Effects of Diacrylate Monomers on the Mechanical Properties of Polymer Concrete Made with Wet Aggregates

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Received 23 January 2003; accepted 23 July 2003
DOI 10.1002/app.13407
Published online in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: Because normal polymer concrete does not work well with wet aggregates, diacrylate (DA) monomers were evaluated for improving the mechanical properties of polymer concrete made with wet aggregates. Zinc diacrylate (ZDA) and calcium diacrylate (CDA) were each used as an additive to resins (two epoxies). The variables were the amount of diacrylate monomers and the aggregate conditions (wet or dry). Compressive strength, flexural strength, workability, working time, and curing time were measured. ZDA was found to improve the workability and the working time, and CDA was found to improve the compressive and the flexural strength. © 2004 Wiley Periodicals, Inc. J Appl Polym Sci 94: 1077–1085, 2004

Key words: strength; monomers; additives; resins; compression

INTRODUCTION

Polymer concrete is the material made by replacing part or all of the cement hydrate binder of conventional mortar or concrete with polymers. This replacement has the effect of strengthening the cement hydrate binder with the polymers. These materials draw continue to much attention as high-performance materials in the construction industry as well as in the mechanical, electrical, and chemical industries.[1,2]

The purpose of this study was to evaluate the mechanical properties of the polymer concrete using the commercial metallic monomers and wet aggregates.

Research significance

Generally speaking, normal polymer concrete does not work well with wet aggregates.[3,4] Because most aggregates used to make polymer concrete are not absolutely dried, some work has been done on the production of commercial metallic monomers to compensate it.

Metallic monomers offer the possibility of the use of wet aggregates in polymer concrete and widen the application fields of polymer concrete repair.

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Contract grant sponsor: 2004 Hongik University Research Fund.

Journal of Applied Polymer Science, Vol. 94, 1077–1085 (2004)

EXPERIMENTAL

Materials

Resins

Two kinds of epoxy resins (A- and B-types) were used in making epoxy PC with wet aggregates. The epoxy resins were very viscous.

Initiators

Initiators are chemical compounds that decompose into free radicals, which are responsible for the initiation of the polymerization process. The initiator used in A-type epoxy PC was an amine initiator. No initiator was used for B-type epoxy PC.

Promoters

An accelerator was used in A-type epoxy PC, and EPI-CURE 3072 curing agent was used in B-type epoxy PC.

Monomers

Two monomers, zinc diacrylate (ZDA) and calcium diacrylate (CDA), were used in this study. They are both white powders that do not readily dissolve in either resins or monomers.

Aggregates

Fine and coarse aggregates, such as river sands and gravels, crushed sands, and stones recommended for ordinary cement concrete, were used for epoxy PC. The fine aggregate used throughout this study was

TABLE I
Mix Design for A-Type Epoxy Polymer Concrete

Material	Proportion (parts by mass)
A-type epoxy resin	5.5
Jeffamine (D-230)	1.8
Accelerator 399	1.1
Coarse aggregate (9.5 mm [three/eight in.])	55
All-purpose sand	27.5
Fly ash	9.2
Based on A-type resin	
Metallic monomer powder	5–15%

all-purpose sand. It was oven dried by the producer. The fineness modulus of sand was 2.35. The ⅜-in coarse aggregate was used in A-type epoxy PC. It was oven dried for 24 h at 250°F for dry aggregate PC. For wet aggregate PC, the 3% water of total aggregate mass was added.

Additives

Fly ash was used for A-type epoxy PC.

Testing procedures

Mixing and casting

In principle, the mix design of PC typically uses an aggregate gradation to provide the lowest possible void volume that will require the minimum polymeric binder contents necessary to coat the aggregates and to fill the voids.[5] In this study, the mix design was optimized for workability and strength without consideration of aggregate gradation because of the use of all-purpose sand.

ASTM C305 mixing was used as the standard mixing procedure for the mortar, using a planetary mixer. ASTM C305 mixing consists of a sequence of mixings that involve a total of 1.0 min at a paddle speed of 140 rpm, followed by a total of 1.5 min at a speed of 285 rpm.

A-type epoxy PC system. The binder formulation-to-graded aggregate ratio was 8.25 : 91.75 by mass. The proportions of the components by mass are shown in Table I.

B-type epoxy PC system. The B-type epoxy resin-to-aggregate ratio was 14.3 : 85.7 by mass. Table II indicates the proportions of all components by mass used in the B-type epoxy PC system.

