the three five-heat switches.

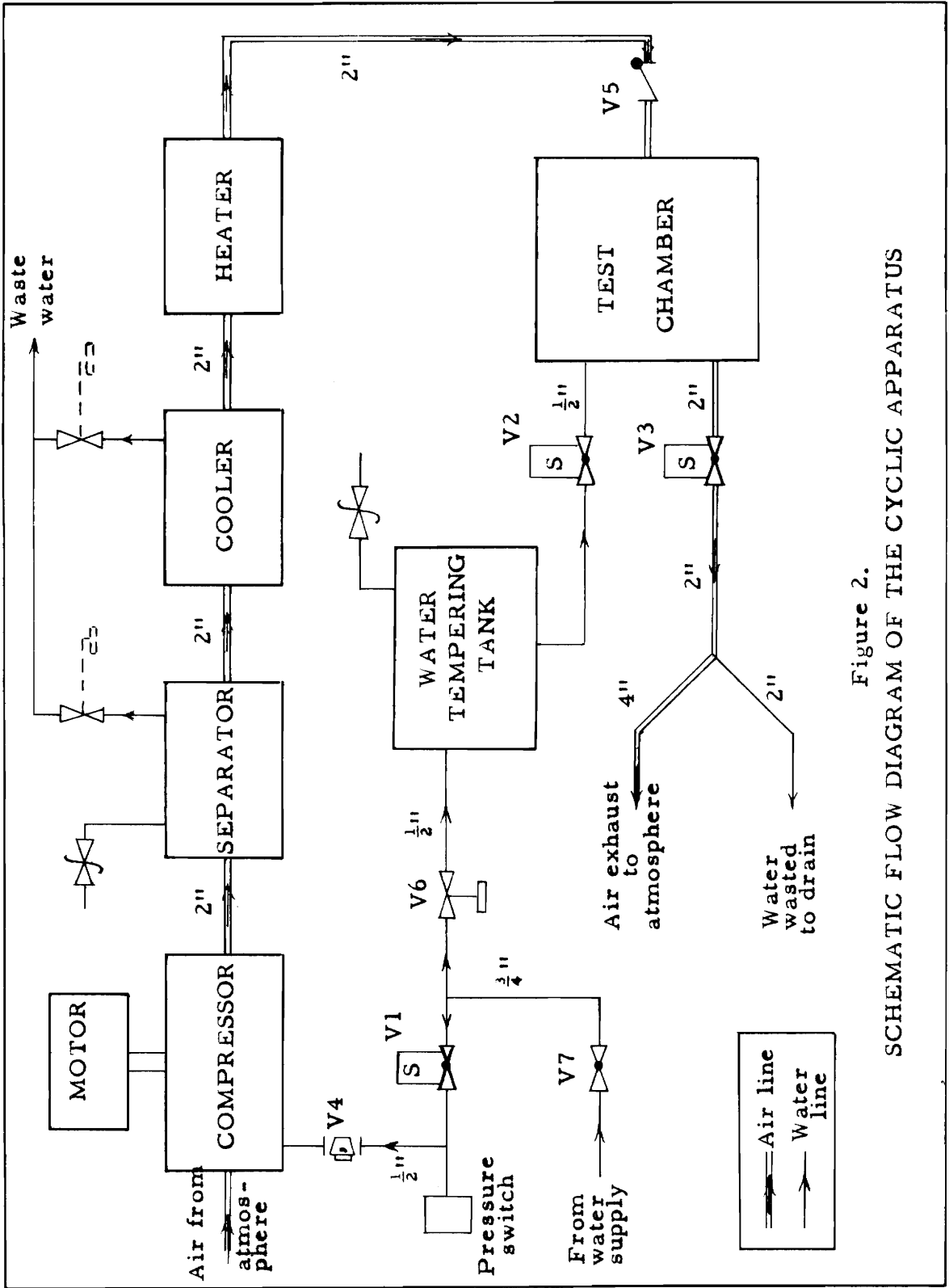


Figure 2.
SCHEMATIC FLOW DIAGRAM OF THE CYCLIC APPARATUS

TABLE III. DESCRIPTION OF MAJOR ELEMENTS OF CYCLIC APPARATUS

Element	Description	Manufacturer	Manufacturer's Descriptive Literature
Compressor and Separator	Nash Hytor Compressor Size L 3 with Diehl 10 HP, 1750 RPM, 220 v., 3 phase, 60 cycle Electric Motor. Direct Drive. Muffler, separator and drain valve.	The Nash Engrg. Co. South Norwalk, Connecticut	Bulletin No. I-P-V-L 355-D Drawing No. NDC-111.
Cooler	Quiet Cool 3/4 HP room air conditioner Model G 7 D. ASRE cooling capacity rating: 8650 Btu. per hour. Cooling coils removed from unit and placed in special chamber.	Quiet-Heet Mfg. Corp. Newark, N. J.	Bulletin (Not numbered)
Heater	Tank: 4' length of 8" diam. steel pipe with plates welded on ends. Heating Units: 3-1250 Watt, 220 v. AC. Frigidaire range surface units controlled by Frigidaire 5-heat switches.	Composite	None
Test Chamber	2' diam. x 2' long tank with spherical heads. Body - 3/16" steel, Heads - 1/4" steel.	Richmond Engrg. Co. Richmond, Virginia	Drawings No. A-52-42 and SK-52-206
Water Tempering Tank	Standard 40 gallon hot water tank with pressure relief valve set at 125 psi.	Unknown	None

Detailed descriptions of the major elements of the apparatus are given in Table III. Photographs of the apparatus are presented as Figures 4 and 5.

Automatic Control

Detailed descriptions of the control elements are given in Table IV. A schematic wiring diagram is shown in Figure 3 to supplement the explanation of the control system given below. A more complete wiring diagram is presented in Appendix A.

The length of the cycle for the cyclic apparatus is determined by the setting of the flexopulse timer, which closes the multiflex timer motor circuit to begin a cycle and opens the circuit to end a cycle. The maximum total of "closed" time plus "open" time is five hours. The minimum for either "closed" or "open" time is 2-1/2 minutes. For the exposure condition for experiments I and II the circuit is closed 4-1/2 hours and open for 3 minutes.

Closing the multiflex timer motor circuit starts the timer motor which actuates the five time switches according to their setting. Each switch may be set to close at any time during the cycle and open again at any later time. Switch number one may be set to stop the timer motor before the end of the cycle, in which event the other switches will be held closed or open (according to their settings) until the end of the cycle. The multiflex timer resets automatically to starting position when the motor circuit is opened by the flexopulse timer switch. Manual switches are also provided in the multiflex timer motor circuit and the control circuits so

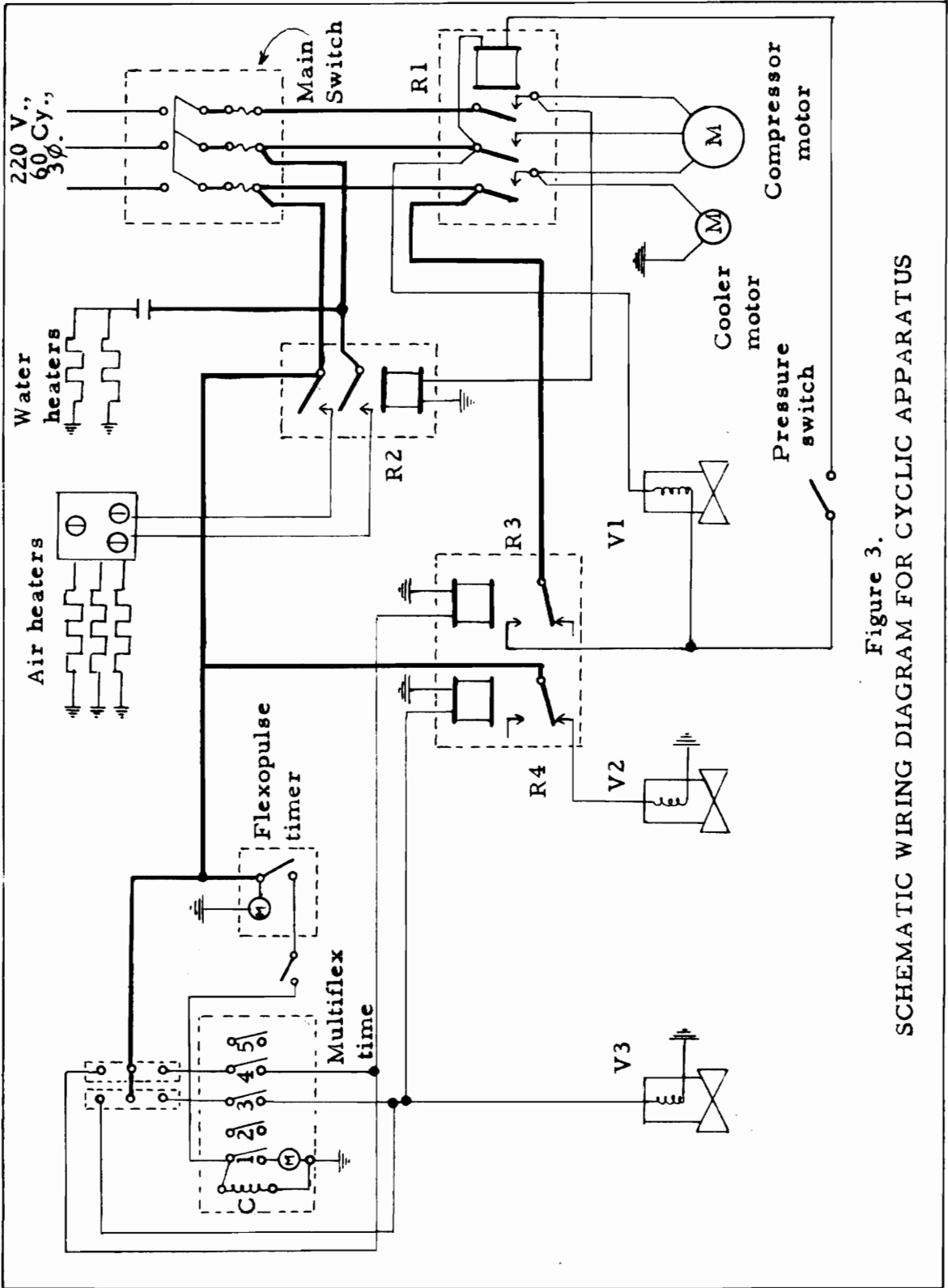


Figure 3.
SCHEMATIC WIRING DIAGRAM FOR CYCLIC APPARATUS

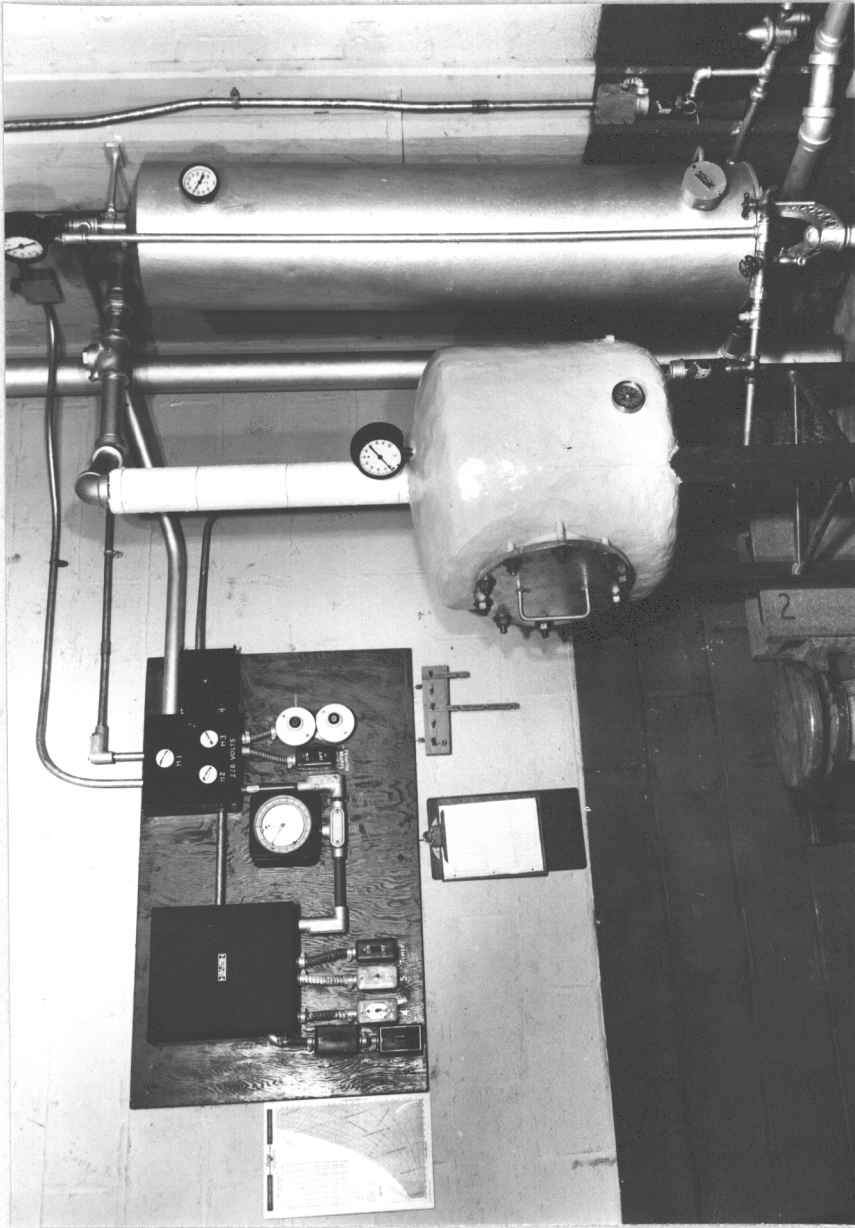


Figure 4.
PHOTOGRAPH OF THE CYCLIC APPARATUS

TABLE IV. DESCRIPTION OF CONTROL ELEMENTS FOR CYCLIC APPARATUS

Element	Description	Manufacturer	Manufacturer's Descriptive Literature
Flexopulse Timer	Flexopulse repeat cycle timer No. HG97A6 in Cabinet No. HN93. 110 v., 60 cy. 5 hr. range	Eagle Signal Corp. Moline, Ill.	Bulletin No. 320
Multiflex Timer	Multiflex reset timer No. HM50PA6 contact form: 3-4-3-7-4. In enclosure No. HN 251	Eagle Signal Corp. Moline, Ill.	Bulletin No. 130
Relay R1	General Electric Magnetic Starter, Catalog No. CR 7006D101B., Contact rating 15 HP for 220 v. 3 phase. Coil: 220 v., 60 cycle.	General Electric Schenectady, N. Y.	Instruction Sheet GEJ-2047B
Relay R2	Magnetic contactor, Normally open contact rating: 45 a. non-inductive. 220 v., 60 cy. coil.	American Inst. Co. Silver Springs, Md	General Catalog
Relay R3	Magnetic relay, d. p. d. t. contact rating 15 amps. coil: 110 v., 60 cycle	American Inst. Co. Silver Springs, Md	General Catalog
Relay R4	Magnetic relay, s. p. d. t. contact rating 5 amps., coil: 110 v., 60 cycle	American Inst. Co. Silver Springs, Md.	General Catalog
Valves	Type A Solenoid Valves, Std. Coils: V1 : $\frac{1}{2}$ " Normally closed, 220 v. coil V2: $\frac{1}{2}$ " Normally open, 110 v. coil V3 : 2" Normally open, 110 v., coil	Davis Regulator Co. Chicago, Ill.	Bulletin No. S1, page 10
Pressure Switch	Square D Pressure Switch, Class 9013, Type ASG-2 Form R. 20 to 50 psi.	Square D Co. Milwaukee, Wis.	Instruction Card L-4058

