Development of Optimal Concrete Mix Designs for Bridge Decks

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Executive Summary

Field inspections and a recent study report ("Cracking in Bridge Decks: Causes and Mitigation", CDOT Report 99-8) showed that the cracking problem of bridge decks in Colorado has not been completely solved, and therefore, there is a pressing need for further improvement of the concrete mix designs currently used in Colorado for concrete bridge decks.

Four different tests were selected for characterizing the mechanical properties and durability properties of concrete. Compressive strength tests at 3 days, 7 days, 28 days, and 56 days; rapid chloride permeability tests (AASHTO T277) at 28 days and 56 days; and crack resistance tests (or ring tests, AASHTO PP34-98) were performed for all concrete specimens. Drying shrinkage tests were performed on selected concrete specimens.

There were two phases in this project. Based on an extensive literature review, the recommended concrete mix in CDOT Report 99-8, and input from the concrete specialists of CDOT, 18 mix designs were formulated in the Phase I study in order to single out some good mix designs satisfying the selected strength and durability requirements. The Phase II study was mainly a fine-tuning of the mixes selected from the Phase I and finalization of the mix designs to be used in the field. The recommended concrete mixes are characterized by good workability, proper air content, adequate strength, low chloride permeability, and low drying shrinkage potential.

It was found in this study that (1) the ratio of water to cementitious materials has the most significant effect on chloride permeability; (2) the permeability is not strongly correlated to the total air entrainment; (3) the time for the first cracking to occur is related directly to the cement content and thus the strength of concrete; (4) Class F fly ash is better than Class C fly ash in improving both the chloride permeability and cracking resistance of concrete; (5) a proper increase of coarse aggregate can improve the permeability, the cracking resistance, and 28-day strength of concrete.

Considering overall performance of the concrete mixes tested, the ranges for optimal concrete design parameters were determined: cement content from 465 to 485 lb/yd^3; water/cementitious ratio from 0.37 to 0.41; 4% silica fume, Class F fly ash from 20% to 25%; and curing time of seven days. Within the optimal ranges of the mix design parameters, two mix designs were recommended for use in the summer and in the winter, respectively; and one mix design was recommended for thin overlays.

The overall achievements of this project are:

- Cement content was reduced from above 600 lb/yd^3 to below 500 lb/yd^3.
- The chloride permeability was reduced from about 6000 Coulomb (at 56 days) to below 2000 Coulomb.
- Specific ranges for concrete design parameters were identified, which provide flexibility for various deviations in concrete mix design to meet specific needs.

Implementation Statement

Recommendations on the three concrete mix designs (two for bridge decks and one for thin overlay) are provided in Section 7 for CDOT to consider. Although similar concrete mixes were already used in the construction project of I-225 & Parker Rd., a follow-up study will be necessary to monitor the performance of the concrete and further modify the mix designs if any one of the recommended mixes is used in an actual construction project in the future.

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1. Introduction

Results of field inspections organized in 1997 by the FHWA division office showed that the cracking problem of concrete bridge decks has not been solved completely in the state of Colorado. Since 1998, several new concrete mix designs (such as Class SF and Class DT) have been used for bridge decks, in addition to Class D. In a recent research report published in 1999 ("Cracking in Bridge Decks: Causes and Mitigation", CDOT Report 99-8), the survey results on four bridges constructed by different concrete mixes indicated that there are still some deck cracking problems, although most of the decks do not have major cracks.

Another concern with the concrete used for bridge decks is the chloride permeability of the concrete. Analyses of the concrete cores taken from several existing bridges in Colorado indicated that the concrete used for bridge decks have high chloride permeability, ranging from 5000 to 10,000 coulombs. The high permeability reflects high porosity and poor pore structure in the concrete, which inevitably affect the properties of drying shrinkage, freeze/thaw resistance and thus the long-term durability.

On the other hand, specifications on the crack resistance and the chloride permeability have not been incorporated in bridge construction projects in Colorado. Inappropriate concrete mix designs may be one of the primary factors responsible for long-term durability problems of bridge decks. Therefore, there is a pressing need to develop a better concrete mix design for bridge deck applications, especially suitable for local applications in Colorado.

There were two phases in this project. We started from an extensive literature review, collected valuable input from the concrete specialists of CDOT, then we determined the testing methods for evaluating the mechanical properties and durability properties of concrete for bridge decks. Eighteen mix designs were then formulated in the Phase I study in order to single out some good mix designs satisfying the selected requirements on concrete durability. The Phase II study was mainly a fine-tuning of the mixes selected from the Phase I and finalization of the mix designs to be used in the field. The recommended concrete mixes are characterized by good workability, proper air content, adequate strength, low permeability, and low drying shrinkage potential.

2. The Concrete Mix Designs Used by State DOTs for Bridge Decks

High Performance Concrete (HPC) has been used in many states for construction of bridge decks. Table 1a lists concrete mix designs used for bridge decks in several states. These mix designs are collected from technical papers published in the literature, not from specifications of the state DOTs. As a comparison, Class DGFA/10 and Class SF from CDOT are also listed. From Table 1a, we can find some common characteristics and some divergences in the concrete mix designs.

The common characteristics are:

- Using pozzolanic materials, especially fly ash and silica fume

- Moderate w/c ratio
- Low permeability
- Moderate air content
- Emphasizing the importance of reasonable strength (i.e. not higher than 10,000 psi)

The divergences are:

- Cement content: the range is from 382 lb/yd^{3}to 750 lb/yd^3.
- Compressive strength: the range is from 4000 psi to 8000 psi.

Table 1a. Concrete Mix Designs for Bridge Decks Used by State DOTs

States	**Cement (lb/yd^3)**	**Fly ash (lb/yd^3)**	**Silica fume (lb/yd^3)**	**w/(c+m)**	**28-d Strength (psi)**	**Permeability 28d (Coul.)**	**Air content (%)**	**Slump (inch)**
Colorado Shing, P.B.et al, 1999)	660	-	50	0.35	5800	-	4-8	
Colorado	615-660	<61-66	-	<0.44	4500	-	5-8	
Illinois (Detwiler,1997)	630	-	70	0.31	6950 at 14d	540	6-8	-
New York (Alampalli,2000)	505	149	42	0.4			6.5	3-4
Washington (FHWA-RD-00-124)	660	75	-	0.39	4000 5300 at56d	2800	6.0	-
Nebraska Beacham, M. W. (1999)	750	75	-	0.31	8000 at 56d	589 at 56d	6.0	-
Texas (Ralls, M. L., 1999)	382-610	88-131	-	0.31-0.43	4000	<2000	5-8	3-9
New Hampshire (Waszczuk, C. M. et al, 1999)	607	-	45	0.383	6000 7200 at 56d	<1000 at 56d	6-9	3-5
Virginia (FHWA-RD-00-123)	560	140	-	0.45	5000	2500	-	-

3. Requirements for Properties of HPC

Table 1b. lists the requirements for HPC used in the U.S. One can see that not only the compressive strengths at 28 days and 56 days but also the rapid chloride permeability (AASHTO T277) have been included in specifications in many states. In addition, the ring test for crack resistance (AASHTO PP34-98), long-term chloride penetration test (AASHTO T259), scaling test (ASTM C672), drying shrinkage test (ASTM C517), freeze-thaw resistance test (AASHTO T161), and creep test (ASTM C512) are also adopted by some of the states.

Table 1b. Requirements for HPC Used in the U.S.

State	Requirements			Notes
	Strength (psi)	Permeability (coulombs) [AASHTO T227]	Other properties	
Arizona				Currently no use of HPC
Colorado	4500 at 56d	2000 at 28d	Ring test: > 14 days [AASHTO PP34-98]	Specified for a IBRC project
Eastern Federal Lands		2000 at 28d		For deck replacement projects
Florida	6000 at 28d	1000 at 28d		Class V concrete with microsilica
Chicago DOT acceptance criteria for Wacker Drive	6000-9500 at 28d	2000 at 28d	90d Chloride penetration at 0.5-1": 0.03%, [AASHTO T259]; Scaling at 50 cycles(0-1 rating)[ASTM C672]; Shrinkage: 600 microstrain at 90d[ASTM C517].	Illinois State DOT approaches mix design by controlling quality and compatibility of the components in the concrete mix. Have strength requirements, but no acceptance criteria for chloride permeability. Use of pozzolans in the right proportions will give the desired characteristics.
Iowa	5000 at 28d	1200 at 28d		For trial batch concrete
Massachusetts	5000 at 28d	1500		
Michigan				Currently no HPC specification

Table 1b. Requirements for HPC Used in the U.S. (continued)

State	**Requirements**			**Notes**
	Strength (psi)	**Permeability (coulombs) [AASHTO T227]**	**Other properties**	
Minnesota				HPC decks used on a limited basis; still working on specification
Missouri	5000 at 28d	1000 (regardless age)		For CIP bridge deck
	design strength required	1000 (regardless age)		For precast girders
Nebraska			Strength and free/thaw requirements	
New Hampshire	5000 at 28d	1000		For bridge deck
	9400 at 28d	2500		For precast beams
New Jersey	5365 at 56d (4350 for production)	1000 at 56d	Scaling at 50 cycles: (2-3 rating)[ASTM C672], Freeze/thaw at 300 cycles: 80% relative dynamic modulus[AASHTO T161]	For bridge deck
	5365 at 56d (4350 for production)	1000 at 56d	Abrasion-1mm[ASTM C944], Freeze/thaw at 300 cycles: 80% relative dynamic modulus[AASHTO T161]	For pier walls in water
	6090-7975 at 56d		Shrinkage at 56d:400-600 microstrain [ASTM C517]. Elasticity: 28-40 Gpa, Creep: 40-60 microstrain[ASTM C512]	For precast/prestressed members

Table 1b. Requirements for HPC Used in the U.S. (continued)

State	Requirements			Notes
	Strength (psi)	Permeability (coulombs) [AASHTO T227]	Other properties	
New York	10150 at 56d		Freeze/thaw at 300 cycles: 80% relative dynamic modulus [AASHTO T161], Scaling at 50 cycles: (0,1,2,3 rating)[ASTM C672], Elasticity: greater than 50 Gpa, Creep at 56d: 60/Mpa [ASTM C512], Chloride penetration at 1": 0.025% [AASHTO T259]	For precast/prestressed members
North Carolina				Prescriptive approach to HPC using varying amounts of pozzolans and corrosion inhibitor depending on member. Durability, not strength, is the main focus.
North Dakota				First HPC bridge deck due in 2002
Ohio				Uses a low permeable concrete for bridge decks. Started work on QC/QA/Warranty specification for scaling, spalling, and cracking

Table 1b. Requirements for HPC Used in the U.S. (continued)

State	Requirements			Notes
	Strength (psi)	Permeability (coulombs) [AASHTO T227]	Other properties	
Tennesee	5000	<1500		Bridge decks
	10000	<2500		Superstructure
	4000	<3000		Substructure
Utah				Currently does not have HPC specification
Virginia	Depends on class of concrete	In accordance with AASHTO T227 with modified curing technique- 1 week at 73°F and 3 weeks at 100±10°F		For low permeability concrete
		1500 at 28d		For overlay and special designs

4. Materials and Testing Methods

4.1 Materials

All materials used in the project were from local sources.

Crushed granite of max. size of ¾ inch and river sand from a local source in Colorado were used in the project. The properties of the aggregates are shown in Table 2.

Type I/II low alkali Portland cement from Holnam Inc. was used. The properties of the cement are listed in Table 3.

Fly ashes of Class F and Class C were from Denver Terminal. The test data of chemical and physical analyses are listed in Table 4.

Silica fume was Rheomac® SF100 dry compacted silica fume from Master Builders Technologies with BSG = 2.22

All admixtures used were from Master Builders Technologies. High Range Water Reducer: Rheobuild ® 3000FL; Air Entraining Agent: MicroAir; Retarder: Delvo Stabilizer.

Table 2. Properties of Aggregates

	BSG (ssd)	BSG (od)	Absorption (%)	Moisture Content (%)	UW (lb/ft^3)	FM
Gravel	2.811	2.800	0.384	0.242	96.81	
Sand	2.57	2.49	4.64	1.52		2.93

Table 3. Chemical and Physical Properties of the Cement

Chemical and Mineral Compositions		Physical Properties	
Item	%	Item	
SiO_2	20.5	Air Content, %	7
Al_2O_3	4.8	Blain Fineness, m^2/kg	379
Fe_2O_3	3.1	Autoclave Expansion, %	0.02
CaO	63.3	Compressive Strength (psi)	
MgO	1.8		
SO3	2.7	3-day	3540
Alkalis	0.57	7-day	4670
Ignition Loss	1.1	Initial Vicat, min.	103
Insoluble Residue	-	Final Vicat, min.	207
C_3S	58		
C_2S	15		
C_3A	7		
C_4AF	9		

Table 4(1). Chemical and Physical Analyses of Fly Ashes

Fly ash	Source	SiO_2	Al_2O_3	Fe_2O_2	SO_2	CaO	Loss on ignition	Alkali As Na_2O
Class F	Denver	57.98	19.55	5.36	0.5	10.19	0.1	0.32
Class C	Denver	35.47	18.37	5.34	2.50	26.43	0.47	1.33

Table 4(2). Chemical and Physical Analyses of Fly Ashes

Fly ash	Source	Fineness On #325 sieve,%	Water requirement, %	28d Strength Activity Index, %	Soundness %	BSG
Class F	Denver	22.85	96.6	85.1	-0.008	2.37
Class C	Denver	16.21	96.6	91.1	0.084	2.7

4.2 Concrete Mix Designs

Water-cement ratio and cement content were selected as two of the testing parameters in the project. Therefore, a modified concrete mix design method was developed based on ACI 211.1-91.

1. The following parameters were selected for the concrete mixes:

- slump = 3 to 4 inches
- max. size of agg. =3/4 inch
- compressive strength = 4500 psi
- air content = 6.5 %

2. Water-cement ratio w/c (weight ratio)

Water-cement ratio is one of the experimental parameters.

3. Cement content W_c

W_c is one of the experimental parameters (in lb/yd^3).

4. Water content W_w

Water content W_w (in lb/yd^3) for each mix design is calculated based on w/c

$$W_w = (w/c)(Wc + \mathbf{W_{sf}} + \mathbf{W_{fa}})$$

in which W_{sf} is the weight of silica fume in lb., and W_{fa} is the weight of fly ash in lb.