Testing method

There are no standard tests that are directly applicable to polymer concrete. Therefore, ASTM standards developed for cement-based materials were used as guidelines whenever applicable.[6,7]

The compressive strength and the modulus of elasticity of specimens were measured using ASTM C 469-94 (Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression). The diameter and the height of cylinders were 3 and 6 in. each. The specimens were placed with the strain-measuring equipment on the lower platen or bearing block of the testing machine. The rate of loading was 0.05 in./min. The flexural strength of polymer concrete at room temperature was measured according to ASTM C 580-93 [Standard Test Method for Flexural Strength and Modulus of Elasticity of Chemical Resistant Mortars, Grouts, and Polymer Concretes (using simple beam with center-point loading)]. The test specimens were 2 × 2 × 12-in. beams. For testing, the beam was placed on two cylindrical supports spaced 9 in. apart. The rate of loading was 0.02 in./min.

The workability of polymer concrete at room temperature was measured in accordance with ASTM C 230-90 and C 109-92. The fresh polymer concrete was uniformly placed into the flow mold at the center of the flow-table top. The mold was gently lifted away from the fresh concrete 1 min after completing the mixing operation. Immediately, the flow table was dropped 25 times in 15 s. The flow was then determined by measuring the diameter of the fresh concrete at four equal intervals. The increase in diameter was averaged and workability was expressed as a percentage of the original base diameter.

The working time of the polymer concrete at room temperature was determined using the method described in JIS A 1186 (Method of Measurement for Working Life of Unsaturated Polyester Resin Concrete Japanese Industrial Standard).[8] The finger-touch method was used to measure the working life. Samples of the fresh polymer concrete in volumes of approximately 20 cm^3 were packed and sealed in polyethylene film bags secured with a rubber band. The moldable polymer concrete was monitored at frequent intervals by feeling the sample through the sides of the bag. As soon as the sample became noticeably stiffer to form, the time was noted and recorded as the end of working time. The period from the time of initiation to the end of working time was recorded as the working life.

Curing time was measured using the method adopted by The University of Texas Construction Ma-

TABLE II
Mix Design for B-Type Epoxy Polymer Concrete

Material	Proportion (parts by mass)
B-type resin	11.35
EPI-CUPE 3072 curing agent	2.95
All-purpose sand	85.7
Based on B-type resin	
Metallic monomer powder	5–15%

TABLE III
Compressive Strength and Modulus of Elasticity for A-Type Epoxy PC

Specimen	Aggregate	DA type	Level of DA (%)	F'_c at 28 days [MPa (psi)]	Modulus of elasticity [GPa (ksi)]
A1	wet		none	64.6 (9375)	33.2 (4816)
B1	wet	ZDA	5	47.0 (6819)	42.7 (6197)
C1	wet	ZDA	15	53.2 (7711)	42.1 (6113)
D1	wet	CDA	5	51.2 (7424)	43.1 (6254)
E1	wet	CDA	15	52.7 (7647)	36.6 (5307)
F1	dry		none	61.3 (8888)	35.9 (5211)
G1	dry	ZDA	5	63.9 (9271)	37.5 (5438)
H1	dry	ZDA	15	103.3 (14987)	48.7 (7059)
I1	dry	CDA	5	82.1 (11909)	49.7 (7213)
J1	dry	CDA	15	89.5 (12974)	47.3 (6856)

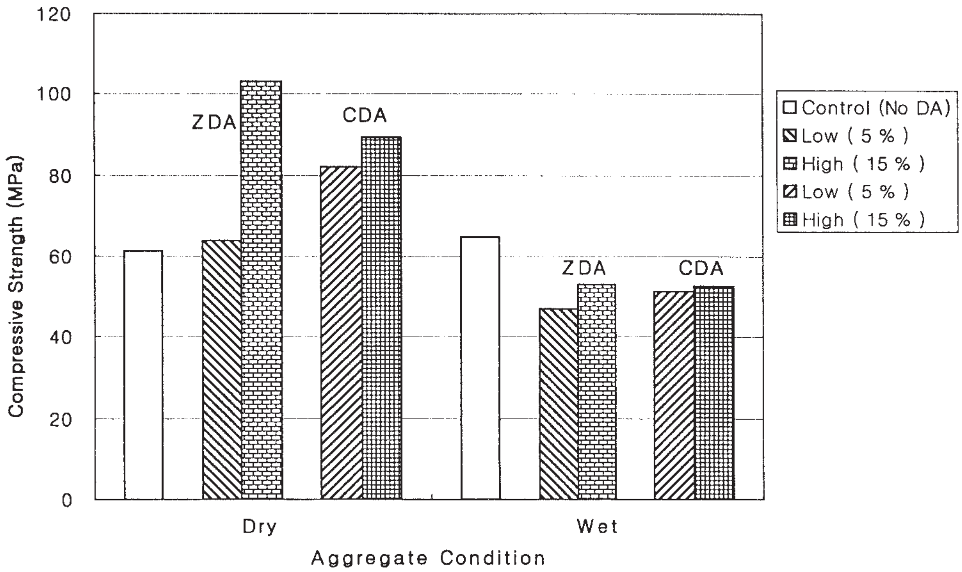

Figure 1 Compressive strength of A-type epoxy PC at 28 days (wet and dry aggregates).