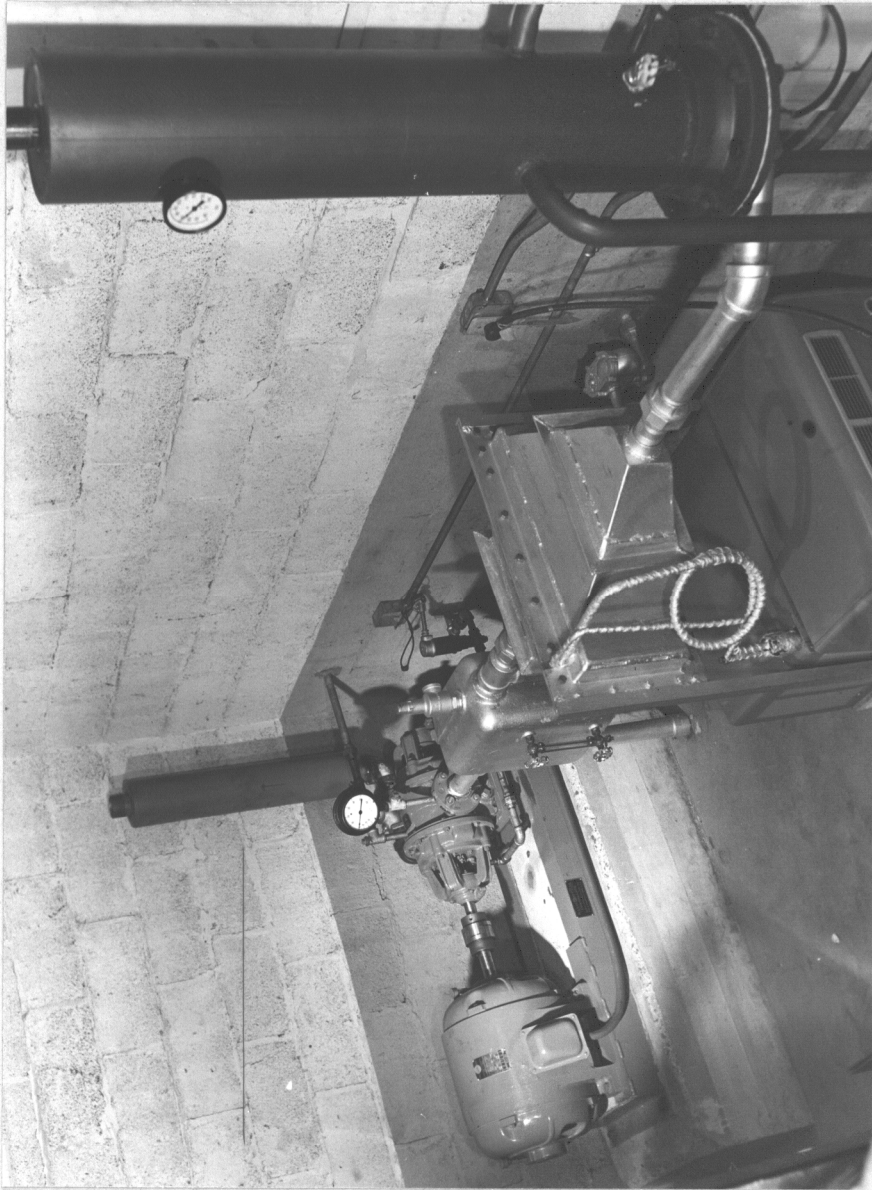


Figure 5.
PHOTOGRAPH OF THE DRYING COMPONENTS OF THE CYCLIC APPARATUS

that the apparatus may be manually operated for check runs and short tests.

Switch number three of the multiflex timer is set to close immediately at the beginning of the cycle, thus energizing valve V3 to close, and through relay R4, de-energizing valve V2 to open. This switch is set to open after one hour, reversing V2 and V3 and ending the wetting period.

Switch number four is set to close one hour and five minutes after the start of the cycle and actuate relay R3. This energizes valve V1 to open (to supply seal water to the compressor) and at the same time actuates relay R1 to start the compressor motor and the cooler motor. Relay R2 is actuated when R1 closes and this allows energy to flow into the heaters. Thus the drying period is started. Switch number one is set to open soon after number four closes and the switches remain, number four closed and all others open, until the flexopulse timer switch opens to reset the multiflex and end the drying period.

The compressor is protected by a pressure switch which opens when the pressure in the seal water line drops below 15 psig and closes when the pressure rises to 30 psig.

The water heater control is independent of the rest of the system, employing a thermostat set for 70°F.

D. EXPERIMENTAL PROCEDURES

Materials

The physical properties of the aggregates used in this investigation are given in Table V. The dolomitic limestone was from the Montgomery Lime Company in Ellet, Virginia. The fine aggregate used with dolomitic limestone was Petersburg sand which had been passed through a No. 10. sieve. The seolian limestone was from Bermuda, West Indies. Crushed seolian stone was used for fine aggregate with the coarse seolian limestone. The cement used was Type I portland cement manufactured by the Lone Star Cement Corporation, Lone Star, Virginia. Tap water from the V. P. I. water system was used for fresh water (H_0), the other water type being sea water (H_1) from Bermuda, having a specific gravity of 1.028.

Seal-Glo 434-T-clear, manufactured by Seal-Peel, Inc., Van Dyke, Michigan was used for waterproofing treatment P_2 . Treatment P_3 used white paint, Number 601 Primer and Number 602 Finisher, produced by the Southport Paint Company, Inc., Savannah, Georgia. The admixture used in treatment P_4 was Plastiment, a product of the Sika Chemical Corporation, Passaic, New Jersey.

Design of Concrete Mixes

Several trial mixes were made to determine (1) percent of sand, (2) cement factors and (3) water/cement ratios, to give workable mixes in the plastic range. The decision regarding cement factor and water/cement ratios are shown in Table I. It was found that the optimum percent of sand was 80% with 1/8 inch coarse aggregate, 75% with 3/16 inch aggregate, 70% with 1/4 inch aggregate and 60% with

3/8 inch aggregate.

Mix proportions were computed as suggested in Section 6 of ACI Standard 613 (6). The final mix proportions, by weights, for the 32 different fresh water mixes are given in Table VI. The mix proportions for the sea water mixes are the same as those for the fresh water mixes, e.g. treatment ADSH used the same mix proportions as treatment ADS, etc.

Preparation of Steel Ribbons

All of the 0.25" x 0.008" steel ribbons, to be embedded in the concrete test sections, were soldered to the copper terminals before mixing was started and were stored in a 50% relative humidity room until needed. The ribbons were removed from storage, stamped with a treatment symbol and prepared for embedment one day prior to casting. The preparation consisted of two steps: (1) The entire surface of the ribbon assembly was thoroughly cleaned with solvent #2 manufactured by Seal-Peel, Inc., Van Dyke, Michigan. (2) Each end of the assembly was covered with three coats of Seal-Glo 434-T-clear, as shown in Figure 1. Cleaning of the steel ribbon was considered necessary to remove preservative oil and make the steel uniformly susceptible to corrosion. The Seal-Glo coating was applied to prevent electro-chemical action between the copper, solder and steel.

Ribbons which were to be used for waterproofing treatment P₃ were given an additional single coating of Seal-Glo over their entire surface.

TABLE V. PROPERTIES OF AGGREGATES

Aggregate	Aggregate Passing United States Standard Sieves, % by weight							Fineness Modulus	Weight lbs./cu ft.	Apparent Specific Gravity	Absorption %	
	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100					
Petersburg Sand	100	100	99.8	81.7	40.7	12.9	3.4	2.61	98	2.55	1.1	
Dolomitic Limestone	1/8" Max.	100	100	98.7	28.6	0.8	0.1	0	3.72	91	2.71	2.2
	3/16" Max.	100	100	31.2	7.5	1.8	0.1	0	4.60	87		
	1/4" Max.	100	69.4	6.7	2.2	1.3	0.9	0	5.20	88		
	3/8" Max.	100	45.9	1.8	0.3	0.2	0.2	0	5.52	87		
Aeolian Limestone	Fine	100	100	100	89.5	55.8	26.6	11.3	2.17	99	2.58	6.3
	1/8" Max.	100	100	91.8	24.3	0.6	0	0	3.83	81	2.59	7.7
	3/16" Max.	100	100	63.7	29.5	10.3	0.8	0	3.96	84		
	1/4" Max.	100	58.6	4.7	1.0	0.3	0.3	0	5.35	77		
3/8" Max.	100	18.6	9.1	7.7	6.7	5.5	0	5.53	78			

Each value is the average of two determinations except for specific gravity and absorption for which only one determination was made.

TABLE VI TABLE OF MIX PROPORTIONS

Treatment Symbol	Mix Proportions* (By Weight)	Treatment Symbol	Mix Proportions* (By Weight)
I	1 : 3.40 : 0.90	C	1 : 2.75 : 0.73
S	1 : 3.18 : 1.13	CS	1 : 2.57 : 0.91
A	1 : 3.44 : 0.86	CA	1 : 2.78 : 0.70
AS	1 : 3.22 : 1.08	CAS	1 : 2.60 : 0.87
D	1 : 2.97 : 1.36	CD	1 : 2.40 : 1.10
DS	1 : 2.55 : 1.81	CDS	1 : 2.06 : 1.46
AD	1 : 3.01 : 1.29	CAD	1 : 2.43 : 1.04
ADS	1 : 2.58 : 1.72	CADS	1 : 2.08 : 1.39
W	1 : 3.22 : 0.86	CW	1 : 2.57 : 0.68
WS	1 : 3.02 : 1.07	CWS	1 : 2.40 : 0.85
WA	1 : 3.26 : 0.82	CWA	1 : 2.60 : 0.65
WAS	1 : 3.06 : 1.02	CWAS	1 : 2.44 : 0.81
WD	1 : 2.82 : 1.28	CWD	1 : 2.25 : 1.02
WDS	1 : 2.42 : 1.71	CWDS	1 : 1.92 : 1.36
WAD	1 : 2.85 : 1.22	CWAD	1 : 2.27 : 0.98
WADS	1 : 2.44 : 1.03	CWADS	1 : 1.95 : 1.30

*Mix proportions are given in the order

cement: fine aggregate: coarse aggregate.

Preparation of Test Sections

Quantities of cement, aggregates and water were weighed with an accuracy of one-half of one percent on a beam balance. Mixing was done in an enameled basin, using a large kitchen spoon. The cement and aggregates were thoroughly mixed in the dry state and then the water was added and mixing continued until the batch appeared to be homogeneous.

Immediately after mixing each batch of concrete the consistency was measured by a flow test carried out in accordance with Paragraph 4, Standard Method of Test for Measuring Mortar-Making Properties of Fine Aggregate, A.S.T.M. Designation: C-87-47. The results of the flow tests are shown in the graphs of Figure 6.

Casting of the test sections was done immediately after the flow tests. The concrete was placed in three layers and each layer was consolidated by tamping with a steel rod which weighed 1.4 pounds and had a one inch square tamping surface. The number of strokes used in tamping was varied with the consistency of the concrete, the wetter mixes requiring less tamping.

The steel ribbon assembly was placed in the mold after the first layer of concrete had been consolidated and was held in place by springs at each end which exerted a slight tensile force on the steel ribbon assembly.

A set of three cylinders, 2" diam. x 4" high, were cast from each batch of concrete at the same time that the test sections were cast. The 28 day compressive strengths and secant moduli of elasticity of

C = Cement Factor, Sacks/cu. yd.
 W = Water/Cement Ratio, lb./lb.

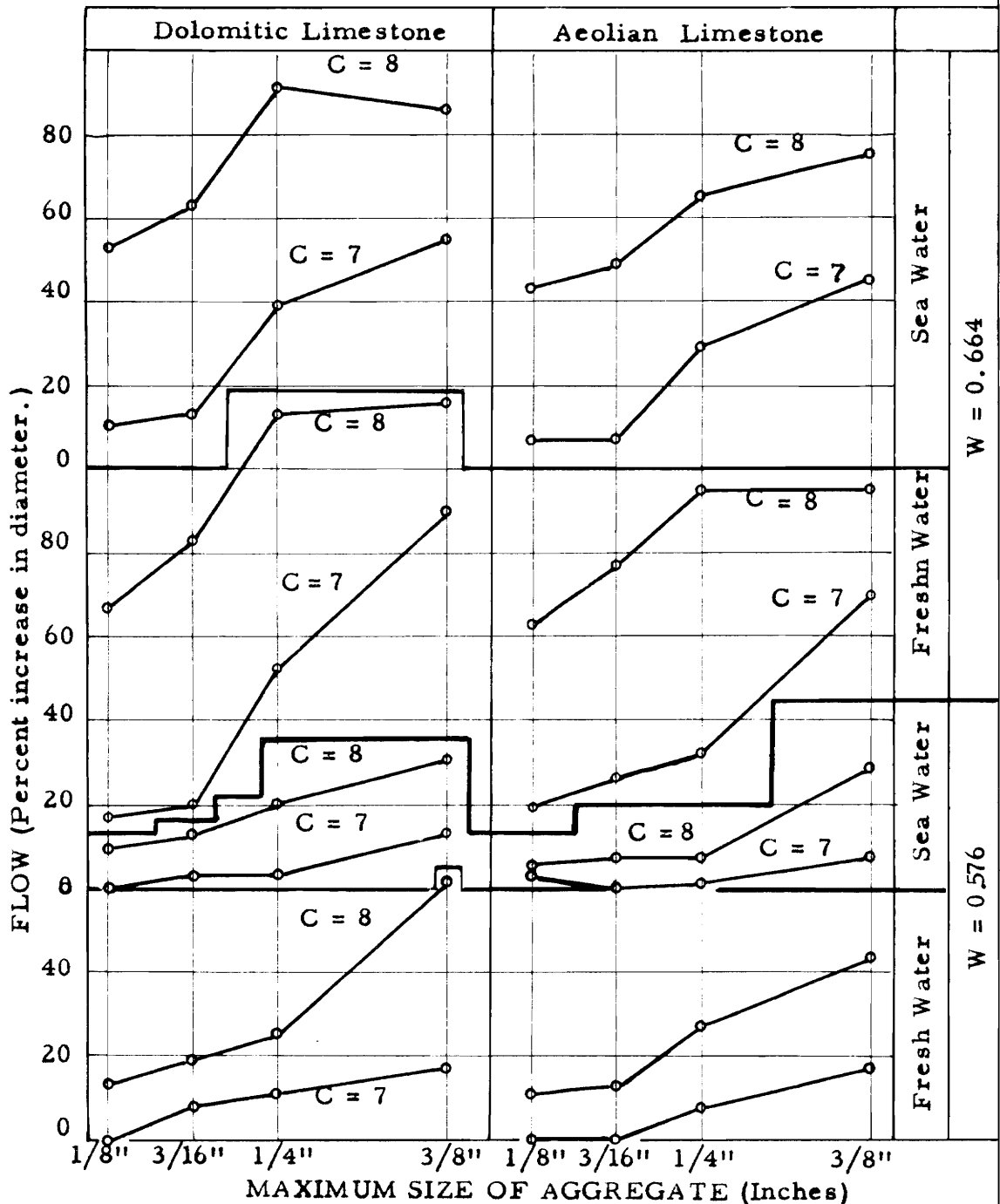


Figure 6.

