SHEAR TRANSFER IN CONCRETE REINFORCED WITH CARBON FIBERS

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NOMENCLATURE

2-D	two-dimensional
3-D	three-dimensional
A_c	concrete cross-sectional area
A_s	reinforcement cross-sectional area
b	beam width
C_{ct}	constant term in ACI building code equation for predicting splitting tensile strength
C_E	constant term in ACI building code equation for predicting modulus of elasticity
C_r	constant term in ACI building code equation for predicting modulus of rupture
D	diameter of carbon fiber
d	effective beam depth
E_c	modulus of elasticity of concrete
F_y	yield strength of reinforcement
f_c'	compressive strength of concrete
f_{ct}	splitting tensile strength of concrete
f_r	modulus of rupture
ft	feet
GPa	gega Pascal = 10^9 Pascal
in.	inch
kg	kilogram

ksi	kips per square inches
L	beam span length
M_{cr}	cracking moment
MPa	mega Pascal = 10^6 Pascal
M_u	ultimate moment
M_y	yield moment
min	minutes
ml	millilitre
mm	millimeter
mph	miles per hour
P_{cr}	cracking load
P_u	ultimate load
P_y	yield load
psi	pounds per square inches
RC	reinforced concrete
S	specific surface area of CF per unit volume of CFRC (cm^2/cm^3)
sec	seconds
V	highly stressed volume
V_f	volume fraction of CF
v_u	nominal shear ultimate stress
W/C	water/cement ratio
w	unit weight of concrete
ε_c	compressive strain

ε_{co}	strain at compressive strength
ϕ	capacity reduction factor
μ	coefficient of friction
μm	micrometer
ρ	reinforcement ratio = A_s / A_c
σ_c	compressive stress
σ_{Nx}	externally applied normal stress

CHAPTER I

INTRODUCTION

1.1 General

This study was conducted as part of an engineering research project at Oklahoma State University in the School of Civil and Environmental Engineering under the sponsorship by Conoco and DuPont during the period June 1, 1996, to May 31, 1998.

The research project investigated carbon fibers (CF) manufactured by Conoco and DuPont. The investigation focused on applications of carbon fibers reinforced concrete (CFRC). Carbon fiber reinforcement can improve tensile and flexural strength, and increase impact resistance of mortar and concrete; it can also aid in the control of crack widths [1-5]. Conoco CF was to compete with pitch-based CF, such as Dialed K6611T, manufactured by Mitsubishi Corporation of Japan. During early stages of the project, Conoco CF was not available for production and Mitsubishi CF was used for most research tasks. Mitsubishi fibers had a diameter of approximately 18 μm and a length of 18 mm. Fibers had a tensile strength of approximately 295 ksi, an elongation at failure of 1%, a static modulus of elasticity of 28,000 ksi, and specific gravity of 1.9. Fibers were formed into wafers of collimated fibers; the wafers were approximately 0.35 mm thick, 18 mm long, and of variable width. Individual fibers were held in this format with a water-soluble sizing material, polyvinyl alcohol (PVA). A typical wafer was composed of approximately 1000 fibers. During the mixing process the wafers were broken down and the CF distributed throughout the mix to obtain the benefits of the reinforcement. Figure 1-1 shows Mitsubishi CF chips.

Later in the project, after Conoco started a pilot production line for CF, some quantities were available for research and testing. Conoco manufactures CF in a loose mat by a spinning process. Most Conoco CF was supplied after the mat had been chopped into clumps of carbon fibers approximately 1-in. square. Conoco CF had a diameter of approximately 11 μm and variable length with an average of 10 mm. Figure 1-2 shows typical Conoco fiber. Conoco and Mitsubishi CF had similar mechanical properties.

A major objective of this applied research program was to identify possible practical applications of CF for use in structural concrete. The project was conducted in four phases with the last phase being the main body of the research reported herein. Information learned during the first three phases of the project were subsequently used and incorporated in the research. The first phase, presented in Appendix A, considered various parameters including fiber dispersion, mixing apparatus, and mix proportions for mortars and concrete. Final work in this phase concentrated on a CFRC mix suitable for manufacture of concrete pipe.

The second phase, presented in Appendix B, was fabrication and test of concrete pipe made with CFRC on a field study conducted at the North Star Concrete Company in Apple Valley, MN. The field study produced reinforced concrete pipe using CF as a replacement for steel stirrups and welded wire mesh. In research conducted at OSU, concrete mixes containing various percentages of CF were developed that would be suitable for use in concrete pipe.

The third phase, presented in Appendix C, involved CFRC prepared under field conditions. In this phase, precast double-tee members were fabricated to determine if CF could replace or supplement wire fabric reinforcement currently used in flanges of these members.

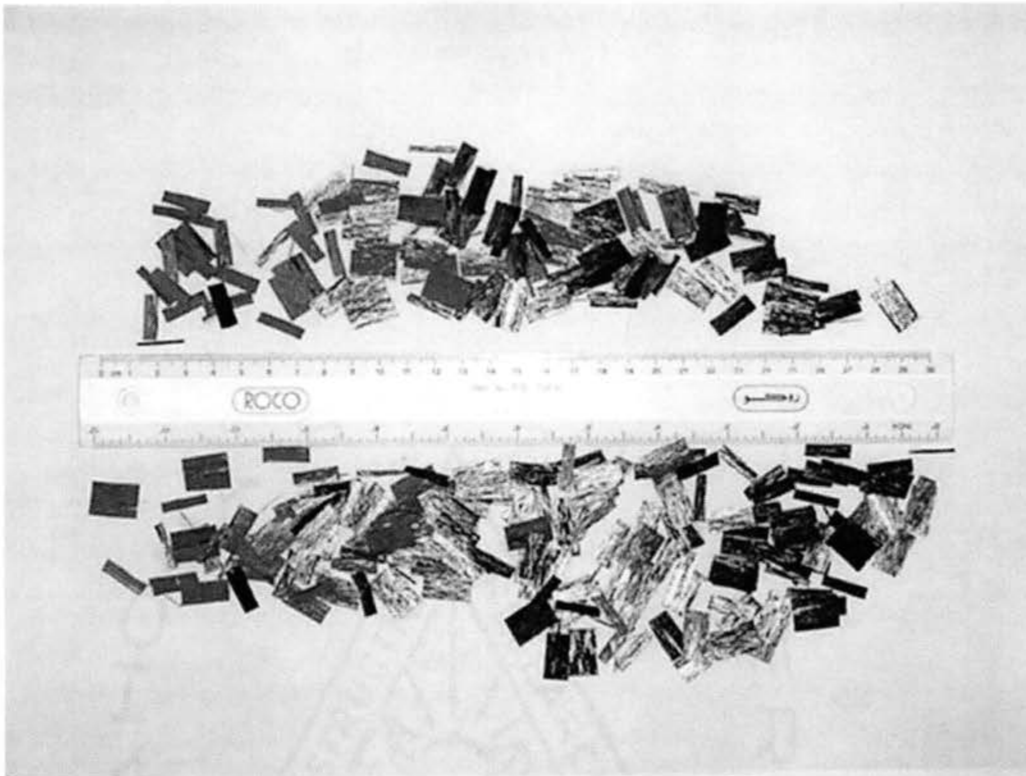

Figure 1-1. Mitsubishi Carbon Fibers

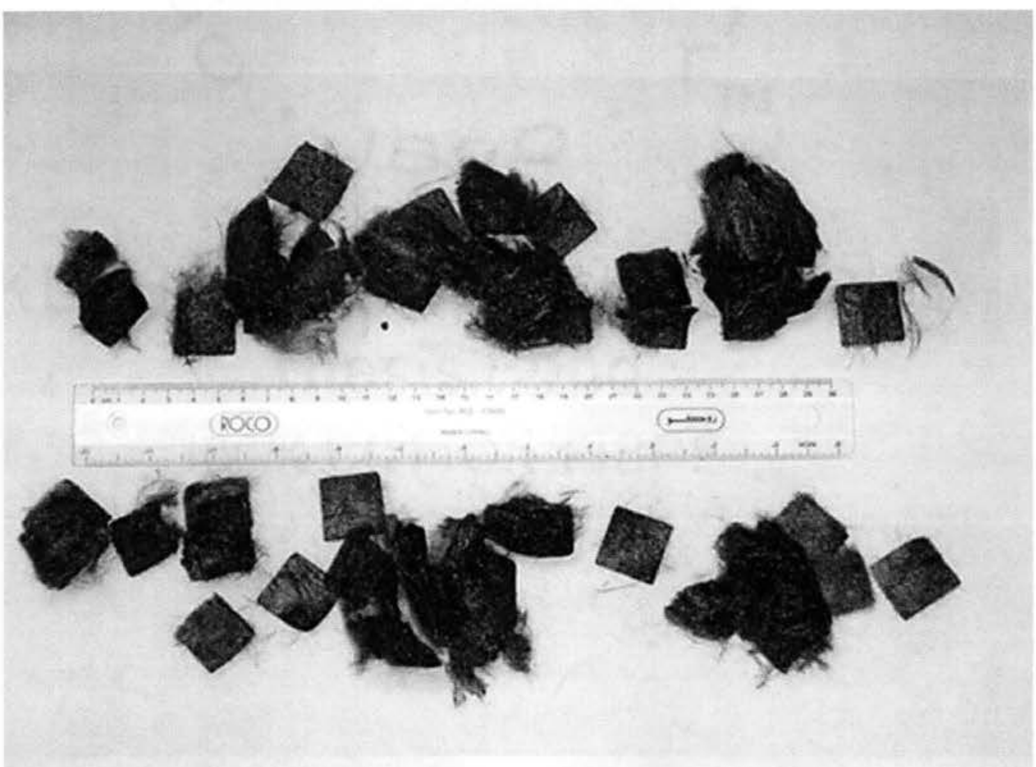

Figure 1-2. Conoco Carbon Fibers

1.2 Statement of the Problem

This research investigates shear transfer in concrete reinforced with CF. Sand-lightweight aggregates concrete, in particular, has exhibited a lower shear transfer than normal weight aggregates concrete [6]. The American Concrete Institute (ACI) building code does not address the shear properties of CFRC [7]. Design equations are needed to predict the amount of shear that can be transferred by adding CF to concrete members. The effect of CF percentage on the shear capacity of CFRC was also investigated in this research.

1.3 Objectives and Scope

The primary objective of this investigation was to study the effect of CF on shear strength and behavior of reinforced sand-lightweight aggregates concrete. Other objectives were to develop design equations to predict shear strength in CFRC and to investigate the relation between CF percentage and the shear properties in sand-lightweight aggregates concrete.

The study focuses on shear strength and behavior of push-off specimens made of sand-lightweight aggregates concrete reinforced with both conventional reinforcement and CF. In this study, the influence of CF volume percentage (V_f), reinforcement ratio crossing the shear plane (ρ), and type of CF were investigated. The results of the study utilized test results of 83 reinforced sand-lightweight aggregates concrete specimens. Some of the specimens were control samples in which no CF is added to the concrete. All specimens were cast from batches having similar workability regardless of CF percentage in the mix. Since the slump test is a good measure of the fresh concrete workability, a slump value of 5 in. was selected for control mixes (batches without CF) and a slump value of 3 in. was selected for batches with CF.

CHAPTER II

LITERATURE REVIEW

Hydrated portland cement is a ceramic-like material with poor tensile strength and low fracture toughness characteristics. These undesirable attributes lead to easy nucleation and propagation of cracks restricting the range of its use. One effective method of improving the mechanical behavior of cementitious materials is by the use of aggregate and macro-reinforcement such as steel rods [8]. However, dispersed discontinuous fibers can serve as micro-reinforcing agents for cement and concrete: for example straw was used to reinforce bricks and horsehair was used to reinforce plaster. Until recently asbestos fibers were the primary agent used to reinforce portland cement; however, patents have been granted since the turn of the century for methods to incorporate metal wires [8].

Research conducted so far with large steel fibers (20 to 60 mm in length and about 0.3 to 1.0 mm in diameter) indicated that although toughness improvements were significant, tensile strength of the composite was not greatly different from that of the host matrix [9, 10]. The inability of the large fibers to improve tensile strength of cement-based materials can be explained as follows. Tensile failure is caused by progressive extension of distributed micro-cracks that eventually coalesce into macro-cracks. For the usual volume fractions, large steel fibers are too far apart to blunt, arrest, or modify these micro-cracks in any significant way [11, 12]. For an improvement in tensile strength, extremely fine fibers are needed. These fine fibers (collectively called "micro-fibers") have their diameters on the same order as cement particle size ($<25\ \mu m$).

This chapter will be divided into two sections: a literature review of shear transfer in reinforced concrete and a literature review of principle, production, and properties of carbon fiber reinforced concrete (CFRC).

2.1 Shear Transfer in Reinforced Concrete

Throughout the history of the structural use of reinforced concrete, research has been ongoing to determine the strength of members subjected to bending and shear. Because of the abrupt nature of shear failures and the difficulty of formulating reliable mathematical analyses of beam behavior in shear, research has tended to concentrate on predicting the collapse load of such members, usually on an empirical basis. The trend has been accentuated by the increasing use of new materials and changes in structural form.

Under a low level of static load, concrete remains uncracked and transfers nearly the entire load through normal and shearing stresses. As the load increases and the principal tensile stress exceeds the concrete tensile strength, cracks begin to form. A redistribution of stresses occurs and the load is then transferred in a more complex manner. The uncracked portion of the concrete continues to transfer part of the load as before; the cracked region transfers some of the load by friction and mechanical interlock of the crack surfaces. The remaining portion of the load is transferred by steel reinforcement through normal and shearing stresses and possibly dowel action [13].

During crack formation, tensile stress in the reinforcement increases rapidly and results in high bond stress [14]. High shearing stresses may also be present in the reinforcement at crack locations as a result of dowel action. The portion of the load transferred by dowel action depends on the amount and distribution of the reinforcement [15] and the relative movement of the crack surfaces [16].

The percentage of load transferred by friction and mechanical interlock depends on crack width [17], bond effectiveness [18], and reinforcement anchorage [19, 20]. These in turn depend on not only amount and distribution of the reinforcement but also stress level in the reinforcement. Any additional load increases tensile stress in the reinforcement and consequently increases crack width and produces further crack propagation. This is accompanied by a reduction in the uncracked concrete area and an increase in the concrete compressive stress. The increase in crack width also reduces the percentage of load transferred by friction and mechanical interlock of the crack surfaces [17, 18].

2.1.1 Nature of Shear Plane

Hanson [21] studied the influence of surface characteristics of the shear plane on strength and behavior of a shear connection between precast and cast-in-place concrete. The effect of a proper bonding procedure was also considered. The results showed that specimens in which the bond was utilized as part of the connection developed high shearing stresses at low joint slip. In contrast, specimens with unbonded joints experienced considerable slip before high shearing stresses were reached. A maximum shearing stress of 500 psi was obtained for specimens with rough bonded surfaces and 300 psi for smooth unbonded surfaces.

The influence of a crack in the shear plane has been examined by Mattock et al. [22]; Mattock et al. [6]; Hofbeck et al. [16]; and Mattock [23]. The used concrete specimens of the push-off type similar to Figure 2-1. Their results indicated similar behavior when cracks pre-existed. In the case of initially-cracked specimens, relative movement was observed from the beginning of the loading. However, for initially-uncracked specimens, no movement was detected until diagonal tension cracks became visible at higher shear stresses. After crack formation, there was a relative movement of the two halves in the initially-uncracked specimens. This motion was not truly slip but

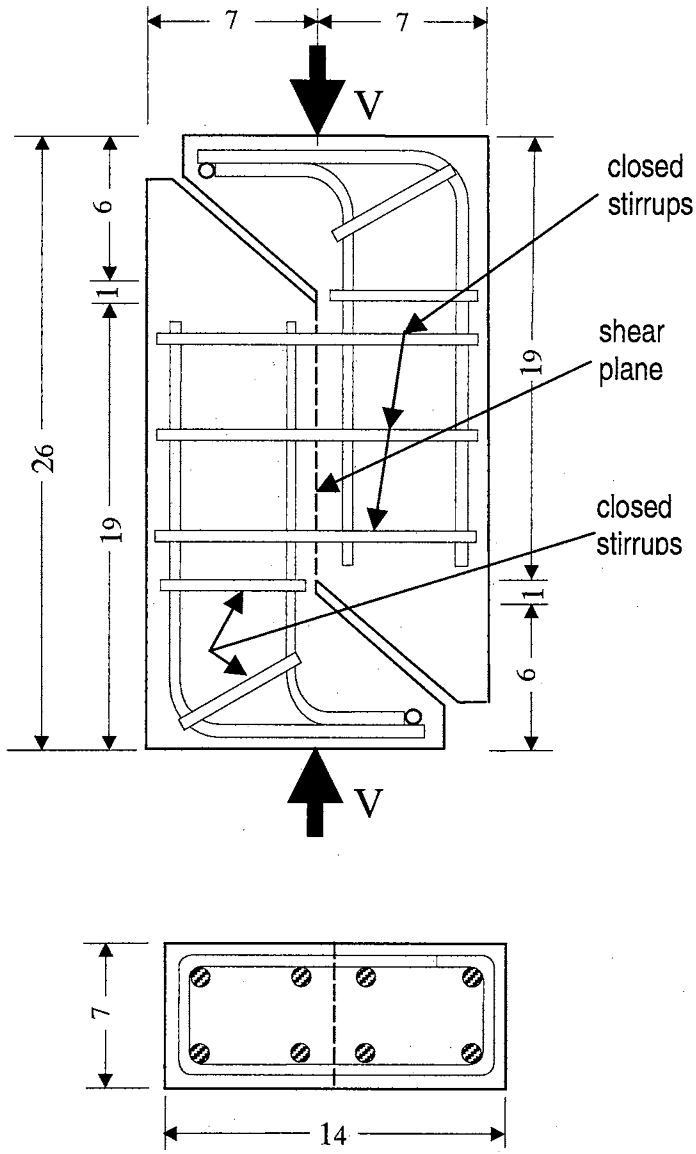

Figure 2-1. Concrete Specimen of Push-Off Type Used in Direct Shear Study [22]

resulted from rotation of the short struts formed by diagonal tension cracks when the stirrups elongated. Similar diagonal cracks were observed in the initially-cracked specimens with a high percentage of stirrup reinforcement.

Analysis of their test data indicated that the existence of a crack prior to a shear test produced a slip at all stages of loading greater than that observed when the crack was not present. The existence of a crack also lowered the ultimate shear strength.

2.1.2 Steel Reinforcement

Hofbeck et al. [16] and Anderson [24] showed the ultimate shear strength of a joint increased as the amount of steel reinforcement crossing the shear plane increased. Hofbeck et al. [16] also found that the higher the strength of web reinforcement the greater the shear strength and that the manner in which the reinforcement ratio (ρ) was varied did not affect the relationship between the shear strength and the parameter ρF_y. They also observed that dowel action did not contribute significantly to the shear strength of initially-uncracked specimens. On the contrary, for initially cracked specimens, consider-able contribution to shear transfer strength by dowel action was observed. They attributed this difference to the manners of crack formation and failure.

Mattock [23] examined shear transfer in concrete having steel reinforcement inclined at an arbitrary angle to the shear plane. Both parallel and orthogonal arranged reinforcements were considered. From analysis of the results, Mattock showed that when reinforcement is normal to the shear plane, shear strength could be expressed as

$$v_u = 400 + 0.8\,\rho F_y \text{ (psi)} \tag{2.1}$$

but

$$v_u \leq 0.3 f_c'$$

The distribution of reinforcement across the shear plane was studied by Mattock, Johal, and Chow [22]. They observed that for zero eccentricity loading, ultimate slip increased as the reinforcement distribution changed from uniform across the shear plane depth to concentration at the shear plane upper end as shown in Figure 2-1. In the case of specimens with uniformly distributed reinforcement, ultimate slip increased as loading eccentricity increased. However, in specimens having reinforcement concentrated near the top of the shear plane, there was very little variation in ultimate slip with eccentricity. If, therefore, both moment and shear are to be transferred across the cracked shear plane, reinforcement will be more effective when located in the flexural tension zone.

2.1.3 Lightweight Concrete

Structural lightweight concrete is concrete having a density between 90 and 120 lb/ft^3 containing naturally occurring lightweight aggregates such as pumice; artificial aggregates made from shales, slates or clays which have been expanded by heating; or of sintered blast furnace slag or cinders. Such concrete is used when a saving in dead load is important. The terms "all-lightweight concrete" and "sand-lightweight concrete" refer to mixes having lightweight sand or natural sand, respectively, in addition to lightweight coarse aggregates.

Hofbeck et al. [16] found that for a reinforcement strength parameter (ρF_y) less than 600 psi, concrete strength did not affect shear strength of cracked specimens. However, for higher values of ρF_y, shear strength was lower for a weaker concrete. Mattock et al. [6] studied mainly the influence of concrete unit weight on shear transfer strength of concrete. They observed that as the compressive strength of concrete increased, specimens exhibited more brittle behavior. In addition, specimens of all-lightweight concrete showed more brittle behavior than those of normal weight concrete.

Shear transfer strength of normal weight concrete was found to be consistently greater than that of lightweight concrete for the same amount of reinforcement and approximately the same compressive strength. Also, sand-lightweight concrete had a greater shear transfer strength than all-lightweight concrete. These differences in shear transfer capacities, however, did not correlate with the differences in concrete splitting tensile strength. Consequently, they recommended that shear transfer strength of lightweight concrete should not be related to splitting tensile strength of concrete.

Based on their results, Mattock et al. [5] determined the coefficient of friction, μ, be modified by a factor of 0.85 for sand-lightweight concrete and 0.75 for all-lightweight concrete. In addition, Equation (2.1) proposed by Mattock [23] for shear transfer in normal weight concrete was found to be unconservative for both sand- and all-lightweight concrete. It was then proposed that for sand-lightweight concrete, Equation (2.1) should be modified to

$$v_u = 250 + 0.8\,\rho F_y \tag{2.2}$$

but not more than 0.2 f_c' or 1000 psi, and for all-lightweight concrete

$$v_u = 200 + 0.8\,\rho F_y \tag{2.3}$$

but not more than 0.2 f_c' or 800 psi.