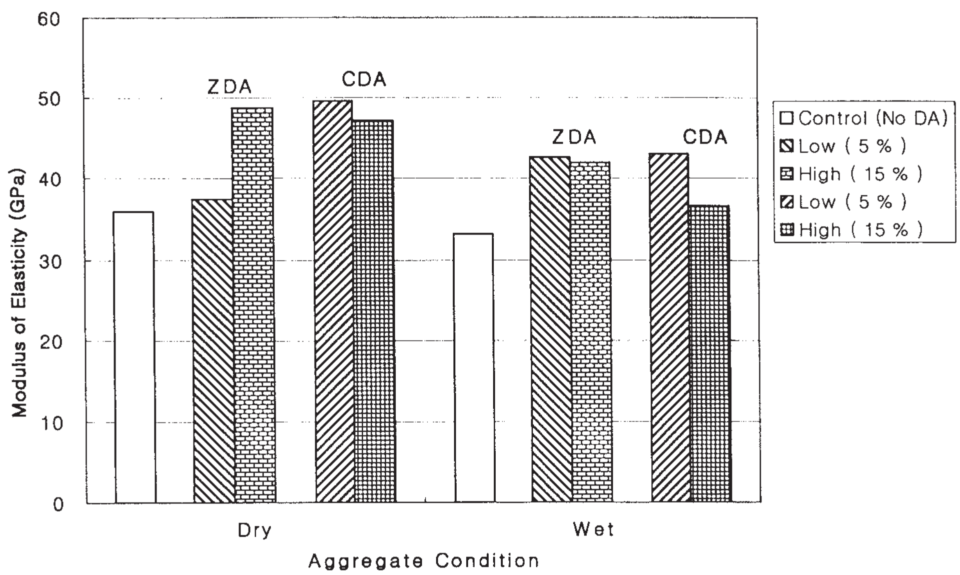

Figure 2 Modulus of elasticity of A-type epoxy PC (wet and dry aggregates).

TABLE IV
Compressive Strength for B-Type Epoxy PC

Specimen	Aggregate	DA type	Level of DA (%)	Compressive strength at 28 days [MPa (psi)]
A2	wet		none	40.3 (5849)
B2	wet	ZDA	5	42.6 (6178)
C2	wet	ZDA	15	47.0 (6819)
D2	wet	CDA	5	41.2 (5973)
E2	wet	CDA	15	49.0 (7110)
F2	dry		none	42.3 (6217)
G2	dry	ZDA	5	55.2 (8004)
H2	dry	ZDA	15	64.2 (9311)
I2	dry	CDA	5	53.6 (7773)
J2	dry	CDA	15	60.1 (8714)

terial Research Group (CMRG PC 02; Method for Determining Cure Times for Polymer Concrete). A thermocouple probe was inserted into the center of mass of a polymer concrete specimen while it was still fluid. At appropriate intervals, the temperature of the matrix was recorded. The interval between the time of initiation (combination of the initiator and the promoter in the matrix) until the time of peak exotherm (highest temperature) was considered the curing time.

RESULTS AND DISCUSSION

Compressive strength

The compressive strengths of A-type epoxy PC are shown in Table III and Figure 1. In general, ZDA and CDA did not work very well in the compressive strength of A-type epoxy PC with wet aggregate. However, as shown in Table III and Figure 2, the modulus of elasticity of PC was increased regardless of aggregate condition. A-type epoxy PC with dry aggregate gave a positive effect on the compressive strength. For instance, 15% of ZDA and 5% of CDA gave about 69 and 34% improvement over that of the control specimen, respectively.

As shown in Table IV and Figure 3, for B-type epoxy PC, ZDA and CDA influenced the compressive strength very well regardless of the aggregate condition. For example, 15% of ZDA and 15% of CDA gave about 17 and 22% improvement, respectively, in the wet aggregate condition. In the dry aggregate condition, 15% of ZDA and 15% of CDA gave about 50 and 40% improvement, respectively.

