This is to certify that the

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DEVELOPMENT AND APPLICATIONS OF LIGHT-WEIGHT

CARBON FIBER REINFORCED CEMENT COMPOSITES

presented by

Mohamad Nagi

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Civil Engr.

Major professor

Date March 16, 1990

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DEVELOPMENT AND APPLICATIONS OF LIGHT-WEIGHT CARBON FIBER REINFORCED CEMENT COMPOSITES

By

Mohamad Nagi

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Civil and Environmental Engineering

1990

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ABSTRACT

DEVELOPMENT AND APPLICATIONS OF LIGHT-WEIGHT CARBON FIBER REINFORCED CEMENT COMPOSITES

By

Mohamad Nagi

The main thrust of this research was to develop light-weight carbon fiber reinforced cement (CFRC) composites for application to thin-sheet cement products. The optimum matrix mix composition and the desirable fiber length and volume fraction for use in the composite material were decided. Various aspects of the composite material performance characteristics were assessed, and applications of the developed material in cladding panels were investigated.

Studies conducted for matrix mix optimization dealt with the selection of the light-weight aggregate size and volume fraction for use in CFRC composites, and also with the selection of effective dispersants for carbon fibers in cement-based materials. The desirable combinations of matrix mix composition and fiber reinforcement conditions were also

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The developed light-weight CFRC composites were characterized through comprehensive experimental studies on the flexural and compressive behavior, impact resistance, shrinkage characteristics, specific gravity, and freeze-thaw durability of the material. All the test results were analyzed statistically in order to reliably establish the trends in the effects of different variables as well as the specimen size on the composite material performance. Statistical variations in material properties were also established.

An experimental study was conducted on large-scale CFRC cladding panels in order to verify the practicality of construction and the performance of light-weight CFRC composites in actual cement products. The results indicated that light-weight CFRC composites present an attractive alternative for the construction of thin-sheet cement products with reduced dimensions and unit weight, as well as extending service life.

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ACKNOWLEDGEMENT

Financial support for the performance of this research program was provided by the U.S. Department of Housing and Urban Development, the Carbon Fibers Division of Ashland Petroleum Company, and the Research Excellence Fund of the State of Michigan. These contributions are gratefully acknowledged.

The author would like to express his sincere gratitude to Dr. Parviz Soroushian whose supervision and guidance and encouragement were heightened not only by his friendly nature, but also by his genuine concern and understanding. He also would like to thank the other guidance committee members, Dr. W. Bradley, Dr. L. Segerlind, and Dr. J. Masterson for their guidance and kindness, and sincere appreciation to Dr. W. Taylor and Dr. L. Drzal and Dr. R. Harichandran for their support throughout this program, and great appreciation to Mr. Sia Ravanbakhsh for his help.

Most of all, he would like to thank his wife, Fardoos, for her love, patience and encouragement, and great appreciation for his family for their support.

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CHAPTER 1

INTRODUCTION

Cementitious materials are weak in tension, and they fail in a brittle manner under different stress conditions. These problems generally result from the ease of initiation and propagation of microcracks and also from the lack of post-cracking tensile resistance of cement-based materials.

Microcracks are initiated in cement products (at the interfaces between the cement paste and mix inclusions), prior to any external loading, by the drying shrinkage and bleeding effects and also by the settlement of the paste. Under tensile stress systems (which could be produced by compressive, flexural or tensile loads), microcracks tend to propagate and interconnect between the internal flaws of cementitious materials. This accounts for the increased nonlinearity in material behavior. Microcrack propagation could also be caused by the fatigue or sustained loads, or by the repeated action of freeze-thaw cycles.

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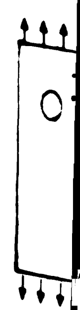

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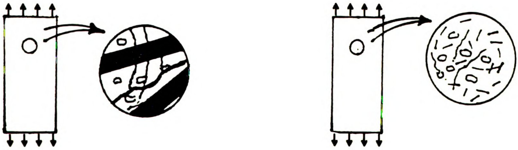
Figure 1.

In order to effectively hinder the propagation of microcracks between internal flaws in cementitious matrices, fibers should be spaced closely enough to fill in between the flaws. Steel fibers, with diameters of the order of 500 microns at typical volume fractions of about 1%, have average spacings of the order of 5000 microns inside the cementitious matrices. They can not effectively prevent the propagation of microcracks between internal flaws, which are typically spaced at about 500 microns (Figure 1.1a). Carbon fibers with diameters of the order of 10 microns are, however, spaced closely enough to be encountered frequently by the microcracks (Figure 1.1b).



(a) Steel Fiber

(b) Carbon Fiber

Figure 1.1 Microcrack Propagation in Steel Vs. Carbon Fiber Reinforced Cementitious Composites.

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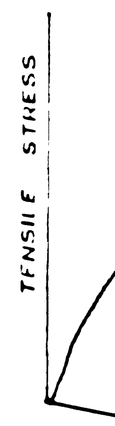

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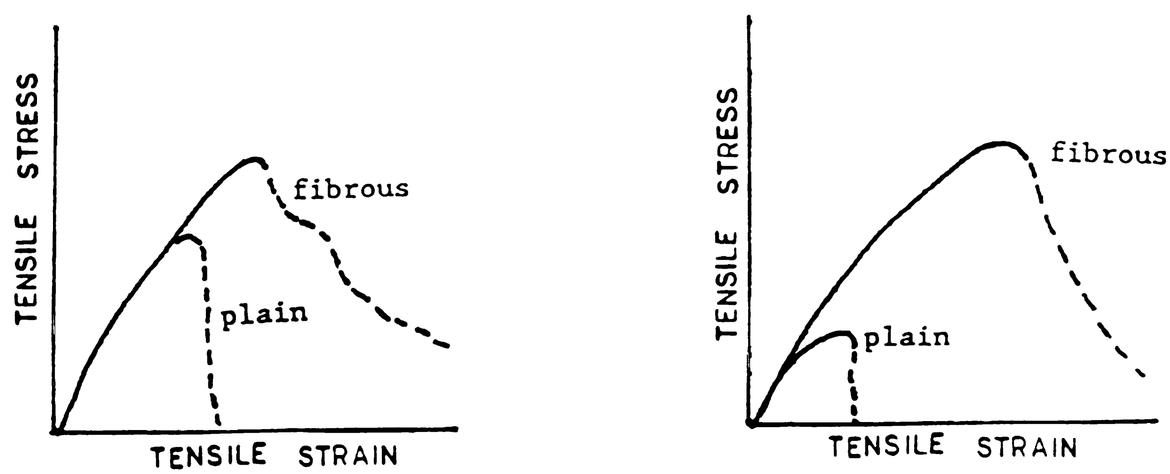
Figure 1

Carbon fibers force the microcrack to be shifted and branched before they can continue their propagation. This phenomenon, the nature of which depends on the fiber-matrix interfacial bond characteristics, delays the formation of an unstable microcrack system, and thus increases the tensile strength and pre-peak toughness of the material. This illustrates the less desirable pre-peak tensile behavior of steel fiber reinforced concrete (Figure 1.2a) when compared with that of carbon fiber reinforced cementitious composites (Figure 1.2b).



(a) Steel Fiber (b) Carbon Fiber

Figure 1.2 Pre-Peak Tensile Resistance of Steel Vs. Carbon Fiber Reinforced Cementitious Composites.

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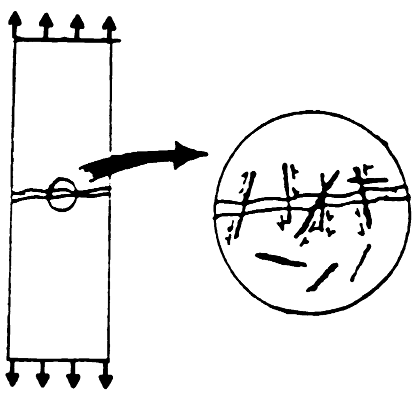
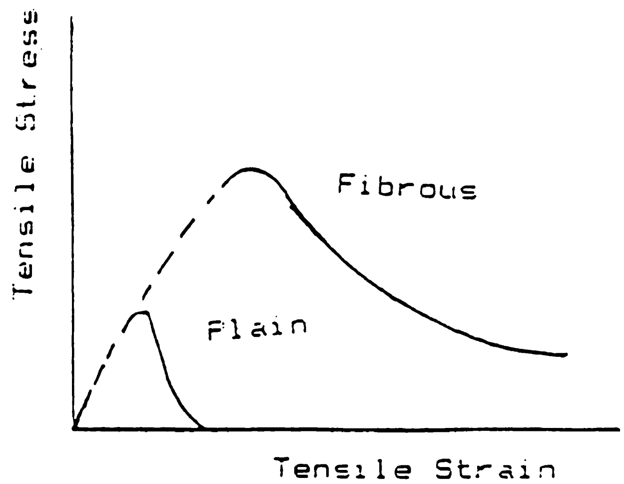
Upon the formation of an unstable microcrack system, which usually occurs at the peak tensile stress, fibers would be bridging the few macrocracks which appear at this stage, restraining the widening of cracks by their pull-out resistance. The effectiveness of fibers in improving the post-peak tensile behavior of cementitious materials depends on their pull-out behavior (Figure 1.3), which is a function of the length of fibers and their interfacial bond characteristics.



(a) Bridging Action



(b) Post-Peak Behavior

Figure 1.3 Pull-Out Behavior of Fibers at Macrocracks in the Post-Peak Region.

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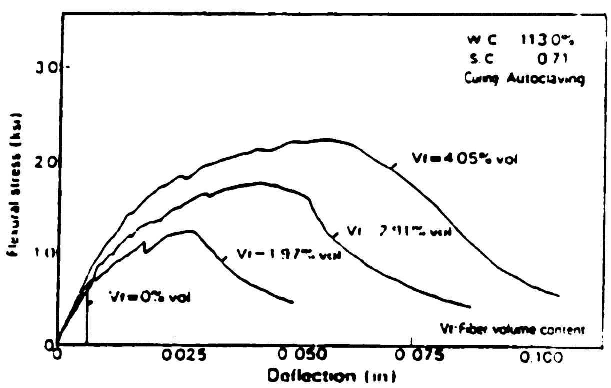
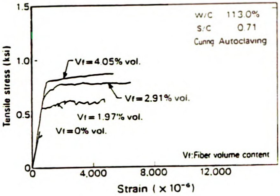
The crack-stabilizing actions of carbon fibers in cementitious matrices result in major improvements in the flexural and direct tensile strength and deformation characteristics (Figures 1.4a, b) [1-4], impact resistance (Figure 1.4c) [1], and freeze-thaw durability (Figure 1.4.d) [1,3] of the composite . The typical improvements shown in Figure 1.4 correspond to the use of carbon fibers with length and diameter of 10 and 3000 microns, respectively.

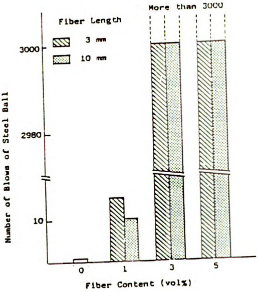


(a) Flexural Behavior

Figure 1.4 (cont'd.)

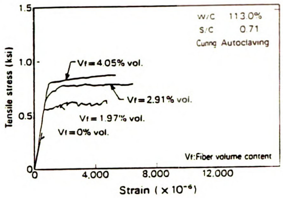


(b) Direct Tensile Behavior

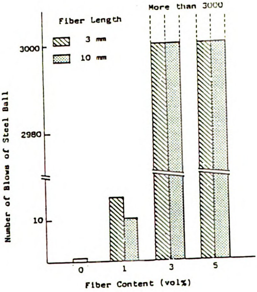


(c) Impact Resistance

Figure 1.4 (cont'd.)



(b) Direct Tensile Behavior



(c) Impact Resistance

Figure 1.4 (cont'd.)

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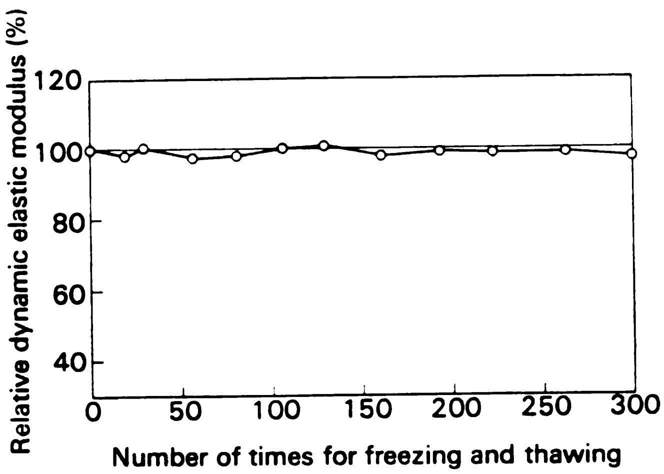

(d) Freeze-Thaw Durability

Figure 1.Typical Improvements in Performance Characteristics of Cementitious Materials Resulting from Carbon Fiber Reinforcement [1-5].

Introduction of carbon fibers to cement-based materials started in the early 70's. The first research study on carbon fiber reinforced cement (CFRC) was published by Ali et al. in 1972 [5]. After this publication, some research activities on CFRC were reported by Waller [6], Sakar and Bailey [7], and Briggs et al.[8], who concentrated on the use of relatively expensive PAN (polyacrilonitrile)-based continuous carbon fibers, and their efforts were not extended towards

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large-scale practical applications. Fabrication processes developed in these projects for CFRC involved hand lay-up and filament-winding The development of relatively low-cost pitch-based short carbon fibers in the recent years, which can be manufactured from either petroleum or coal tar pitch, has led to the commercialization of cement products reinforced with short, uniformly dispersed carbon fibers [3,4,9,10].

The desirable durability characteristics and mechanical properties of carbon fiber reinforced cement composites make them strong candidates for use in thin-sheet cement products exposed to severe load and environmental effects. There are potentials for making the material more attractive through the use of light-weight aggregates for reducing its unit weight and controlling dimensional instabilities.

This dissertation presents the results of a research work on the development and characterization of light-weight carbon fiber reinforced cement composites for application to cladding panels and other thin-sheet cement products. For this purpose, the optimum cementitious matrices and fiber reinforcement conditions were selected, and the mechanical, physical and durability characteristics of the composite material were assessed. The size effects and statistical variations in the properties of CFRC composites were also investigated, and practical issues related to the construction and field performance of cladding panels made with carbon fiber reinforced cement composites were also addressed.

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Variations in the mechanical properties of carbon fiber reinforced cement composites are reviewed in Chapter 2. Statistical analyses were conducted on replicated test data in order to investigate these variations and their practical implications.

Optimized use of light-weight aggregates in carbon fiber reinforced cement composites is the subject matter for Chapter 3. In order to decide the optimum size and loading of light-weight aggregates, composites with different fiber volume contents incorporating different fractions of light-weight aggregates with two different maximum particle sizes were tested for flexural strength and toughness, compressive strength, impact resistance, specific gravity and restrained drying shrinkage.

In Chapter 4, the results of an experimental study on the effectiveness of different dispersing agents in uniform dispersion of carbon fibers in cementitious matrices are reported. This presents an effort towards optimizing the matrix mix composition in CFRC composites.

Chapter 5 presents the results of an experimental study on the effects of cross-sectional dimensions on the flexural strength of carbon fiber reinforced cement composites. Three different specimen sizes were considered and statistical analyses were conducted on replicated test data to verify these effects. The results can help in deriving conclusions for actual cement products using test data obtained with relative

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Any construction material developed for outside exposure in cold climates has to be frost resistant. The freeze-thaw durability of light-weight carbon fiber reinforced cement composites incorporating different fiber and aggregate volume fractions is reviewed in Chapter 6.

Application of carbon fiber reinforced cement composites to cladding panels is the suject matter for Chapter 7. The practicality of construction, and the performance characteristics of carbon fiber reinforced cement cladding panels and their connections under wind loads were investigated through large-scale tests.

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CHAPTER 2

STATISTICAL VARIATIONS IN THE MECHANICAL PROPERTIES OF CARBON FIBER REINFORCE CEMENT COMPOSITES

2.1 INTRODUCTION

There are several factors which tend to increase the statistical variations in properties of fiber reinforced cement composites when compared with those of the corresponding plain cementitious materials. These factors include: (a) variations in the concentration of fibers at different locations inside the mix; (b) uncertainties in the degree of fiber coating by the cementitious matrix which decides the interfacial bond properties; (c) the possibility of realignment of fibers during construction; and (d) relatively low workability (compactibility) of fibrous mixes which may leave a system of entrapped air with different local concentrations inside the mix.

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All the above factors contributing to the variations in fibrous cement properties are strongly dependent on the mixing, handling, placing and compaction techniques used for manufacturing the composite, and also on the details of the fibrous mix proportions and the geometry of the final product. The fact that carbon fiber reinforced cement composites possess improved cracking characteristics may result in a better control of shrinkage cracks; this could reduce variations in material properties resulting from different shrinkage cracking conditions in different environments.

The main objectives of this research were: (a) to assess the statistical variations in the properties of typical carbon fiber reinforced cement composites constructed by the common manufacturing techniques; and (b) to compare these variations with those of plain concrete.

2.2 BACKGROUND

Table 2.1 presents the factors contributing to variations in the compressive strength of plain concrete [11]. The suggested values for the standard deviation of compressive strength (for an average strength of 4,000 Ksi, 27,600 MPa) are presented in Table 2.2.

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Table 2.1 Factors Affecting Strength Variations in Concrete [11].

Factor	Probable Maximum Variation in Strength *per cent*
Cement from one source	25
Cement from different sources	50
Grading of aggregate	20
Bulking of fine aggregate	25
Batching: 1. By weight	8
2. By volume—	
(*i*) Good	15
(*ii*) Normal	30
(*iii*) Bad	50
Poor compaction	50
Handling, mixing and transporting	Unknown, but may be eliminated by attention to detail.
Temperature	Unimportant after 28 days, provided temperature is above freezing.
Making and testing specimens	30

Table 2.2 Expected Variations in Concrete Strength Under Different Degrees of Control (1 psi=0.00689 MPa).

Coefficient of Variation *per cent*	Degree of Control	Standard Deviation Pounds per square inch for an average compressive strength of 4000 lb/sq.in.
5	Well-controlled laboratory test	200
10	Excellent	400
$12\frac{1}{2}$	Very Good	500
15	Good	600
$17\frac{1}{2}$	Fair	700
20	Poor	800
25	Bad	1000

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In determining the standard deviation of concrete strength, considering the probable variations, Reference 1 suggests that at least 24 test results are required.

References 12 and 13 propose that at least 30 consecutive tests, or two groups of consecutive tests totalling at least 20, shall be performed on concretes with compressive strengths within 1000 psi (6.9 MPa) of the specified strength for determining the standard deviation of concrete at a specified strength.

An important application of standard deviation is in deciding the required strength during construction for providing concretes safely satisfying the specified strength requirement. According to Reference 14, there should be also a probability of 1-in-100 for the average of three consecutively constructed concrete specimens dropping below the specified value of strength. There also should be a similar probability of individual test results falling more than 500 psi (3.45 MPa) below the required strength. Reference 12 suggests a required average concrete compressive strength in construction (f'_c) as follows for satisfying these requirements:

When standard deviation (S) is known:

$$f'_{cr} = \text{larger of} \begin{cases} f_c' + 1.34\ S \\ f_c' + 2.38\ S - 500\ \text{psi} \end{cases} \qquad (1)$$

When standard deviation (S) is unknown:

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$$f'_{cr} = \begin{cases} f_c' + 1000 \text{ psi for } f_c' < 3000 \text{ psi} \\ f_c' + 1200 \text{ psi for } 3000 < f_c' < 5000 \text{ psi} \\ f_c' + 1400 \text{ psi for } f_c' > 5000 \text{ psi} \end{cases} \qquad (2)$$

Reference 15 has reported a comparative statistical study on the compressive and flexural strengths of plain and fiber reinforced concretes. This study was based on the results of flexure and compression tests on 36 specimens. The 3.94 in. (100 mm) cubic specimens for compression were cast in three batches (12 specimens per batch). In addition to these, 36 prisms of steel fiber reinforced concrete were also cast in two batches (18 specimens from each batch), and were tested for evaluating statistical variations in flexural strength and toughness of steel fiber reinforced concrete. The fiber reinforced concrete mixtures considered in this study incorporated fly ash to achieve improved workability. This is expected to have favorable effects on reducing the variations in material properties.

The concretes (plain and fibrous) tested in Reference 15 had a mix proportion with water-to-binder (cement + fly ash) ratio of 0.43, aggregates-to-binder ratio of 0.45, fine-to-coarse aggregate ratio of 0.80, and fly ash-to-binder ratio of 0.30. Ordinary portland cement was used, and the maximum particle size of aggregates was 0.39 in. (10 mm). The steel fibers were cold drawn (straight - round) with a length of 1.5 in. (38.1 mm). All the fibrous mixtures incorporated a fiber volume fraction of 1%.

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Table 2.3 presents the means and standard deviations of the compressive and flexural Strength test results for plain and fibrous concretes. There seems to be a slight increase in standard deviation resulting from the presence of steel fibers in the workable mixes of this study.

Table 2.3 Means and Standard Deviations of the Measured Values of Flexural and Compressive Strengths for Plain and Fibrous Concretes [12].

Mix	Flex. Strength (Ksi)		Comp. Strength (Ksi)	
	mean	std. dev.	mean	std. dev.
Plain Concrete	0.645	0.032	6.22	0.281
Steel Fiber Concrete	1.050	0.034	6.42	0.304

Figures 1.a through 1.d present the cumulative frequency distributions of the measured values of compressive and flexural strengths for plain and fibrous concretes, together with the normal probability curves obtained by using the means and standard deviations from all tset results.

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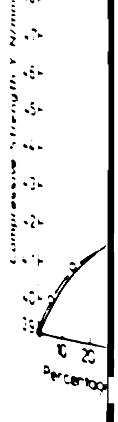

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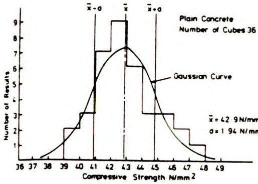
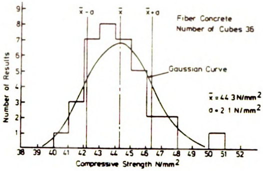
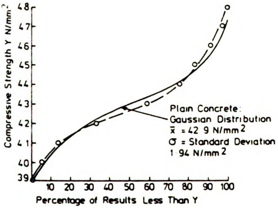
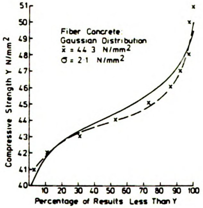




(a) Compressive Strength (Plain Concrete)

(b) Compressive Strength (Fibrous Concrete)





(c) Flexural Strength (Plain Concrete)

(d) Flexural Strength (Fibrous Concrete)

Figure 2.1 Cumulative Distributions: Test Results Vs. Normal Distributions Curve [12].

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In the test results reported in Reference 15, the coefficients of variation for steel fiber concrete within a batch and between batches were well below the recommended levels of 5% and 15%, respectively, and were of the same order as those obtained for plain concrete. It was therefore possible to conclude that in steel fiber reinforced concrete, where good quality control is exercised throughout fabrication, the number of test specimens for obtaining a reliable average need to be no more than that required for plain concrete. Reference 15, however, suggests that until the technology of fiber reinforced cement composite is fully understood, there is some argument in favor of testing fibrous specimens in addition to those required for plain concrete even when strict quality control procedures are applied.

Tests on the differences between the fibrous and plain concrete compressive strengths performed in Reference 2 indicated that the slight increase observed in compressive strength in the presence of steel fibers is insignificant in light of the random variations in test results.

Reference 12 has also reported the results of a study on statistical variations in flexural toughness of steel fiber reinforced concrete. This study was based on limited test results, and indicated relatively large variations in toughness and major deviations from the normal distribution. Flexural toughness could not be correlated to flexural strength. In Reference 12, the relatively large variation in flexural toughness were attributed to the high variability of the fiber debonding process in steel fiber reinforced concrete (which determines toughness characteristics).

2.3 EXPERIMENTAL PROGRAM

The mechanical properties of carbon fiber reinforced cement (CFRC) compsites were investigated experimentally.

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Table 2.

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The basic mix ingredients in carbon fiber reinforced ycement were: Type I portland cement (see Table 4 for some physical and chemical properties) [16], silica fume (Table 5) [17], superplasiticizer (with naphthalene formaldehyde sulfonate as an active ingredient) [18], Carboflex pitch-based carbon fibers manufactured by Ashland Petroleum Company (Table 6) [19], anti foaming agent [20], and Ceramic Spheres (ML 1430 Macrolite [21]) as light-weight aggregates with particle size ranging from 0.02 - 0.06 in. (0.6 to 1.5 mm) and specific gravity of 0.85 (see Table 7 for gradation).

The presence of silica fume (with its fine particles) in CFRC facilitates the dispersion of carbon fibers, while the superplasticizer helps in overcoming the workability problems resulting from the use of carbon fibers and silica fume in cementitious materials.

Table 2.4 Physical and Chemical Properties of Portland Cement Type I [16].

Chemical	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O
(%)	63.24	21.14	5.76	2.93	2.06	2.46	0.79

Physical	Specific Gravity	Specific Surface	Compressive Strength (28 days)
	3.15	160	4000
		m^2/kg	psi

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Table 2.5 Physical and Chemical Properties of Silica Fume [17]

Chemical (%)	SiO_2	C	Fe_2O_3	MgO	Al_2O_3	K_2O	Na_2O
	96.5	1.4	0.15	0.20	0.15	0.04	0.20

	Specific Gravity	Bulk Density	Specific Surface	Avg. Particle Size	Particles smaller than 0.018 in.
Physical	2.3	14 lb/ft^3 (225 Kg/m^3)	200,000 cm^2/g	6x10^{-5} in. (0.15 microns)	145 microns 99.55%

Table 2.6 Physical Properties of Carboflex Carbon Fibers [19].

Diameter	Specific Gravity	Tensile St.	Modulus of Elasiticity	Elongation
4 x 10^{-4} in (10 micron)	1.6	100 Ksi (690 MPa)	8000 Ksi (55,000 MPa)	1.4%

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Table 2.7 Gradation of Light-Weight Aggregates ML 1430 [21]

U.S. Sieve	8	16	20	30	50
Passing (%)	100	61	26.6	2.2	0

Both carbon fibers and silica fume have relatively large surface areas and adsorb considerable water, thus negatively influencing the workability of fresh mix. This tendency is further pronounced by the interlocking of carbon fibers.

The optimum mix considered in this study, which was selected after a number of trials, has a water/binder (cement + silica fume) ratio of 0.30, silica fume/binder ratio of 0.23, aggregate/binder ratio of 0.2, superplasticizer/binder ratio of 0.032, and 2% volume fraction of 1/8 in. (3mm) long carbon fibers, and antifoaming agent/binder ratio of 0.001.

The workability (flow) of this mix was 60% (Flow Table Test ASTM C-230), and the air content was 10% (ASTM C-138).

A conventional mortar mixer was used for the manufacturing of carbon fiber reinforced cement. The following mixing procedure was chosen in order to achieve a uniform dispersion of fibers: (1) add all the water followed by the cement and mix for 30 seconds at a medium speed; (2) gradually add 1/2 of silica fume followed by 1/2 of superplasiticizer over a period of 1 minute; (3) add the remainder of silica fume followed by the remainder of

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superplasticizer, this process takes approximately 2 minutes until a uniform mixture is achieved; (4) gradually add all aggregates while the mixer is running over a period of about 1 minute, and then add the anti-foaming agent; (5) gradually add the fibers while the mixer is running at low speed over a period of 3 minutes; and (6) turn the mixer to high speed and mix for 2 minutes.

After testing the fresh mix flowability (ASTM C-230), air content and unit weight (ASTM C-138), the specimens were cast in molds, and were compacted through external vibration. The following specimens were manufactured:

a. Thirty 1.5 x 1.5 x 6 in. (38 x 38 x 152 mm) prismatic specimens from two batches of 15 each for flexure tests;

b. Thirty 3 in. diameter by 6 in. height (76 mm diameter by 152 mm height) cylindrical specimens from three batches of 10 each for compression test; and

c. Thirty 6 in. diameter by 2.5 in. height (152 mm diameter by 64 mm height) cylindrical specimens in two batches of 15 each for impact tests.

The specimens were demolded after 24 hours during which they were covered by wet burlap and plastic sheet and stored at 74°F (22°C) thereafter, they were cured in air at 74°F (22°C) and 65% RH for 14 days.

2.4 TEST PROCEDURES

The fresh mix workability was assessed by the flow table test (ASTM C-230). The unit weight and air content tests on fresh mix were conducting following ASTM C-138. The flexural tests o

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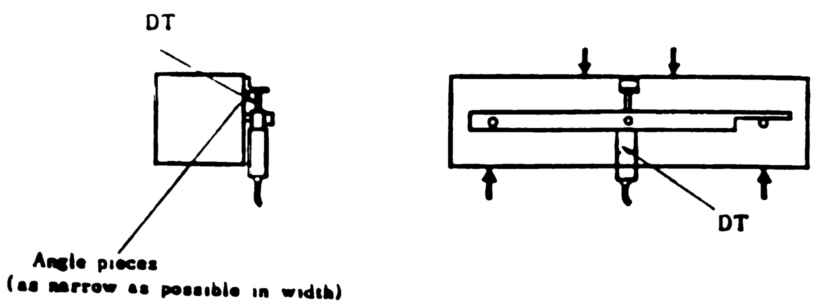
tests on hardened materials were performed by 4-point loading on a span of 4.5 in. (114 mm), with the displacement transducers attached to the specimen at supports and the load-point deflections measured with respect to support points on the specimen (Figure 2.a). This method of displacement measurement eliminates any errors associated with rigid body movement of the specimen or penetration at support or load points into the specimen. The flexural loading was displacement-controlled with a quasi-static deflection rate of about 1/1000 times the span length per minute.



(a) Deflection-Measurement Apparatus

Figure 2.2 (cont'd.)

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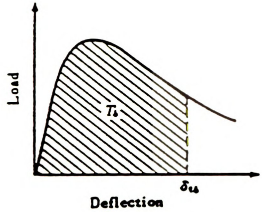

(b) Load-Deflection Curve

Figure 2.2 Flexural Deflection Measurement Apparatus and Load-Deflection Curve [22].

These flexural tests will produce flexural load-deflection curves (Figure 2.b), which can be characterized by maximum load (typically represent in the form of modulus of rupture) and toughness (the area underneath the load deflection curve up to a deflection equal to the span length divided by 150). It should be noted that the displacement measurement techniques and toughness characterization were done following the Japanese Concrete Institute specifications [22].

In compression, the test was again displacement-controlled with a quasi-static strain rate of 10^{-5}/sec. The ultimate compressive strength was measured.

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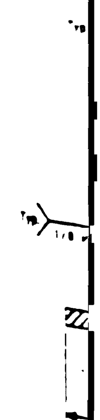

Figure

The impact test was conducted following the procedure recommended by the ACI committee 544 [23]. This test measures the amount of impact energy necessary to start a visible crack in fiber concrete and then to continue to open that crack until failure. The equipment for impact test (Figure 3) consists of a standard 10-pound (44.8-N) compaction hammer with 18-in. (457-mm) drop, a 2.5-in (63.5-mm) diameter steel ball, and positioning fixtures.