2.1.4 Loading

Mattocket al. [22] examined the influence of bending moment and tension force across the shear plane on shear transfer strength of reinforced concrete push-off specimens shown in Figure 2-1. In the case of specimens with tension across the shear plane, their results indicated that it is appropriate to add the normal stress σ_{Nx} to the reinforcement parameter ρF_y when calculating the shear transfer strength by the shear-friction method (σ_{Nx} is taken as positive when compression and negative when tension). Then the shear stress is given by

$$v_u = (\phi\rho F_y + \sigma_{Nx})\mu \tag{2.4}$$

In addition, Equation (2.1) for shear transfer strength in concrete proposed by Mattock [23] was also applicable if the above modification was performed, giving

$$v_u = 400 + 0.8\,(\rho F_y + \sigma_{Nx}) \tag{2.5}$$

but not greater than 0.3 f_c'. It appeared that the ultimate shear which can be transferred across the shear plane was not significantly affected by the presence of moment in the plane provided the applied moment was less than or equal to the flexural capacity of the section at the shear plane.

Paulay and Loeber [17] used both static and cyclic loading in their investigation of the contribution of aggregate interlock in shear transfer. In cyclic load tests, the load was fluctuated between 0 and 70 to 80% of the ultimate static load. Although failure was similar to that encountered in static tests, no sudden breakdown of aggregate interlock action was observed. However, there was, with progressive loading, an accumulation of shear displacements that increased proportionally with crack width. They observed, after testing, that crack surfaces were heavily striated, surface irregularities were worn down, and edges of aggregate indentations were rounded off.

2.1.5 Shear Transfer in Lightweight Concrete

Lightweight concrete specimens exhibited lower cracking loads and lower ultimate load-carrying capacity [25, 26, 27]. In addition, the shear force transferred by lightweight concrete has been determined to be lower than that of normal weight concrete [6]. The pertinent properties of structural lightweight concrete—such as elastic modulus, tensile strength, and bond and anchorage—are lower than those of normal-weight concrete [28]. Furthermore, bond strength between the mortar and aggregate particles is usually greater than the tensile strength of the aggregate particles [29]. Cracks, therefore, propagate through the aggregate particles instead of around them, as in normal weight concrete. This results in fewer irregular crack surfaces, more relative movement between the crack surfaces, and smaller ultimate load transfer capacity [16, 30].

2.2 Principles of Fiber Reinforcement

Discontinuous fibers have been added to a variety of polymeric, metallic, ceramic, and cementitious binders to enhance stiffness, strength, and toughness [8]. For all fiber-reinforced composites, stiffness and tensile strength are related to the mechanisms by which load is transferred from the continuous binder phase into the fiber. Several models have been developed to describe this load transfer. The central feature of these models is that the action of shear stresses imposed by the matrix over the fiber surface is countered by a tensile stress in the fiber [8]. The tensile stress is zero at the fiber ends and builds up to a maximum value toward the mid-length of the fiber. The distance from the fiber end to a position the stress approaches the maximum (usually taken as 95%) is referred to as the ineffective length of the fiber. As the imposed load on the binder is increased, the fiber will eventually break at some flaw along the fiber length [8]. As the two ends resulting from the break attempt to pull away from each other, shear stresses acting on the newly generated fiber fragments are countered by the build-up of tensile stress in the fragment. Again, parts of the fragment near the break will not support their share of the load so the average stress that can be sustained by the fragment is less than that of an unbroken fiber. However, as long as the strength capability of the fragment is larger than the applied stress, the fragment continues to contribute to the reinforcement. As the imposed load increases, a critical fragment length is reached (that approaches the ineffective length) which is too short to transfer sufficient stress and cause new failure.

The critical length is dependent upon fiber diameter and properties of the matrix, fiber, and interfacial shear strength [8]. Weak interfaces can fail and partially debond, thus substantially increasing the ineffective fiber length (and decreasing the reinforcing efficiency). Consequently, considerable effort has been directed to improve bonding strength in order to enhance stiffness and strength. On the other hand, if the bond strength is high, a crack in the binder phase may tend to propagate around the fibers, giving rise to a local plane of catastrophic brittle failure. In contrast, if the bond strength is weak, the crack can be diverted along the fiber surface, giving rise to a more tortuous path that can maintain the integrity of the part through these benign distributed failures. Consequently, some optimum (not necessarily a maximum) bond strength exists for various matrix-fiber systems. A good bond is needed to enhance the reinforcing efficiency for stiffness and strength; a weak bond is needed to enhance toughness. In general, a trade-off between load transfer efficiency and toughness is required.

For compliant yet tough polymeric binders (with high strain to failure), the role of the reinforcing fiber is to improve stiffness and strength. For brittle cementitious (and ceramic) binders (with low strain to failure), the primary role of the fiber is to lend toughness by controlling cracking and alter the behavior of the system after cracking has been initiated. Important factors that influence the behavior of a fiber-reinforced brittle binder are elastic constants of the fiber and binder, volume fraction of the fiber, aspect ratio (length divided by diameter) of the fiber, and the orientation distribution of the fibers. Two types of orientation distributions are investigated: 2-D and 3-D. The 2-D planar distributions are associated with thin-section composites where the fibers are confined to essentially lie in a plane and develop quasi-isotropic states of orientation. The 3-D distributions are associated with thick-section materials where fibers can tilt out of plane. However, processing conditions can induce a 2-D-like orientation near the surface of thick-section parts. In both 2-D and 3-D random orientations, shear moduli are greater than the case for aligned fibers. Orientations other than random cause the material to exhibit anisotropic behavior with different moduli in different directions. Orientation effects and their influence on performance are well known for discontinuous fiber polymeric composites [8]. Orientation effects do not appear to have received much attention in cementitious-based short-fiber composites. These orientation effects could be responsible for variations in properties of materials processed under different mixing and flow conditions. Eduljee and McCullough [31] studied fibers with various cross sections (elliptical, cylindrical, tapered) and also studied the aggregation effects. The elliptical shape was found to be the most efficient for load transfer; fibers aggregated into bundles significantly reduced reinforcing efficiency which is defined as the fiber percentage required to achieve certain level of reinforcement in the matrix.

2.2.1 Mixing Process of Fiber-Cement Matrix

The premix process is the most common procedure for producing cementitious products. In this process fibers are treated as an extra ingredient and combined in a mixer. The major feature of mixing is to introduce a sufficient volume of uniformly dispersed fibers to develop improvement in mechanical performance while retaining workability of the fresh mix. The performance of the hardened material is improved by high-aspect ratio fibers (aspect ratio is more than 1000). Alternately, high-aspect ratio fibers reduce the workability of the fresh mix. Bentur and Mindess [8] summarized various approaches to affect a trade-off:

- Modification of fiber geometry to increase bonding without increase in length (e.g., hooked fibers, deformed fibers or fibrillated networks);
- Chemically treating the fiber surface to improve its dispersion in the fresh mix; and

- Modifying rheological properties of the matrix through the use of chemical admixtures and mineral admixtures (e.g., silica fume and fly ash).

One of the chief difficulties in obtaining a uniform distribution of fibers is the tendency for fibers to clump together, either prior to addition into mix or during the mixing procedures.

Asbestos, glass, carbon, and several organic fibers are usually introduced as bundles of filaments. These bundles contain on the order of thousands of individual filaments with diameters of approximately 20 μm or less. The affinity of asbestos for the wet slurry facilitates break-up of the bundles; however, remnants of the bundle structure usually remain. Attempts have been made to chemically treat the fiber surface of man-made fibers to increase the affinity for wet slurry; however, these treatments can affect the bond strength [8].

The spacing between filaments within bundles (or bundle remnants) is much smaller than the dimension of the typical cement grain, so that only the external filaments have access to the matrix. Consequently, upon hydration and hardening the interior of the bundle consists of void spaces between filaments or limited local zones of hydration products. Interior filaments have freedom of movement, with stress transfer occurring through frictional effects.

Processing aids and admixtures are added to improve dispersion while maintaining workability of the mixture. Superplasticizers are added to improve workability. Superplasticizers (ASTM C494, Type F) are sulfonated melamine formaldehyde, sulfonated naphthalene formaldehyde and lignosulonates. Finely-divided mineral admixtures are added to improve workability and promote dispersion of the fibers. These admixtures include pozzolans such as diamaceous earth, clays, shales, volcanic tuffs, fly ash, and silica fume. Fly ash and silica fume appear to be particularly effective in promoting dispersion. Fly ash (derived from the combustion of coal in power generating plants) is primarily silicate glass containing silica, alumina, iron, and calcium.

Particle sizes of spherical fly ash range from 1 to l00 μm. Silica fume (also referred to as microsilica) is a byproduct of the reduction high-purity quartz with coal in the manufacture of silicon. Silica fume is essentially amorphous silicon dioxide in the form of spherical particles less than 1 μm in diameter; the average diameter is about 0.1 μm. Evidently, these fine particles can readily penetrate fiber bundles to promote filament dispersion. In addition, they can alter hydration products composition and properties in an interphase zone in the vicinity of fiber surfaces.

The practical level of mix workability limits the volume fraction of fibers that can be obtained in the premix approach. Only about 2% steel fibers can be introduced; glass and CF content can approach 5 to 8% while polypropylene appears to be limited to a few tenths of a percent [10].

Extrusion is a common process for producing discontinuous fiber polymeric composites. In this process a mixture of the fiber and binder are forced through a die of the desired cross-sectional shape. Although more difficult to apply, this process has been used for cementitious materials. Volume fractions of 1.5% steel fiber have been achieved. The Center for Advanced Cement-Based Materials (ACBM) at Northwestern University has patented an extrusion technology capable of achieving 2 to 8% of carbon, polypropylene, steel, cellulose, and polyvinyl alcohol fibers. Special techniques and additives are needed to modify the rheology. Shah et al. [32] claimed the material produced by this process can achieve levels of performance comparable to those obtained with continuous fibers. Although these workers did not report results concerning the nature of the fiber orientation, it is likely the enhanced behavior was due to the alignment of discontinuous fibers induced by the extrusion process. A skin of highly aligned fibers and a core of random fibers are typically observed in extruded short-fiber polymeric materials.

2.2.2 Fiber-Matrix Interface

Load transfer from the matrix to the fiber is dependent upon elastic constants of fiber and matrix, aspect ratio of fiber, and degree of bonding of fiber to binder. In addition to any chemical bonding of fiber to the matrix, mechanical forces acting normal to the fiber surface may influence bond strength. These clamping forces increase the frictional characteristics of the bond. Normal stresses may arise from a variety of sources:

- Volume changes due to matrix shrinkage can cause residual stresses. In particular, drying shrinkage of a cementitious matrix can aid mechanical locking.
- Upon tensile loading, materials tend to contract in a direction normal to the load, i.e., the Poisson effect. If Poisson's ratio of the fiber is lower than that of the matrix, tensile loading can promote compressive stresses and enhance mechanical locking across the interface between the matrix and the fibers parallel to the load direction.

The microstructure of the hydration material particles in the vicinity of the fiber surface can differ from that at some distance from the interface. These interface effects are well established for aggregates used in concrete, where an approximately 50-μm affected zone adjacent to the aggregate interface was observed. Modified morphologies were also observed in steel- and glass-reinforced systems. General features of this "transition zone" were described by Bentur and Mindess [8] as a calcium hydroxide rim in contact with the surface of the inclusion followed by a porous layer consisting mainly of needle-like calcium silicates transitioning into the typical dense cement matrix. The porous (and weak) zone occurred at approximately 20 μm from the surface and may have been the site of failures rather than the fiber matrix interface. The structure of the transition zone tended to vary with time, thus introducing certain aging characteristics. The composition of the transition zone was thought to be associated with composition of the mix, chemical activity of the inclusion surface, processing conditions, and size of cement particles. In particular, pozzolans such as fly ash and silica fume reduced alkalinity and calcium hydroxide content. It should be noted that formation of transition zones was inhibited in asbestos-reinforced cements [8]. This may be related to the hydrophilic surface of the asbestos fiber, small fiber diameters, and processing conditions that mitigate the formation of water-filled spaces in the vicinity of the fiber.

It is clear that the transition zone may add a significant complication to the design of optimum compositions and selection of processing conditions for fiber-reinforced cementitious products. Modifications of composition, structure, and extent of the transition zone can have a significant impact on the composite toughness [8].

2.2.3 Concrete Reinforced with Carbon Fibers

Carbon fiber reinforced cements and concretes are often abbreviated as "CFRC." Carbon fiber cement-matrix composites are structural materials that are gaining in importance due to the decrease in carbon fiber cost [33] and the increasing demand of superior structural and functional properties. Historically, the first study of carbon fibers in cement-based matrices was in the form of continuous high-modulus polyacrylonitrile (PAN) fibers by Ali et al. in 1972 [34] whereby significant improvements in the mechanical properties were noted. After their publication, some studies on CFRC were presented by Waller [35], Sarkar and Bailey [36], and Briggs et al. [37]. However, this type of fiber reinforcement did not prevail because of the high cost of these fibers. In the early 1980s, interest in the use of CF in cements was revived with the development of inexpensive low-modulus CF made from coal and petroleum pitches. This product, denoted as pitch-based CF, was developed in Japan and improvements in the composite properties were reported by Ohama et al. [38], Akihama et al. [39], and Tsuji et al. [40].

Carbon fiber cement-matrix composites contain short CF, typically 5 mm in length, as the short fibers can be used as an admixture in concrete (whereas continuous fibers cannot be simply added to the concrete mix) and short fibers are less expensive than continuous fibers. However, due to the weak bond between short fibers and the cement matrix, continuous fibers are more effective than short fibers in reinforcing concrete [41]. Surface treatment of CF (for example; by heating [42] or by using ozone [43], silane [44], SiO_2 particles [45] or hot NaOH solution [46]) is useful for improving the bond between fiber and matrix, thereby improving the properties of the composite.

Discontinuous fibers are not intended as a substitute for conventional macroreinforcements such as steel rods. However, Bentur and Mindess [8] point out there are certain applications in which fiber reinforcement is preferred to conventional reinforcing bars. These include:

- Thin sheet material in which conventional reinforcing bars cannot be used.
- Components which must withstand high loads or deformations.
- Components in which fibers are added as secondary reinforcement to control cracking.

The effect of carbon fiber addition on the properties of concrete increases with fiber volume fraction [47], unless the fiber volume fraction is so high that the air void content becomes excessive [48]. The air void content increases with fiber content and air voids tend to have a negative effect on many properties, such as the compressive strength. In addition, the workability of the mix decreases with fiber content [47]. Moreover, the cost increases with fiber content. Therefore, a rather low volume fraction of fibers is desirable. A volumetric fiber content as low as 0.2% is effective [49] although fiber contents exceeding 1% are more common [50].

Effective use of the carbon fibers in concrete requires dispersion of the fibers in the mix. Silica fume as an admixture enhances the dispersion [48]. Typical silica fume content is 15% by weight of cement. The silica fume is typically used along with a small amount (0.4% by weight of cement) of methylcellulose for helping the dispersion of the fibers and the workability of the mix [48]. Latex (typically 15-20% by weight of cement) is less effective than silica fume for helping the fiber dispersion, but it enhances the workability, flexural strength, flexural toughness, impact resistance, frost resistance and acid resistance [48, 51].

The improved structural properties rendered by carbon fiber addition pertain to the increased tensile and flexural strengths, the increased tensile ductility and flexural toughness, the enhanced impact resistance, the reduced drying shrinkage and the improved freeze-thaw durability [47, 48, 50-55, 38, 56]. The tensile and flexural strengths decrease with increasing specimen size, such that the size effect becomes larger as the fiber length increases [57]. C-shaped carbon fibers are more effective for strengthening than round carbon fibers [58], but their relatively large diameter makes them less attractive. Carbon fibers can be used in concrete together with steel fibers, as the addition of short carbon fibers to steel fiber-reinforced mortar increases the fracture toughness of the interfacial zone between steel fiber and the cement matrix [59]. Carbon fibers can also be used in concrete together with steel bars [60, 61], or together with carbon fiber reinforced polymer rods [62].

The advantage of CF reinforcement over steel, polypropylene, or glass fibers is in finishability, thermal resistance, weatherability, ability to mix high volume fractions, and long-term chemical stability in alkaline and other chemically aggressive environments [50, 52, 63]. Weatherability is defined as the ability to maintain mechanical properties after rapid cycles of freezing/thawing in air, submerging in hot water, long-term outside exposure, and saltwater spray tests [4]. Carbon fibers cause no rust stain problems on concrete surfaces as do steel fibers, and do not lose tensile strength and ductility with aging as do glass fibers. Another merit led by CF chemical inertness is the possibility of accelerated curing [3]—for example, autoclaving—for the cement composite at elevated temperature without degrading the fibers. Further, the use of CF is not associated with any potential health hazards, as is the use of asbestos fibers. These benefits along with reported improvements in mechanical properties make CF reinforcement a favorable proposition.

2.2.4 Materials for CFRC

Carbon fibers: Carbon fibers used for CFRC were chemically classified as PAN- and pitch-based, and fabricated in short and long (or continuous) fibers. Table 2-1 gives a comparative account of the properties of PAN- and pitch-based CF [63]. In the use of short CF, their length was normally 10 mm or less (3, 6 or 10 mm) and their aspect ratio was 200 to 700.

Fiber surface characteristics are a significant attribute to CFRC characteristics. An important advantage of CF is the ability to tailor surface characteristics by a straightforward technique [64]. In particular, electrolytic oxidation processes may be inserted on-line to systematically alter chemical activity of the fiber surface. The importance of surface characteristics to toughness and processability has prompted considerable effort to alter surface characteristics of CF for use in cement-based systems. These efforts include:

- Chemical treatments to sulphonate CF surfaces to increase hydrophilicity [65]
- Ultraviolet photoxidation of PAN-based CF surfaces [66]
- Steam treatment of CF [42]
- Application of water-soluble arninosilane coupling agents to the fiber surface [67]
- Coating CF with an emulsion of epoxy and colloidal silica [68]
- Coating CF with epoxy resin containing fine metal particles [69]
- Dipping CF in an aqueous slurry of silica fume [70].

TABLE 2-1

Properties of Pan- and Pitch-Based Commercial Carbon Fibers [63]

Fiber Type	Diameter (μm)	Specific Gravity	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Approximate Cost Ratio
PAN-based	7-8	1.6-1.7	3000-4000	250-400	7
Pitch-based	14-18	1.7-1.8	600-2000	30-200	1

Cement: To ensure the uniform dispersion of CF in a cement matrix and a good bond between the CF and cement matrix, dense packing of cement particles around the fibers is essential and the cement particles must be infiltrated between the CF. Accordingly, the use of cement with smaller particle size of less than 45 μm is generally recommended for CFRC [71]. Such cements are fine-ground ordinary portland cement, high early-strength portland cement, and ultrahigh early-strength portland cement. In the use of coarser cements like ordinary portland cement and alumina cement, very fine inorganic admixtures such as silica fume [55] and ground blast furnace slag [40] are mixed into the cements. Use of these admixtures is recommended because of the effective dispersion of CF and increased bond between the fibers and matrix due to filling the matrix voids around the fibers with the admixtures.

Fine Aggregates: In the production of CFRC, fine aggregates are used for CFRC with short CF, but are not used for CFRC with long CF. A proper fine aggregate size at which their uniform dispersion is achieved in CFRC ranges from 50 to 200 μm [72]. The fine aggregates recommended for CFRC are ground silica sand, fly ash, and Shirasu balloons. The Shirasu balloons are low-cost lightweight aggregates used in Japan, which are produced by burning volcanic ash at about 1000°C.

Admixtures: In the fabrication processes of CFRC with short CF, the use of any admixtures is indispensable for uniform dispersion of very fine, nonstiff CF, good bond between fibers and cement matrix and improved consistency. The admixtures recommended for CFRC are high-range water-reducing agents (super-plasticizers), air-entraining agents, latex-type cement modifiers [73], carboxyl methyl-cellulose [73], condensed silica fume [38, 74], and ground blast furnace slag [40]. For CFRC, a silica-cement ratio of 0.2 or more and a minimum superplasticizer content of 2% by weight of cement were suggested [75]. In particular, methylcellulose and very fine inorganic admixtures act as dispersants for the CF. These admixtures cause an increase in the cement matrix viscosity to hold and disperse the CF in the matrix.

Bindiganavile and Banthia [76] investigated the effectiveness of four different mineral admixtures – fly ash, silica fume, high reactivity metakaolin and carbon black – with varying particle size gradations and shapes with fiber reinforced dry-mix shotcrete. The authors claimed that the mineral admixtures were highly efficient in controlling rebound in dry-mix shotcrete. Particle size of the admixture was of a greater importance than its shape, and finer the particles, greater was the effectiveness of the admixture in controlling material and fiber rebound. The authors also found that a reduction in rebound did not ensure high performance in matured fiber reinforced dry-mix shotcrete. While silica fume was very successful in reducing fiber rebound and ensuring a high in situ fiber volume fraction, the brittleness introduced into the matrix due to silica fume, adversely affects the toughness characteristics. The authors suggested the solution was in blending silica fume with another admixture, such as high reactivity metakaolin whereby a significant reduction in fiber rebound was achieved without a compromise in the toughness and deformability.

Fabrication: Given the high specific surface area of CF, mixing by conventional means is usually difficult. Ordinarily, CF tends to ball and disperse nonuniformly. Fabrication processes for CFRC with long CF and mats/cloths made of long fibers are hand lay-up and filament-winding methods, which are almost the same methods as used for FRP (fiber-reinforced plastics). Fabrication processes for CFRC with short CF are the spray-up method in a two-dimensional orientation and casting, pressing, and extrusion molding methods in a three-dimensional orientation after uniform mixing. Of these molding processes, the casting method is most widely applied. In the casting method, the short CF is first randomly dispersed in three dimensions inside the cement matrix by using a proper mixer, and the mixed fresh CFRC is then cast in various forms. The reinforcement effectiveness due to the three-dimensional random orientation is generally lower than that due to one- or two-dimensional random orientation. However, if the three-dimensional random orientation of the CF is easily obtained by using an effective mixer and the casting is possible like conventional concrete, the lower mechanical properties of CFRC are compensated by reduction in the production cost due to the ease of such molding process [39].