RESULTS OF FLOW TESTS

the 64 different concrete mixes as determined from these cylinders, are shown in the graphs of Figures 7 and 8.

Seven test sections were cast from mixes 1, A, W, WA, C, CA, CW, and CWA: four for Experiment II and one each for Experiments I, III, and IV. This required a batch too large to be mixed in the enamel basin, so two batches were made for each of these mixes.

The test sections and cylinders were cured under damp cloths, in the molds, for two days and then for seven days in a 100% relative humidity room maintained at 75°F. After this curing the test sections were stored in a 70°F., 50% relative humidity room until all the test sections had been prepared and the experiments could be started. The total time required for casting, and thus the maximum age difference of the specimens, was 37 days.

The cylinders remained in the 100% relative humidity room until age 27 days, were dried in the 50% relative humidity room one day and were tested at 28 days.

The photographs in Figures 9 through 16 show the texture of the finished test sections. The upper test section of each pair is labeled with its treatment symbol and shows the texture of the trowelled top surface. The lower of each pair is the corresponding section made with sea water and shows the cast bottom surface. Changes in type of water or in maximum size of aggregate appeared not to change the texture.

C = Cement Factor, Sacks/cu. yd.
 W = Water/Cement Ratio, lb./lb.

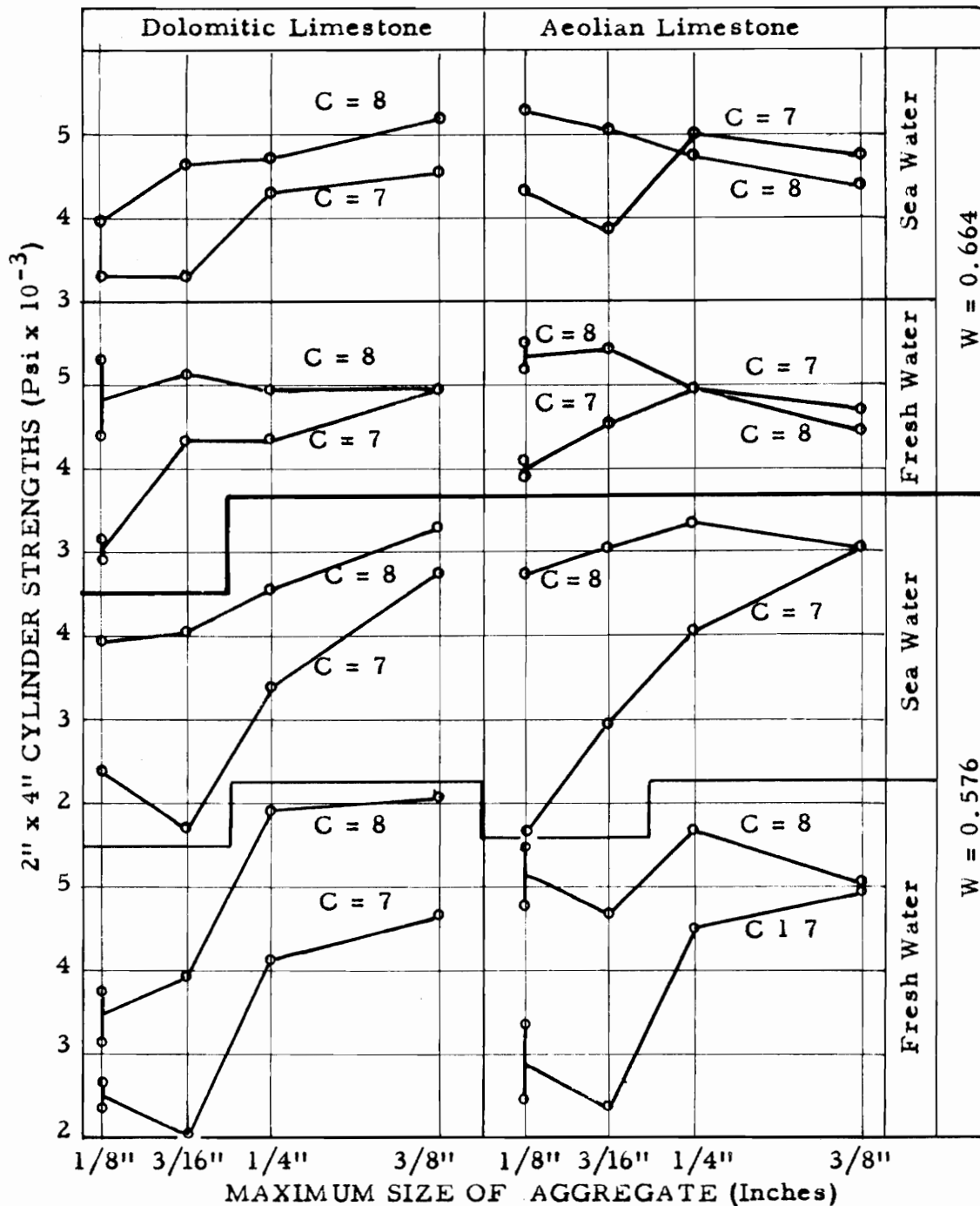


Figure 7.

COMPRESSIVE STRENGTHS

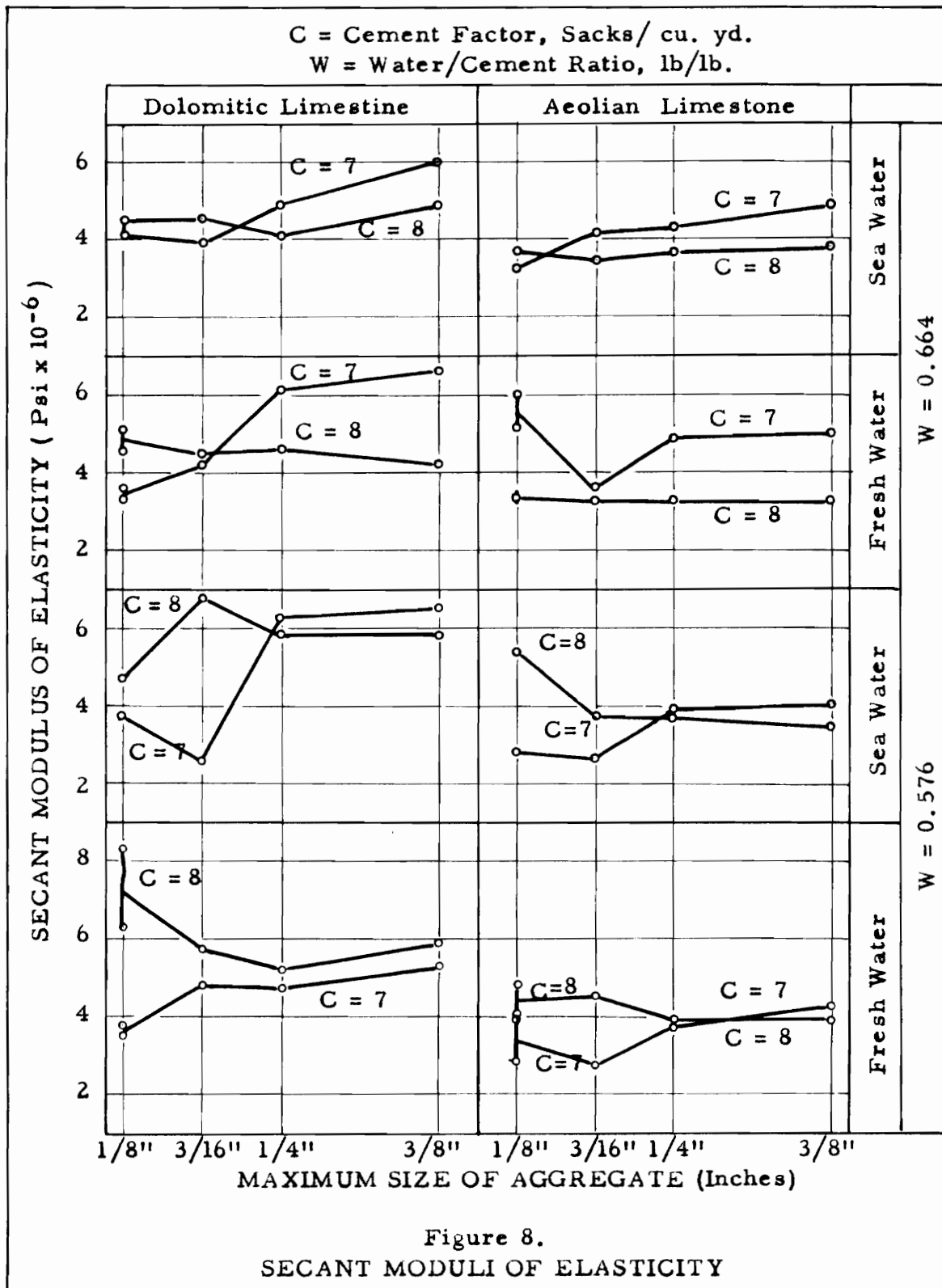




Figure 9.

PHOTOGRAPH SHOWING TEXTURE FOR TEST SECTIONS 1 AND A



Figure 10.

PHOTOGRAPH SHOWING TEXTURE FOR TEST SECTIONS D AND AD

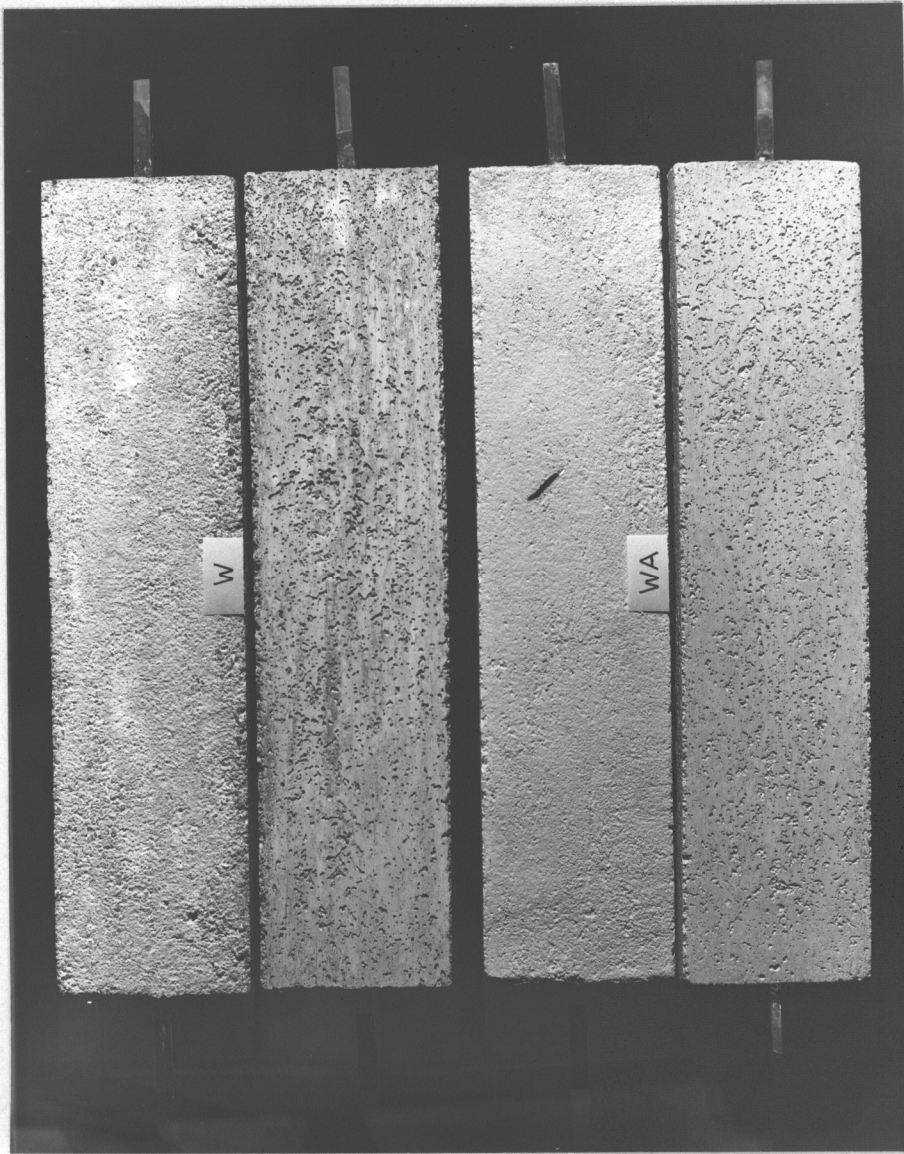


Figure 11.

