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December 30, 1974

MEMO TO: J. R. Harbison
             State Highway Engineer
             Chairman, Research Committee

SUBJECT: Research Report No. 414; "Voidless Concrete Mixtures for Bridge Decks;"
             HPR-PL-1(10), Part III; KYP-72-39

Report No. 402, "Bridge Decks Constructed for Increased Durability," and my commentary therewith related some improvements already implemented and some that may yet be needed to assure long-term durability of concrete bridge decks. Elimination of now-hidden unsoundness in aggregates and reduction of mixing water have seemed thus far to be somewhat untouchable recourses. Particles of normal-weight aggregates which absorb as much as 4% water (by weight) cannot withstand freezing; absorption tests on bulk samples yield average values only and may not reveal the presence or proportion of freezing-susceptible particles. Current specifications admit particles absorbing nearly 5% water (based on a bulk specific gravity of 2.35). A more favorable limit would be about 2%. This aspect of durability was discussed more extensively in Report No. 325 ("Expansive Limestone Aggregate in a Concrete Pavement," pages 48-53). Although our Class AA concrete complies with the cement factor and maximum limits on water-cement ratio (0.44) recommended in the PCA's 1970 report on the "Durability of Concrete Bridge Decks," any measures taken to reduce water to less than 30 gallons per cubic yard (w/c $\approx$ 0.40) would surely strengthen the concrete and improve durability. Any reduction in mixing water decreases permeability and absorption. Significant reductions in mixing water are achievable through air entrainment, water-reducing admixtures, fly-ash admixtures, and by improving the shape of crushed aggregates. The latter of these remains untried and unpersuasive. Alternatives have arisen in the form of protective coatings and injections into the concrete and admixtures of latexes to supplant portions of the excess mixing water. The report submitted herewith addresses an idealized approach to supplanting all mixing water in excess of that needed for hydration of the cement. Emulsions and latexes containing approximately 50% water seemed uniquely suited for the purpose of supplying the total mixing liquid, providing water for hydration, and providing an indwelling, space filler, excluding water. Unfortunately, many otherwise stable emulsions and latexes "break" or "demulsify" prematurely in the mixing process. If this problem could be overcome, the idea would seem more feasible and practical for otherwise normal methods of producing concrete mixtures. We are very disappointed that none of the asphalt or linseed oil emulsions tried withstood the mixing process sufficiently to permit molding concrete beams and cylinders.
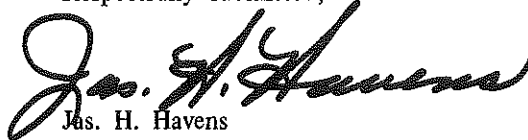
Our first trials of emulsifiable epoxies (PC-10) in 1969 in the laboratory were so encouraging that we proposed its use for repair work under way on the North-South Expressway in Louisville in 1971. Trial batches were made in a ready-mix truck in Louisville, August 25, 1971; the mixture foamed unexpectedly and was obviously unacceptable. On August 30, a trial was made through a Concrete-Mobile, at Jeffersonville; the trial was seemingly more successful; but confidence in the proposal had waned; and Celanese was left with more homework to do. Celanese then proposed to demonstrate mixing and

patching on the south bridge at the Waddy-Peytonia interchange on I 64 in October 1971. Apparently, no full-scale concrete decking has been done with this material or the styrene-butadiene or saran-type latexes.

Dow's latex mortar and concrete formulas have never provided the concentration of latexes or degree of water reduction sought in these studies. Dow's formulas generally have supplanted one-half to two-thrids of the non-essential water as defined by our idealized, minimum of 0.24 (2.75 gallons per bag of cement). Perhaps we were too idealistic in this study. Our assumnptions attributed 9 to 10% voids in concrete to non-essential water; a reduction of slightly over three-fourths, or to approximately 2%, might have been sufficient to accomplish the practical objective -- that is, to assure extended durability.

Respectfully submitted,

Jas. H. Havens
Director of Research

JHH:gd
Enclosure
cc's: Research Committee

Research Report
414

VOIDLESS CONCRETE MIXTURES FOR BRIDGE DECKS

KYP-72-39, HPR-PL-1(10), Part III

by

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Division of Research
Bureau of Highways
DEPARTMENT OF TRANSPORTATION
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16. Abstract

The purpose of this study was to modify concrete mix-design formulas to supplant all water over and above that needed for hydration with a non-evaporable material -- thus producing a no-void concrete. It was adjudged that a water-cement ratio of 0.244 would be practical for hydration of the cement. Several polymeric materials, asphalts, and oils were used to replace the excess mixing water. Success was achieved using two latexes and one epoxy. The use of these materials in concrete resulted in improved strength, reduction of air voids and permeability, and enhancement of resistance to corrosive chloride salts.

17. Key Words		18. Distribution Statement
Concrete Voids Durability Non-Evaporable Liquids Latex	Epoxy Corrosion Resistance Permeability	

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INTRODUCTION

Extensive research conducted in Kentucky *(3, 4)* and other states have identified and explained the mechanisms causing premature deterioration of concrete bridge decks. Some suggest that the causal factors have been compounded by the increasingly heavy traffic and widespread use of deicing agents.

It is widely recognized that the most destructive forces in the deterioration of concrete arise from the absorption and freezing of water within the pores of the mortar and aggregates and corrosion of the embedded steel. These factors lead to scaling, spalling, and structural breakups. Tests have shown repeatedly that damage by freezing and thawing is related directly to porosity of the concrete, rate of water absorption, degree of saturation, and total water content. Corrosion of the steel is also related to soundness of concrete. Water carrying chloride salts absorbed by the concrete and contacting the steel initiates corrosion.

If one accepts the hypothesis or premise that the quality of portland cement concrete may yet be improved to provide adequate durability and resistance and to, thereby, assure long-time, maintenance-free service in bridge decks, several improvements are needed. Two basic needs would be (1) the elimination of porous, highly absorptive, reactive, or expansive aggregates, and (2) the improvement of the shape or workability features of aggregates to obtain significant reduction in mixing-water in making the concrete. Ideally, protection and assurances against premature deterioration should be a prerequisite consideration in the design of the structure. From the engineer's point of view, this becomes a process of purification and implementations in stages until history provides the necessary proofs and balances. Emerging alternatives have included protective coatings on normal-quality concrete and injections of polymers into hardened concrete.

The intent of this study is to demonstrate, in yet another way, the immunization of concrete against deterioration. The concept employed involves the use of oils and(or) polymerizable liquids to supplant a due portion of mixing water and to fill unwanted spaces in the concrete. Latex-type modifiers have been used rather extensively in Kentucky for patching and overlaying bridge decks. They have been used in lesser concentrations than are considered to be ideally void-filling; that is, the amount of water used has not been limited to that needed for hydration.

Voids occur in concrete through the entrapment of air, the use of excess mixing water, differences in the specific volumes of reactants and hydration products, leaching of hydration products (CaO), and the use of porous aggregates. Only about one-half of the normal mixing water is needed for hydration of the cement; the remainder, or excess, is normally required to fluidize the fresh concrete. If the cured concrete is used in a drying environment, most of the excess water evaporates and leaves voids or spaces. The voids which are easily saturated or resaturated upon rewetting affect the durability unfavorably

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while those which are less permeable are highly favorable to durability. Water occluded in concrete in the form of excess mixing water and water absorbed in the aggregate remains within the mass unless exposed to severe drying conditions. Concrete which has not been allowed to dry following curing may perform poorly upon freezing and thawing *(3)*. Eliminating the permeable voids from the concrete could alleviate many of the shortcomings leading to early deterioration and poor durability.

The largest percentage of voids in the concrete is attributed to the excess mixing water. Excess mixing water is defined here as any water over and above that needed for hydration of the cement. By eliminating the excess water, which is needed for workability, and leaving only the amount of water needed for hydration, a watertight, nearly voidless and impermeable concrete could be attained. The workability of the mixture could be provided by a non-evaporable liquid replacing the excess mixing water. Such liquid could be of the polymeric, asphaltic, or oil type.

The two critical questions which have to be resolved in order to make the idea of a voidless concrete possbile are:

1. What type of material could successfully replace the excess mixing water without adversely affecting the concrete?

2. How much water is needed for hydration of the cement (Type I cement)?

The fluid material to replace the excess mixing water might have the following characteristics:

1. Should be a liquid soluble in or emulsifiable with water and have a consistency of water or light oil; water should be the continuous phase; may be an inert oil or polymeric compound. Ideally, the disperse phase should remain dispersed throughout the concrete-mixing process.

2. Might be a liquid which would eventually solidify: a latex, epoxy, etc.

3. If solidification is sought, which should take place within a reasonable time after mixing, the material should exhibit sufficient strength and not contribute to weakening of the hardened concrete.

There are different opinions about the amount of water needed for hydration of the cement. The specificity of the amount varies with the type of cement and method of analysis. The extent of hydration appears to be dependent on the amount of water available, time, and compactness of the cement particles. Dense hydration shells or matrices of hydration products slow and perhaps arrest the hydration process. According to Powers *(5)*, portland cement when completely hydrated binds about 0.23 g water per g cement. This amounts to about 2.6 gal/bag cement. It has also been reported *(6)* that if only the minimum water needed for hydration is added to the cement, the possibility of near complete hydration is very remote. For this reason, 0.244 g water per g cement (2.75 gal/bag cement, w/c = 0.244) was adjudged to be a more practical amount of essential water for the purposes of this study. Others *(1)* have indicated a minimum w/c of 0.24.

MATERIALS

As mentioned previously, the material replacing the mixing water could be of the polymeric, asphaltic, or oil type. Several latex polymers were used; but only two, Dow Latex Modifiers A and B, were considered successful; and one, DuPont chloroprene latex, was unsuccessful. The DuPont latex hardened very fast and made placing the concrete very difficult; the hardened concrete exhibited low strength. One epoxy-type polymer was successfully used. Many other emulsified asphalts and oils were tried but could not be successfully blended into the concrete. Some were abandoned at the mixing stage because the dispersion "broke" before mixing was completed.