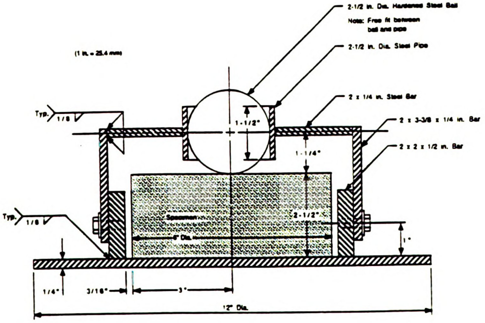

Figure 2.3 Impact Test Apparatus [23].

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The impact test is performed by dropping the hammer repeatedly and recording the number of blows required to cause the first visible crack on the top and the ultimate failure.

2.5 EXPERIMENTAL RESULTS AND STATISTICAL ANALYSES

Flexural strength and toughness, compressive strength, and impact resistance are the mechanical properties of CFRC which were statistically analyzed in this investigation.

2.5.1 Flexural Strength

Table 8 presents a list of the flexural strength test results for the thirty CFRC specimens.

The sample mean of these measurements is 0.956 Ksi (6.66 MPa), and the standard deviation (S) is 0.15 Ksi (1.035 MPa), giving a coefficient of variation of 15.7%. The confidence interval for mean is (0.9, 1.01 Ksi) (6.21, 6.97 MPa), indicating that there is a 95% confidence that the interval from 0.9 to 1.01 Ksi (6.21 to 6.97 MPa) contains the true mean.

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Table 2.8 Flexural Strength Test Results in Ksi

(1 kis = 6.9 MPa)

Batch 1	Batch 2
0.646	0.808
0.742	1.330
0.805	1.167
0.832	1.020
0.899	0.896
0.853	1.070
1.000	1.173
1.100	0.924
0.817	1.070
1.129	0.965
1.080	0.925
0.785	1.131
0.882	1.019
0.898	0.840
1.003	0.913

Sample Mean = 0.965 Ksi
Standard Deviation = 0.150 Ksi
Coeff. of Variation = 15.7%

Goodness of fit tests (Kolmogorov-Smirnov and Chi-Square tests) [24-26] confirmed the normality of the sample distribution for flexural strength test results at 5% level of significance.

The distribution of the results is shown in Figure 5, and the normal curve overlapping the histogram presents an indication of the normality of sample distribution.

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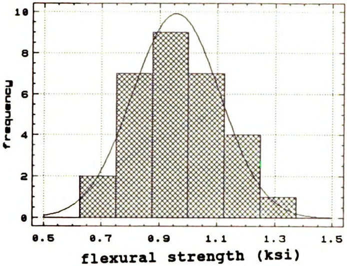

Figure 2.5 Distribution of Flexural Strength Test Results for Carbon Fiber Reinforced Cement.

Cosidering the normality of the flexural strength test results, we can conclude (at 0.05 level of significance) that 68% of the test results fit in the range from 0.81 to 1.11 Ksi (5.59 to 7.66 MPa) and 95% of the results in the range from 0.66 to 1.25 (4.55 to 8.625 MPa).

Figure 2.6 shows the normal probability plot of the flexural strength test results. This figure indicates that about 60% of the results are above 0.9 Ksi (6.2 MPa) and about 80% above 0.8 Ksi (5.5 MPa), and that the cumulative distribution of the measurements is close to a straight line, which gives another indication of the normality of results [26].

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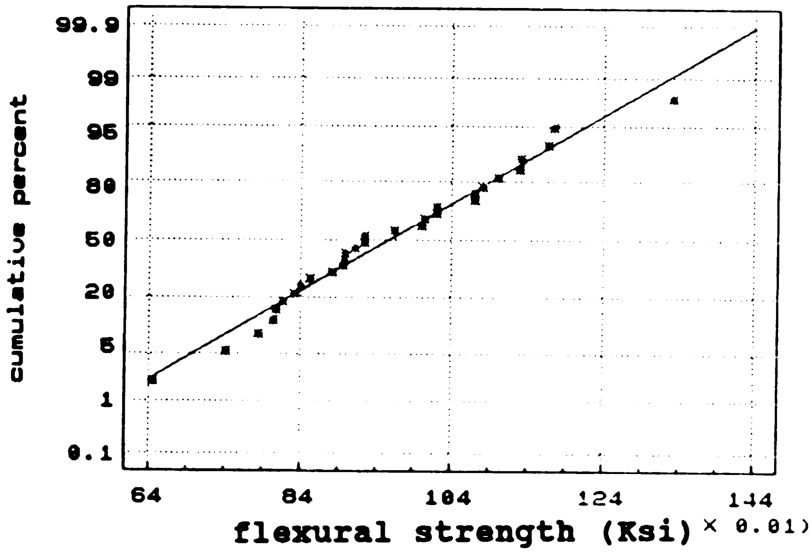

Figure 2.6 Normal Probability Plot of Flexural Strngth Test Results for Carbon Fiber Reinforced Cement Composites.

The sample means within batches were 0.897 and 1.01 Ksi (6.18 and 6.97 MPa), and the corresponding standard deviations were 0.130 and 0.141 Ksi (0.90 and 0.97 MPa). The coefficients of variation were 15.3% and 13.9% respectively.

A Bartlett's test of hypothesis was conducted to compare the variations in flexural strength whithin and between batches [24]. The results indicated that the variations within and between batches are equal at 5% level of significance.

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2.5.2 Flexural Toughness

Table 9 presents the flexural toughness test results. The sample mean was 0.004 K.in (0.45 N.m) and standard deviation was 0.0015 K.in (0.169 N.m).

Table 2.9 Flexural Toughness Test Results in K.in (1 K.in = 113 N.m).

Batch 1	Batch 2
0.0022	0.0027
0.0020	0.0040
0.0030	0.0060
0.0026	0.0054
0.0029	0.0030
0.0030	0.0050
0.0045	0.0060
0.0047	0.0023
0.0030	0.0067
0.0040	0.0051
0.0030	0.0035
0.0020	0.0050
0.0079	0.0040
0.0018	0.0032
0.0034	0.0050

Sample Mean = 0.0040 Kip.in
Standard Deviation = 0.0015 Kip.in
Coeff. of Variation = 36.8%

The coefficient of variation was 36.8% and the standard error of mean was 0.00027 K.in (0.03 N.m). The 95% confidence interval was 0.0025 to 0.0040 K.in (0.28 to 0.45 N.m).

Chi-Square goodness-of-fit test showed poor fitness of the test results to normal distribution at 5% level of significance. This might be result of the limited sample size and the relatively large variations in toughness test results.

The means within the batches were 0.0033 and 0048 K.in. (0.37 and 0.54 N.m) and the corresponding standard deviations were 0.0013 and 0.0013 K.in. (0.14 and 0.14). The coefficients of variation were 39.9% and 27.4%, respevtively. Based on Bartlett's test of hypothesis it was decided that the variations in flexural toughness within and between batches are equal at 5% level of significance.

Figure 2.7 shows the distribution of flexural toughness test results, with the histogram overlapped on the normal distribution curve.

Figure 2.8 presents a normal probability plot which indicates that the distribution of toughness test results is not close to normal (the curve does not fit a straight line), at least for the limited test data generated in this investigation.

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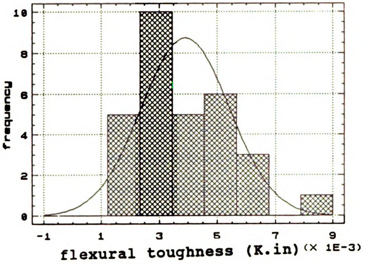

Figure 2.7 Distribution of Flexural Toughness Test Results for Carbon Fiber Reinforced Cemen Composite.

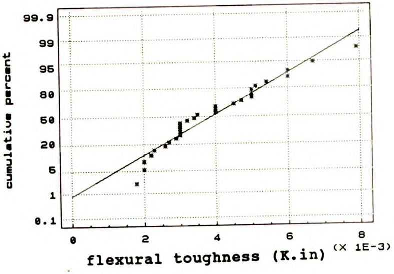

Figure 2.8 Normal Probability Plot of Flexural Strength Test Results for CFRC Composites.

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2.5.3 Comprssive Strength

Table 2.10 presents the compressive strength test results. The sample mean was 3.88 Ksi (26.8 MPa) and the standard deviation was 0.524 (3.6 MPa). The coefficient of variation was 13.5%, and the standard error of mean was 0.096 Ksi (0.662 MPa). The 95% confidence interval was 3.69 to 4.08 Ksi) (25.5 to 28.2 MPa).

Table 2.10 Compressive Strngth Test Results.

Batch 1	Batch 2	Batch 3
3.41	3.76	3.81
4.38	2.99	4.02
4.67	3.37	2.79
4.67	3.23	3.64
4.35	4.62	4.06
4.18	3.29	3.33
3.89	3.91	3.82
4.97	4.33	4.31
3.52	3.91	3.49
4.31	4.11	3.52

Sample Mean = 3.88 Ksi
Standard Deviation = 0.52 Ksi
Coeff. of Variation = 13.5%

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The means within the batches were 4.21, 3.75 and 3.68 Ksi (29.1, 25.9 and 25.4 MPa). The corresponding coefficients of variations were 11.6%, 13.9% and 11.7%. The varitions within and between batches were decided to be equal, based on the Bartlette's test of hypothesis at 5% level of significance.

The Kolmogorov-Smirnov and Chi-Square goodness-of-fit tests confirmed the normality of the compressive strength test results at 5% level of significance.

Figure 2.9 shows a histogram of the 30 compressive strength test results overlapped with a normal curve, and Figure 2.10 presents the normal probability plot for these results. These figures provide for the evidence of the normality of compressive strength test results.

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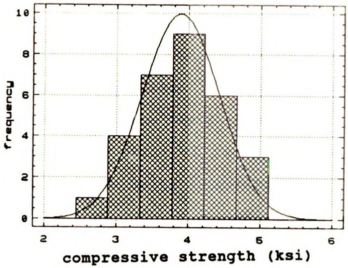

Figure 2.9 Distribution of Compressive Strength Test Results for Carbon Fiber Reinforced Cement Composite.

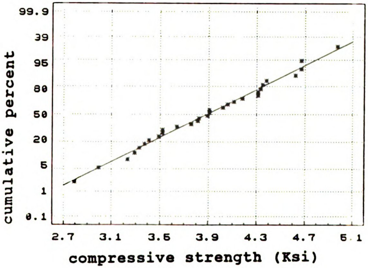

Figure 2.10 Normal Probability Plot of Compressive Strength Test Results for CFRC Composites.

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2.5.4 Impact Resistance

Table 2.11 presents the impact resistance test results for the thirty specimens cosidered in this study. The sample mean for all specimens was 33 blows, and the standard deviation was 18 blows; the coefficient of variation was thus 54%, and the standard error of mean was 4 blows. The 95% confidence interval was 26 to 40 blows.

Table 2.11.Impact Resistace Test Results.

Batch 1	Batch 2
30	26
58	40
70	17
47	12
39	30
72	30
26	21
52	29
64	16
54	14
51	13
43	12
42	17
18	18
23	19

Sample Mean = 33 blows
Standard Deviation = 18 blows
Coeff. of Variation = 54%

The means within the batches were 46 and 21 blows, and the corresponding standard deviations were 17 and 8. The coefficients of variation were 36.3 and 39.5%, respectively. The Bartlett's test of hypothesis indicated that the variations in impact resistance within batches are different from the variations between batches at 5% level of significance.

The goodness-of-fit test indicated poor fitness of the impact resistance test results produced in this study to the normal distribution at 5% level of significance. Because of the large variations in impact resistance test results, a larger sample size would be helpful in making more realiable conclusions regarding the normality of the distribution of imact test results.

Figure 2.11 shows the scatter in the impact resistance test results with the normal curve overlapping them. Figure 2.12 presents the normal probability curve which is not close to a straight line, indicating poor normality of the impact resistance test results.

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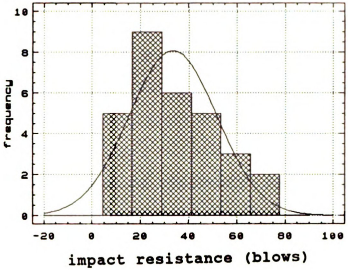

Figure 2.11 Distribution of Impact Resistance Test Results for CFRC Composites.

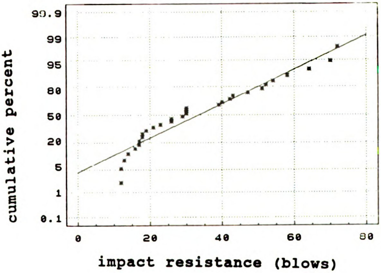

Figure 2.12 Normal Probability Plot of Impact Resistance Test Results for CFRC Composite.

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2.6 EVALUATION AND DISCUSSION OF TEST RESULTS

Table 12 presents the means, standard deviations and coefficients of variation for different test results produced in this investigation (flexural strength and toughness, compressive strength and impact resistance).

The Bartlett's test of hypothesis was performed in order to compare the variations in different properties of CFRC composites. It was concluded that, at 5% level of significance, the variations in flexural strength, flexural toughness and compressive strength were comparable while those in impact resistance were different (higher).

Table 2.12 Statistical Parameters for the Mechanical Properties of CFRC Composites.

Property	Mean	Std. Dev.	Coef. of Variation
Flexural Strength (Ksi)	0.956	0.150	15.77%
Flex. Toughness (K. in.)	0.0040	0.0015	36.80%
Comp. Strength (Ksi)	3.88	0.524	13.50%
Impact Res. (No. of Blows)	33	18	54.60%

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The coefficient of variation in compressive and flexural strengths of plain and steel fiber reinforced concrete obtained in controlled laboratory conditions is about 5% [11,15]. Hence, the variations in the flexural and compressive strengths of CFRC presnted in Table 2.12 are relatively high. This could be attributed to the difficulty of uniformly dispersing the carbon fibers and the fact that these fibers show some variations in length even within the same shipment. Noting that CFRC is most suitable for precast production in controlled conditions, the coefficients of variation of 15.7% and 13.5% in flexural and compressive strengths, respectively, are acceptable between batches; as shown in Table 2.2, a 15% coefficient of variation in plain concrete strength is expected with a good degree of control in field conditions [11,15].

The standard deviations (and coefficients of variation) presented in Table 2.12 can be used to decide relationships between the required properties of CFRC during construction and the ones specified during design. This relationship reflects the fact that, because of the variability in material properties becomes necessary to produce a material with an average strength greater than the specified strength in order to limit the percentage of low tests to certain levels. This is true not only for CFRC but also for conventional concrete (see Equations 1,2). The required average properties (with property refering to being flexural strength, flexural toughne

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toughness, compressive strength, or impact resistance) can be determined from the following formula, which is applicable when the distribution is normal.

$$P_r = P + a.S \qquad (3)$$

When: P_r = required property;

P = specified property;

S = standard deviation of the property (see Table 2.12).

a = probability factor based on the percentage of tests the designer will allow to fall below P. Examples of values for "a" are 1.3 and 1.6 when the specified percentages of low tests are 9.7 and 5.5 respectively.

The coefficients of variation presented in Table 2.12 can also be used to decide the minimum number of tests (n) required to assure that the percentage error in the average measured value is below specified limit (e) at a certain level of significance [15]:

$$n = t^2\ V^2/e^2 \qquad (3)$$

Where v = coefficient of variation; and

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It should be noted that the value of t is dependent not only on the specified level of significance, but also on the degree of freedom (related to the number of tests). For large sample sizes, t approaches 1.645 and 1.282 at 5% and 10% levels of significance, respectively. For example, Equation (3) indicates that for compressive and flexural strengths of CFRC, at 10% level of significance, if the error in average measured value is to be kept below 10%, the minimum number of tests are 4 and 3, respectively, (noting that the coefficient of variation in the flexural and compressive strengths are 15.7% and 13.5%, respevtivelty).

2.7 SUMMARY AND CONCLUSIONS

Replicated tests were conducted on light-weight carbon fiber reinforced cement composites in order to study the variations in the flexural strength and toughness, compressive strength and impact resistance of the material. The results indicated that:

1. The flexural and compressive strength test results had a normal distribution at 5% level of significance. The flexural toughness and impact resistance test data generated in this study, however, showed poor fitness to

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the normal distribution at 5% level of significance, this could result from the relatively large variations in toughness and impact test results and the limited sample size.

2. The variations within and between batches in flexural strength, flexural toughness and compressive strength are comparable, while those in impact resistance are different, at 5% level of significance.

3. The observed coefficients of variation of the properties of carbon fiber reinforced cement composites were 15.7% for flexural strength, 36.8% for flexural toughness, 13.5% for compressive strength, and 54.6% for impact resistance. These variations are larger than what is typically expected for plain concrete in controlled laboratory conditions. The variations in flexural and compressive strength are, however, comparable with those in the strength of plain concretes constructed at job site with good quality control. The increase in coefficient of variation in the presence of carbon fibers could be attributed to the varitions in fiber length and concentration within matrix, and relatively low compactibilty of fibrous cement composites.

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4. The information on variations in the mechanical properties of CFRC composites should be considered while deciding on the minimum number of tests required for measuring certain material properties, or when selecting the required level of a certain property based on a specified design level.

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CHAPTER 3

OPTIMIZATION OF THE USE OF LIGHT-WEIGHT AGGREGATES IN CARBON FIBER REINFORCED CEMENT COMPOSITES

3.1 INTRODUCTION

Low-cost and low-modulus carbon fibers can be manufactured from either petroleum or coal tar pitch. Beside their desirable mechanical properties, carbon fibers are distinguished from other fiber types by their durability in a variety of severe exposure conditions [1,2,9,27-29]. Table 1 presents typical properties of pitch-based carbon fibers [19,30].

The development of the relatively low-cost pitch-based carbon fibers in the recent years has led to the commercialization of cement products reinforced with short, uniformly dispersed carbon fibers. The reinforcement of cementitious materials with pitch-based carbon fibers can lead to im

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to important gains in the flexural strength and toughness characteristics, tensile performance, impact resistance and durability characteristics of the materials [1-4]. Current applications of carbon fiber reinforced cement (CFRC) in Japan include cladding panels, free access floor panels, repair and protective coating of structural elements in aggressive environments, light-weight decorative frames, permanent formwork for concrete, wave absorbers, conductive floor panels, and ferrocement [10,29]. These applications have been encouraged by the durability and high efficiency of carbon fibers as reinforcement for cement.

The desirable performance of carbon fibers in cementitious materials results from their small cross-sectional dimensions which lead to relatively close spacing of fibers, and also from their strong and durable bonding to cementitious matrices. The closely-spaced carbon fibers encounter microcracks in the matrix rather frequently, thus effectively arresting and deflecting these microcracks. The result is an increase in fracture energy, tensile (flexural) strength and toughness of cementitious materials incorporating carbon fibers.

The high fiber count at a specific volume fraction of fibers generally makes it difficult to achieve a uniform fiber dispersion during the production of carbon fiber reinforced cement. Special manufacturing technique and/or the use of dispersants can help in improving the fiber dispersability of cemen

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cementitious matrices [2].

The research reported herein has been concerned with the use of light-weight aggregates in carbon fiber reinforced cement for reducing the unit weight and controlling the dimensional instability of the materials.

3.2 BACKGROUND

Aggregates typically occupy an important fraction of volume in cement-based materials, and thus have important effects on different aspects of the material properties. In addition to their role as an economical filler, aggregates help in controlling the dimensional instability of cement-based materials which may be considered to consist of a framework of cement paste with relatively large shrinkage movements which are restrained by the aggregates.

In the presence of fibers in cement-based materials, however, the introduction of aggregates with a particle size larger than the average fiber spacing leads to bunching and greater interaction of fiber between the large aggregate particles, and the effect becomes more pronounced as the volume and the maximum size of particles increase. The principle is demonstrated in Figure 3.1. This figure shows diagrammatically that an increase in aggregate size makes it more difficult to achieve a uniform dispersion of fibers. It is cle

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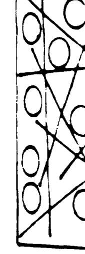

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is clear from this figure that the greater the volume and size of aggregates, the more clumping and interaction of fibers would occur.

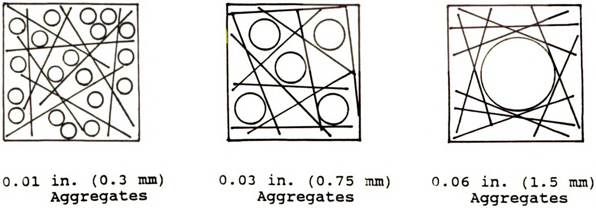
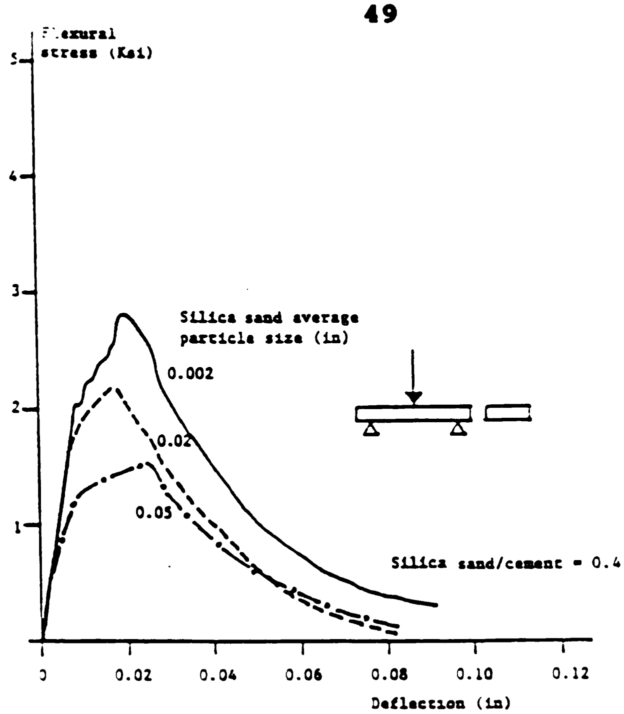


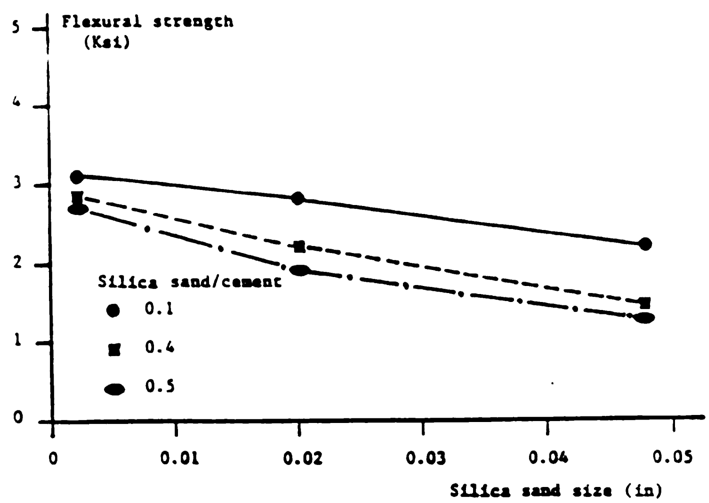
Figure 3.1 Effect of Aggregate Size on Fiber Dispersion within Side Length Equal to Fiber Length (1/8 in., 3 mm, for carbon fibers).

Hence, in spite of the positive effects of aggregates on the dimensional stability and economy of fiber reinforced cement composites, there are limits on aggregate size and volume content beyond which problems with fiber dispersability and fresh mix workability may start to damage the composite material performance characteristics.

Results of flexural tests indicating negative effects of the increase in the maximum particle size of (normal-weight) silica sand on flexural behavior of carbon fiber reinforced cement are presented in Figure 3.2.a.



(a) Flexural Stress-Deflection Behavior



(b) Flexural Strength

Figure 3.2 Effects of Aggregate Size and Amount on Flexural Behavior of Carbon Fiber Reinforced Cement Composites [9].

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Flexural strength test results presented in Figure 3.2.b are indicative of the negative effects of increased aggregate content and maximum particle size on flexural strength of carbon fiber reinforced cement composites [9].

No systematic studies have been reported in the literature on the effects of particle size and volume content of light-weight aggregates on the performance characteristics of carbon fiber reinforced cement. This study was conducted to produce information for optimizing the use of light-weight aggregates in carbon fiber-cement composites.

3.3 EXPERIMENTAL PROGRAM

Effects of aggregate content and maximum particle size, and fiber volume fraction, on the material properties of carbon fiber reinforced cement were investigated experimentally.

The basic mix ingredients in carbon fiber reinforced cement were: Type I portland cement, silica fume (see Table 2.5 for some physical and chemical properties) [17], superplasticizer (with naphthalene formaldehyde sulfonate as an active ingredient) [18], and Carboflex pitch-based carbon fibers manufactured by the Carbon Fibers Division of Ashland Petroleum Company (Table 2.6) [19], and light-weight aggregates with two different particle sizes: ML 1430

Macrolite Ceramic Spheres with particle size ranging from 0.06 - 0.02 in. (1.5 to 0.6 mm) and specific gravity of 0.85, and ML 3050 Macrolite Ceramic Spheres with particle size ranging from 0.02 - 0.01 in. (0.6 to 0.3) and specific gravity of 1.05, both manufactured by 3M company [21]. Tables 3.1 and 3.2 show the gradation of light-weight aggregates ML 1430 and ML 3050, respectively.

Table 3.1 Gradation of Light-Weight Aggregates ML 1430 [21].

U.S. Sieve	8	16	20	30	50
Passing (%)	100	61	26.6	2.2	0

Table 3.2 Gradation of Light-Weight Aggregates ML 3050.

U.S. Sieve	20	40	60	70	80
Passing (%)	100	46.4	1.6	0.4	0

The presence of silica fume in CFRC facilitates the dispersion of carbon fibers, while the superplasticizer helps in overcoming the workability problems resulting from the use of carbon fibers and silica fume in cementitious materials.

The experimental program was based on a 2 (agg. sizes) x 3 (agg.contents) x 4 (fiber vol. fractions) factorial design.

Twenty four mixes with two different aggregate sizes (0.06 in.,1.5 mm and 0.02 in., 0.6 mm max. particle sizes) and three different aggregate contents (0, 0.2 and 0.3) aggregate/binder ratios corresponding to 0, 27, and 35% aggregate volume fractions, respectively and four carbon fiber volume fractions (0, 1, 2, and 3% of 1/8 in., 3 mm long carbon fibers) were considered in this study. Details of this factorial design are presented in Table 3.3.

Table 3.3 Aggregates and Fiber Reinforcement Conditions in the Experimental Program.

	Max. Agg. Size					
	0.02 in. (0.6 mm)			0.06 in. (1.5 mm)		
	Agg./Binder			Agg./Binder		
V_f	0.0	0.2	0.3	0.0	0.2	0.3
0	*	*	*	*	*	*
1	[illegible]	*	*	*	*	*
2	*	*	*	*	*	*
3	*	*	*	*	*	*

For all mixes, a 0.23 silica fume-binder (cement + silica fume) ratio was used and the superplasticizer-binder ratio was

0.032.

The workability of all mixes was comparable, with a flow ranging from 60 to 70% (flow table test ASTM C-230). For this purpose, depending on the fiber and aggregate loadings, adjustments were made in the water-binder ratios. ranged from 0.248 to 0.358 (Table 3.4).

Table 3.4 Water-Binder Ratios Considered in the Experimental Program.

	Max. Particle Size					
	0.02 in. (0.6 mm)			0.06 in. (1.5 mm)		
	Agg./Binder			Agg./Binder		
Vf	0.0	0.2	0.3	0.0	0.2	0.3
0	0.248	0.268	0.278	0.248	0.278	0.288
1	0.278	0.288	0.308	0.278	0.298	0.318
2	0.288	0.298	0.328	0.288	0.308	0.348
3	0.298	0.308	0.338	0.298	0.328	0.358

This table indicated that the increase in aggregate content and fiber volume fraction lead to an increased demand for water required to maintain workability. An anti-foaming agent [20] was also used to maintain the fresh mix air content at about 8 to 12%. The anti-foaming agent content ranged from

.04 to .18% of cement weight. The dosage of anti-foaming agent had to be increased with increasing fiber and aggregate loading in order to keep air content constant.

A conventional mortar mixer was used for the manufacturing of carbon fiber reinforced cement. The following mixing procedure was chosen in order to achieve a uniform dispersion of fibers: (1) add all the water followed by the cement and mix for 30 seconds at a medium speed; (2) gradually add 1/2 of silica fume followed by 1/2 of superplasticizer over a period of 1 minute; (3) add the remainder of silica fume followed by the remainder of superplasticizer, this process takes approximately 2 minutes until a uniform mixture is achieved; (4) gradually add all aggregates while the mixer is running over a period of about 1 minute, and then add the anti-foaming agent; (5) gradually add the fibers while the mixer is running at low speed over a period of 3 minutes; and (6) turn the mixer to high speed and mix for 2 minutes.

After testing the fresh mix for flowability (ASTM C-230), air content and unit weight (ASTM C-138), the specimens for hardened material tests were cast in molds, and were compacted through external vibration. The following specimens were manufactured for each mix composition: (a) three 1.5 x 1.5 x 6 in. (38 x 38 x 152 mm) prismatic specimens for flexural tests; (b) three 3 in. diameter by 6 in. height (76 mm diameter by 152 mm height) cylindrical specimens for compression tests; (c) three 6 in. diameter by 2.5 in height (152 mm diameter by 64 mm height) cylindrical specimens for impact tests (ACI committee 544-2R) [23]; and (d) two ring-shaped specimens for restrained shrinkage test (dimension and details are shown in Figure 3.3).

The specimens were demolded after 24 hours during which they were covered by wet burlap and plastic sheet and stored at 74°F (22°C). Thereafter, the specimens for shrinkage test were cured in moist room at 20°C and 100% RH for 4 days, while the other specimens were cured in air at 74°F (22°C) and 65%RH for 14 days.

3.4 TEST PROCEDURES

The fresh mix workability was assessed by the flow table test (ASTM C-230). The unit weight and air content tests on fresh mix were conducting following ASTM C-138. Test procedures for flexure, compressive and impact resistance are presented in Chapter 2.

Shrinkage cracking of cementitious materials occurs due to external and internal restraint of free shrinkage movements. Hence, the free shrinkage movements of the material as well as its cracking characteristics are factors influencing the shrinkage cracks. The free shrinkage test measures only the shrinkage strains but not the cracking properties of cement-based materials. A restrained shrinkage test procedure was thus adopted in this study to provide more comprehensive information on shrinkage cracking characteristics of CFRC composites.

In this test (Figure 3.3) the shrinkage movement of a ring-shaped specimen are restrained by a rigid steel ring placed inside the specimen during casting. The restraint provided leads to the formation of typically radial cracks in the ring. The results of this restrained shrinkage test are presented in the form of the relationship between maximum crack width and the air-drying period following the initial moist curing.

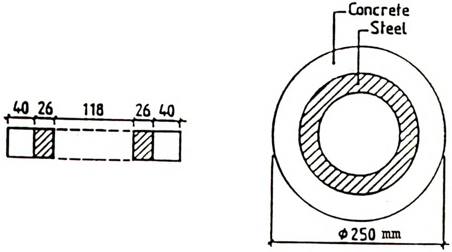

Figure 3.3 Restrained Shrinkage Test Specimen.

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The specific gravity tests were conducted on hardened cement-based materials following the ASTM C-642 test procedures.