PHOTOGRAPH SHOWING TEXTURE FOR TEST SECTIONS W AND WA

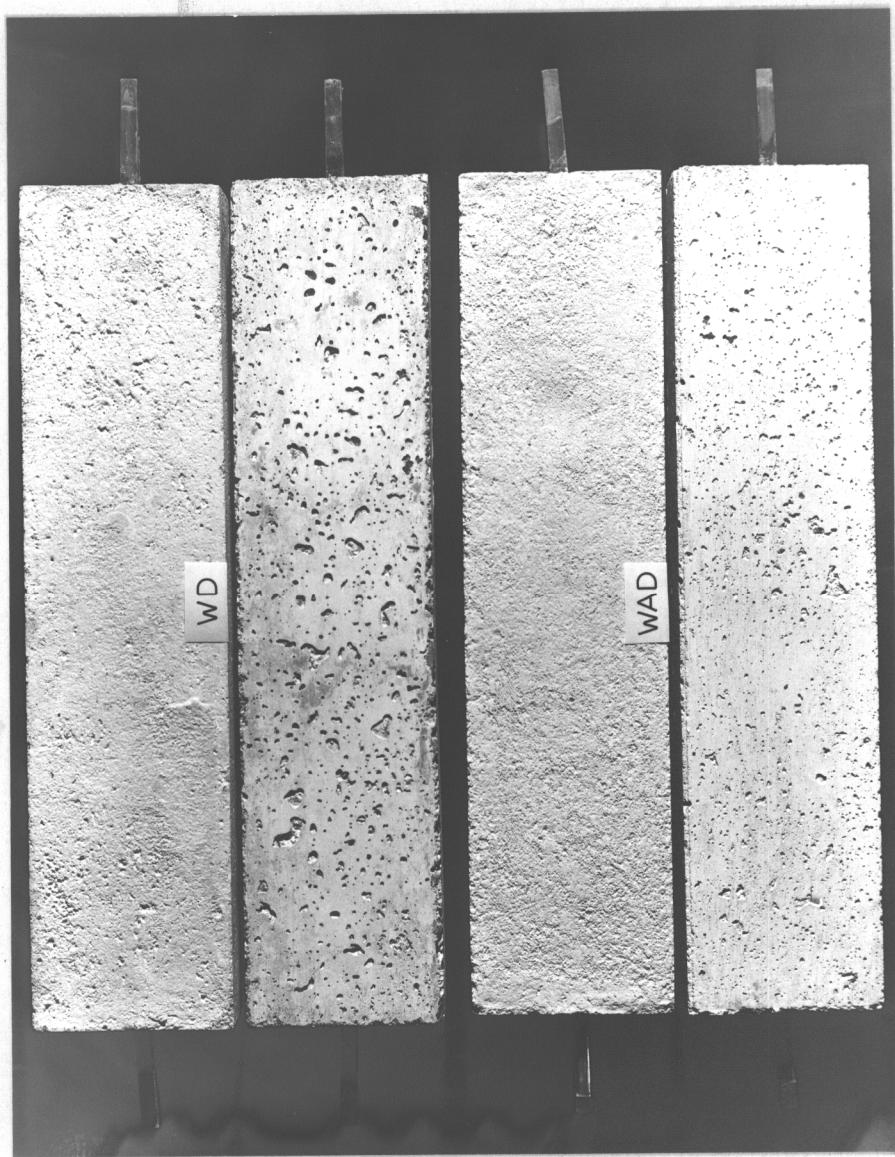


Figure 12.
PHOTOGRAPH SHOWING TEXTURE FOR TEST SECTIONS WD AND WAD

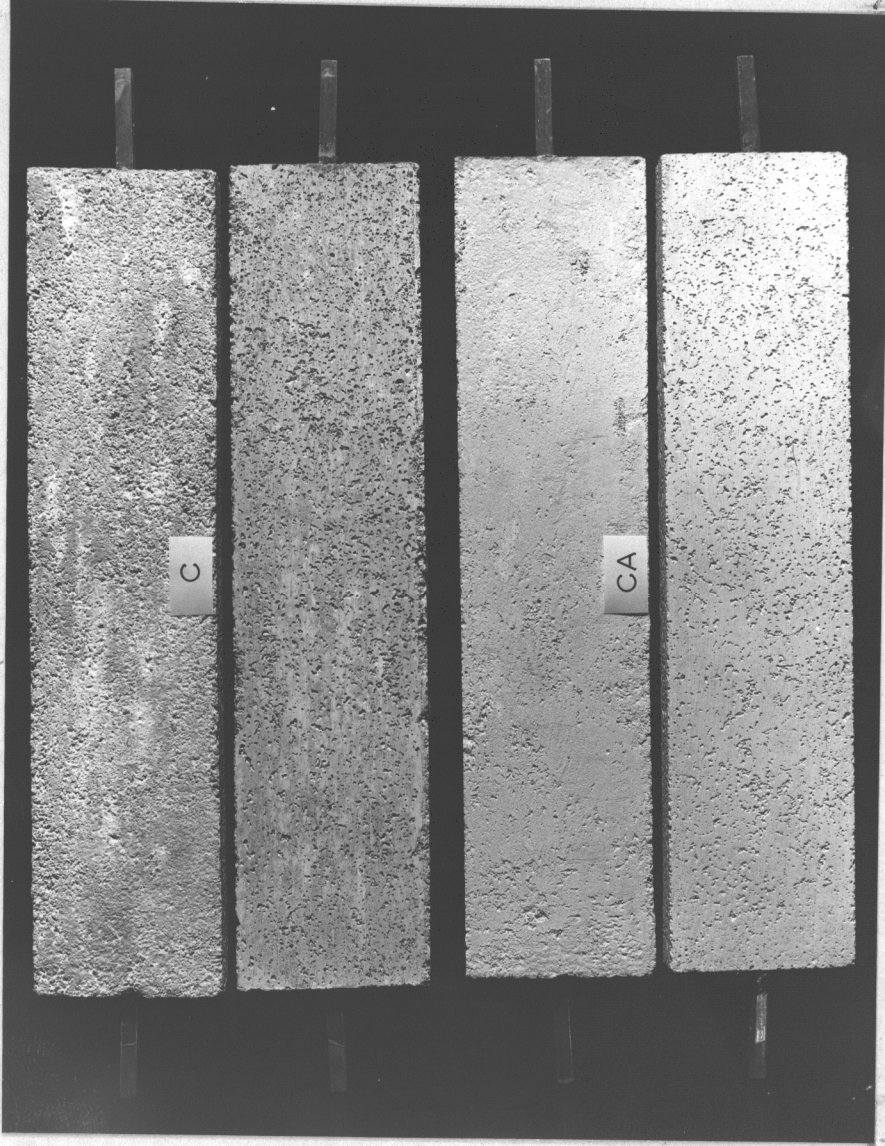


Figure 13.

PHOTOGRAPH SHOWING TEXTURE FOR TEST SECTIONS C AND CA

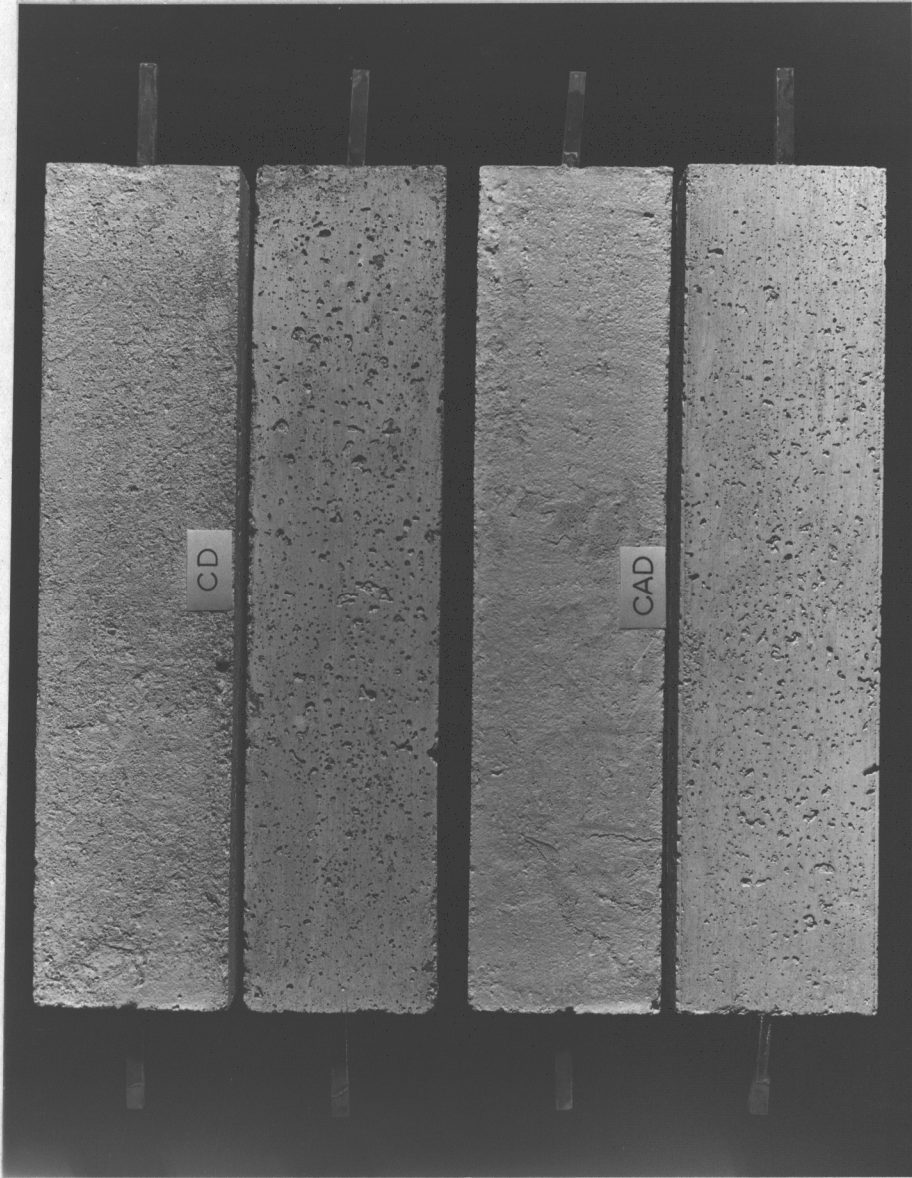


Figure 14.

PHOTOGRAPH SHOWING TEXTURE FOR TEST SECTIONS CD AND CAD

SECTION CONTENT

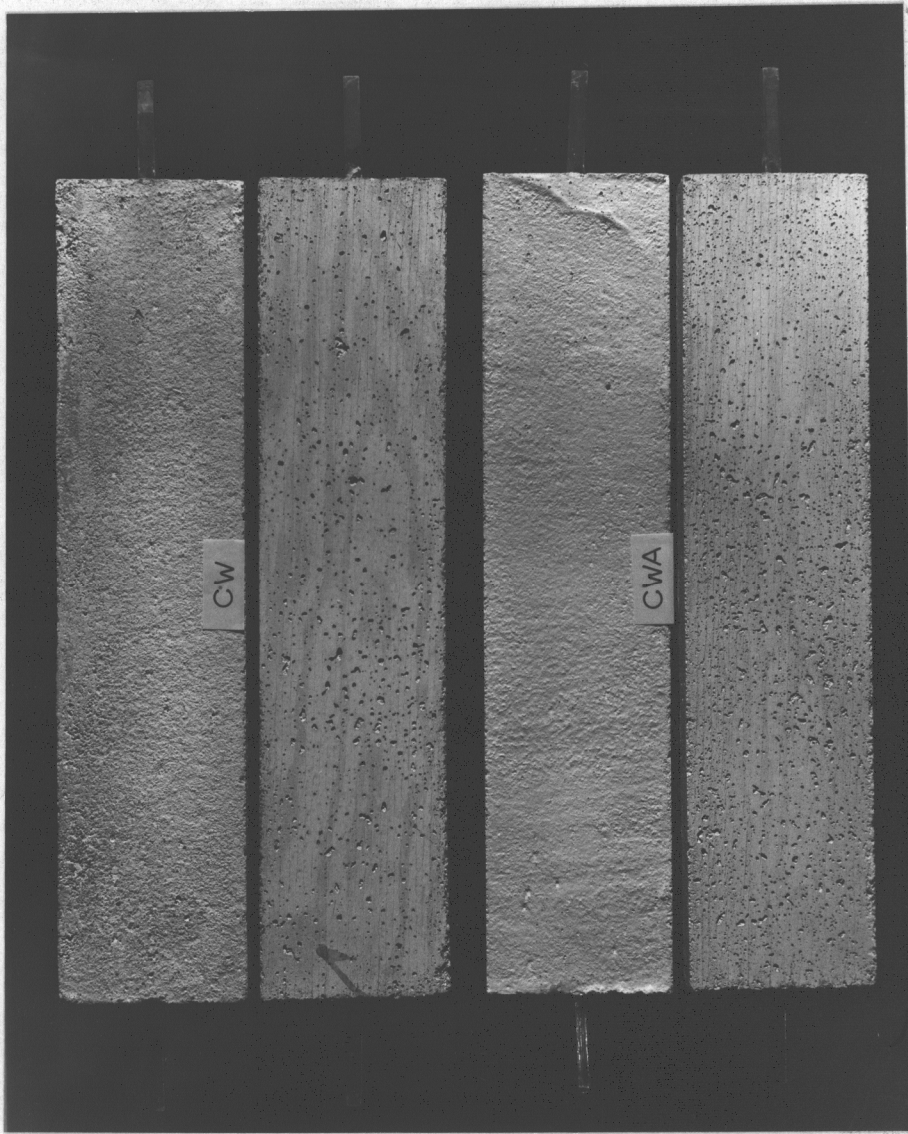


Figure 15.

PHOTOGRAPH SHOWING TEXTURE FOR TEST SECTIONS CW AND CWA



Figure 16.

PHOTOGRAPH SHOWING TEXTURE FOR TEST SECTIONS CWD AND CWAD

Waterproofing Procedure

Waterproofing treatment P₁ consisted of a cement slurry applied to the steel ribbon immediately before placing the ribbon in the mold. The slurry was made by mixing two parts of tap water with one part, by weight, of ordinary portland cement.

Treatment P₂ consisted of a single coating of Seal-Glo applied to the ribbon and allowed to dry before the test section was cast.

The exterior surfaces of the test sections were painted for treatment P₃. A thin paste was made by mixing 3/4 pound of white lead paste (90% basic lead carbonate and 10% linseed oil) with enough 601 Primer to make 1/2 pint of paste. This paste was scrubbed into each surface of the test section with a brass-bristled brush. Excess paste was wiped away and a coat of 601 Primer was brushed onto the concrete. The primer coat dried for one day and then a coat of 602 Finisher was applied.

The fourth treatment consisted of mixing Plastiment into the concrete in the proportion of one pound per sack of cement.

Flexural Cracking of Test Sections for Experiment IV

Since the test sections were virtually un-reinforced it was found necessary to fit them with end plates and four post-tensioning rods (as shown in Figure 17) to prevent complete failure. The sections were placed in the bonding clamps (also shown in figure 17) and a load applied with the loading screw until the predetermined center deflection was reached. The deflections were 0.0111 inch for 3/4 inch thick sections and 0.0067 inch for 1-1/4 inch thick sections,

calculated by the formula given in Section B, Design of Experiments. The stress on the post-tensioning rods was next adjusted so that the width of the crack in each test section was approximately the same. Crack widths were measured with a microscope. The mean crack width was 0.0039 inch, individual cracks ranged from 0.0030 to 0.0045 inch.

The weighing of ingredients, mixing of batches and casting of test sections and cylinders were all carried out by the same person (the author) and all possible attention was given to following a uniform procedure as outlined above.

Exposure Conditions

The test sections for Experiments I and II were subjected to a cyclic exposure condition in the test chamber of the cyclic apparatus described in Section C. Each cycle of the exposure consisted of a wetting period and a drying period. The wetting period was one hour in length during which time the test chamber was filled with water under a pressure of 35 to 55 psig. at a temperature of $70^{\circ} \pm 3^{\circ}\text{F}$. The original design pressure of 60 psig. could not be maintained from the supply line pressure. Air was blown over the test sections during the 3-1/2 hour drying period with a velocity of approximately 110 feet per minute. The heating and cooling elements of the apparatus generally required one-half hour to stabilize the air conditions at approximately 100°F. and 20% relative humidity. These air conditions were maintained for the remaining three hours of the period. The cycle of wetting and drying was repeated automatically until the apparatus was stopped in order to remove the test sections and measure