Latexes

A latex is a water suspension of a polymeric material of either natural or synthetic origin. The latexes used in this study were the following:

A. Dow Latex Modifier A

    Polymer Type   Styrene Butadiene

    Stabilizers

        (a) Latex   Nonionic Surfactant

        (b) Portland Cement

                Composition   Polydimethyl Siloxane

    Percent Solids   46 - 49

    Weight at 25 C   8.4 lb/gal (100 kg/m^3)

    Color   White

B. Dow Latex Modifier B

    Polymer Type   75% Saran

                                        25% Styrene Butadiene

    Stabilizers

        (a) Latex   Nonionic Surfactant

        (b) Portland Cement

                Composition   Polydimethyl Siloxane

    Percent Solids   47 - 49

    Weight at 25 C   9.7 lbs/gals (1162 kg/m^3)

    Color   White

C. DuPont Latex

    Polymer Type   Neoprene (Polychloroprene)

Stabilizers

    (a) Latex   Nonionic Surfactant

    (b) Portland Cement   2 parts anti-oxidant/100 g solids

            Composition

Percent Solids   48

Weight at 25 C   9.35 lbs/gal (1119 kg/m^3)

Color   White

Several other latex systems were tried but could not be successfully mixed into the concrete. The main factors leading to the choice of such systems were their emulsifying and curing properties. All three latexes used were emulsifiable with water and cured at ambient temperatures within a desirable time.

Emulsified Epoxy Resins

Epoxy resins are polymers which are mixed with another ingredient to form combinations referred to as formulations. The formulation used in this study consisted of an epoxy resin and a hardener. The hardener reacts with the resin and becomes an integral part of the final plastic material [10].

For the purpose of this study, an formulation had to be emulsifiable with water. Emulsifiable epoxies are not readily available, and a special formulation was developed by Celanese Coatings Company of Louisville, Kentucky. Following are the properties of that epoxy:

EPI-TOP PC-l0 Epoxy

Polymer Type   Liquid Bisphenol A epoxy type resin

Stabilizers   Surfactants (water dispersible)

Percent Solids   100

Weight at 25 C   9.6 lbs/gal (1145 kg/m^3)

Emulsified Asphalts and Oils

The emulsified asphalts utilized in this study were predominantly of the slow setting type. Some of the asphalts were paving grade and the others were experimental. The paving grade asphalts included SS-1 and SS-lH (ASTM D-977). The experimental asphalt was a specially formulated emulsion made by the Ashland Oil Company for use in these experiments. Emulsified linseed oil was used unsuccessfully.

DESIGN OF MIXTURES

The mix designs were based on a typical concrete mixture used by the Kentucky Bureau of Highways, Department of Transportation, for bridge decks, namely Class AA Concrete, Special Provision No. 35-B (APPENDIX A).

Class AA concrete mixture design (Table 1) was used unchanged for the control mixtures designated "C". All other mixtures incorporated in them basically the same materials with the following, experimental modifications:

1.   The water requirement was reduced and confined to that estimated for hydration of the cement.

2.   A non-evaporable liquid was added for workability.

Modified or experimental mixture designs are shown in Table 2.

TEST PROCEDURES

Strength

Unconfined compression tests were made on 6- by 12-in. (152- by 305-mm) cylinders in accordance with ASTM C 39. The specimens were molded according to ASTM C 31 in single-use molds conforming to ASTM C 470. All cylinders were covered with wet burlap immediately after molding and were removed from the molds one day later. They were placed in a moisture room and cured until the time of testing. All cylinders were capped and tested in a wet condition.

Flexure tests wery run on 3- by 4- by 16-in. (75- by 100- by 400-mm) specimens in accordance with ASTM C 293 (center-point loading). All beams were made according to ASTM C 31 using steel molds. The specimens were removed from the molds one day later and cured in a moisture room until tested. All flexure beams were tested in a wet condition.

Specific Gravity, Absorption and Voids

Hardened concrete samples were sawed from beams and cylinders and tested in accordance with ASTM C 642 for specific gravity, absorption, permeable void volume, and bulk unit weight. The test was modified slightly to insure complete saturation by applying a vacuum to the container while the specimens were immersed in water. Test values listed in Table 3 are average values from three tests.

Air Void Content

Air void content in the hardened concretes was measured on sawed and polished sections taken from beams and cylinders. The linear traverse method was used in accordance with ASTM C 457. Three samples were tested from each mix. Average results are listed in Table 3.

Freezing and Thawing

The freezing and thawing test of the different mixtures was conducted on beams measuring 3 by 4 by 16 in. (75 by 100 by 400 mm). Three beams from each mix were tested in accordance with ASTM C 666. The specimens were cast in steel molds and consolidated by vibration. Finishing was done immediately afterwards; the same procedure was used on each specimen. Wet burlap was placed on the specimens; and, after 24 hours, the specimens were removed and placed in the moisture room where

TABLE 1

CLASS AA MIX DESIGN

ITEM	MAGNITUDE	
	(lb/yd^3)	(kg/m^3)
Cement	620	368
Water	275	163
Coarse Aggregate	1814	1076
Fine Aggregate	1196	710
Air Content	6%	6%
Slump	1 1/2 - 2 1/2"	38 - 64 mm
Approximate Average 28-Day Compressive Strength	4500 psi	38027 kPa
Flexural Strength (minimum)	275 psi	3968 kPa

TABLE 2

EXPERIMENTAL MIX DESIGNS

	ITEM	MAGNITUDE	
		(lbs/yd^3)	(kg/m^3)
All Mixes	Cement	620	368
	Coarse Aggregate	1814	1076
	Fine Aggregate	1196	710
	Water Needed for Hydration	152	90
Dow Latex Modifier A	Percent Solid = 46 - 49 ≈ 47 Amount of Liquid Required (includes 152 lbs/yd^3 of water for hydration) = 152/0.53	287	170
Dow Latex Modifier B	Percent Solid = 48 Amount of Liquid Required (includes 152 lbs/yd^3 of water for hydration) = 152/0.52	292	173
PC 10 Epoxy	Amount of Epoxy Required	129	76.5
	Part A = 74.1%	95.6	56.7
	Part B = 25.9%	33.4	19.8
	Water Needed for Hydration	152	90

TABLE 3

FRESH AND HARDENED CONCRETE
TEST RESULTS FOR ALL MIXTURES

CONCRETE MIXTURE	FRESH CONCRETE					HARDENED CONCRETE							
	AIR CONTENT	SLUMP		UNIT WEIGHT		SPECIFIC GRAVITY			UNIT WEIGHT (BULK)		PERMEABLE VOIDS (%)	ABSORPTION MOISTURE (%)	AIR CONTENT (%) LINEAR TRAVERSE	PERMEABILITY (cm/min)
		(in.)	(mm)	(lbs/ft^3)	(kg/m^3)	SAT. SUF. DRY	BULK	APPARENT	(lbs/ft^3)	(kg/m^3)				
Dow Latex Modifier A	3.1	2.4	6.1	151.8	2432	2.40	2.36	2.47	147.3	2360	4.6	1.90	1.92	0.0
Dow Latex Modifier B	2.8	1.4	3.6	153.0	2451	2.46	2.42	2.50	151.0	2419	7.1	1.51	1.94	0.0
PC 10 Epoxy	4.1	1.2	3.0	149.5	2395	2.41	2.33	2.52	145.4	2329	7.6	3.29	2.73	1.19×10^{-7}
Class AA PCC	4.2	2.4	6.1	148.5	2379	2.44	2.30	2.68	143.5	2299	14.0	6.10	3.06	2.91×10^{-7}

they were cured wet for 13 more days (making a total of 14 days wet cure). The freeze-thaw cycles were started immediately after the curing was discontinued. Prior to placing in the freeze-thaw chamber, the initial, longitudinal, resonant frequency of each beam was measured using a sonometer.

The freezing and thawing test ran continuously 7 days a week and continued until each specimen reached 300 cycles of freezing and thawing or until the relative modulus of elasticity diminished to 60 percent of the initial modulus -- whichever occurred first.

Permeability

A special apparatus was designed and built to measure permeabilities (Figure 1). The apparatus is similar to that used by Virginia Highway Research Council for permeability studies on aggregates *(7)*.

The sample to be tested was cut from a circular cylinder 4-in. (100-mm) in diameter, had parallel ends, and had a thickness of 1 and 1/8 in. (29 mm). This sample was mounted in a stainless steel ring (Figure 2), and the margin between the walls of the ring and sample was sealed with epoxy resin to prevent leakage. Care was taken to be sure that the sample was free of cracks and excessively large voids.

The procedure for testing was to vacuum saturate the sample with distilled water, first allowing enough time for all air to escape. The sample was then surrounded with water on both sides by filling the inlet and outlet sides of the chamber housing it with boiled, distilled water. A capillary tube was connected to the outlet side and filled partially with distilled water. With pressure applied from a nitrogen tank to the inlet side, the flow rate could be measured by monitoring the rise in the capillary tube. Measurements were made repeatedly until three consecutive, consistent readings were obtained. Permeability was calculated for each reading and an average was obtained. A detailed explanation, schematic of the apparatus, and data sheet of the permeability test are included in APPENDIX B.

Corrosion Protection

Two types of laboratory tests of corrosion potential were conducted to evaluate the effectiveness of the various types of concretes in preventing corrosion. The first test was done on blocks (slabs) and the other on beams.

In the first test, concrete test specimens were 14 by 14 by 3.75 in. (356 by 356 by 95 mm). In each test block, two No. 5 reinforcing bars were centered. One bar was positioned 1 in. (25 mm) below the surface, the second 2.5 in. (64 mm) below the surface. A copper wire was then soldered to the reinforcing bar nearest the surface and extended through the mold.

Four concrete designs, Class AA conventional, Latex Modifier A, Latex Modifier B, and PC-10 Epoxy concretes were used. Three blocks were molded from each mix -- making a total of twelve test specimens.