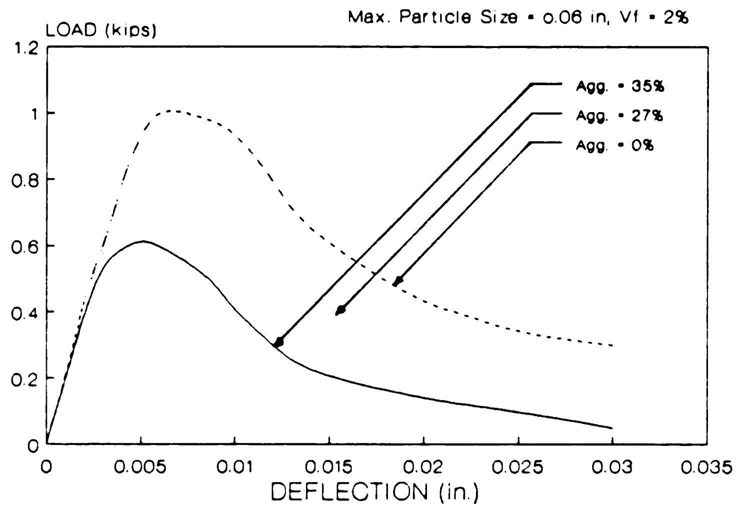
3.5 EXPERIMENTAL RESULTS

The raw test data and discussion based on statistical analyses are presented in the section.

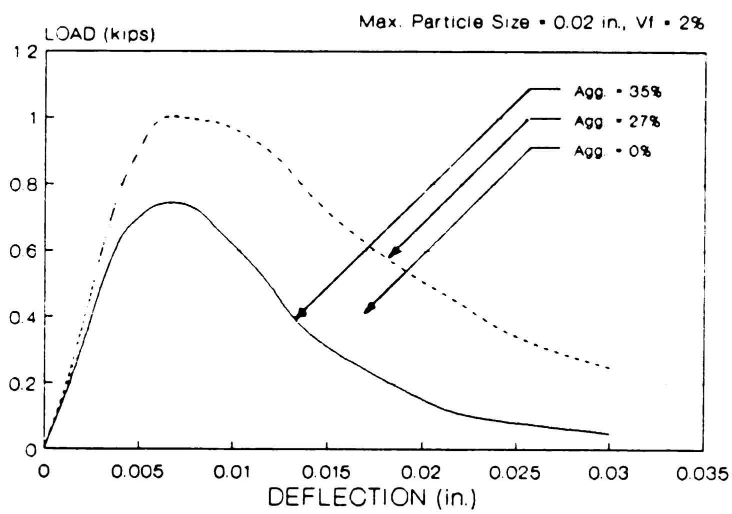
3.5.1 Flexural Behavior

Typical load-deflection curves for carbon fiber reinforced cement composites incorporating 2% volume fraction of carbon fibers, and different volume fractions of light-weight aggregates with different particle sizes, are presented in Figure 3.4. Further discussions on the tends observed in flexural behavior are presented below.

Regression analysis techniques were used to establish the trends in the effects of fiber volume fraction, aggregate sizes and aggregate contents, and their interactions on flexural strength. The test results and regression curves for flexural strength versus aggregate content relationship for different aggregate sizes and fiber volume fractions are presented in Figure 3.5. This figure indicates that:

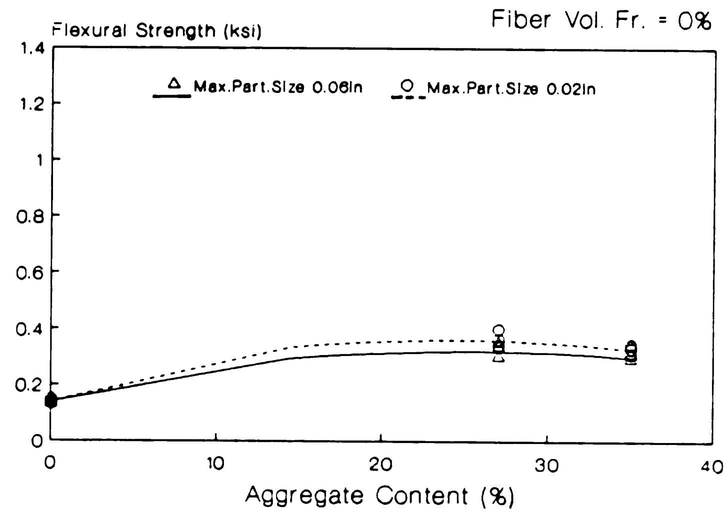


(a) **Max. Particle Size 0.06 in.,Vf = 2%**

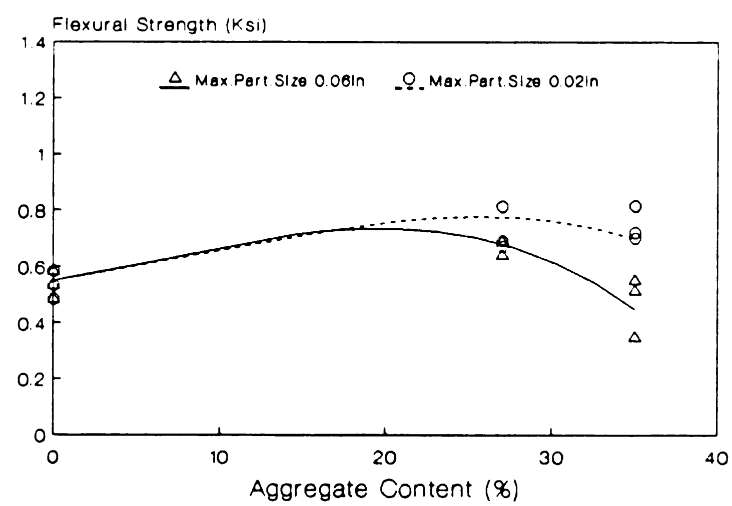


(b) **Max. Particle Size 0.02 in., Vf = 2%**

Figure 3.4 Typical Effects of Aggregate Size and Volume Fraction on Flexural Behavior of Carbon Fiber Reinforced Cement.

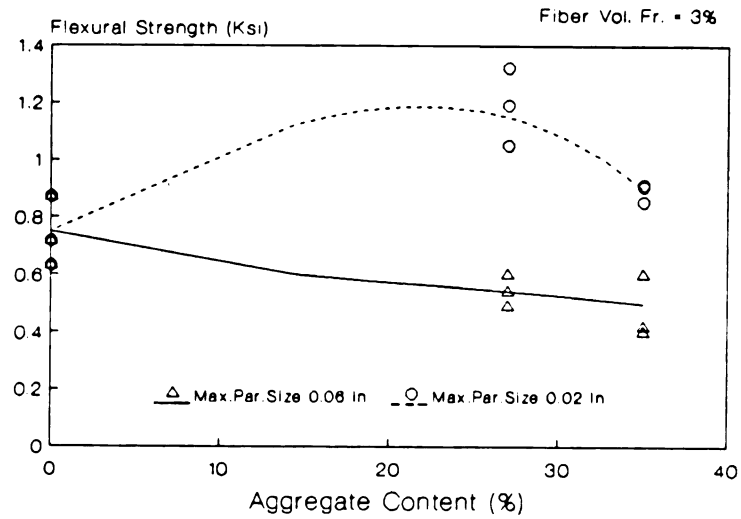


(a) Vf = 0%



(b) Vf = 1%

Figure 3.5 (cont'd)



(c) Vf = 3%

Figure 3.5 Regresion Analysis of Flexural Strength Test Results.

1. The increase in aggregate content up to a certain volume fraction, particularly for finer aggregates, results in an increase in flexural strength, and this tendency reverses at higher aggregate contents; and

2. Finer aggregates tend to perform better than coarser ones at higher fiber volume fractions.

The above results indicate that aggregates, as far as they do not interfere with the uniform dispersion of fibers, positively influence the flexural strength of the materials. This could be due to the control of shrinkage movements and the consequent cracks by aggregates. Aggregates can also play the role of microcrack-arrestors in the paste, further improving the material behavior; this is particularly true for light-weight aggregate size with low elastic modulus being more comparable with that of cement paste, thus causing less microcracks at transition zones. The interference of aggregates with fiber dispersion, which tends to be more pronounced a higher volume fraction of larger aggregates, however, can reduce the effectiveness of fibers. This effect is observed in Figure 3.5.c to cause a reduction in flexural strength with increasing volume fraction of larger aggregate (0.06 in., 1.5 mm, particle size) in CFRC composite with 3% fiber volume fraction. At such relatively high volume contents, the negative effects of larger aggregates on fiber dispersion and thus flexural strength seem to overshadow the positive effects of aggregates on material behavior.

For the three-factor experimental design of this study, the analysis of variance results are presented in Table 3.5. The first column in this Table introduces the main or interaction effects considered, the second column presents the computed F-distribution value, and the last column presents the corresponding critical value of (F) at 5% level of significance [24].

Table 3.5 Analysis of Variance of Flexural Strength Test Results.

MAIN OR INTERACTION EFFECT	F DISTRIBUTION	
	COMPUTED F	CRITICAL F
Maximum Aggregate Size (M)	50.8	4.04
Aggregate Content (A)	11.2	3.18
Fiber Volume Fraction (V)	133	2.80
M A Interaction	10.0	3.18
M V Interaction	12.7	2.80
A V Interaction	5.23	2.30
M A V Interaction	5.50	1.90

If a value in column 2 (computed F) is greater than that in column 3 (critical F), this means that the corresponding factor (a main factor or an interaction) has an influence on the specific property under consideration study (here flexural strength), with only 5% possibility of error. If an interaction of two factors has an effect on the outcome it means that the specific level of each factor influences how variations in the other factor effect the outcome.

The three-factor analysis of results presented in Table 3.5 indicate that all the main effects (max. aggregate size, aggregate content, and fiber volume fraction) influence flexural strength, with the computed values for fiber volume fraction and maximum aggregate size being particulary high reflecting the significance of these main effect. The two-factor interactions also seem in Table 3.5 to be of some significance. This also applies to the three-factor interaction.

3.5.2 Flexural Toughness

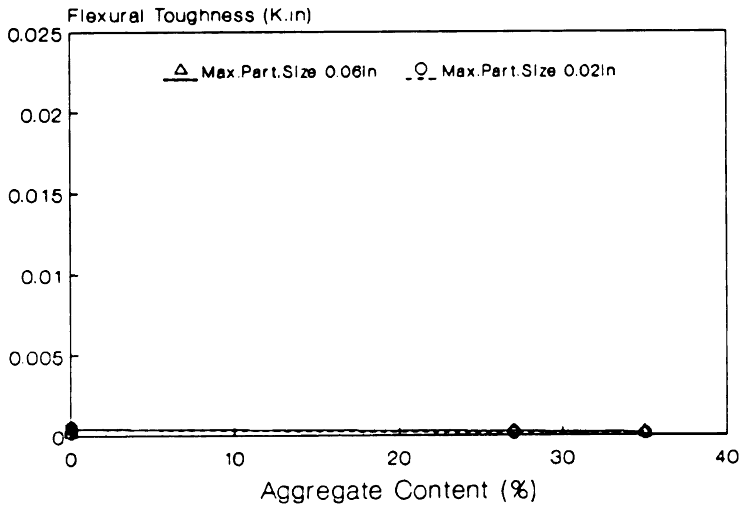
Regression analyses of flexural toughness test results in Figure 3.6 indicate that:

1. There are major improvement in toughness resulting fromcarbon fiber reinforcement;

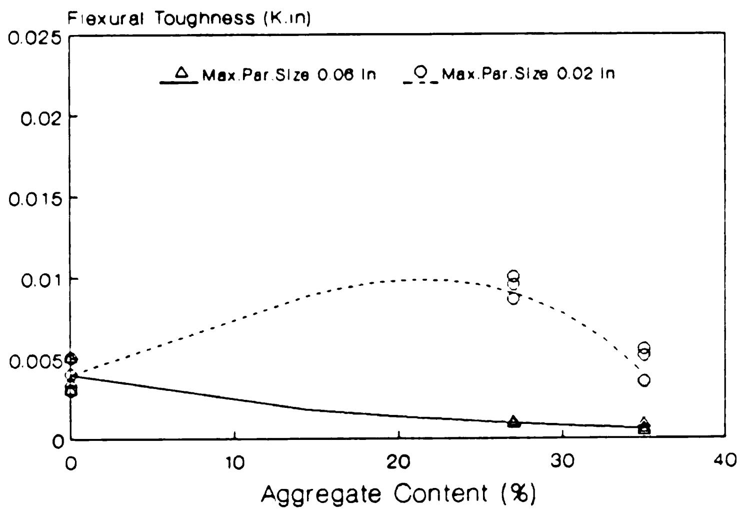
2. The increase in finer aggregate content up to a certain level increases the toughness characteristics of CFRC, but further increase negatively influences toughness; and

3. The increase in coarser aggregate content constantly damages the toughness characteristics of carbon fiber reinforced cement.

The negative effect of aggregate size and aggregate content on toughness may be attributed to the corresponding damages to the uniform dispersion of fibers.

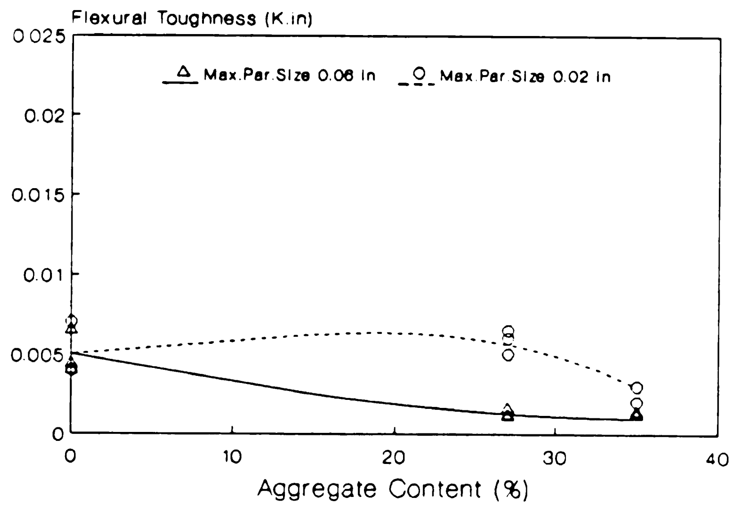


(a) Vf = 0%

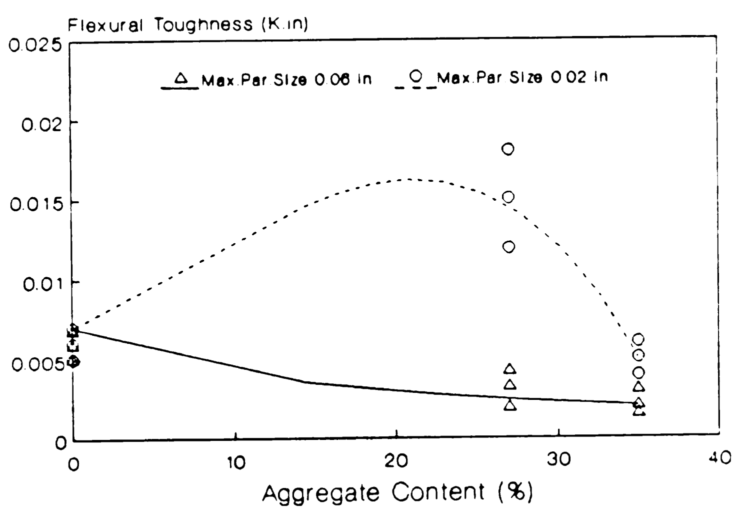


(b) Vf = 1%

Figure 3.6 (cont'd)



(c) Vf = 2%



(d) Vf = 3%

Figure 3.6 Regression Analysis of Flexural Toughness Test Results.

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The balling of fibers encouraged by coarse aggregates at high aggregate contents prevents sufficient coating of fibers by the matrix and thus reduces the fiber-to-matrix bonding, which is an important factor deciding toughness. The fact that there is an optimum content of fine aggregates for achieving desirable toughness characteristics is indicative of the dominance of positive effects of such aggregates at relatively low contents in the composite.

A 3-Factor analysis of variance was conducted on the measured toughness values. The results presented in Table 3.6 show that the maximum aggregate size, aggregate content and fiber volume fraction all have significant effects on flexural toughness at the 5% level of significance.

Table 3.6 Analysis of Variance of Flexural Toughness Test Results.

MAIN OR INTERACTION EFFECT	F DISTRIBUTION	
	COMPUTED F	CRITICAL F
Maximum Aggregate Size (M)	70.0	4.04
Aggregate Content (A)	40.5	3.18
Fiber Volume Fraction (V)	53.0	2.80
M A Interaction	48.9	3.18
M V Interaction	10.5	2.80
A V Interaction	6.11	2.30
M A V Interaction	5.50	1.90

The interaction between maximum aggregate size and aggregate content is also significant.

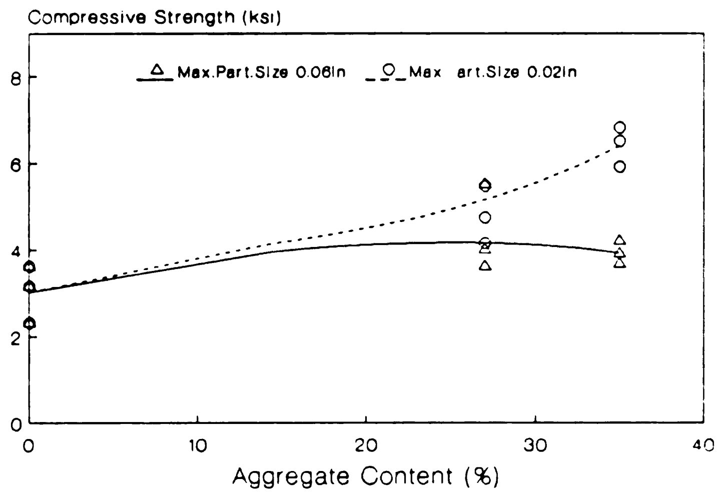
3.5.3 Compressive Strength

The compressive strength test results are shown in Figure 3.7 together with the corresponding regression curves. These results indicate that:

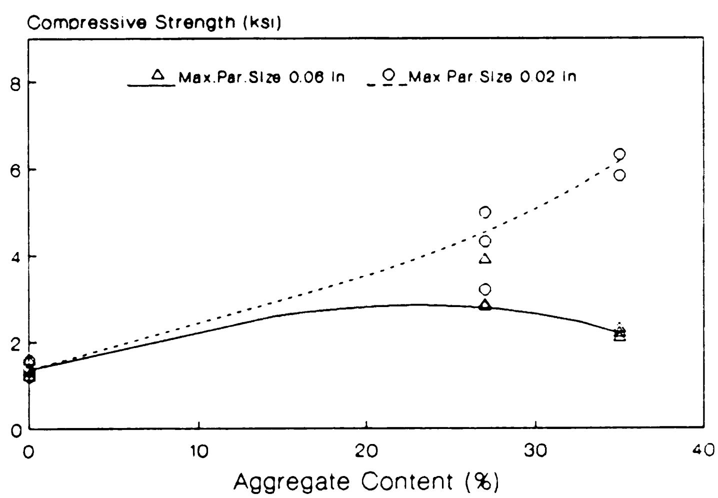
1. An increase in the loading of smaller size aggregates (within the range considered in this study) content leads to an increase in compressive strength;

2. The compressive strength, in the presence of coarser aggregates, is lower than the corresponding values with finer aggregates. There is a limit in the coarser aggregate content beyond which, particularly at higher aggregate loadings, the increase in aggregate content leads to reduction in compressive strength; and

3. There seems to be some negative effects of carbon fiber reinforcement on compressive strength.

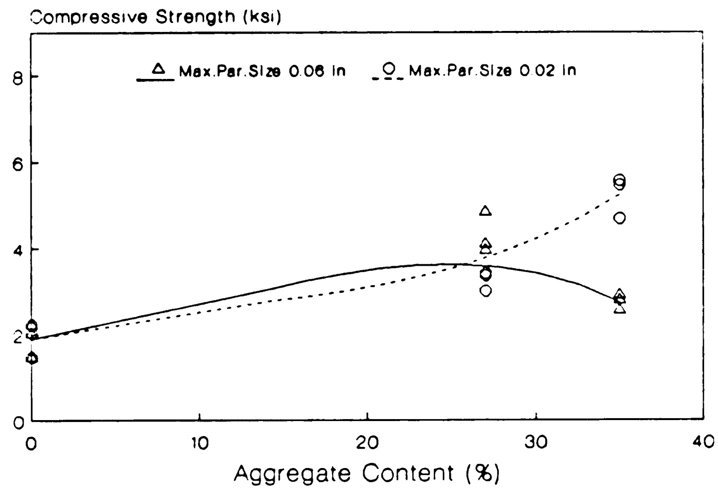


(a) Vf = 0%

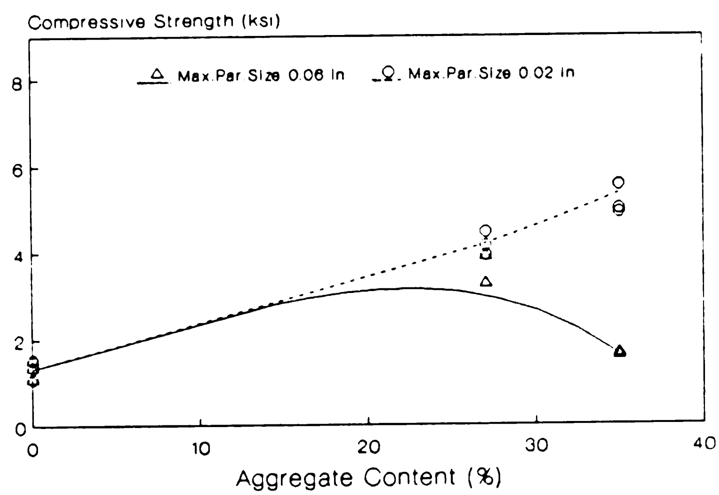


(b) Vf = 1%

Figure 3.7 (cont'd)

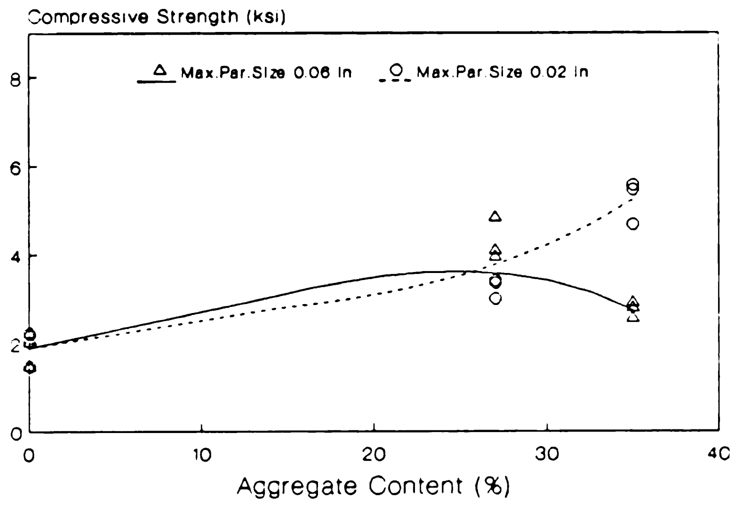


(a) Vf = 2%

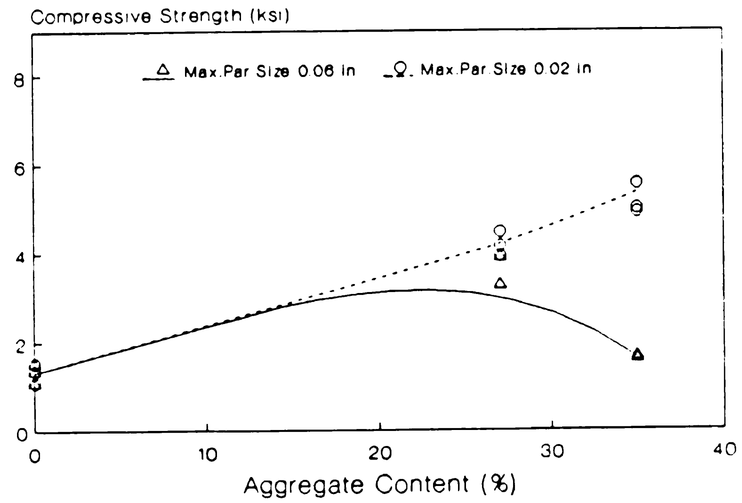


(d) Vf = 3%

Figure 3.7 Regression Analysis of Compressive Strength Test Results.



(a) Vf = 2%



(d) Vf = 3%

Figure 3.7 Regression Analysis of Compressive Strength Test Results.

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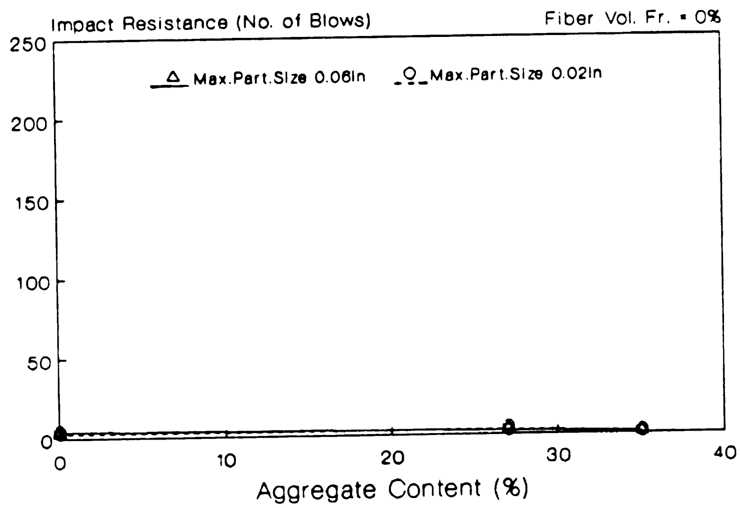
3-Factor analysis of variance for compressive strength test results (Table 3.7) indicates that the aggregate content and maximum aggregate size as well as their interaction have significant effects on compressive strength, and there is also some fiber volume fraction effects. Other interactions have less significance effects.

Table 3.7 Analysis of Variance of Compressive Strength Test Results.

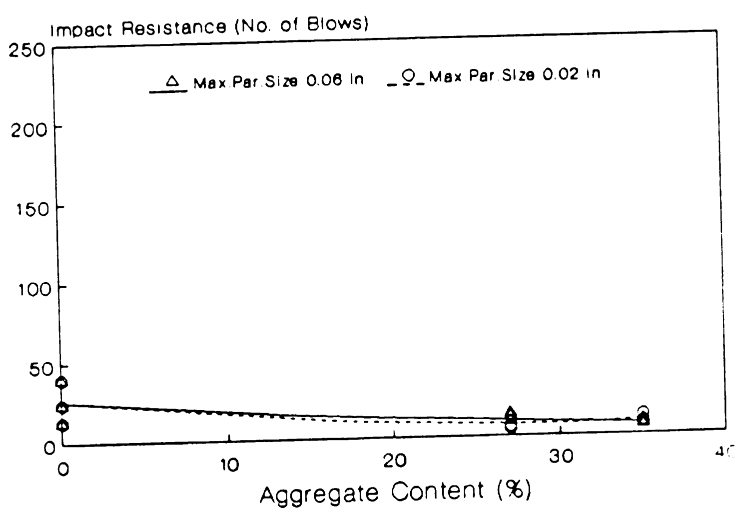
MAIN OR INTERACTION EFFECT	F DISTRIBUTION	
	COMPUTED F	CRITICAL F
Maximum Aggregate Size (M)	97.6	4.04
Aggregate Content (A)	179.8	4.04
Fiber Volume Fraction (V)	23.4	3.18
M A Interaction	84.9	3.18
M V Interaction	3.08	2.80
A V Interaction	3.21	2.30
M A V Interaction	2.06	1.90

3.5.4 Impact Resistance

Regression analyses of the impact resistance test results in Figure 3.8 indicate that:

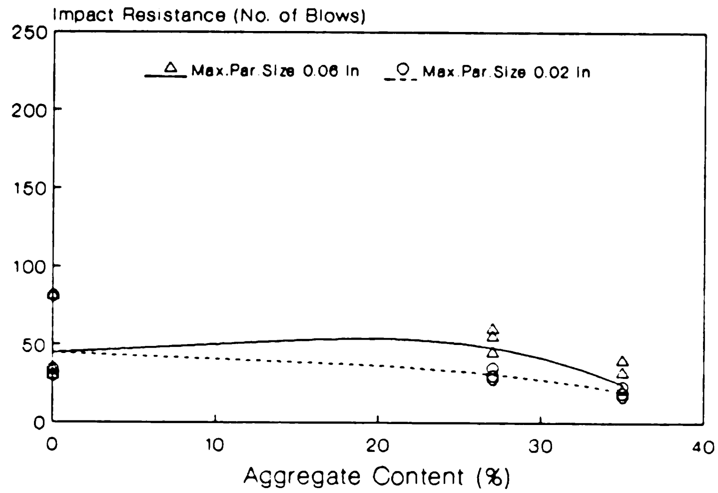


(a) Vf = 0%

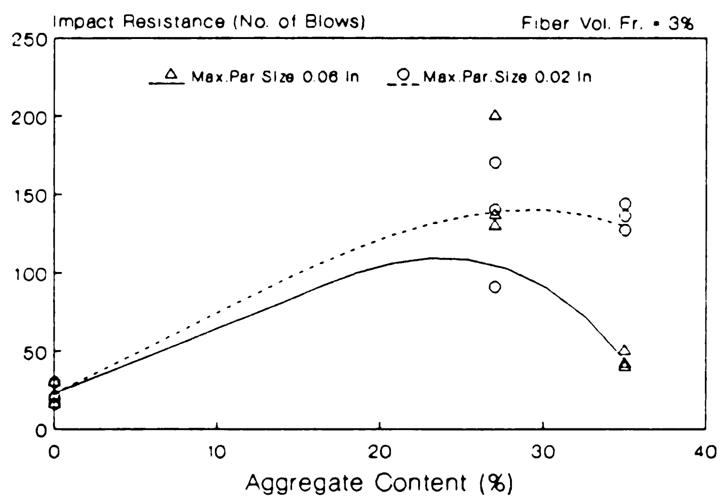


(b) Vf = 1%

Figure 3.8 (cont'd)



(c) Vf = 2%



(d) Vf = 3%

Figure 3.8 Regression Analysis of Impact Strength Test Results.

1. The increase in fiber content leads to important gains in impact resistance, particularly for certain conditions of aggregates addition to the composite;

2. At lower fiber volume fractions, aggregates generally have negative effects on impact resistance, but at the highest fiber volume fraction considered in this investigation (3%), a certain level of aggregate addition can lead to important improvements in impact strength;and

3. High contents of coarser aggregates, even at 3% fiber volume fraction, can damage impact resistance.

Table 3.8 presents results of the analysis of variance for the impact resistance test results.

Table 3.8 Analysis of Variance of Impact Resistance Test Results.