5. Silica fume content W_{sf}

W_{sf} (in lb/yd^3) is fixed in all mix designs as 4% of the cement content (in addition to the cement content, not a replacement).

6. Fly ash content W_{fa}

W_{fa} (in lb/yd^3) is one of the experimental parameters (in addition to the cement content, not a replacement).

7. Gravel content W_g

For max. size of aggregate ¾ in., and fineness modulus of 2.93. The volume fraction of coarse aggregate can be determined from Table 6.3.6 (ACI 211.1-91) as 0.61.

$$V_g = 0.61 \text{ x } 27 = 16.47 \text{ ft}^3 \text{ /Yard}^3$$
$$W_g = 16.47 \text{ x } 96.81 = 1595 \text{ lb/yd}^3$$

in which V_g and W_g are volume and weight of aggregate per cubic yard of concrete, respectively; 27 is the conversion factor (1 yd^3 = 27 ft^3); 96.81 is the unit weight of gravel.

Taking into account the moisture content for the gravel, the weight content for the gravel in stock, W_{gs}, in lb/yd^3 can be evaluated

$$W_{gs} = W_g \cdot (1 + 0.0024) = 1599 \text{ lb/yd}^3$$

in which 0.0024 is the moisture content of the gravel.

8. Sand content W_s

Ws was calculated by using the volume basis method, since the bulk specific gravities of the Class F fly ash and the Class C fly ash are different. Two different formulas were developed for the sand content.

For Class F fly ash, the volume of sand, V_s, in ft^3 can be calculated

$$\begin{aligned} V_s &= 27 - V_w - V_c - V_{fa} - V_{sf} - 1595/(2.80 \text{ x } 62.4) - 6.5\% \text{ x } 27 \\ &= 16.12 - V_w - V_c - V_{fa} - V_{sf} \\ &= 16.12 - W_w/62.4 - W_c/(3.15 \text{ x } 62.4) - W_{fa}/(2.37 \text{ x } 62.4) - W_{sf}/(2.22 \text{ x } 62.4) \\ &= 16.12 - 0.016W_w - 0.0051W_c - 0.0068\, W_{fa} - 0.0072\, W_{sf} \end{aligned}$$

in which W_{fa} and W_{sf} are the weight of the fly ash and silica fume, respectively; W_w and W_c are the weight of water and cement, respectively; 2.80 is the bulk specific gravity (BSG) of the gravel; 62.4 is the specific weight of water, lb/ft^3; and 6.5% is the targeted air content.

For Class C fly ash, the volume of sand, V_s, in ft^3 can be calculated in a similar manner

$$V_s = 16.12 - 0.016W_w - 0.0051W_c - 0.0059\, W_{fa} - 0.0072\, W_{sf}$$

Then, the weight content of sand, W_s, in lb/yd^3 can be evaluated

$$W_s = V_s \cdot 2.49 \cdot 62.4 = 155.38V_s$$

in which 2.49 is the BSG of the sand.

Taking into account the moisture content for the sand, the weight content for the sand in stock, Wss, in lb/yd^3 can be evaluated

$$W_{ss} = W_s \cdot (1+0.0152)$$

in which 0.0152 is the moisture content of the sand.

9. Moisture adjustment for the water content

$$\begin{aligned} W_{w2} &= W_w + Wg(0.384\%-0.242\%) + W_s(4.64\%-1.52\%) \\ &= W_w + 1595 \times 0.0014 + 0.0312Ws \\ &= W_w + 2.27 + 0.0312\,Ws \qquad \text{lb/yd}^3 \end{aligned}$$

in which W_{w2} is the adjusted water content; 0.384% and 4.64% are the moisture contents of the saturated gravel and sand, respectively; 0.242% and 1.52% are the moisture contents of the gravel and sand in stock, respectively.

4.3 Specimen Preparation

Concrete materials were mixed by following ASTM C-192 " Standard Method of Making and Curing Concrete Test Specimens in the Laboratory". Coarse aggregate together with some of the water and solution of admixtures are added into the mixer first, and after a few revolutions of the mixer, fine aggregate, cement and remaining water are added. The mixer runs for 3 minutes after all ingredients are added into it, then rests for 3 minutes, and finally runs for another 2 minutes.

The slump test (ASTM C-143 " Standard Test Method for Slump of Portland Cement Concrete") and the air content test (ASTM C-231 "Air Content of Freshly Mix Concrete by the Pressure Method") were performed before the cast of concrete specimens. The concrete specimens were placed in a curing room of 68°F, 100% relative humidity.

4.4 Test Methods

When the concrete specimens reached the specific ages, the following tests were performed:

- Compressive strength test. The strength tests were performed at 3 days, 7 days, 28 days, and 56 days. 4" by 8" cylinders were used for the compressive strength test. Two cylinders were used for each test at 3 days, 7 days, 28 days, and 56 days.

- Rapid chloride permeability test (ASTM C 1202, AASHTO T277 "Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration"). The permeability tests were performed at 28 days and 56 days. Cylindrical specimens of 4" in diameter by 2" in height were used for the permeability test. Two specimens were used for each test at 28 days and 56 days.

- Crack resistance test (or ring test, AASHTO PP34-98 " Standard Practice for Estimating the Crack Tendency of Concrete"). Two concrete rings of 6'' in height with outer diameter 18'' and inner diameter 12'' were made for each concrete mix. After one day of curing under room temperature, the molds were removed and the concrete rings were placed in the lab (temperature = 72°F and relative humidity = 35%) until the first crack was observed. The apparatus of the ring test is shown in Appendix II. The cracks were monitored by unaided eye as well as by a zoom.

- Drying shrinkage test (ASTM C-157 " Standard Test Method for Length Change of Hardened Hydraulic-cement Mortar and Concrete"). Two concrete prisms of 3" by 3" by 12" were made for the drying shrinkage test. After 7 days of curing in a fog room (68°F, 100% Relative Humidity), the prisms were removed from the fog room and placed in the lab (temperature 72°F and relative humidity 35%). Shortening of the prisms due to drying shrinkage was then measured. The shrinkage test was only performed for some concrete mixes.

5. Phase I Study

In the Phase I study, cement content (Wc), water-cement ratio (w/c) and fly ash content (Wfa) were selected as experimental parameters:

- Three w/c were tested, 0.37,0.41, 0.45.
- Three Wc were tested, 450, 485, and 515 lb/yd^3.
- Two different Wfa were used in the project: 20% and 25% of the cement content.

The objective of the Phase I study was to identify the optimal concrete mix design in terms of moderate compressive strength, low chloride permeability, and high crack resistance.

5.1 Test Results of the Phase I Study

Twenty concrete mixes were tested in the Phase I study. The concrete mix proportions and test results from the Phase I study are summarized in Table 5.

Table 5. Mix Designs and Test Results of the Phase I Study

		Mix 1	Mix 2	Mix 3	Mix 4-2
Cement content (lb/yd^3)		450	450	450	450
Fly ash, Class F lb/yd^3 (% of cement)		90 (20)	90 (20)	90 (20)	112.5 (25)
Silica fume, lb/yd^3,(% of cement)		18 (4)	18 (4)	18 (4)	18 (4)
W/(C+M)		0.37	0.41	0.44	0.37
Sand (lb/yd^3)		1480	1458	1436	1450
Gravel (lb/yd^3)		1595	1595	1595	1595
HRWR (oz/100 lb cement)		12	6.7	0	10
Micro Air (oz/100 lb cement)		5.64	5.0	5.0	3.36
Retarder (oz/100 lb cement)		3.75	3.75	3.75	3.75
Slump (inch)		3	2	0.5	1
Air content (%)		9	7	4	4.5
Permeability at 28 days (Coulomb)		2309 3352	4764 4123	6668 5975	3265
Permeability at 56 days (Coulomb)		1560	1430	3650	1385 1578
First cracking (days)		34	67	-	30
Compressive strength (psi)	3 days	2252	2225	2062	3376
	7 days	3232	2699	3152	4339
	28 days	3837	3900	4156	5573
	56 days	3790	4326	4617	6130

Table 5. Mix Designs and Test Results of the Phase I Study (continued)

		Mix 5-2	Class DGFA/10	Class D
Cement content (lb/yd^3)		450	595	650
Fly ash, Class F lb/yd^3, (% of cement)		112.5 (25)	Class C 59.5(10)	0
Silica fume, lb/yd^3, (% of cement)		18 (4)	0	0
W/(C+M)		0.41	0.41	0.44
Sand (lb/yd^3)		1426	1334	1348
Gravel (lb/yd^3)		1595	1690	1628
HRWR (oz/100 lb cement)		10	7.5	6.86
Micro Air (oz/100 lb cement)		1.34	2.55	2.33
Retarder (oz/100 lb cement)		2.65	2.84	2.58
Slump (inch)		2.5	1.5	2
Air content (%)		8	8.5	7.5
Permeability at 28 days (Coulomb)		3115 3252	3260 2850	3762
Permeability at 56 days (Coulomb)		2278 2339	2714 2102	3146 3439
First cracking (days)		30	30	16
Compressive strength (psi)	3 days	2146	3276	3061
	7 days	2985	4474	3224
	28 days	3949	5422	4777
	56 days	4570	5310	5231

Table 5. Mix Designs and Test Results of the Phase I Study (continued)

		Mix 6-2	Mix 7	Mix 8	Mix 9
Cement content (lb/yd^3)		450	485	485	485
Fly ash lb/yd^3 (% of cement)		112.5 (25)	97 20	97 20	97 20
Silica fume, lb/yd^3 (% of cement)		18 (4)	19.4 (4)	19.4 (4)	19.4 (4)
W/(C+M)		0.45	0.37	0.41	0.45
Sand (lb/yd^3)		1403	1421	1397	1373
Gravel (lb/yd^3)		1595	1595	1595	1595
HRWR (oz/100 lb cement)		8.93	11.45	12.6	11.34
Micro Air (oz/100 lb cement)		1.56	3.35	3.8	0.9
Retarder (oz/100 lb cement)		2.7	3.8	3.8	2.7
Slump (inch)		4.3	0	3.5	2
Air content (%)		6.5	7.5	7	4
Permeability at 28 days (Coulomb)		5381 5252	2498 2549	2847 3461	4070
Permeability at 56 days (Coulomb)		3274	1493 1521	1751 1748	2030 2228
First cracking (days)		20	18	19	12
Compressive strength (psi)	3 days	2054	2866	2349	2707
	7 days	2850	3861	3264	3941
	28 days	3877	5032	4339	5155
	56 days	4411	5000	4737	6146

Table 5. Mix Designs and Test Results of the Phase I Study (continued)

		Mix 10-2	Mix 11	Mix 12	Mix 13
Cement content (lb/yd^3)		485	485	485	515
Fly ash lb/yd^3 (% of cement)		121.2 (25)	121.2 (25)	121.2 (25)	103 (20)
Silica fume, lb/yd^3 (% of cement)		19.4 (4)	19.4 (4)	19.4 (4)	20.6 (4)
W/(C+M)		0.37	0.41	0.45	0.37
Sand (lb/yd^3)		1388	1363	1338	1370
Gravel (lb/yd^3)		1595	1595	1595	1595
HRWR (oz/100 lb cement)		11.1	10.4	9.4	10.5
Micro Air (oz/100 lb cement)		1.25	2.1	1.25	1.16
Retarder (oz/100 lb cement)		2.5	2.5	2.5	2.33
Slump (inch)		2	4	5	3
Air content (%)		6	8	5.5	7
Permeability at 28 days (Coulomb)		2475 2811	3538 3281	4269 3933	2760 2845
Permeability at 56 days (Coulomb)		1285 1095	1675 1742	2281 2329	1447 1373
First cracking (days)		12	11	10	12
Compressive strength (psi)	3 days	3256	2635	2500	3392
	7 days	4260	3264	3185	4395
	28 days	5693	4474	4777	5477
	56 days	6449	4713	4984	6122

Table 5. Mix Designs and Test Results of the Phase I Study (continued)

		Mix 14	Mix 15	Mix 16	Mix 17	Mix 18
Cement content (lb/yd^3)		515	515	515	515	515
Fly ash, Class F lb/yd^3 (% of cement)		103 (20)	103 (20)	128.8 (25)	128.8 (25)	128.8 (25)
Silica fume, lb/yd^3 (% of cement)		20.6 (4)	20.6 (4)	20.6 (4)	20.6 (4)	20.6 (4)
W/(C+M)		0.41	0.45	0.37	0.41	0.45
Sand (lb/yd^3)		1345	1319	1335	1308	1281
Gravel (lb/yd^3)		1595	1595	1595	1595	1595
HRWR (oz/100 lb cement)		9.72	8.75	10.5	8.75	7
Micro Air (oz/100 lb cement)		1.17	1.17	1.17	1.36	1.17
Retarder (oz/100 lb cement)		2.34	2.34	2.34	2.34	2.34
Slump (inch)		2	7.5	3.7	8	8
Air content (%)		5.5	4.5	5.2	4.5	5.0
Permeability at 28 days (Coulomb)		2946 2962	4489 4781	2656 2593	4127 4014	5704 5871
Permeability at 56 days (Coulomb)		1635 1623	3403 2905	1594 1723	2164 2384	3241 3621
First cracking (days)		14	-	11	11	-
Compressive strength (psi)	3 days	3085	2620	3495	2611	2205
	7 days	4339	3125	4243	3603	2954
	28 days	5494	4403	5927	4896	4359
	56 days	6123	5271	6385	5382	5060

5.2 Discussion

1. The ratio of water to cementitious materials has the most significant effect on rapid chloride permeability. It can be seen clearly from Figs. **a, b, c** and **d** that the permeability is almost proportional to the w/(c+m) ratios, either at 28d or 56d.