The concrete was placed in three layers; each later was mechanically vibrated. After finishing the
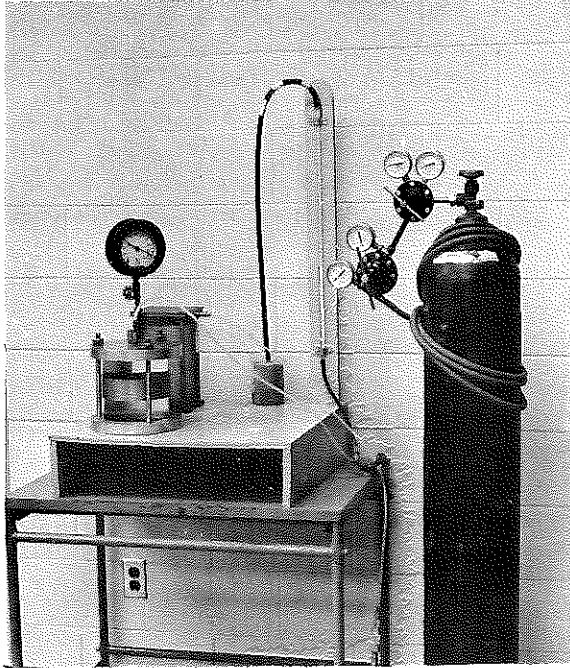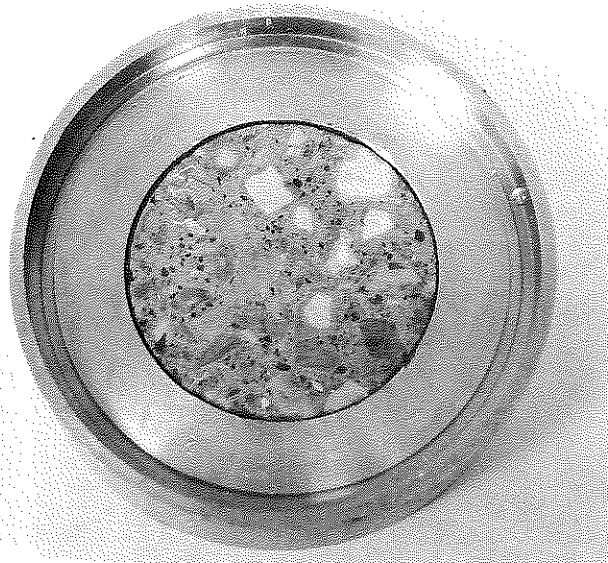
Figure 1.   Permeability Apparatus.

Figure 2.   Permeability Sample Mounted in Test Ring.

top surface, the specimens were covered with wet burlap and allowed to cure in their molds for 24 hours. They were then removed and cured in a moisture room for the remainder of a 28-day curing period. A paraffin wall was then constructed around the perimeter of each specimen to provide a pool with a depth of 0.5 in. (12.7 mm) for 3-percent NaCl solution (Figure 3).

The specimens were placed on a concrete floor in the laboratory and covered with the salt solution; the solution was renewed from time to time. Potential readings of each specimen were made and recorded weekly. The electrical potentials of the reinforcing steel were referenced to a saturated, copper-copper sulfate half-cell. The potential readings were made with a Hewlett Packard, d.c., null voltmeter connected to the saturated, copper-copper sulfate half-cell and the steel in the test block. In making readings, the saturated, copper-copper sulfate electrode probe was placed on a test block at three locations to determine an average reading.

For the beam test, twelve concrete beams measuring 4.5 by 2.5 by 15 in. (114 by 64 by 380 mm) were molded (Figure 4). Three beams were molded from each of the four concretes. A No. 4 reinforcing bar was placed in each test beam so that a minimum of one inch cover was provided. Each reinforcing bar was thoroughly cleaned by sandblasting prior to the molding of the beams. The concrete was placed in three layers and mechanically vibrated. After finishing, the beams were covered with wet burlap and cured 24 hours in their molds. The beams were then immersed in water at a temperature of approximately 73 F (23 C) for the remainder of the 28-day curing period. After curing, the specimens were immediately transferred to a tank containing a 3-percent solution of sodium chloride. The NaCl solution was maintained at 3-percent and a depth of 5 in. (127 mm) throughout the experiment. A plywood cover was placed over the tank to reduce evaporation and aid in the maintenance of the 3-percent NaCl solution.

Electrical connection to each rebar was made with spring clips. A set of 12 conductors connected each rebar to a central selector switch. This switch was connected to a Hewlett Packard, d.c., null voltmeter. The switch allowed reading the half-cell potential of the reinforcing bars in all specimens without connecting and disconnecting circuits. The half-cell potentials of the rebars were referenced to a saturated, calomel half-cell. Potential readings were taken several times weekly.

Workability

Slump tests were conducted on mixtures immediately after mixing and at 3-minute intervals thereafter.
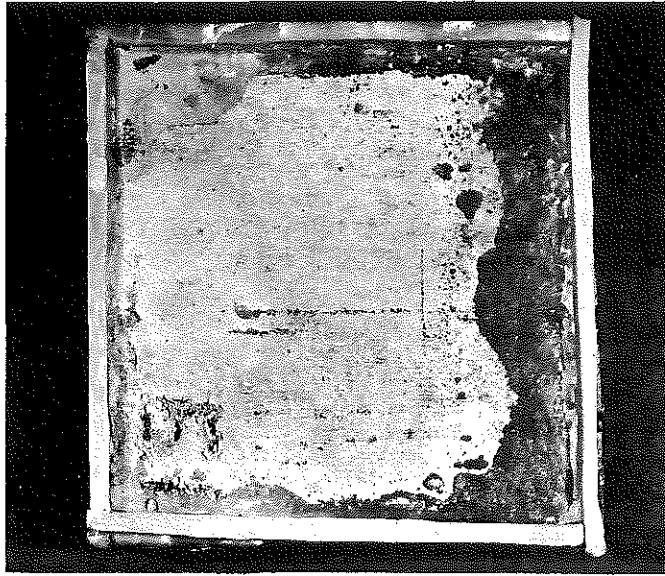
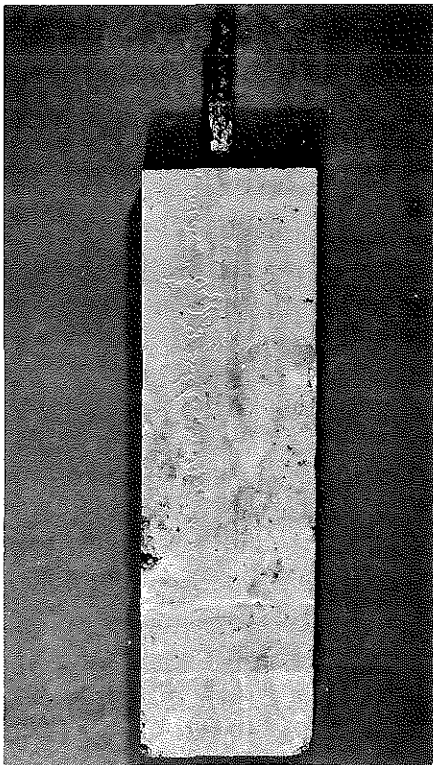Figure 3.   Corrosion Test Block With Paraffin Wall.
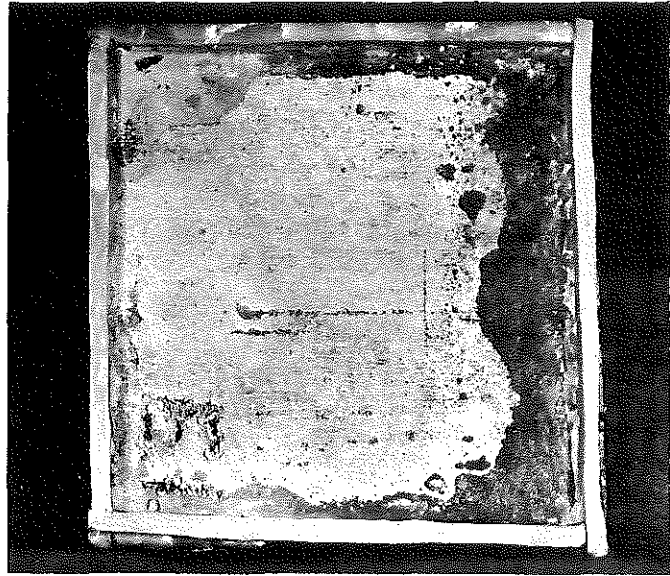

Figure 4.   Corrosion Test Beam.

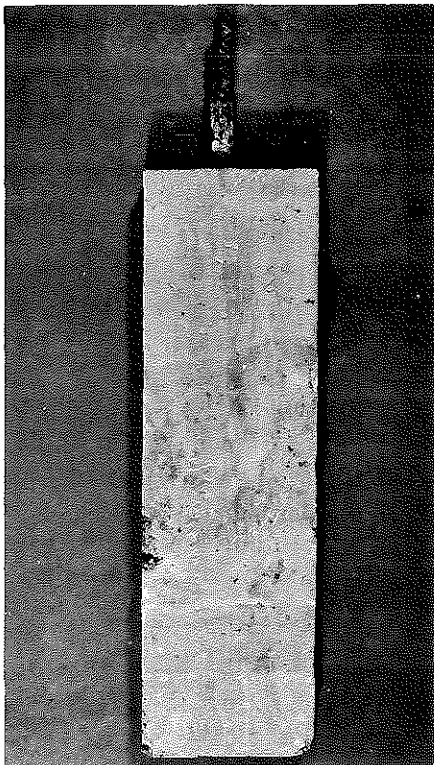Figure 3.   Corrosion Test Block With Paraffin Wall.

Figure 4.   Corrosion Test Beam.

RESULTS

Strength

Results of the compressive and flexure strengths are listed in Table 4. Each listed value represents an average from three specimens.

It is apparent from Figure 5 that all experimental mixtures exhibited higher compressive strengths than the control concrete. Dow Latex Modifier B resulted in the highest compressive strength throughout the testing period; PC-10 epoxy and Dow Latex Modifier A gave respectively lower strengths.