MAIN OR INTERACTION EFFECT	F DISTRIBUTION	
	COMPUTED F	CRITICAL F
Maximum Aggregate Size (M)	.143	4.04
Aggregate Content (A)	11.2	3.18
Fiber Volume Fraction (V)	40.3	2.80
M A Interaction	4.60	3.18
M V Interaction	1.78	2.80
A V Interaction	12.2	2.30
M A V Interaction	7.23	1.90

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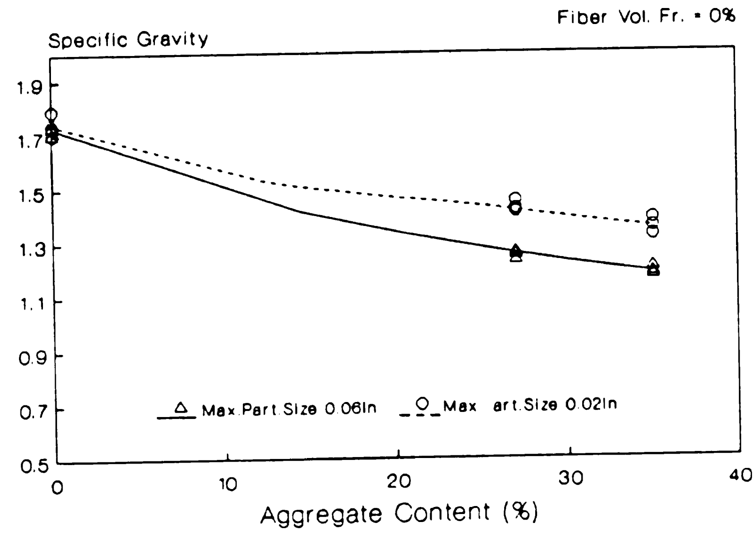
Fiber volume fraction followed by aggregate content have the most important effects on impact resistance. The maximum aggregate size does not seem to influence impact resistance at 5% level of significance. This means that the average tendency observed in Figure 3.8 regarding the maximum aggregate size effects are overshadowed by the variations in test results. As far as interactions are concerned, Table 3.8 indicates that those between maximum aggregate content and fiber volume fraction, and between maximum aggregate size and aggregate content as well as the three factor interaction are influencing the impact resistance. The interaction between aggregate size and fiber volume fraction, however, is insignificant.

3.5.5 Specific Gravity

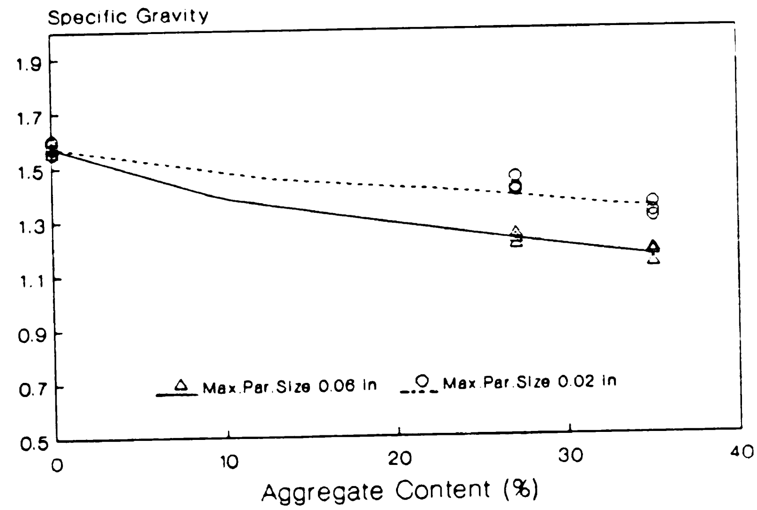
Regression analyses of the specific gravity test results in Figure 3.9 indicate that:

1. The increase in light-weight aggregate content, as expected, leads to reductions in the specific gravity of the composite;

2. Aggregates with larger particle size due to their lower specific gravity, produce lighter composites; and

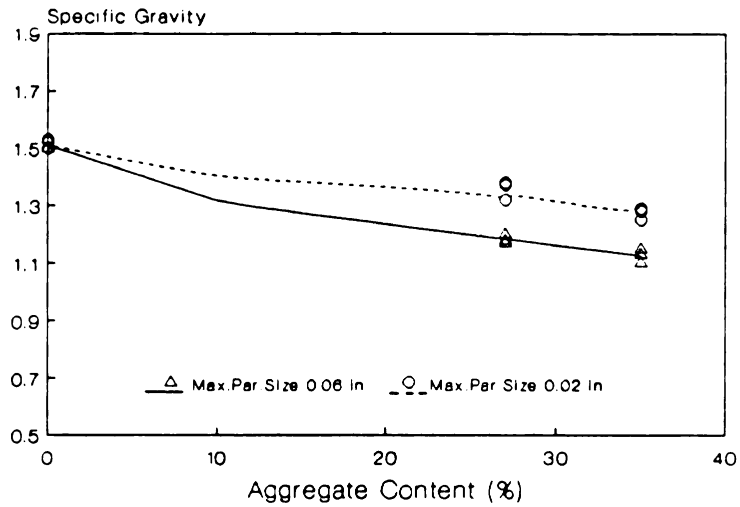


(a) Vf = 0%

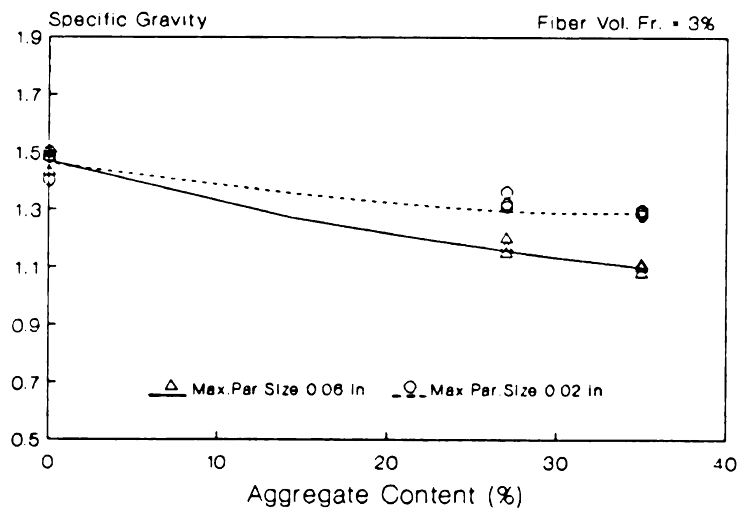


(b) Vf = 1%

Figure 3.9 (cont'd.)



(c) Vf = 2%



(d) Vf = 3%

Figure 3.9Regression Analysis of Specific Gravity Test Results.

3. An increase in the fiber volume fraction generally leads to reductions in the specific gravity of the composite.

The analysis of variance results (Table 3.9) indicate that the specific gravity is most influenced by the lightweight aggregate content, and then by the maximum aggregate size and fiber volume fraction.

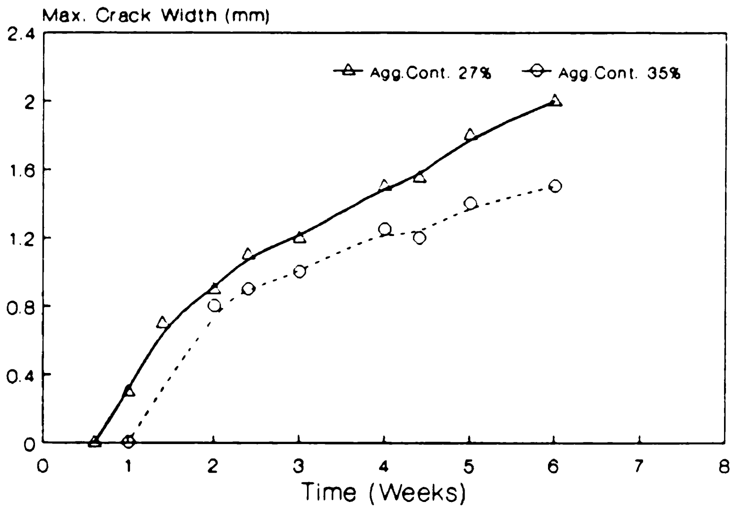
Table 3.9 Analysis of Variance of Specific Gravity Test Results.

MAIN OR INTERACTION EFFECT	F DISTRIBUTION	
	COMPUTED F	CRITICAL F
Maximum Aggregate Size (M)	383	4.04
Aggregate Content (A)	1345	2.80
Fiber Volume Fraction (V)	111	2.80
M A Interaction	700	4.04
M V Interaction	0.50	2.80
A V Interaction	20.0	2.30
M A V Interaction	11.6	1.90

The interaction between maximum aggregate size and aggregate content is also significant.

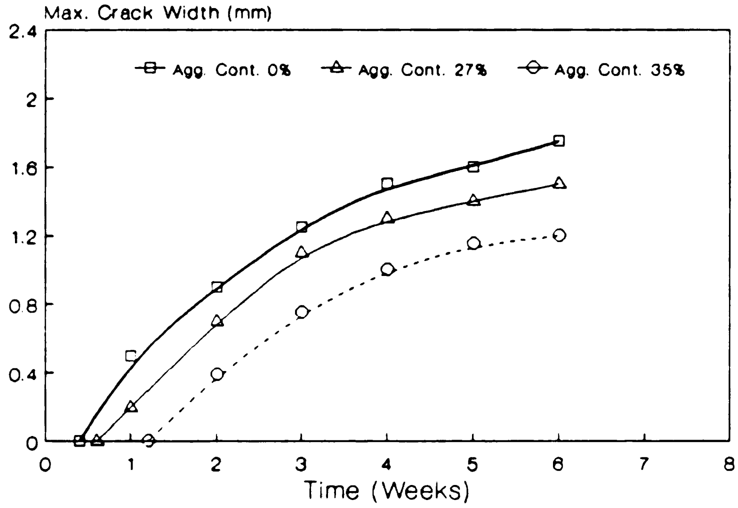
3.5.6 Restrained Shrinkage

The restrained shrinkage test results are presented in Figure 3.10 in the form of the maximum crack width versus the period of air-drying. It should be reminded that this test were performed with coarser (0.06 in., 1.5 mm particle size) aggregates. The increase in aggregate content is observed to delay cracking and to reduce the width of cracks caused by restrained shrinkage movements. The increase in carbon fiber content also causes reductions in the maximum restrained shrinkage crack width.

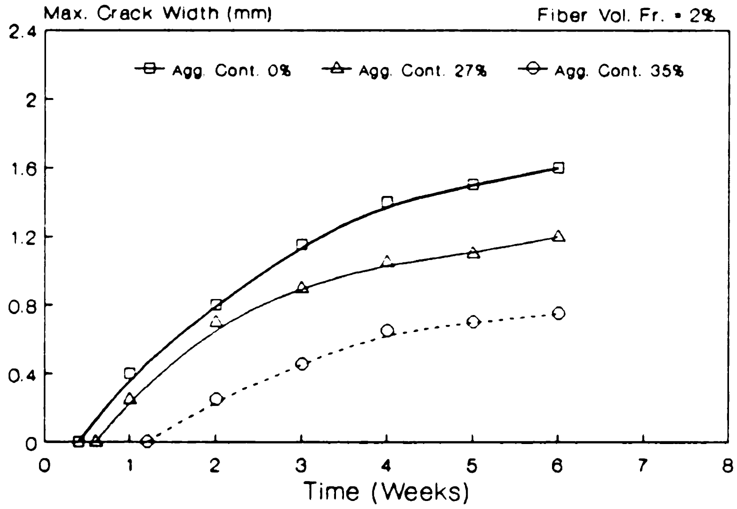


(a) Vf = 0%

Figure 3.10 (cont'd.)



(b) Vf = 1%



(c) Vf = 2%

Figure 3.10 (cont'd.)

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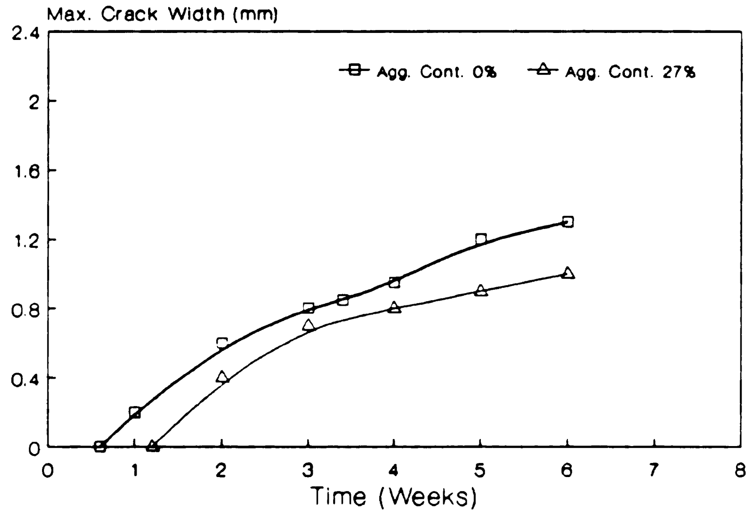


(d) Vf = 3%

Figure 3.10 Restrained Drying Shrinkage Test Results.

3.6 SUMMARY AND CONCLUSIONS

An experimental study was conducted on the interaction of light-weight aggregates with carbon fibers in cementitious materials. The effects of using light-weight aggregates with different particle sizes at different volume fractions on the following properties of carbon fiber reinforced cements with different fiber contents were investigated: flexural behavior, compressive strength, impact resistance, specific gravity, and restrained shrinkage cracking.

Regression analysis and analysis of variance of test results indicated that the flexural and compressive strength, flexural toughness and impact resistance of carbon fiber reinforced cement could be improved through the addition of light weight aggregates; this was true as far as the maximum size and content of aggregates did not increase certain limits, beyond which aggregates start to interfere with the uniform dispersion of fibers and negatively influence the composite material properties. The best results in this investigation were obtained with the finer aggregates (maximum particle size 0.02 in., 0.6 mm) when added at an aggregate/binder ratio of 0.2 to carbon fiber reinforced cement with 3% fiber volume fraction. The negative effects of aggregate interference with fiber dispersion are particularly pronounced in composites with higher fiber volume fractions when relatively large content of coarser aggregates are used. The positive effects of using aggregates in cementitious materials result possibly from the consequent improvements in dimensional stability of the material, which reduce the formation of microcracks associated with shrinkage movements.

The increase in light-weight aggregate content, as expected, leads consistently to reductions in the specific gravity of CFRC composites. Coarser aggregates, which have lower specific gravities, are more effective in reducing the specific gravity of the composite.

The increase in fiber volume fraction, when reasonably fine aggregates are used in the matrix at relatively low contents, leads to significant improvements in the flexural strength and toughness of the material. Compressive strength tends to be reduced with increasing fiber volume fraction and the specific gravity tends to be less at higher fiber loadings.

Under restrained shrinkage conditions, the increase in aggregate content and fiber volume fraction lead to reductions in the maximum crack width in CFRC composites. The increase in aggregate content also delays the appearance of cracks under restrained shrinkage movements.

CHAPTER 4

ALTERNATIVE DISPERSANTS FOR CARBON FIBERS IN CEMENT-BASED MATERIALS

4.1 INTRODUCTION

Fibers, because of their small cross-sectional dimensions, are not directly usable in engineering applications; they are, therefore, embedded in matrix materials to form fibrous composites. In the case of cementitious matrices, fiber reinforcement leads to improvements in the ductility, impermeability, impact resistance and tensile strength of the material.

One of the major problems associated with the use of short fibers in cementitious materials is in achieving a uniform dispersion of fibers in the matrix. Different dispersing agents such as silica fume or methyl cellulose can be used in order to overcome this problem.

4.2 DISPERSION OF FIBERS IN CEMENTITIOUS MATERIALS

Fibers tend to tangle and matt together when added to cementitious matrices at relatively high loadings. The dispersion of fibers in cementitious materials can be facilitated by the use of thickening agents such as polyethylene oxide or methyl cellulose [31,32]. Polyethylene oxide has been used for the mixing of chopped polypropylene fibers with cement or mortar. Another water-soluble resin, Polyox [33] which is an effective thickening agent, can be used for the dispersion of glass fibers in cementitious materials. Methyl cellulose, with its deflocculating action, breaks down the matrix components into uniformly dispersed basic particles; it also plays a thickening role and helps in improving the fiber dispersability of cement-based materials.

Dispersion of short carbon fibers in cementitious materials has been achieved by the use of silica fume [2], methyl cellulose [4] or slag cement [34]. The increase in silica fume content has been obtained to improve the dispersability of carbon fibers and also the quality of the matrix,thereby improving the composite material performance characteristics. Figure 4.1 shows that the increase in silica fume/cement ratio up to 0.4 leads to increased flexural strength of carbon fiber reinforced cement composites incorporating 5% volume fraction of 0.4 in (10 mm) carbon fibers. Silica fume helps with the dispersion of carbon fibers in cementitious matrices partly by its thickening action and also because its fine particles can effectively coat the low-diameter fibers, thus preventing the formation of dry fiber balls inside the matrix.

Slag cement has also been used at about 40% of the cement weight to improve fiber dispersability in carbon fiber reinforced cement composites with 1 to 5% fiber volume fractions [34]. The presence of slag cement helps in dispersing carbon fibers and thus improves the flexural strength of the composite. Methyl cellulose was used in Reference 4 at a loading equal to 1% of the cement weight to disperse 2% of 0.4 in (10 mm) carbon fibers in cement-based matrices.

4.3 EXPERIMENTAL PROGRAM

Effects of three types of dispersant on the hardened material properties of carbon fiber reinforced cement composites were investigated experimentally. Silica fume [17], fly ash [51] and methyl cellulose [32] were the constituents considered in this investigation to help with the dispersion of carbon fibers in cementitious materials.

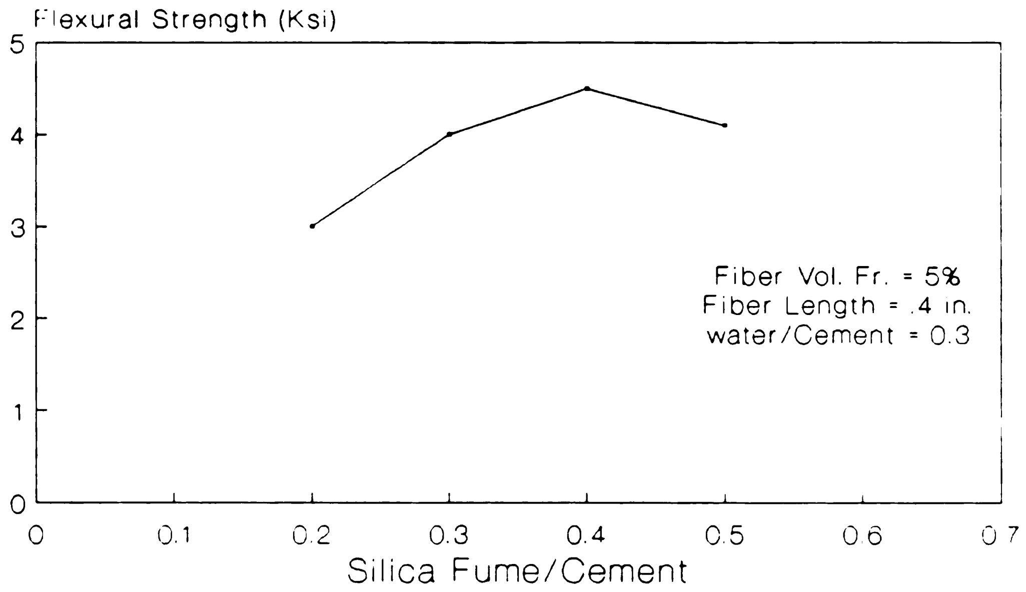


Figure 4.1 Effect of Silica Fume / Cement Ratio on the Flexural Strength of Carbon Fiber Reinforced Cement Composites [8].

The basic mix ingredients in the carbon fiber reinforced cement composite were: Type I portland cement, light-weight ceramic spheres (ML 3050) with particle size ranging from 0.02 to 0.01 in. (0.6 to 0.3 mm) and specific gravity of 1.05 [21], superplasticizer (with naphthalene formaldehyde sulfonate as the active ingredient) [18], and "Carboflex" pitch-based carbon fibers [19]. The mix proportions are presented in Table 1. The fly ash-to-binder (cement + fly ash) ratio as well as the silica fume-to-binder (cement + silica fume) ratios were both 0.23 by weight. The methyl cellulose-to-binder (cement) ratio was 0.006.

Table 4.1 Mix Proportions of CFRC Composites Considered in this Study.

	W/B	SF/B	FA/B	MC/B	SP/B	Ag/B	AF/B(%)	V_f (%)
Silica Fume Mix	0.25	0.23	-	-	0.032	0.2	0.06	3
Methyl Cellulose Mix	0.42	-	-	0.6%	-	0.2	0.12	3
Fly Ash Mix	0.25	-	0.23	-	0.024	0.2	0.08	3

C=Cement; FA=Fly Ash; Ag=Aggregate; AF=Anti-Foam; W=Water; SF=Silica Fume

B=Binder (C+SF) for Silica Fume Mix, (C+FA) for Fly Ash Mix and (C) for Methyl Cellulose Mix

A conventional mortar mixer was used for the manufacturing of carbon fiber reinforced cement composites. The mixing procedures for the silica fume and fly ash mixes were the same as the one presented in Chapter 2. For the methyl cellulose mix, the mixing procedures was as follows: (1) add 2/3 of water followed by cement and mix for 30 seconds at medium speed; (2) add the methyl cellulose and mix for 30 seconds; (3) gradually add the aggregates followed by the remainder of water while the mixer is running over a period of 1 minute; (4) add the anti-foaming agent; (5) add the fibers gradually while the mixer is running at low speed over a period of 3 minutes; and (6) turn the mixer to high speed and mix for another 2 minutes.

After testing the fresh mix for flowability (ASTM C-230), air content and unit weight (ASTM C-138), the specimens for hardened material tests were cast in molds, and were compacted through external vibration.

The average flows, based on replicated tests on three different mixes, were 60% for the silica fume mix, 66% for the fly ash one, and 45% for the methyl cellulose mix. The air contents were 8%, 9% and 12%, respectively.

The following specimens were manufactured for each mix composition: (a) Fifteen 1.5 x 1.5 x 6 in. (38 x 38 x 152 mm) prismatic specimens for flexural tests by third-point loading on a span of 4.5 in. (114 mm); and (b) fifteen 6 in. diameter by 2.5 in. height (152 mm diameter by 64 mm height) cylindrical specimens for impact tests (ACI committee 544-2R) [23].

The specimens were demolded after 24 hours during which they were covered by wet burlap and plastic sheet and stored at 74°F (22°C). Thereafter, they were cured in air at about 74°F (22°C) and 65% RH until the test age of 14 days.

4.4 EXPERIMENTAL RESULTS AND STATISTICAL ANALYSIS

Flexural strength and impact resistance are the mechanical properties of carbon fiber reinforced cement incorporating three different types of dispersants which were statistically analyzed in this investigation.

4.4.1 Flexural Strength

Table 4.2 presents the flexural strength test results and the associated sample means, standard deviations and coefficients of variation for the three types of mix incorporating three different dispersants.

The flexural strengths for silica fume and methyl cellulose mixes were comparable, and they were larger than the one for the fly ash mix. The coefficient of variation for the methyl cellulose mix was relatively lower than those for the other two mixes.

Analysis of variance and multiple-sample tests ("Duncan's and "Least Significant Differences" tests) were conducted in order to statistically verify the dependence of flexural strength on the dispersant type. The results of one way analysis of variance [24] indicated that the mean flexural strengths obtained with different dispersants are different at 5% level of significance.

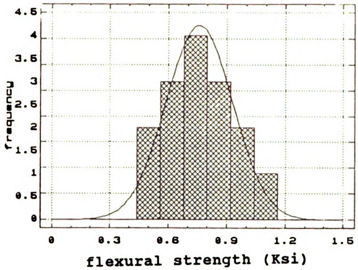
Table 4.2 Flexural Strength Test Results (in Ksi) of Carbon Fiber Reinforced Cement Composites Incorporating Different Dispersants (1 Ksi = 6.9 MPa).

	Dispersant Type		
	Silica Fume	Methyl Cellulose	Fly Ash
	0.648	0.561	0.323
	0.763	0.778	0.402
	0.548	0.942	0.466
	0.815	0.699	0.446
	0.583	0.681	0.256
	0.507	0.681	0.256
	0.795	0.698	0.278
	0.681	0.784	0.298
	1.107	0.625	0.529
	0.568	0.615	0.428
	0.921	1.034	0.421
	0.754	0.708	0.437
	0.857	0.619	0.456
	0.942	1.030	0.511
	0.885	0.850	0.322
Mean (Ksi)	0.758	0.754	0.401
Std. Dev.(Ksi)	0.171	0.245	0.085
Coef.of Var.	22.4%	19.7%	21.3%

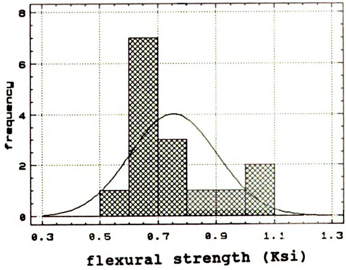
Duncan's and Least Significant Differences tests indicated that there is no significant difference between the flexural strength of the silica fume and methyl cellulose mixes considered in this study at 5% level of significance, but the flexural strength for both these mixes were different from that of the fly ash mix.

Chi-square goodness-of-fit tests indicated good fitness of the flexural strength test results for the silica fume and fly ash mixes to the normal distribution. A poor fitness was, however, observed for the methyl cellulose mix; this could result from the fact that, given the relatively large variations in test results, a larger sample size may be necessary to better assess the distribution of the flexural strength test results.

Figures 4.2.a, b and c show the distributions of the flexural strength test results for the three types of dispersant; the histograms in these figures are overlapped by the corresponding normal distribution curves. Normal probability plots are shown in Figures 4.3.a, b and c. The approximate linearity of the normal probability plot in Figures 4.3.a and 4.3.c confirms the normality of these test results.

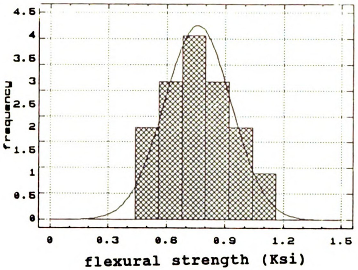


(a) Silica Fume Mix

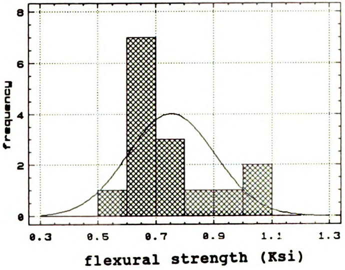


(b) Methyl Cellulose Mix

Figure 4.2 (cont'd.)

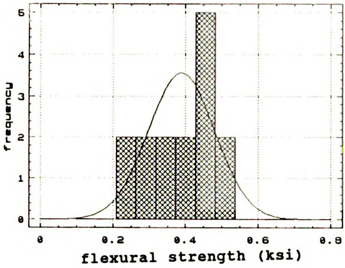


(a) Silica Fume Mix



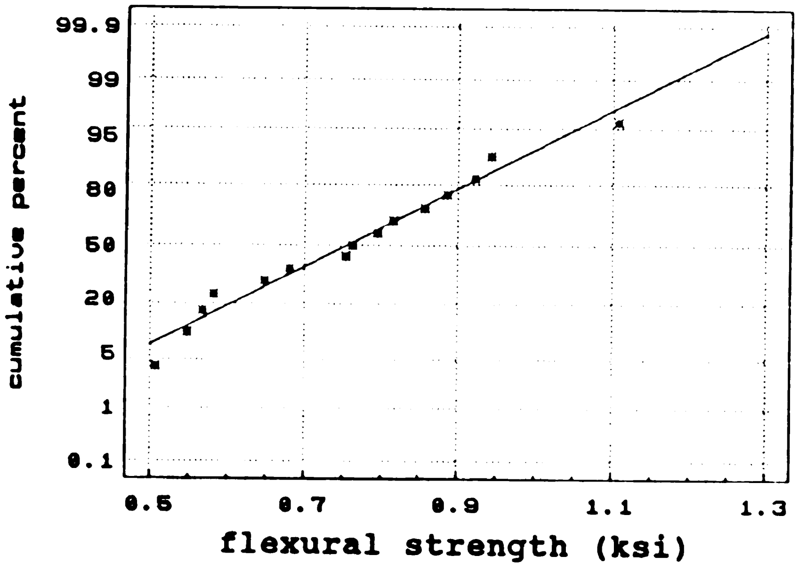
(b) Methyl Cellulose Mix

Figure 4.2 (cont'd.)

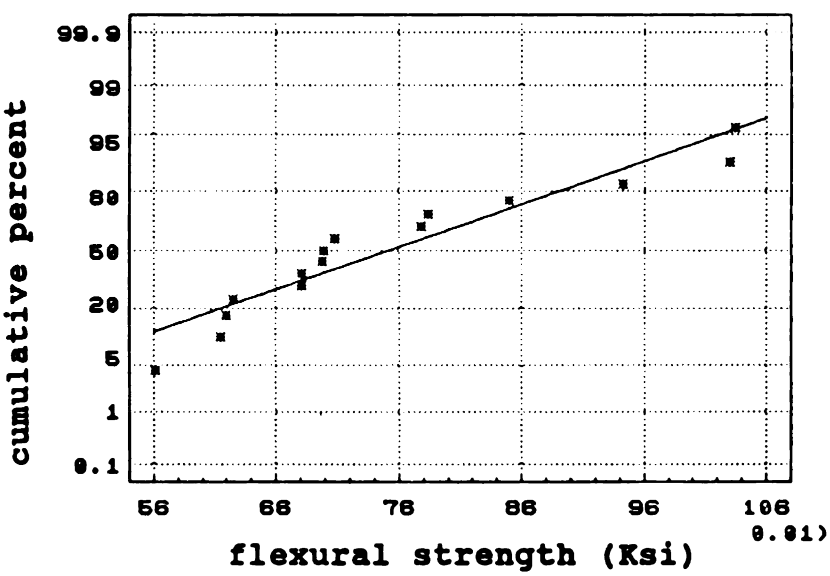


(c) Fly Ash Mix

Figure 4.2 Distribution of Flexural Strength Test Results for CFRC Composites.

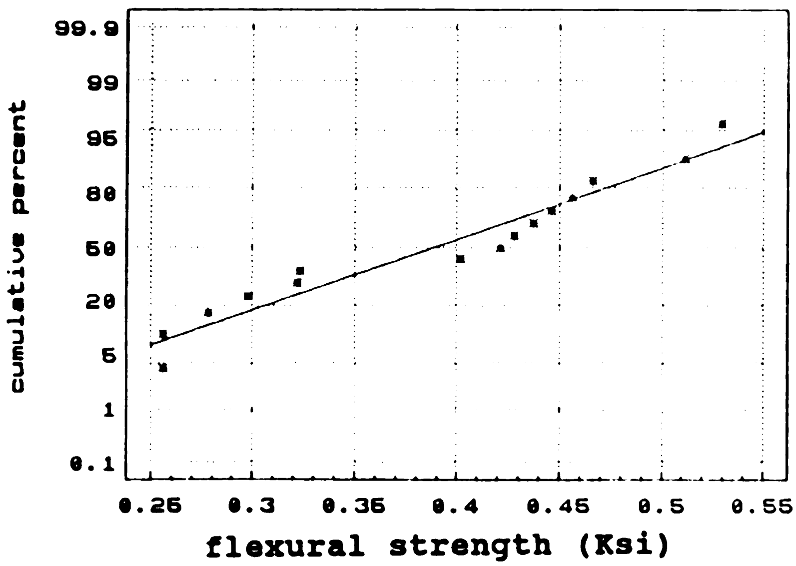


(a) Silica Fume Mix



(b) Methyl Cellulose Mix

Figure 4.3 (cont'd.)



(c) Fly Ash Mix

Figure 4.3 Normal Probability Plots of Flexural Strength Test Results for CFRC Composites.

The reduction in Flexural strength when fly ash is used as dispersant is clearly shown in Figure 4.4. This suggests that silica fume and methyl cellulose may be better dispersing agents than fly ash for use in carbon fiber reinforced cement composites.

The 95% confidence intervals for the flexural strengths corresponding to different types of dispersant are shown in

Table 4.3. A comparison of these intervals confirms the reduction in flexural strength when fly ash is used as dispersant.