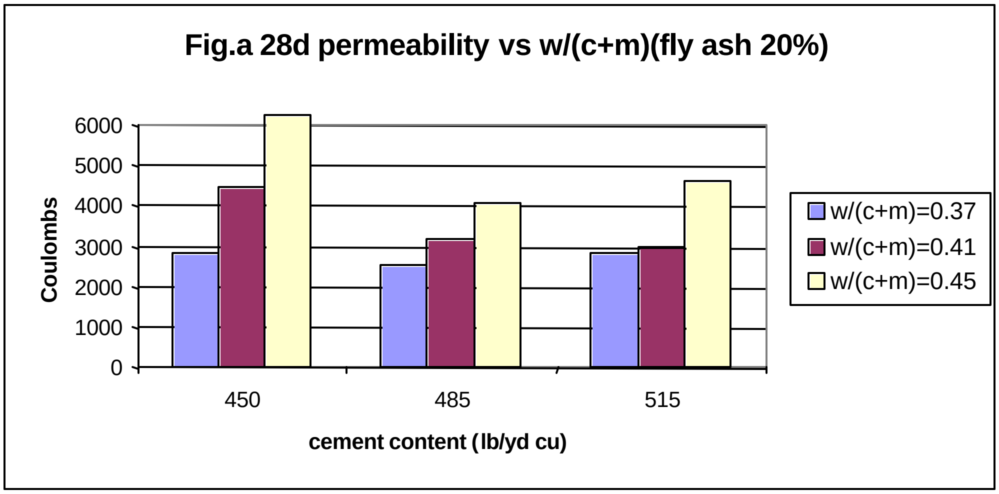


Fig.a 28d permeability vs w/(c+m)(fly ash 20%)

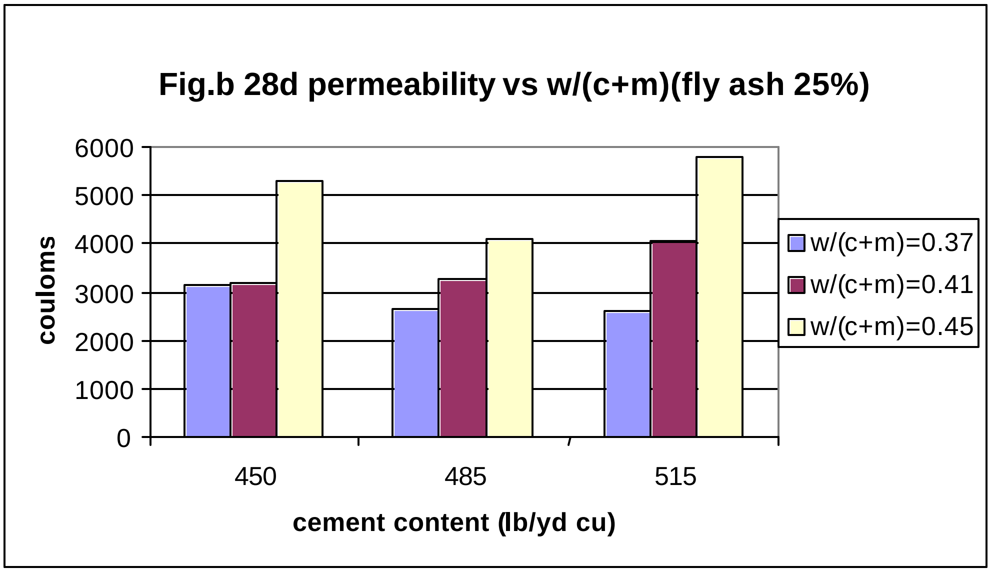


Fig.b 28d permeability vs w/(c+m)(fly ash 25%)

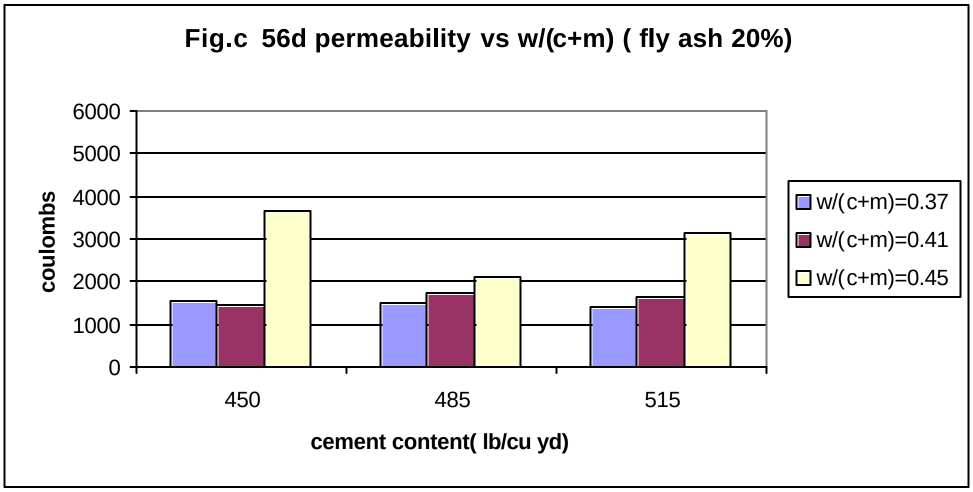


Fig.c 56d permeability vs w/(c+m) (fly ash 20%)

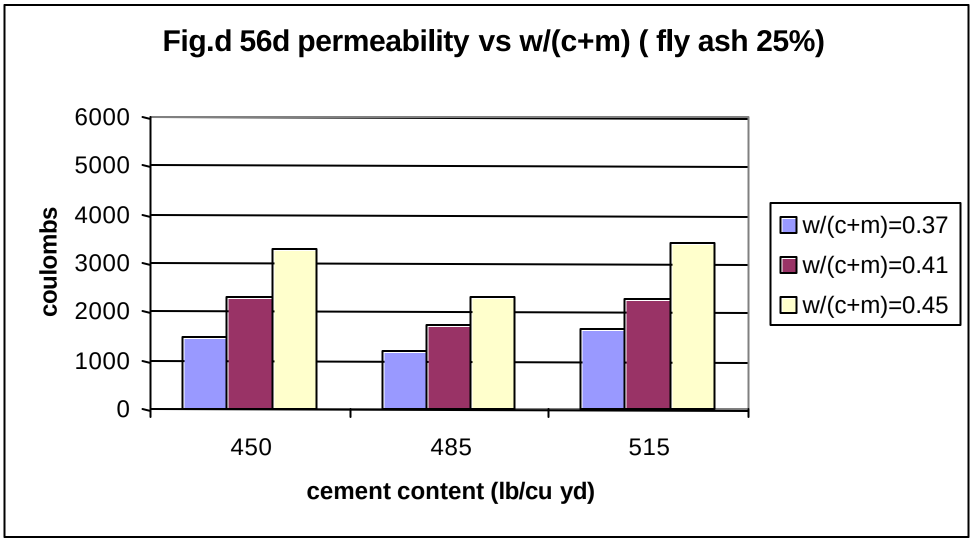


Fig.d 56d permeability vs w/(c+m) (fly ash 25%)

2. The increase of the Class F fly ash content from 20% to 25% of cement content does not significantly affect the permeability (Fig. **e**, Fig. **f**).

3. The permeability appears to be correlated to slump (Fig. **g**), but further examination indicates that the correlation should be attributed to the water/ cementitious ratio, as those mixes with higher water/cementitious ratios also tend to have higher slump values. From Fig. **g**, one can see that the low slumps and low permeabilities occur for Mixes 1, 4, 7, 10, 13, 16, which, from Table 5, are the mixes with low water/cementitious ratio 0.37 (Fig. **g** was obtained by converting the permeability test data into percentages).

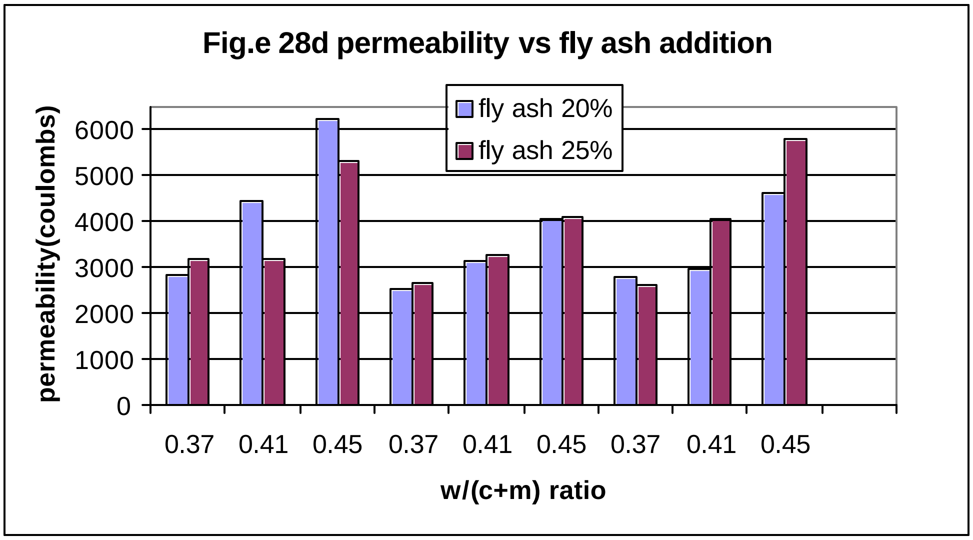


Fig.e 28d permeability vs fly ash addition

Note: In Fig. e and Fig. f, the cement content of the first three groups is 450 lb/yd^3
the cement content of the second three groups is 485 lb/yd^3
the cement content of the third three groups is 515 lb/yd^3

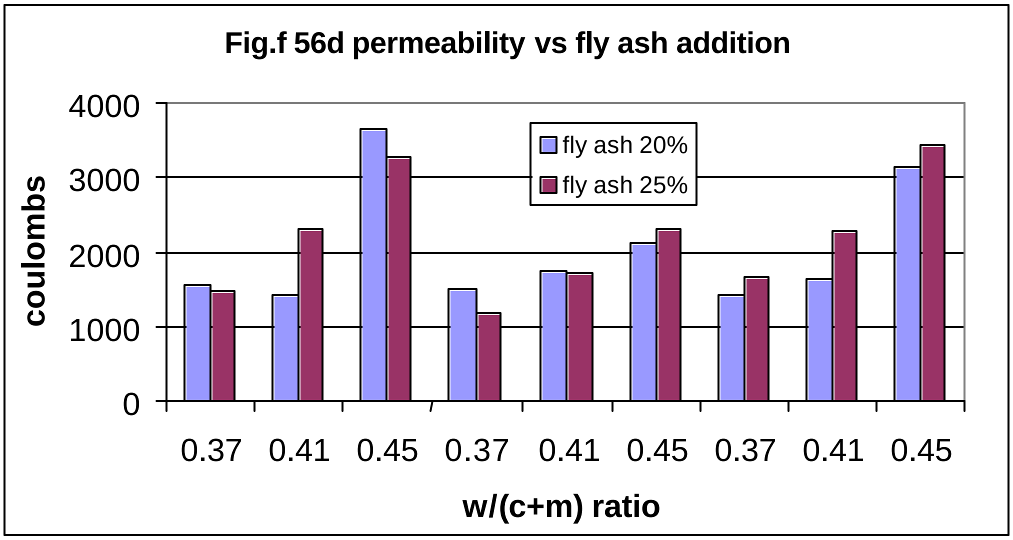
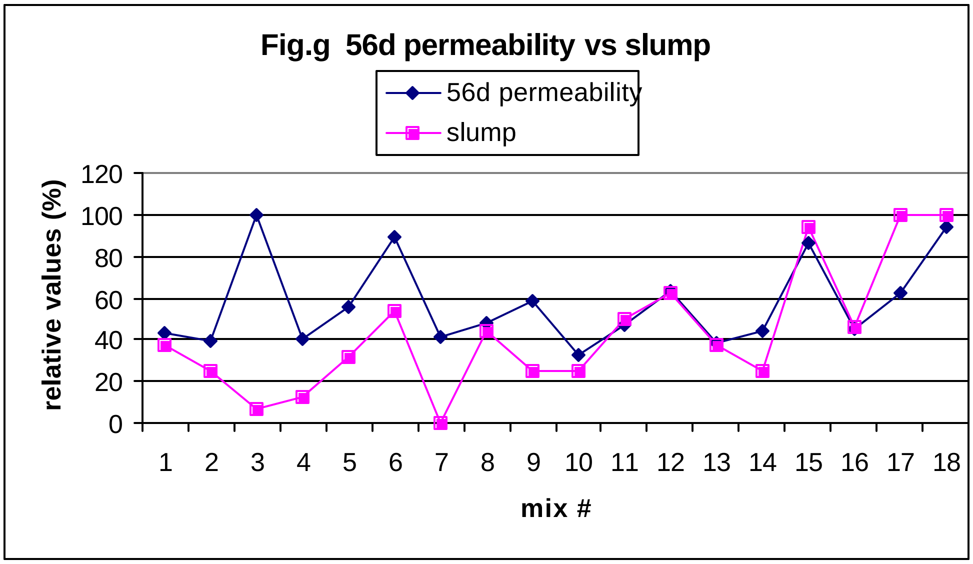


Fig.f 56d permeability vs fly ash addition



*100% relative permeability corresponds to 3650 coulombs

* 100% relative slump corresponds to 8 inches of slump measured for fresh concrete mix

4. The permeability is not correlated to the air content. It can be seen in Fig**. h** that when the air content increases, the permeability tends to decrease. This might suggest that the air-entraining agent, if applied properly, increases the volume fraction of capillary pores, but does not increase the connectivity of the pore system. The permeability depends strongly on the connectivity of the capillary pore system.

5. The permeability appears to be related to the compressive strength (Fig**. i**, Fig. **j**). When the permeability is high, the strength is low. In fact, this is mainly attributed to the effect of water/(c+m). However, the permeability is not remarkably reduced by the increased strength caused by the increase in the cement content from 450 lb/yd^3 to 515 lb/yd^3.

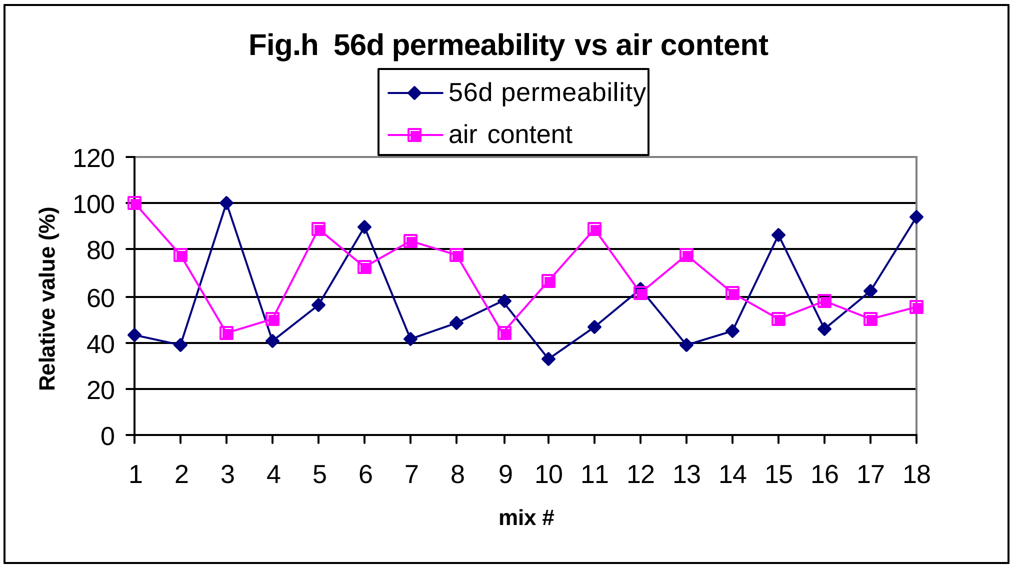


Fig.h 56d permeability vs air content

* 100% relative air content corresponds to 9% air content in fresh concrete mix.
*100% relative permeability corresponds to 3650 coulombs.