All experimental mixtures had significantly higher flexural strengths than the control mix; this is shown in Figure 6. The modulus of rupture and compressive strength for the experimental mixtures are related in the same manner as with normal portland cement concrete. This relationship is shown graphically in Figure 7. The relationship for predicting the modulus of rupture from compressive strength is given by

$$f_{r'} = K\sqrt{f_{c'}},$$

where $f_{r'}$ = modulus of rupture,

             $f_{c'}$ = compressive strength, and

             K = constant.

The value of K is usually between 8 and 10. The average value of K for the Class AA control mixture was 15.5 (15.42 - 15.72); these average values were calculated from test data and plotted in Figure 7. The average values of K for the other mixtures are:

Dow Latex Modified A   18.46 (17.84 - 18.78)

Dow Latex Modified B   18.18 (17.74 - 18.78)

PC-10 Epoxy   19.86 (19.5 - 20.15)

Resistance to Rapid Freezing and Thawing

The test data indicate that all beams endured the 300 cycles of freezing and thawing specified by ASTM C 666 without failure. Further evaluation of the test results follows.

During the progress of the freeze-thaw tests, the specimens were periodically removed and tested for fundamental resonant frequency, from which the relative dynamic modulus was calculated. Figure 8 shows the average relative dynamic modulus of elasticity (Table 5) plotted against time expressed as numbers of cycles of freezing and thawing for the various mixtures. It should be noted that a downward trend of the curves indicates deterioration of the specimens. There is a downward inclination in the Dow Latex Modifier curves between 160 and 240 cycles after which they start leveling off as they approach 300 cycles. There is no apparent reason for this downward trend (no cracking or scaling). It could be attributed to several factors which will be discussed later. The other specimens performed very well.

TABLE 4

COMPRESSIVE AND FLEXURE STRENGTH
TEST RESULTS

CONCRETE MIXTURE	NUMBER OF DAYS	COMPRESSIVE STRENGTH		FLEXURE STRENGTH	
		(psi)	(MPa)	(psi)	(MPa)
	3	4192	28.90	1263	8.71
Dow Latex	7	5117	35.28	1381	9.52
Modifier A	28	6532	45.04	1496	10.31
	90	6948	47.91	1950	13.44
	3	5440	37.51	1375	9.48
Dow Latex	7	6408	44.18	1375	9.48
Modifier B	28	7210	49.71	1563	10.78
	90	8952	61.72	1850	12.76
	4	4616	31.83	1325	9.14
PC 10 Epoxy	7	6031	41.58	1620	11.17
	28	7269	50.12	1680	11.58
	90	8177	56.38	1740	12.00
	3	3684	25.40	950	6.55
Class AA PCC	7	4525	31.20	1043	7.19
	28	6019	41.50	1212	8.36
	90	6349	43.78	1275	8.79

TABLE 5

AVERAGE DYNAMIC YOUNG'S MODULI
OF ELASTICITY FOR ALL MIXTURES

CLASS AA PCC			LATEX MODIFIER A			LATEX MODIFIER B			PC 10 EPOXY		
DF** = 70.53			DF = 80.76			DF = 70.75			DF = 82.85		
	DE*			DE			DE			DE	
CYCLE NUMBER	psi (x10^{-6})	MPa (x10^{-4})	CYCLE NUMBER	psi (x10^{-6})	MPa (x10^{-4})	CYCLE NUMBER	psi (x10^{-6})	MPa (x10^{-4})	CYCLE NUMBER	psi (x10^{-6})	MPa (x10^{-4})
0	6.95	4.79	0	7.07	4.87	0	7.29	5.03	0	5.72	3.94
24	6.65	4.58	16	7.26	5.01	25	6.79	4.68	73	5.70	3.93
46	6.60	4.55	63	7.27	5.01	57	6.74	4.65	129	5.61	3.87
78	6.41	4.42	114	7.08	4.88	81	6.69	4.61	189	5.36	3.70
102	6.39	4.41	138	7.22	4.98	101	6.69	4.61	266	5.13	3.54
134	6.34	4.37	160	7.12	4.91	130	6.61	4.56	299	4.76	3.28
158	6.09	4.20	192	6.82	4.70	151	6.52	4.50			
191	5.89	4.06	216	6.74	4.65	182	6.52	4.50			
225	5.38	3.71	248	6.55	4.52	233	5.80	4.00			
249	5.38	3.71	272	6.22	4.29	264	5.47	3.77			
269	5.38	3.71	306	5.60	3.86	293	5.19	3.58			
299	4.92	3.40				300	5.12	3.53			

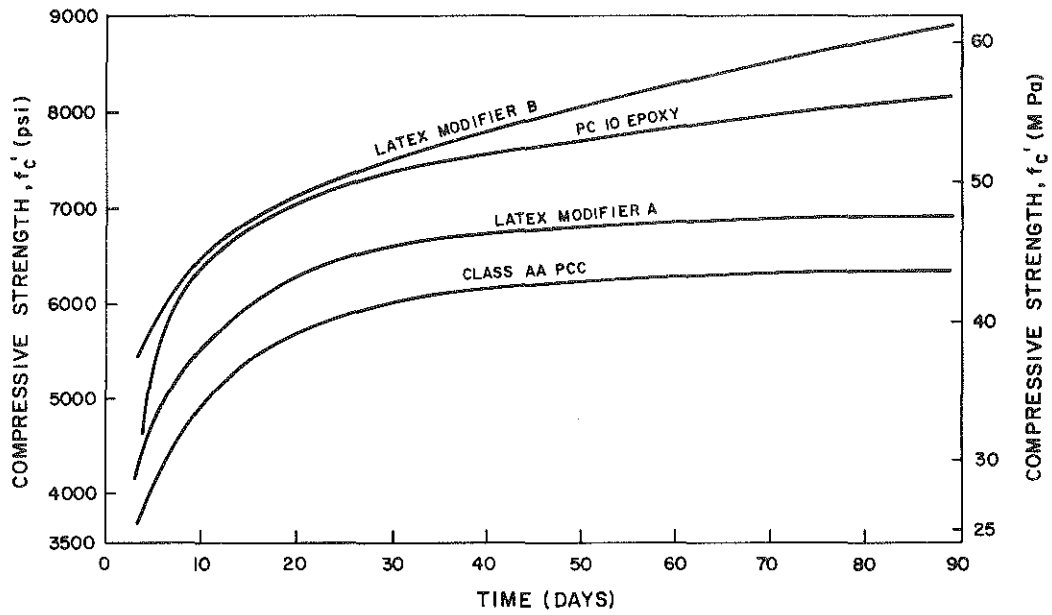*DE = Dynamic Young's Modulus of Elasticity
**DF = Durability Factor

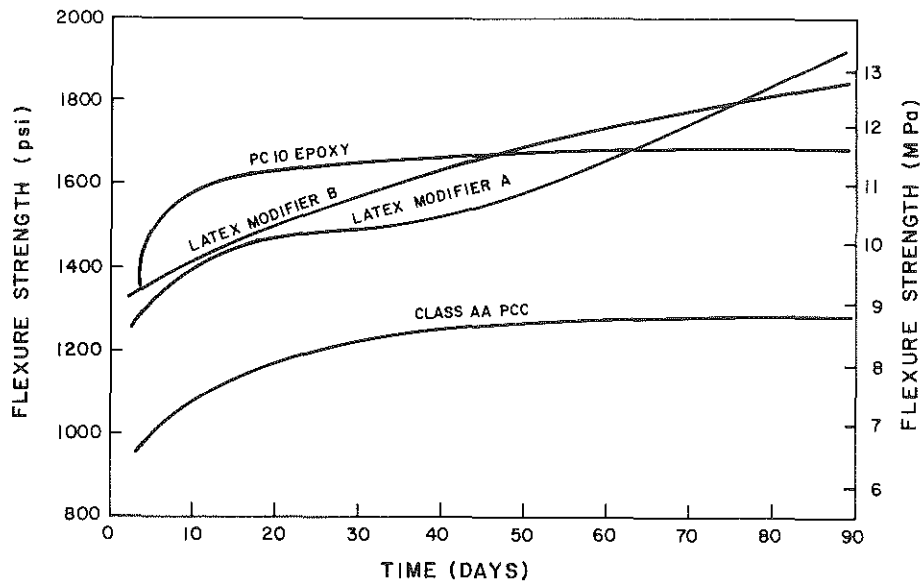Figure 5.   Compressive Strength Versus Time for All Mixtures.