Using a conventional mortar mixer and no dispersing agent, about 1% CF by volume may be evenly mixed in a normal ASTM Type I cement paste matrix. With a finer cement (ASTM Type III), however, fiber volume fractions may be increased to about 3% with substantial quantities of superplasticizer [77]. Beyond this fiber volume fraction, a suitable dispersing agent is needed. Alternatively, availability of a specialized type mixer (Omni mixer) may facilitate uniform mixing and dispersion even at high fiber volume fractions.

The workability of CFRC is often quantified by the flow index. Ando et al. [4] presented the results of multiple regression analysis for the effect of CF properties on the flow index of CFRC slurry and suggested the following equation:

$$F = 0.098\,D - 0.146\,S - 5.31\,V_f + 155.6 \tag{2.6}$$

where: F = flow index (mm);

D = CF diameter (mm);

S = specific surface area of CF per unit volume of CFRC (cm^2/cm^3); and

V_f = volume fraction of CF.

The flow index was found to be proportional to the fiber diameter and inversely proportional to the specific surface area of the fibers used. The flow index, was also inversely proportional to the fiber volume fraction. Flowability of CFRC mixes was not dependent on length of fibers used [38]. Further, mixer size was not found to have a particular effect on the observed flow index, i.e., smaller laboratory mixers produce flow indices reproducible in the field [4]. One interesting observation was the inverse dependence of flow index on tensile strength of the fiber itself. This dependence, however, developed as a consequence of the tensile strength of the fiber, and not that of bulk carbon, being inversely proportional to fiber diameter (based on Griffith's theory); and the flow index, as mentioned previously, being directly proportional to fiber diameter.

For CFRC mixes in the fresh state, although flowability is only moderate, proper proportioning and mixing can assure appreciable moldability and finishability. CFRC mixes ordinarily require longer than usual compaction times.

2.2.5 Compressive Behavior of Carbon Fiber Cement

Ohama and Amano [55] concluded that the compressive strength of the mortars is almost unaltered by carbon fiber inclusion up to about 1% of CF by volume followed by a decrease at higher volume fractions. Similar conclusions were also drawn by Sheng [77] and Kucharska et al. [78]. Also, shorter fibers (3 mm) were found to impart a better compressive strength than the longer fibers (10 mm). In the case of the mortars reinforced with CF, Ohama and Amano [55] reported increases in the compressive strength with an increase in the silica fume/cement ratio. The compressive strength of unreinforced mortar, on the other hand, appeared to have the maximum value at a silica fume/cement ratio of 0.4. The quantity of superplasticizer in the mix, on the other hand, was not found to have any influence on the compressive strength.

2.2.6 Tensile Behavior of Carbon Fiber Cement

Ohama, Amano and Endo [38] conducted Uniaxial tensile tests on carbon fiber reinforced cement paste using 3 and 10 mm long fibers. Akihama, Suenaga and Banno [79] and Akihama, Suenaga and Nakaeawa [39] tested carbon fiber reinforced cement mortars by using 10 mm long fibers. In both cases, the fibers used were 14.5 μm in diameter with a tensile strength of 767 MPa and a modulus of elasticity of 37 GPa. They reported a substantial increase in the strength and toughness in direct tension by the presence of fibers. Their stress-strain curves for the mortar matrix composites become distinctly bi-linear at a fiber content of about 2% by volume. They noticed a stiffer response of paste matrix composites and concluded that such a response may be related to the considerably increased heterogeneity in mortars over pastes that allows for increased pre-peak deformability and non-linearity. Akihama et al. [39] assumed that if the fibers were failing by pull-out, the average fiber length projecting from the fractured surface would be 0.25 * fiber length, the authors reported average projecting length in their case was less than 0.11 mm, and therefore most of the fibers in their tests had fractured.

Wen and Chung [80] studied the electrical resistivity of carbon fiber reinforced cement under uniaxial tension. They stated that the resistivity in the stress direction increased upon tension, due to slight fiber pull-out that accompanied crack opening, and decreased upon compression, due to slight fiber push-in that accompanied crack closing. They concluded that uniaxial tension of carbon fiber reinforced cement in the elastic regime was found to cause reversible increases in both longitudinal and transverse resistivity, such that the gage factor was comparable in magnitude in the two directions. Without the fibers, the resistivity increase under uniaxial tension was smaller and less reversible.

2.2.7 Flexural Behavior of Carbon Fiber Cement

Ohama et al. [38] and Banthia et al. [12] studied flexural strength of carbon fiber cement paste using three-point beam test. They used 3, 6 and 10 mm long fibers and specimen size of 40 x 10 x 160 mm beams. They reported an increase in the first crack and flexural strengths of the specimens with the increase in CF percentage. The increase in strengths was about three times at CF volumetric percentage of 3%. They also reported an increase in the fracture energy consumption by the presence of CF. The fracture energy consumption is defined as the area under the load-deflection curve in flexural test. The mechanical behavior of CFRC in flexure is influenced not only by the length of the fibers used but also by other factors such as cement matrix strength, fiber elastic modulus, fiber-matrix bond, extent of fiber dispersion, etc.

Kim and Park [81] investigated the Effects of three types of carbon fiber shapes (c, round, and hollow shape) on tensile and flexural strength developments of randomly oriented carbon-fiber-reinforced lightweight cement composites. They found that the flexure and tensile strength of the composite proportionally increased with the increase in fiber dosage. They also concluded that silica fume was a significant factor for increasing tensile strength of the composite. The silica fume added to cement matrix probably penetrates well into a hole or surface groove of fibers and densifies the matrix, resulting in improvement of fiber-matrix interfacial bonding zone. Kim and Park [81] showed that the hollow CF had the highest increase in the flexure and tensile strength followed by the c-shaped and the round fibers.

2.2.8 Specimen Size and CF Diameter Effect on the Tensile Characteristics of CF Cement

Akihama et al. [82] studied the size effects in CFRC load behavior under flexure. They reported a decrease in the flexural strength of CFRC beams as the width and the span increased and proposed a power law for estimating the factored decrease in the flexural strength as a function of the specimen span and depth.

Urano et al. [57] attempted to quantify the size effect of test specimen on tensile and flexural strength of CF concrete by using fracture mechanics concepts. They also studied the influence of CF length on flexural strength. The materials used in their research were: low-shrinkage cement; silica sand; lightweight aggregate; dispersing, water-reducer, and foam reducing agents; retarder; and CF. The CF was pitch-based (chopped filament) with 17 μm in diameter, 1770 MPa (257 ksi) tensile strength, 177 GPa (25,700 ksi) Young's modulus, and 1.9 specific gravity. Three different fiber lengths were investigated--6, 10 and 18 mm. Fiber dosage was 1.8% by total volume of the mix and water/cement ratio was 0.475. The samples were tested after 28 days of air curing. The test method was three-point bending on prism samples.

The size effect was evaluated by using the "Highly Stressed Volume" approach proposed by Torrent [83]. The highly stressed volume is defined as volume of the specimen subjected to >95% of the maximum tensile stress. This approach is based on the "weakest link of chain" concept and can be applied for correlating results of different tensile tests of concrete-like materials. The highly stressed volume, V, prism-shaped specimen with three-point bending is equal to:

$$V = 6.25 \times 10^{-4}\ bdL \tag{2.7}$$

where b is beam width, d is beam depth, and L is the span length.

The authors used seven different prism sizes and correlated the value V to a standard prism size of 10 mm x 10 mm x 12 mm (4 in. x 4 in. x 12 in.). The compressive stress-strain relationship for flexural analysis of CFRC beams was determined using Popovic's [84] equation:

$$\sigma_c/f_c' = n(\varepsilon_c/\varepsilon_{co})/[(n-1) + (\varepsilon_c/\varepsilon_{co})^n] \tag{2.8}$$

where σ_c is compressive stress, f_c' is compressive strength, ε_c is compressive strain, ε_{co} is ε_c value at f_c', and n is a constant. The tensile stress-strain relationship for flexural analysis of CFRC beams was determined by using the analytical method proposed by Urano et al. [85].

Reference [86] describes the size effect on compressive characteristics of CFRC is small. The research found that tensile and flexural strengths of CFRC decreased as specimen size increased and the size effect became larger as fiber length increased. The research also showed that, generally, tensile and flexural strengths increased as fiber length increased.

The research proved that size effect on total tensile strain was equal to size effect on tensile strength of CFRC. The author defined the size effect on flexural strength of a specific prism size as the ratio of flexural strength of that prism size to the flexural strength of a standard prism size, 4 x 4 x 12 in. The author compared analytical and experimental results and suggested that the size effect for one prism size of 6 x 10 x 80 in. is 0.77, 0.67 and 0.67 for fiber lengths 6, 10 and 18 mm, respectively. The author also suggested the dispersion of test results was large and further investigation was needed.

2.2.9 Flexural Behavior of Reinforced Concrete Beams Strengthened with CF

Takeda, Mitsui, and Murakami [87] studied the flexural behavior of medium-sized RC beams strengthened with CF sheets bonded to the beam soffits using epoxy resin adhesive. One of the specimens was initially crack damaged by preloading and subsequently strengthened with CF sheets. In the research, a large-sized RC beam specimen was also tested to simulate the performance in real structures. The specimen was initially crack damaged by preloading and subsequently repaired by injecting epoxy resin into the cracked parts and strengthened with CF sheets.

The material used was ready-mix ordinary concrete with normal portland cement and water/cement ratio of 0.585, slump of 7½ in., and air content of 4.3%. A water-reducing agent was used as an admixture. The CF sheets used were high performance pitch-based CF manufactured by Mitsubishi Chemical Corp with 0.28 sheet thickness, 2058 MPa (298 ksi) tensile strength, 235 GPa (34,100 ksi) Young's modulus. The specimens were reinforced with deformed bars at tension and compression sides of the beam in addition to stirrups. Flexural tests were four-point bending for most specimens and three-point bending for one specimen.

Takeda, Mitsui, and Murakami [87] proposed two assumptions in their analysis: the stress-strain relationship of CF sheets was linear until the stress reached tensile strength of the sheets, and the bond between the concrete and sheets was perfect until the ultimate stage. In their research, they determined that as the number of CF sheets increased, flexural rigidity and deformation capacity decreased. Also, CF sheets increased beam width where the crack developed. Sudden drops in load-deflection curves were due to local separation of the CF sheets. The authors found the measured cracking moment, M_{cr}, of the strengthened beams (beams with CF sheets) was unchanged as compared with that of the control beam (a beam without CF sheets) in spite of an increase in number of sheets. The measured yield moment, M_y, of the strengthened beams was about 1.4 to 1.9 times higher than that of the control beam and proportionally increased with increased number of CF sheets. Also, the measured ultimate moment, M_u, of the strengthened beams was about 1.9 to 2.4 times higher than that of the control beam; however, the reinforcing effect of the sheets had a tendency to be saturated with increase in number of sheets. Similar behavior patterns were observed for the strengthened beam and strengthened crack-damaged specimen.

For the large-sized beam, cracking load, P_{cr}, of the strengthened beam was unchanged as compared with that of the control beam; ultimate load, P_u, of the strengthened beam was about 1.7 times higher than that of the control beam. Most of the cracks for the strengthened beam occurred at places different from the repaired part, which proves that the repairing method was very effective, as claimed by the author.

The paper suggested that an analysis considering the concrete-sheet interface is needed for ultimate moment. The paper did not present a comparison between repairing RC beams with epoxy resin adhesive alone and CF sheets alone.

2.2.10 Bonding Characteristics of CFRC

Chen, Xuli Fu, and Chung [88] studied improvement in bonding between old and new concrete by adding CF to new concrete. The study suggested that adding CF in the amount of

0.35% by volume improved bond between old and new mortar by up to 89%. The CF used were 6 mm in length, unsized and made from isotropic pitch. Carbon fibers used were 10 μm in diameter, 690 Mpa in tensile strength, 48 GPa in tensile modulus, 1.4% elongation at break, 1.6 specific gravity and 98% by weight carbon content. The dispersion of CF required the use of latex, methyl-cellulose, and/or silica fume additives. The research studied five types of mortar: plain mortar, mortar with methyl-cellulose, mortar with methyl-cellulose and silica fume, mortar with latex, and mortar with epoxy. In all cases, other than plain mortar, mortars with and without CF were compared. For all batches, a slump of 160 to 170 mm was maintained by adjusting the water/cement ratio and the amount of water-reducing agent. A defoamer was used with all batches that contain latex.

Mortar with latex had the highest increase in bond strength between old and new concrete (89%) followed by mortars with methyl-cellulose and silica fume (67%). The research studied the effect of adding CF on the drying shrinkage of mortar. The drying shrinkage decreased with CF addition. The lowest drying shrinkage was achieved by mortar with methyl-cellulose, followed by mortar with methyl-cellulose and silica fume, followed by mortar with latex. The research also found that compressive strength of mortar decreased slightly by adding CF regardless of the additive type used.

2.2.11 Effect of Matrix Composition on the Aging of CFRC

According to Laws [89] there may be cases when the reinforcement of portland cement—with fibers of high aspect ratio and bond strength—may result in loss of toughness when bond strength exceeds a critical value, as may happen with time. This phenomenon is more likely to occur when using fine CF dispersed in a high strength cement matrix. However, only a few works have dealt with the study of long-term properties of CF-reinforced cements (CFRC).

Akihama et al. [54] tested long-term properties of pitch-based CF reinforcing lightweight concrete. They found an unexplained reduction of approximately 10% in flexural strength after reaching a maximum at four weeks for specimens cured in hot water (75°C) for five months. A similar trend was also observed by Ali et al. [34] for PAN-based CF cured in 50°C for one year. However, as the reduction was small, it was suggested that CFRC properties do not change with time [90].

Katz and Bentur [91] presented research to resolve certain formulations of CFRC that may show signs of loss of mechanical properties during aging, in particular, compositions with a dense matrix. In their research, properties of PAN-based CF-reinforced cementitious composites were tested after aging in water at 20 and 60°C for up to 10 and 7 months, respectively. Composites with water-binder ratios of 0.25 and 0.40 and silica fume contents of 0 to 28% were investigated. The results showed an increase in flexural strength and toughness with time up to a maximum at two to four weeks, and a reduction thereafter with a loss of up to 65% of the maximum value. The loss was higher at 60°C aging temperature and at higher silica fume contents. Flexural strength and micro-hardness tests of the matrix showed a continuous increase with time, in agreement with observations of matrix densification and pore structure refinement, as observed by mercury intrusion porosimetry (MIP) tests.

Maximum flexural strength and toughness values at early ages were obtained with mixes containing 7 to 14% of silica fume. Higher silica fume contents led to a reduction in early age strength and toughness values, although the matrix became denser and exhibited finer pore structure. Scanning electron microscope (SEM) observations of the fractured specimens after loading showed crumbling of the matrix near inclined fibers. Such matrix damage suggested that fiber-bending rupture is a major mechanism responsible for loss in mechanical properties which accompanied matrix densening with increase maximum flexural strength and toughness values at early ages were obtained with mixes containing 7 to 14% of silica fume. Higher silica fume contents led to a reduction in early age strength and toughness values, although the matrix became denser and exhibited finer pore structure.

2.2.12 Applications of Carbon Fiber Cement Composites

Given the improvements in the mechanical properties of weak and brittle cement matrices by carbon fiber reinforcing and the physical properties of these composites, there are numerous possible uses [63]. One of the major uses of these composites is in thin precast products like roofing sheets, panels, tiles, curtain walls, ferrocements, wave absorbers, permanent forms and free-access floor panels [63]. The first large scale application of CFRC was in the form of panels with tile cladding; in the Al Shaheed Monument in Iraq. CFRC curtain walls have been used in Japan for some time now.

Shi and Chung [92] studied using carbon fiber reinforced concrete for traffic monitoring and weighing in motion. They found that concrete containing CF at a dosage of 0.5% or 1.0% by weight of cement was effective in traffic monitoring for speeds up to 55 mph. They measured the electrical resistivity of Concrete with CF and found that the resistance decreased reversibly with increase in stress level and was independent of speed.

In the cast in place applications, CFRC has potential for use in mortars for external walls especially for structures in seismic regions, for thin repairs, for small machinery foundations, etc. The good conductivity of these composites may be put to use in the secondary anode system in the cathodic protection of reinforced concrete bridge decks, in conductive floor panel systems and in the concrete for lightning arresters [63].

CHAPTER III

SHEAR TRANSFER EXPERIMENTAL PROGRAM

3.1 Summary of Results From Initial Phases of the Research

The initial phases of this research, presented in Appendices A, B, and C, provided information that were used during the experimental program of this research, direct shear transfer. It is necessary to summarize those findings at the beginning of this chapter to help understanding some of the decisions and procedures that were adopted in this research. Complete details and summaries of all the findings in those initial phases are presented in the Appendices.

One of the first challenges in incorporating CF in mortar and concrete was to breakdown the sizing material, polyvinyl alcohol (PVA), that holds individual fibers in wafer form during shipping and subsequently disperse fibers in the mix. It was found that the standard mix water permitted breakdown of the wafer; no special pretreatment with a special water solution was needed. Results indicated that approximately 0.5% methyl-cellulose (a dispersing agent) by weight of water promotes dispersion of CF in cement and water. Results from mechanical properties tests showed that adding CF to mortar mixes increased the tensile strength by 20% and decreased the compressive strength by 5 to 10%. The presence of dispersed fibers in mortar increased the amount of entrapped air, which is responsible for the observed loss in compressive strength. A defoamer can be used to decrease the amount of entrapped air mortar, thus increasing compressive and tensile strengths. The presence of superplasticizer in mortar increased mix fluidity and consequently increased fiber dispersion. Results indicated that the optimum mix ingredients for using CF in mortar mixes included: methyl-cellulose at a dosage of 0.2% by weight of cement, the maximum recommended dosage of superplasticizer, and a defoamer.

In concrete mixes with CF, good fiber dispersion was accompanied by a loss in compressive strength (5 to 10%) but a gain in splitting tensile strength and flexural strength (20 to 30%). Factors that lead to improved fiber dispersion include use of methyl-cellulose (a dispersing agent), breakdown of the PVA coating on fibers by preheating, and any action that increased mix fluidity. The use of methyl-cellulose led to the need for a defoamer to counteract the air entrapped by the action of methyl-cellulose. Concrete samples with Mitsubishi CF had better performance than samples with Conoco CF. Samples with Mitsubishi CF had higher compressive strength, strain at failure, splitting tensile strength, and flexural strength than mixes with Conoco CF. Concrete with Mitsubishi CF had a lower modulus of elasticity than concrete with Conoco CF. For mixes with Conoco CF, increasing the amount of cement by 5% slightly improved the average mechanical properties, 10% increase in compressive strength, 8% increase in splitting tensile strength, and 2% increase in flexural strength.

Increasing fluidity of the mix was achieved in several ways: using superplasticizer, allowing air to be entrapped and later removing it with a defoamer, using mix proportions which result in high slump and reducing slump after fiber dispersion with metakaolin (dispersing agent), and increasing paste fluidity by increasing the water-to-cement ratio. Use of a defoamer or metakaolin that is added after a period of wet mixing might not be preferred in the field. Of these, the use of superplasticizer was probably the most practical. The effect of using two types of additives—water reducer vs. superplasticizer—was not noticeable in the mechanical property results for concrete with CF.

Adding CF to concrete decreased the workability that is required for precast production. To achieve the required workability for precast CF concrete production, the water/cement ratios and the water reducer agent dosage had to increase in the mix design. The slump test was used in measuring the workability of batches with and without CF. A comment from mixing personnel at the OSU concrete laboratory that batches with CF had an apparent stiffness in the matrix that the slump test was not the accurate indication for workability. In some CF batches, the slump tests showed values 3 to 4 in. but the batches appeared to be able to consolidate as 5 to 6 in. slump for batches without CF.

3.2 Introduction

The experimental work for this research was designed to study the influence of CF and interaction between steel reinforcement and CF on direct shear transfer strength. The advice of a precast concrete plant in Oklahoma City was sought as of the types of aggregate and concrete mix designs that should be used in order that the results of this study would have the widest practical applicability. Lightweight coarse aggregate was chosen for this study because past research indicated that concrete specimens made with this type of aggregate exhibited lower cracking loads and lower ultimate load-carrying capacity [25, 26, 27]. Past research also indicated that the shear force transferred by concrete made using lightweight coarse aggregate was lower than that of normal weight concrete [6]. Tension cracks were initiated as a result of internal shear stresses in concrete specimens under direct shear [16]. On the other hand, initial phases of this research [Appendices A, B, and C] in addition to past research [1-5] indicated that CF reinforcement can improve tensile and flexural strength of mortar and concrete and can also aid in the control of crack widths. Normal weight sand was chosen for this study since sand-lightweight concrete is widely used in the industry more than all-lightweight concrete.

For carbon fiber reinforced concrete (CFRC) to have practical applications, fresh concrete must have a suitable workability. For precast concrete applications, mix proportions as well as unit weight and air content of concrete affect workability. In this research, unit weight and air content of concrete were approximately the same for all specimens by fixing the ratio of cement to sand to lightweight coarse aggregate and also by fixing the consolidation procedures for all specimens. Because slump is often considered related to workability, it was decided that all batches would have approximately the same slump regardless of CF percentage in the mix. Based on discussions with personnel at a precast plant in Oklahoma City, a slump value of 5 to 6 in. was considered acceptable for precast production. Based on results obtained during earlier phases of this research, concrete specimens made from batches with CF and with slump values of 3 to 4 in. appeared to consolidate as easily as specimens made from batches without CF and with slump values of 5 to 6 in. Therefore a target slump value of 5 ± 0.5 in. was selected for control mixes (batches without CF) and a target slump value of 3 ± 0.5 in. was selected for batches with CF.

3.3 Specimens

The test specimens were of the push-off type shown in Figure 3-1 with dimensions of 5 x 12 x 22 in. and two gap wedges on the two 5 x 22 in. sides that extend half the length of the 12-in. side. When loaded as indicated by the arrows, direct shear was produced on the shear plane, between the tips of the two wedges. The shear plane area was 10 x 5 in. with a 50 in.^{2} area. The reinforcement crossing the shear plane was in the form of welded closed stirrups made of #3 deformed bars, each with shear cross sectional area of 0.22 in.^{2}. Each stirrup was made of two equal channel-shape bars welded along the shorter legs to form the required stirrup shape. This ensured symmetry and effective anchorage of reinforcement on both sides of the shear plane.