Flexural strength

The flexural strengths of A-type epoxy PC are shown in Table V and Figure 4. As in the case of compressive

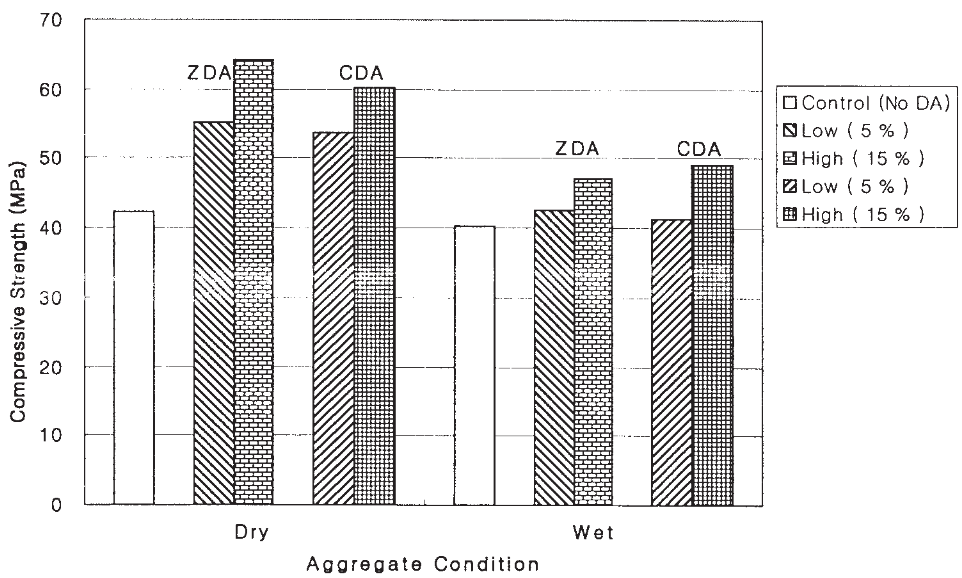

Figure 3 Compressive strength of B-type epoxy PC at 28 days (wet and dry aggregates).

TABLE V
Flexural Strength for A-Type Epoxy PC

Specimen	Aggregate	DA type	Level of DA (%)	Flexural strength at 28 days [MPa (psi)]
A1	wet		none	25.5 (3696)
B1	wet	ZDA	5	18.5 (2678)
C1	wet	ZDA	15	17.5 (2531)
D1	wet	CDA	5	20.9 (3038)
E1	wet	CDA	15	22.2 (3218)
F1	dry		none	29.6 (4292)
G1	dry	ZDA	5	31.2 (4528)
H1	dry	ZDA	15	31.8 (4613)
I1	dry	CDA	5	32.5 (4708)
J1	dry	CDA	15	33.3 (4832)

TABLE VI
Flexural Strength for B-Type Epoxy PC

Specimen	Aggregate	DA type	Level of DA (%)	Flexural strength at 28 days [MPa (psi)]
A2	wet		none	16.1 (2340)
B2	wet	ZDA	5	19.2 (2779)
C2	wet	ZDA	15	20.0 (2897)
D2	wet	CDA	5	20.5 (2970)
E2	wet	CDA	15	25.4 (3684)
F2	dry		none	25.5 (3701)
G2	dry	ZDA	5	25.7 (3729)
H2	dry	ZDA	15	26.2 (3797)
I2	dry	CDA	5	25.9 (3758)
J2	dry	CDA	15	26.8 (3893)

strength, ZDA and CDA did not work very well in the flexural strength of A-type epoxy PC with wet aggregate. A-type epoxy PC with dry aggregate positively influenced the flexural strength. For instance, 15% of ZDA and 5% of CDA gave about 7 and 13% improvement over that of the control specimen, respectively.

As shown in Table VI and Figure 5, for B-type epoxy PC, ZDA and CDA positively influenced the compressive strength, especially in the wet aggregate condition. For example, 15% of ZDA and 15% of CDA gave about 24 and 57% improvement, respectively, in the wet aggregate condition. For the dry aggregate condition, 15% of ZDA and 15% of CDA gave about 3 and 5% improvement, respectively.

Workability

The workability was measured through the use of a flow table. (see Tables VII and VIII; Fig. 6 and 7). The metallic DAs did not have a significant effect on the workability, regardless of the PC type. That is attributed to the fact that two DAs (ZDA and CDA) do not dissolve in epoxy monomers, and the viscosity of the epoxy monomers was not changed with the addition of those DAs.

Working time

The working time is a very important factor that influences the casting operation and the quality of the product. Longer times allowed too much monomer evaporation, and faster times did not allow enough batching and placement time. As shown in Table VII and Figure 8, in the case of A-type epoxy PC, it was observed that the working time for ZDA-modified batches with wet aggregate was increased with additional DA quantities. However, the working times for ZDA-modified batches with dry aggregate and CDA-modified batches were slightly reduced or maintained with additional DA quantities.