Figure 6.   Flexure Strength Versus Time for All Mixtures.
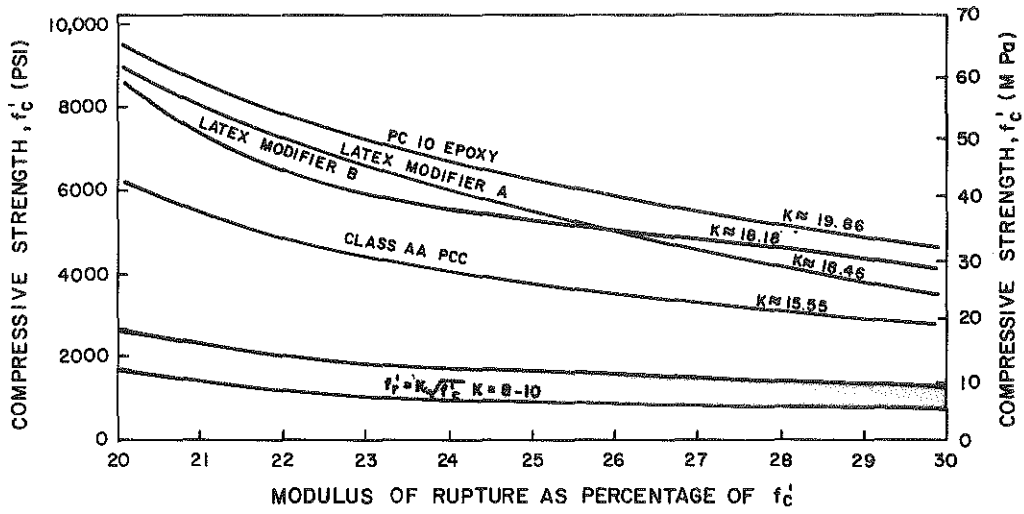
Figure 7. Relationship between Compressive Strength and Modulus of Rupture for All Mixtures.
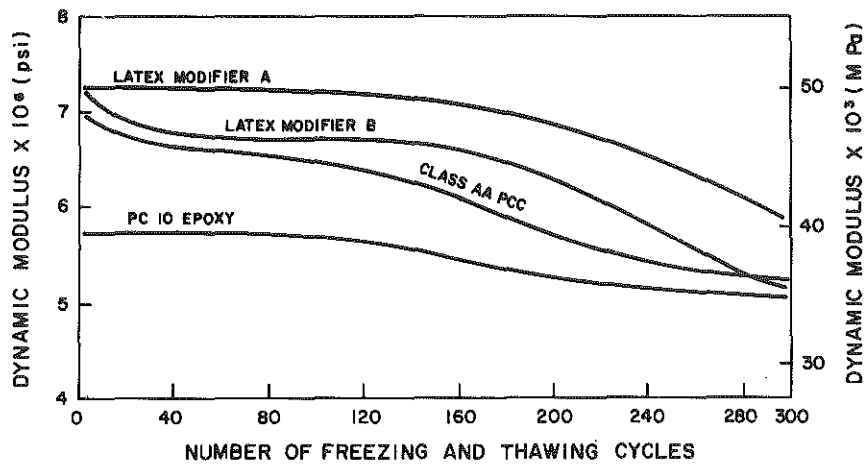

Figure 8. Average Dynamic Modulus of Elasticity Versus Time (Number of Cycles of Freezing and Thawing).

Since all testing was discontinued after 300 cycles of freezing and thawing, only a limited comparison could be made using the average durability factors. Figure 9 is a bar graph of average durability factors deduced from all specimens in each group.

Permeability

Table 3 shows the permeabilities for the four different concretes included in this study. The latex mixtures had the lowest permeability (measured zero for all specimens). Also evident is the fact that the control mixture (Class AA concrete) had the highest permeability; more than twice the permeability of PC-10 epoxy concrete.

Table 3 reveals that there ·is an evident correlation between permeability and absorption on one hand and permeability and air content on the other. The latex modifier specimens had zero permeability, low absorption, and low air content; whereas the control, Class AA concrete specimens had the highest permeability, absorption, and void content.

Air Void Content

This void content does not include capillary passages, voids in the aggregate, or any other submicroscopical openings. The voids are usually larger than 2 μm in diameter and are entrapped, entrained, or generated.

In an effort to produce a no-void concrete, no air entrainment was attempted in the experimental mixtures. Class AA concrete, which is the control mix, was entrained for 6 ± 2 percent air by volume. The air contents of all fresh concretes were measured shortly after mixing, in accordance with ASTM C 231, and are shown in Table 3.

In freshly mixed concrete, voids could serve two purposes. When distributed uniformly in the form of air bubbles, they tend to fluidize the fresh concrete. The presence of air bubbles could also help reduce the amount of water in the mixture, decrease the water-cement ratio, and enhance strength *(2)*. An excessive percentage of air content (5-8 percent) could, however, be detrimental to strength and durability.

In the hardened concretes, the air content was measured on sawed and polished surfaces using the linear traverse method according to ASTM C 457. By this method the void and solid volumes are microscopically examined along series of regularly spaced lines, and the percentage of void spaces is determined. The air content for the hardened concrete from each mixture is shown in Table 3. Each value listed is the average void content of three specimens.

It is readily recognizable that all Dow latex and epoxy concretes had lower air void contents than Class AA concrete. Latex Modifier A concrete exhibited the lowest measured air content (1.92 percent). Class AA concrete exhibited the highest air void content (3.06 percent). It may be noted that

Figure 9.   Comparision of Average Durability Factors.
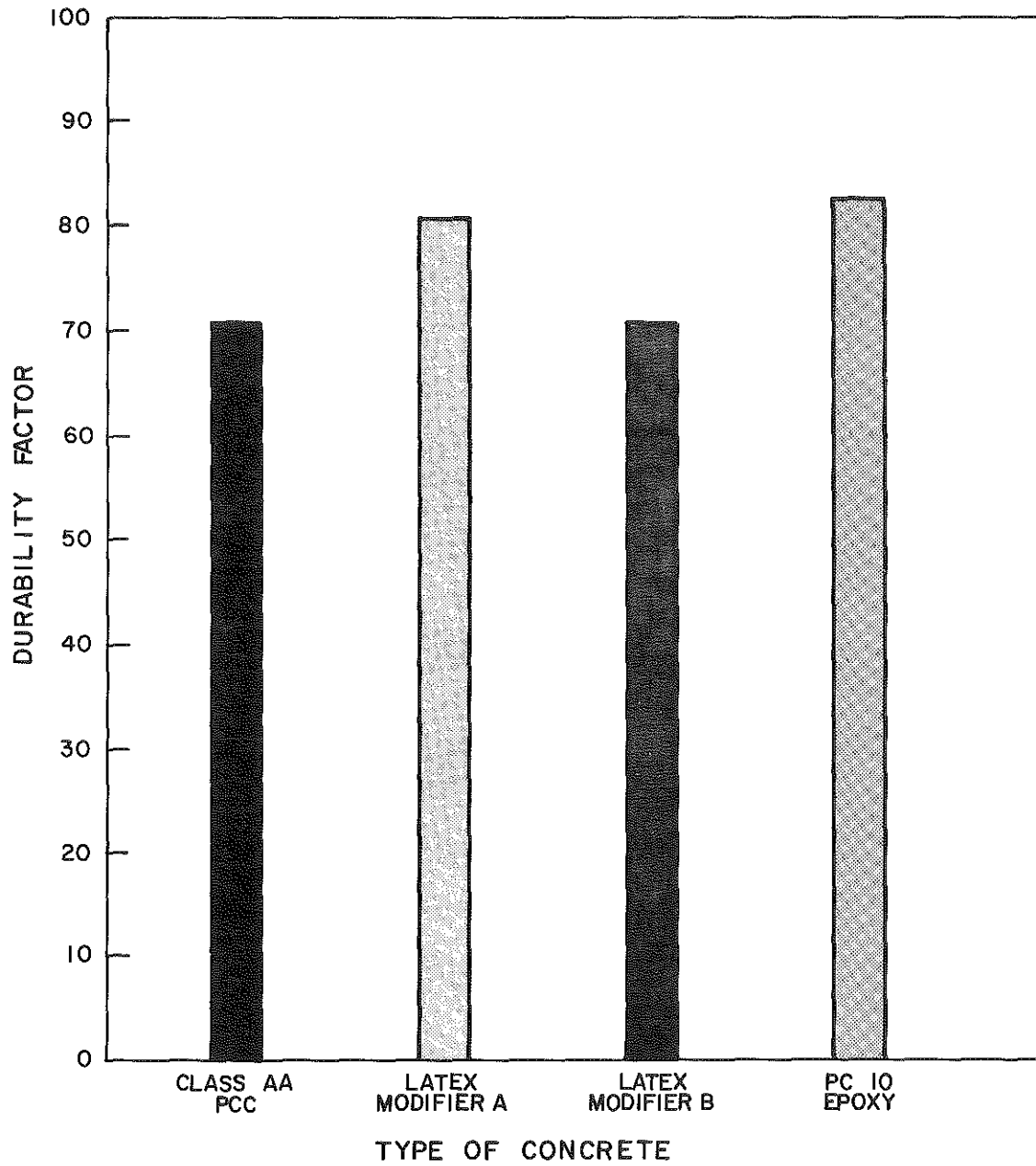
approximately 3 percent air was lost during the molding of the Class AA concrete.

Corrosion Protection

The half-cell potential readings of the reinforcing steel on the ponded blocks varied considerably during the 10 months of the corrosion potential test. The reinforcing steel had very high half-cell potential readings when referenced to a saturated, copper-copper sulfate electrode. Such unusually high readings would tend to indicate a very active corrosion process occurring on the surface of the reinforcing steel. No cracking or rust stains were observed on the surface of the test blocks, however. At the end of the 10-month test period, several of the concrete test blocks were broken in order to inspect the embedded steel. No corrosion was found on any of the reinforcing bars. A plot of potential versus time is shown in Figure 10.

One probable reason for the high potential readings could have been the fact that the reinforcing steel was not sandblasted prior to placement in the concrete. Sandblasting would have removed any oxide film which may have been present on the steel bars. The presence of an oxide film may have caused the readings to appear higher than normal. No other explanation could be found to explain the high potential readings. The test was discontinued and another series of tests on beams was initiated.

Potential readings were made on the beams for a period of 10 months. The results from this test were satisfactory, and a plot of potential versus time is shown in Figure 11.

The potential curves for this test (Figure 11) showed a decreasing half-cell potential the first two months of the test. Initial, relatively high, readings indicate active corrosion. This was due primarily to corrosion on the exposed portion of the rebar. The corrosion was caused by moisture during the curing process. After several months, the active corrosion of the exposed rebar changed to a passive state and resulted in a passive half-cell potential (lower than .27 v, referenced to a calomel electrode) *(8)*. During the next 7 to 8 months of the test, the Latex Modifier A, Latex Modifier B, and PC-10 epoxy concrete specimens demonstrated passive and nearly constant half-cell potentials; there was almost no tendency to increase. However, Class AA, conventional concrete specimens showed a small increase in potential during the last 6 months of the test. The increase in potential of Class AA concrete specimens was probably due to the slow penetration of the salt solution to the rebar. Test data after the 10-month period strongly indicated that the potential in the Class AA specimens was changing to an active state while staying passive in the others. Thus far, corrosion potential measurements are subject to empirical interpretation; the electrochemical basis has not been thoroughly established.