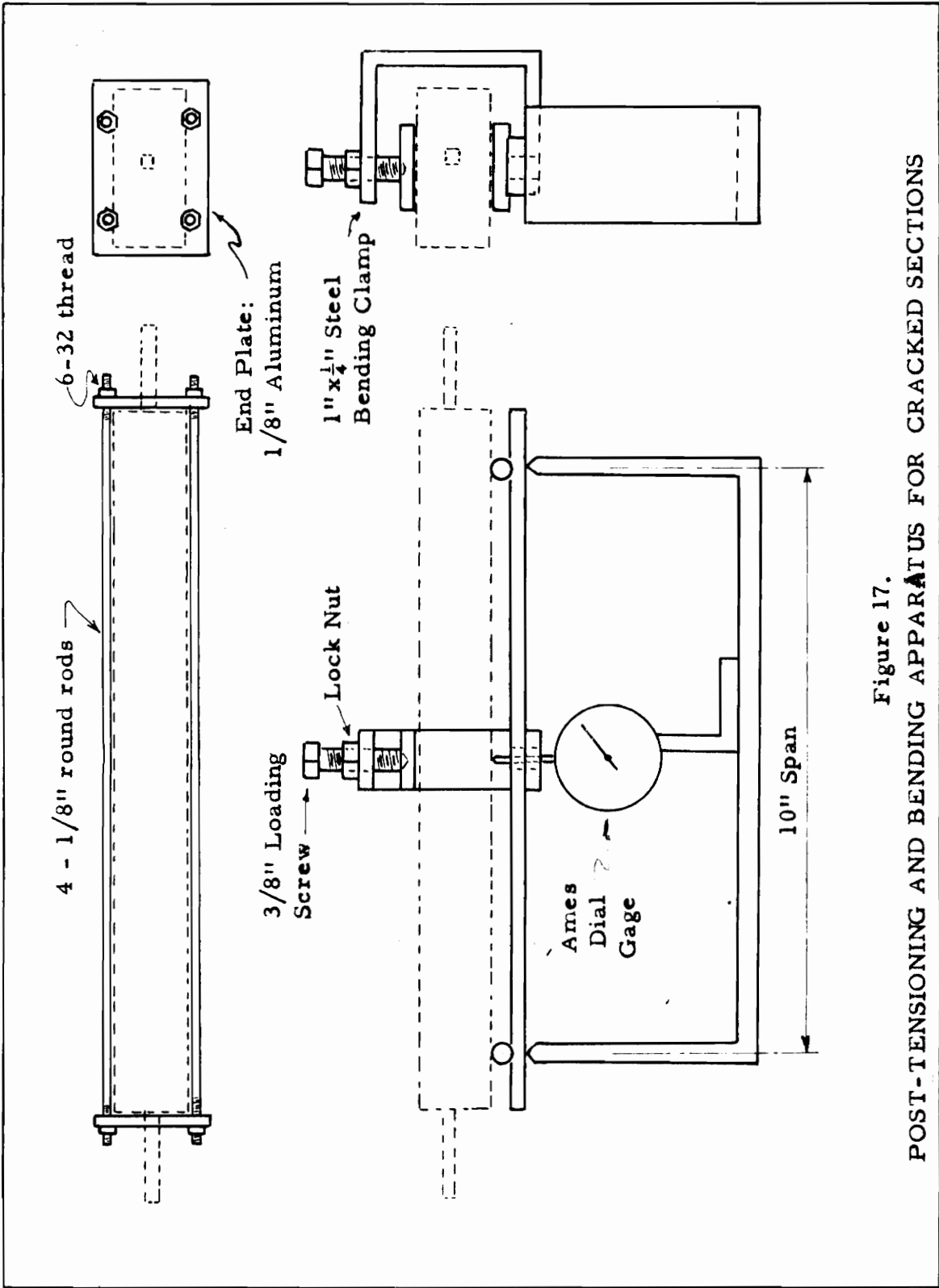


Figure 17.
POST-TENSIONING AND BENDING APPARATUS FOR CRACKED SECTIONS

the resistance of the steel ribbons. Before measurements were made, the sections were placed in a 70°F., 50% relative humidity room for at least 24 hours to allow the temperature of the interior of the concrete to stabilize at room temperature. It is doubtful that the exposure condition was uniform for all positions in the test chamber. To eliminate any bias due to possible non-uniform conditions the test sections were placed in the test chamber in a random order. A different random order was used each time the sections were replaced in the chamber.

The sections for Experiments III and IV were exposed to a continuous exposure condition of moist air (95 to 98% relative humidity) at a temperature of 75°F. \pm 5°F. These test sections were removed periodically to a 70°F. 50% relative humidity room and dried for three days before measurements were made.

Measurements

Three different quantities were measured periodically for each of the test sections: (1) the resistance of the steel ribbon, (2) the weight of the test section and (3) the natural frequency of vibration of the test section. The first of these measurements was used as an indication of the corrosion of the steel ribbon, the latter two were used to detect changes in the moisture contents and moduli of elasticity of the concrete.

Resistance measurements were made with a Leeds and Northrop Portable Kelvin Bridge Ohmmeter No. 4285. The resistance measurement technique used was the same as that used in previous tests (7).

Weights of test sections were obtained with a beam balance with an accuracy of $\pm 0.25\%$ or better.

Natural frequencies were determined with a sonic analyzer built by Hogentogler and Company, Chevy Chase, Maryland. This equipment utilized an audio oscillator with a range from 550 to 6000 cycles per second. The first vibrational nodes were detected with a crystal pickup the output from which was amplified and indicated on a millimeter.

E. DATA AND RESULTS

Data from Experiments I and II are reported and discussed herein. Conclusive data from Experiments III and IV are not available at present due to their less severe exposure conditions.

Transformation of Data

The original corrosion data for Experiments I and II consist of periodic measurements of the resistance of the steel ribbon in each of the 96 test sections. The times τ at which measurements were made, in number of cycles of exposure from start of test were 0, 30, 65, 90, 125, 160, 211, 278 and 328 cycles. The original data was first corrected for temperature at time of reading, since the room temperature could not be controlled precisely. A correction was applied to correct the resistance measurements to a standard temperature of 70°C. The values of $\rho = R_{\tau}/R_0$ were calculated, where R_{τ} = corrected resistance at any time τ , R_0 = corrected resistance at start of test ($\tau = 0$). Finally values of $\log \rho$ were tabulated. The data was assembled in this form to take advantage of the linear relationship which appears to exist between $\log \rho$ and time. (4).

Regression Analysis

Regression equations were calculated by the least squares method for each of the 96 treatments instead of plotting the data and fitting straight lines by eye. A transformation to $\gamma = 10^4 \log \rho$ was used to eliminate decimals from the data. Values of γ for $\tau = 90, 125, 160, 211, 278, 328$ cycles were used for the regression analysis. The regression equations were calculated in the form $\hat{\gamma} = a + b\tau$, where

$\hat{\gamma}$ = value of γ predicted by the equation for any given value of τ .
The variance of the γ 's about the regression line based on four degrees of freedom was calculated for each regression. The half-life for each test section was obtained from the regression equations by calculating the values of τ for $\gamma = .30103 \times 10^4$. The coefficients, a and b , for the regression equations, the variances and the half-life values are presented in Table VII for Experiment I and Table VIII for Experiment II.

An analysis of variance of the slopes of the regression lines was made for each of Experiments I and II. The slopes were used because they correspond to rates of corrosion and therefore are more likely to be additive than are the half-life values. The results of these analyses of variances are discussed in Article V. The analysis of variance tables and a more detailed discussion are presented in Appendix B.

TABLE VII
 COEFFICIENTS, VARIANCES AND HALF-LIFE VALUES
 FOR EXPERIMENT I

Treatment	a (Y-Intercept)	b (Slope)	T. Half-Life (Cycles)	Variance about Regression
l	12.9	.15	20,000	18.
H	22.4	.29	10,300	38
S	1.8	.18	16,700	30.
SH	47.2	.33	8,980	40
A	7.4	.14	21,500	28.
AH	24.8	.35	8,530	52.
AS	-0.2	.15	20,100	66.
ASH	34.0	.31	9,600	28.
D	13.9	.19	15,800	12
DH	26.7	.32	9,320	109.
DS	17.5	.18	16,600	37
DSH	35.4	.25	11,900	163.
AD	9.2	.17	17,700	32.
ADH	35.2	.30	9,920	120.
ADS	25.3	.13	23,000	85.
ADSH	29.5	.17	17,500	46.
W	12.8	.23	13,000	65.
WH	18.4	.82	3,650	834.
WS	14.0	.16	18,700	85.
WSH	139.2	.24	12,000	86.
WA	11.2	.17	17,600	65.
WAH	-36.7	2.57	1,190	785.
WAS	5.5	.17	17,700	75.
WASH	89.7	.89	3,280	928.
WD	26.0	.15	19,900	50.
WDH	28.5	.29	10,300	109.
WDS	18.8	.13	23,000	166.
WDSH	12.6	.21	14,300	38.
WAD	17.3	.15	20,000	48.
WADH	27.6	.52	5,740	197.
WADS	10.7	.17	17,600	51.
WADSH	22.5	.18	16,600	76.

(Continued Next Page)

TABLE VII
 COEFFICIENTS, VARIANCES AND HALF-LIFE VALUES
 FOR EXPERIMENT I -- CONTINUED

Treatment	a (\bar{Y} -Intercept)	b (Slope)	T. Half-Life (Cycles)	Variance about Regression
C	1.2	.23	13,100	17
CH	0.7	.23	13,100	20
CS	2.0	.21	14,300	12
CSH	48.1	.39	7,600	77
CA	1.8	.20	15,000	32
CAH	-167.5	3.78	841	2462
CAS	-3.5	.22	13,700	83
CASH	-156.8	2.78	1,140	1141
CD	12.2	.19	15,800	17
CDH	22.0	.62	4,820	213
CDS	-1.9	.24	12,600	14
CDSH	-4.7	.76	3,970	482
CAD	4.1	.22	13,700	12
CADH	2.2	.42	7,160	58
CADS	5.5	.25	12,000	17
CADSH	9.2	.22	13,600	12
CW	-5.5	.21	14,400	41
CWH	8.4	.26	11,500	8
CWS	9.3	.19	15,800	41
CWSH	-12.5	.44	6,870	21
CWA	-8.2	.21	14,400	32
CWAH	24.6	.59	5,060	152
CWAS	5.7	.18	16,700	43
CWASH	30.3	.41	7,270	99
CWD	11.7	.19	15,800	80
CWDH	22.4	.20	14,900	57
CWDS	9.4	.22	13,600	49
CWDSH	4.4	.26	11,600	38
CWAD	9.5	.21	14,300	67
CWADH	3.6	.31	9,700	24
CWADS	6.5	.21	14,300	54
CWADSH	35.2	.26	11,400	65

TABLE VIII
 COEFFICIENTS, VARIANCES AND HALF-LIFE VALUES
 FOR EXPERIMENT II

Treatment	a (Y-Intercept)	b (Slope)	T. Half-Life (Cycles)	Variance about Regression
11	-5.5	.19	15,800	43
12	-0.9	.23	13,100	30
13	-19.0	.18	16,700	67
14	-0.5	.15	20,100	148
A1	2.0	.17	17,700	69
A2	7.1	.16	18,800	38
A3	13.9	.20	15,000	78
A4	17.0	.15	20,100	32
W1	3.4	.15	20,100	21
W2	5.6	.21	14,300	44
W3	7.2	.11	27,300	64
W4	2.1	.17	17,700	29
WA1	8.0	.13	23,100	47
WA2	6.1	.15	20,100	25
WA3	36.2	.05	59,500	149
WA4	18.6	.12	24,900	22
C1	1.7	.15	20,100	33
C2	4.1	.25	12,000	48
C3	-21.0	.18	16,700	125
C4	-17.5	.22	13,700	75
CA1	-1.1	.17	17,700	94
CA2	1.5	.23	13,100	51
CA3	-18.6	.17	17,700	50
CA4	-11.1	.21	14,300	53
CW1	-6.8	.17	17,700	40
CW2	-6.5	.20	15,100	35
CW3	16.0	.13	23,000	222
CW4	0.0	.15	20,100	32
CWA1	-13.1	.17	17,700	32
CWA2	-8.6	.35	8,600	103
CWA3	-5.4	.14	21,500	30
CWA4	-18.4	.27	11,200	14

V. DISCUSSION OF RESULTS

A. ASSUMPTIONS

A linear relationship was assumed to exist between $\log p$ and τ . This assumption was very well justified by the results of the regression analyses. The variance due to regression was tested against the variance about the regression with a variance ratio test and in all but four of the 96 regressions was found to be significant at the 5% level or better. Seventy-eight of the regressions were significant at the 1% level or better and twenty-six at the 0.1% level or better.

The assumption of linearity has also been justified mathematically on the basis of the electrolytic theory of corrosion(8). The mathematical development required several assumptions, the principal one being that the corroded area must be somewhat uniformly distributed over the surface of the steel. Steel ribbons taken from test sections of previous investigations have generally shown a uniform distribution of the corroded area. However, in some cases, localized corrosion was observed which may have resulted from honeycombing or other defects allowing moisture to gain easy access to the steel. Electrochemical reactions may also cause localized corrosion, especially if a good electrolyte, such as sea water, is present in the concrete. When corrosion is localized the $\log p$ -time relationship becomes definitely nonlinear.

The first regression equations calculated for treatments WAH and CAH gave values for b of 4.55 and 4.94 respectively, with variances

5,842 and 11,059. While these regressions were significant at the 0.1% level, the variances were extremely large when compared with the variances for the other 94 treatments. Graphs of the data for these two treatments exhibited an increase in slope for large values of τ and indicated that either the rate of corrosion was increasing or localized corrosion was present. These two test sections will not be broken open for inspection until corrosion has progressed further and the data will remain questionable until that time. The regression equations for WAH and CAH were re-calculated using values of γ for $\tau = 30, 65, 90, 125, 160,$ and 211 cycles and for $\tau = 65, 90, 125, 160, 211,$ and 278 cycles respectively. The coefficients and variances reported for WAH and CAH in Table VII were from the second calculation and were believed to be better indications of the corrosion protection.

B. TIME OF STARTING OF CORROSION

A definite time lapse between the starting of exposure and starting of corrosion of the steel ribbon was noted in previous investigations carried out at VPI. Whether this was related to the properties of the concrete or only to the condition of the steel has not been determined.

Such a time lapse is indicated by a negative value for α , the γ - intercept, in the regression equations for Experiments I and II of this investigation. The values for γ - intercepts appear to be normally distributed with mean values of 10.8 for Experiment I and -0.10 for Experiment II. The positive values seem to be anomalous but might be explained as the result of an error in the determination of the room temperature during the measurement of R_0 . Such an error would affect only the γ - intercepts, not the slopes.

The largest of the negative intercepts, -167.5 for CAH, indicates a time lapse of 45 cycles or 5% of the half-life. The indications of time lapse for treatments CAH and CASH may be due to non-linear effects of localized corrosion. No significant time lapse is indicated for the other treatments.

Graphs of γ vs. τ are presented in Figure 18 for test sections WAH, CAH and CAH. The latter is included as a representative graph.

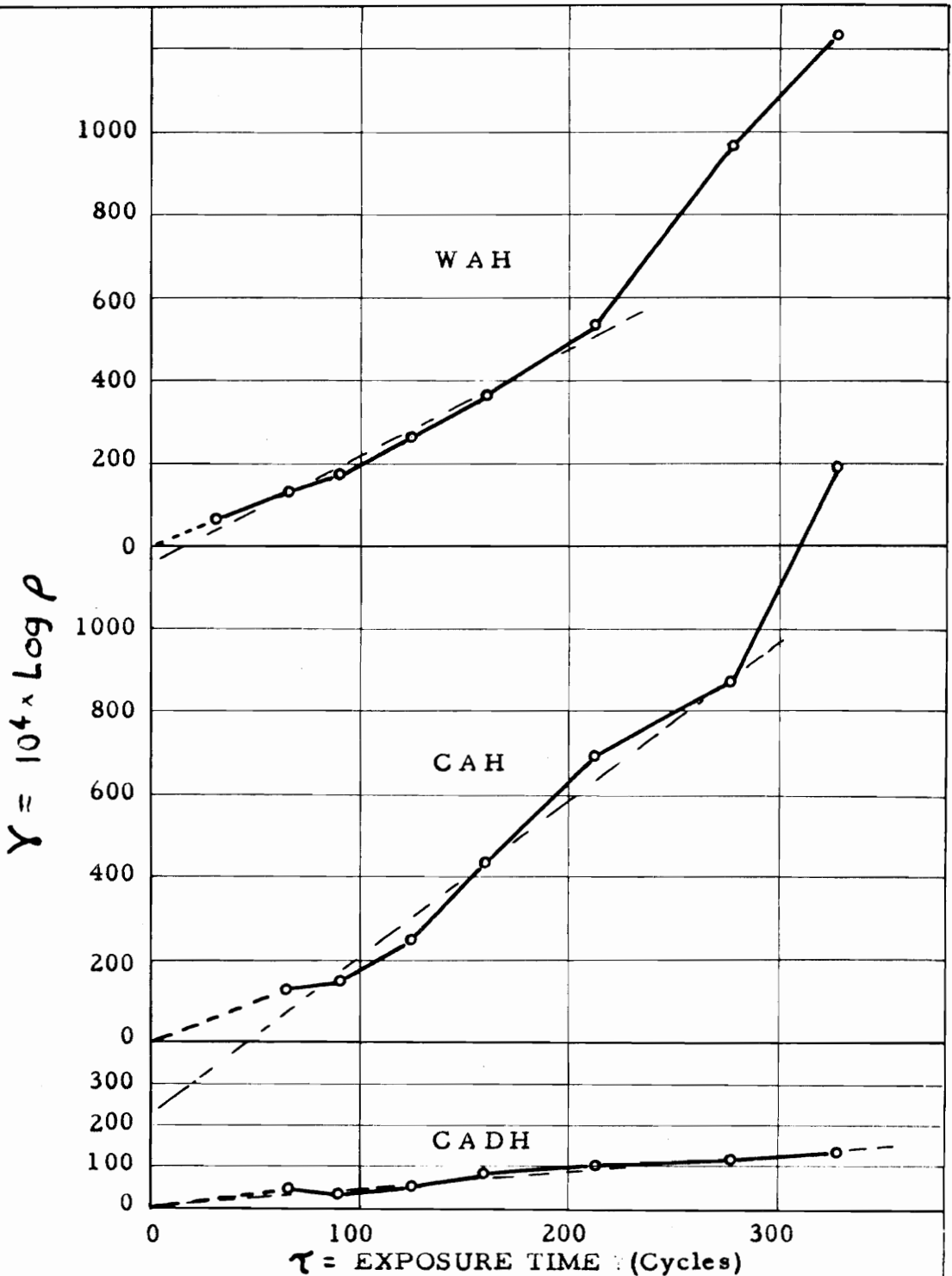


Figure 18.