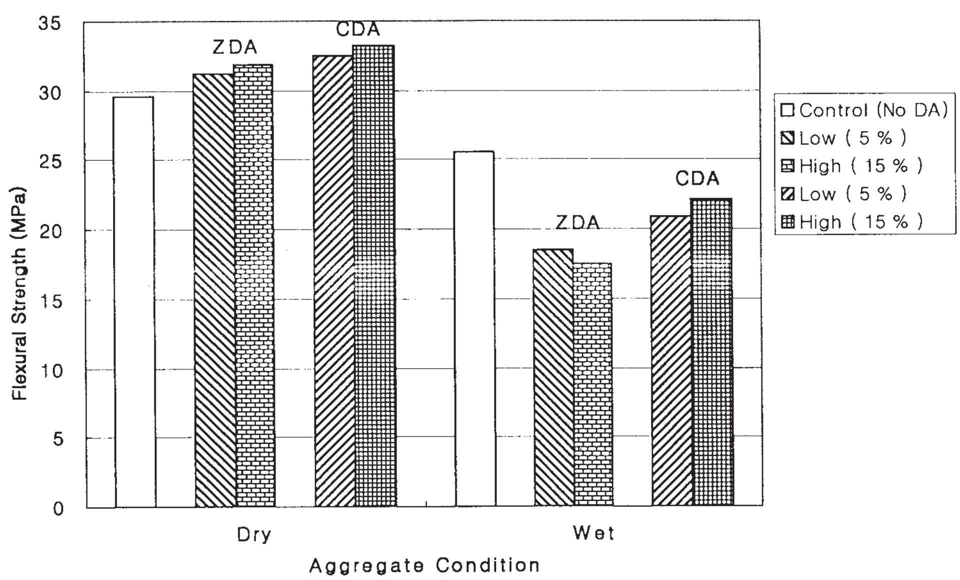

Figure 4 Flexural strength of A-type epoxy PC at 28 days (wet and dry aggregates).

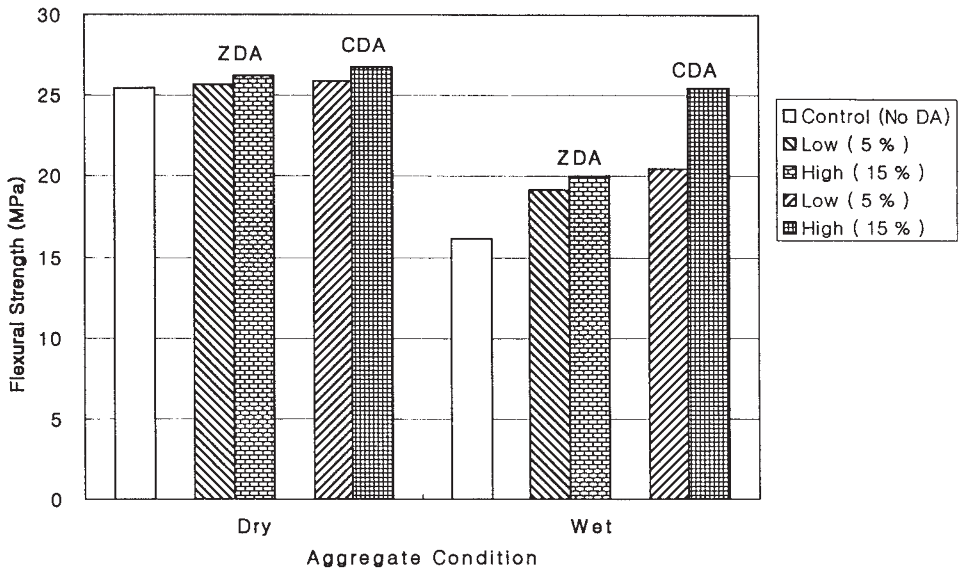

Figure 5 Flexural strength of B-type epoxy PC at 28 days (wet and dry aggregates).

In the case of B-type epoxy PC, as shown in Table VIII and Figure 9, it was observed that the working time for ZDA-modified batches was significantly increased with additional DA quantities. Therefore it was concluded that ZDA cannot be used for B-type epoxy resin. However, the working times for CDA-modified batches were slightly increased or maintained with additional DA quantities.

Curing time

As shown in Table VII and Figure 10, for A-type epoxy PC, it was observed that the curing time for ZDA-modified batches was slightly increased and decreased with aggregate conditions. However, the curing times for CDA-modified batches were almost the same with additional DA quantities.