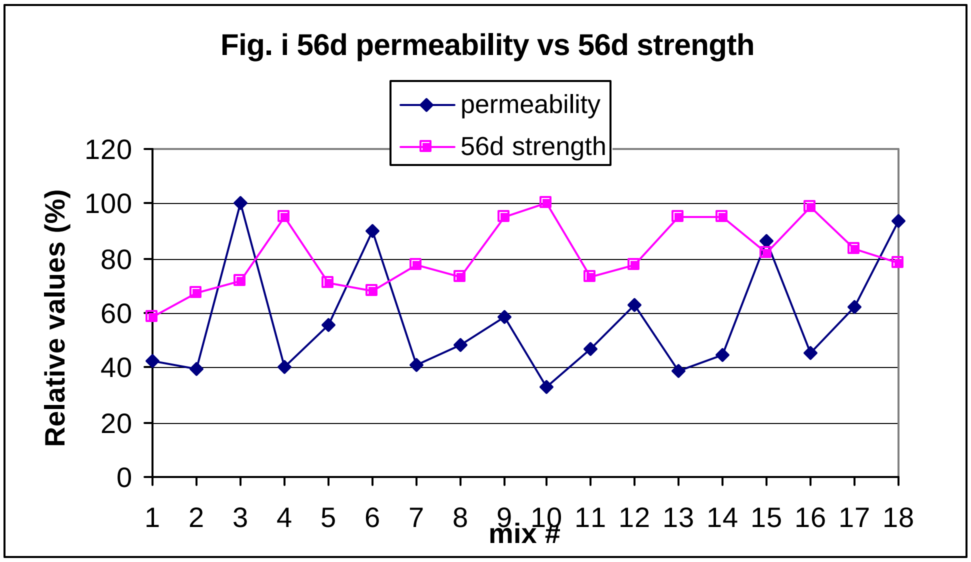
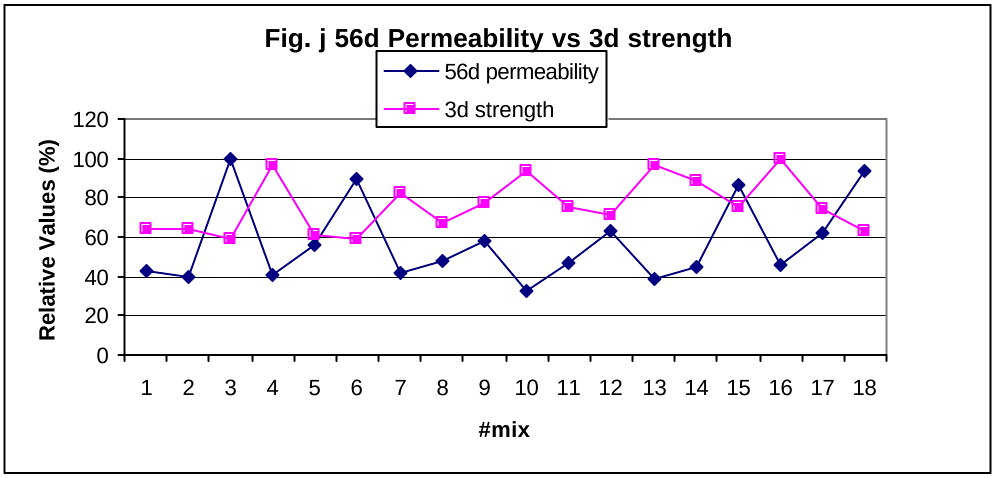


Fig. i 56d permeability vs 56d strength

*100% relative permeability corresponds to 3650 coulombs.
*100% relative strength corresponds to 6385 psi.

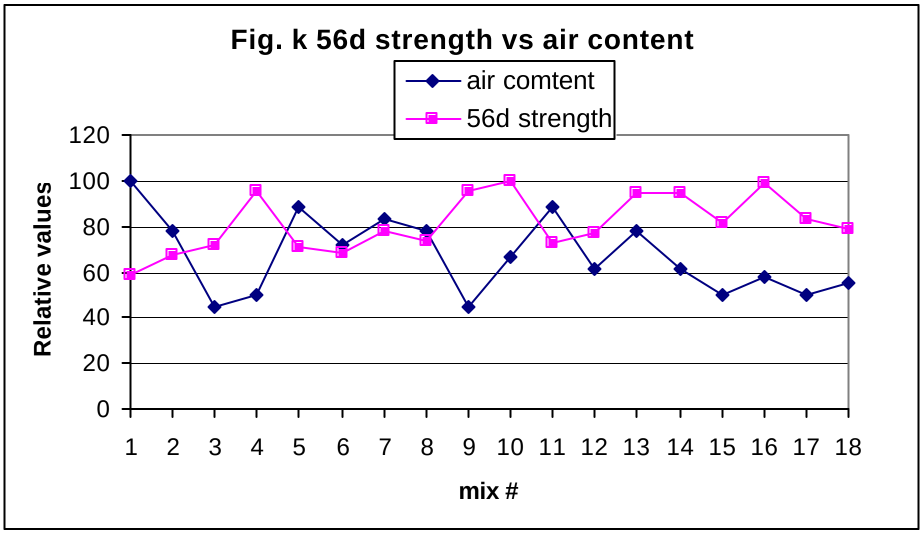


*100% relative permeability corresponds to 3650 coulombs
*100% relative strength corresponds to 3495 psi.

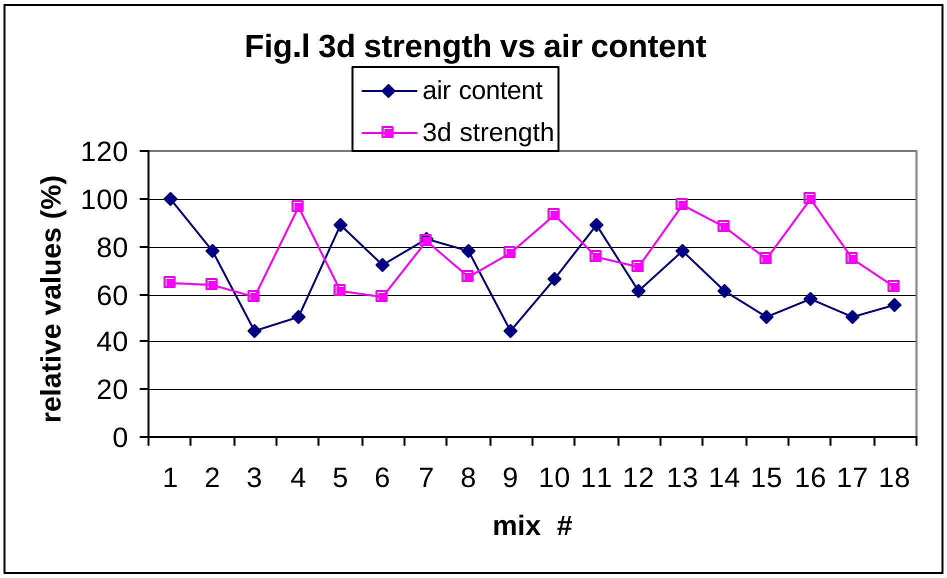
6. Fig. **k** and Fig. **l** show that the effect of air content on the compressive strength depends on the level of air content. When the air content is below about 6.3% (70% line in the figures), the strength is not significantly affected. When the air content is above 6.3%, the strength is low.

7. From Fig. **m** through Fig. **p**, one can see that w/(c+m) ratio also has significant effect on the strength, especially for the cases of 25% fly ash addition (Fig. **n** and Fig. **p**), that is, the strength is decreased by the increasing water/cementitious ratio. In the cases of 20% fly ash content (Fig. **m** and Fig. **o**), the relationship between strength and water/(c+m) is interfered by air content. For example, Mixes 1, 2, and 3 should have decreasing order of the strength, but exhibit the opposite trend. This is because their air contents are in a decreasing order.

8. Fig. **q** compares the compressive strength measured at different ages. It can be seen that the compressive strengths show excellent consistency among the different ages. Therefore, we can use the strength at any age (e.g., 3-d strength) in developing a relationship between the strength and other parameters.



* 100% relative air content corresponds to 9% air content in fresh concrete.
* 100% relative strength corresponds to 6385 psi.



*100% relative air content corresponds to 9% air content in fresh concrete.
*100% relative strength corresponds to 3495 psi.

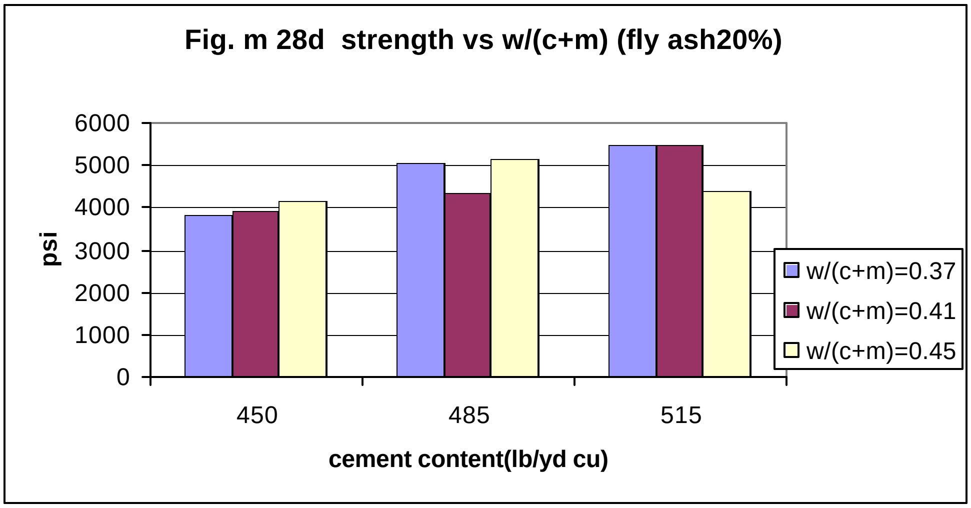


Fig. m 28d strength vs w/(c+m) (fly ash20%)

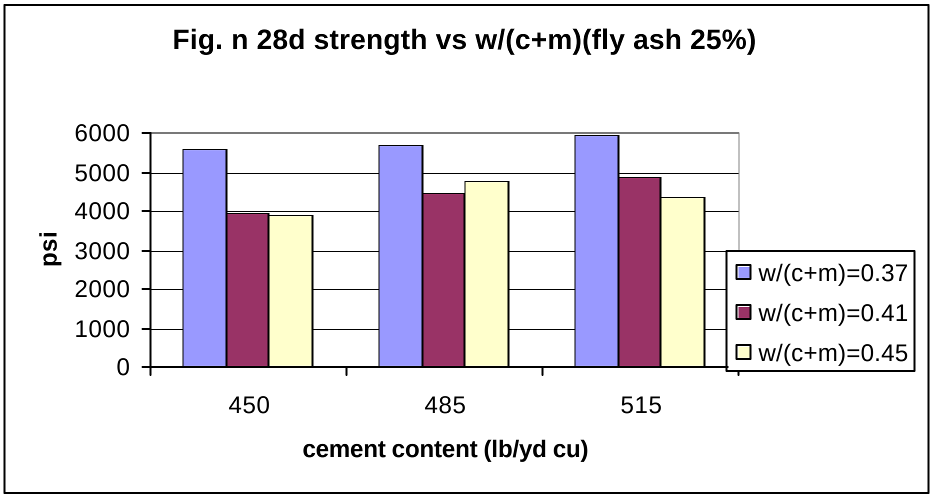


Fig. n 28d strength vs w/(c+m)(fly ash 25%)

Fig. O 56d strength vs w/(c+m) (fly ash 20%)