GRAPHS OF Y VS. τ FOR TEST SECTIONS WAH, CAH, AND CADH

C. RATE OF CORROSION

The half-life values, in terms of cycles of exposure in the cyclic apparatus, have no quantitative meaning without the "calibration factor" for cyclic apparatus. This must await the results of Experiment III. However, valuable qualitative information can be gained from a study of the slopes of the regression lines presented in Tables VII and VIII. These slopes are assumed to represent the rates of corrosion of the steel ribbons. Comparisons of the slopes are equivalent to comparisons of the protective ability of the concretes, and a lower value for the slope corresponds to better protection by the concrete.

Analysis of Variance

Analysis of variance techniques were used to determine which concrete mix factors had significant effects upon the corrosion protection afforded by the concrete. These techniques were also used to detect the possible existence of interactions. An interaction exists if the effect due to change in the level of one factor is influenced by changing the level of one or more of the other factors. A level of significance is attached to most of the statements regarding the existence of effects or interactions. For example, if it is decided to postulate the existence of effects which are significant at the 5% level, then, 5% of the time, effects will be postulated to exist which actually do not exist. Similarly, using the 1% level of significance one postulate in a hundred will be wrong. The details of the analyses are discussed in Appendix B.

Significant Effects for Experiment I.

Experiment I was designed as a factorial experiment with six factors each at two levels (Refer to Table I). For this design it was assumed that interactions involving three or more factors would not be significantly large and thus an estimate of error could be obtained. The analysis of variance for the experiment indicated the possibility of the existence of a $C \times W \times A \times D \times H$ interaction. This invalidated the above assumption and since the experiment was not replicated there is some question regarding the appropriate method for testing the significance of this interaction. The author believes that, tentatively, the interaction should be considered to exist and should be further investigated.

The only main effect which attained significance for the six-factor analysis was the effect due to type of water (factor H). The mean values of b for the two levels of factor H were:

$$\bar{b}(H_1) = 0.19 \text{ for fresh water}$$

$$\bar{b}(H_2) = 0.62 \text{ for sea water}$$

These mean values were each based on data from 32 test sections. It was inferred that the concrete made with fresh water gave better protection against corrosion than did the concrete made with sea water.

In order to investigate the possible $C \times W \times A \times D \times H$ interaction the experimental data was divided into two five-factor experiments, one with fresh water and one with sea water. An analysis of variance of the group of specimens made with fresh water showed no indication of significant interactions. The effect of the cement factor (C) was tested

by a variance ratio test and found significant at the 0.1% level. None of the other main effects were significant. Mean values of b were:

$$\bar{b}(C_0) = 0.16 \text{ for 7 sacks/cu. Yd.}$$

$$\bar{b}(C_1) = 0.21 \text{ for 8 sacks/ cu. Yd.}$$

The conclusion was drawn that a cement factor of 7 sacks/cu. yd. was better than 8 sacks/cu. yd. and that it was a matter of indifference which of the two levels was used for variables W, A, D and S.

The CxWxDxD interaction that was suspected from the first analysis was further indicated, in the form of a CxWxD interaction, by the analysis of variance for the group of specimens made with sea water. The S main effect attained significance at the 5% level for the sea water mixes but, since an SxH interaction was not indicated in the complete analysis (all six factors), the existence of this S effect is questionable.

This method of breaking the experiment down into smaller experiments was continued until all significant effects and interactions had been investigated. The results of this sub-division are shown in simplified form in the chart of Figure 19. Each box in the chart represents a particular subdivision of the experiment and contains information regarding that subdivision. Consider, for example, the box similar to this one:

$\bar{b}(D_1) = 0.33$
C, W, A, S (CxW, WxA)

The first item, $\bar{b}(D_1) = 0.33$, indicates that this subdivision of the

experiment was at level 1 of factor B (1/2" depth of cover) and the mean value for b for the 16 test sections of this sub-division was 0.33. The letters C,W,A,S, indicate that this sub-division was, essentially, a four-factor experiment with C, W, A, and S each at two levels. The third item indicates that two interactions, CW and WA, were found to be significant.

The chart of Figure 19 may be used as a guide in designing a concrete mix for maximum protection against corrosion, using the levels of mix design factors that were used in this investigation. This is done by following the lines downward from the top, choosing, whenever possible, that level of a factor which gives the lower mean value for b. In some cases there may be several nearly equivalent choices, e.g.: a mix using H_1 , D_1 , W_1 and either level of C, A and S will probably give as good protection as one with H_1 , D_1 , W_0 , C_0 and either level of A and S.

The reader is reminded that only two levels of each factor were used and that these factors were chosen with practical considerations in mind. The results of this experiment cannot be used for inferences regarding the effect of other levels of such factors as C, W, D and S. The fact that variable B had no significant effect on corrosion protection in the fresh water mixes does not mean that a level for S of 1 or 1.5 would also have no effect. The case for variables H and A is slightly different. The principle difference between the two types of aggregate was one of porosity, hence the inference might be made, subject to further investigation, that the less porous

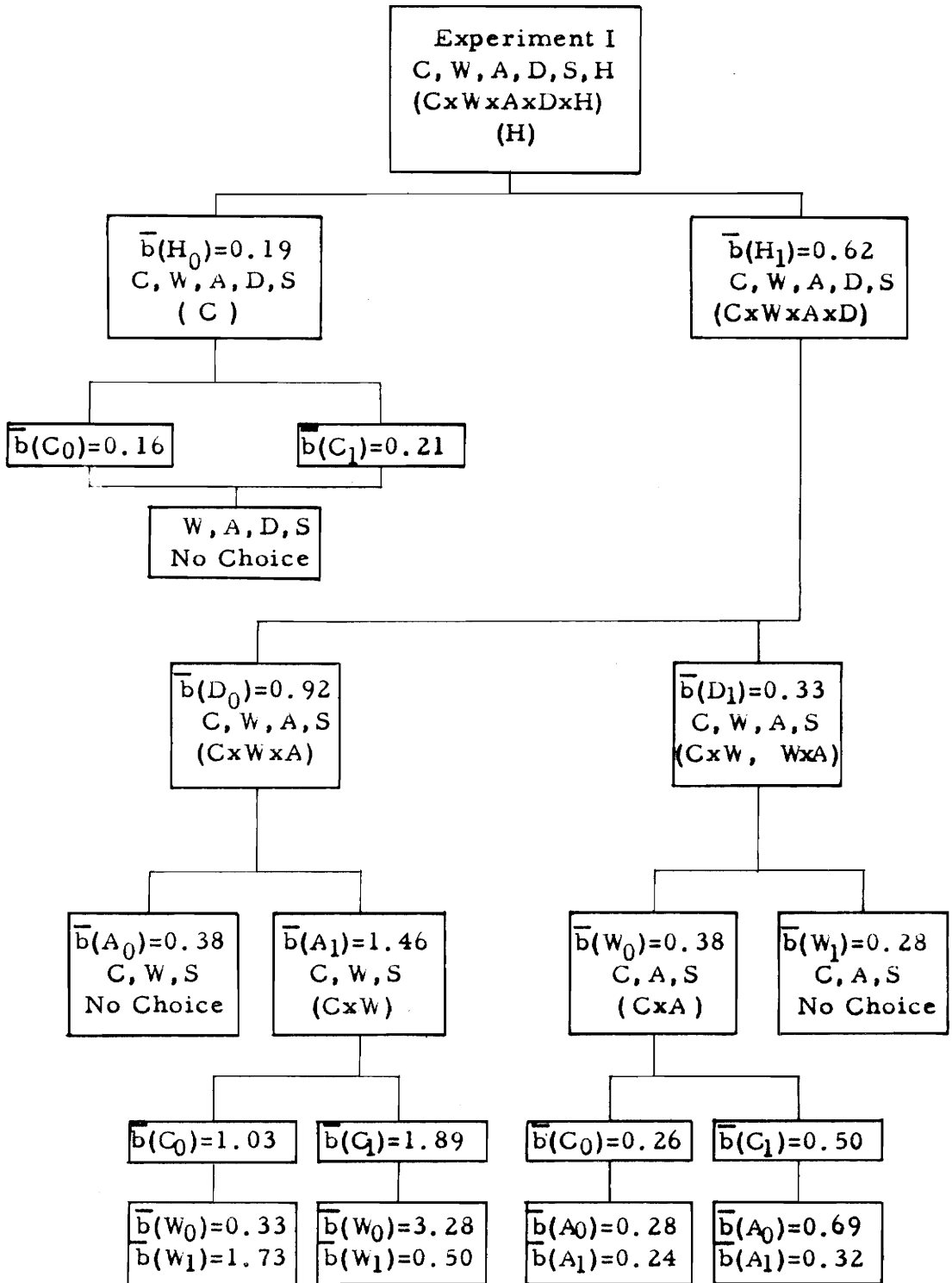


Figure 19.
RESULTS OF EXPERIMENT I

an aggregate is the better its protective ability will be.

Significant Effects for Experiment II.

The analysis of variance for Experiment II showed the C and P main effects (refer to Table II) to be significant at the 1% level. No other effects or interactions were shown to be significant. Mean values of b for the various levels of C and P are given below.

$$\bar{b}(C_0) = 0.16 \qquad \bar{b}(C_1) = 0.20$$

$$\bar{b}(P_0) = 0.19, \bar{b}(P_1) = 0.16, \bar{b}(P_2) = 0.22, \bar{b}(P_3) = 0.15, \bar{b}(P_4) = 0.18$$

A statistical test applied to the mean values for the various levels of waterproofing showed that $\bar{b}(P_1)$ and $\bar{b}(P_3)$ were significantly less than $\bar{b}(P_0)$ using the 5% significance level, but the differences between $\bar{b}(P_2)$ and $\bar{b}(P_0)$ and between $\bar{b}(P_4)$ and $\bar{b}(P_0)$ were shown to be not significant. Thus it was inferred that the cement slurry applied to the steel or the paint applied to the exterior of the concrete test sections gave better corrosion protection than the plain concrete.

Changes in Modulus of Elasticity

Young's Modulus for concrete prisms and cylinders can be determined experimentally according to Pickett, using the relation:

$$E = C_1 W n_1^2 \quad (14)$$

where E = Young's Modulus in psi.

W = Weight of Specimen in lbs.,

n_1 = Resonant frequency of first mode of flexural vibration in cps.,

C_1 = Factor depending on shape, size and Poisson's ratio.

Weights and resonant frequency measurements were made for Experiment I and II so that a study could be made of changes in the moduli of the various test sections. This study has not yet been undertaken. A brief survey of the data indicates that, generally, the modulus increased considerably during the first 100 to 160 cycles of exposure and either increased slowly or remained constant thereafter.

D. RECOMMENDATIONS

Experiment III should be completed and a "calibration factor" determined for the cyclic apparatus. This factor may not be constant for all mixes. Experiments I and II should be continued for a time to see if corrosion rates reported herein continue to hold constant.

A limit for half-life values should be established beyond which corrosion can be considered to be negligible. Future investigations should concentrate on those treatments from Experiment I for which the half-life value (after translation by calibration factor) falls within the limit of non-negligible corrosion. Since a five-factor interaction is strongly indicated, future investigations should be replicated in order to obtain a more valid estimate of error variance.

A multiple correlation study would be of value to see if any relationships exist between strength, modulus of elasticity, consistency and corrosion rate for the concrete mixes of Experiment I. The data for such a study is available.

VI. CONCLUSIONS

The following conclusions are drawn from results reported herein and apply only within the range of variables investigated.

1. The concrete mixes using fresh water gave better protection to the steel ribbon than did the sea water mixes.
2. Fresh water mixes with seven sacks of cement per cubic yard gave better protection than mixes with eight sacks.
3. Varying the water/cement ratio, the depth of cover, the type of aggregate and the ratio of maximum size of aggregate to depth of cover had no significant effect on the corrosion protection for the fresh water mixes.
4. An interaction between cement factor, water/cement ratio, type of aggregate and depth of cover seems to exist for the sea water mixes, so that the level of each of these variables should be carefully considered in designing a concrete mix for corrosion protection if sea water is to be used.
5. The existence of the effect on corrosion protection due to changing the ratio of maximum size of aggregate to depth of cover is questioned for the sea water mixes and should be further investigated.

6. The cement slurry applied to the steel ribbon and the paint applied to the exterior of the concrete gave better protection to the steel than did the plain concrete.

7. The cyclic apparatus described herein provides an exposure which considerably accelerates the qualitative testing of corrosion protection of thin precast concrete sections.

VII. ACKNOWLEDGEMENTS

The author wishes to express, to Professor D. H. Plette, his gratitude for the inspiration and supervision given throughout the investigation.

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IX. VITA

The author was born in Unadilla, New York in 1924. He was graduated from Franklin High School, Franklin, New Hampshire, in 1941. After a year of study at The University of New Hampshire he served in the armed forces of the United States for three years, and was later recalled for an additional year. He received the degree of Bachelor of Science in Civil Engineering from the Virginia Polytechnic Institute in 1952.

The author is at present a candidate for the degree of Master of Science in Applied Mechanics at the Virginia Polytechnic Institute.

Richard N. Southworth

X. APPENDICES

APPENDIX A: DESIGN OF CYCLIC APPARATUS

Very little quantitative information is available regarding moisture absorption rates and drying rates for concrete specimens. Hence, the cyclic apparatus, which was to subject the concrete test sections to cycles of wetting and drying, had to be designed on the basis of some rather arbitrary assumptions. The design assumptions and design calculations are discussed in the following section for the wetting cycle components and in the succeeding section for the drying cycle components of the apparatus.