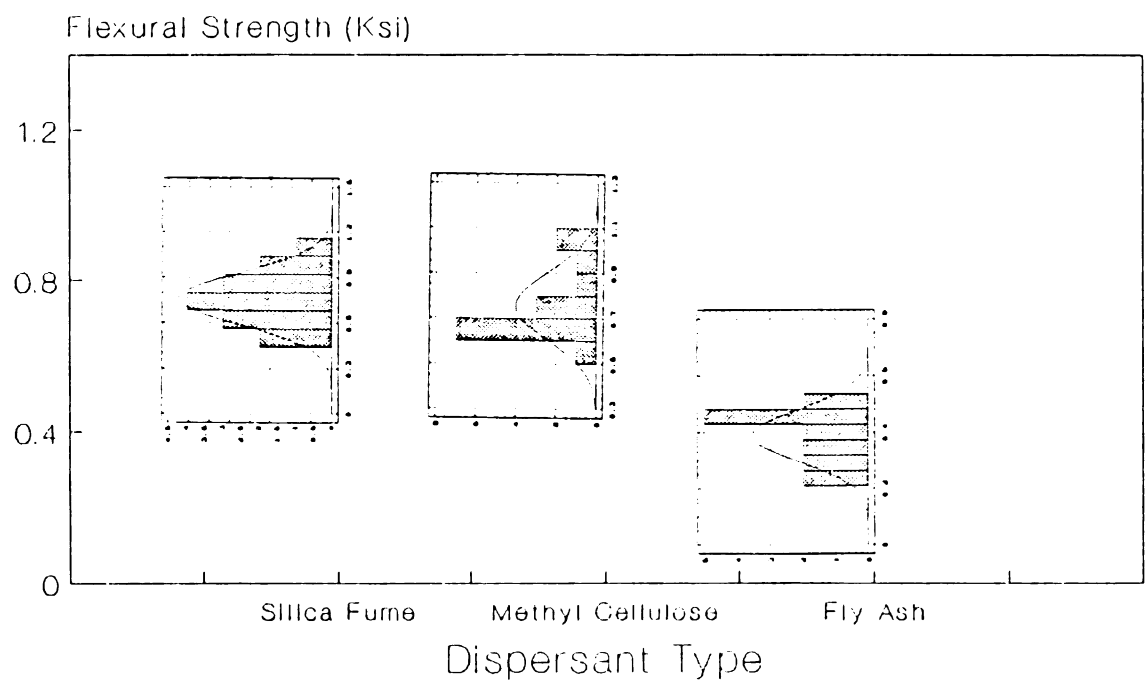


Figure 4.4 Effects of Dispersant Type on Flexural Strength of CFRC Composites. (1 Ksi = 6.9 MPa)

The relatively low flexural strength test results obtained in this study for different dispersant types may indicated that, for the simple mixing technique used in this investigation, for the 1/8 in. (3 mm) carbon fibers, the 3% volume fraction used for 1/8 in, (3 mm) carbon fibers, is relatively high from the points of view of fiber dispersability and compactibility of fresh mix. Better results could possibly be obtained through the use of lower fiber volume fractions or smaller fiber lengths.

Table 4.3 95% Confidence Intervals of Flexural Strength Test Results Considered in This Study.

Dispersant Type	Confidence Interval (Ksi)	
	Lower Limit	Upper Limit
Silica Fume	0.664	0.852
Methyl Cellulose	0.672	0.836
Fly Ash	0.354	0.449

4.4.2 Impact Resistance

Table 4.4 presents the impact resistance test results for the three types of dispersant considered in this investigation. Means, standard deviations and coefficients of variation corresponding to each case are also presented. Impact resistance for the fly ash mix are much lower than those for the other two mixes, and methyl cellulose seems to improve impact resistance more than silica fume.

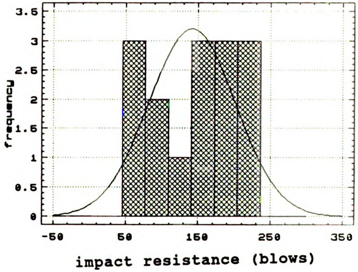
Chi-square goodness-of-fit tests indicated poor fitness of the impact resistance test results with the normal distribution for silica fume and methyl cellulose mixes, while a good fitness was obtained for the fly ash mix.

Table 4.4 Impact Resistance Test Results for CFRC Composites.

	Dispersant Type		
	Fly Ash	Methyl Cellulose	Silica Fume
	24	465	80
	26	266	53
	33	95	175
	20	103	51
	14	240	72
	28	126	151
	36	105	207
	22	170	80
	28	285	192
	41	144	130
	37	83	150
	38	380	220
	20	531	172
	30	247	183
	25	241	205
Mean (bolws)	28	232	141
Std.Dev.(blows)	8	138	59
Coef.of Var.	27.4%	59.4%	42.1%

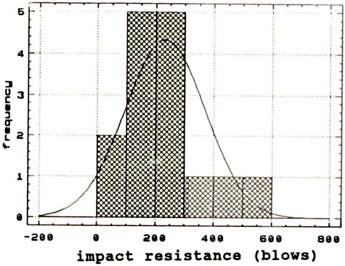
Because of the large variations in impact resistance test results, a larger sample size may be needed to derive more reliable conclusions regarding the normality of test results.

Figures 5.5.a, b and c shows the scatter in the impact resistance test results, with the normal curve overlapping them. Figure 5.6 presents the normal probability curves which are not close to straight line, especially for cases with silica fume and methyl cellulose (Figures 5.5.a and b, respectively), indicating poor fitness of the limited test results generated in this investigation to normal distribution.

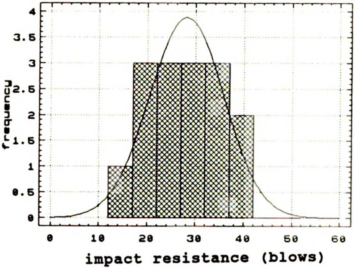


(a) silica Fume Mix

Figure 4.5 (cont'd.)

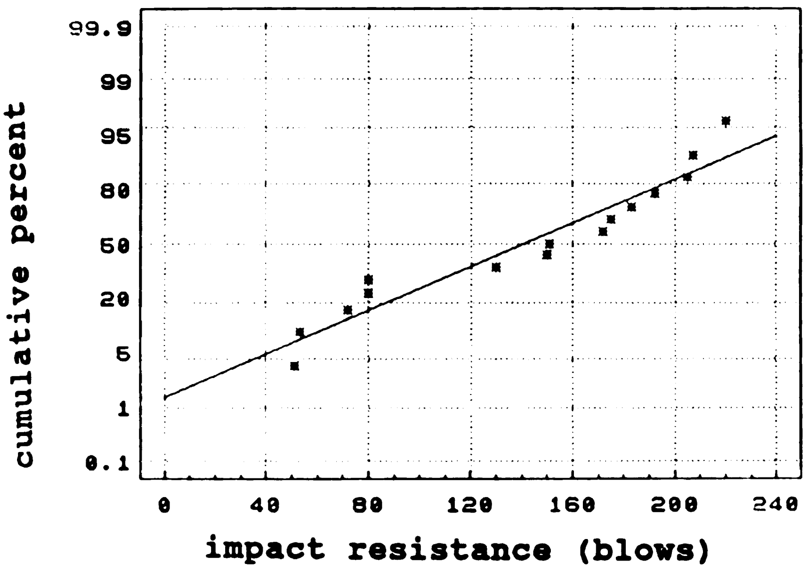


(b) Methyl Cellulose Mix

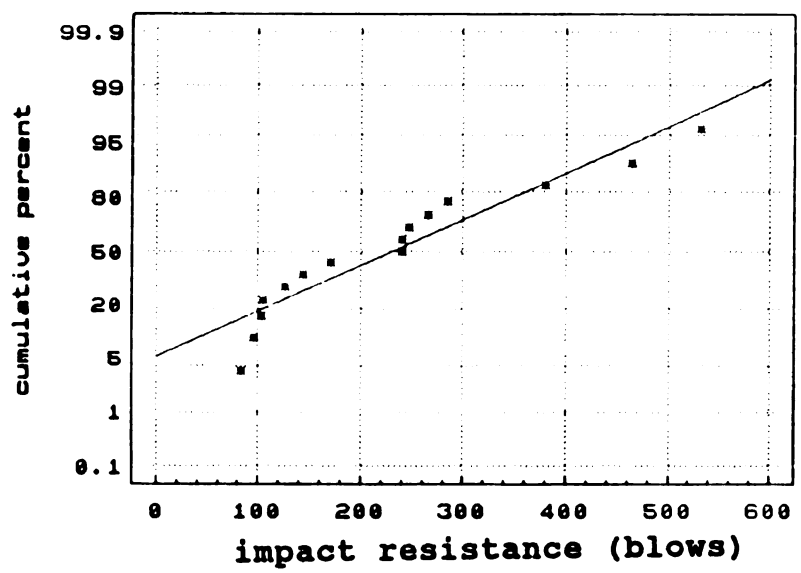


(c) Fly Ash Mix

Figure 4.5 Distributions of Impact Resistance Test Results for CFRC Composites.

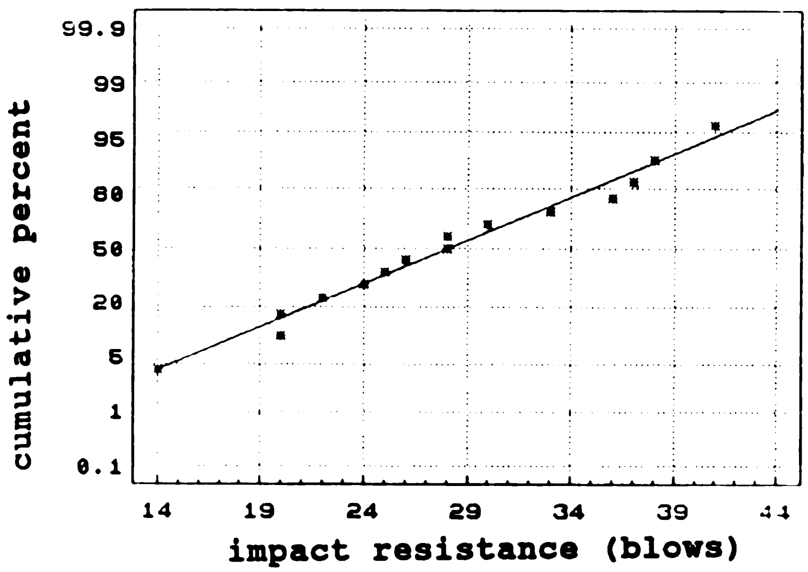


(a) Silica Fume Mix



(b) Methyl Cellulose Mix

Figure 5.6 (cont'd.)



(c) Fly Ash Mix

Figure 4.6 Normal Probability Plots of Impact Resistance Test Results for CFRC Composite.

The 95% confidence intervals for the impact resistance test results corresponding to different types of dispersant are presented in Table 4.5. This table confirms the relatively low impact resistance of the fly ash mix.

One-way analysis of variance and multiple-sample tests were also conducted for the impact resistance test results.

Table 4.5 95% Confidence Intervals of Impact Resistance Test Results Considered in this Study.

Dispersant Type	Confidence Interval (blows) Lower Limit	Upper Limit
Silica Fume	108	174
Methyl Cellulose	155	308
Fly Ash	23	32

Results ofone-way analysis of variance tests indicated that there is a significant effect of dispersant type on mean impact resistance. The multiple sample tests showed that there was no similarity between the impact resistance test results obtained with any two dispersants. Methyl cellulose tends to produce composites with the highest impact resistance.

4.5 SUMMARY AND CONCLUSIONS

An experimental study was conducted to investigate the effectiveness of different materials in the dispersion of carbon fibers in cementitious matrices. Judgement on the effectiveness of a dispersing agent was made based on the flexural strength and impact resistance of the hardened composite material. An effective dispersion of fibers is expected to produce composites with higher flexural strength and impact resistance.

The three dispersants considered in this investigation were silica fume, methyl cellulose, and fly ash. Replicated tests were conducted and statistical analysis techniques were employed to produce reliable information on the trends in the effects of dispersant type. All the mixes considered in this investigation incorporated 3% volume fraction of 1/8 in. (3 mm) pitch-based carbon fibers. The results indicated:

1. As far as the flexural strength and impact resistance are concerned, silica fume and methyl cellulose produce comparable levels of flexural strength, but fly ash gives lower results for the mix composition and manufacturing techniques considered in this investigation. This conclusion was verified at 5% level of significance.

2. Methyl cellulose gave the highest impact resistance, and fly ash gave very low impact resistance test results. These effects of dispersant types on impact resistance were verified at 5% level of significance.

It should be noted the effects of dispersant type on hardened material properties result not only from the corresponding effect on fiber dispersion, but also from the refinement of the matrix structure and properties as well as its bonding to carbon fibers.

CHAPTER 5

SPECIMEN SIZE EFFECTS ON THE FLEXURAL STRENGTH OF CARBON FIBER REINFORCED CEMENT COMPOSITES

5.1 INTRODUCTION

There are several factors affecting results of concrete strength tests; these include: (a) size and shape of the specimen; (b) conditions of casting; (c) moisture content of the specimen; (d) temperature of the specimen; (e) bearing conditions; and (f) rate of loading [1]. The research reported herein has been concerned with the effects of cross-sectional dimensions on the flexural strength of carbon fiber reinforced cement composites.

5.2 BACKGROUND

Under compressive stresses, tests show that the larger the specimen size the lower would be the strength [35,36]. Table 5.1 presents the relative compressive strengths for various sizes of cylindrical specimens with height-to-diameter ratio of 2; the relative strength is expressed as a percentage of that for a 6 x 12 in. (152.4 x 304.8 mm) cylindrical specimen (ASTM C-39). This table clearly shows that compressive strength increases with decreasing specimen size.

Table 5.1 Effects of Size of Compression Specimen on Indicated Strength of Concrete [35].

Size of cykinder, in.	Relative strength %	Size of cylinder in.	Relative strength %
2 x 4	109	12 x 24	91
3 x 6	106	18 x 36	86
6 x 12	100	24 x 48	84
8 x 16	96	36 x 72	82

Shape of specimens also affects the compressive strength test results. Tests by the U.S. Bureau of Reclamation indicate somewhat lower strengths for the rectangular prisms when compared with cylindrical ones [35].

As in the case of compression test, size and shape of the specimen also affect the flexural strength test results. Typical effects of specimen size on modulus of rupture are shown in Figure 5.1 [37]. Effects of size on strength can be explained partly by the "weakest link" theory. That is, the strength of a concrete specimen is governed by the weakest element (link) within it; the larger the size of the specimen, it would be more possibly contain an element that will fail at a given low load [37]. Relation of the fracture process to specimen size provides another illustration for size effects [38].

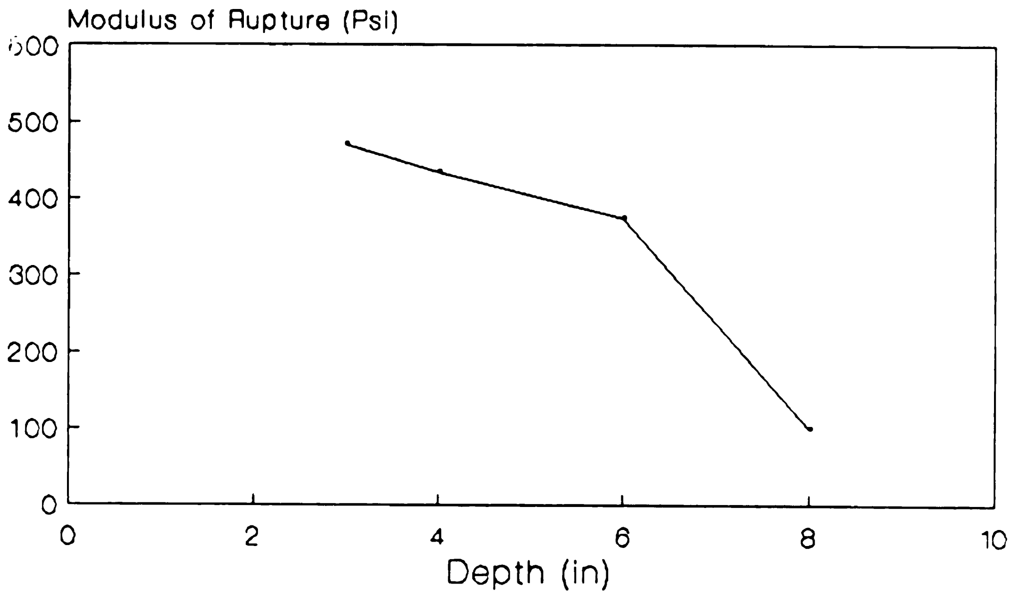


Figure 5.1 Effects of Depth of Specimen on the Modulus of Rupture of Concrete [37].

The fracture process in cement-based materials takes place over a relatively large fracture process zone around the crack tip with a size which, for the usual laboratory specimens, is of the same order of magnitude as the size of specimen itself; the specimen size (boundaries) thus may influence the fracture process, this provides another illustration for size effect [37].

Effects of specimen geometry on the flexural and compressive strengths of carbon fiber reinforced cement composites are discussed in Reference 5. Effects of cross-sectional dimensions, span, and the ratio of shear span (a) to depth (D) (a/D) were studied.

Figure 5.2 shows that flexural strength decreases with increasing span (l) for a/D ratios of 1 and 2.

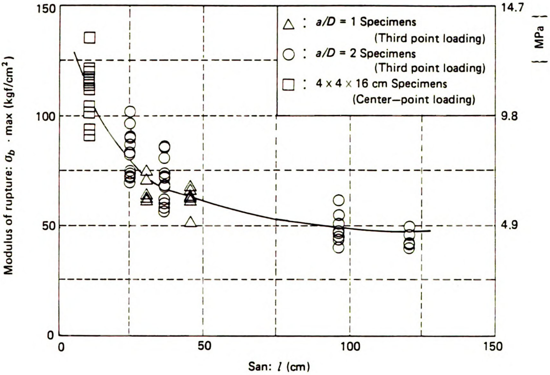


Figure 5.2 Effects of Length of Specimen (Span) on the Flexural Strength of CFRC [38].

Figure 5.3 indicates that the flexural strength of carbon fiber reinforced cement decreases linearly with increasing (l x D)/log (l x d) values.

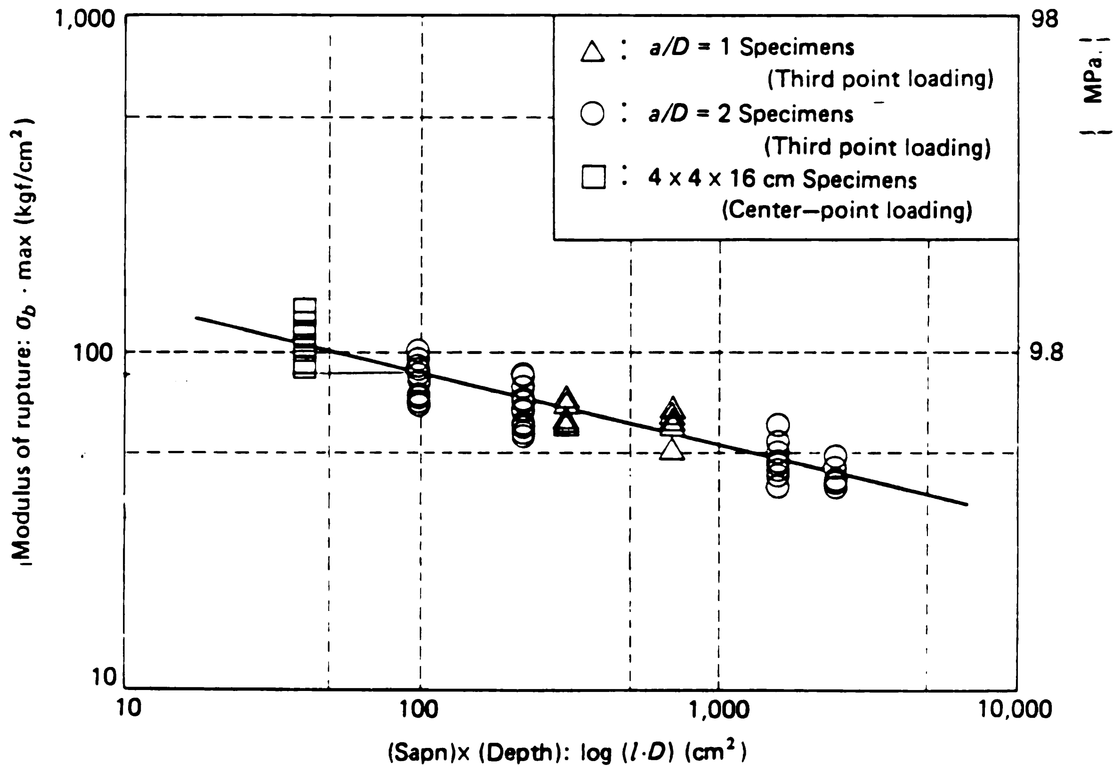


Figure 5.3 Effects of Length by Depth Value (l x D) on the Flexural Strength of CFRC [38].

Reference 4 also indicates that the compressive strength of carbon fiber reinforced cement composites decreases with increase in the size of specimens. In the case of longer fibers (e.g., steel fibers), the reorientation of fibers when the specimen thickness becomes less than the fiber length may pronounce the size effects on material properties. Carbon fibers, however are relatively short when compared with the product thicknesses expected in practice.

5.3 EXPERIMENTAL PROGRAM

The effects of specimen size on the flexural strength test results of carbon fiber reinforced cement were investigated experimentally. It should be noted that the flexural strength of fiber reinforced cement composites is an important design factor in typical applications such as thin sheet products.

The basic mix ingredients in carbon fiber reinforced cement were: Type I portland cement [16], silica fume [17], class C fly ash (see Table 5.2 for properties) [51], superplasticizer (with naphthalene formaldehyde sulfonate as an active ingredient) [18], grade 20 silica sand (gradation shown in Table 5.3), and Carboflex pitch-based carbon fibers [21].

An Omni mixer (30-liter capacity) was used for the manufacture of CFRC [39]. Omni mixer is capable of applying greatly varying accelerations to the mix particles and fibers in many different directions (Figure 5.4), forcing all materials to come into intimate contact with the cement-water mixture in a very short time, thus eliminating the possibility of dry fiber balls forming in the mixture. The use of an Omni mixer results in more flexibility in the selection of the mix proportions.

Table 5.2 Chemical Properties of Class C Fly Ash [51].

Constituent	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	SO_4	K_2O	Na_2	C
Amount (%)	48.7	18.5	8.5	1.1	13.5	3.3	1.3	0.6	5.8	1

Table 5.3 Gradation of Grade 20 Silica Sand.

U.S. Sieve	20	30	40	50	70
Remainder (%)	1	29	53	15	2.0

The mixing procedure was as follows: (1) prewet the mixer; (2) add carbon fibers, then silica fume, fly ash and half of sand; (3) mix the dry ingredients for 30 seconds; (4) add 70% of the water; (5) mix for 3 minutes; (6) add cement and remainder of water, and mix for 1 minute; (7) add superplasticizer and remainder of sand; and (8) mix for 5 minutes.

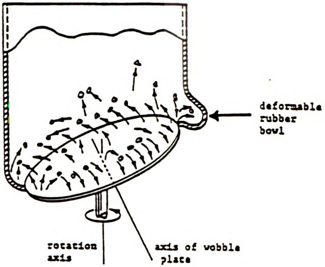


Figure 5.4 Omni Mixer [39]

The mix proportions considered in this study were as follows: silica fume/binder (cement + silica fume + fly ash) ratio of 0.125, fly ash/binder ratio of 0.175, water/binder ratio of 0.223, superplasticizer/binder ratio of 0.032, silica sand volume fraction of 20%. The carbon fiber volume fraction was 1%, and the fibers were 1/16 in. (1.5 mm) long. The fresh mix properties were characterized through the performance of the flow table test (ASTM C-230) and the air content of the fresh mix (ASTM C-138). The flow of the mix considered in this study was 80% and the air content was 8%.

Three different sizes of prismatic specimens for flexural strength tests were considered, with fifteen specimens constructed for each case. The standard specimen size was 1.5 x 1.5 x 6 in. (38 x 38 x 152 mm), the others were 1.0 x 1.5 x 6 in. (25.4 x 38 x 152 mm), and 1.0 x 1.0 x 6.0 in. (25.4 x 25.4 x 152 mm). The fresh mixture of carbon fiber reinforced mortar was cast inside molds in one layer, and compaction of the material was achieved through external vibration.

The specimens were demolded after 24 hours during which they were covered by wet burlap and plastic sheet, and stored at 74°F (22°C). Thereafter, they were cured in air at 74°F (22°C) and 65% RH for 14 days.

The flexural test specimens were tested by third-point loading on a span of 4.5 in. (114 mm). The loading was quasi-static and displacement-controlled.

5.4 EXPERIMENTAL RESULTS

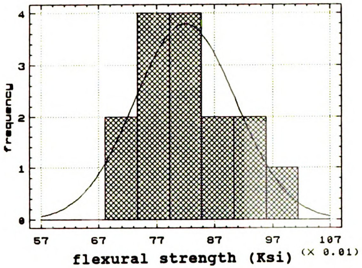
Table 5.5 presents the flexural strength test results and the associated sample means, standard deviations and coefficients of variation for the three different specimen sizes considered in this study. There is a tendency in flexural strength to decrease with increasing specimen size; the trends are comparable to those reported in Reference 28 (see Figures 5.2 and 5.3) for carbon fiber reinforced cement composites.

Table 5.2 Flexural Strength Test Results (in Ksi) of Carbon Fiber Reinforced Cement Specimens.

	Specimen Size (in.)		
	1.5 x 1.5	1.0 x 1.5	1.0 x 1.0
	0.831	0.796	1.091
	0.759	0.999	0.965
	0.768	0.808	1.050
	0.906	0.756	1.188
	0.691	0.953	1.110
	0.953	0.934	1.299
	0.751	0.924	0.892
	0.998	1.020	1.060
	0.899	0.934	1.114
	0.798	0.654	1.045
	0.724	0.868	0.985
	0.803	0.983	0.897
	0.815	1.083	1.123
	0.744	0.974	0.954
	0.851	0.896	1.201
Mean	0.818	0.906	1.06
Std.Dev.	0.086	0.112	0.115
Coef.of Var.	10.55	12.04	10.7

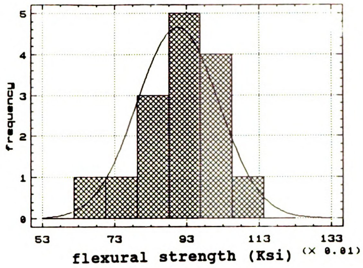
Kolmogorov-Smirnov goodness-of-fit tests confirmed the normality of the distribution of flexural strength test results for all the three specimen sizes at 5% level of significance.

Figures 5.6.a, b and c show the distributions of flexural strength test results for the three specimen sizes, with the histogram overlapped by the corresponding normal distribution curve. Figure 5.6 presents the normal probability plots (cumulative distribution curves) for the three specimen sizes considered in this study.

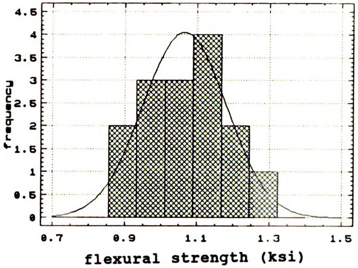


(a) 1.5 x 1.5 in. Cross-Section Specimens

Figure 5.5 (cont'd.)

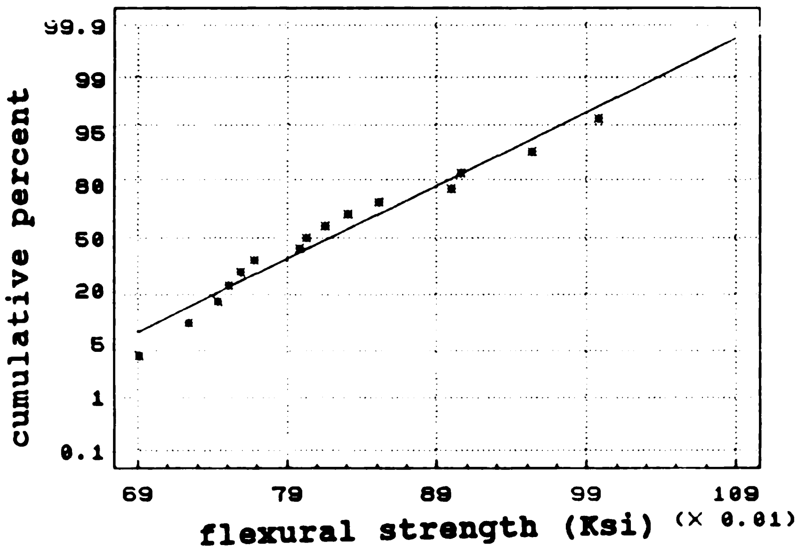


(b) 1.0 x 1.5 in. Cross-Section Specimens

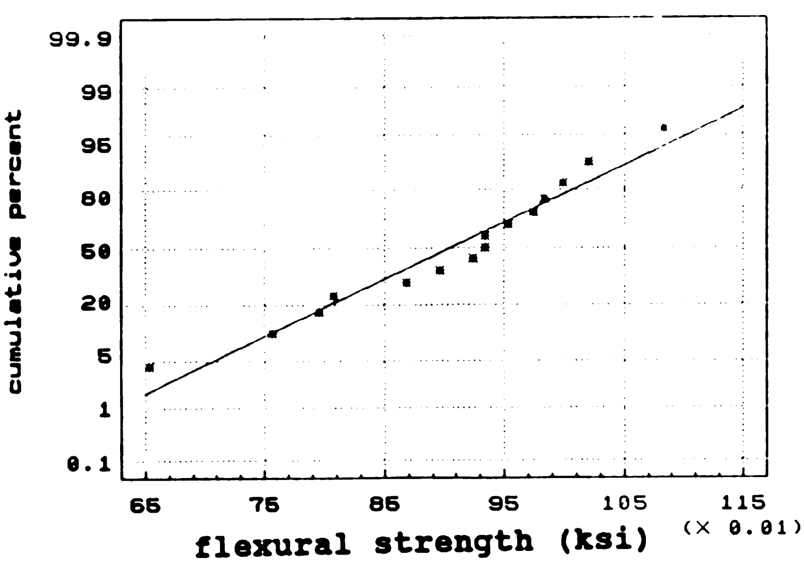


(c) 1.0 x 1.0 in. Cross-Section Specimens

Figure 5.5 Distribution of Flexural Strength Test Results for CFRC Composites.

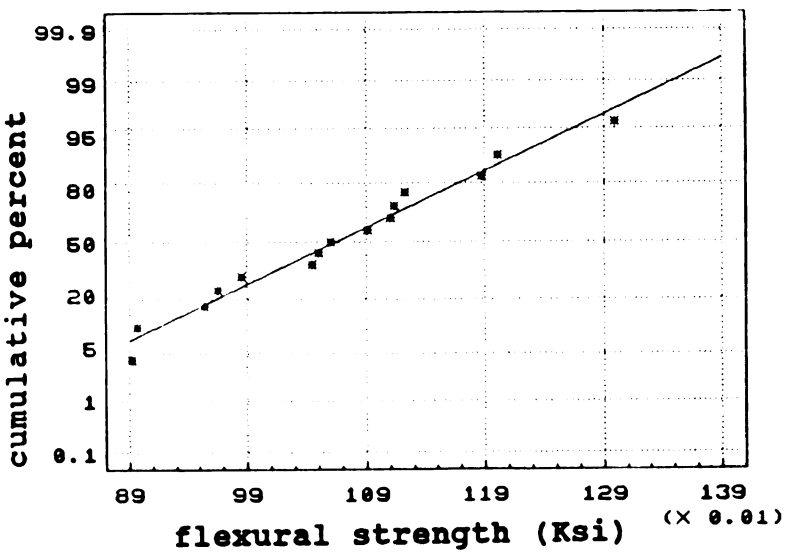


(a) 1.5 x 1.5 in. Cross-Section Specimens



(b) 1.0 x 1.5 in. Cross-Section Specimens

Figure 5.6 (cont'd.)