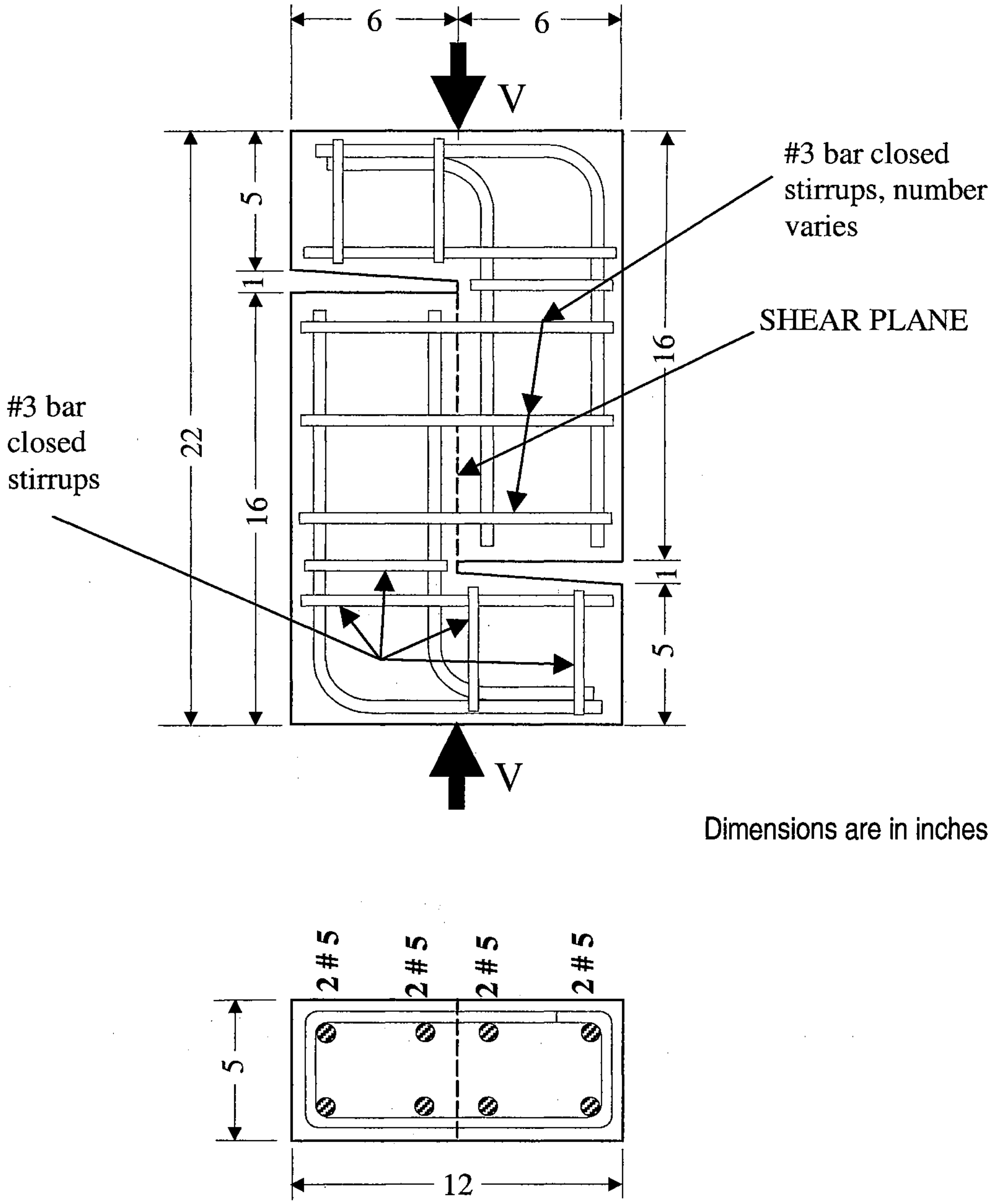

Figure 3-1. Push-Off Specimen

One, two or three stirrups crossed the shear plane. The two cantilever portions of the sample were reinforced with #5 deformed bars that extend along the edges of the sample to ensure integrity of the samples and force failure in shear along the shear plane rather than flexural failure in the cantilever portions. Additional closed stirrups were used to hold the reinforcement in plane during casting.

Specimens were cast in wooden forms sealed with wax. The wedge gaps were formed with steel wedges as shown in Figure 3-2. Form release agent was used to oil the inner surface of the form before each cast for ease of demolding. Six series of push-off specimens with volumetric percentage of CF in the mix of 0, 0.25, 0.5, 0.75, 1.0 or 1.25% were tested; the required workability could not be achieved with CF volumetric percentages exceeding 1.25%. The number of stirrups crossing the shear plane ranged from 1 to 3; at least 1 stirrup was required to hold the two halves of the specimen and more than 3 stirrups in a specimen was congested and the specimen could not be consolidated.

3.4 Materials

Aggregate: sand used in the research had a fineness modulus of 2.77, specific gravity of 2.62, and absorption of 0.4% and conformed to ASTM C-33 limits. The sand gradation along with the ASTM C-33 limits is presented in Figure B-1. The sand was placed in ambient temperature to dry and then stored in bins where the moisture was measured. The specific gravity was measured at Saturated Surface Dry (SSD) condition and at the time of batching the amount of mixing water was adjusted to reflect the differences in moisture content between sand from bins and SSD condition.

The coarse aggregate was the production of rotary kiln expanded lightweight aggregate with crushed surface and conformed to ASTM C-330, size 1/2 to No. 4, with a fineness modulus of 6.30 and a specific gravity of 1.89. The lightweight aggregate gradation used in this research along with

Figure 3-2. Push-Off Specimen Form

the ASTM C-330 size 1/2 to No. 4 limits is presented in Figure C-1. The lightweight aggregate were delivered at OSU concrete laboratory and immediately stored in barrels. The lightweight aggregate were soaked in water for 24 hours and then set in covered containers to drain excess water for another 24 hours and then used in batching. The specific gravity for the lightweight aggregate was measured at the same condition where the aggregate was used in batching.

Cement: Type III portland cement was used in both control batches and batches with CF.

Reinforcement: The deformed bar reinforcement used in shear samples conformed to ASTM A615 and was supplied from a local distributor. Random samples from the deformed bars were tested to failure in tension to measure the yield and ultimate strengths. The #5 bar longitudinal reinforcement had a yield point of 77 ksi and ultimate strength of 138 ksi. The #3 bars used for shear transfer reinforcement had yield strength of 63 ksi and ultimate strength of 105 ksi.

Carbon Fibers: Mitsubishi and Conoco CF were used in this phase of the research. Mechanical properties of both CF are presented in section 1.1. Dosages of CF were added as a volumetric percentage of the total volume of the mix. Percentages used for Mitsubishi CF were 0.25, 0.5, 0.75, 1 or 1.25; percentages used for Conoco CF were 0.25, 0.5 or 0.75. Several trials to increase the dosage of CF more than 1.25% for Mitsubishi CF and more than 0.75% for Conoco CF were conducted, but the required workability with 3-in. slump was not achieved. Several control batches were cast without CF.

Superplasticizer: To reduce the number of variables in this phase of the research, only one type of superplasticizer was used in the control mixes and in mixes with CF; Daracem ML500 manufactured by Grace. The manufacturer's recommended dosages for Daracem ML500 are 6 to 16 ml/kg of cement. Earlier phases of this research indicated that adding CF to the mixes reduced the mix workability; thus a high dosage of superplasticizer (16 ml/kg of cement) was used in mixes with CF. A dosage of 10 ml/kg of cement was used for control batches, which was the same dosage used in a precast plant with the same mix proportions and yielded a slump of 5 to 6 in.

Mix Proportions: The ratios of cement to sand to lightweight coarse aggregate were 1:1.459:1.749, respectively. These ratios were used during earlier phases of this research (Appendix C; Application of CFRC in Precast Production). Since it was decided that all mixes would have the same slump value, 3 in., the water/cement ratio needed to be adjusted for each mix depending on the percentage of CF used. After several trial batches and based on results obtained from earlier stages of the research, the following water/cement ratios were used:

CF%	0	0.25	0.5	0.75	1.0	1.25
W/C ratio	0.34	0.38	0.43	0.51	0.56	0.61

Results obtained during earlier stages of this research (Appendix C) show that the average air content percentage of CF concrete samples was 6.0%, and this value was assumed when calculating mix proportions for this phase of the research. Table 3-1 presents mix proportions (weights and volumes) of each component used in the mix for each percentage of CF. Specific gravities for the mix components used in the table were as follows:

Cement = 3.15
Sand = 2.65
Coarse aggregate = 1.89
Carbon Fibers = 1.9

Concrete Mixing Equipment, Batching, and Casting: A drum mixer with 3-ft^3 capacity was used and the volume of each batch was maintained at 2.25 to 2.35 ft^3. The full capacity of the mixer was not used to allow the fibers to disperse during the dry mix operation. The dry mixing duration was constant at 10 sec for all batches; the wet mixing duration was 2 min for control batches and 4 min for batches with CF. Slump tests were performed after adding the

Table 3-1

Mix Proportions for Direct Shear Samples

CF volume %		Cement	Sand	Coarse	Water	CF	Air	Σ
0	ratio by weight	1	1.458	1.749	0.34	0.00		
	weight (lb)	62	90	108	21	0.000		281
	volume (ft^3)	0.314	0.545	0.915	0.336	0.000	0.135	2.25
0.25	ratio by weight	1	1.458	1.749	0.38	0.01		
	weight (lb)	62	90	108	23	0.680		284
	volume (ft^3)	0.314	0.545	0.915	0.376	0.006	0.138	2.29
0.5	ratio by weight	1	1.458	1.749	0.43	0.02		
	weight (lb)	62	90	108	27	1		288
	volume (ft^3)	0.314	0.545	0.915	0.425	0.012	0.141	2.35
0.75	ratio by weight	1	1.458	1.749	0.51	0.04		
	weight (lb)	57	84	100	29	2		272
	volume (ft^3)	0.292	0.506	0.850	0.469	0.017	0.136	2.27
1	ratio by weight	1	1.458	1.749	0.56	0.05		
	weight (lb)	57	84	100	32	3		276
	volume (ft^3)	0.292	0.506	0.850	0.514	0.023	0.140	2.32
1.25	ratio by weight	1	1.458	1.749	0.61	0.06		
	weight (lb)	55	80	96	34	3		269
	volume (ft^3)	0.280	0.487	0.817	0.539	0.029	0.137	2.29

superplasticizer and the water/cement ratio was then adjusted slightly, if necessary, to reach a target slump of 3 $\pm$ 0.5 in. One or two shear specimens in addition to a total of 6 cylinders (4 x 8 in.) and 3 prisms (4 x 4 x 14 in.) were made from each batch.

Consolidation: A spud vibrator was used to consolidate shear, cylinder, and prism specimens. In addition, pressure was applied to the concrete surface to complete the consolidation process for cylinder and beam specimens.

Curing: Approximately 5 hours after molding, specimens were placed in steam cabinet at 49°C for about 19 hours. After removing from the cabinet, specimens were stored in the laboratory temperature and humidity until tested. All specimens were tested at an age of 7 days.

3.5 Experimental Procedures

One or two push-off specimens were made from each batch to give total of 90 push-off specimens from 64 batches. The push-off specimens were tested using a hydraulic testing machine. Typical set up for tests is shown in Figure 3-3.

The specimen stood on the table of the testing machine and was loaded through the upper fixed head of the testing machine and a set of parallel plates and rollers. The rollers ensured that the testing machine head did not restrain separation of the two halves of the push-off specimen. After performing a few tests with this arrangement, the rollers were crushed under the load and replaced with gypsum cement grout material. To ensure that the separation of the two halves was not restrained, the upper fixed head of the machine was replaced with a pinned head and was set parallel to the lower table before testing each specimen. The grout material was cast on top of each specimen immediately before testing and was consolidated by applying a small pressure from the upper head of the testing machine until hardening. This testing machine set-up ensured that

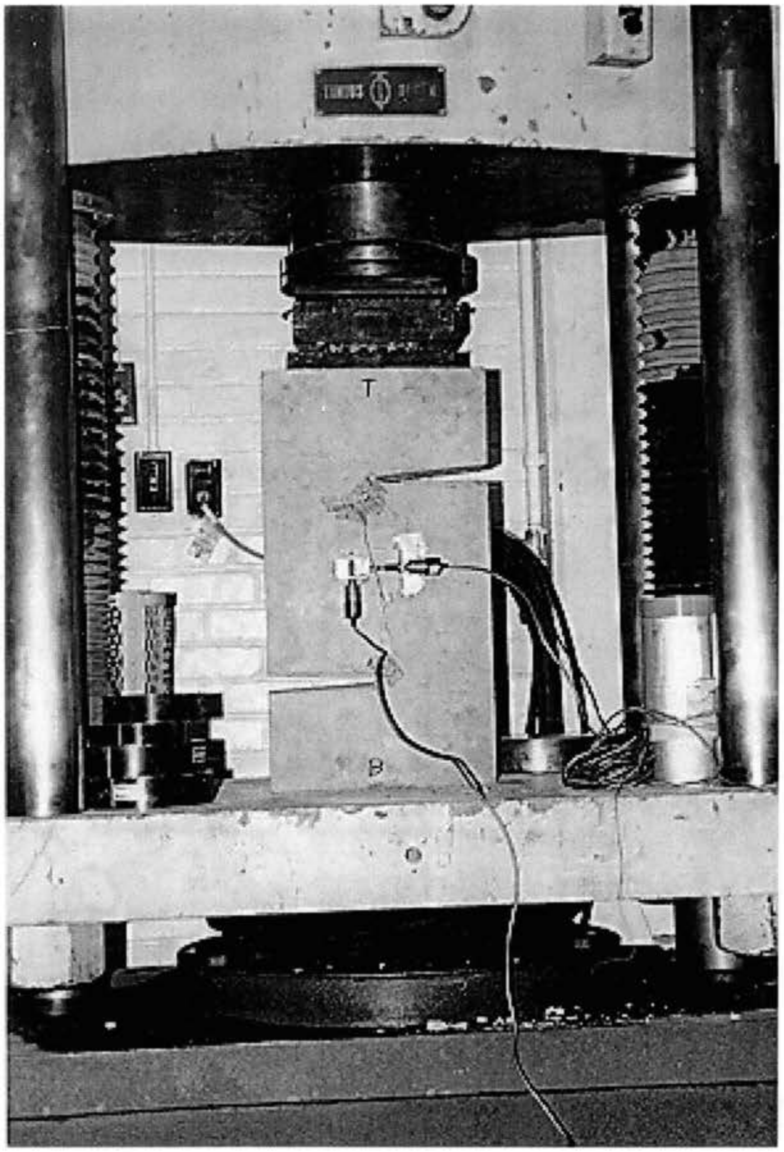

Figure 3-3. Set Up for Test of Push-Off Specimen

the load from the machine would always be vertical even if the top and bottom sides of the push-off specimen were not parallel. Under the applied load and after the formation of cracks, the two halves of the push-off specimens exhibited relative motion up to failure. The component of this relative motion parallel to the shear plane (vertical direction) is referred to as slip; the component normal to the shear plane (horizontal direction) is referred to as separation.

Four LVDTs were used to record slip along the shear plane and separation across; two each attach to the front and back faces of the specimens, as shown in Figure 3-4. Readings from the four LVDTs in addition to load signals from the testing machine were recorded continuously by data acquisition software. On each face, the slippage along the shear plane and separation across it were measured from the same two locations on the specimen, 2 in. apart across the shear plan and along the horizontal centerline of the specimen.

Readings from 7 push-off specimens were not usable due to errors in the set-up during testing; thus only 83 usable data points from push-off specimens were recorded. The testing machine was operated under manual control mode. The rate of displacement was adjusted manually for each test so that the specimens were subject to continuously increasing load at a rate of 0.5 to 0.8 kips/sec up to maximum load. The displacement rate was then increased to the end of the test and the load-displacement data points after maximum load were recorded. The average length of time for a test was about 5 min. The peak load was defined as the maximum load that could be carried by the specimen. The specimen failure was defined as the point where the two halves of the specimen were only connected by the stirrups crossing the shear plane and the failure load was the load at that point. The failure points were difficult to determined for specimens with high shear reinforcement or high CF percentage and the tests were stopped for those cases when excessive displacements were reached.

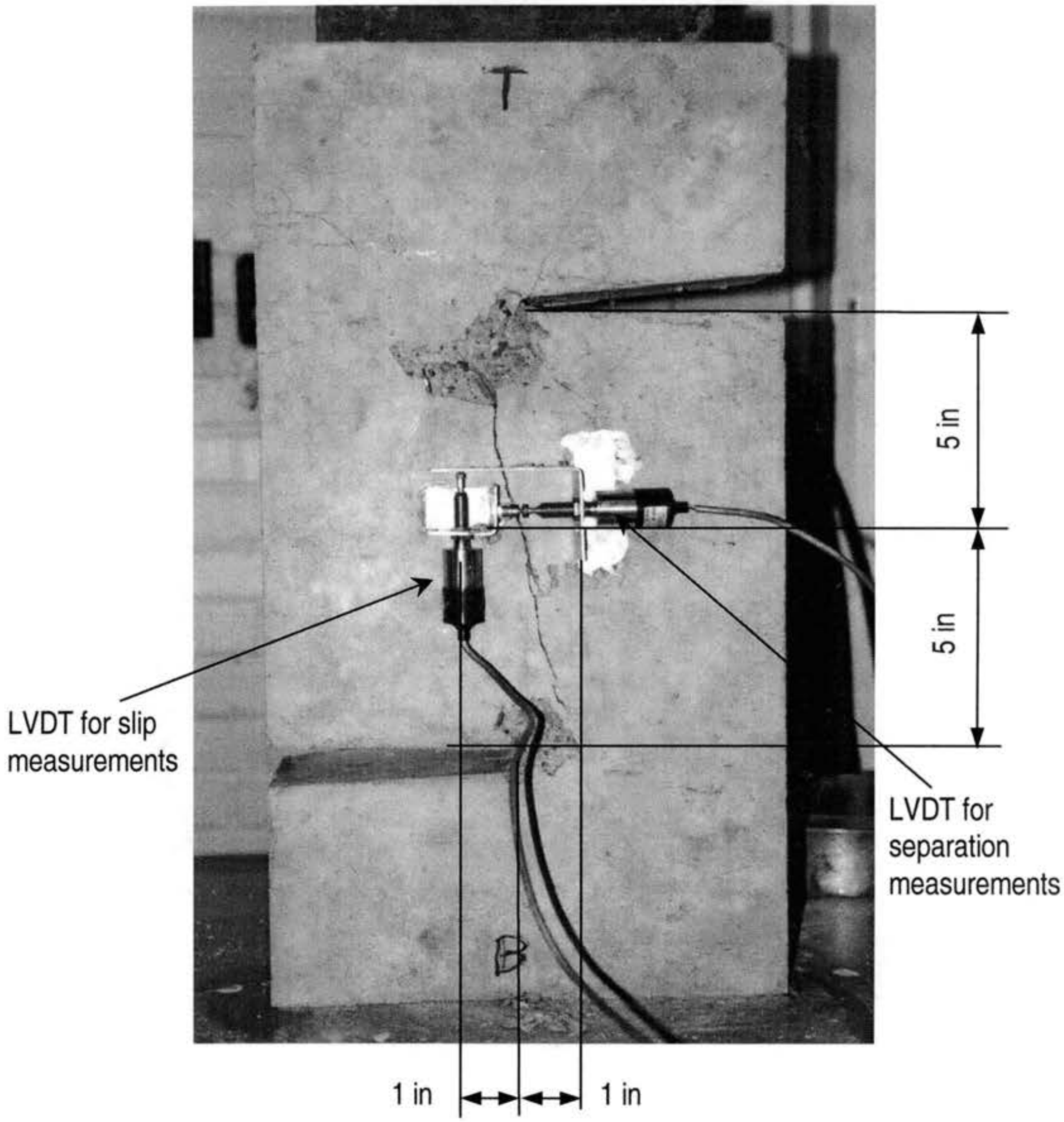

Figure 3-4. Details for LVDT on One Side of the Specimen

Cylinders and prisms were tested at the same age as the push-off specimen. Compressive strength and modulus of elasticity, splitting tensile strength, and flexural toughness of the concrete were determined in accordance with ASTM methods; C39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, C496 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, and C78 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam With Third-Point Loading), respectively. Good fiber dispersion was considered to be the absence of fibers in wafer or chip form. Scanning electron micrographs (SEM) of unhardened samples of concrete with CF indicated good fiber dispersion and hydration process around CF as shown in Figures 3-5 and 3-6. Examining the failure surfaces of the concrete specimens after testing indicated that most of the fibers had fractured, as oppose to pulled-out, as shown in Figure 3-7.

3.6 Results

3.6.1 Mechanical Properties

Results for compressive strength, splitting tensile strength, modulus of rupture and modulus of elasticity from cylinder and prism samples are shown in Figures 3-8, 3-9, 3-10 and 3-11, respectively. The results are also shown in Table 3-2 in addition to the specimens calculated unit weight. The figures and table show results for several dosages of both Mitsubishi and Conoco CF. Compressive strength, splitting tensile strength, modulus of elasticity, and concrete unit weight decreased with increase of CF percentage for both Mitsubishi and Conoco CF. Flexural strength decreased with increase in Conoco CF percentage and increased with increase in Mitsubishi CF percentage up to 1% and then decreased at percentage of 1.25. Specimens with Mitsubishi CF had higher compressive strength than the corresponding specimens with Conoco CF.