Wetting Cycle Components

The length of time for the wetting period was set at one hour, based on absorption tests reported in Article IV, Section C. Design of the wetting components then consisted of calculating the volume of water required and the heat required to raise the temperature of the water to test temperature.

Volume of the specimen chamber and seven feet of 2" pipe	= 5.30 cu. ft.
Volume of 96 test sections	= <u>1.62</u> cu. ft.
Volume of air at 15 psia. = V_1	= 3.68 cu. ft.

Let the volume of air at 75 psia be V_2 then $V_2 = \frac{15}{75} V_1 = 0.74$ Cu.ft.

Hence, volume of water at 60 psig required to fill the chamber was $3.68 - 0.74 = 2.94$ cu. ft. or 22.0 gallons.

The temperature of the water for the wetting process was set at 70°F. The temperature of the available water supply varied from 55°F.

to 65°F. Hence, a tempering tank was required. A 40 gallon hot water storage tank was selected and thermostatically controlled immersion heaters used to bring the water temperature up to 70°. The length of the drying period was still undetermined but minimum possible was estimated to be one hour. Hence, the immersion heaters were designed to heat 27 gallons (183 pounds) of water from 55°F. to 70°F. in one hour.

$$\text{Heat Required} = 183 (70-55) = 2745 \text{ Btu,}$$

Hence the output of the heaters must be

$$2745/3413 = 0.80 \text{ KW.}$$

Two 500 watt heaters were used.

The water was to pass from the supply line into the tempering tank and at the proper time would be released into the specimen chamber through a solenoid operated globe valve. The pressure in the specimen chamber was to be maintained from the supply line pressure.

Drying Cycle Components

The purpose of the drying components of the cyclic apparatus was to remove the moisture from the saturated test sections in a few hours. For design purposes it was assumed that the average saturation moisture content would be 5% based on a dry unit weight of 150 lb/cu. ft.

$$\text{Volume of 96 test section} = 1.62 \text{ cu. ft.}$$

$$\text{Dry Weight of 96 test sections} = 243 \text{ lb.}$$

$$\text{Wt. of absorbed moisture} = 12.15 \text{ lb.}$$

Thus, the problem is to evaporate 12.2 lb. of water from the 96 test sections in, say, four hours. The rate of evaporation from

a water surface parallel to the direction of air flow is given by Marks (9) as :

$$W = .093 (1 + V/230) (e' - e) \text{ ----- (1)}$$

Where : W = rate of evaporation , lb./hr./sq.ft.

V = velocity of air flow, ft./min.

e'-e = difference in vapor pressures between the water and the air, In. of Hg.

Solving (1) for V we have:

$$V = \frac{2473 W}{e' - e} - 230 \text{ ----- (2)}$$

Now, assuming that the moisture in the concrete will move to the surface as rapidly as the water at the surface is evaporated, the velocity (and volume) of flow required to dry the test sections in two hours can be calculated.

Area of Test sections parallel to air flow = 44 sq. ft.

Rate of evaporation = $W = \frac{12.2}{4 \times 44} = 0.1386 \text{ lb/hr./sq.ft.}$

If the air is at 90°F and 18% relative humidity,

$$e' - e = 1.166 \text{ in. of Hg.}$$

Then From equation (2) we find

$$V = \frac{2473 (0.1386)}{1.166} - 230 = 64 \text{ ft./min.}$$

Cross-section area of the chamber = 3.01 sq. ft.

Area of Test sections perpendicular to flow = 1.68 sq. ft.

Area of Air space = 1.33 sq. ft.

Volume of air required = 1.33 x 64 = 85 cu. ft./min.

But, the assumption that the moisture in the concrete will move to the surface as rapidly as the water at the surface is evaporated is, admittedly, problematical. Following the reasoning of Sherwood and Comings (10) it was assumed that the shape of the drying curve for the

concrete would be similar to that shown in Figure 20. After a short adjustment period there would be a period of drying at a constant rate (Section AB of the curve) followed by a period during which the drying rate would be decreasing. After some time the curve would become asymptotic to a line representing the equilibrium water content. The slope of section AB of the curve can be calculated by formula (1) since during this constant rate period the surface of the concrete would be wet, and the drying rate would depend only on the condition of the air around the concrete. However, the moisture content at which the constant-rate period ends (point B of the curve) and the ensuing drying rate would be affected by the nature of the concrete, and would likely be different for each concrete test section.

In view of these further assumptions the following design criteria for the drying components were established:

- (1) Volume of drying air of at least 125 cu. ft./min.
- (2) Relative humidity of drying air of about 20% at 100°F.
- (3) Length of drying period of 2 to 4 hours.

The compressor chosen for the apparatus (See Article IV, Section C) would supply approximately 145 Cu. ft./ min. of free air, at 70°F, saturated.

Three methods of moisture removal were considered for obtaining dry air : (1) absorption, using calcium chloride, (2) adsorption, using silica gel and (3) condensation using refrigeration. The condensation method was adopted as being the most economical since the first two require either expensive equipment or considerable attention and

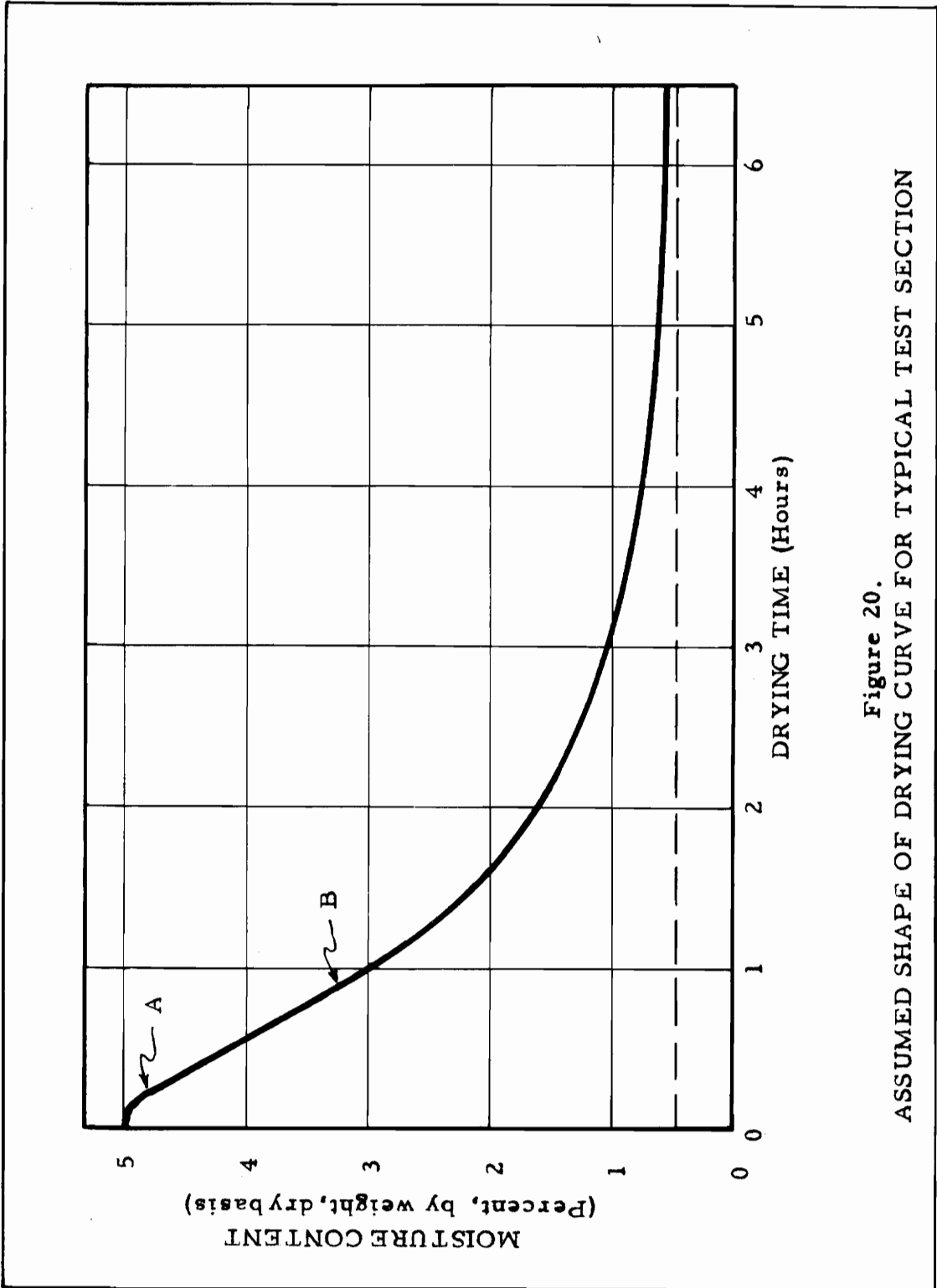


Figure 20.
ASSUMED SHAPE OF DRYING CURVE FOR TYPICAL TEST SECTION

replacement of drying agent.

The condensation method would require two processes to provide the warm dry air. First, the saturated air from the compressor would be cooled until a sufficient quantity of moisture had been removed by condensation. Second, the saturated air from the cooler would be heated to the operating temperature.

A psychrometric chart shows that to obtain a relative humidity of 20% at 100°F. the air must first be cooled to 50°F. Assuming that the air from the compressor is at 70°F., and saturated, the refrigerating capacity of the cooler must be such that the 145 cu.ft./min. of air will be cooled from 70°F. to 50°F.

$$\begin{aligned} \Sigma \text{ heat content at } 70^{\circ} &= 33.4 \text{ Btu/lb. of dry air} \\ \Sigma \text{ heat content at } 50^{\circ} &= 20.1 \text{ Btu/lb. of dry air} \\ \text{Difference} &= \underline{13.3} \text{ Btu/lb. of dry air} \end{aligned}$$

$$\text{Enthalpy of vapor} = (110/700 \times 20 = 0.3 \text{ Btu/lb. of dry air.}$$

$$\text{Heat to be removed} = 13.3 + 0.3 = 13.6 \text{ Btu/lb. of dry air.}$$

$$\text{Weight of air} = 145/13.7 = 10.6 \text{ lb. of dry air / min.}$$

$$\text{Heat to be removed} = 13.6 \times 10.6 = 144 \text{ Btu/min.}$$

$$\text{Hence, refrigeration required} = 144/200 = 0.72 \text{ Tons.}$$

A window air conditioning unit of 3/4 ton refrigerating capacity was selected. The cooling coils were separated from the unit and placed in a pressure tight tank through which the air from the compressor would pass.

The 50°F. saturated air would have to be heated to 100°F. before passing on to the specimen chamber.

Enthalpy of dry air at 100°F and 18% P.H. = 32.1 Btu/lb. of dry air.
Enthalpy of dry air at 50°F. saturated = 20.1 Btu/lb. of dry air.
difference = 12.0 Btu/lb. of dry air.

Enthalpy of vapor = $(53/7000) \times 50 = 0.4$ Btu/ lb. of dry air.

Total heat to be added = $12.0 + 0.4 = 12.4$ Btu/ lb. of dry air.

Flow of air = 10.6 lb. of dry air/min.,
hence ,

Heat required = $12.4 \times 10.6 = 132$ Btu/min. or 7920 Btu/hour.

Since 3413 Btu. = 1 Kw-hr.,

Heating capacity required = $7920/3413 = 2.3$ KW.

Three heating elements of 1.25 Kw each were selected for the heater. The total capacity of 3.75 KW provided a maximum temperature of about 130°F.

Choice of the control elements for automatic operation completed the design of the cyclic apparatus. A detailed wiring diagram in Figure 21 shows both control and power wiring for the apparatus.

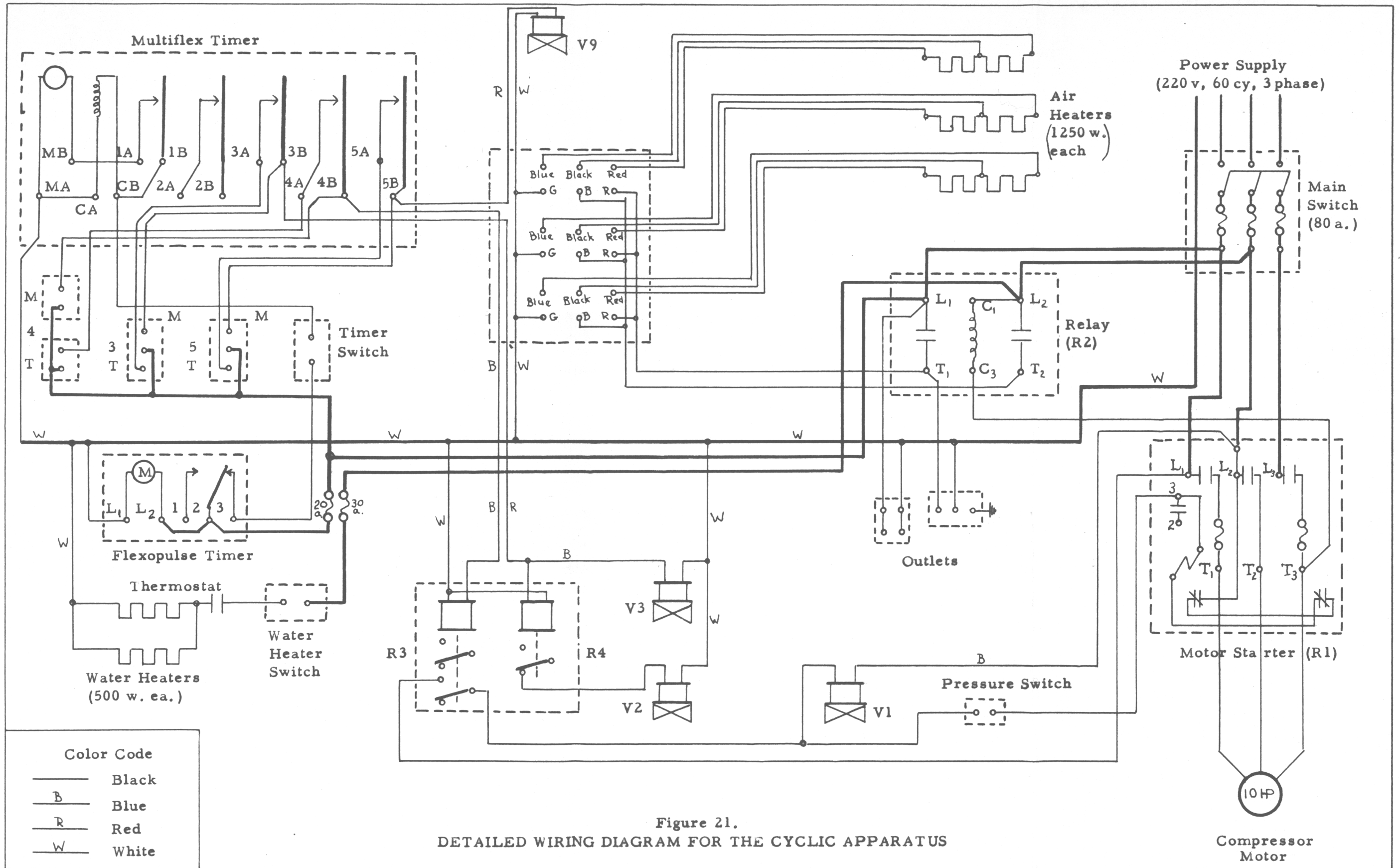


Figure 21.
DETAILED WIRING DIAGRAM FOR THE CYCLIC APPARATUS

APPENDIX B: STATISTICAL TREATMENT OF DATA

The analyses of variance and significance tests presented here form the basis for the conclusions presented in Article VI. "Industrial Experimentation" by K. A. Brownlee (11) was used as a guide for the statistical treatment and is recommended as a reference for those readers who are unfamiliar with statistical terminology and methods.