Workability

There appears to be a slight difference in workability between the different mixtures having the same slump. The latex and epoxy mixtures had a rubbery consistency; more effort was required to

Figure 10.   Half-Cell Potential Versus Time for All Mixtures on Test Blocks
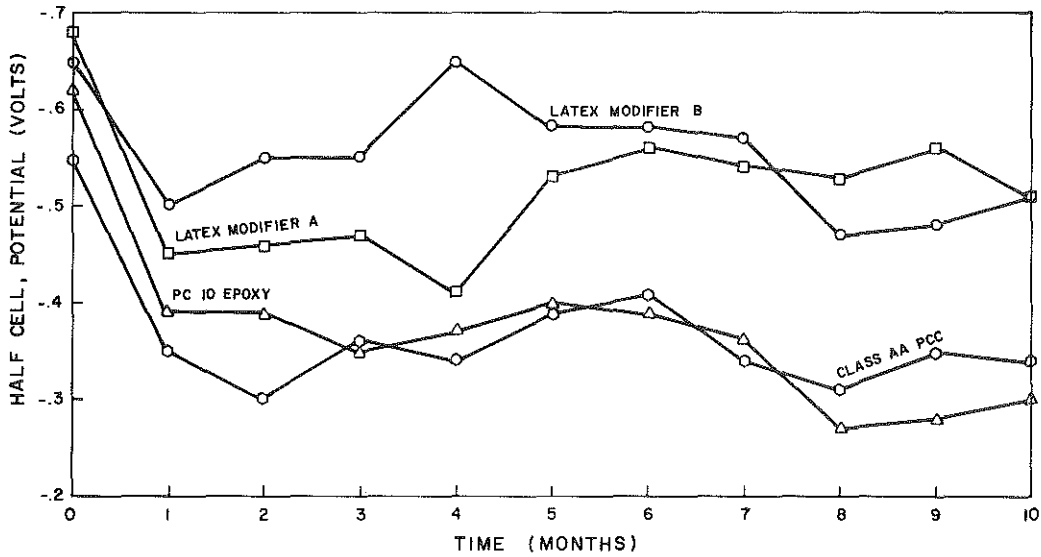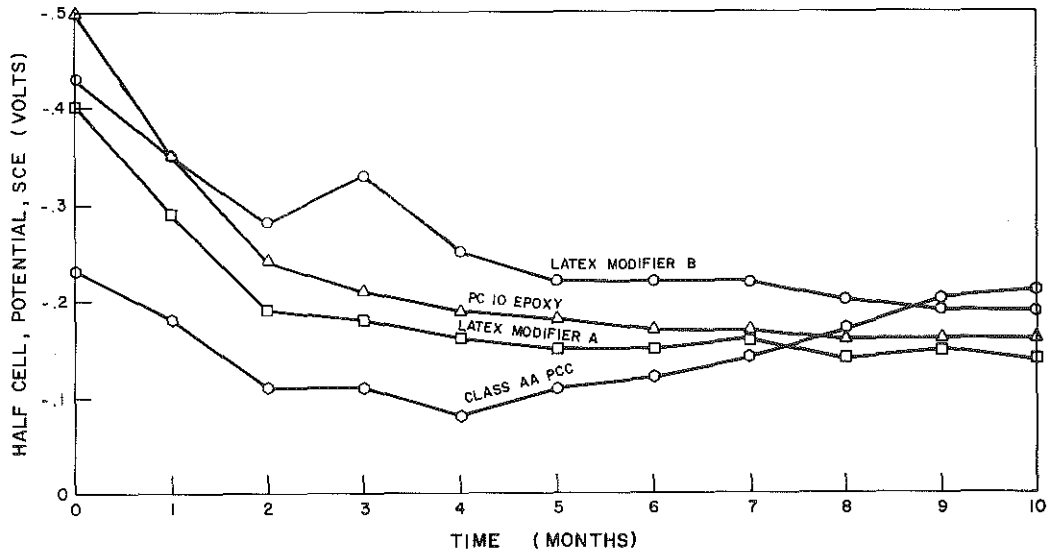Referenced to Copper-Copper Sulfate Half-Cell.

Figure 11.   Half-Cell Potential Versus Time for All Mixtures on Test Beams
Referenced to Calomel Half-Cell.

work latex and epoxy concretes than the Class AA concrete.

Slump-loss test results are shown in Figure 12. All mixtures had an acceptable initial slump of 2 1/2 to 3 1/2 in. (63.5 to 88.9 mm). Latex Modifier A concrete could be worked up to 30 minutes without revibration and up to 40 minutes upon revibration. Latex Modifier B concrete stiffened more rapidly and reached a slump of 1 in. (25.4 mm) within 20 minutes. Modifier B concrete responded to revibration after 30 minutes but could not be worked after 40 minutes. PC-10 epoxy concrete mixture maintained a 2-in. (50.8-mm) slump up to 15 minutes after mixing; between 20 and 30 minutes, the slump diminished rapidly until the mix was unworkable after 30 minutes. Revibration was not very effective in improving the workability of epoxy concrete. More effort was needed to finish epoxy concrete than the latex concretes. Even though the slump-loss test could be interchangeably used to measure both workability and consistency for concretes containing the same materials, it may not be a good indication of workability in the case of latex and epoxy concretes.

DISCUSSION AND CONCLUSIONS

Emphasis in this report, as suggested by the title, has been directed toward reduction of voids in a concrete mixture. Figure 13 shows the solids-voids relationships for Class AA concrete and a polymer concrete. It is assumed here that a water-cement ratio of 0.244 is needed for hydration; any water above that amount adds to the void space in the hardened concrete. None of the concretes were entirely voidless, but there was a very significant decrease in void space (actual void space is 1.9 percent for Dow Modifier A compared to 12 percent for Class AA concrete). Other studies (3) on aggregates have shown that a 4-percent absorption, together with near saturation, gives nearly a 100-percent probability of rupture in four cycles of freezing and thawing. The low probability or likelihood of saturation together with a low probability of damage at 1.9-percent porosity (0.8-percent absorption) provide a high degree of assurance against deterioration by freezing and thawing. In the case of Class AA concrete, the probability of deterioration could be high if saturation occurred; there, resistance to freezing and thawing is determined by the improbability of saturation.

The mere number of rapid or slow freezing and thawing cycles which a concrete specimen is able to withstand before saturation becomes critical is probably not as significant as the time-duration of the conditions causing absorption of water and eventual saturation. That is to say, concrete which does not absorb water could withstand any number of cycles of freezing and thawing. So, up to the point of critical saturation, the number of cycles depends upon the freeze-thaw process schedule. This applies to both normal and polymer concretes.

There are other factors which could affect the performance of polymer concretes exposed to heat
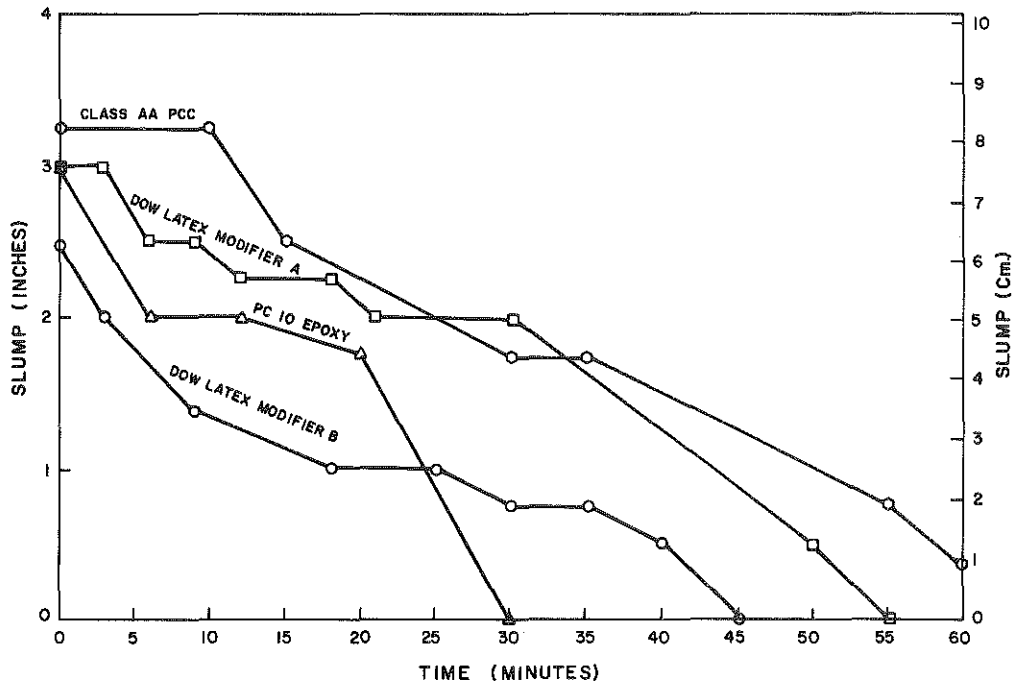
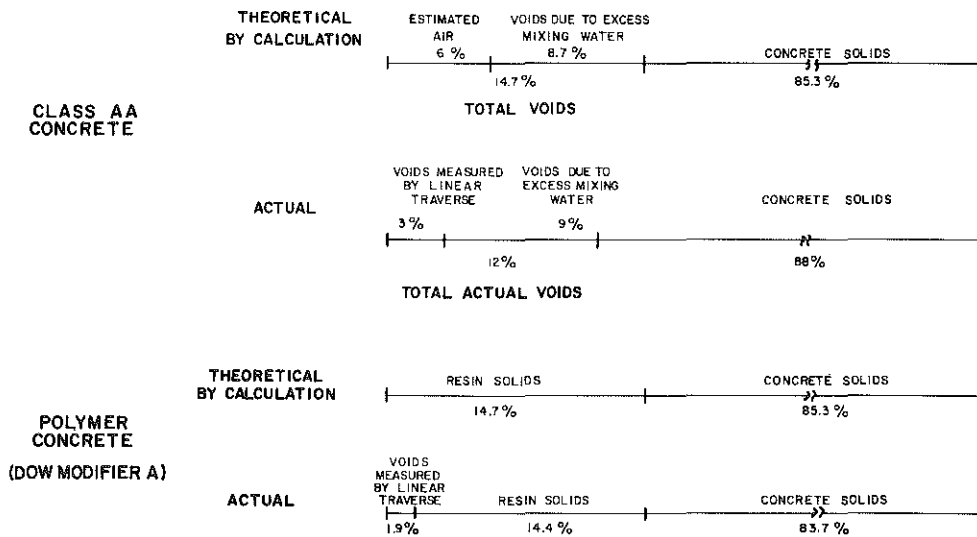Figure 12.   Slump Loss Characteristics, All Concretes.