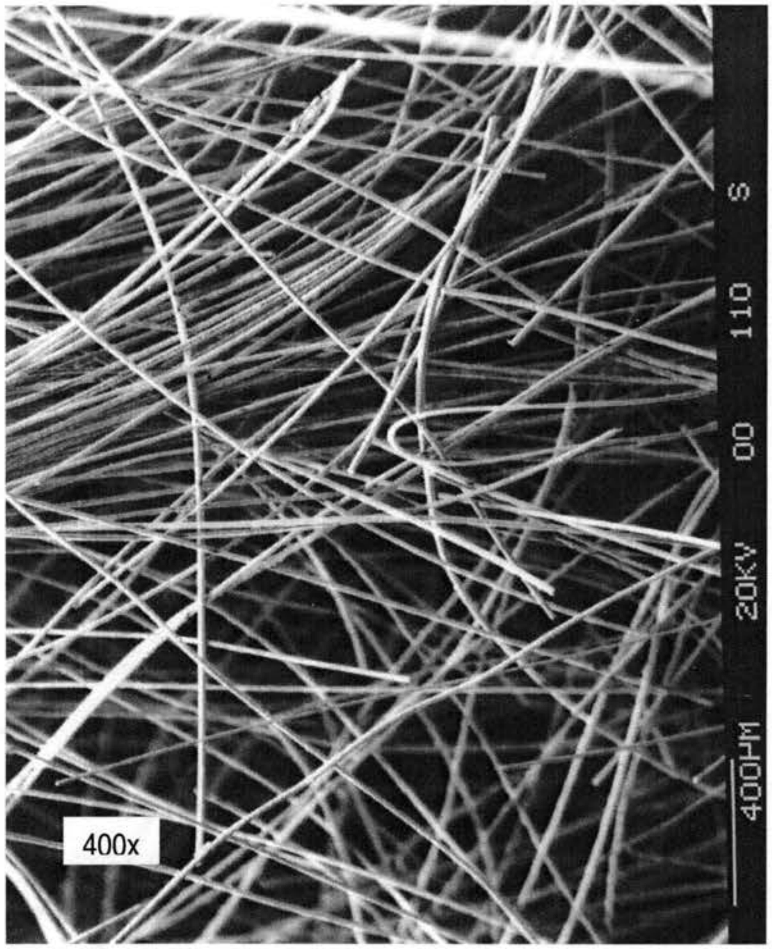

Figure 3-5. SEM Analysis for Unhardened Concrete Samples Showing Good Fiber Dispersion and Breakdown of the PVA Sizing Material.

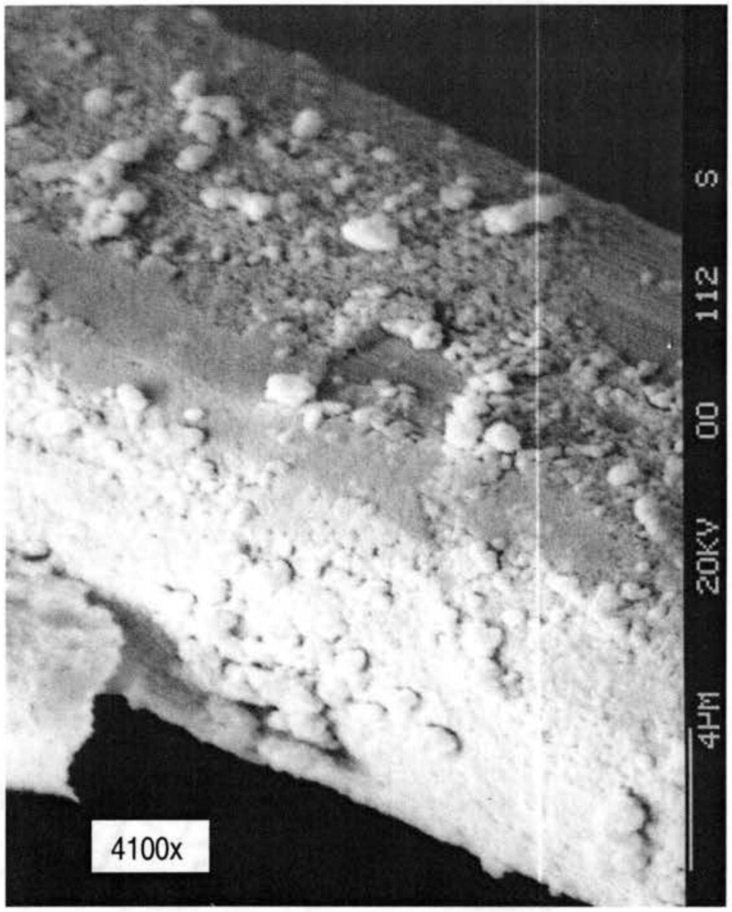

Figure 3-6. SEM Analysis for Unhardened Concrete Samples Showing Hydration Process Around CF.

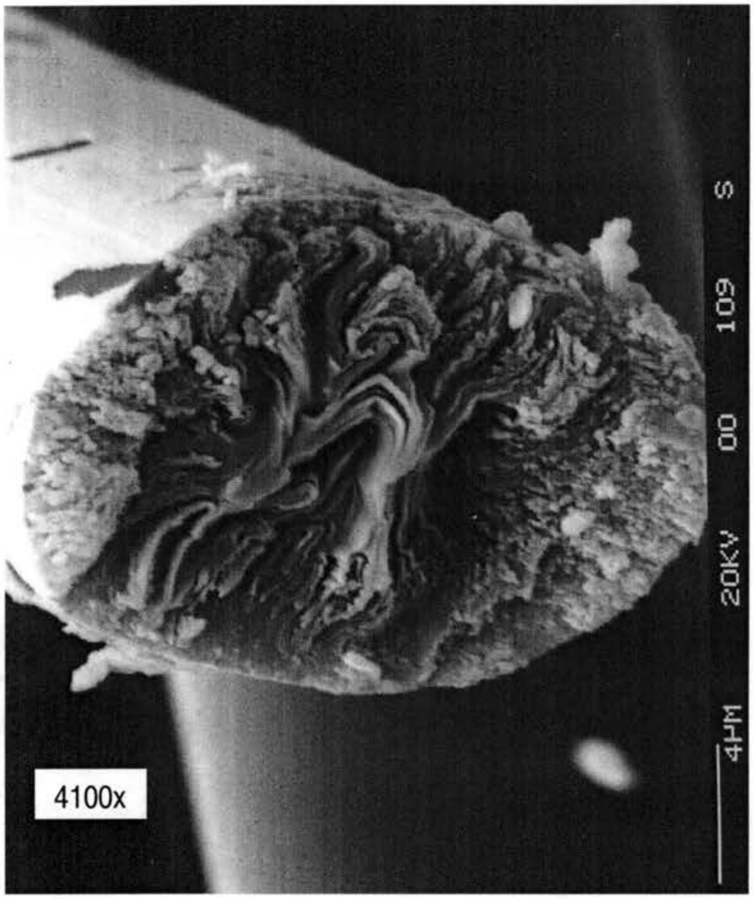

Figure 3-7. SEM Analysis for CF Cross Section After Fracture.

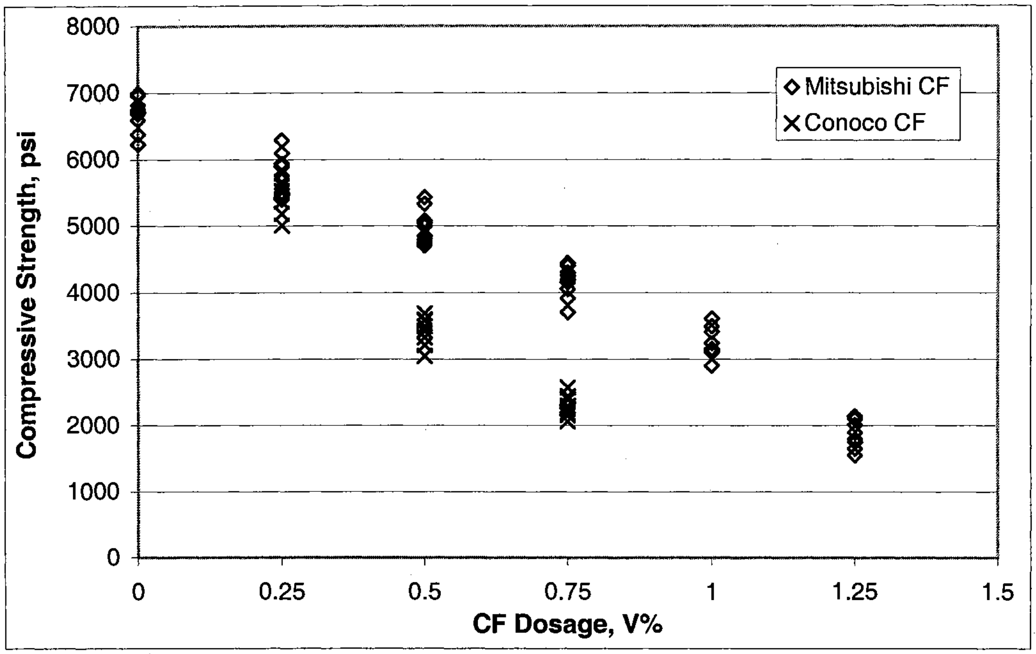

Figure 3-8. Decrease in Compressive Strength with Increase in CF Dosages

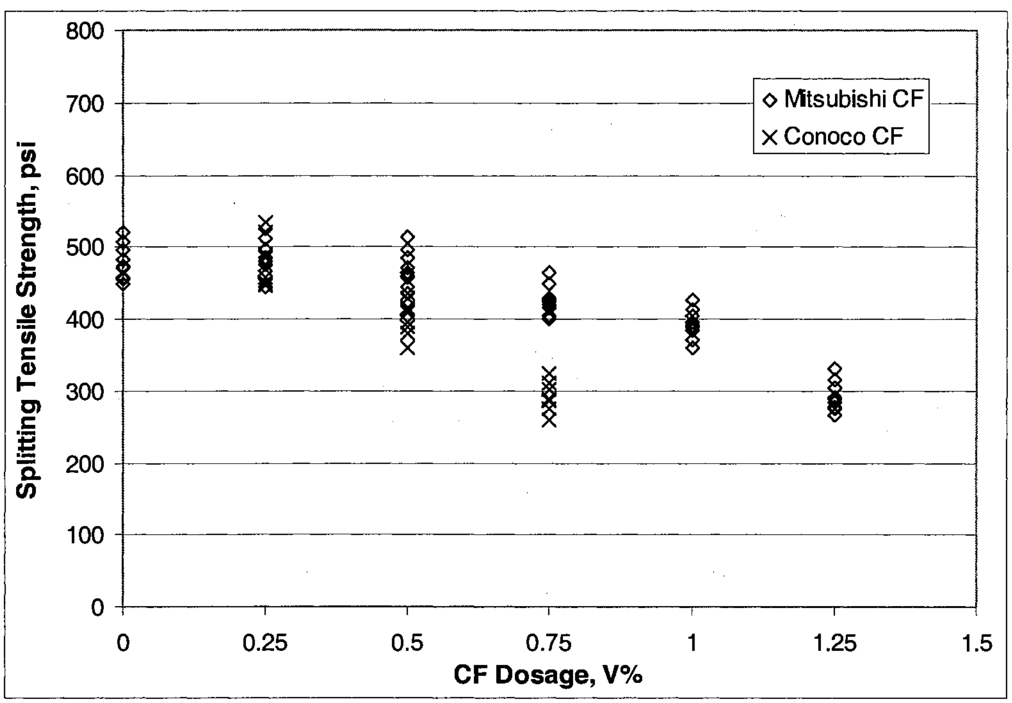

Figure 3-9. Decrease in Splitting Tensile Strength with Increase in CF Dosages

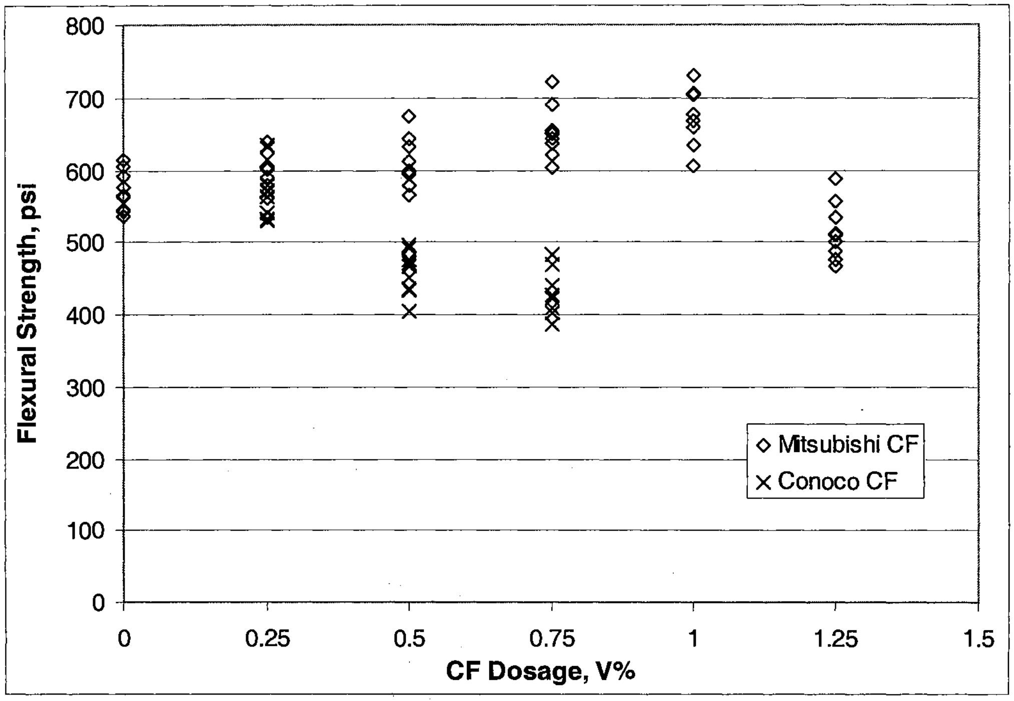

Figure 3-10. Change in Modulus of Rupture with Increase in CF Dosages

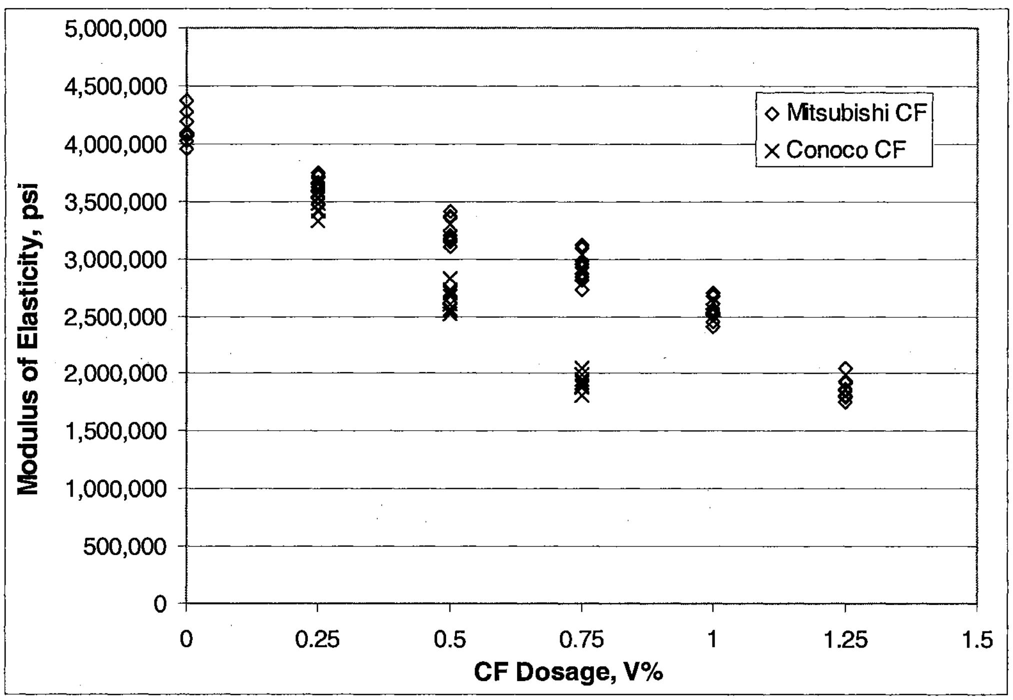

Figure 3-11. Decrease in Modulus of Elasticity with Increase in CF Dosages

Table 3-2

Mechanical Properties for Cylinder and Prism Samples

Samples with Mitsubishi CF

CF %	f_c' (psi)	f_{ct} (psi)	f_r (psi)	E (psi)	w (lb/ft^3)
0.0	6690 ± 250	480 ± 25	570 ± 30	4,140,000 ± 130,000	128
0.25	5780 ± 300	485 ± 25	590 ± 30	3,630,000 ± 100,000	128
0.5	5000 ± 260	470 ± 25	610 ± 35	3,240,000 ± 110,000	127
0.75	4160 ± 240	425 ± 20	650 ± 35	2,920,000 ± 130,000	121
1.0	3240 ± 220	395 ± 20	670 ± 40	2,550,000 ± 100,000	118
1.25	1890 ± 220	290 ± 20	515 ± 40	1,870,000 ± 90,000	116

Samples with Conoco CF

CF %	f_c' (psi)	f_{ct} (psi)	f_r (psi)	E (psi)	w (lb/ft^3)
0.0	6690 ± 250	480 ± 25	570 ± 30	4,140,000 ± 130,000	128
0.25	5470 ± 230	485 ± 30	570 ± 35	3,470,000 ± 90,000	124
0.5	3420 ± 200	405 ± 25	460 ± 30	2,650,000 ± 100,000	121
0.75	2310 ± 160	365 ± 20	430 ± 30	1,910,000 ± 80,000	118

- f_c' = Compressive Strength
- f_{ct} = Splitting Tensile Strength
- f_r = Modulus of Rupture
- **E** = Modulus of Elasticity
- **w** = Unit Weight of Concrete
- Values are: average ± standard deviation
- Standard deviation = $\sqrt{\dfrac{n\sum x^2 - \left(\sum x\right)^2}{n(n-1)}}$
- n = number of samples = 9

3.6.2 General Observation of Shear Specimens without Carbon Fibers

Figure 3-12 shows typical photograph of specimens without CF after failure. Figures 3-13 and 3-14 show typical load-slip and load-separation graphs, respectively, for specimens without CF. Additional graphs for specimens with 1, 2 or 3 stirrups crossing the shear planes will be presented in the next chapter; Analysis and Discussion of Results. The general behavior of all specimens without CF was similar. No slip along the shear plane or separation across the shear plane occurred in these specimens until the formation of diagonal tension cracks in the region of the shear plane, as shown in Figure 3-12, at a shear stress from 800 to 1000 psi where the load was defined as the cracking load. These cracks were inclined at 25 to 45^{0} to the shear plane. Relative motion between the two halves of the specimen often initiated as a result of rotation and compression of the inclined concrete struts formed by diagonal tension cracks. As the load increased, some cracks lengthened and additional cracks formed, so that at peak load there were in general a larger number of cracks in more heavily reinforced specimens than in more lightly reinforced specimens. At peak load some cracks propagated parallel to the shear plane, linking with others, and extensive compression spalling occurred in the inclined concrete struts as the reinforcement crossing the shear plane started to yield.