(c) 1.0 x 1.0 in. Cross-Section Specimens

Figure 5.6 Normal Probability Plots of Flexural Strength Test Results for CFRC Composites.

The approximate linearity of the normal probability plots are indicatve of the normality of the distribution of flexural strength test results.

The reduction in the flexural strength of carbon fiber reinforced cement composites with increasing specimen size (cross-section) can be clearly observed in Figure 5.7.

The 95% confidence intervals for the flexural strengths corresponding to different cross-sectional sizes, are shown in Table 5.3. A comparison of these confidence intervals also provides indications of the increase in flexural strength with decreasing specimen size.

Analysis of variance and multiple-sample tests ("Duncan's" and "Least Significant Differences" tests) were conducted in order to statistically verify the dependence of flexural strength test results on specimen size.

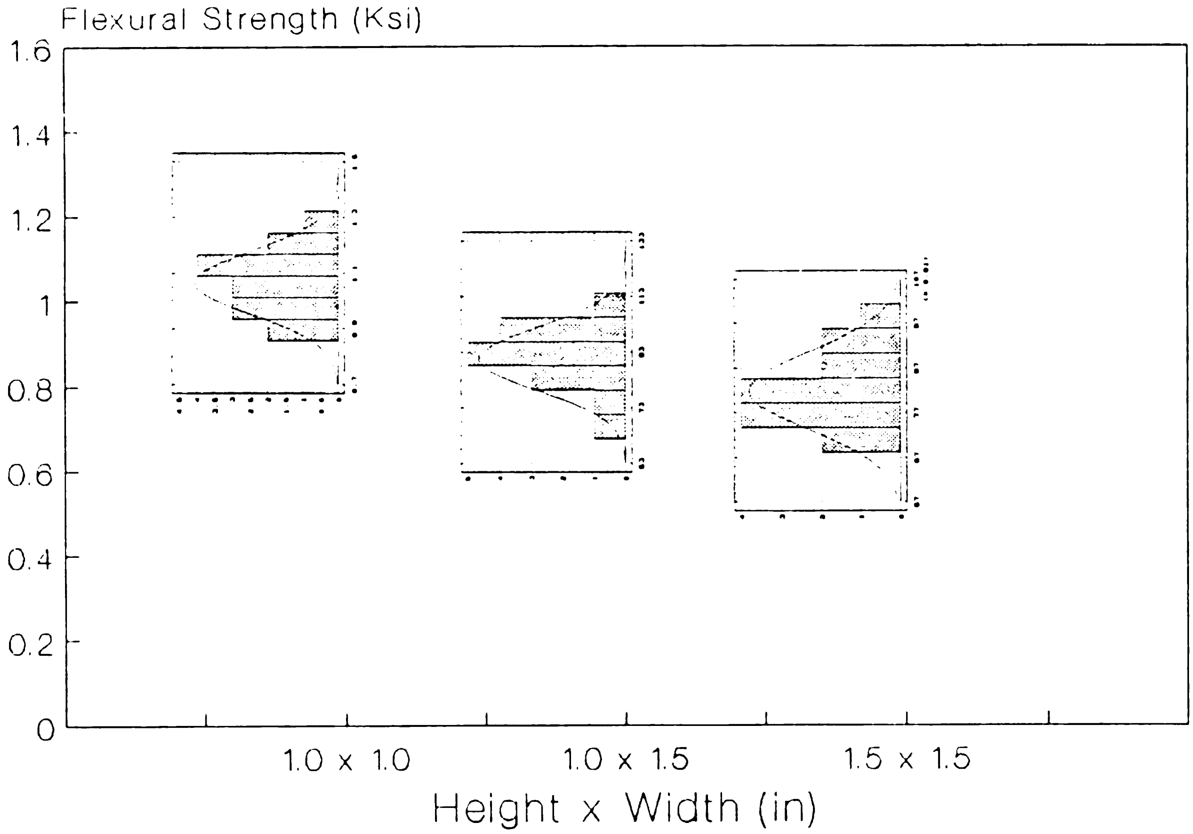


Figure 5.7 Effects of Specimen Size on the Flexural Strength of CFRC Composites.

Table 5.3 95% Confidence Interval of Flexural Strength Test Results Considered in this Study.

Specimen Size (in) Height x Width	Confidence Interval (Ksi) Lower Limit	Upper Limit
1.5 x 1.5	0.771	0.867
1.0 x 1.5	0.843	0.967
1.0 x 1.0	1.00	1.13

One-way analysis of variance [24] indicated that the means of the three sets of results (corresponding to the three different specimen sizes) differ significantly at 5% level of significance.

Duncan's and Least Significant Differences tests [26] confirmed that there is a size effect on flexural strength at 5% level of significance, and the flexural strength for each specimen size is different from that for any other size. This indicates that reductions in either (or both) of the cross sectional width and depth lead to increased flexural strength in carbon fiber reinforced cement composites.

5.4 SUMMARY AND CONCLUSIONS

Prismatic specimens made of carbon fiber reinforced cement composites with different cross-sectional dimensions were tested in flexure to investigate size effects on flexural strength test results. All specimens incorporated 1% volume fraction of 1/16 in. (1.5 mm) pitch-based carbon fibers. The span length was constant (4.5 in., 114.3 mm), and three cross-sectional dimensions were considered: 1.5 in. (38 mm) square, 1.5 in. (38 mm) depth x 1.0 in. (25.4 mm) height, and 1.0 in. (25.4 mm) square. These specimens were tested quasi-statically by third-point loading. Fifteen tests were performed at each specimen size, and the results were analyzed statistically.

It was concluded, based on statistical analysis of the replicated test results, at 5% level of significance, the flexural strength tends to increase with reductions in the width and/or depth of the specimen. The flexural strength of 1.0 in. (25.4 mm) square cross section specimens was about 30% greater than that of 1.5 in. (38 mm) square cross-section specimens.

At a constant width of 1.5 in. (38 mm), the reduction in specimen depth from 1.5 in. (38 mm) to 1.0 in. (25.4 mm) resulted in about 10% increase in flexural strength.

CHAPTER 6

FREEZE-THAW DURABILITY OF LIGHT-WEIGHT CARBON FIBER REINFORCED CEMENT COMPOSITES

6.1 INTRODUCTION

Among exposure conditions with major disintegrating effects, repeated freezing and thawing has particularly disruptive effects on cementitious materials.

The increase in volume accompanying the freeze of water in capillaries, large-scale migration of water from small pores to large cavities where it can freeze at lower temperature, and osmotic pressure resulting from local salt concentration gradients are considered to be the key mechanisms causing frost attack on cement-based materials [40].

Entrainment of cement-based materials with closely-spaced air bubbles provides escape boundaries for the water being pressed out as a result of the above mechanism of frost attack, and thus present the build-up of internal pressure and the consequent rapture of the material. The capillary pore system characteristics and degree of saturation are also among the factors influencing the freeze-thaw durability of cement-based materials.

Like the cement paste, the aggregate particles may be subject to internal hydraulic pressure. Aggregates that become saturated must accommodate the expansion of freezing water either by expelling the excess or expanding. Aggregate normally has a greater tensile strength than hydrated cement paste, and thus it may not fracture but its expansion will cause distress in the surrounding paste [41].

Aggregate particle sizes also effects the frost damage of concrete via aggregate damage. At a certain degree of saturation and freezing rate, larger aggregates may cause damage, but smaller particles of the same aggregates would not [37]. Very porous aggregates, such as light-weight aggregates have a very high permeability, so that water can readily escape during freezing and high degree of saturation is not critical [37]. However, these aggregates can cause damage to the transition zone between aggregates and the cement paste matrix when water under pressure is expelled from aggregate particles.

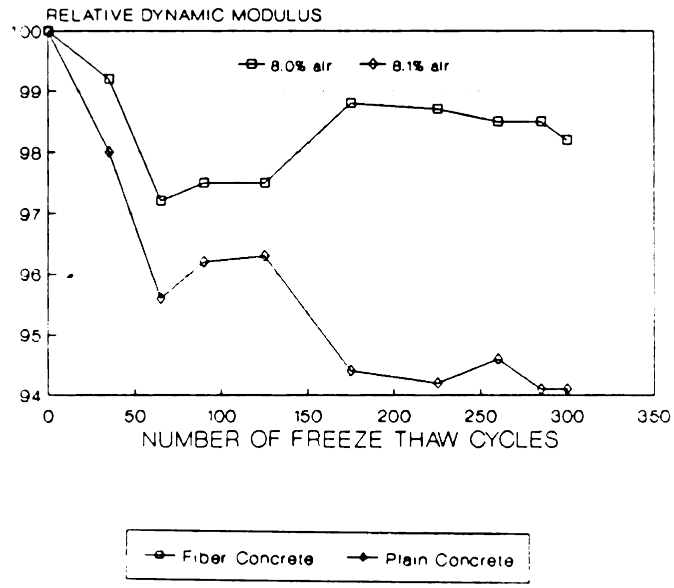
Reference 42 has reported that the spread in durability among the concretes made with the different light-weight aggregates appears no greater than might be encountered with normal weight-aggregates.

6.2 FREEZE-THAW DURABILITY OF FIBER REINFORCED CEMENT COMPOSITES

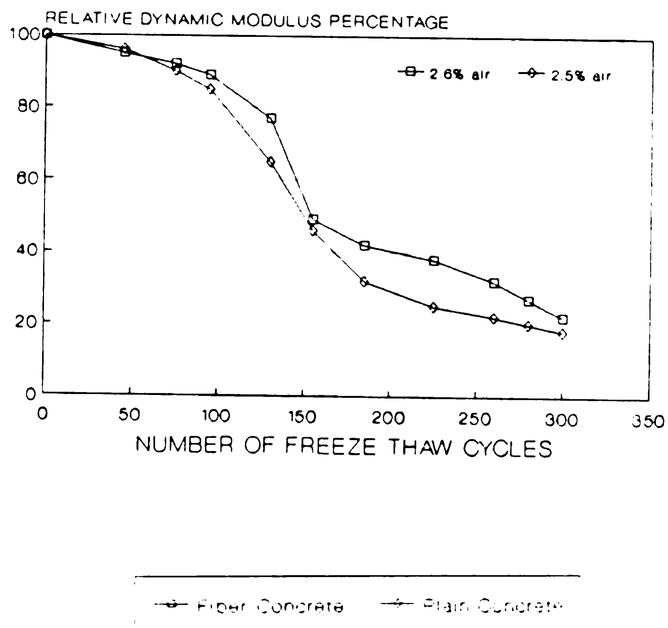
The durability characteristics of fiber reinforced concrete are influenced by the durability characteristics of fibers, cementitious matrices and the interface between them. The freeze-thaw resistance of air-entrained steel fiber reinforced concrete with high sand-to-aggregate ratios is comparable to that of air- entrained plain concrete [43]. At relatively high air contents (Figure 6.1.a), fiber reinforced concrete exhibits slightly better freeze-thaw durability than plain concrete (both fibrous and plain materials showed excellent durability) [44]. At lower air contents, fibrous specimens showed freeze-thaw durability characteristics which are comparable with plain specimens (Figure 6.1.b).

The freeze-thaw durability of carbon fiber reinforced cement has been studied in Reference 4. As shown in Figure 6.2, after 300 cycles of freezing and thawing, carbon fiber reinforced cement specimens show only minor reductions in the dynamic modulus of elasticity, which indicate the high resistance of CFRC to repeated freeze-thaw cycles.

Carbon fibers, through their desirable crack-arresting properties and effectiveness in increasing the tensile strength of cement-based matrices can produce cement composites with excellent freeze-thaw durability [4].



(a) High Air Content



(b) Low Air Content

Figure 6.1 Effects of Steel Fibers on Freeze-Thaw Durability.

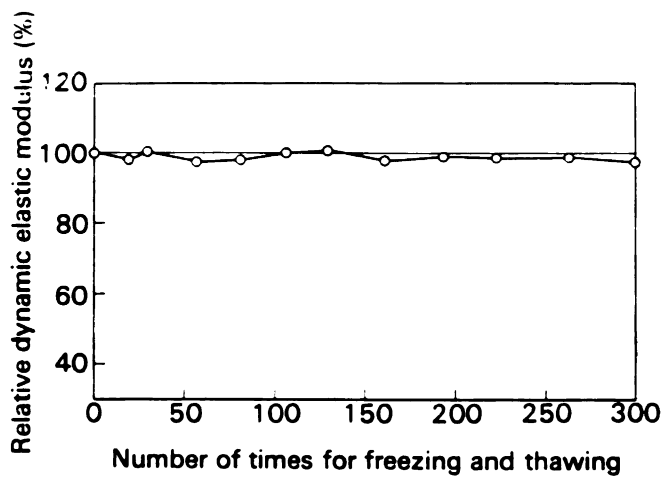


Figure 6.2 Effects of Freeze-Thaw Cycles on the Dynamic Modulus of Elasiticty of Carbon Fiber Reinforced Cement [4].

6.3 EXPERIMENTAL PROGRAM

Effects of light-weight aggregate content and fiber volume fractions on the freeze-thaw durability of carbon fiber reinforced cement were investigated experimentally.

The basic mix ingredients in Carbon fiber reinforced cement were: Type I portland cement, silica fume (see Table 2.5 for some physical and chemical properties) [17], superplasticizer (with naphthalene formaldehyde sulfonate as an active ingredient) [18], and Carboflex pitch-based carbon fibers (see Table 2.6) [19], and ML 1430 Macrolite Ceramic Spheres as light aggregates (see Table 3.1 for gradation) [21].

The presence of silica fume in CFRC facilitates the dispersion of carbon fibers, while the superplasticizer helps in overcoming the workability problems resulting from the use of carbon fibers and silica fume in cememtitious materials.

The experimental program was based on a 3 (agg. contents) x 4 (fiber vol. fractions) factorial design. Twelve mixes with three different aggregate contents, 0, 0.2, and 0.3 aggregate/binder ratios corresponding to 0, 27 and 35% aggregate volume fractions, respectively, with a maximum particle size of 0.06 in. (1.5 mm), and four fiber volume fractions (0, 1, 2, and 3% of 1/8 in., 3mm long carbon fibers) were considered in this study.

For all mixes, a 0.23 silica fume-binder (cement + silica fume) ratio was used and the superplasticizer-binder ratio was 0.032.

The workability of all mixes was comparable, with flow ranging from 60 to 70% (flow table test ASTM C-230). For this purpose, depending on the fiber and aggregate loadings, adjustments were made in the water-binder ratios ranged from 0.248 to 0.358. An anti-foaming agent [20] was also used to maintain the fresh mix air content at about 8 to 12% (ASTM C-138). The anti-foaming agent content ranged from 0.04 to

0.18% of cement weight. The dosage of anti-foaming agent had to be increased with increasing fiber and aggregate loading in order to keep air content constant, no air entraining agent was used with any of the mixes.

A conventional mortar mixer was used for the manufacturing of carbon fiber reinforced cement. The following mixing procedure was chosen in order to achieve a uniform dispersion of fibers: (1) add all the water followed by the cement and mix for 30 seconds at medium speed; (2) gradually add 1/2 of silica fume followed by 1/2 of superplasticizer over a period of 1 minute; (3) add the remainder of silica fume followed by the remainder of superplasticizer, this process takes approximately 2 minutes until a uniform mixture is achieved; (4) gradually add all aggregates while the mixer is running over a period of about 1 minute, and then add the anti-foaming agent; (5) gradually add the fibers while the mixer is running at low speed over a period of 3 minutes; and (6) turn the mixer to high speed and mix for 2 minutes.

After testing the fresh mix for flowability (ASTM C-230), air content (ASTM C-138), the specimens for freeze-thaw test were cast in molds, and were compacted through external vibration.

The specimen were demolded after 24 hours during which they were covered by wet burlap and plastic sheet and stored at 74°fF (22°C). Thereafter, they were cured in air at 74°F

(22°C) and 65% Relative humidity for 14 days.

Freeze-thaw test specimens were prismatic with a 3 x 4 in. (76.2 x 101.6 mm) cross section, and length of 16 in. (405.6 mm). Freeze-thaw tests were performed following the procedure A (both freezing and thawing in wet environment) of ASTM C-666. The freeze-thaw damage was assessed through measurement of the fundamental transverse frequency of specimens when simply supported on a span of 7.728 in. (196.3 mm), from which the relative dynamic modulus of elasticity (P_k) was derived using the following equation:

$$P_k = (n_1)^2/(n)^2 \times 100$$

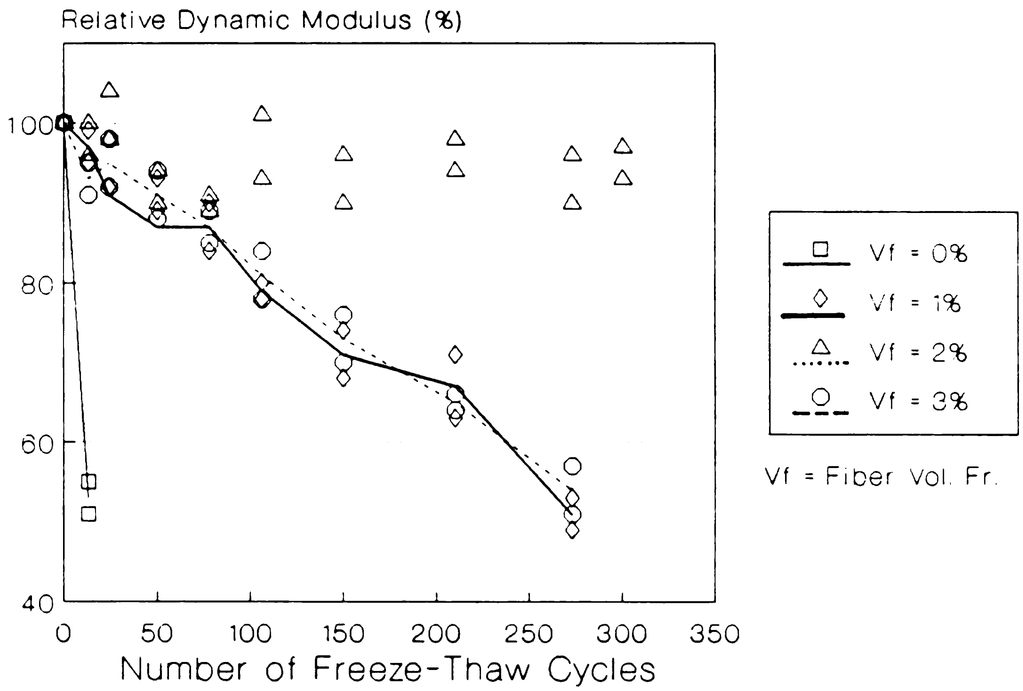
Where n = fundamental transverse frequency at 0 freeze-thaw cycles;

n_1 = fundamental transverse frequency at k freeze-thaw cycles.

Two specimens were tested for each mix composition and a maximum number of 300 cycles were applied, selected to represent a typical frost action on the material throughout the life of structures (ASTM C-666).

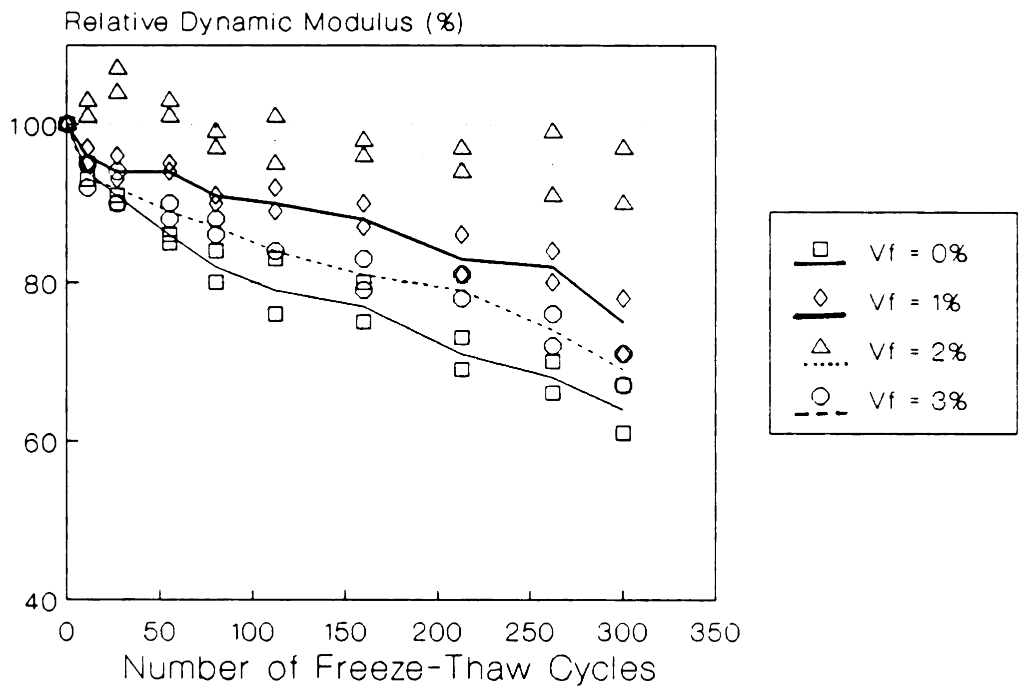
6.4 EXPERIMENTAL RESULTS

Figure 6.3 and 6.4 present the effect of aggregate contents and fiber volume fractions on the relative dynamic modulus of elasticity of carbon fiber reinforced cement composites with an average of air content of 10%.



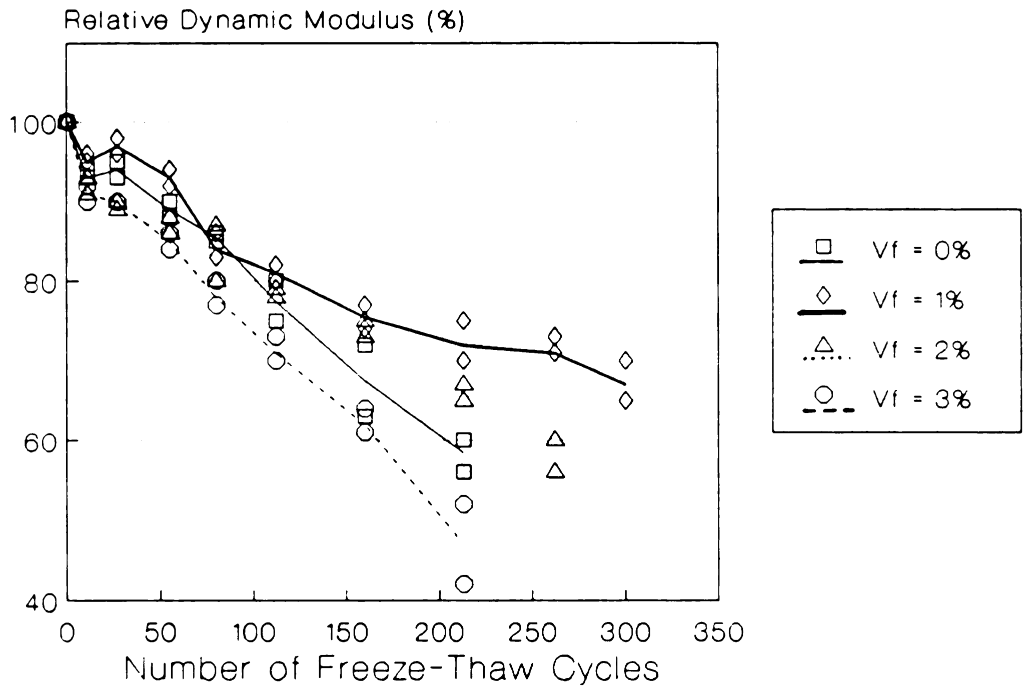
(a) Aggregate Volume Fraction = 0%

Figure 6.3 (cont'd.)



(b) Aggregate Volume Fraction = 27%

Figure 6.3 (cont'd.)

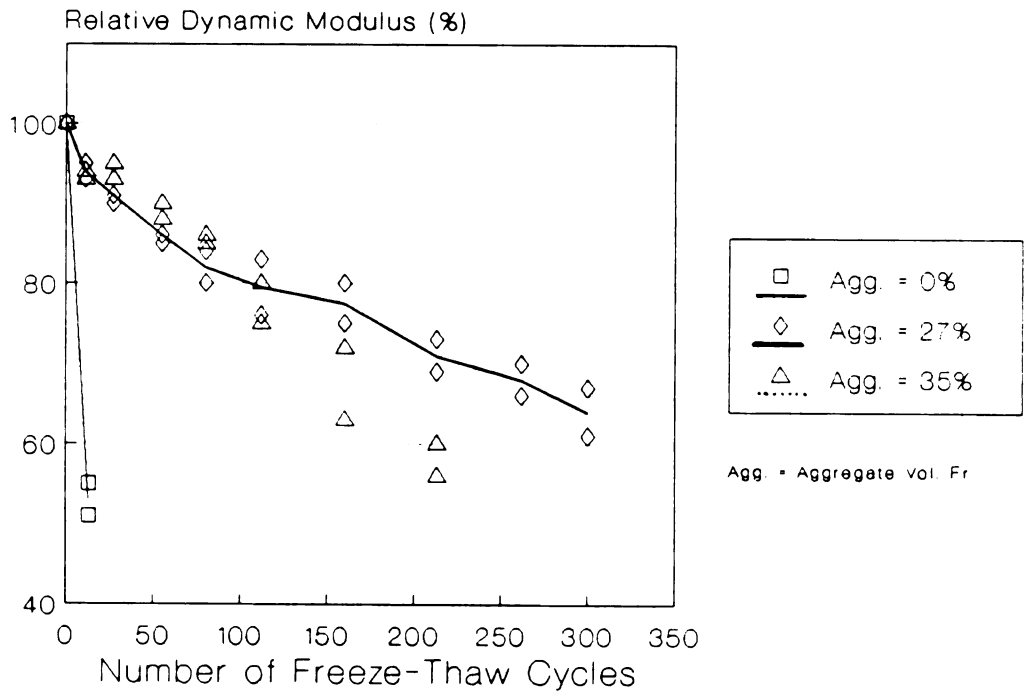


(c) Aggregate Volume Fraction = 35%

Figure 6.3 Effects of Fiber Volume Fraction on the Relative Dynamic Modulus of CFRC at Different Aggregate Contents.

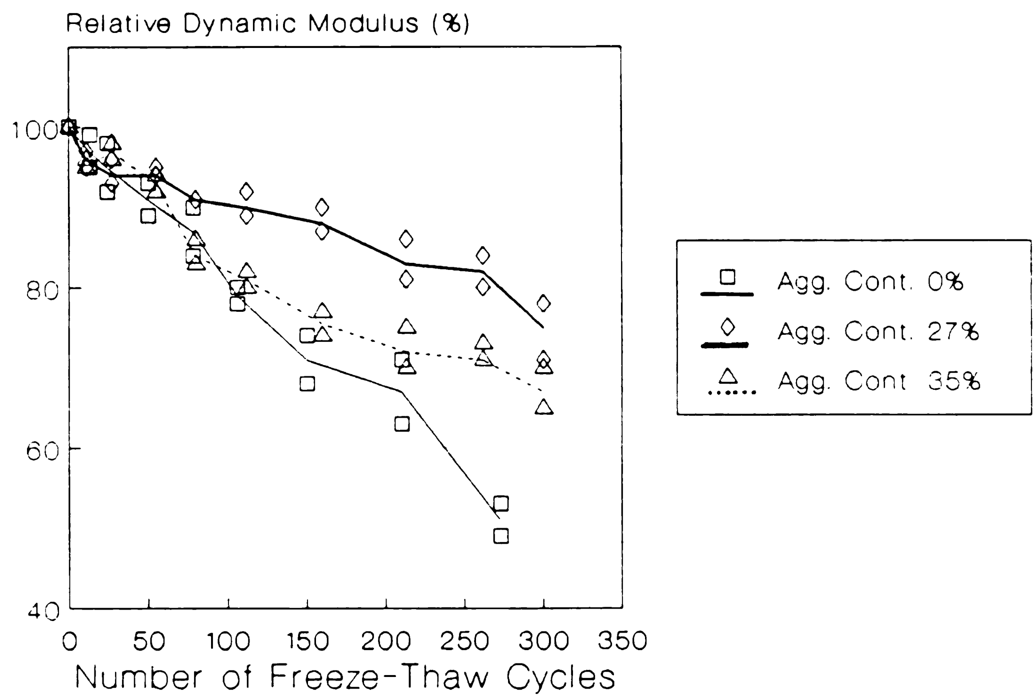
Figure 6.3 shows that the increase in fiber volume fraction to a certain limit improve the freeze thaw durability of the composite, but further increase negatively affects freeze-thaw durability (possibly due to the lack of uniform dispersion of fibers in the matrix, especially at higher aggregate contents in Figure 6.3.c).

The relative dynamic modulus was above 90% after 300 cycles of freezing and thawing for the composite with the desirable combination of 2% fiber volume fraction and aggregate volume fraction of 27%. It should be emphasized that the composites considered in this investigation were not air-entrained. Hence, well-proportional CFRC composites do not seem to require air entrainment for achieving desirable levels of freeze-thaw durability.



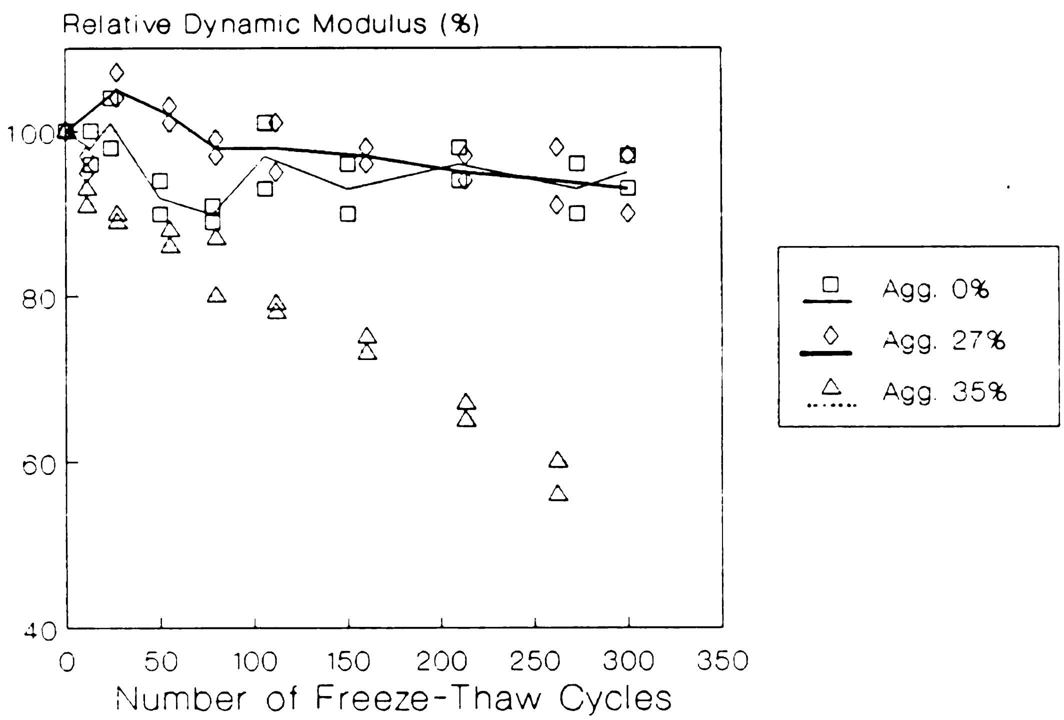
(a) Fiber Volume Fraction = 0%

Figure 6.4 (cont'd.)