Figure 13.   Voids-Solids Relationship, Class AA and Dow Latex Modifier A Concretes.

and freezing and thawing. One which needs to be explored extensively is the thermal expansions and contractions of resins, plastics, and oils in the confined, rigid spaces in the concrete. Plastics, resins, and oils have a higher coefficient of thermal expansion than concrete. This fact could have contributed to the apparent inconsistency in the decrease in dynamic modulus of elasticity of the Dow Modifier mixtures during freezing and thawing. It would have been very beneficial to this study to have cycled at least a few specimens of the polymer concretes up to temperatures of 150 F (66 C) or higher. However, this remains an item to be considered in any ensuing researches on concretes of the type demonstrated in this study.

Another area of research and improvement could be the stability of the emulsions of asphalts and oils in the presence of $Ca(OH)_2$. It is very unfortunate that no success was achieved in the use of these two materials, for they are more economical than polymers. The instability of asphalt and oil emulsions upon mixing of the concrete suggests that either a new breed of emulsifying agents is badly needed, or else new mixing procedures should be employed. There is reason to believe that an instantaneous type of mixing method that does not necessitate continuous stirring or shearing of the ingredients might result in successful apshalt and oil concrete mixtures. It is also doubtful that polymer concretes could be successfully produced in large quantities without the use of special mixing equipment, which means that the mixing procedures of polymers, asphalts, and oils is a worthy item to be considered in any ensuing research.

REFERENCES

1. Bogue, R. H.; The Chemistry of Portland Cement, Reinhold, 1955; p 529.

2. Havens, J. H.; *An Investigation of Core-Strengths of a Portland Cement Concrete Pavement*, Division of Research, Kentucky Department of Highways; December 1969.

3. Havens, J. H.; *Freeze-and-Thaw Phenomena in Concretes and Aggregates*, Division of Research, Kentucky Department of Highways, March 1970.

4. Havens, J. H.; *Thermal Analysis of the Freeze-Thaw Mechanism in Concrete*, Bulletin No. 59, Engineering Experiment Station, University of Kentucky, March 1961.

5. Locker, F. W.; *Stoichiometry of Tricalcium Silicate Hydration*, Symposium on Structure of Portland Cement Paste and Concrete, Special Report 90, Highway Research Board, 1966; p 300-308.

6. Powers, T. C. and Brownyard, T. L., *Studies of the Physical Properties of Hardened Portland Cement Paste*, Bulletin 22, Portland Cement Association, 1948, p 972-992.

7. Sherwood, W. C., Huang, J. H., Dudash, J. J. and McGhee, K. H.; *Porosity and Permeability Studies of Virginia Aggregates*, Virginia Highway Research Council, June 1972.

8. Stratfull, R. F.; *Half-Cell Potential and the Corrosion of Steel in Concrete*, Materials and Research Department, California Division of Highways, Sacramento; November 1970.

9. Troxell, G. E., Davis, H. E., and Kelly, J. W., Composition and Properties of Concrete, Second Edition, McGraw-Hill, 1968; p 135.

10. Winding, C. C. and Hiatt, G. D.; Polymeric Materials, McGraw-Hill, 1961; p 262-268.

APPENDIX A

SPECIAL PROVISION NO. 35-B FOR
CLASS AA CONCRETE

KENTUCKY DEPARTMENT OF HIGHWAYS

SPECIAL PROVISION NO. 35-B
CLASS "AA" CONCRETE

This Special Provision shall be applicable when indicated on the plans, in the proposal, or in the bidding invitation, and shall supersede any conflicting requirements of the Department's 1965 Standard Specifications. Section references herein are to the Standard Specifications.

- -

I. DESCRIPTION

This work shall consist of the furnishing and construction of Class "AA" Concrete in bridge superstructures in accordance with the applicable requirements of Sections 403, 404, and 411, except as otherwise provided.

II. MATERIALS

All ingredients of the Class "AA" Concrete shall comply with the material requirements of Section 403.

III. CONSTRUCTION METHODS

The construction methods shall conform to the applicable requirements of the Standard Specifications, and, in addition, the Class "AA" Concrete shall conform to the following requirements:

Coarse Aggregate Size..........	No. 57.
Free Water Content.............	Max. of 5 gal./bag cement.
Cement Content.................	Min. of 6.6 bags/cu. yd. concrete.
Air Content....................	6 ± 2 per cent by volume.
Slump..........................	Max. of 2", with a ½" plus tolerance with vibratory placement methods. Max. of 2½", with a 1" plus tolerance with non-vibratory placement methods.
Expected 28-day Compressive Strength......................	4500 pounds/sq. in. (See page 2 for details)
Modulus of Rupture.............	Min. of 575 pounds/sq. in. for removal of falsework. Min. of 625 pounds/sq.in. for opening to traffic.

Truck Mixers................ When truck mixers are used,
the concrete shall be mixed
a minimum of 70 revolutions
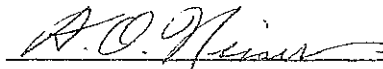at the batching plant.

28-day Compressive Strength Tolerances

In accordance with a method of ASTM C94,
the adequacy of the concrete will be
determined as hereinafter specified. Not
more than 20 per cent of the strength tests
shall have values less than 4500 psi, and
the average of any 6 consecutive strength
tests shall be equal to or greater than
4500 psi.

When the number of tests made is six or less,
the average of all the tests shall be equal
to or greater than the values shown in the
following table:

No. of Tests	Required Average Strength of Consecutive Tests
1	3555
2	4050
3	4230
4	4365
5	4455
6	4500

APPROVED JANUARY 15, 1969

A. O. NEISER
STATE HIGHWAY ENGINEER

APPENDIX B

PERMEABILITY TEST PROCEDURE,
SCHEMATIC, AND DATA SHEET

PERMEABILITY TEST PROCEDURE

1. Scrape all epoxy from sample ring and clean ring thoroughly with methyl ethyl ketone (MEK).

2. Cover bottom surface of ring, including hole, using glass fiber tape.

3. Cover top surface of ring with glass fiber tape and trim neatly around hole so that sample can be inserted.

4. Cut a sample approximately 1 1/8 in. (28.6 mm) thick from a 4-in. (101.6-mm) diameter concrete core. Measure thickness and diameter at several points, record and average. Calculate 'C' (see Data Sheet).

5. Cover both ends of the sample thoroughly with glass fiber tape.

6. Mix epoxy.

7. **Wipe sample hole in ring again with MEK; then being very careful not to touch inside the hole,** apply a thin coat of epoxy to sample hole.

8. Apply thin coat of epoxy to edge of sample, **being sure to fill all voids** along bonding surface.

9. Place sample into ring and place ring on circular plywood support.

10. Move sample around and add epoxy until all air is evacuated from between sample ring and sample.

11. Allow epoxy to set overnight.

12. Clean all O-rings, O-rings grooves, and plexiglass cylinders. Coat O-rings and cylinders with thin coat of silicone stopcock grease and assemble apparatus, being sure that outside connectors are aligned directly over each other. **Tighten the nuts securely by hand. Never use wrench or pliers on brass nuts.** If apparatus should leak when pressure is applied, disassemble and reclean. Leakage is normally caused by foreign object trapped in O-ring groove.

13. Fill upper chamber with distilled water by placing vacuum hose to outside connector and hose to water bottle to center connector and applying vacuum. Tilt chamber so that the vacuum connector is the highest point of the chamber and shake gently so that all air possible is removed.

14. Invert apparatus and connect hose from bottom of water reservoir to **center hole** on bottom of permeability chamber. **Place hose in water chamber first and allow water to run out of hose before connecting to permeability chamber, thus eliminating air from hose.**

15. Connect air hose to top of water reservoir and apply 95 psig (655 kPag) pressure. Place vacuum hose to **outside hole** in top chamber of permeability apparatus and tilt apparatus such that the vacuum hole is at the highest point of the chamber. Apply vacuum and watch for leaks in epoxy seal. If no leaks appear, allow sample to saturate for 24 hours under pressure and vacuum. If evidence of a leak does appear, **release pressure and vacuum,** disconnect hose, and invert chamber. Connect vacuum hose to upper chamber (containing water) and attach air hose directly to bottom of chamber.

Apply 95 psig (655 kPag) pressure and full vacuum and watch for air bubbles. If bubbles are coming through the sample but **not through the epoxy**, set the test up again and resume 24-hour saturation. If, however, the **bubbles are coming through the epoxy seal**, remove sample from ring according to procedure which follows (Step 23) and start test over.

16. After 24 hours, top chamber will be nearly filled with water. At this time observe sample to see if air is still being released. If air bubbles are still escaping from sample, allow the sample to saturate for another 24 hours. Repeat this step as required until sample is saturated. When no bubbles are observed at the end of saturation period, continue with test.

17. In most cases, the top chamber will be heavily coated with air bubbles so it must be drained. To accomplish this, **release pressure and vacuum** and disconnect all hoses. Invert chamber and place hose to sink to one connector and air hose to the other. Apply air pressure and drain water from bottom of chamber.

18. Disconnect hoses and invert chamber. Refill empty chamber as before (Step 13), except this time use distilled water which has been heated nearly to the boiling point and stirred vigorously to remove all dissolved air.

19. Invert chamber and connect hose from water reservoir as before (Step 14) and apply 95 psig (655 kPag) pressure to water reservoir.