TABLE VII
Workability, Working Time, and Curing Time for A-Type Epoxy PC

Specimen	Aggregate	DA type	Level of DA (%)	Workability	Working time (min)	Curing time (min)
A1	wet		none	110	50	40
B1	wet	ZDA	5	106	60	45
C1	wet	ZDA	15	106	62	50
D1	wet	CDA	5	109	50	45
E1	wet	CDA	15	110	50	45
F1	dry		none	104	38	40
G1	dry	ZDA	5	104	34	35
H1	dry	ZDA	15	104	32	30
I1	dry	CDA	5	104	34	45
J1	dry	CDA	15	104	33	45

TABLE VIII
Workability, Working Time, and Curing Time for B-Type Epoxy PC

Specimen	Aggregate	DA type	Level of DA (%)	Workability	Working time (min)	Curing time (min)
A2	wet		none	110	220	200
B2	wet	ZDA	5	105	1440 (1 day)	190
C2	wet	ZDA	15	109	21,600 (2 weeks)	230
D2	wet	CDA	5	109	250	165
E2	wet	CDA	15	108	300	165
F2	dry		none	105	160	135
G2	dry	ZDA	5	105	1440 (1 day)	155
H2	dry	ZDA	15	104	21,600 (2 weeks)	145
I2	dry	CDA	5	105	200	105
J2	dry	CDA	15	105	250	110

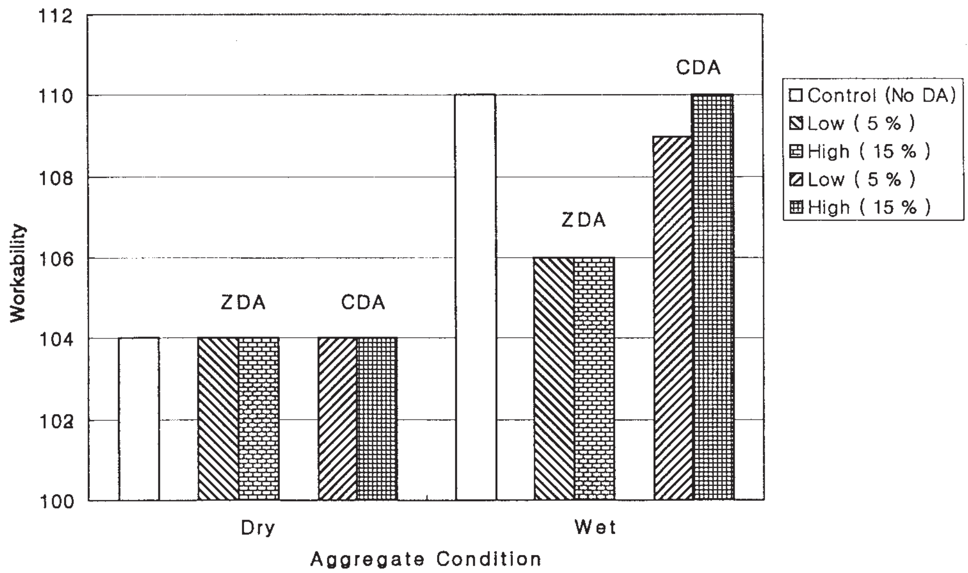

Figure 6 Workability of A-type epoxy PC (wet and dry aggregates).

For B-type epoxy PC, as shown in Table VIII and Figure 11, the curing time for ZDA-modified batches was slightly increased with additional DA quantities. However, the curing times for CDA-modified batches were slightly decreased with additional DA quantities.

CONCLUSIONS

The following conclusions can be drawn from the results of this study:

1. ZDA and CDA did not function positively with respect to compressive strength of A-type epoxy PC with wet aggregate. However, the modulus of elasticity of the PC was increased regardless of aggregate condition. A-type epoxy PC with dry aggregate exerted a positive effect on the compressive strength. For B-type epoxy PC, ZDA and CDA favorably affected the compressive strength regardless of the aggregate condition.
2. Similar to the case of compressive strength, ZDA and CDA did not work very well with respect to the flexural strength of A-type epoxy PC with wet aggregate. A-type epoxy PC with dry aggregate positively affected the flexural strength. For B-type epoxy PC, ZDA and CDA positively affected the compressive strength especially in the wet aggregate condition.
3. The metallic DAs did not have a significant effect on the workability regardless of the PC type. This