Analyses of the variations in the slopes of the regression lines described in Article IV, Section E, were made. The slopes of these lines were assumed to correspond to the rates of corrosion of the steel ribbons embedded in the concrete test sections, thus lower values of b (slope) indicated better protective ability in the concrete. Absolute values for the variances and for the main effects were not of interest since only comparisons are to be made of the relative protective ability of the various concretes. The data (slopes) from Tables VII and VIII were multiplied by 100 to eliminate decimals. An entirely satisfactory analysis of Experiment I could not be made since the experiment was not replicated (due to spatial limitations of the specimen chamber), however, the results are important as basic information and indicate the directions in which further investigation should be made.

Analysis of Experiment I

The data for Experiment I is presented in Table IX. The analysis of variance shown in Table X was based on the original assumption that the interactions of order two and higher could be pooled for an

estimated residual mean square. In this first analysis the CxW, AxD, AxH and DxH interactions appeared to be significant at about the 5% level and none of the main effects attained significance due to these large interaction mean squares that were appropriately used to test the main effects. The pooled residual mean square was larger than had been expected (assuming it to be an estimate of error variance only) so the mean squares for all higher order interactions were calculated (see Table XI). A large mean square value (11,852.80) was observed for CxWxAxDxH and, to be conservative, a pooled estimate of CxWxAxDxH interaction variance was obtained following the method used by Brownlee (12). A pooled interaction sum of squares was obtained by pooling with the CxWxAxDxH sum of squares, the sums of squares for all those interactions whose mean square contained the CxWxAxDxH component of variance, except that the sums of squares for CxW, CxWxAxH, DxH, AxDxAxH and AxD, whose mean squares were larger than the CxWxAxDxH mean square, were not included. The mean squares of CxW, CxWxAxH, etc., were then tested against the pooled mean square for CxWxAxDxH with an F-test, were found to be not significant at the 5% level and were then included to obtain a new pooled mean square for CxWxAxDxH. This new estimate was 6,214.43, based on 26 degrees of freedom. The remaining interaction sums of squares were pooled for an estimate of error of 649.65 with 31 degrees of freedom. The variance ratio, then, is $F = 6,214.43 / 649.65 = 9.57$, with $\nu_1 = 26$ and $\nu_2 = 31$. This is highly significant (better than 0.1% level) and the CxWxAxDxH interaction was assumed to exist.

TABLE IX
SLOPES OF REGRESSION LINES
EXPERIMENT I

			C ₀				C ₁			
			W ₀		W ₁		W ₀		W ₁	
			A ₀	A ₁	A ₀	A ₁	A ₀	A ₁	A ₀	A ₁
D ₀	S ₀	H ₀	15	14	23	17	23	20	21	21
		H ₁	29	35	82	257	23	378	26	59
	S ₁	H ₀	18	15	16	17	21	22	19	18
		H ₁	33	31	24	89	39	278	44	41
D ₁	S ₀	H ₀	19	17	15	15	19	22	19	21
		H ₁	32	30	29	52	62	42	20	31
	S ₁	H ₀	18	13	13	17	24	25	22	21
		H ₁	25	17	21	18	76	22	26	26

TABLE X
ANALYSIS OF VARIANCE
EXPERIMENT I

SOURCE	SUMS OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARES
C	3,378.52	↑ ONE DEGREE OF FREEDOM EACH ↓	↑ SAME AS SUM OF SQUARES ↓
W	1,570.14		
A	10,125.39		
D	13,776.89		
S	2,244.39		
H	30,493.89		
CxW	15,781.64		
CxA	1,610.01		
CxD	695.64		
CxS	708.89		
CxH	1,530.76		
WxA	656.64		
WxD	236.39		
WxS	467.64		
WxH	1,378.28		
AxD	12,853.89		
AxS	1,838.27		
AxH	10,634.77		
DxS	1,032.02		
DxH	13,776.89		
DxH	2,197.27		
Residual	116,315.40	42	2,769.41
TOTAL	243,303.61	63	

TABLE XI
 SUMS OF SQUARES FOR HIGHER ORDER INTERACTIONS
 EXPERIMENT I

SOURCE	SUM OF SQUARES	SOURCE	SUMS OF SQUARES
CxWxA	8,953.90	CxWxAxD	10,998.74
CxWxD	9,384.77	CxWxAxS	643.90
CxWxS	1,753.51	CxWxAxH	8,395.12
CxWxH	14,671.28	CxWxDxS	1,378.26
CxAxD	3,178.15	CxWxDxH	8,534.13
CxAxS	47.26	CxWxSxH	1,838.63
CxAxH	1,341.39	CxAxDxS	4.51
CxDxS	70.14	CxAxDxH	3,235.76
CxDxH	921.64	CxAxSxH	23.78
CxSxH	534.77	CxDxSxH	166.77
WxAxD	3,178.15	WxAxDxS	11.38
WxAxS	1.26	WxAxDxH	2,956.63
WxAxH	763.14	WxAxSxH	13.16
WxDxS	319.52	WxDxSxH	192.53
WxDxH	395.01	AxDxSxH	656.65
WxSxH	310.63	CxWxAxDxS	276.41
AxDxS	511.89	CxWxAxDxH	11,852.80
AxDxH	13,659.77	CxWxAxSxH	962.89
AxSxH	1,925.00	CxWxDxSxH	1,095.90
DxSxH	819.38	CxAxDxSxH	8.76
		WxAxDxSxH	9.26
		CxWxAxDxSxH	318.87

Next the main effects were tested. The S effect, since it did not contain the CxWxAxDxH interaction variance among its components, was tested against the pooled estimated error variance which had 31 degrees of freedom, and found to be not significant. The other main effects were tested against the CxWxAxDxH interaction estimate and only the H effect was found to be significant. For the H effect $F = 30,493.89/6214.43 = 4.91$, with $\beta_1 = 1$ and $\beta_3 = 26$. This is significant at slightly better than the 5% level, hence the H effect was assumed to exist.

In order to study the import of the CxWxAxDxH interaction, Experiment I was subdivided into two separate experiments, one at each level of factor H. The H_0 experiment (see Table XII) showed only the C main effect to be significant, this being at the 0.1% level. No evidence of interaction was observed for the H_0 experiment so that data was not further subdivided.

Table XII also shows the analysis of variance for the H_1 experiment. The large mean square for CxWxAxD indicated a possible interaction (stemming from the CxWxAxDxH interaction) so an estimate was obtained, again following Brownlee. The sums of squares for C, W, A, CxA, CxD, WxA, WxD, CxWxA, CxWxD, CxAxD and WxAxD were pooled with the sums of squares for CxWxAxD to get a mean square of 8805.7 with 12 degrees of freedom. The other interactions of order two and higher were pooled for an estimate of error of 932.0 with 11 degrees of freedom. The D main effect and the CxW and AxD interactions were tested against the CxWxAxD interaction estimate and found

TABLE XII
ANALYSIS OF VARIANCE
EXPERIMENT I
FIRST SUBDIVISION

SOURCE	SUMS OF SQUARES FOR	
	H ₀	H ₁
C	180.50	4,728.8
W	3.12	2,945.3
A	3.12	20,757.0
D	0.00	27,553.8
S	0.13	4,441.5
CxW	10.13	30,442.7
CxA	6.13	2,945.3
CxD	8.00	1,610.2
CxS	6.12	1,237.5
WxA	2.01	1,417.8
WxD	10.13	621.2
WxS	8.00	770.3
AxD	6.13	26,507.5
AxS	0.50	3,762.8
DxS	6.12	1,845.3
CxWxA	4.48	17,344.5
CxWxD	10.12	17,907.9
CxWxS	0.50	3,591.4
CxAxD	0.12	6,412.9
CxAxS	2.00	69.0
CxDxS	10.13	225.9
WxAxD	2.00	6,132.8
WxAxS	3.12	11.2
WxDxS	8.00	504.1
AxDxS	4.50	1,164.0
CxWxAxD	8.00	22,844.5
CxWxAxS	15.15	1,582.1
CxWxDxS	8.00	2,417.3
CxAxDxS	0.50	13.7
WxAxDxS	0.12	19.6
CxWxAxDxS	1.12	653.8
TOTAL	328.00	212,481.7

significant at about the 10% level which leaves some doubt about their existence. The S main effect was tested against the estimate of error and found nearly significant at the 5% level. The CxWxXxD interaction, tested against the error term was significant at the 0.1% level. Based on these tests the CxWxXxD interaction was assumed to exist but the S main effect was questioned since the S X H interaction in the complete analysis was negligible.

The data of the H₁ experiment was further subdivided into two experiments, one at each level of factor D. The analysis of variance is shown in Table XIII for both experiments. For the D₀ experiment a CxWxA interaction was suspected. The CxW and A sums of squares were not significantly larger than the first estimates of CxWxA (based on 5 degrees of freedom) so the final estimate included sums of squares for CxW and A with those for C, W, CxA, WxA and CxWxA. This gave a mean square of 22,775.3 with 7 degrees of freedom. The remaining sums of squares for interactions were pooled to give a mean square of 2179.40 for error, based on 7 degrees of freedom. The CxWxA interaction tested against the error term was significant at the 1% level. The S main effect was not significant.

For the D₁ experiment the CxW and C sums of squares were pooled, as were the W and WxA sums of squares, to estimate the CxW and WxA interactions. These were significant at the 5% level when tested against an error mean square based on sums of squares for the three and four factor interactions.

The D₀ experiment was broken down into two three-factor

TABLE XIII
ANALYSIS OF VARIANCE
EXPERIMENT I
SEA WATER MIXES ONLY

SOURCE	SUMS OF SQUARES FOR	
	D ₀	D ₁
C	5,929.0	410.0
W	3,136.0	430.5
A	47,089.0	175.5
S	6,006.2	280.5
CxW	47,524.0	826.6
CxA	9,025.0	333.2
CxS	1,260.3	203.1
WxA	6,724.0	826.7
WxS	1,260.3	14.1
AxS	4,556.3	370.7
CxWxA	40,000.0	189.0
CxWxS	6,006.2	52.6
CxAxS	72.2	10.4
WxAxS	30.2	0.4
CxWxAxS	2,070.3	115.6
TOTAL	180,689.0	4,238.9

experiments at the two levels of A. There were no significant effects for the A_0 experiment. The CXW interaction was significant at the 5% level for the A_1 experiment and no other effects were significant.

The D_1 experiment was also subdivided into two experiments at the two levels of W. For the W_0 experiment the CXA interaction was significant at about the 5% level and no other effects were significant. There were no significant effects for the W_1 experiment.

The analysis of variance tables for the A_0 , A_1 , W_0 and W_1 experiments are presented as Table XIV and Table XV.

The results of this method of analysis can best be followed by referring to the chart of Figure 19 in Article V, Discussion of Results. Explanation of the chart may be found on the page preceding the chart.

Analysis of Experiment II

The data for Experiment II is presented in Table XVI. The analysis of variance (see Table XVII) showed no significant interactions. For the P main effect $F = 69.85/14.3 = 4.9$ with $\beta_1 = 4$ and $\beta_2 = 17$. This was significant at the 1% level. For the C main effect $F = 160.0/14.3$ with $\beta_1 = 1$ and $\beta_2 = 17$. This was also significant at the 1% level. No other main effects were significant.

The significance of the C main effect indicated that the difference between the means for the two levels of factor C was significantly greater than zero. However, for the P main effect, which had five levels, the F test did not tell which differences were significantly greater than zero. For the purposes of this

TABLE XIV. ANALYSIS OF VARIANCE
EXPERIMENT I, SEAWATER MIXES
 $\frac{1}{4}$ " DEPTH OF COVER, ($H_1 D_0$)

Source	Sums of Squares	
	A_0	A_1
C	162.0	14,792.0
W	338.0	9,522.0
S	50.0	10,512.5
CxW	162.0	87,362.0
CxS	968.0	364.5
WxS	450.0	840.5
CxWxS	512.0	7,564.5
TOTAL	2,642.0	130,958.0

TABLE XV. ANALYSIS OF VARIANCE
EXPERIMENT I. SEAWATER MIXES
 $\frac{1}{2}$ " DEPTH OF COVER ($H_1 D_1$)

Source	Sums of Squares	
	W_0	W_1
C	1,200.5	36.13
A	882.0	120.13
S	84.5	210.12
CxA	512.0	10.11
CxS	24.5	231.13
AxS	200.0	171.13
CxAxS	98.0	28.13
TOTAL	3,001.5	806.88

TABLE XVI
SLOPES OF REGRESSION LINES
EXPERIMENT II

		P ₀		P ₁		P ₂		P ₃		P ₄	
		A ₀	A ₁	A ₀	A ₁	A ₀	A ₁	A ₀	A ₁	A ₀	A ₁
C ₀	W ₀	15	14	19	17	23	16	18	20	15	15
	W ₁	23	17	15	13	21	15	11	5	17	12
C ₁	W ₀	23	20	15	17	25	23	18	17	22	21
	W ₁	21	21	17	17	20	35	13	14	15	27

TABLE XVII
ANALYSIS OF VARIANCE
EXPERIMENT II

SOURCE OF VARIANCE	SUMS OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARES
C	160.0	1	160.0
W	14.4	1	14.4
A	2.5	1	2.5
P	279.4	4	69.85
CxW	12.1	1	12.1
CxA	78.4	1	78.4
CxP	63.0	4	15.75
WxA	6.4	1	6.4
WxP	117.6	4	29.40
AxP	17.0	4	4.25
Residual	243.1	17	14.3
TOTAL	993.9	39	

investigation it was considered sufficient to compare the means for the four higher levels of P with the zero level (no waterproofing.). A t-test was used for this comparison. (13) The sums of squares of deviations and the means were calculated for each of the levels of factor P and are shown below.

<u>Level of Factor P</u>	<u>Mean</u>	<u>Sum of Squares</u>
P ₀	19	85.5
P ₁	16	23.5
P ₂	22	269.5
P ₃	14.5	166.0
P ₄	18	170.0

The number of observations was eight for each level of P. The standard deviations were calculated for the four combinations of level P₀ with the levels P₁, P₂, P₃, and P₄. The symbols used for these standard deviations were s₀₁, s₀₂, s₀₃ and s₀₄. The values were calculated as: s₀₁ = 2.79, s₀₂ = 5.04, s₀₃ = 4.24 and s₀₄ = 4.27. The value of t for the first comparison, $\bar{b}(P_0) - \bar{b}(P_1)$, was calculated as:

$$t = \frac{(19 - 16)}{2.79} \sqrt{\frac{8 \times 8}{8 + 8}} = 2.15 \text{ with 14 degrees of freedom.}$$

Similarly, the value for $\bar{b}(P_0) - \bar{b}(P_2)$ was t = 1.19, for $\bar{b}(P_0) - \bar{b}(P_3)$ t = 2.12 and for $\bar{b}(P_0) - \bar{b}(P_4)$ t = 0.47. For significance at the 5% level the value of t must be 2.15 or greater, at the 10% level 1.76 or greater and at the 25% level 1.20 or greater, for 14 degrees of freedom. The differences $\bar{b}(P_0) - \bar{b}(P_1)$, and $\bar{b}(P_0) - \bar{b}(P_3)$ were significant at the 5% level and were assumed to exist. The other two differences were not significant, even at the 25% level, and were assumed to be due to random error or experimental error.