3.6.3 General Observation of Shear Specimens with Carbon Fibers

Figure 3-15 shows typical photograph of specimens with CF after failure. Figures 3-16 and 3-17 show typical load-slip and load-separation graphs, respectively, for specimens with CF. Additional graphs for specimens with 1, 2 or 3 stirrups crossing the shear planes and for Mitsubishi or Conoco with several percentages of CF will be presented in the next chapter; Analysis and Discussion of Results. The Figures show high value of slip and separation at peak and failure loads

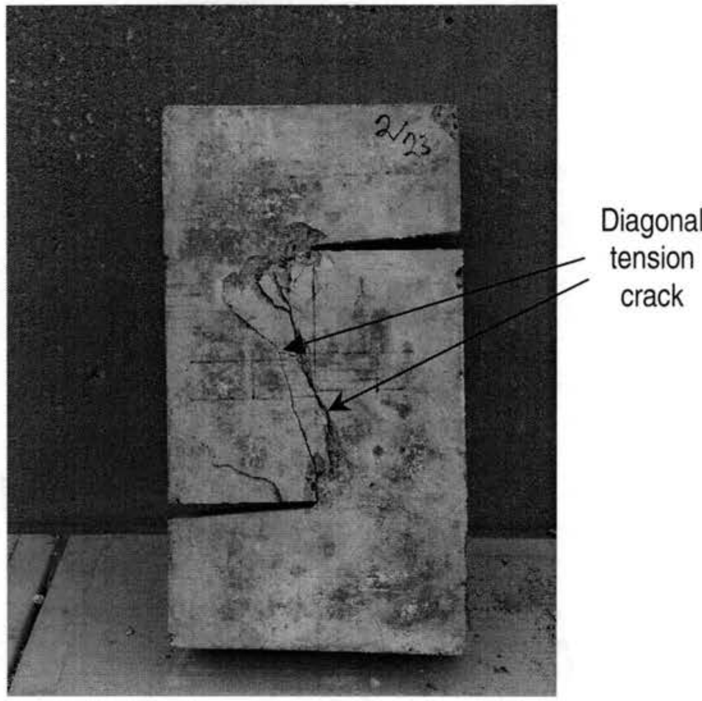

Figure 3-12. Specimens Without CF after Failure; Few Wide Cracks and Small Displacement at Failure

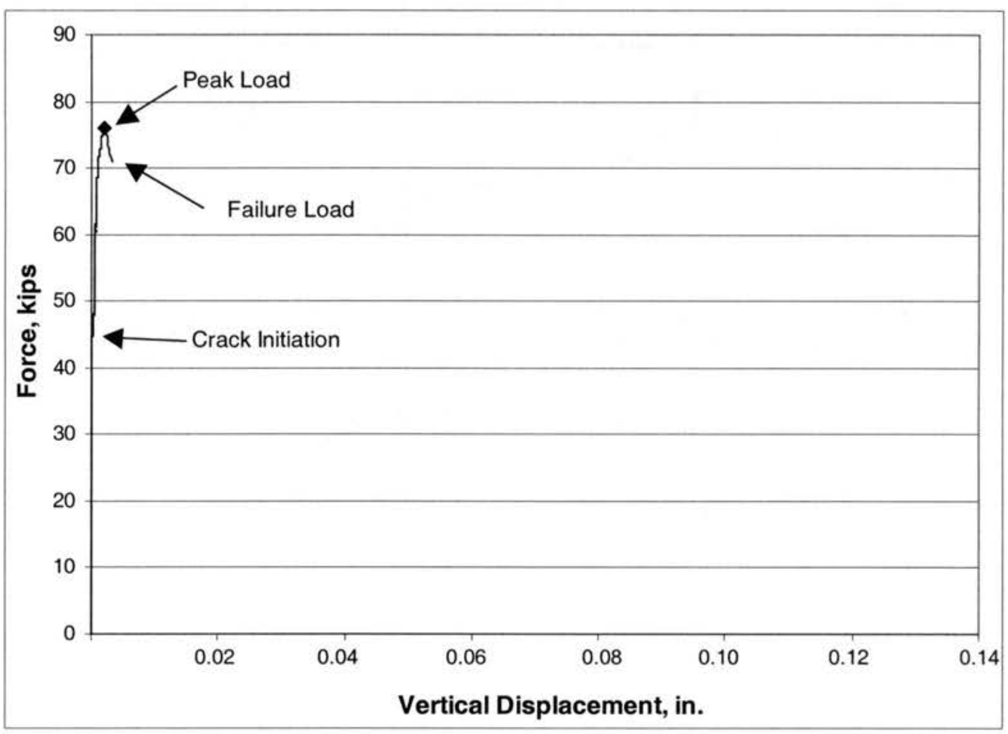

Figure 3-13. Typical Load-Slip Graph for Specimens Without CF; Small Slip at Peak Load

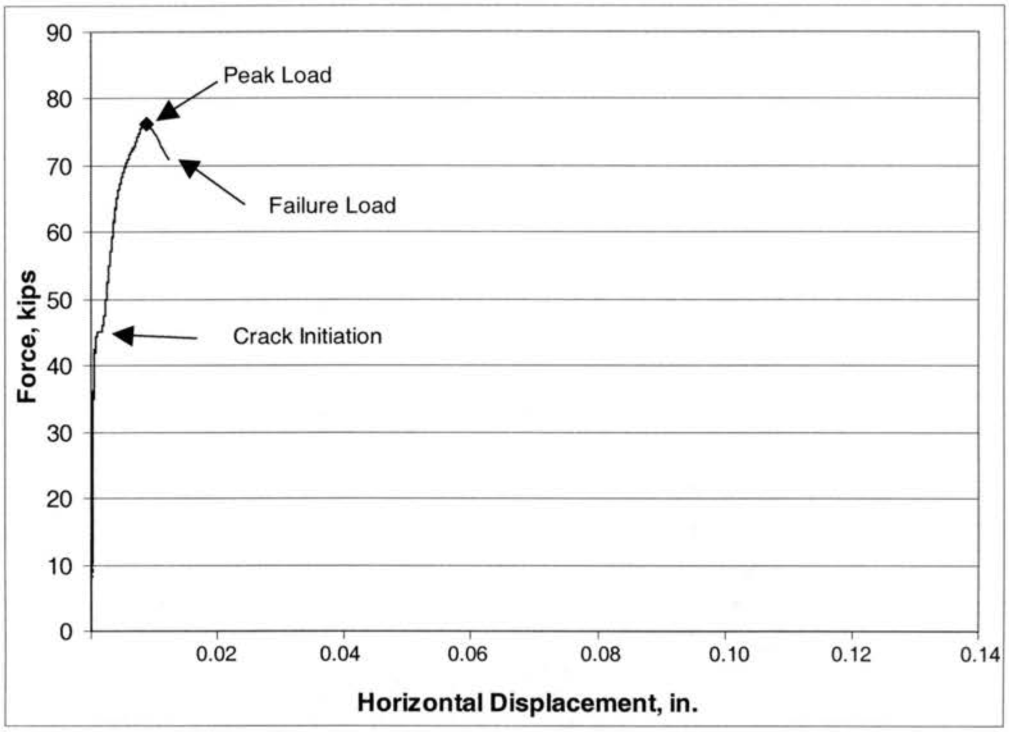

Figure 3-14. Typical Load-Separation Graph for Specimens Without CF; Small Separation at Peak Load

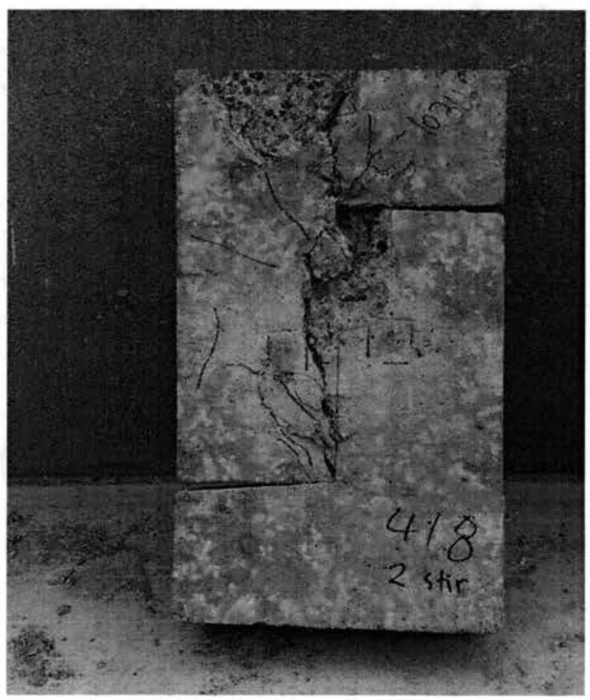

Figure 3-15. Specimens With CF after Failure; Many Small Cracks and High Displacement at Failure

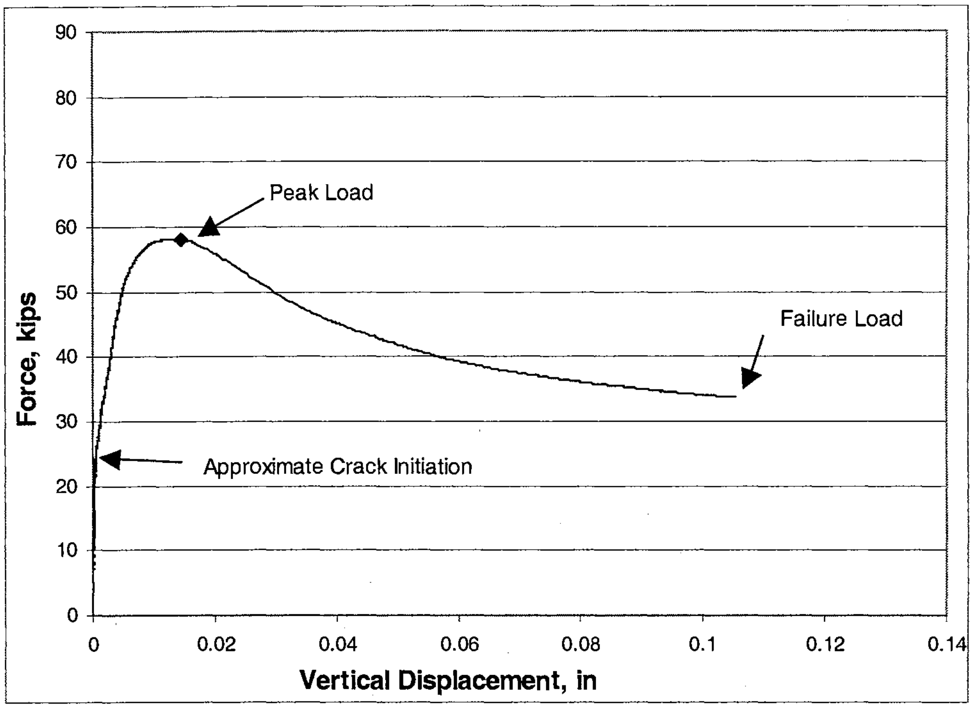

Figure 3-16. Typical Load-Slip Graph for Specimens With CF; Large Slip at Peak and Failure Loads

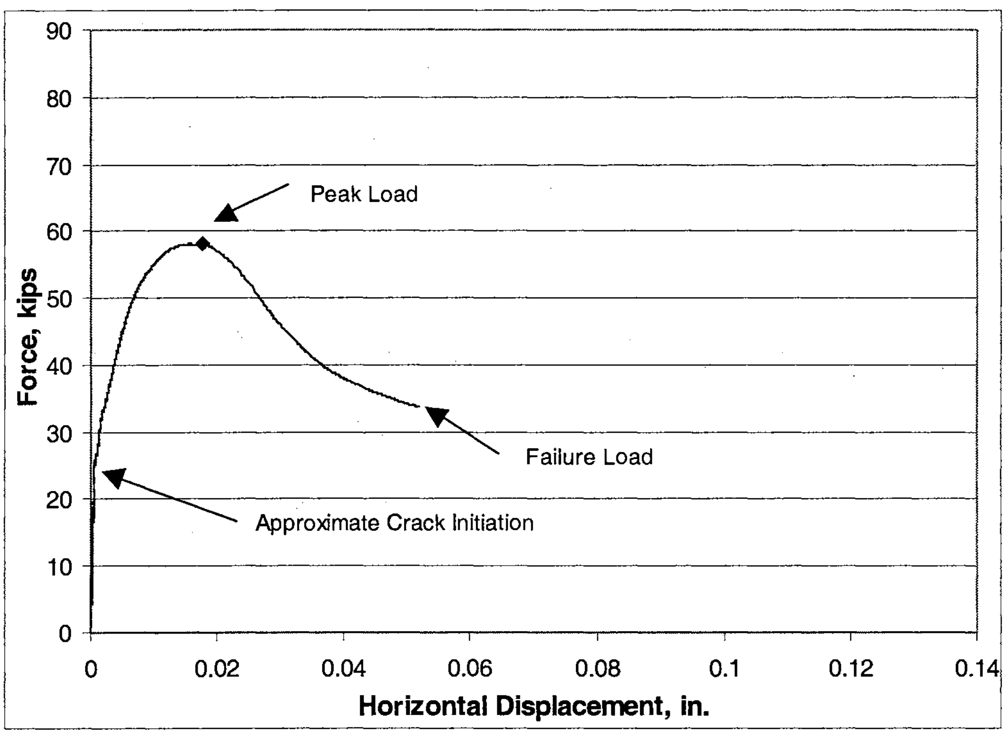

Figure 3-17. Typical Load-Separation Graph for Specimens With CF; Large Separation at Peak and Failure Loads

as compare to specimens without CF. In most specimens with CF, no sudden increase in slip or separation curves occurred. The approximate initiation of diagonal cracks in the shear plane region was determined when the slope of the slip or separation curves increased suddenly. These cracks were inclined from 5 to 35° to the shear plane at initial formation then angle increased from 25 to 45° as load approached peak load. As load increased above cracking, several cracks were formed which in general were more numerous than the cracks that formed in specimens without CF. The number of cracks increased as the CF percentage increased. At peak load crack widths were usually smaller than crack widths for specimens without CF, and crack widths decreased with the increase of CF percentage within the mix. At and above peak load some cracks propagated parallel to the shear plane, linking with others; extensive compression spalling occurred in the inclined concrete struts formed by diagonal tension cracks.

3.6.4 Direct Shear Test Results for Push-Off Specimens

Table 3-3 shows the average values for maximum shear stress resisted by push-off specimens for several percentages of CF and with 1, 2 or 3 stirrups crossing the shear plane. Maximum shear stress decreased as the CF percentage increased for all specimens with different shear reinforcement and for both Mitsubishi and Conoco CF specimens. Table 3-4 shows the average values for vertical displacement (slip) at peak load for several percentages of CF and with 1, 2 or 3 stirrups crossing the shear plane. Table 3-5 shows the average values for horizontal displacement (separation) at peak load for several percentages of CF and with 1, 2 and 3 stirrups crossing the shear plane. The slip and separation at peak load increased as the CF percentage increased for all specimens.

Table 3-3

Average Maximum Shear Resisted by Push-Off Specimens

Shear Stress in psi for Specimens with Mitsubishi CF:

CF%	1 stirrup	2 stirrups	3 stirrups
0	1520	1560	1590
0.25	1220	1420	1590
0.5	1070	1400	1420
0.75	760	1160	1140
1	730	940	890
1.25	515	735	870

Shear Stress in psi for Specimens with Conoco CF:

CF%	1 stirrup	2 stirrups	3 stirrups
0	1520	1560	1590
0.25	1150	1340	1610
0.5	970	1060	1220
0.75	785	1070	1210

Table 3-4

Average Vertical Displacement (Slip) at Peak Load for Push-Off Specimens

Slip in inches for Specimens with Mitsubishi CF:

CF%	1 stirrup	2 stirrups	3 stirrups
0	0.0023	0.0052	0.0055
0.25	0.0067	0.0068	0.0069
0.5	0.0113	0.0115	0.0118
0.75	0.0117	0.0143	0.0150
1	0.0131	0.0145	0.0156
1.25	0.0151	0.0157	0.0163

Slip in inches for Specimens with Conoco CF:

CF%	1 stirrup	2 stirrups	3 stirrups
0	0.0023	0.0052	0.0055
0.25	0.0078	0.0107	0.0124
0.5	0.0093	0.0129	0.0147
0.75	0.0153	0.0155	0.0156

Table 3-5

Average Horizontal Displacement (Separation) at Peak Load for Push-Off Specimens

Separation in inches for Specimens with Mitsubishi CF:

CF%	1 stirrup	2 stirrups	3 stirrups
0	0.0076	0.0086	0.0100
0.25	0.0114	0.0129	0.0133
0.5	0.0139	0.0152	0.0168
0.75	0.0140	0.0174	0.0185
1	0.0148	0.0175	0.0192
1.25	0.0153	0.0166	0.0196

Separation in inches for Specimens with Conoco CF:

CF%	1 stirrup	2 stirrups	3 stirrups
0	0.0076	0.0086	0.0100
0.25	0.0116	0.0127	0.0140
0.5	0.0152	0.0165	0.0187
0.75	0.0163	0.0182	0.0196

CHAPTER IV

ANALYSIS AND DISCUSSION OF RESULTS

4.1 Mechanical Properties for Cylinder and Prism Specimens

Mechanical properties for cylinder and prism specimens were shown in Table 3-2. The decrease in compressive strength with the increase in CF percentage can be explained by two factors: increase in surface area of non-cementitious mix components and increase in water/cement ratio. The presence of CF increased the total surface area of concrete components so that some cement particles (bonding agent) were used to cover CF and not to provide adhesion between aggregate components. Also, the strength of concrete is governed in large part by the water/cement ratio [93]. A lower water/cement ratio reduces the porosity of the hardened concrete and thus increases the number of interlocking solids and increases the compressive strength. A certain minimum amount of water is necessary for the proper chemical action in the hardening of concrete. In this research, increasing water/cement ratio increased workability but reduced strength. A water/cement ratio of 0.45 corresponds to compressive strength of 4000 to 5000 psi, while for a water/cement ratio of 0.65 the corresponding range is 2500 to 3300 psi [93]. Results obtained during earlier stages of the research indicated that the presence of CF decreased the compressive strength of specimens by 5 to 10%. Therefore, the loss in compressive strength was due to both the increase in water/cement ratio and the presence of CF.

For specimens without CF, splitting tensile strength, modulus of rupture, and modulus of elasticity are often assumed related to the compressive strength of concrete. The values for those mechanical properties are frequently expressed as proportional to the square root of the compressive strength. ACI building code [7] section R11.2 states that the splitting tensile strength for normal weight concrete is approximately equal to:

$$f_{ct} = 6.7\sqrt{f_c'} \tag{4-1}$$

and for sand-lightweight concrete, this value can be multiplied by 0.85. Thus the splitting tensile strength for sand-lightweight concrete is approximately equal to:

$$f_{ct} = 5.7\sqrt{f_c'} \tag{4-2}$$

ACI building code specifies the modulus of rupture for normal weight concrete as:

$$f_r = 7.5\sqrt{f_c'} \tag{4-3}$$

and for sand-lightweight concrete this value can be multiplied by 0.85. Thus the modulus of rupture for sand-lightweight concrete is approximately equal to:

$$f_r = 6.4\sqrt{f_c'} \tag{4-4}$$

ACI building code section 8.5.1 specifies the modulus of elasticity for concrete as:

$$E_c = 33\,(w^{1.5})\sqrt{f_c'} \tag{4-5}$$

for values of w (concrete unit weight) between 90 and 150 lb/ft^3; the unit weight of all concrete in this research was in this range.

Based on the results shown in Table 3-2, the constant terms in Equations (4-2), (4-4), and (4-5) will have different values as CF percentage and water/cement ratio increase in specimens. Table 4-1 shows the calculated values for constant terms shown in Equations (4-2), (4-4), and (4-5) as C_{ct}, C_r, and C_E, respectively, for both Mitsubishi and Conoco CF. The C_{ct} and C_r terms increase

Table 4-1

Calculated Terms Used in ACI Equations for Specimens Mechanical Properties

Specimens with Mitsubishi CF

CF %	C_{ct}	C_r	C_E
0.0	5.9	7.0	35
0.25	6.4	7.8	33
0.5	6.6	8.6	32
0.75	6.6	10.1	34
1.0	6.9	11.8	35
1.25	6.7	11.8	34

Specimens with Conoco CF

CF %	C_{ct}	C_r	C_E
0.0	5.9	7.0	35
0.25	6.6	7.7	34
0.5	6.9	7.9	34
0.75	7.6	8.9	31

with the increase in CF percentage for both types of fibers except at higher dosage of CF (1.25 percentage for Mitsubishi CF). The C_E term remains almost unchanged with the increase in CF percentage. For Mitsubishi CF, the rate of increase in the C_{ct} term was lower than the rate of increase in the C_r term. Specimens with Mitsubishi CF had higher splitting tensile strength and modulus of rupture than Specimens with Conoco CF.

The significance of the data shown in Table 4-1 is that if specimens with and without CF have the same compressive strength, the splitting tensile strength and modulus of rupture would increase with increase in CF percentage. Figures 4-1 and 4-2 show graphs for C_{ct} and C_r terms for several dosages of CF for Mitsubishi and Conoco CF. Linear interpolation between data points gave the following Equations for Mitsubishi CF:

$$C_{ct} = 6.1 + 0.64\ V_f \qquad (4\text{-}6)$$

$$C_r = 6.8 + 4.33\ V_f \qquad (4\text{-}7)$$

and for Conoco CF:

$$C_{ct} = 5.9 + 2.22\ V_f \qquad (4\text{-}8)$$

$$C_r = 7.0 + 2.44\ V_f \qquad (4\text{-}9)$$

where V_f is the CF volumetric percentage.

To conform with ACI building code Equations (4-2) and (4-4) the constant terms in Equations (4-8) to (4-7) need to equal the corresponding terms in ACI Equations. Thus for design, the splitting tensile strength and modulus of rupture can be expressed as: for Mitsubishi CF:

$$f_{ct} = (5.7 + 0.6\ V_f)\ \sqrt{f_c^{'}} \qquad (4\text{-}10)$$

$$f_r = (6.4 + 4.3\ V_f)\ \sqrt{f_c^{'}} \qquad (4\text{-}11)$$

and for Conoco CF:

$$f_{ct} = (5.7 + 2.2\ V_f)\ \sqrt{f_c^{'}} \qquad (4\text{-}12)$$

$$f_r = (6.4 + 2.4\ V_f)\ \sqrt{f_c^{'}} \qquad (4\text{-}13)$$

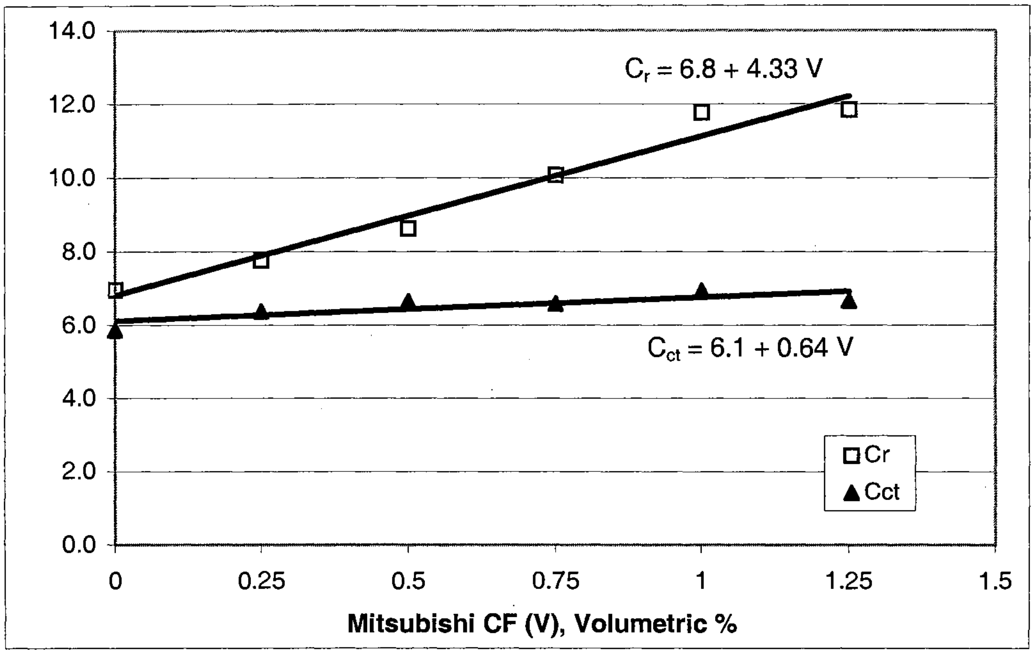

Figure 4-1. Increase in C_{ct} and C_r Terms with Increase in Mitsubishi CF Percentage

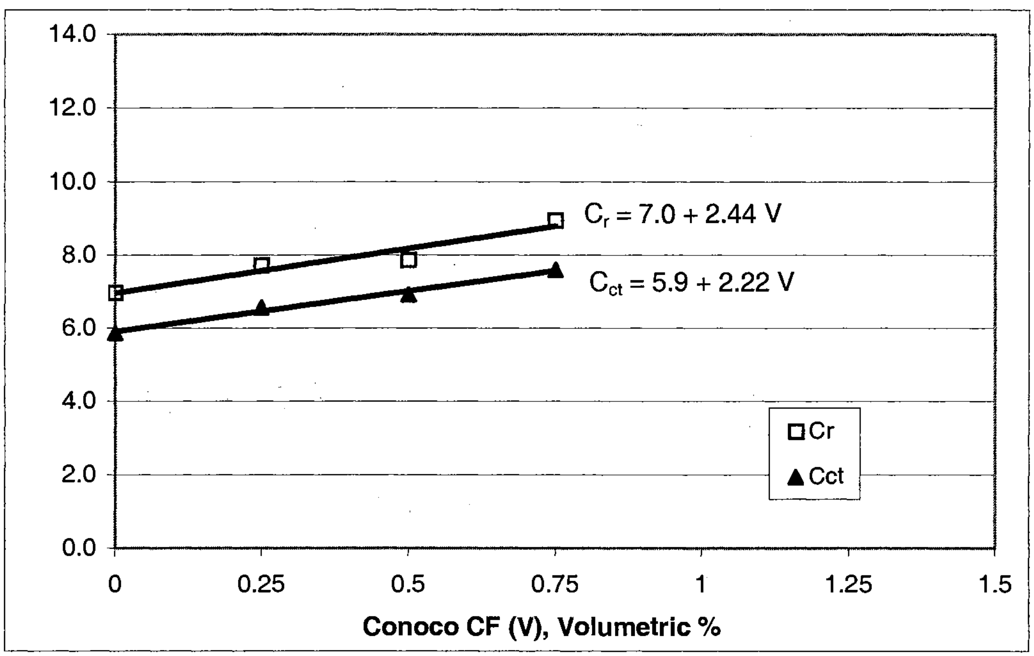

Figure 4-2. Increase in C_{ct} and C_r Terms with Increase in Conoco CF Percentage

In addition to CF percentages, the values representing slope of the curves shown in Figures 4-1 and 4-2 will depend on several factors related to CF; length, diameter, strength, fiber efficiency, and fibers orientation in the samples will greatly affect these values. Some or all of these factors are responsible for the difference in tensile strength behavior between Mitsubishi and Conoco CF. More studies are needed to break down these numbers to include all factors.