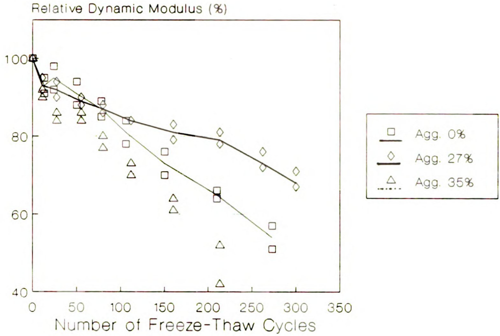
(b) Fiber Volume fraction = 1%

Figure 6.4 (cont'd.)



(c) Fiber Volume Fraction = 2%

Figure 6.4 (cont'd.)



(d) Fiber Volume Fraction = 3%

Figure 6.4 Effects of Aggregate Content on the Relative Dynamic Modulus of CFRC Composites at Different Fiber Volume Fractions.

Effects of aggregate content are more clear in Figure 6.4. This figure shows that the increase in aggregate content up to a certain limit increases the freeze-thaw durability of CFRC; higher aggregate contents, however, negatively affect freeze-thaw durability of the composite (possibly by damaging the uniform dispersion of carbon fibers).

Durability factors for all mixes considered in this investigation are shown in Table 6.1. The durability factor DF is defined as follows (ASTM C-666):

$$DF = P.N / M$$

Where

P = relative dynamic modulus at N cycles, expressed as percentage;

N = number of cycles at which P reaches the specified minimum value (60% in this investigation) for discontinuing the test, or the specified number of cycles (300 in this investigation) at which the exposure is to be terminated, whichever is less; and

M = specified number of cycles at which the exposure is to be terminated.

The effects of aggregate content and fiber volume fraction on durability factor are shown in Figure 6.5. This figure shows that the durability factor of CFRC composites increases by increasing the fiber volume fraction and aggregate content up to a certain limits beyond which this trend is reversed.

Table 6.1 Durability Factors of the Different Mixes Considered in this Investigations.

V_f (%)	Aggregate Volume Fraction (%)		
	0	27	35
0	2 5	61 67	51 49
1	55 43	78 71	75 79
2	81 95	90 97	57 53
3	61 49	67 71	42 38

The optimum condition for the mix composition and manufacturing techniques used in this investigation is reached at a fiber volume fraction of 2% an aggregate volume fraction of 27%.

In order to study the significance (considering the variations in replicated test data) of the effects of fiber volume fractions and aggregate content, and their interaction on the durability factor, 2-factor analysis of variance test was conducted [24].

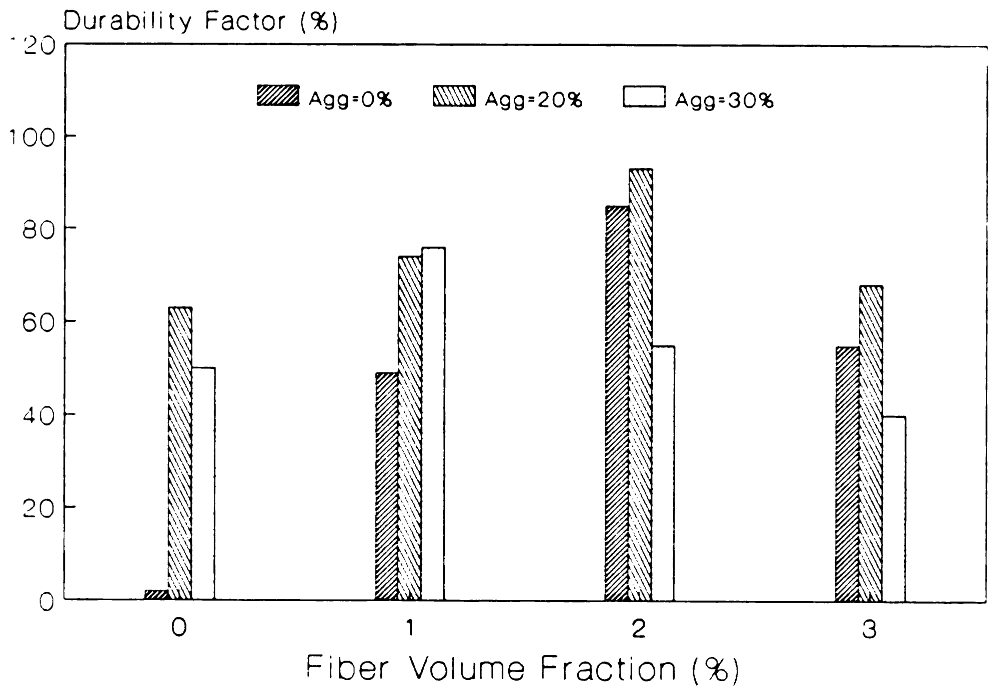


Figure 6.6 Effects of Fiber Volume Fraction and Aggregate Content on the Durability Factor of CFRC Composites.

The results indicated that fiber volume fraction is the most significant factor followed by the aggregate content in deciding the freeze-thaw durability of CFRC composites at 5% level of significance. The interaction between aggregate content and fiber volume fraction was also found to influence freeze-thaw durability at 5% level of significance.

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6.5 SUMMARY AND CONCLUSIONS

The effects of fiber volume fraction and aggregate content on the freeze-thaw durability of light-weigh carbon fiber reinforced cement composites were investigated experimentally. All the composites considered in this investigation were non-air-entrained. The freeze-Thaw durability test results indicated that:

Desirable levels of freeze-thaw durability can be reached in cement-based materials at certain levels of carbon fiber and aggregate contents with no need to air entrainment.

The increase in fiber and aggregate contents beyond the optimum levels causes reductions in freeze-thaw durability, possibly by negatively influencing the uniform dispersion of carbon fiber.

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CHAPTER 7

APPLICATION OF LIGHT-WEIGHT CFRC COMPOSITES TO CLADDING PANELS

7.1 INTRODUCTION

Cladding Panels (also referred to as curtain walls or facades) are basically architectural units which should resist wind pressure and protect the interior of structures from environmental effects [45,46]. Cladding panels are usually attached to the load-bearing structural system [46].

For many years engineers have worked on developing new cladding panel materials and designs with improved aesthetic and durability, and higher load-carrying capacity at lighter weights. Reinforced concrete has been a popular material for cladding panels, and aluminum and stainless steel are also among the more common materials in this application [47]. In the recent years, the use of Fiber Reinforced Cementitious composites for the construction of cladding

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panels has received considerable attention. Glass, wood, and more recently carbon fibers have been used for strengthening concrete panels. The use of fibers can eliminate the costly and time-consuming construction of the reinforcement cage, and can also reduce the weight and enhance the durability and dimensional stability of cladding panels.

Carbon fiber seems to be more attractive than glass and wood for cladding panel construction. The superior durability characteristics and the high efficiency of carbon fibers in improving concrete properties are the key advantages of carbon fiber over other fiber types. A brief discussion on the action of fibers in general, and carbon fibers in particular, in cementitious matrices is given in Chapter 1.

The desirable performance characteristics of carbon fiber reinforced cement (CFRC) composites make them strong candidates for substituting the conventional materials used in the construction of cladding panels. The research reported in this chapter was aimed at resolving the practical and theoretical problems related to the application of light-weight carbon fiber reinforced cement composites to cladding panels.

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7.2 EXPERIMENTAL PROGRAM

This section illustrates the geometry, wind loading and flexural design of cladding panels, and their material properties. The specific connection and panel tests performed in this phase of research are also reviewed.

7.2.1 General Configuration of Cladding Panels, Wind Loading and Flexural Analysis

The configuration selected for CFRC cladding panels is shown in Figure 7.1. The ratio of longer to shorter planar dimensions in the selected panel is greater than two. This panel is thus basically a one-way slab which behaves like a beam under lateral loads as shown in Figure 7.2 [48].

The Uniform Building Code (UBC) guidelines [49] were used to determine the design wind pressure. A typical cladding panel installed on a multi-story building at a height of 100 ft. (30.5 M) in Chicago was considered. It was decided, following the UBC guidelines, that a design wind pressure of 43 lb/sq.ft. (N/mm^2) and a suction of 16 lb/sq.ft. (N/mm^2) would be the design wind loads acting on the panel (see Figure 7.3). The critical load on the panel is the 43 lb/sq.ft (N/mm^2) pressure (Figure 7.3.a). The main concern in the case of suction (Figure 7.3.b) is the tension load applied on bolted connections, which may lead to

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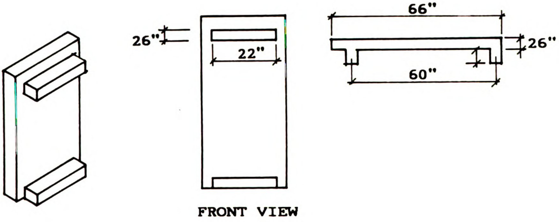
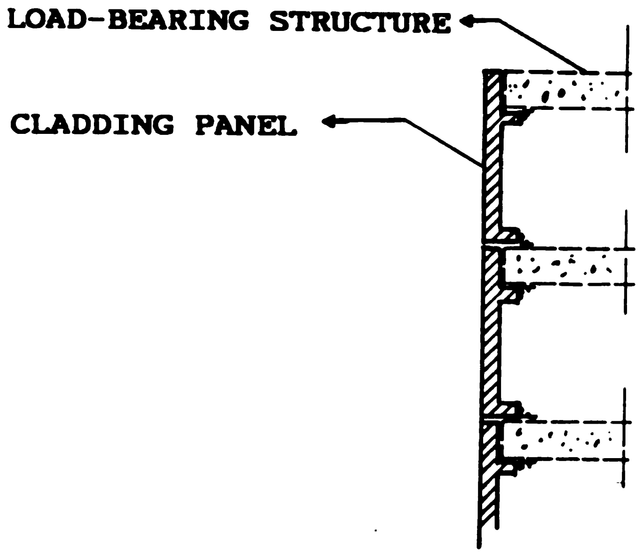
to a pull-out type of failure.

In flexural design of the selected cladding panel (which acts basically as a one-way slab), a simple beam analysis indicated that the maximum bending moment is equal to 2638 ft.lb (363 m.N), as shown in Figure 7.4.



(a) Individual Panel

Figure 7.1 (cont'd.)



(b) Installed Panel

Figure 7.1 General Configuration of CFRC Cladding Panel

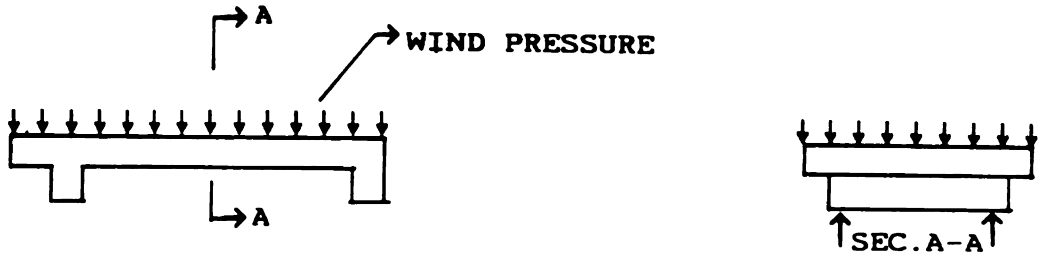
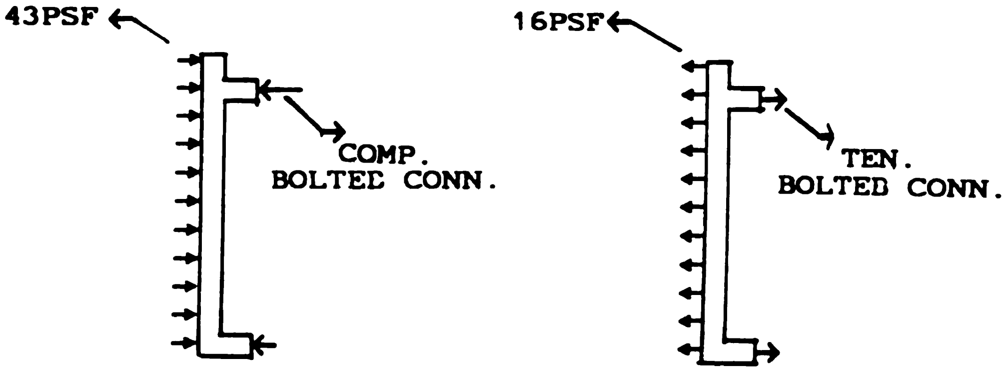


Figure 7.2 Cladding Panel Under Wind Pressure.



(a) Pressure

(b) Suction

Figure 7.3 Design Wind Load.

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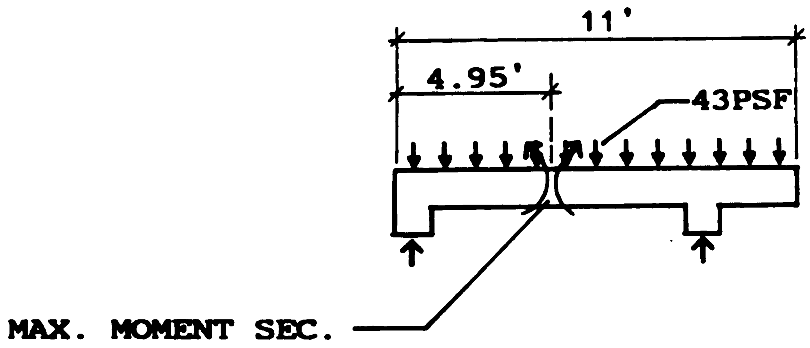

Figure 7.4 Flexural Moment in the Panel

The panel thickness should be selected to provide resistance this bending moment.

7.2.2 Mix Proportions and Flexural Properties of CFRC and Selection of Panel Thickness

1. CFRC has relatively large cementitious content and thus, in spite of the desirable effects of carbon fibers, has relatively large shrinkage movements. This is not a problem in the construction of relatively small material test specimens. However, in large cladding panels, shrinkage movements of CFRC together with the restraint provided by the formwork and non-uniform drying across the thickness may lead to the development of shrinkage cracks at early ages. This problem was tackled in this

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phase of the project by the use of dimensionally stable fillers in the composite material. These fillers were selected to be small enough to allow uniform dispersion of carbon fibers.

2. Cladding panels are principally precast products which should be transferred to the construction site and installed at high levels on load-bearing structural systems. Their weight thus has decisive effects on the final in-place cost of the product. The gravity and earchquake loads associated with the panel mass should also be resisted by the load-bearing structural system. The use of hollow fillers, which could also act as dimension stabilizers, was encouraged by the potential benefits of reducing the unit weights of the cladding panel material.

The final mix proportion selected for CFRC panels, together with the flexural and tensile strengths of the material, are given in Table 7.1. The resulting CFRC composite had a specific gravity of 1.2. The light weight filler used was 3M Macrolite No. 1430 [21] with a maximum particle size of 0.06 in. (1.2 mm) and a specific gravity of 0.85. The carbon fibers were pitch-based [19] with an average length of 1/16 in. (1.5 mm).

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Table 7.1 Mix Proportions of Light-Weight CFRC Used in Cladding Panel

MATRIX (ratios by weight)				CARBON FIBER		STRENGTH (psi)	
w/b	s/b	sp/b	f/b	length (in)	Vf	Flex.	Tensile
0.25	0.23	0.08	0.20	1/16	3%	1000	350

Note: w-water, b-binder, s-silica fume, sp-superplasticizer, f-filler.

The microsilica used in this investigation was the same as introduced in Chapter 2 [17] with a specific gravity of 2.3, and the superplastisizer was Daracem 100 produced by Grace Construction Products [18]. The volume fraction of Macrolite in the composite material was 25%.

For the maximum bending moment under service load of 2638 lb.ft (363 m.N) across a 5 ft. (1.52 m) width, the required thickness (t) of the panel can be derived form:

$$t = [(6Mu)/(\phi.fr.b)]^{0.5}$$

where: Mu = max. bending moment;

ϕ = capacity reduction factor (0.9 for flexure [13] is

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b = panel width; and

fr = flexural strength of CFRC.

The required thickness obtained from the above equation is 2.33 in (59 mm) for resisting the maximum wind pressure. A thickness of 5 in (102 mm) was selected in this investigation to provide resistance against wind pressure in the cladding panel when it is solid (as shown in Figure 7.1) and also when a window opening is present (which reduces the available panel width by half).

7.2.3 Connection Tests

Considering the great variety of panel shapes, sizes and design requirements, many different panel connection details have been developed over years to suit particular requirements. These connections basically link the cladding panels to the structural system. They have to transfer the panel weight to the structure, and might also have to accommodate for different external excitations, thermal and shrinkage movements, etc.

In this investigation, assuming typical conditions of a multistory building, a simple connection system capable of accommodating for the panel dimensional movements was selected. The connection performance under load (more

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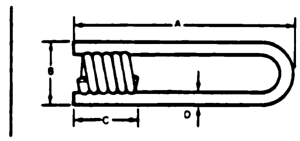
specifically under wind pressure) depends on an interaction between the connection and the panel material (light weight CFRC, a newly developed material). An experimental program was conducted to generate the information needed for the selection of connection size for CFRC panels.

The two alternative connection systems selected for consideration in this study were both bolted, one with straight coil loop insert (Figure 7.7.a), and the other with loop ferrule insert (Figure 7.7.b) [50]. The general configurations and the exact dimensions of the selected connections are presented in Figures 7.7.a and 7.7.b. The capacities given in this figure are the ones expected when the connections are embedded in conventional concrete cladding panels, and do not necessarily apply to CFRC panels. The given capacity, however,.provide a first estimate for the selection of the connection sizes shown in Fig. 7.7. An experimental program was performed to assess the adequacy of the selected connections.

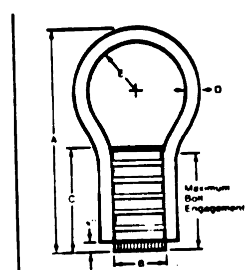
Considering the level of wind load to be applied on the panel, and the available loading equipment and data acquisition systems, it was decided to use half-scale specimens with the actual materials in laboratory experiments. The size effects at such relatively large-scale experimental models, when compared with the prototype panels, are expected to be insignificant.

B-16 Coil Loop Insert Straight Selection Chart							
Bolt Dia. X Insert Length	Safe Working Load Tension (lbs.)	Concrete Strength P.S.I.	Minimum Edge Distance	Dimensions			
				A	B	C	D
½" x 4"	2 250	2 000	5"	4"	1 [illegible]/16"	1 [illegible]/16"	223"



(a) Straight Coil Loop Insert

F-42 Loop Ferrule Insert Selection Chart									
Bolt Dia. (NC Thread)	Safe Working Load Tension (lbs.)	Concrete Strength P.S.I.	Minimum Edge Distance	Maximum Bolt Engagement	Dimensions				
					A	B	C	D	E
¼"	500	3 000	5"	⅜"	2¾"	9/16"	1¼"	240"	½"

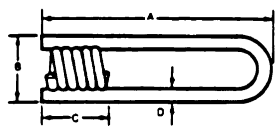


F-42 Loop Ferrule Insert

(b) Loop Ferrule Insert

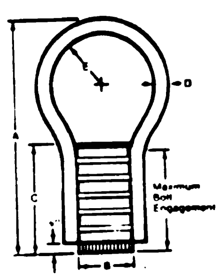
Figure 7.7 Selected Bolted Connections for Cladding Panels

B-16 Coil Loop Insert Straight Selection Chart							
Bolt Dia. x Insert Length	Safe Working Load Tension (lbs.)	Concrete Strength P.S.I.	Minimum Edge Distance	Dimensions			
				A	B	C	D
½" x 4"	2,250	2,000	5"	4"	1 [illegible]"	1 [illegible]"	223"



(a) Straight Coil Loop Insert

F-42 Loop Ferrule Insert Selection Chart									
Bolt Dia. (NC Thread)	Safe Working Load Tension (lbs.)	Concrete Strength P.S.I.	Minimum Edge Distance	Maximum Bolt Engagement	Dimensions				
					A	B	C	D	E
¼"	500	3,000	5"	[illegible]"	2[illegible]"	[illegible]"	1¼"	240"	[illegible]"



F-42 Loop Ferrule Insert

(b) Loop Ferrule Insert

Figure 7.7 Selected Bolted Connections for Cladding Panels

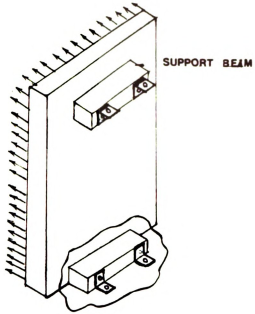
It should be emphasized that all the linear dimensions in laboratory specimens (Figure 7.1) are half the corresponding prototype dimensions. The material in experimental models was, however, similar to that in actual panels and thus the ultimate stresses and applied pressures should be equal in the model and actual panels. This means that the wind pressure causing failure in the model is equal to the one causing failure in the prototype. With the linear dimensions in model being one-half and the pressure equal to the corresponding prototype values, the concentrated forces (specifically the connection forces) in the model are one-quarter of the corresponding forces in the prototype. Following the same logic, the moments (including the ultimate flexural moment) in the model are one-half the corresponding values in the prototype.

In order to assess the behavior of the selected connections in CFRC, a test program was conducted. The connection test setup simulated the conditions of connections in cladding panels under the action of wind suction. The embedded bolts of connections in this critical condition tend to pull out from the panel.

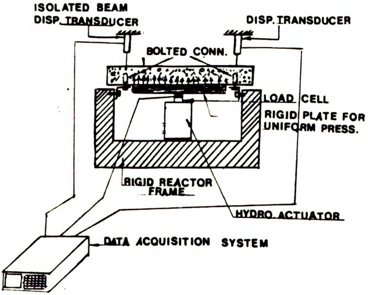
The connection test specimens were basically the isolated support beams of the panels (see Figure 7.8.a), and were subjected to a uniform pressure inducing tension in the insert bolted connections (see Figure 8.8.b for the test set-up). The beams were 4 x 4 x 22 in (102 x 102 x 559 mm), representing half-scale models of prototype panel beams. The CFRC material mix proportions, manufacturing procedures and curing conditions for these connection specimens were similar to those used in a panel tests.

The load was applied in a displacement-controlled manner using a hydraulic actuator. A rigid steel plate was used to produce a uniform pressure on the beam (see Figure 7.8.b). A rigid steel reaction frame was used to simulate the load-bearing structure to which the panels were attached. The applied force and the beam displacements at connection locations were monitored during the tests using a computer-based data acquisition system. A load cell and two displacement transducers were the sensors used in connection tests, and the maximum errors in force and displacement values were about 1% of the measured values.

A total of four connection specimens were tested in this phase of experimental program. Two of the specimens were identical, using straight coil loop insert connections with a bolt diameter of 1/2 in (12.6 mm) and a straight length of 4 in (102 mm), as shown in Figure 7.7.a. The other two specimens were also identical, with the alternative loop ferrule insert connection having a bolt diameter of 1/4 in (6 mm) and an insert length of 2.75 in. (70 mm), as shown in Figure 7.7.b.



(a) Panel Connections and Beams



(b) Isolated Beam Connections and Idealized Conditions

Figure 7.8 Connection Test Specimen

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It is worth emphasizing that the Carbon Fiber content in test specimens was 3% and the fiber length was 1/16 in. (1.5 mm), as in the cladding panels. As mentioned earlier, the main reason for conducting the connection test program was to evaluate the interaction of the insert bolted connections with CFRC composites, noting that the connections have been calibrated by manufacturers for use in conventional concrete.

7.2.4 Cladding Panel Tests

The main objectives of performing relatively large-scale tests on cladding panels were:
(a) assessment of the practicality of panel construction with CFRC; (b) detection of the potential problems which may arise, for example due to shrinkage movements or relatively fast setting of the material, in actual panels which behave differently from small test specimens; and (c) assessment of any size effects on material properties, noting that the panel thickness and all other dimensions are larger than those in material test specimens.

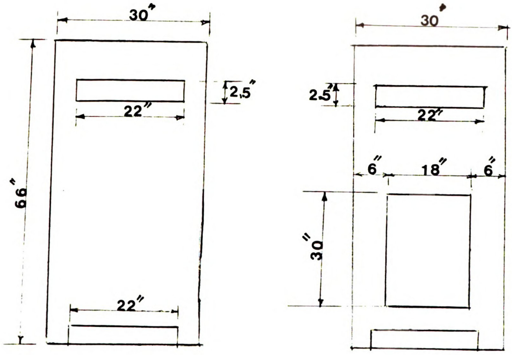
The performance of this task was a very important component of the whole research project. With CFRC being a new material with its own distinct characteristics, it was extremely critical to assess its performance in actual large-scale panel conditions. The performance of this phase

of the experimental program led to some major modifications in the original material mix proportions. In order to reduce the shrinkage movements of CFRC, which caused major cracking in young panel specimens prior to removal of their forms, light-weight fillers where incorporated in the mixture. These fillers were effective in reducing the drying shrinkage movements and the unit weight of CFRC.

As mentioned earlier, considering the available laboratory facilities and the desire to test the largest scale specimens possible, a decision was made to use half-scale panel specimens. Figures 7.9.a and 7.9.b show the cladding panel test specimens without and with window openings, respectively. It should be emphasized that all the dimensions shown in this figure are half the dimensions of the actual panel.

A 110 litre capacity conventional mortar mixer was used in the construction of cladding panels (two batches were needed for the construction of the panel without opening which was cast in two layers, and one batch for the panel with opening). The specimens were cast in wood forms, and were vibrated internally. The panels were kept under plastic sheet for 48 hours, and were then demolded and cured in air for 28 days.

The connections used in panel tests were straight coil loop insert type with a bolt diameter of 1/2 in. (12.6 mm) and an insert length of 4 in. (102 mm), which were selected based on the connection test results (to be presented later in this chapter).



(a) Without Opening (b) With Opening

Figure 7.9 Half-Scale Test Specimens With and Without Opening

It was important to prepare the formwork such that the insert part of the connection could be kept vertically during the casting of CFRC and vibration of the specimen. Figures 7.10.a and 7.10.b present pictures of the two cladding panel specimens.

The CFRC mix proportions and material properties are given in Table 7.1. The larger mixer and the internal method of vibration used in the construction of cladding panels had relatively small effects on material properties, when compared with those obtained in tests on small specimens constructed using a small mortar mixer by internal vibration.

(a) Without Opening

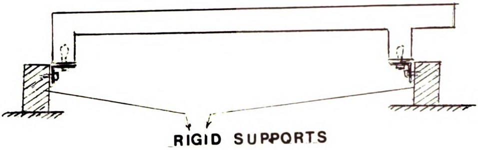
Figure 7.10 (cont'd.)

(b) With Opening

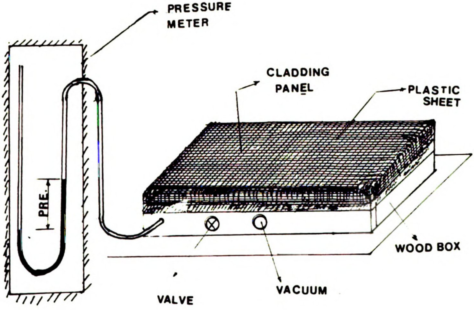
Figure 7.10 Pictures of Cladding Panel Specimens Prior to Test.

At the age of 28 days the panels were tested under a loading condition which simulated wind pressure on building cladding panels. Figure 7.11.a presents the supports of cladding panels on load-bearing structures.

The panel test setup is shown in Figure 7.11.b. The panel specimens were placed inside a wood box which was sealed at its bottom and was covered with a plastic sheet at its top.



(a) Support Condition



(b) Test Setup

Figure 7.11 Panel Support Condition and Test Setup.

The plastic sheet was sealed on the sides of the wood box, and a vacuum pump was used to reduce the pressure inside the box (underneath the panel). In this condition, due to the difference in pressure inside and outside the box, a uniform pressure was applied by the plastic sheet on the panel. A valve installed on the box was used to control the flow of air into the box. A gradual closure of this valve was measured using a U-shaped tube filled with water, one end of which was in air and the other end was inside the box. The difference in liquid height at the two legs os the U-shaped tube (see Figure 7.11.b) is representative of the pressure applied in the panel. The tube used for pressure measurement had a diameter of 0.25 in. (6 mm), selected to minimize the possible errors caused by capillary action.

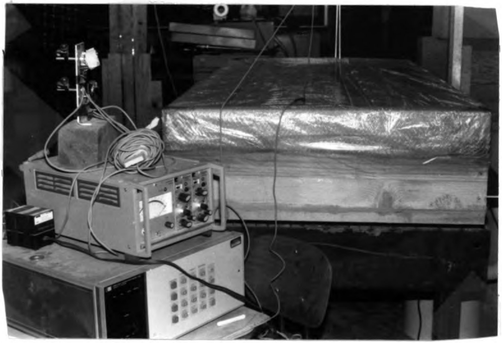
Figures 7.12.a and 7.12.b present pictures of the test specimens without and with an opening, respectively, before the installment of the plastic sheet, and Figure 7.12.c shows the complete test setup.

During the panel tests, the values of displacement were measured at a location where the maximum displacement is expected to take place. The values of strain at four locations on the panel without opening and at two locations for the panel with opening were also monitored.

(a) Panel Without Opening

(b) Panel With Opening

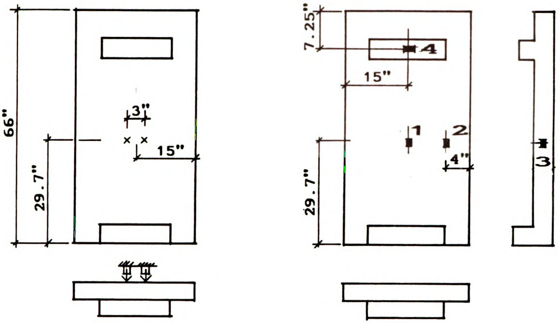
Figure 7.12 (cont'd.)