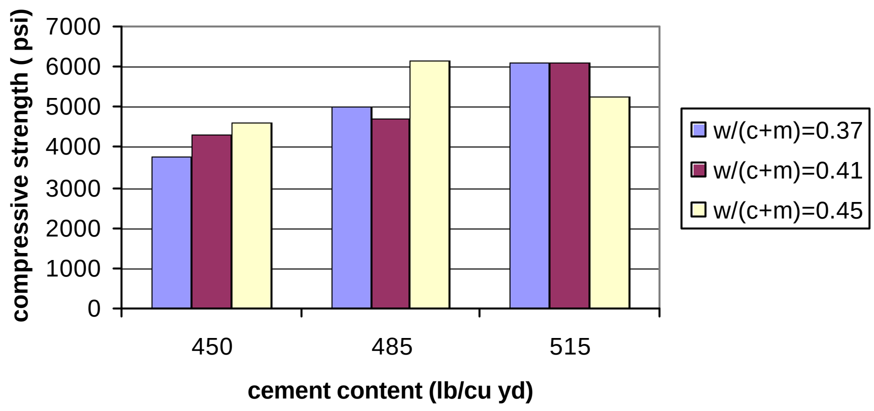
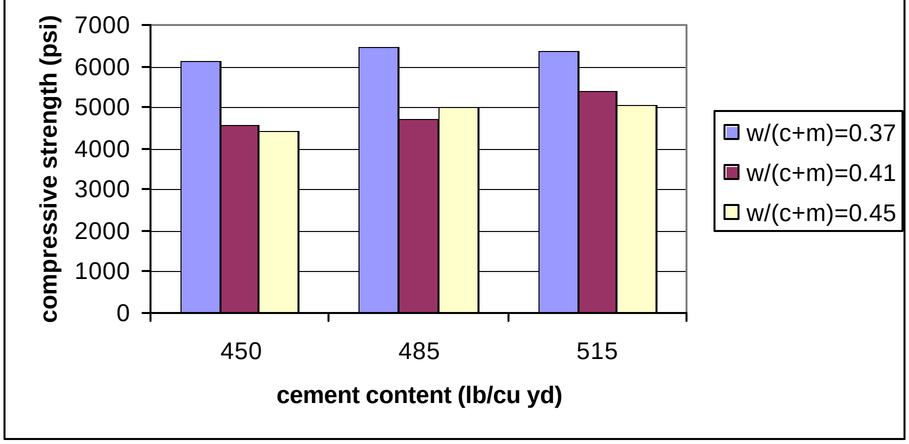
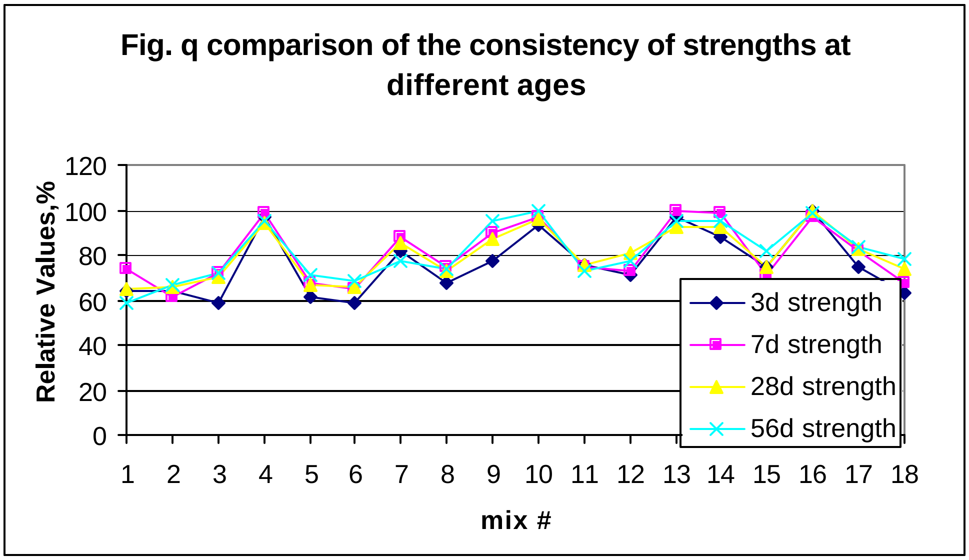


Fig. P 56d strength vs w/(c+m) (fly ash 25%)

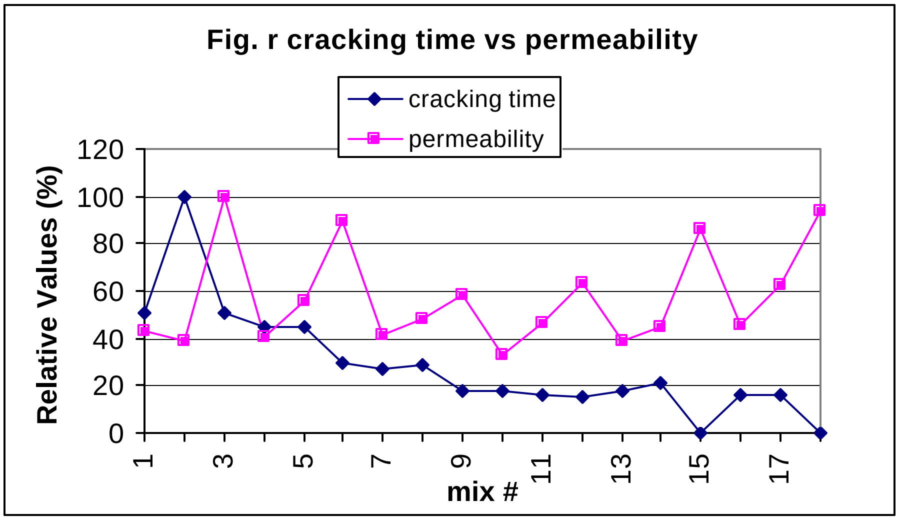




*100% 3d relative strength corresponds to 3495 psi.
*100% 7d relative strength corresponds to 4395 psi.
*100% 28d relative strength corresponds to 5927 psi
*100% 56d relative strength corresponds to 6385 psi.

9. The time for the first cracking to occur is not strongly correlated to the permeability (Fig. **r**).

10. With an increase of the cement content and thus the strength of concrete, the time for the first cracking to occur is shortened, as seen in Fig. **s** through Fig. **u**.



*100% permeability is corresponding to 3650 coulombs.
* 100% cracking time corresponding to 67 days.

Fig. S cracking time vs cement content

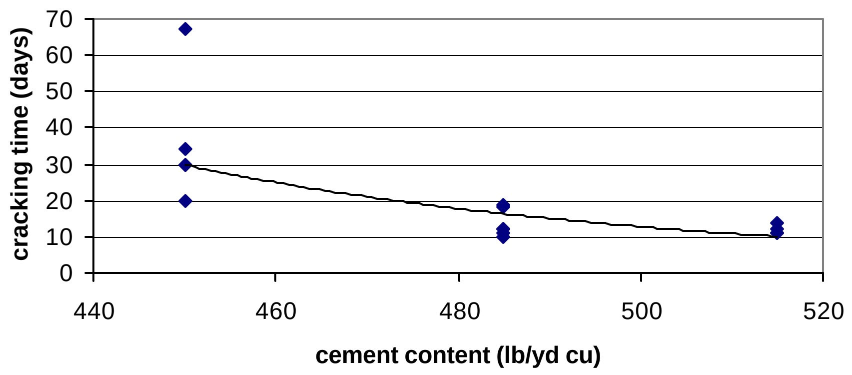
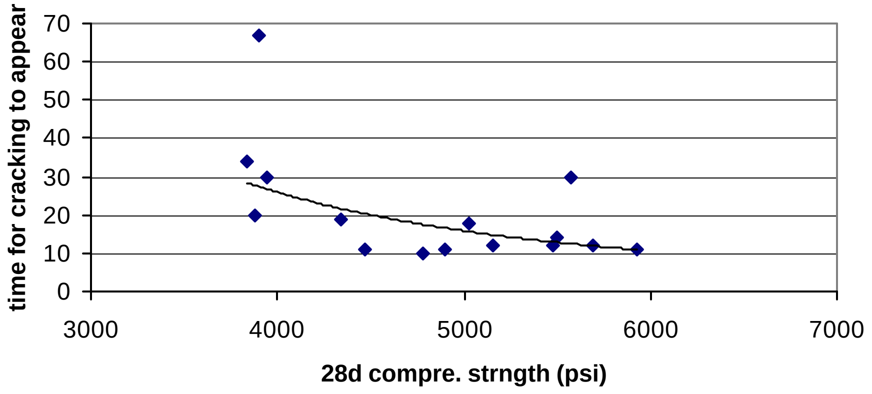
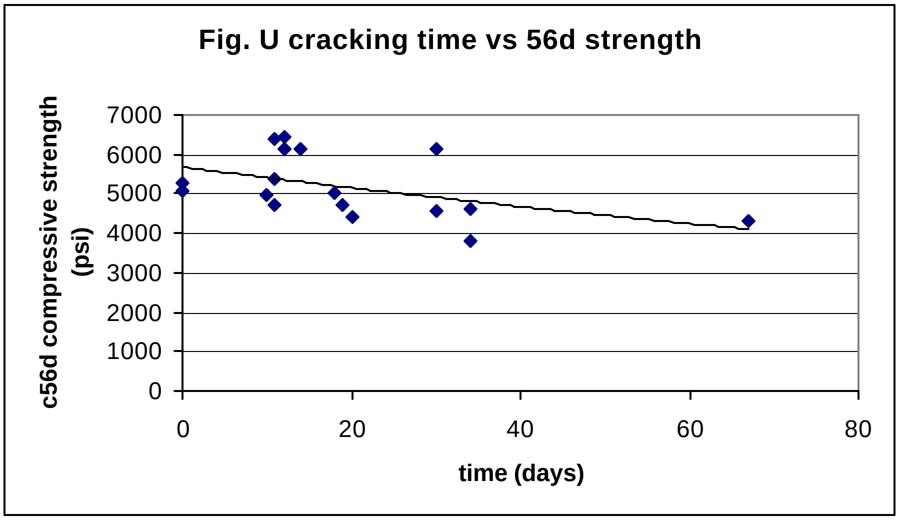
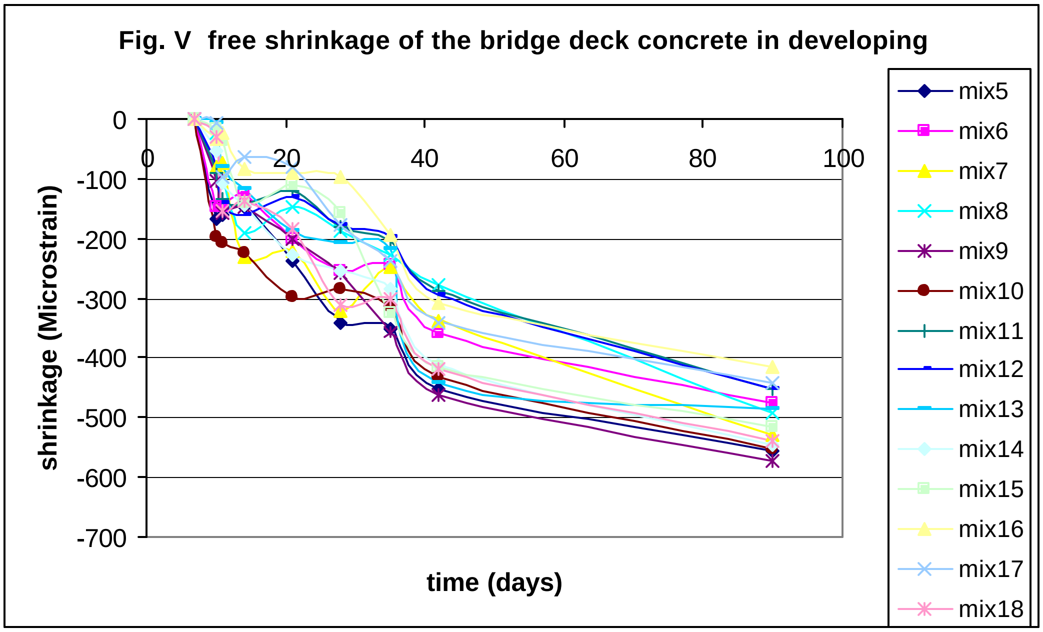


Fig. t cracking time vs 28d strength







11. The free shrinkage test was not very successful due to large scattering (see Fig. **v**). But, one important observation is that all concrete specimens have drying shrinkage less than 600 microstrain after about 90 days of exposure.

12. With the addition of silica fume in 4%, Class F fly ash in 20% of cement content, and water/cementitious ratio of 0.41 or lower, the 56d chloride permeability can be effectively reduced to below 2000 coulombs.

13. Based on the above discussion of the test results obtained in the Phase I study, the ranges of the concrete design parameters are

- cement content about 450 to 485 lb/yd^3
- w/m about 0.37 to 0.41
- fly ash addition about 20% to 25%
- silica fume 4%

5.3 Selection of Optimal Mix Designs for the Phase II Study

Step 1: Select the mixes with low chloride permeability from Fig. **g**. It is clear that Mixes 1, 2, 4, 7, 8, 10, 11, 13, 14, and 16 have relatively low chloride permeability. These mixes are marked in the first row of Table 6.

Step 2: Select the mixes with high compressive strength at 56 days from Fig. **k**. It is clear that Mixes 4, 7 through 18 have relatively high strength. These mixes are marked in the second row of Table 6.

Step 3: Select the mixes with long cracking time from Fig. **r**. It is clear that Mixes 1 through 8 have relatively longer cracking time. These mixes are marked in the third row of Table 6.

Step 4: Those mixes marked three times in Table 6 are selected as the optimal mix designs for the Phase II study. The selected mixes are: Mix 4, Mix 7, and Mix 8.

Table 6. Selection of the Optimal Mix Designs for the Phase II

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Permeability	✓	✓		✓			✓	✓		✓	✓		✓	✓		✓		
Strength				✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Cracking	✓	✓	✓	✓	✓	✓	✓	✓										
Selections				✓			✓	✓										

6. Phase II Study

The Phase II study was focused on Mixes 4-2, Mix 7, Mix 8, and Mix 14. Some important influential parameters on concrete properties that had not been examined in Phase I were studied in Phase II, including the type of fly ash, curing time, and aggregate gradation.

In addition to the selected mixes from Phase I, more mix designs were incorporated into the Phase II study, including two mix designs from Lafarge (the material supplier for the construction project of I-225 & Parker Rd.), and two mixes from CDOT - Class DT, and Class SF. Class SF was further modified for the application in the thin overlay on bridge decks.

The compressive strength test, the rapid chloride permeability test, and the ring test, as described in Section 4.4, were conducted for all mixes in the Phase II study.

In order to improve repeatability of the ring test, a trial test was conducted by using strain gages on the steel ring and on the surface of concrete.

6.1 Description of the Mixes in Phase II

1.	**Mix II7**	Same mix design as Mix 7 in Phase I.
2.	**Mix II8**	Same mix design as Mix 8 in Phase I, with higher w/c than II7.
3.	**Mix II8C**	Same mix design as II8, but with Class C fly ash.
4.	**Mix II8C-7d**	Same mix design as II8C but with 7-day curing. Ring test only.
5.	**Mix II8C-12d**	Same mix design as II8C but with 12-day curing. Ring test only.
6.	**La2**	Same mix design as Mix 2 of Lafarge.
7.	**La3**	Same mix design as Mix 3 of Lafarge.
8.	**La3F**	Same mix design as Mix 3 of Lafarge, but with Class F fly ash.
9.	**CD-SF**	Same mix design as Class SF of CDOT.
10.	**CD-DT**	Same mix design as Class DT of CDOT.
11.	**SFSP-C**	Modified mix design based on Class SF of CDOT with class C fly ash.
12.	**SFSP-F**	Modified mix design based on Class SF of CDOT with class F fly ash.
13.	**SFSP-I**	Modified mix design based on Class SF of CDOT with class F fly ash and adjusted aggregate gradation. The aggregate with intermediate size replaces 10% of the course aggregate.
14.	**II4**	Same mix design as Mix 4-2 in Phase I.
15.	**II4-3**	Modify Mix 4-2 in Phase I with more cement.
16.	**II4-4**	Modify Mix 4-2 in Phase I with higher gravel content.
17.	**II14**	Same mix design as Mix 14 in Phase I.
18.	**II 14-2**	Same mix design as Mix 14, and use intermediate size of gravel to replace a part of course gravel.
19.	**II 14-3**	Same mix design as Mix 14, and use intermediate size of gravel to replace a part of course gravel and a part of sand.