4.2 General Behavior for Push-Off Shear Specimens

4.2.1 Shear Specimen without Carbon Fibers

Figures 4-3 and 4-4 show shear-slip and shear-separation curves, respectively, for specimens without CF and with 1, 2 or 3 stirrups crossing the shear plane. The average values of peak load (in kips) as well as the average values of slip and separation (in inches) at peak load are also shown in Figures 4-3 and 4-4. It is noted that each numerical value shown is the average of three values while each graph is typical.

The maximum load increased with increase of reinforcement crossing the shear plane. Slip and separation of the two halves of the specimens decreased with increase of reinforcement crossing the shear plane. This result is due to increase in confinement on the shear area with increase in number of stirrups.

Separation of the two halves of the specimens was always higher than slip along the shear plane. Separation of the two halves caused by rotation and compression of the inclined concrete struts as reinforcement crossing the shear plane stretched. Under the applied load, slip is restricted by aggregate interlock and dual action of the shear reinforcement.

Slip and separation of the two halves of the specimen were limited until the formation of the first crack (sudden incline in the curves at values of load from 40 to 50 kips). The dual action of

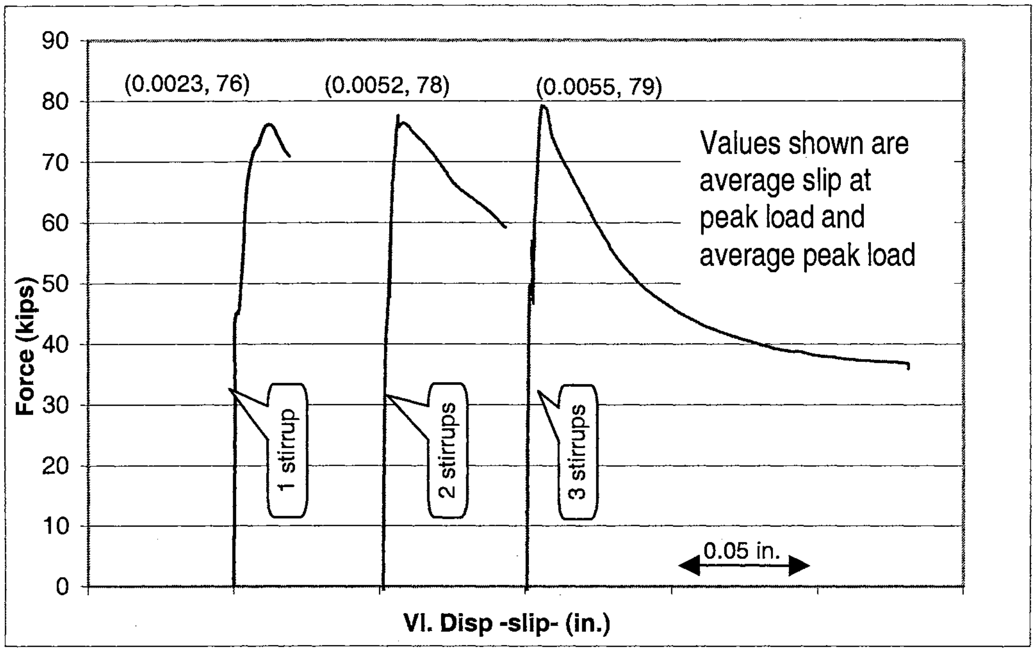

Figure 4-3. Shear-Slip Curves for Specimens Without CF Showing Increase in Peak Load and Slip at Peak Load with Increase in Stirrups Crossing Shear Plane

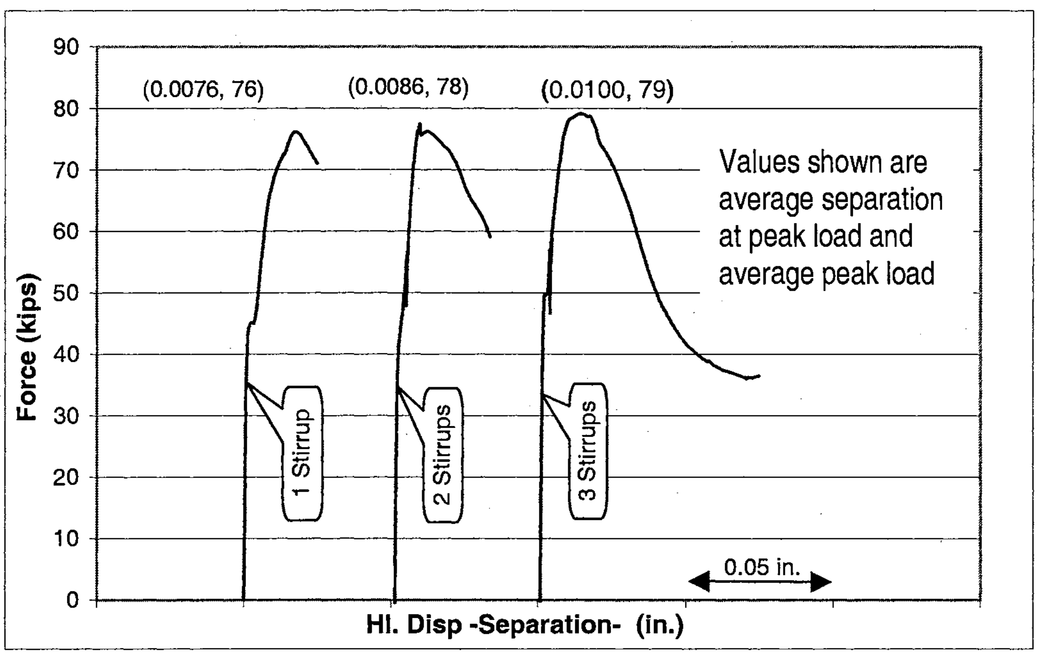

Figure 4-4. Shear-Separation Curves for Specimens Without CF Showing Increase in Peak Load and Separation at Peak Load with Increase in Stirrups Crossing Shear Plane

stirrups and aggregate interlock start resisting the shear load with the increase of slip and separation of the two halves. With the increase in separation of the two halves and concrete crushing across cracks, the aggregates interlock lost strength and specimens reached maximum load.

After reaching maximum load, the load declined rapidly with the increase in slip and separation until it reached a plateau of load corresponding to yielding of reinforcement. This plateau can be seen in the curves for more heavily reinforced specimens (3 stirrups crossing the shear plane). For specimens with lighter reinforcement (1 or 2 stirrups crossing the shear plane) the plateaus were not shown in the curves due to the increase in out-of-plane rotation of the two halves. At this stage of loading, the instruments for the LVDTs were not aligned and lost contact across the two halves of the specimens.

4.2.2 Shear Specimen with Carbon Fibers

Figures 4-5, 4-6, and 4-7 show shear-slip curves for push-off specimens with 1, 2 or 3 stirrups crossing the shear plan, respectively, for several percentages of Mitsubishi CF. Figures 4-8, 4-9 and 4-10 show shear-slip curves for push-off specimens with 1, 2 or 3 stirrups crossing the shear plane, respectively, for several percentages of Conoco CF.

Shear Strength: Figures 4-11 and 4-12 show the relationship between maximum load (in kips) and dosage percentage of Mitsubishi and Conoco CF, respectively, for 1, 2 or 3 stirrups crossing the shear plane. In general, the maximum load increased with the increase in reinforcement crossing the shear plane. Except for Mitsubishi CF at dosages of 0.75 and 1 percent, the maximum load for specimens with 2 stirrups crossing the shear plane is higher than that for specimens with 3 stirrups crossing the shear plane. Specimens with Mitsubishi CF had higher shear strength than specimens with Conoco CF for the same shear reinforcement and

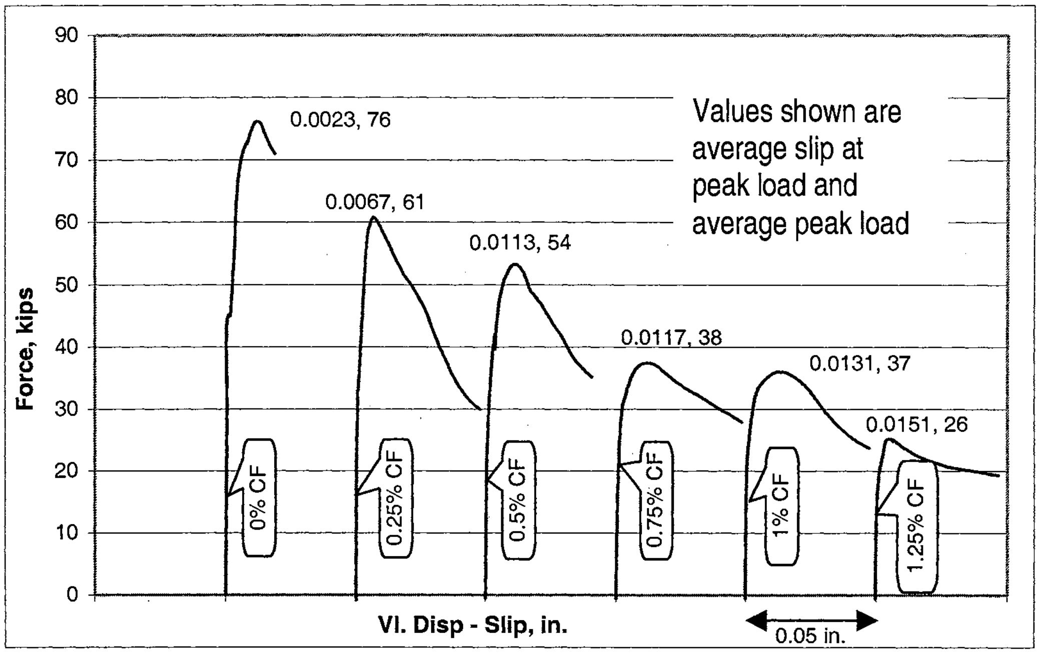

Figure 4-5. Shear-Slip Curves for Specimens With Mitsubishi CF and with One Stirrup Showing Decrease in Peak Load with Increase in CF Percentage

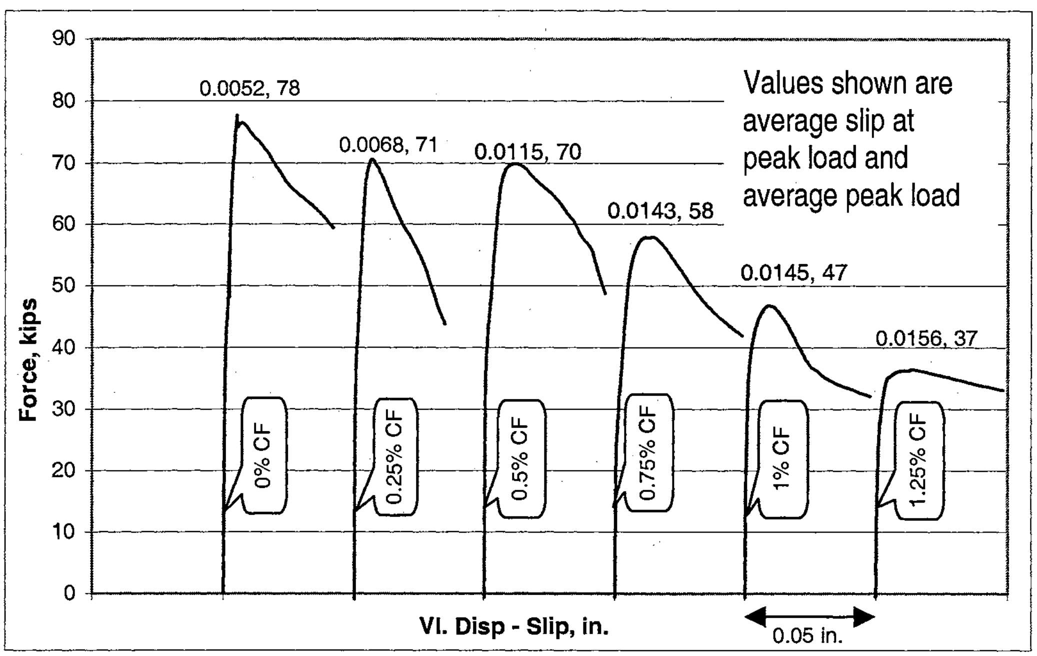

Figure 4-6. Shear-Slip Curves for Specimens With Mitsubishi CF and with Two Stirrups Showing Decrease in Peak Load with Increase in CF Percentage

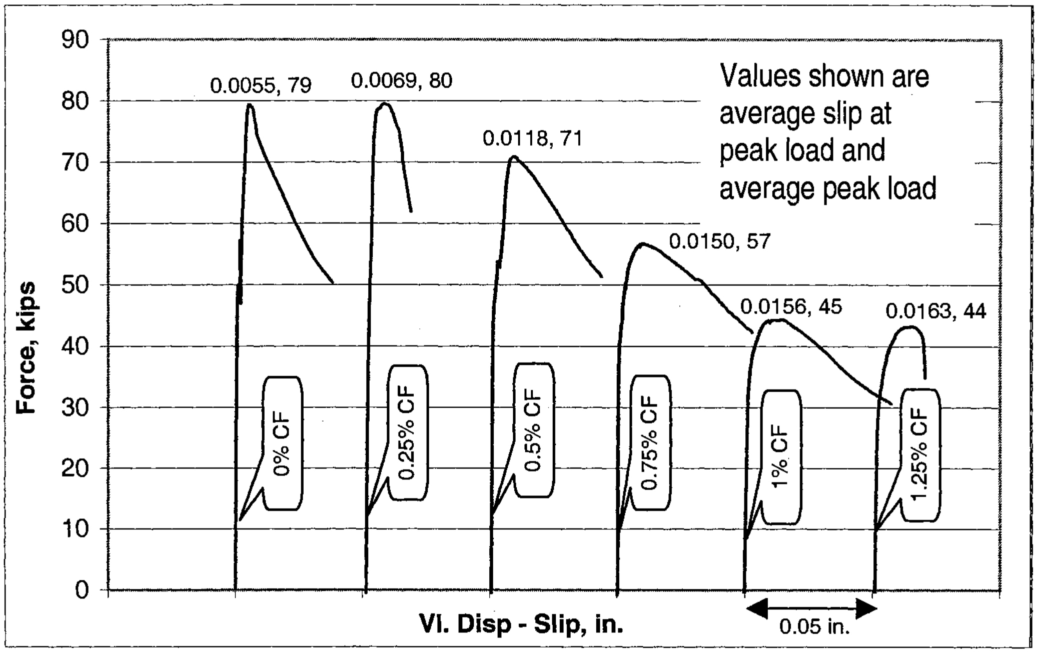

Figure 4-7. Shear-Slip Curves for Specimens With Mitsubishi CF and with Three Stirrups Showing Decrease in Peak Load with Increase in CF Percentage

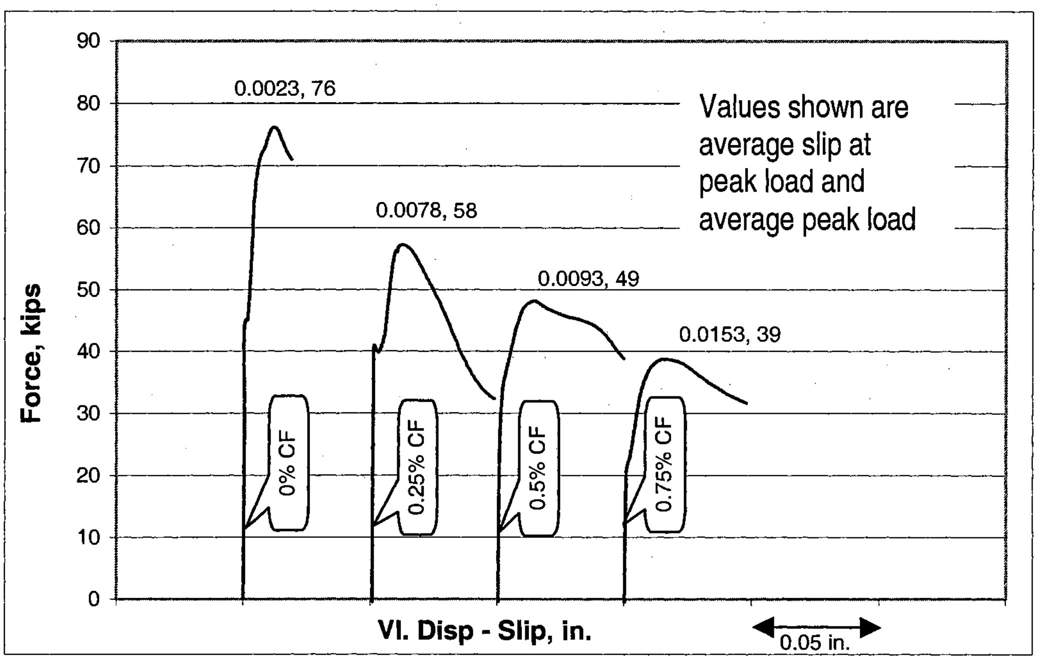

Figure 4-8. Shear-Slip Curves for Specimens With Conoco CF and with One Stirrup Showing Decrease in Peak Load with Increase in CF Percentage

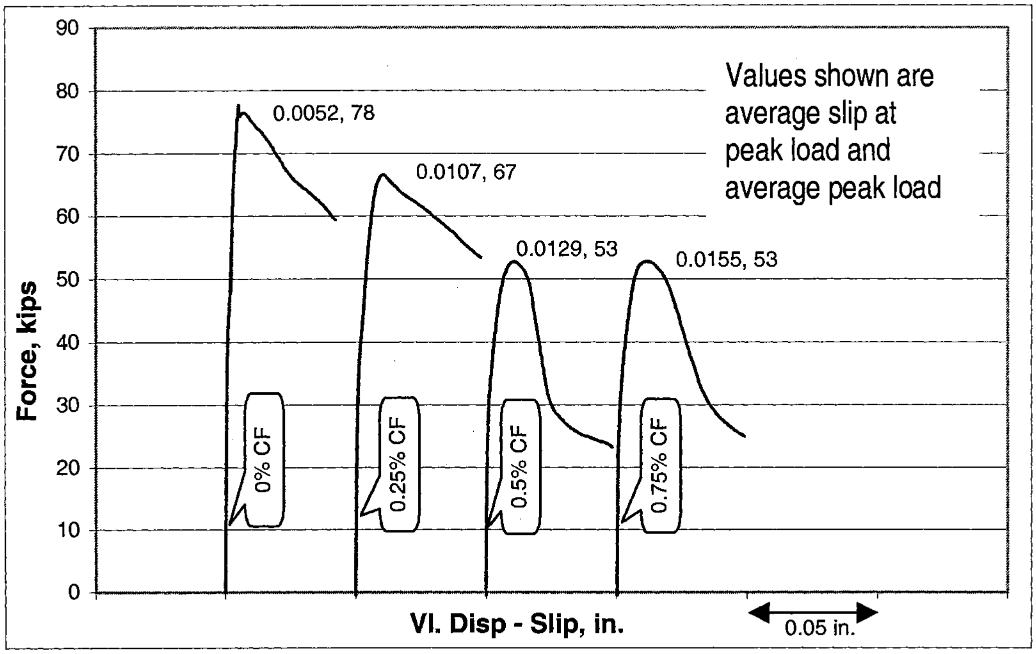

Figure 4-9. Shear-Slip Curves for Specimens With Conoco CF and with Two Stirrups Showing Decrease in Peak Load with Increase in CF Percentage