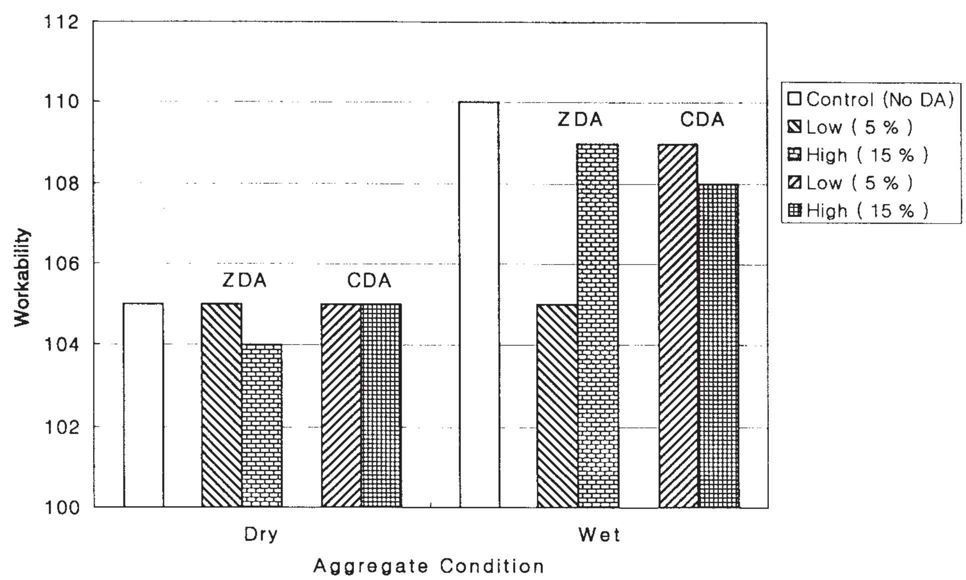

Figure 7 Workability of B-type epoxy PC (wet and dry aggregates).

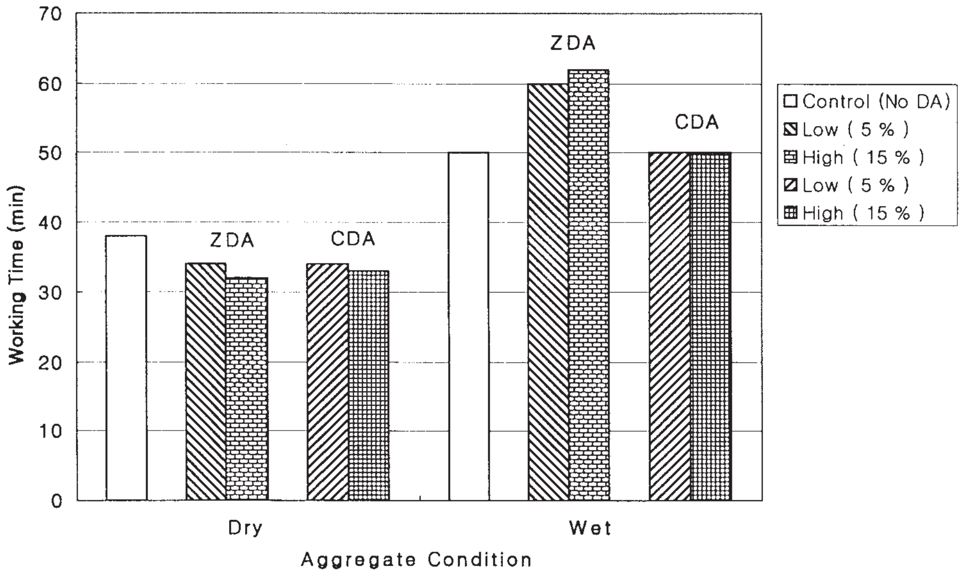

Figure 8 Working time of A-type epoxy PC (wet and dry aggregates).

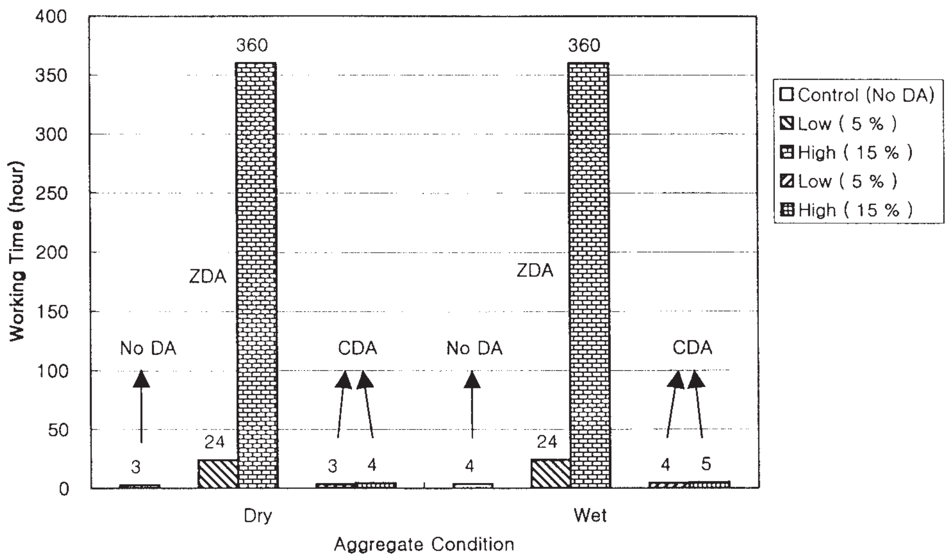

Figure 9 Working time of B-type epoxy PC (wet and dry aggregates).