6.2 Test Results from Phase II

The test results from Phase II are summarized in Table 7.

Table 7. Testing Results of the Mixes in Phase II

		II 7	II 8	II 8-C	II8C-7d
Cement content (lb/yd^3)		485	485	485	485
Fly ash lb/yd^3 (wt. % of cement)		F97 (20)	F97 (20)	C110 (22.7)	C110 (22.7)
Silica fume lb/yd^3 (wt.% of cement)		19.4 (4)	19.4 (4)	19.4 (4)	19.4 (4)
W/(C+M)		0.37	0.41	0.41	0.41
Sand (lb/yd^3)		1422	1398	1380	1380
Gravel (lb/yd^3)		1595	1595	1595	1595
HRWR (oz/100 lb cement)		11.45	11.14	11.45	11.45
Micro Air (oz/100 lb cement)		1.56	1.6	1.04	1.04
Retarder (oz/100 lb cement)		3.1	3.2	3.1	3.1
Slump (inch)		3.0	5.5	4.5	3.2
Air content (%)		5.5	8.5	7.0	7.0
Permeability at 28 days (Coulomb)		2397 2355	2941 3161	4151 3938	N/a
Permeability at 56 days (Coulomb)		1475 1588	1393 1609	1894 2124	N/a
First cracking (days)		12	14	12	16
Compressive strength (psi)	3 days	3487	2512	3081	3081
	7 days	4419	3695	4060	4060
	28 days	5255	4657	5143	5143
	56 days	6513	5414	5541	5541

Table 7 (continued)

		IL8C-12d	La 2	La 3	La 3F
Cement content (lb/yd^3)		485	450	470	470
Fly ash lb/yd^3 (wt.% of cement)		C110 (22.7)	C130 (29)	C90 (19)	F79 (17)
Silica fume, lb/yd^3 (wt.% of cement)		19.4 (4)	25 (5.5)	25 (5.3)	25 (5.3)
W/(C+M)		0.41	0.42	0.42	0.42
Sand (lb/yd^3)		1380	1210	1250	1265
Gravel (lb/yd^3)		1595	1780	1780	1780
HRWR (oz/100 lb cement)		11.45	MRWR 2.2	MRWR 2.55	MRWR 2.55
Micro Air (oz/100 lb cement)		1.04	1.94	1.56	1.35
Retarder (oz/100 lb cement)		3.1	2.2	2.08	2.08
Slump (inch)		3.2	6.0	6.5	6.0
Air content (%)		7.0	6.5	7.5	6.5
Permeability at 28 days (Coulomb)		N/a	6859 9202	5281 5735	5893 4250
Permeability at 56 days (Coulomb)		N/a	3687 4184	2961 3361	3311 2370
First cracking (days)		13	10	16	17
Compressive strength (psi)	3 days	3081	2810	2070	2508
	7 days	4060	3662	3463	3065
	28 days	5143	4745	4355	4084
	56 days	5541	5255	5302	4769

Table 7 (continued)

		CD-SF	CD-DT	SFSP-C	SFSP-F
Cement content (lb/yd^3)		614	630	490	490
Fly ash lb/yd^3 (wt.% of cement)		0	C70 (11)	C111 (23)	F98 (20)
Silica fume lb/yd^3 (wt.% of cement)		46 (7.5)	0	19.6 (4)	19.6 (4)
W/(C+M)		0.35	0.44	0.41	0.41
Sand (lb/yd^3)		1146	1088	1322	1340
Gravel (lb/yd^3)		1776	1778	1595	1595
HRWR (oz/100 lb cement)		10.17	4.0	5.13	5.13
Micro Air (oz/100 lb cement)		1.9	0.96	1.2	0.82
Retarder (oz/100 lb cement)		2.62	2.4	2.05	2.05
Slump (inch)		3.0	6.0	4.5	4.5
Air content (%)		6.0	5.0	5.5	7.0
Permeability at 28 days (Coulomb)		917 1146	9207 6715	5682 5468	4392 4141
Permeability at 56 days (Coulomb)		538 560	6267 5429	4048 4748	2212 2346
First cracking (days)		9	11	12	15
Compressive strength (psi)	3 days	4299	3595	3025	3105
	7 days	5095	4857	4005	3583
	28 days	6425	5255	5167	4634
	56 days	6521	5414	5621	5541

Table 7 (continued)

		SFSP-I	II-4	II4-3	II4-4
Cement content (lb/yd^3)		490	450	465	465
Fly ash lb/yd^3 (wt.% of cement)		F98 (23)	F112.5 (25)	F116 (25)	F116 (25)
Silica fume lb/yd^3 (wt.% of cement)		19.6 (4)	18 (4)	18.6 (4)	18.6 (4)
W/(C+M)		0.41	0.37	0.37	0.37
Sand (lb/yd^3)		1340	1450	1436	1231
Gravel (lb/yd^3)		1595	1595	1595	1780
HRWR (oz/100 lb cement)		5.13	12.3	11.91	11.91
Micro Air (oz/100 lb cement)		1.02	0.87	0.87	0.54
Retarder (oz/100 lb cement)		1.71	2.16	2.16	2.16
Slump (inch)		6.5	5.5	6.5	6.0
Air content (%)		7.8	8	8	5.5
Permeability at 28 days (Coulomb)		8090 5850	3439 3084	3691 3592	3290 2747
Permeability at 56 days (Coulomb)		4265 3240	2270 2024	3057 3292	2528 2005
First cracking (days)		16	14	11	18
Compressive strength (psi)	3 days	2229	2412	2221	3487
	7 days	2826	3025	2962	4363
	28 days	3806	4140	4060	5645
	56 days	4204	4682	4307	5661

Table 7 (continued)

		II-14	II14-2	II14-3
Cement content (lb/yd^3)		515	515	515
Fly ash lb/yd^3 (wt.% of cement)		F103 (20)	F103 (20)	F103 (20)
Silica fume lb/yd^3 (wt.% of cement)		20.6 (4)	20.6 (4)	20.6 (4)
W/(C+M)		0.41	0.41	0.41
Sand (lb/yd^3)		1345	1345	1345
Gravel (lb/yd^3)		1595	1595	1595
HRWR (oz/100 lb cement)		4.89	4.89	4.89
Micro Air (oz/100 lb cement)		0.59	0.59	0.59
Retarder (oz/100 lb cement)		1.96	1.96	1.96
Slump (inch)		6.0	6.5	7.0
Air content (%)		5.0	7.0	8.0
Permeability at 28 days (Coulomb)		5364 4331	5540 6346	3497 4200
Permeability at 56 days (Coulomb)		2947 2947	3718 3626	3046 2717
First cracking (days)		17	10	13
Compressive strength (psi)	3 days	2811	2834	3081
	7 days	3981	3575	3925
	28 days	5605	4594	5032
	56 days	5963	4968	5645

6.3 Discussion

The 19 mixes in the Phase II study can be divided into six groups:

Group 1: II7 and II8-x;
Group 2: La-x;
Group 3: CD-x;
Group 4: SFSP-x;
Group 5: II4-x;
Group 6: II14-x.

in which x is for the testing variable in each group. For example, II8C (Mix 3) means Class C fly ash is used in the mix. The experimental results can then be compared between the groups and within each group.

(1) Chloride Permeability

It can be seen from Fig.1 that the permeability of Group 1 and Group 5 behaves better than the other groups. Within Group 1, higher w/c and Class-C fly ash result in higher value of the permeability (see II8C). Within group 5, an increase in cement content leads to an increase in the permeability (comparing II4 and II4-3), but an increase in the ratio of gravel to sand reduces the permeability (comparing II4-3 and II4-4).

Group 2 has a high level of chloride permeability, this may be a result of the relative high w/c (0.42). Class F fly ash helps to reduce the permeability slightly which can be seen by comparing La3 and La3F. La2 has high chloride permeability due to its high content of Class C fly ash.

In Group 3, CD-SF has the lowest permeability of all 19 mixes. This is because of its low w/c and relative high silica fume content. On the other hand, CD-DT has the highest permeability due to its high w/c and zero silica fume content.

Group 4 indicates the benefit of Class F fly ash in reducing permeability (comparing SFSP-C and SFSP-F). SFSP-I has relatively higher permeability; this might be due to its adjusted (or reduced) aggregate sizes.

Group 6 shows that the replacement of a part of coarse aggregate by gravel of smaller size is not beneficial for improving the permeability, but it is good when both gravel and sand are replaced by the intermediate aggregate at the same time.

The 56-day permeability results agree very well with the 28-day results.

Fig.1a 28d Permeability of phase II

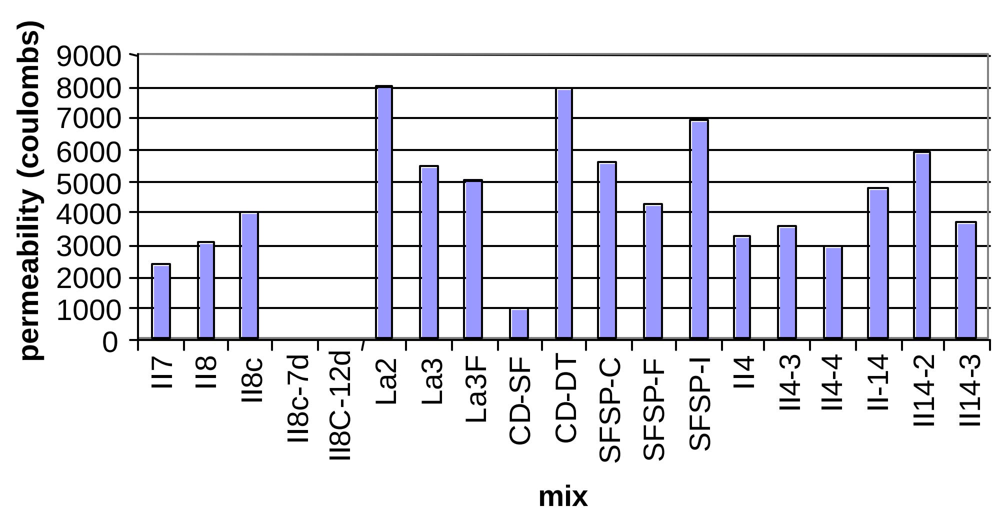
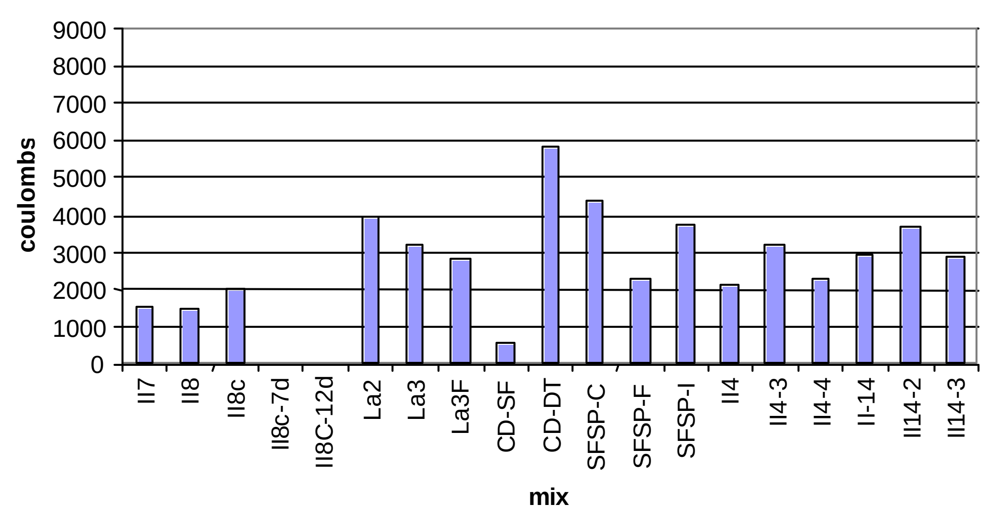


Fig.1b Permeability of 56 days



(2) Cracking time

In Group 1, II8 has longer cracking time than II7; and 7d curing for II8C (II8C-7d) results in a longer cracking time than 1d curing (II8C) and 12d curing (II8C-12d).

In Group 2, La3 has longer cracking time than La2, and Class F fly ash further extended the cracking time (La3F).

In Group 3, both of the mixes have shorter cracking times than others. So, the current CDOT DT and SF mixes have low crack resistance.

In Group 4 Class F fly ash shows its beneficial effect on crack resistance (See SFSP-F and SFSP-I).

In Group 5, higher cement content causes shortening of the cracking time (comparing II4 and II4-3), while increasing the content of course aggregate improves the cracking resistance (comparing II4-3 and II4-4).

Group 6 shows that using smaller aggregate to replace coarse aggregate reduces the cracking resistance (comparing II14 and II14-2). When part of the sand is replaced by larger aggregate, the cracking resistance is improved (comparing II14-2 and II14-3). So, the more coarse aggregate, the higher the cracking resistance.