20. Place connector from burette tube to the outside connector on the top chamber of the permeability apparatus and tilt chamber so that the outside hole is at the high point of the apparatus. Take inlet hose from vacuum water jar off the vacuum nozzle and place it on the compressed air nozzle. Open air valve slightly until water flows freely from quick connect. When all air has been purged from the vacuum jar hose, connect this hose to the center connector of the top chamber, thus forcing water through the burette hose and into the burette tube. **Remove all air from the burette tube hose and valve by tapping on hose while water is flowing.** Close burette tube valve and allow water to rise nearly to the top of the burette. **Shut off air, allow a few millimeters of water to flow back into vacuum jar,** then remove vacuum jar hose from center connector. At this point, all air should be removed from the system. If large bubbles of air should remain in the system, repeat Steps 17 through 20 on either chamber as needed.

21. Take reading of water level in water reservoir. Open burette tube valve and set water level in burette at approximately the reading taken on the water level in the water reservoir (+0.5 ml or -1.0 ml).

22. Record time, water level in burette, and water pressure at beginning of test. Allow 3 to 6 ml of water to pass through the sample or run test 24 hours, whichever occurs first. Record water level and elapsed time (in minutes) at the end of the test. Calculate permeability. Repeat Step 22 until

three consistent permeabilities are obtained. Should air get into the chambers or lines during test, stop test and remove air as before (Steps 17 through 20), and then continue test.

23. At the end of the test, **release pressure** and disconnect all hoses. Disassemble apparatus and remove sample ring. Remove O-rings from sample ring and wipe off all silicon grease. Heat ring and sample using torch until epoxy has been weakened. Knock sample out with hammer.

Note 1: Always keep approximately 1 in. (25.4 mm) of water in the evaporation beaker.

Note 2: Anytime water is added to water reservoir, the reservoir should be placed under vacuum for 24 hours to remove all dissolved air from the reservoir.

DIVISION OF RESEARCH
KENTUCKY BUREAU OF HIGHWAYS

CONCRETE PERMEABILITY DETERMINATION

Research Study No. _____   Date of Test _____

Sample No. _____   Identification _____

Tested by _____   Computed by _____

Thickness _____ cm   Diameter _____ cm

_____   _____

_____   _____

_____   _____

_____   _____

_____   _____

_____   _____

Average (L) _____ cm   Average (d) _____ cm

$$C = L/55.27d^2 = \underline{\hspace{2cm}}$$

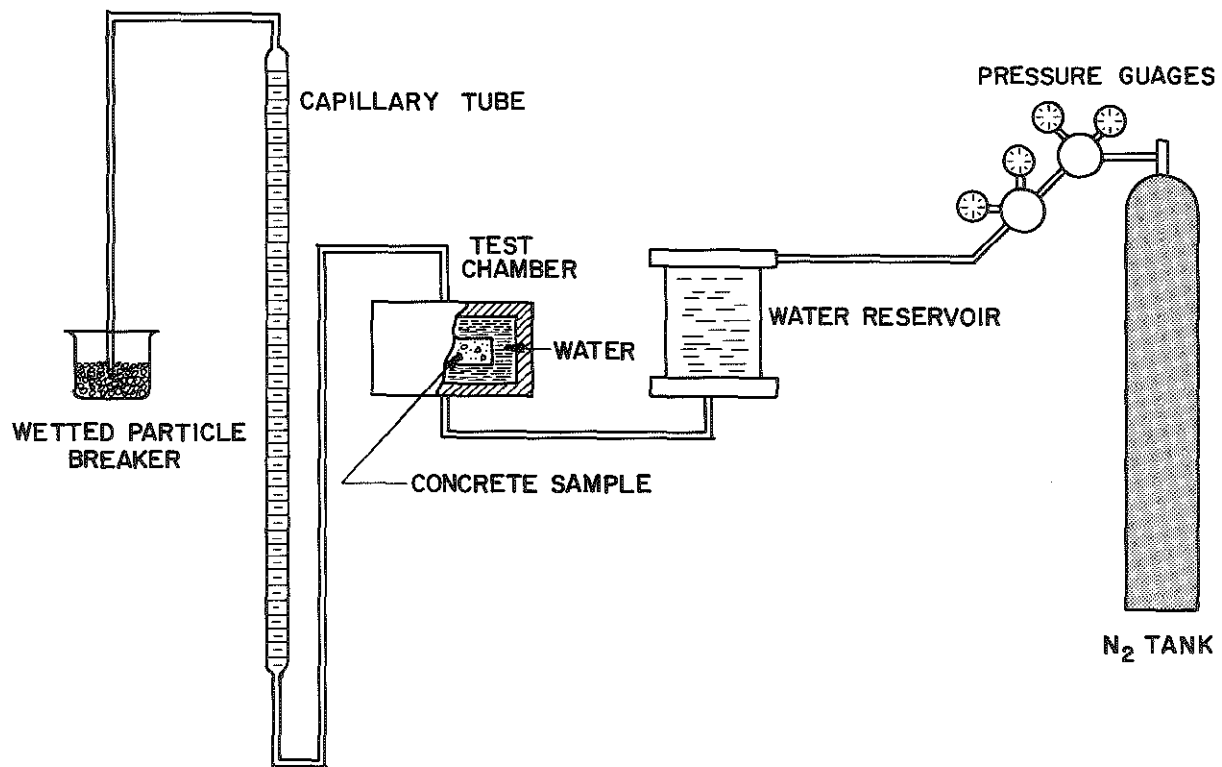| Test No.	1	2	3
Length of Test (T) (min)	_____	_____	_____
Pressure (P) (psi)	_____	_____	_____
Initial Volume (V_1)	_____	_____	_____
Final Volume (V_2)	_____	_____	_____
Discharge $(D = V_1 - V_2)(cm^3)$	_____	_____	_____

Coefficient of permeability $k = DC/PT$

$k_1 =$ _____ cm/min

$k_2 =$ _____ cm/min

$k_3 =$ _____ cm/min

Average $k =$ _____ cm/min

CAPILLARY TUBE

PRESSURE GUAGES

TEST
CHAMBER

WATER RESERVOIR

WATER

WETTED PARTICLE
BREAKER

CONCRETE SAMPLE

N$_2$ TANK

Schematic of Permeability Apparatus
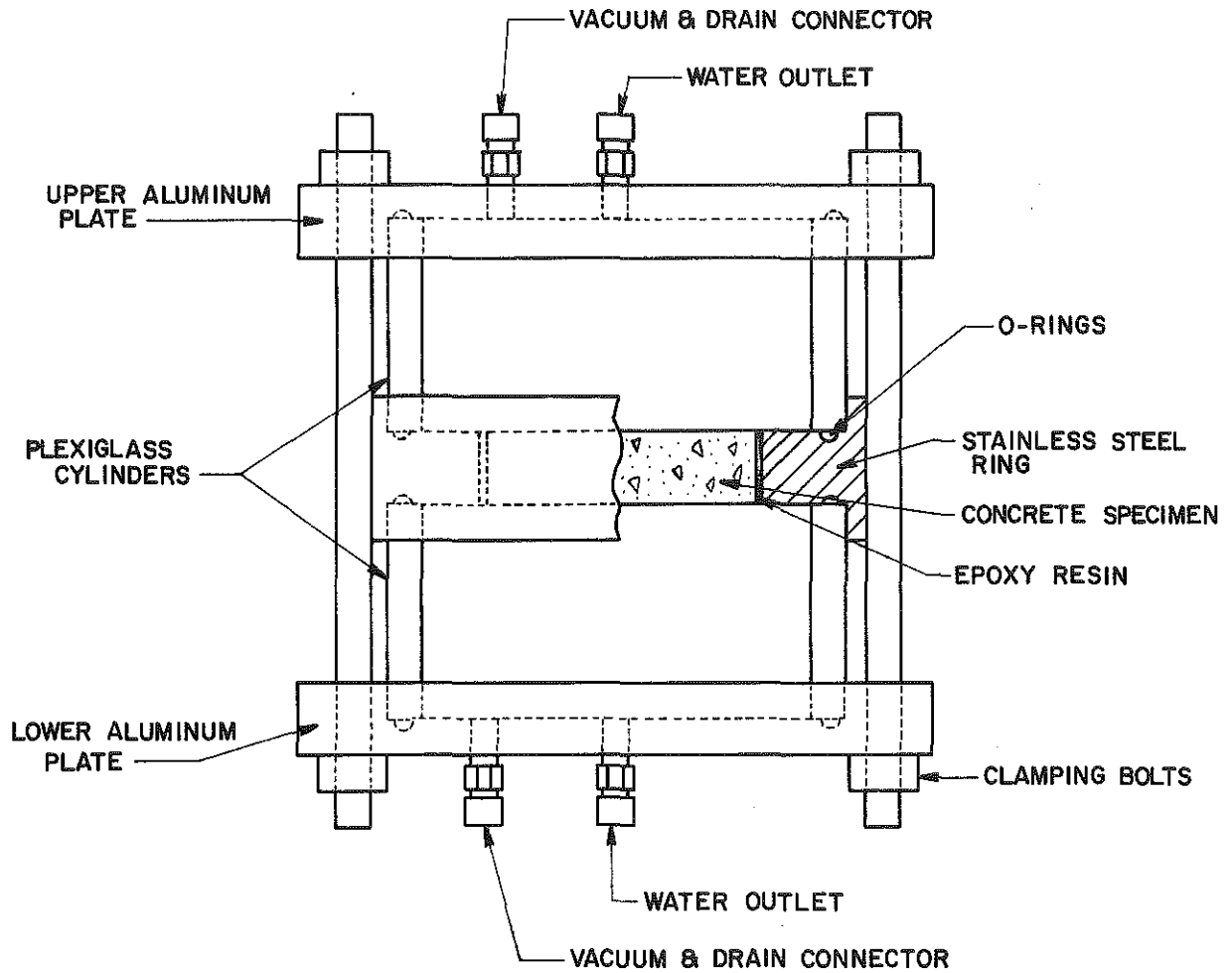
TEST CHAMBERS FOR PERMEABILITY MEASUREMENTS