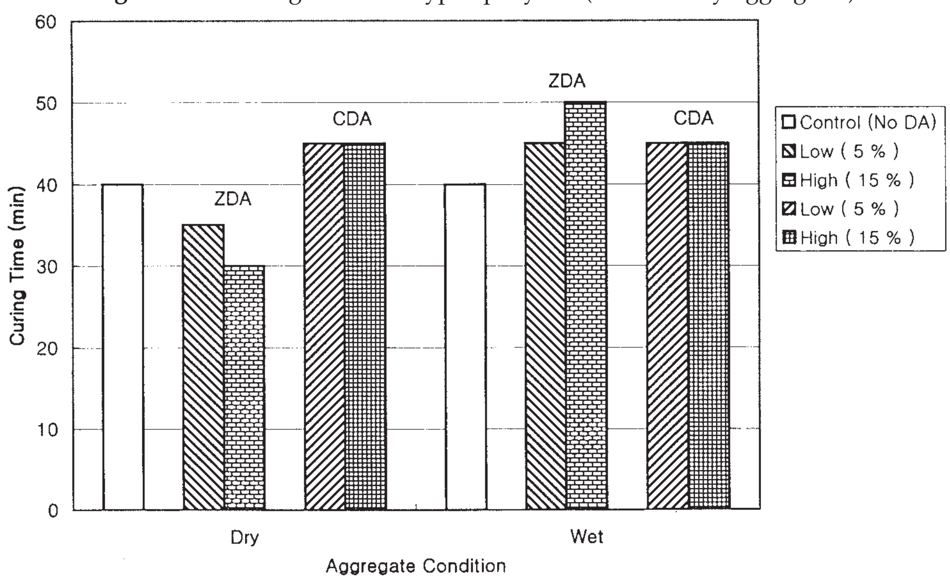

Figure 10 Curing time of A-type epoxy PC (wet and dry aggregates).

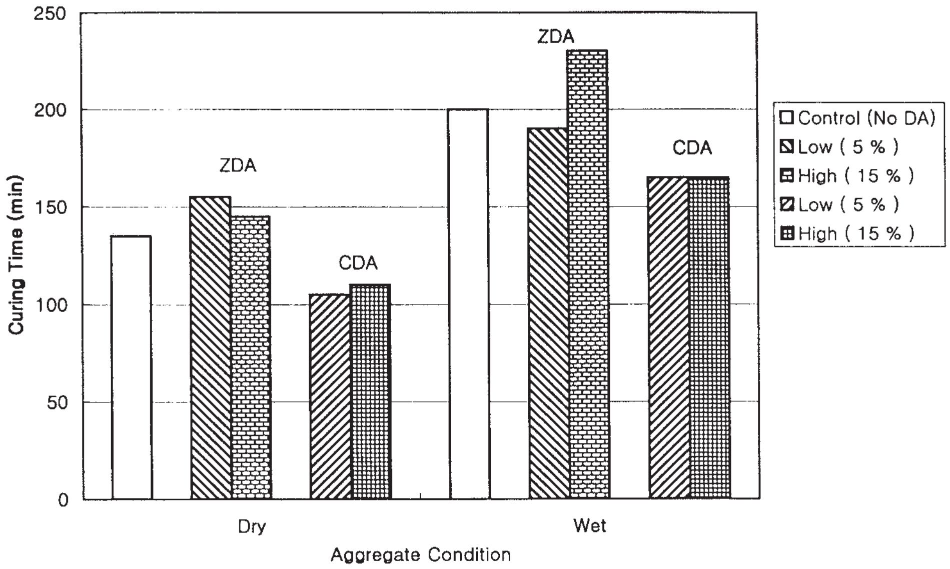

Figure 11 Curing time of B-type epoxy PC (wet and dry aggregates).

is attributed to the fact that two DAs (ZDA and CDA) do not dissolve in epoxy monomers, and the viscosity of the epoxy monomers was not changed with the addition of those DAs.

4. In the case of A-type epoxy PC, it was observed that the working time for ZDA-modified batches with wet aggregate was increased with additional DA quantities. However, the working times for ZDA-modified batches with dry aggregate and CDA-modified batches were slightly reduced or maintained with additional DA quantities. For B-type epoxy PC, it was observed that the working time for ZDA-modified batches was substantially increased with additional DA quantities. Therefore it was concluded that ZDA cannot be used for B-type epoxy resin. However, the working times for CDA-modified batches were slightly increased or maintained with additional DA quantities.
5. For A-type epoxy PC, it was observed that the curing time for ZDA-modified batches was slightly increased and decreased with aggregate conditions. However, the curing times for CDA-modified batches were almost the same with additional DA quantities. In the case of B-type epoxy PC, it was observed that the curing time for ZDA-modified batches was slightly increased with additional DA quantities. However, the curing times for CDA-modified batches were slightly decreased with additional DA quantities.

This work was supported by 2004 Hongik University Research Fund.

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