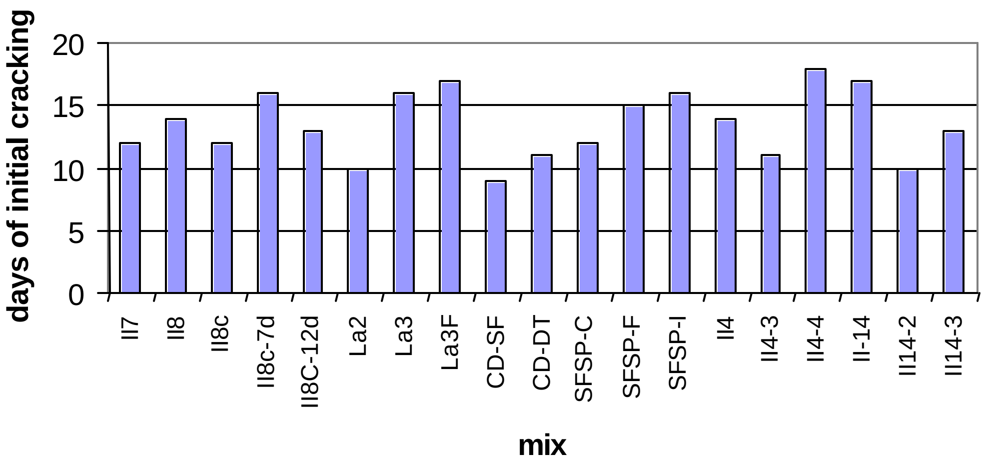
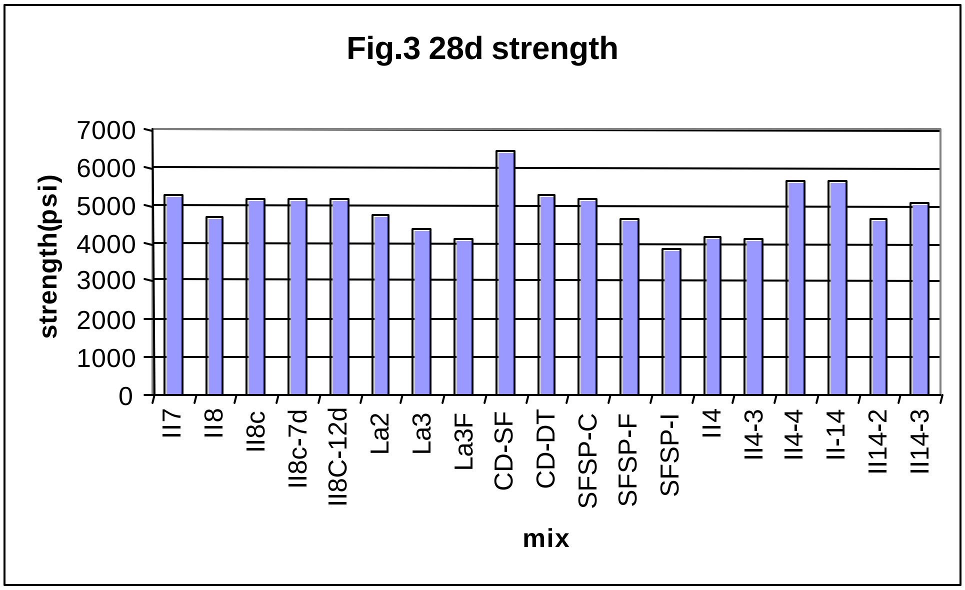
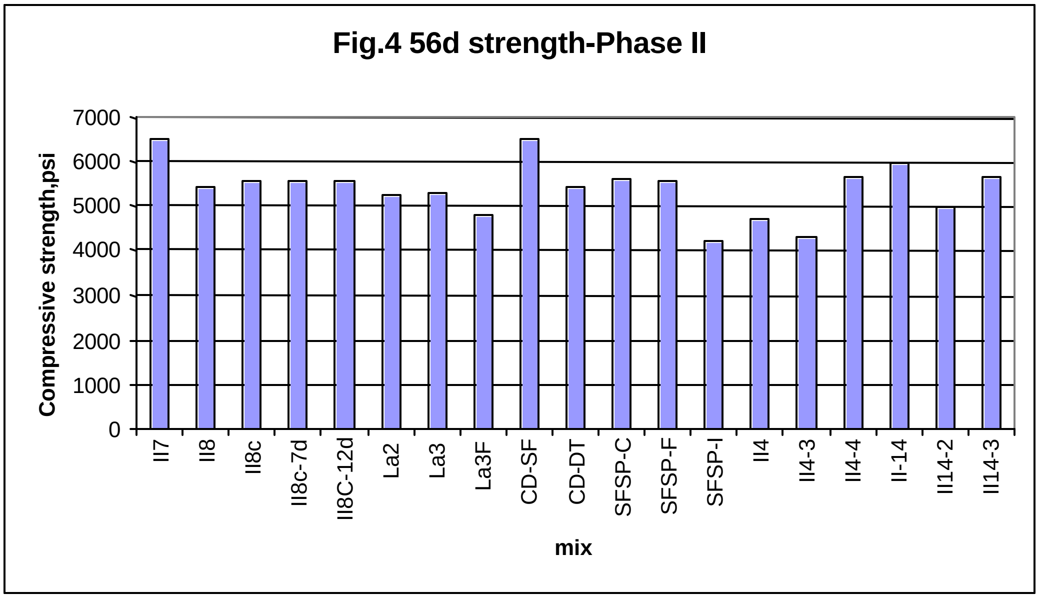


Fig.2 cracking time

(3) Compressive Strengths

The 28-day compressive strengths of the 19 mixes are shown in Fig.3. It can be seen that most of the mixes are above the design strength of 4500 psi. Group 5 seems relatively low, but may be improved by increasing the content of coarse aggregate (comparing II4-3 and II4-4) or by slightly reducing w/c. 56-day strengths are shown in Fig. 4; most of the mixes are above 5000 psi.





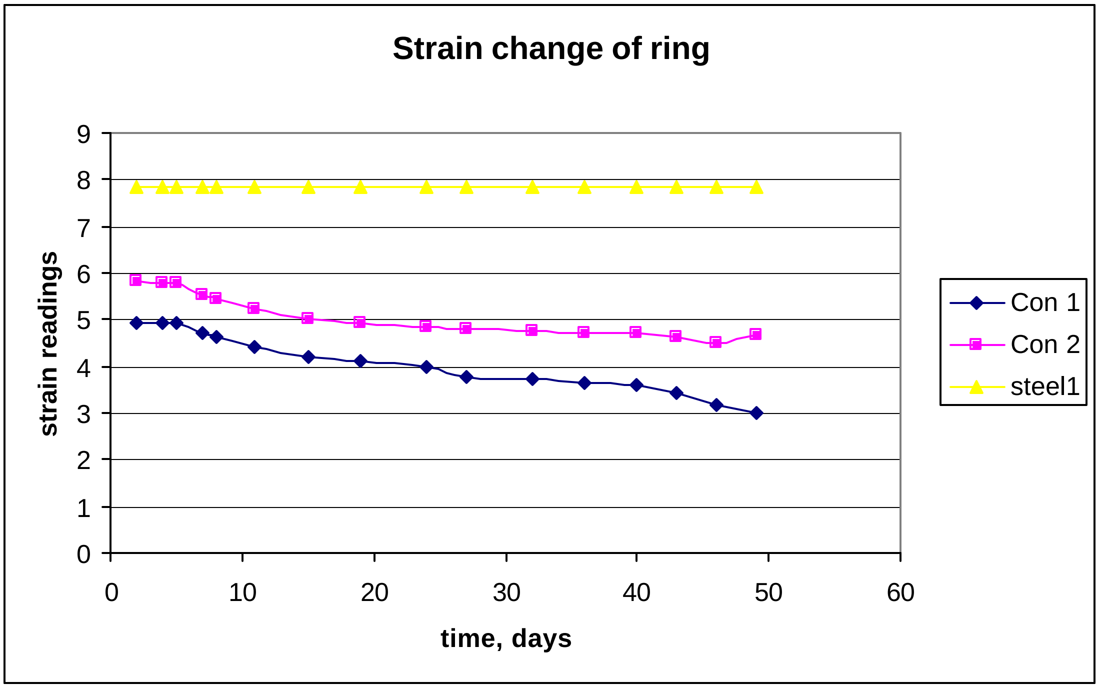
(4) Strain monitoring of a concrete ring

The strains measured on the outer surface of concrete and on the inner surface of the steel ring are plotted in Fig. 5. The experimental setup and the test data are listed in Appendix III. The concrete mix for this test was Mix II14-3.

One can see that there is basically no change in the level of strain in the steel ring, which is expected. The stiffness of the steel ring must be sufficiently high so that there is no noticeable deformation taking place when the concrete ring shrinks.

The strains on concrete started to drop after about 7 days, which is an indication of the formation of microcracking in the concrete. In general, the strain at the exact location of a crack increases with the propagation of the crack, all other locations experience unloading (i.e., decrease of strain). Visual observation on the concrete ring detected the first cracking on 13 days (see Table 7, the last mix). This means that strain monitoring is a more sensitive tool for detecting the microcracks on concrete rings. But the reliability of this technique needs to be confirmed by more tests. Moreover, since there is no sharp decline in the measured strains, the exact time of cracking cannot be determined.

Fig. 5 The recorded strains on the concrete and on the steel ring



6.4 Conclusions of the Phase II Study

1. Class F fly ash is better than Class C fly ash in improving both the chloride permeability and cracking resistance of concrete.

2. A proper increase in the content of coarse aggregate can improve the permeability, the cracking resistance, and 28-day strength.

3. Increase in the proportion of an intermediate size of gravel does not improve the cracking resistance of concrete, nor the permeability. A larger size and higher proportion of gravel should be used.

4. Longer curing time (12 days) seems to have an unfavorable effect on cracking resistance of concrete, but this need to be confirmed by a more detailed experimental study.

5. Strain monitoring on the surface of concrete ring provides an alternative method for determining the cracking time in the ring test. More tests need to be done to improve the technique.

7. Selection of the Best Mixes

Applying the same approach used in the Phase I study, the best mix designs for bridge decks can be selected from the 19 mixes.

Step 1: Select the mixes with low chloride permeability from Fig. 1b. It is clear that Mixes 1, 2, 3, 9, 12, 14 and 16 have relatively low chloride permeability. The critical level of the permeability used here for selecting the best mixes is about 2000 Coulomb. The selected mixes are marked in the first row of Table 8.

Step 2: Select the mixes with long cracking time from Fig. 2. It is clear that Mixes 2, 4, 7, 8, 12, 13, 14, 15 and 16 have relatively longer cracking time. The critical level of the cracking time used here for selecting the best mixes is about 13 days. The selected mixes are marked in the second row of Table 8.

Step 3: Select the mixes with high compressive strength at 28 days from Fig. 3. It is clear that Mixes 1, 3, 4, 5, 9, 10, 11, 16, 17 and 19 have relatively high strength. The critical level of the compressive strength used here for selecting the best mixes is about 5000 psi. The selected mixes are marked in the third row of Table 8.

Step 4: Those mixes marked three times in Table 8 are selected as the best mix designs. The selected mix is: Mix 16, which is Mix II4-4. If we use the compressive strength of 5000 psi at 56 days as the criterion in Step 3 (see Fig. 4), then Mixes 2 and 12 can also be selected, which correspond to Mix II8 and Mix SFSP-F.

Table 8. Selection of the best mix designs

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Permeability	✓	✓	✓						✓			✓		✓		✓			
Cracking		✓		✓			✓	✓				✓	✓	✓	✓	✓			
Strength (28d)	✓	✓*	✓	✓	✓				✓	✓	✓	✓*				✓	✓		✓
Selections		✓*										✓*				✓			

* If the compressive strength of 5000 psi at 56 days is used as the selecting criterion.

Considering overall performance of the concrete mixes tested, the ranges for the concrete design parameters can be determined. The range for cement content is from 465 to 485 lb/yd^3; water/cementitious ratio from 0.37 to 0.41; and Class F fly ash from 20% to 25%. Curing time is seven days.

Two mix designs are recommended for use in the summer and in the winter, respectively. In the summer season, Mix II4-4 is preferable. It has a low cement content of 465 lb/yd^3 and a high fly ash content of 25 wt.% of cement. The water/cementitious ratio can be slightly increased if necessary to improve workability. In the winter season, Mix II8 is preferable. It has higher cement content and lower fly ash content than Mix II4-4. In Mix II8, gravel content could be increased to 1780 lb/yd^3 and w/c could be slightly reduced. In both mixes, Class F fly ash should be used.

For the thin overlay concrete, Mix SFSP-F or Mix II4-4 or Mix II8 can be selected. If Mix II4-4 or Mix II8 is used for thin overlays, smaller aggregate should be used in the mix.

8. Overall Accomplishments

Compared with Class DT, the overall accomplishments of the Phase I and Phase II studies can be summarized:

- Cement content is reduced from above 600 lb/yd^3 to below 500 lb/yd^3.
- The chloride permeability is reduced from about 6000 Coulomb (at 56 days) to below 2000 Coulomb.
- Narrow ranges for concrete design parameters are identified, which provide flexibility for various deviations in concrete mix design to meet specific needs.
- Class F fly ash results in better durability performance than Class C fly ash.

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Appendix I. Size Distribution of Aggregate

Fig. I-1. The size distribution of the aggregate in most of the mixes

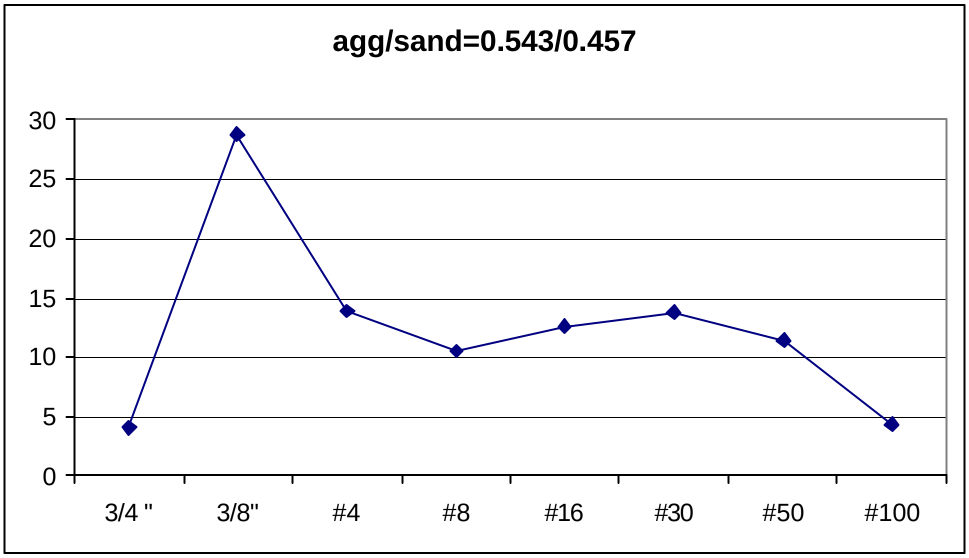


Fig. I-2. The size distribution of the aggregate used in Mix II14-2.