(c) Complete Test Set Up

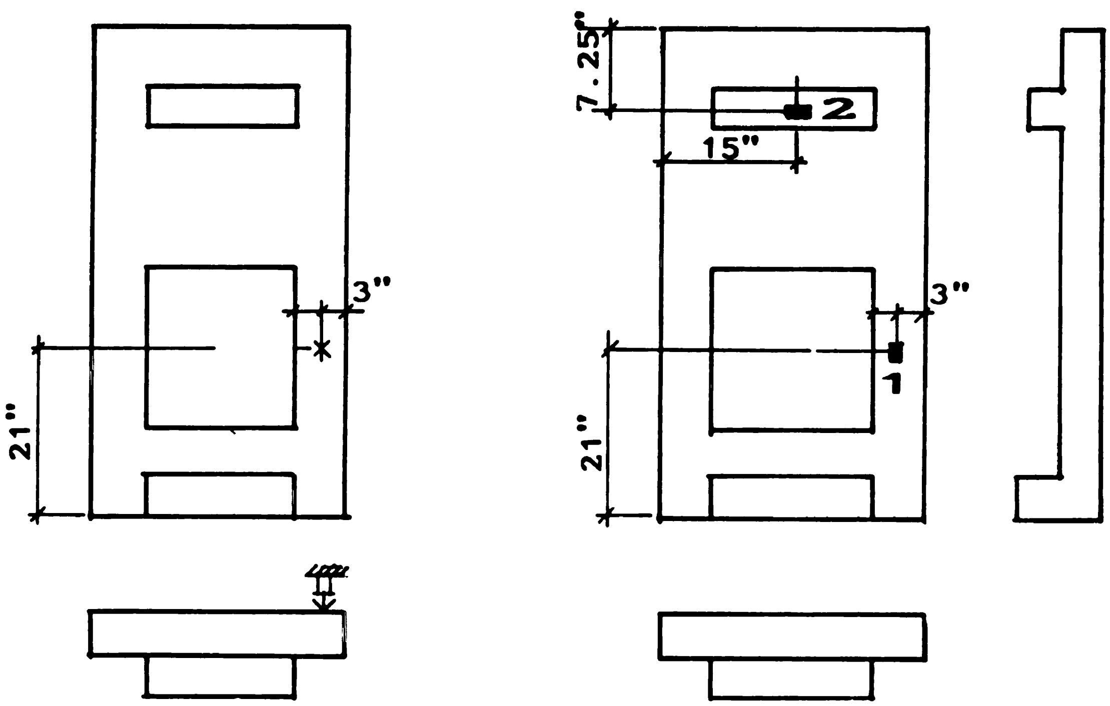
Figure 7.12 Test Conditions

Figures 7.13.a and 7.13.b show the locations of displacement transducers and electric strain gages for panel specimens without and with an opening, respectively. A computer-based data acquisition system (Figure 7.14) was used to monitor the displacement and strain changes during the tests. The instrumentation of panel specimens was designed to reveal important information on the overall structural behavior of the panels, and also on the material properties of CFRC in the actual panel conditions.



(a) Panel Without Opening

Figure 7.13 (cont'd.)



(b) Panel With Opening

Figure 7.13 Instrumentation of the Panel Test Specimens

Figure 7.14 Computer-Based Data Acquisition System

The applied pressure on panels was increased gradually at small increments (quasi-static testing), and measurements were taken at each increment.

7.3 EXPERIMENTAL RESULTS

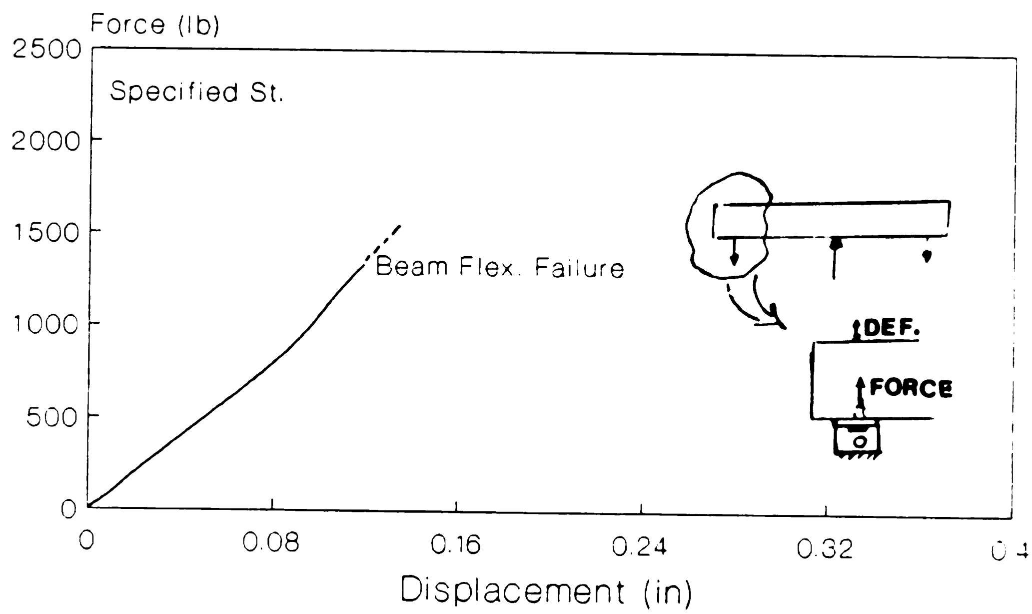
This section summarizes the results of the connection and panel tests. The connection test program was conducted for evaluating the behavior of bolted connections inserted in CFRC under pull out forces. The panel tests were performed for the assessment of the practicality of the construction of CFRC cladding panels, and also for evaluating the performance of CFRC in larger-scale panels under flexural loads caused by wind pressure.

7.3.1 Connection Test Results

Figures 7.15.a and 7.15.b present the relationships between pull-out force applied to each connection and pull-out displacement, as measured form the test set up shown in Figure 7.8. The design strength of connections (specified by their manufacturer) are also shown in Figure 7.15. Each curve in this figure presents the average of two measurements made by the two displacement transducers installed on each connection test specimen.

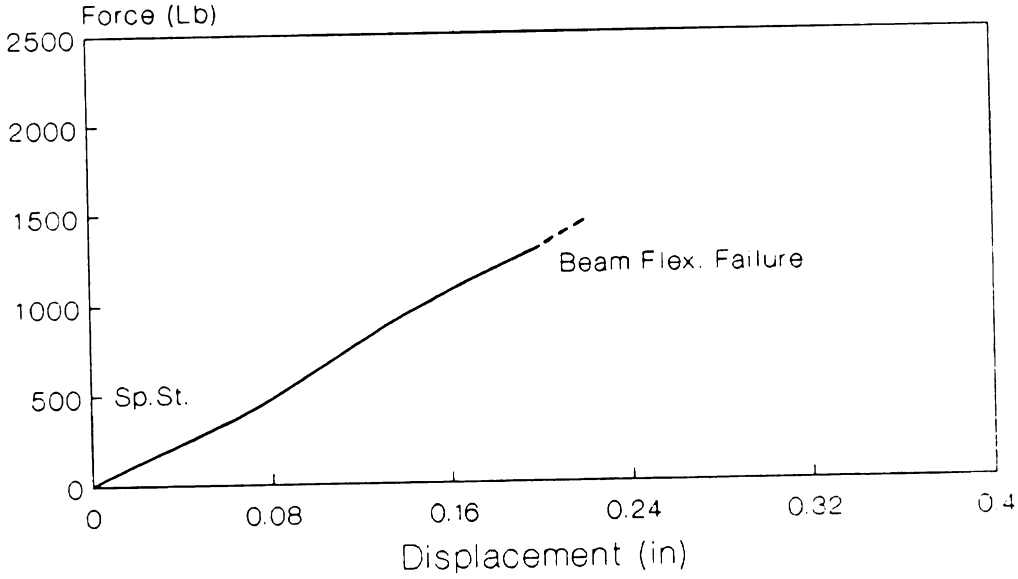
All the connection test specimens performed satisfactorily under pull out forces. The only sign of damage was the appearance of some hairline splitting crack (Figure 7.16.a). Failure never occurred by pull out, but always by flexural cracking of the connection test specimens (Figure 7.16.b).

Based on the pull out test data generated on bolted connections inserted in CFRC specimens, it was concluded that these connections perform satisfactorily when used in CFRC, providing pull-out capacities in excess of those expected when conventional concrete is used.



(a) Straight Coil Loop Insert (bolt dia. 0.5 in.)

Figure 7.15 (cont'd.)

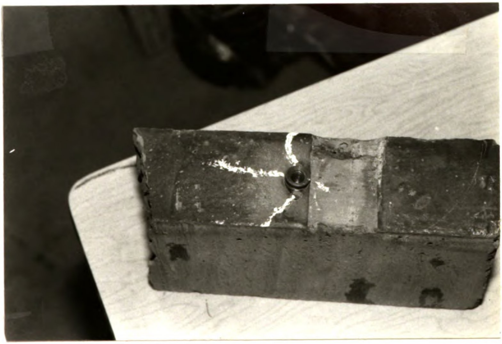


(b) Loop Ferrule Insert (bolt dia. 0.25 in.)

Figure 7.15 Pull-Out Force-Displacement Relationship for Bolted Connections.

(a) Splitting Crack

Figure 7.16 (cont'd.)

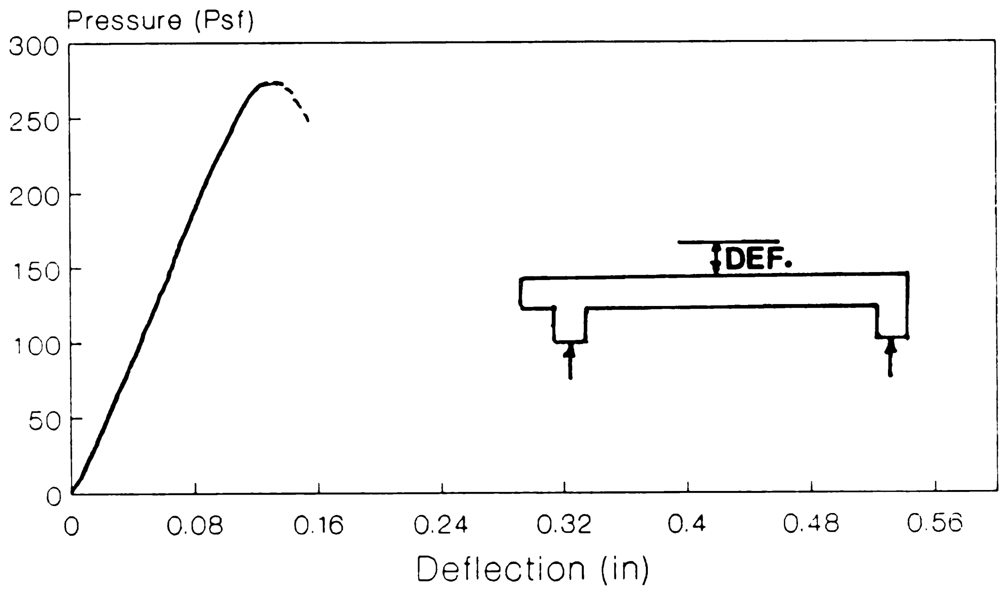


(b) Flexural Failuer

Figure 7.16 Splitting Cracks Around Bolts and Flexural Failure of Connection Specimens

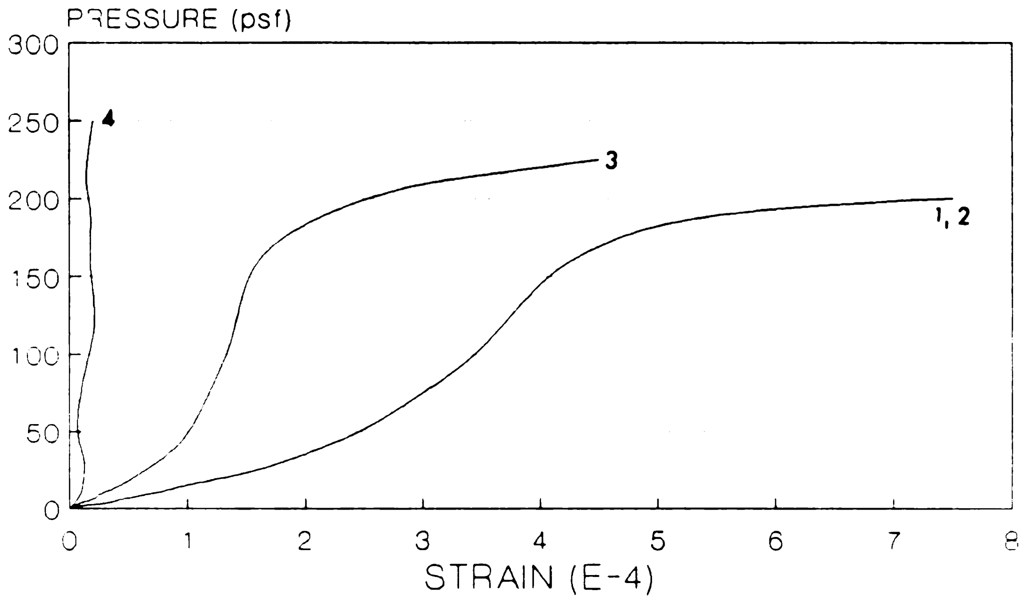
7.8.2 Panel Test Results

The relationship between the applied pressure on the panel without opening and the maximum deflection is presented in Figure 7.17.a. Figure 7.17.b gives the relationship between the applied pressure and the measured strains.



(a) Pressure Vs. Deflection

Figure 7.17 (cont'd.)



(b) Pressure Vs. Strain

Figure 7.17 (cont'd.)

(c) Failed Specimen

Figure 7.17 Test Results For Panel Without Opening

Flexural failure occurred at the section with maximum theoretical moment. A view of the panel specimen without opening after failure is given in Figure 7.17.c.

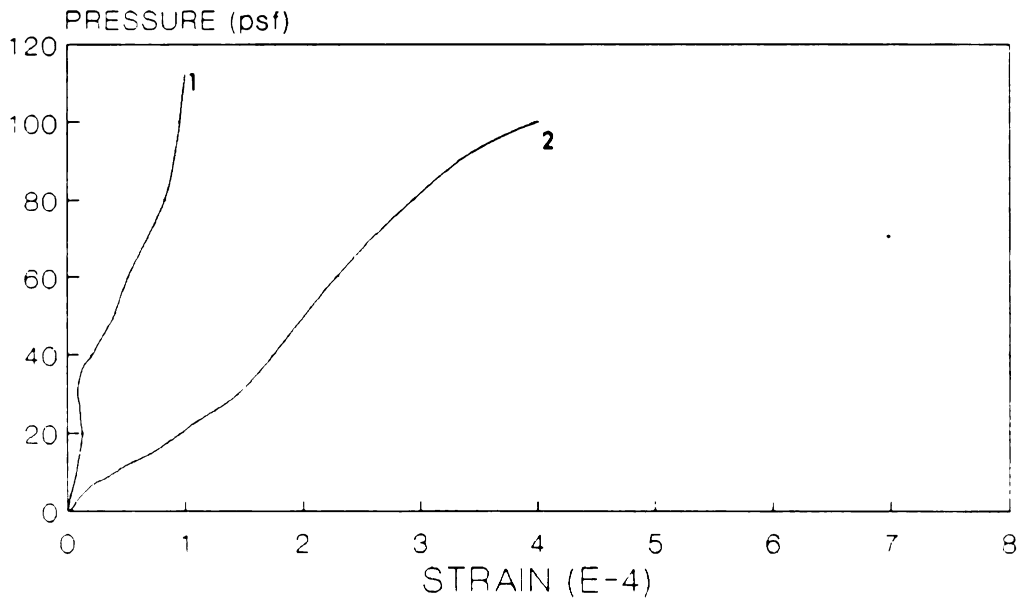
Failure of the panel without opening occurred at a maximum flexural stress (calculated assuming an elastic behavior) equal to 800 psi (5.5 MPa). It should be noted that this flexural strength of the 2.5 in (63 mm) thick panel is lower than the 1000 psi (6.9 MPa) modulus of rupture obtained in tests on 1.5 in (38 mm) thick flexural specimens. This level of size effect has also been reported in Referenc 28 for CFRC specimens. The data presented in Referenec 28, however, is indicative of the reduction in size effect at larger thicknesses.

The strain measurements (Figure 7.17.b) confirm that the panel behavior is basically one-way. The longitudinally oriented strain gages No. 1, 2 and 3 show relatively large strain readings, while the transversely oriented gage No. 4 hardly reads any strain.

The test results on panel with a window opening are presented in Figure 7.18 noting that the pressure in this test was applied over the full surface of panel (simulating the actual conditions where the glass on window opening tolerates the wind pressure). The relationship between pressure and maximum deflection is shown in Figure 7.18.a. Figure 7.18.b presents the relationship between pressure and measured strains. A view of the broken specimen, which failed at the section with maximum theoretical moment, is also given in Figure 8.18.c.

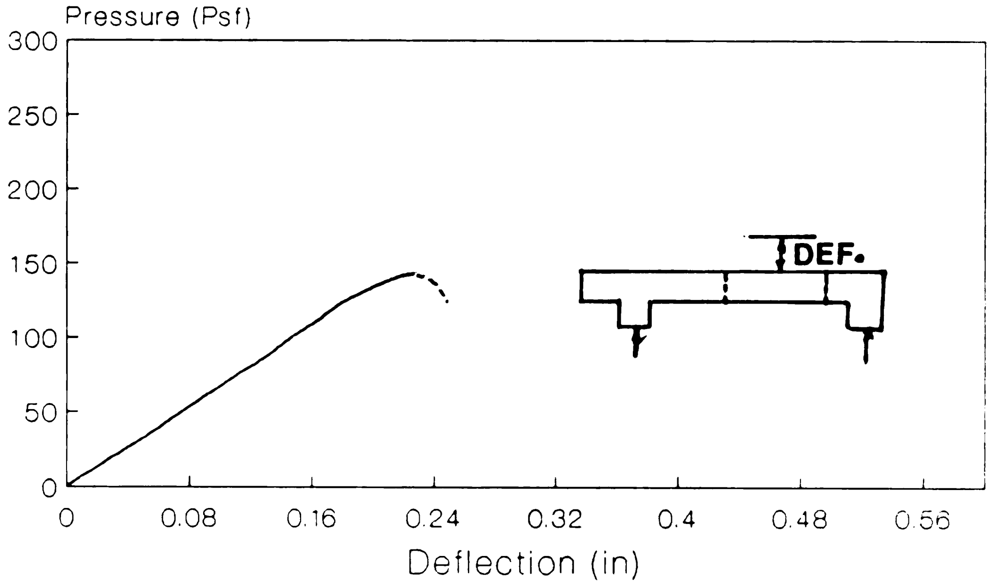
The calculated flexural stress at failure was 830 psi (5.73 MPa), which is consistent with the result obtained for the panel without opening.

The flexibility of the panel with opening is observed to result in higher deflections at comparable pressures (when compared with the one without opening, see Figures 7.17.a and 7.18.a).



(a) Pressure Vs. Deflection

Figure 7.18 (cont'd.)



(b) Pressure Vs. Strain

Figure 7.18 (cont'd.)

(c) Failed Specimen

Figure 7.18 Test Results for Panel With Window Opening

The strain measurements presented in Figure 7.18.b confirm the one-way action of the panel with opening. The longitudinally oriented gage No. 1 gives considerably higher strains than the transversely oriented gage No. 2.

The calculated flexural strengths of the two panel specimens show that as far as the size effects are accounted for, the design approach used in this study (based on the conventional analysis techniques and using the modulus of rupture of CFRC) provides panels with satisfactory performance under external load effects. The panel test specimens were half-scale, and the size effects are expected to be relatively small at thicknesses greater than the 2.5 in (63 mm) used in the test specimens. It may thus be concluded from the generated panel test results that the full-scale panel without opening is capable of resisting a wind pressure of 270 lb/sq.ft (12.9 KPa), and the one with opening resists a maximum pressure of 113 lb/sq.ft (5.41 KPa) at failure, noting that the pressure scale factor is 1.0 in the conditions of this experimental study. Both these values are higher than the design factored load (with a wind load factor equal to 1.7) of 1.7*43 = 73 lb/sq.ft (3.5 KPa). This is indicative of the success achieved in this study in the design and construction of light weight cladding panels with a specific gravity of 1.2. Important cost savings can be achieved by the use of light weight CFRC panels noting that a major fraction of the in-place cost of panels results form the reinforcement cage construction, and also from the handling and installation of panels. CFRC panels do not require any reinforcement cage, and their light weight is also a major advantage in reducing the handling and installation costs. The long-term expenses related to the maintenance of CFRC panels are also expected to be lower than conventional panels, due to the desirable durability characteristics of CFRC.

Finally, it should be mentioned that the panels tested in this investigation were all air-cured. Further improvements in material properties, and consequently in the panel performance, can be achieved through the use of more effective curing techniques. Autoclaving or hot water curing of panels, which are applicable in precast plant conditions, are expected to significantly enhance the dimensional stability, durability and load carrying capacity of CFRC panels.

7.4 SUMMAY AND CONCLUSION

An experimental program was conducted to assess the practicality of construction of Carbon Fiber Reinforced Cement (CFRC) cladding panels, and to generate the information needed for the development of design procedures for CFRC panels. The experimental program consisted of two phases: (1) Connection Tests; and (2) panel tests under wind pressure.

(1) Connection Tests: Cladding panels are supported on load-bearing structural systems, usually be insert bolted connections. The inserted bolts of these connections will be subjected to pull-out or push-in forced under wind loads. The specified pull-out strength of such connections (the

critical design value) is developed for bolts inserted in conventional concrete panels. In order to assess the pull-out strength of bolts inserted in CFRC, tests were performed on specimens which simulated the pull-out action of panel connections under wind loading. The results indicated that bolted connections inserted in CFRC performed better than those placed in conventional concrete under pull-out forces. The specified strength values of such connections (with plain concrete) can thus be safely used in the design of CFRC panels.

(2) Panel Tests Under Wind Pressure: Typical cladding panels with bolted connections were designed following the conventional panel design procedures, using the flexural strength values obtained CFRC. Two panels, one without opening and one with a window opening, were designed, constructed and tested. The test specimens were half-scale, and were constructed using the actual panel CFRC material suitable for use in prototype panels. A conventional mortar mixer was used for the construction of panels, and compaction of the material was achieved by the use of a regular internal vibrator. The panel test specimens were cured in air. The test conditions simulated those expected under wind pressure. A vacuum box was used to apply uniform pressure on the panel. The panel test specimens were instrumented by the use of displacement transducers and

strain gages in order to monitor their overall behavior under wind pressure. A computer-based data acquisition system was used to take measurements during the panel tests.

From the panel test results it could be conclude that: (a) Conventional design and construction techniques are applicable to CFRC cladding panels; (b) The CFRC panels behave as expected under wind pressure. In the tests performed in this study, failure occurred in flexure at sections with maximum theoretical moment. Considering the size effect which is expected to reduces the flexural strength by about 20% in actual panel conditions, the maximum pressure on panel specimens at failure satisfied the design requirements, and the panels behaved in one-way bending as expected; and (c) Light-weight CFRC panels provide an economic alternative to the common cladding panel types. They offer a low unit weight which reduces the cost of handling and installation of panels, and reduce the gravity and seismic loads applied on structural systems. CFRC cladding panels also eliminate the need for costly reinforcement cages. Finally, the service life of CFRC panels is expected to be larger than that of the conventional concrete panels, and the maintenance costs also tend to be lower, due to the desirable durability characteristics of carbon fiber reinforced cement.

CHAPTER 8

SUMMARY AND CONCLUSIONS

An experimental study was conducted to determine the optimum matrix composition and fiber reinforcement conditions in light-weight carbon fiber reinforced cement (CFRC) composites, and to establish the mechanical, physical and durability charateristics of the composite material for application to cladding panels and other thin-sheet cement products.

The research was conducted in six steps concerned with: (1) statistical variations in mechanical properties of CFRC composites; (2) optimum utilization of light-weight aggregates; (3) selection of dispersing agents for carbon fibers in cementitious matrices; (4) determination of size effects in the composite material; (5) assessment of the freeze-thaw durability of CFRC composites; and (6) application of CFRC composites to cladding panels. A summary of the activities related to these steps togther with the corresponding conclusions are given below.

8.1 Statistical Variations in Mechanical Properties

Replicated tests were conducted on light-weight carbon fiber reinforced cement composites in order to study the variations in the flexural strength and toughness, compressive strength and impact resistance of the material. The results indicated that:

- The flexural and compressive strength test results had a normal distribution at 5% level of significance. The flexural toughness and impact resistance test data generated in this study, however, showed poor fitness to the normal distribution at 5% level of significance; this could result from the relatively large variations in toughness and impact test results and the limited sample size.

- The variations within and between batches in flexural strength, flexural toughness and compressive strength are comparable, while those in impact resistance are different, at 5% level of significance.

- The observed coefficients of variation of the properties of carbon fiber reinforced cement composites were 15.7% for flexural strength, 36.8% for flexural toughness, 13.5% for compressive strength, and 54.6% for impact resistance. These variations are larger than what is typically expected for plain concrete in controlled laboratory conditions. The variations in flexural and compressive strength are,however, comparable with those in the strength of plain concretes consturcted at job site with good quality control. The increase in coefficient of variation in the presence of carbon fibers could be attributed to the varitions in fiber length and concentration within matrix, and relatively low compactibilty of fibrous cement composites.

- The information on variations in the mechanical properties of CFRC composites should be considered while deciding on the minimum number of tests required for measuring certain material properties, or when selecting the required level of a certain property based on a specified design level.

8.2 Optimization of the Use of Light-Weight Aggregates

An experimental study was conducted on the interaction of light-weight aggregates with carbon fibers in cementitious materials. The effects of using light-weight aggregates with different particle sizes at different volume fractions on the following properties of carbon fiber reinforced cements with different fiber contents were investigated: flexural behavior, compressive strength, impact resistance, specific gravity, and restrained shrinkage cracking.

Regression analysis and analysis of variance of test results indicated that the flexural and compressive strength, flexural toughness and impact resistance of carbon fiber reinforced cement could be improved through the addition of light weight aggregates; this was true as far as the maximum size and content of aggregates did not increase certain limits, beyond which aggregates start to interfere with the uniform dispersion of fibers and negatively influence the composite material properties. The best results in this investigation were obtained with the finer aggregates (maximum particle size 0.02 in., 0.6 mm) when added at an aggregate/binder ratio of 0.2 to carbon fiber reinforced cement with 3% fiber volume fraction. The negative effects of aggregate interference with fiber dispersion are particularly pronounced in composites with higher fiber volume fractions when relatively large content of coarser aggregates are used. The positive effects of using aggregates in cementitious materials result possibly from the consequent improvements in dimensional stability of the material, which reduce the formation of microcracks associated with shrinkage movements.

The increase in light-weight aggregate content, as expected, leads consistently to reductions in the specific gravity of CFRC composites. Coarser aggregates, which have lower specific gravities, are more effective in reducing the specific gravity of the composite.

The increase in fiber volume fraction, when reasonably fine aggregates are used in the matrix at relatively low contents, leads to significant improvements in the flexural strength and toughness of the material. Compressive strength tends to be reduced with increasing fiber volume fraction and the specific gravity tends to be less at higher fiber loadings.

Under restrained shrinkage conditions, the increase in aggregate content and fiber volume fraction lead to reductions in the maximum crack width in CFRC composites. The increase in aggregate content also delays the appearance of cracks under restrained shrinkage movements.

8.3 Alternative Dispersants for Carbon Fibers

An experimental study was conducted to investigate the effectiveness of different materials in the dispersion of carbon fibers in cementitious matrices. Judgement on the effectiveness of a dispersing agent was made based on the flexural strength and impact resistance of the hardened composite material. An effective dispersion of fibers is expected to produce composite with higher flexural strength and impact resistance.

The three dispersants considered in this investigation were silica fume, methyl cellulose, and fly ash. Replicated tests were conducted and statistical analysis techniques were employed to produce reliable information on the trends in the effects of dispersant type. All the mixes considered in this investigation incorporated 3% volume fractio of 1/8 in. (3 mm) pitch-based carbon fibers. The results indicated:

- As far as the flexural strength and impact resistance are concerned, silica fume and methyl cellulose produce comparable levels of flexural strength, but fly ash gives lower results for the mix composition and manufacturing techniques considered in this investigation. This conclusion was verified at 5% level of significance.

- Methyl cellulose gave the highest impact resistance, and fly ash gave very low impact resistance test results. These effects of dispersant types on impact resistance were also verified at 5% level of significance.

It should be noted the effects of dispersant type on hardened material properties result not only from the corresponding effect on fiber dispersion but also from the refinement of the matrix structure and properties as well as its bonding to carbon fibers.

8.4 Size Effects on Flexural Strength

Prismatic specimens made of carbon fiber reinforced cement composites with different cross-sectional dimensions were tested in flexure to investigate size effects on flexural strength test results. All specimens incorporated 1% volume fraction of 1/16 in. (1.5 mm) pitch-based carbon fibers. The span length was constant (4.5 in., 114.3 mm), and three cross-sectional dimensions were considered: 1.5 in. (38 mm) square, 1.5 in. (38 mm) depth x 1.0 in. (25.4 mm) height, and 1.0 in. (25.4 mm) square. These specimens were tested quasi-statically by third-point loading. Fifteen tests were performed at each specimen size, and the results were analyzed statistically.

It was concluded, based on statistical analysis of the replicated test results, at 5% level of significance that:

- The flexural strength tends to increase with reductions in the width and/or depth of the specimen. The flexural strength of 1.0 in. (25.4 mm) square cross section specimens was about 30% greater than that of 1.5 in. (38 mm) square cross-section specimens.
- At a constant width of 1.5 in. (38 mm), the reduction in specimen depth from 1.5 in. (38 mm) to 1.0 in. (25.4 mm) resulted in about 10% increase in flexural strength.

8.5 Freeze-Thaw Durability of CFRC Composites

The effects of fiber volume fraction and aggregate content on the freeze-thaw durability of light-weigh carbon fiber reinforced cement composites were investigated experimentally. All the composites considered in this investigation were non air-entrained. The freeze-thaw durability test results indicated that:

- Desirable levels of freeze-thaw durability can be reached in cement-based materialsat certain levels of carbon fiber and aggregate contents with no need to air entrainment.
- The increase in fiber and aggregate contents beyond the optimum levels causes reductions in freeze-thaw durability, possibly by negatively influencing the uniform dispersion of carbon fiber.

8.6 Application of CFRC Composites to Cladding Panels

An experimental program was conducted to assess the practicality of construction of Carbon Fiber Reinforced Cement (CFRC) cladding panels, and to generate the information needed for the development of design procedures for CFRC panels. The experimental program consisted of two phases: (1) connection tests; and (2) panel tests under wind pressure.

<u>Connection Tests:</u> Cladding panels are supported on load-bearing structural systems, usually be insert bolted connections. The inserted bolts of these connections will be subjected to pull-out or push-in forced under wind load. The specified pull-out strength of such connections (the critical design value) is developed for bolts inserted in conventional concrete panels. In order to assess the pull-out strength of bolts inserted in CFRC, tests were performed on specimens which simulated the pull-out action of panel connections under wind loading. The results indicated that bolted connections inserted in CFRC performed better than those placed in conventional concrete under pull-out forces. The specified strength values of such connections (with plain concrete) can thus be safely used in the design of CFRC panels.

<u>Panel Tests Under Wind Pressure:</u> Typical cladding panels with bolted connections were designed following the conventional panel design procedures, using the flexural strength values obtained for CFRC. Two panels, one without opening and one with a window opening, were designed, constructed and tested. The test specimens were half-scale, and were constructed using the CFRC material suitable for use in prototype panels. A conventional mortar mixer was used for the construction of panels, and compaction of the material was achieved by the use of a regular internal vibrator. The panel test specimens were cured in air. The test conditions

simulated those expected under wind pressure. A vacuum box was used to apply uniform pressure on the panel. The panel test specimens were instrumented by the use of displacement transducers and strain gages on order to monitor their overall behavior under wind pressure. A computer-based data acquisition system was used to take measurements during the panel tests.

From the panel test results it could be conclude that:

- Conventional design and construction techniques are applicable to CFRC cladding panels.
- The CFRC panels behave as expected under wind pressure. In the tests performed in this study, failure occurred in flexure at sections with maximum theoretical moment. Considering the size effect which expected to reduce the flexural strength by about 20% in actual panel conditions, the maximum pressure on panel specimens at failure satisfied the design requirements, and the panels behaved in one-way bending as expected.
- Light-weight CFRC panels provide an economic alternative to the common cladding panel types. They offer a low unit weight which reduces the cost of handling and installation of panels, and reduce the gravity and seismic loads applied on structural systems. CFRC cladding panels also eliminate the need for costly reinforcement cages. Finally, the service life of CFRC panels is expected to be larger than that of the conventional concrete panels, and the maintenance costs also tend to be lower, due to the

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