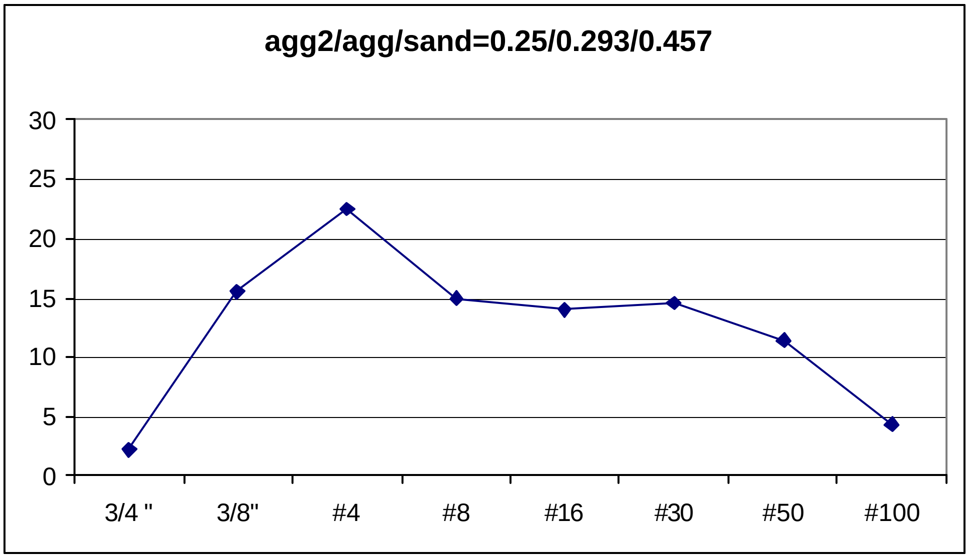
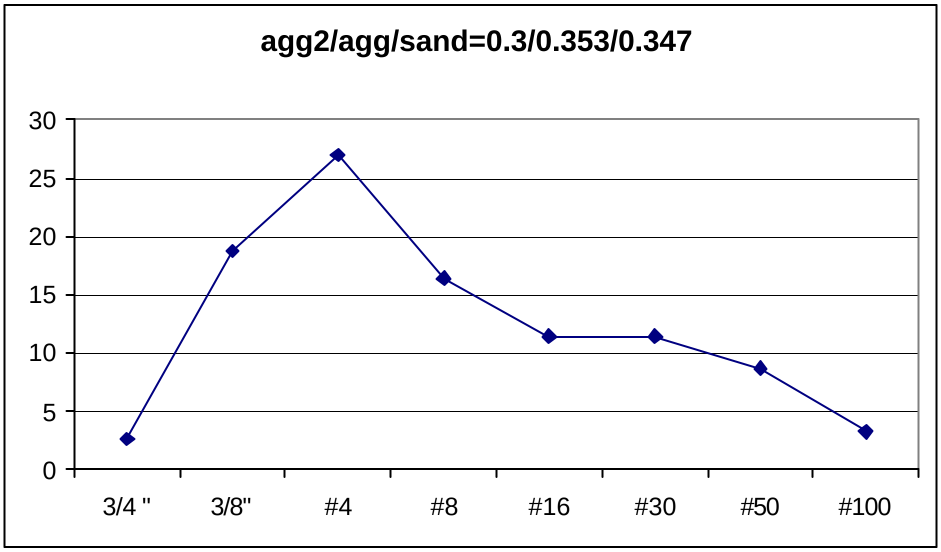


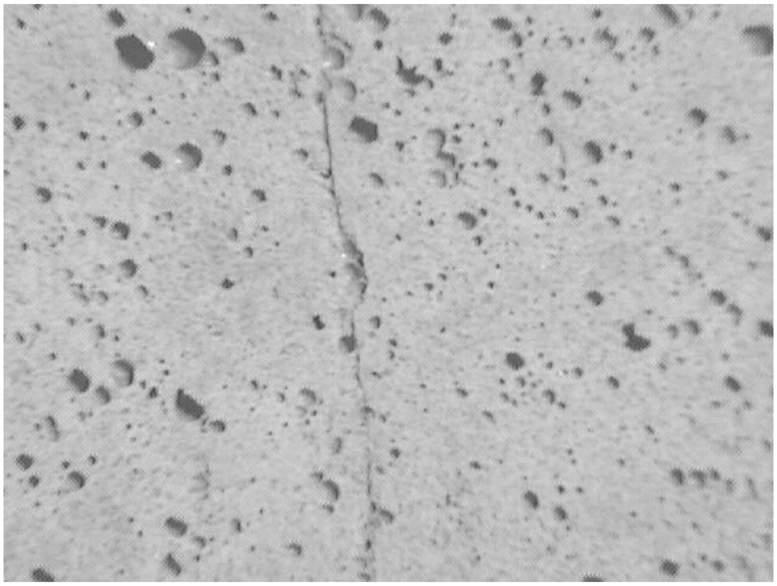
Fig. I-3. The size distribution of the aggregate used for Mix II14-3.

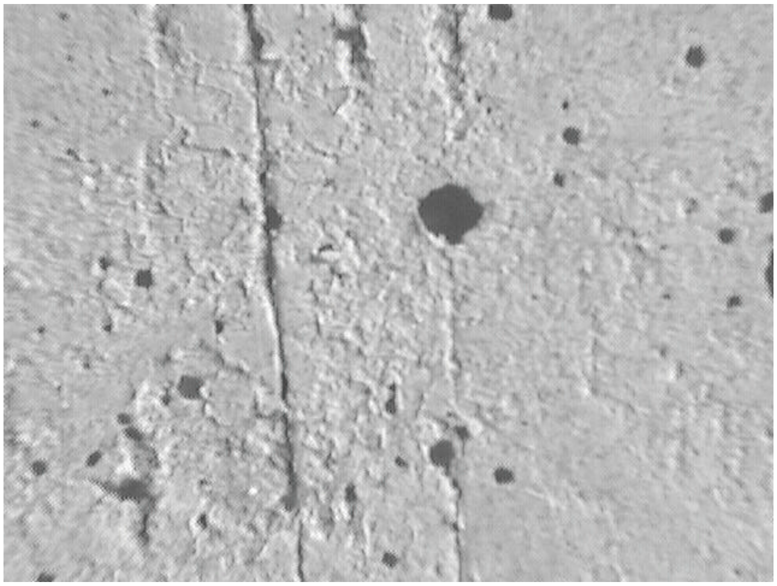


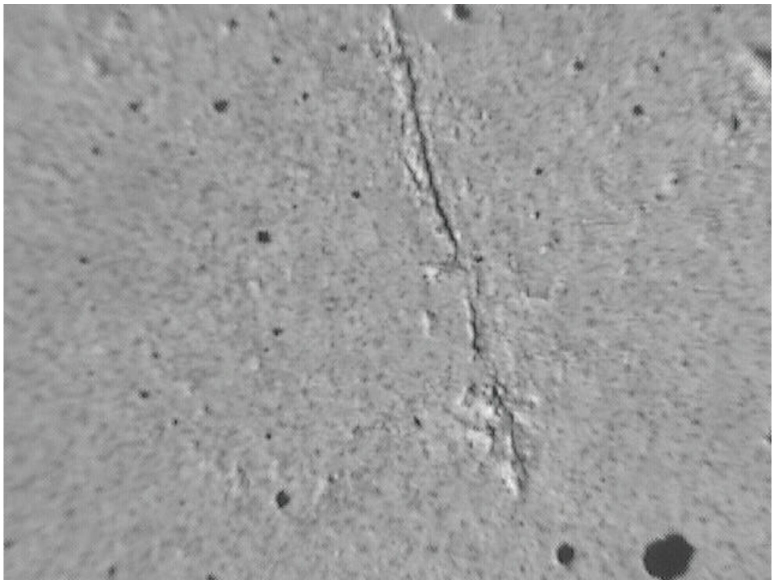
Appendix II. Apparatus and Images of Ring Tests

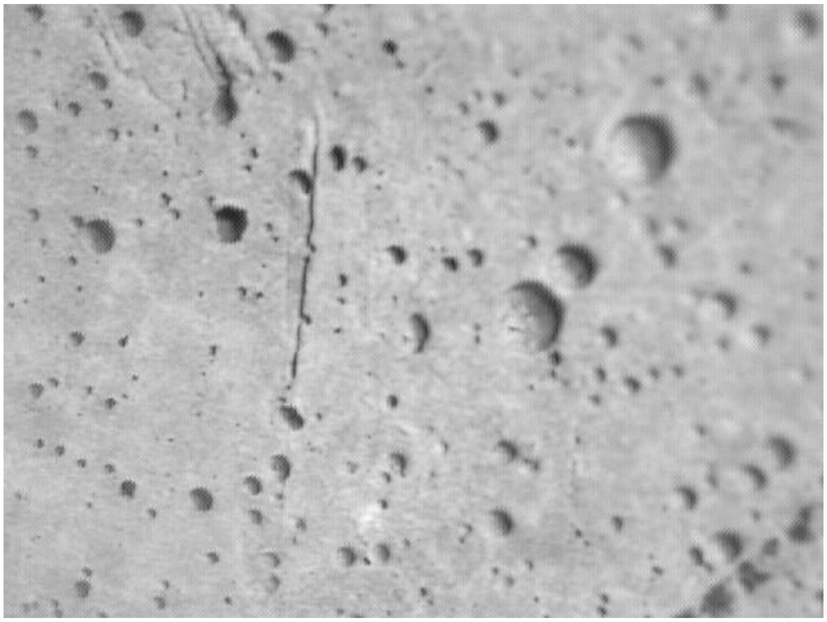
Fig. II-1. The experimental setup monitoring surface cracking on the concrete ring.

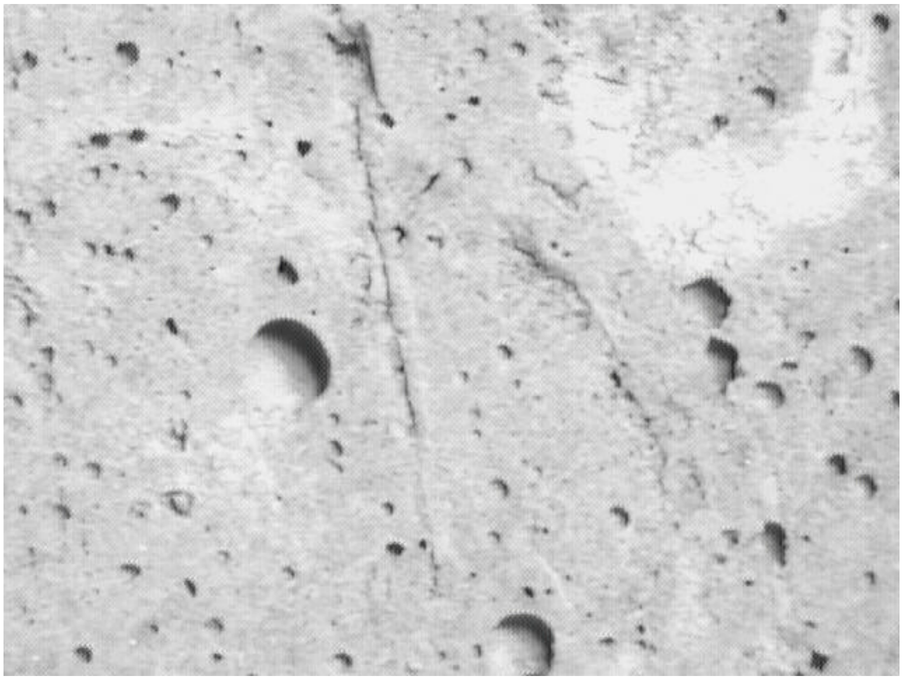
Fig. II-2. Surface cracks from the ring test.

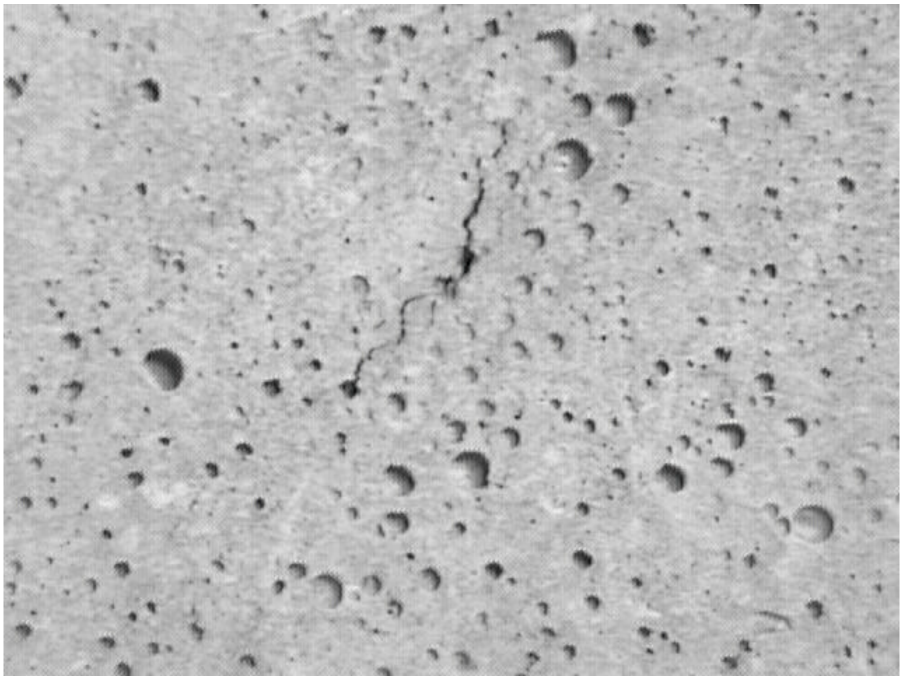












Appendix III. Monitoring Strains of the Ring Test

Fig. III-1 The data acquisition system used for monitoring the strains on the inner surface of the steel ring and on the outer surface of concrete.

Table III-1 Recorded strains (in unit e)

Time (days)	Con 1	Con 2	steel1
2	4.94	5.82	7.83
4	4.91	5.77	7.83
5	4.92	5.78	7.83
7	4.7	5.53	7.83
8	4.64	5.46	7.83
11	4.4	5.21	7.83
15	4.18	5.03	7.83
19	4.1	4.95	7.83
24	3.97	4.85	7.83
27	3.78	4.81	7.83
32	3.71	4.75	7.83
36	3.63	4.73	7.83
40	3.58	4.73	7.83
43	3.42	4.63	7.83
46	3.17	4.48	7.83
49	2.98	4.68	7.83