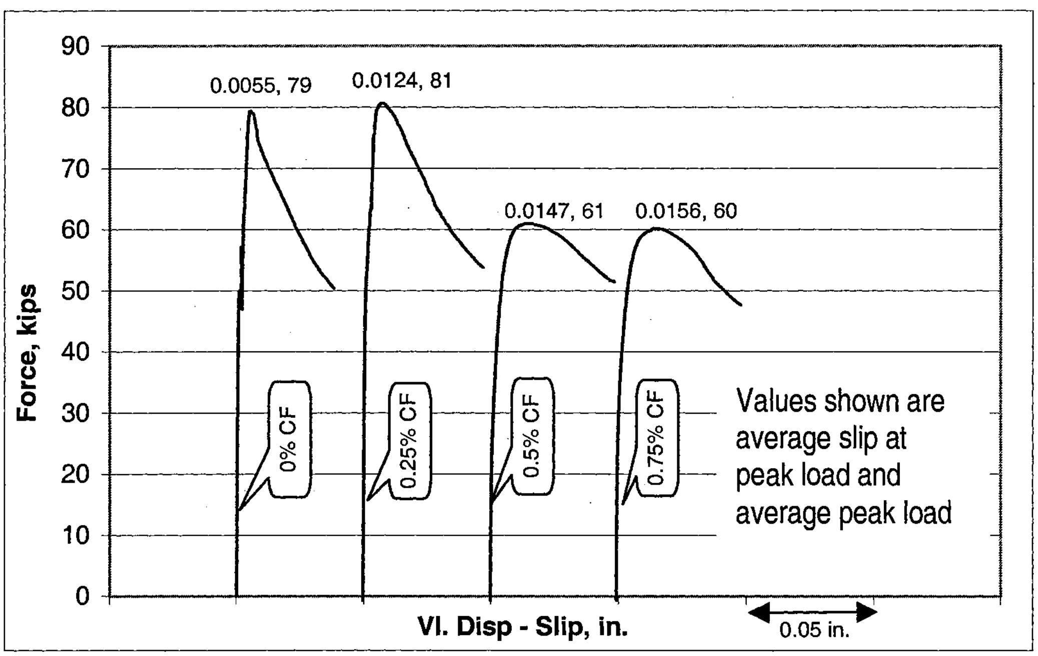

Figure 4-10. Shear-Slip Curves for Specimens With Conoco CF and with Three Stirrups Showing Decrease in Peak Load with Increase in CF Percentage

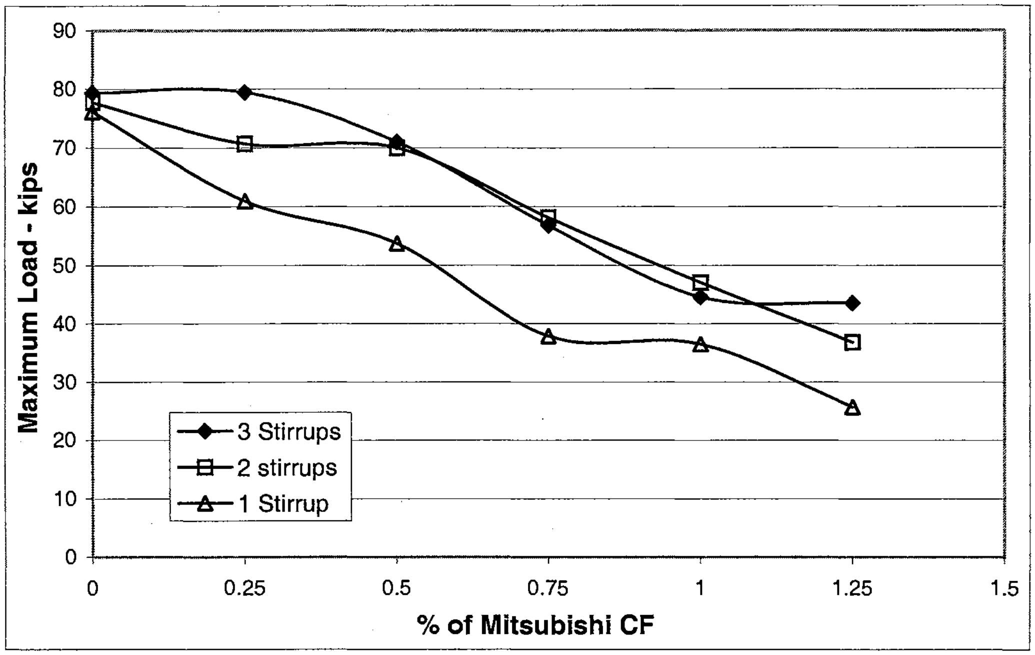

Figure 4-11. Decrease in Maximum Loads With Increase in Mitsubishi CF Dosages for 1, 2 or 3 Stirrups Crossing the Shear Plane

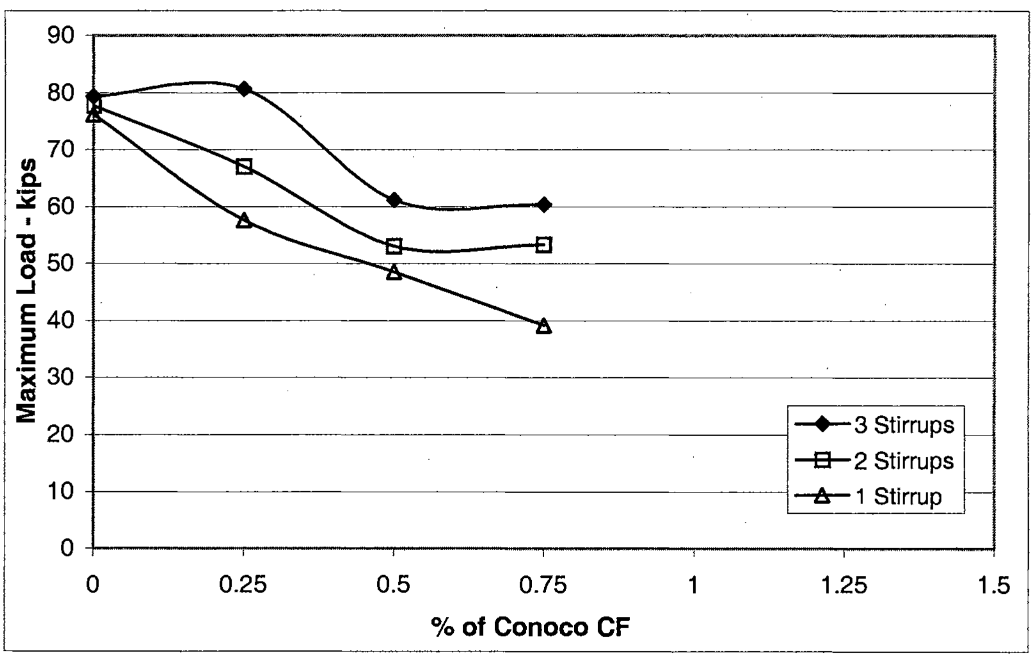

Figure 4-12. Decrease in Maximum Loads With Increase in Conoco CF Dosages for 1, 2 or 3 Stirrups Crossing the Shear Plane

percentage of CF. In Figures 4-5 to 4-12, most of the specimens with CF exhibit lower shear capacity than the corresponding control mixes (mixes with 0% CF). The shear capacity for specimens with 0.25 percent of CF (Mitsubishi or Conoco CF) and three stirrups crossing the shear plane were slightly higher than the corresponding specimens without CF. Also, the specimens shear strength decreased with the increase in CF percentage. This is true for both types of CF and for all shear reinforcement configurations (I, 2 or 3 stirrups crossing the shear plane). This result might be deceiving and lead to the impression that the presence of CF decreased the shear capacity of the specimens, but rather the specimens shear capacity decreased due to several other reasons. For example, the shear capacity decreased due to the decrease in compressive strength of concrete since shear strength is often related to compressive strength. Also, the presence of CF increased the surface area of mix components so that cement particles (binder agent) were used to cover fibers rather than providing required bonding between mix components.

If the compressive strength of the specimens can be factored out from the shear strength/CF percentage relation, the effect of CF on shear capacity can be seen. When dividing the shear strength of the specimens by the corresponding compressive strength, values in Table 4-2 are obtained. Figures 4-13 and 4-14 show the relationship between the shear strength divided by the compressive strength and the shear reinforcement ratio of the specimens. The shear reinforcement ratio (ρF_y) is defined as:

$$\rho F_y = \frac{\text{Shear reinforcement area}}{\text{Area of shear plane}} \text{ x Yield strength of shear reinforcement} \qquad (4\text{-}14)$$

The shear reinforcement ratio will depend on the number of stirrups crossing the shear plane, thus the ρF_y values are:

For one stirrups, $\rho F_y = \dfrac{0.22\,\text{in}^2}{50\,\text{in}^2}$ x 63,000 psi = 277 psi

Table 4-2

Ratio of Shear Strength to Compressive Strength for Push-Off Specimens

Specimens with Mitsubishi CF

ρF_y (psi)	CF %					
	0.0	0.25	0.5	0.75	1.0	1.25
277	0.228	0.211	0.215	0.182	0.225	0.272
554	0.232	0.245	0.280	0.279	0.291	0.389
832	0.237	0.275	0.284	0.273	0.275	0.461

Specimens with Conoco CF

ρF_y (psi)	CF %			
	0.0	0.25	0.5	0.75
277	0.228	0.211	0.284	0.339
554	0.232	0.245	0.310	0.462
832	0.237	0.295	0.358	0.523

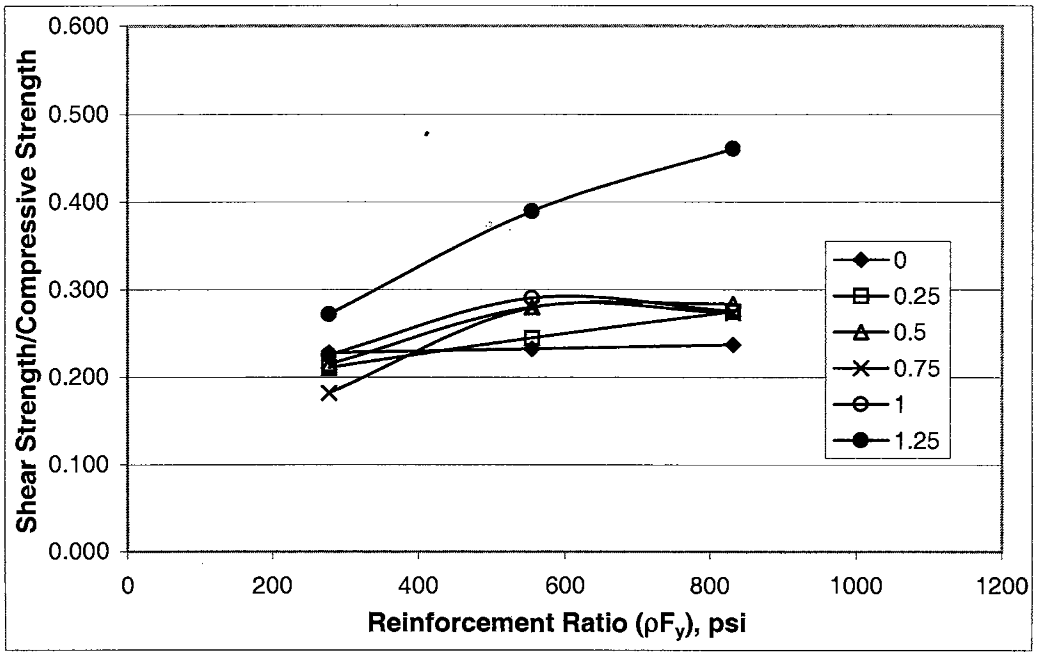

Figure 4-13. Increase in Shear Strength to Compressive Strength Ratio with Increase in Reinforcement Ratio for Specimens With Mitsubishi CF

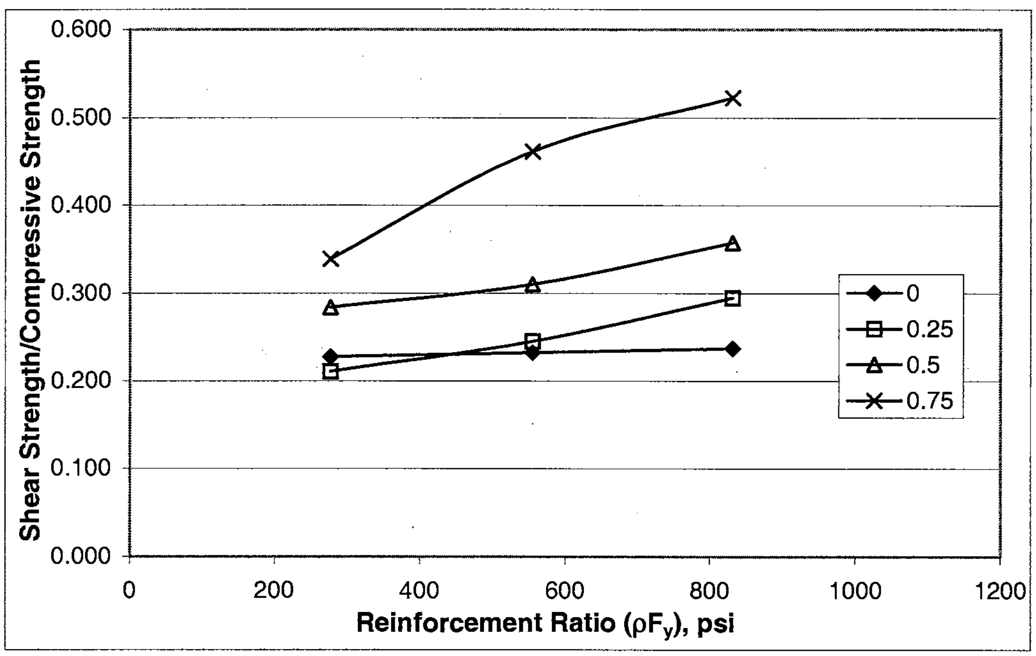

Figure 4-14. Increase in Shear Strength to Compressive Strength Ratio with Increase in reinforcement Ratio for Specimens With Conoco CF

For two stirrups, $\rho F_y = \dfrac{0.44\,in^2}{50\,in^2}$ x 63,000 psi = 554 psi

For three stirrups, $\rho F_y = \dfrac{0.66\,in^2}{50\,in^2}$ x 63,000 psi = 832 psi

In Figure 4-13, the ratios of shear strength to compressive strength for specimens with Mitsubishi CF were similar to that of a control mix at lower shear reinforcement ratio and were slightly higher at higher values of shear reinforcement. The ratios for CF dosage of 1.25 percent were significantly higher than ratios for other dosages due to the much lower compressive strength for specimens with 1.25 percent CF. In Figure 4-14 Specimens with Conoco CF showed higher ratios of shear strength to compressive strength than those of specimens with Mitsubishi CF.

Shear Slip at Failure: Figures 4-15 and 4-16 show the relationship between slip at maximum load and dosage of Mitsubishi and Conoco CF, respectively, for 1, 2 or 3 stirrups crossing the shear plane. For the same percentage of CF, the value of slip at failure increased with the increase in shear reinforcement crossing the shear plan. As load increased the reinforcement crossing the shear plane stretched allowing the formation of more cracks before reaching the specimen capacity in shear. For the same amount of shear reinforcement crossing the shear plane, the value of slip at failure increased with the increase of CF percentage. The CF presence in the specimens provided similar behavior as shear reinforcement by bridging over the cracks allowing the shear load to distribute over larger area of concrete and increasing the aggregate interlock capacity.

Shear Separation at Failure: similar behavior was observed for shear slip as was observed for separation across the shear plane. Also as observed for specimen without CF, the value of separation was higher than the value of slippage for all percentage of CF. Figures 4-17 and 4-18 show the relationship between separation at maximum load and the dosages of Mitsubishi and

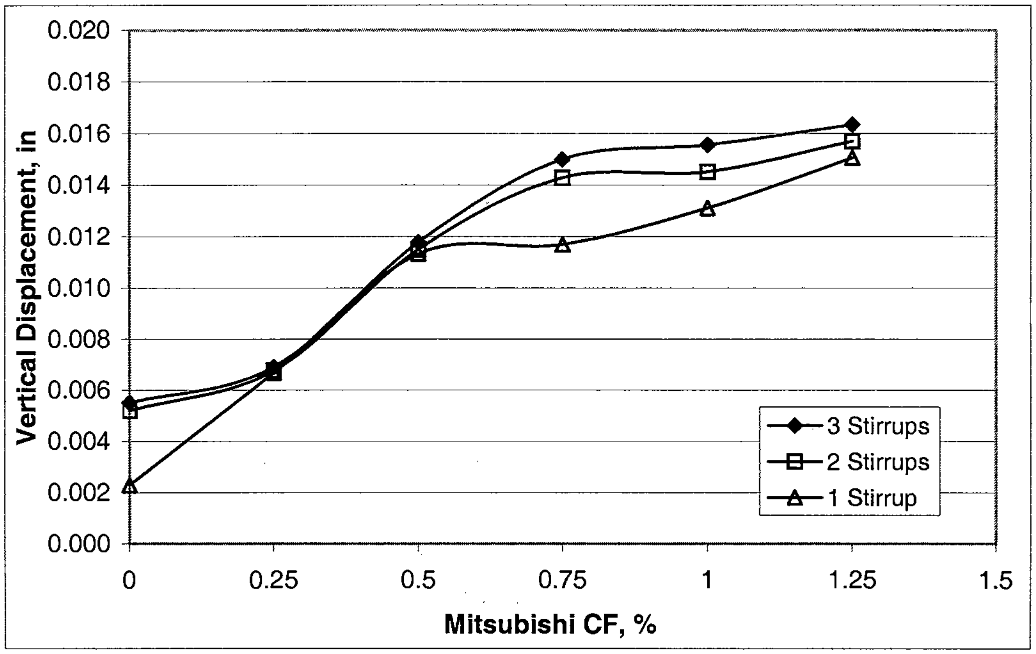

Figure 4-15. Increase in Slip at Maximum Loads with Increase in Dosage of Mitsubishi CF for 1, 2 or 3 Stirrups Crossing the Shear Plane

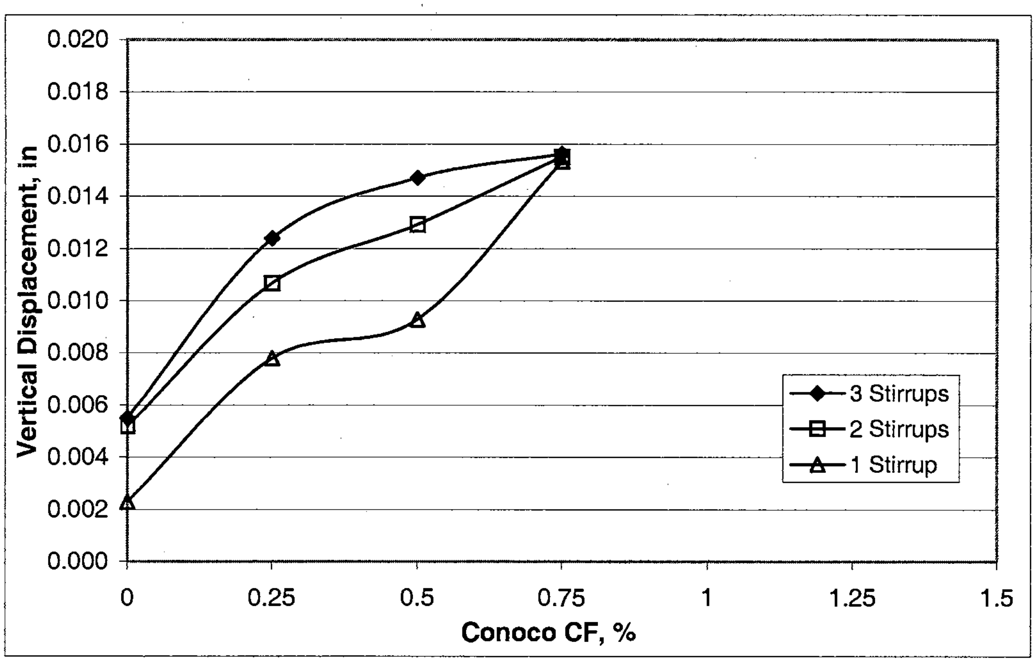

Figure 4-16. Increase in Slip at Maximum Loads with Increase in Dosage of Conoco CF for 1, 2 or 3 Stirrups Crossing the Shear Plane

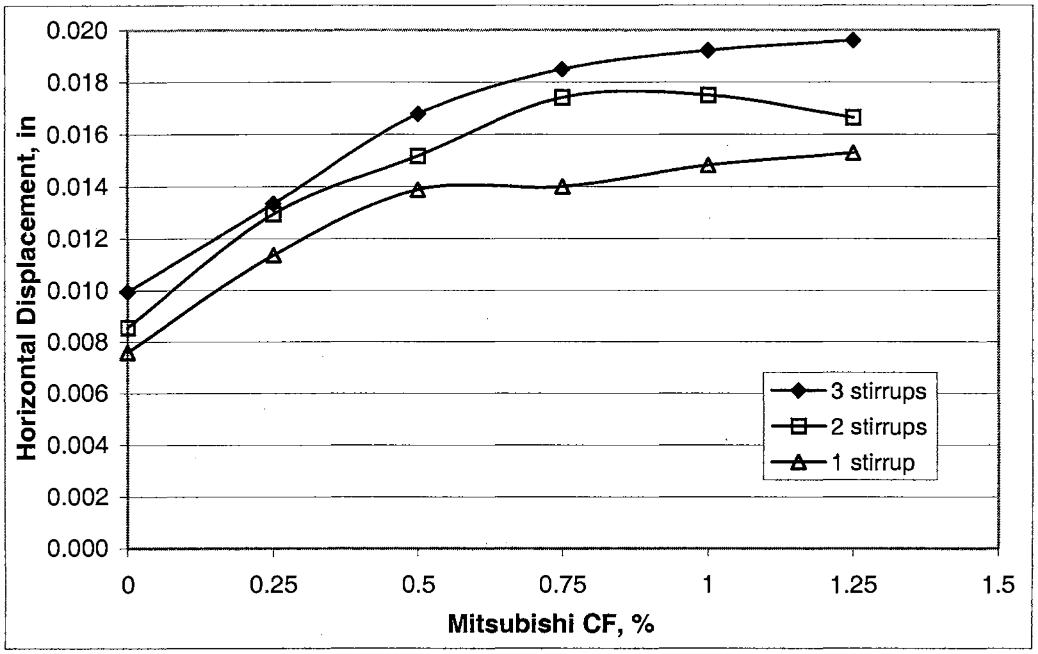

Figure 4-17. Increase in Separation at Maximum Load with Increase in Dosage of Mitsubishi CF for 1, 2 or 3 Stirrups Crossing The Shear Plane

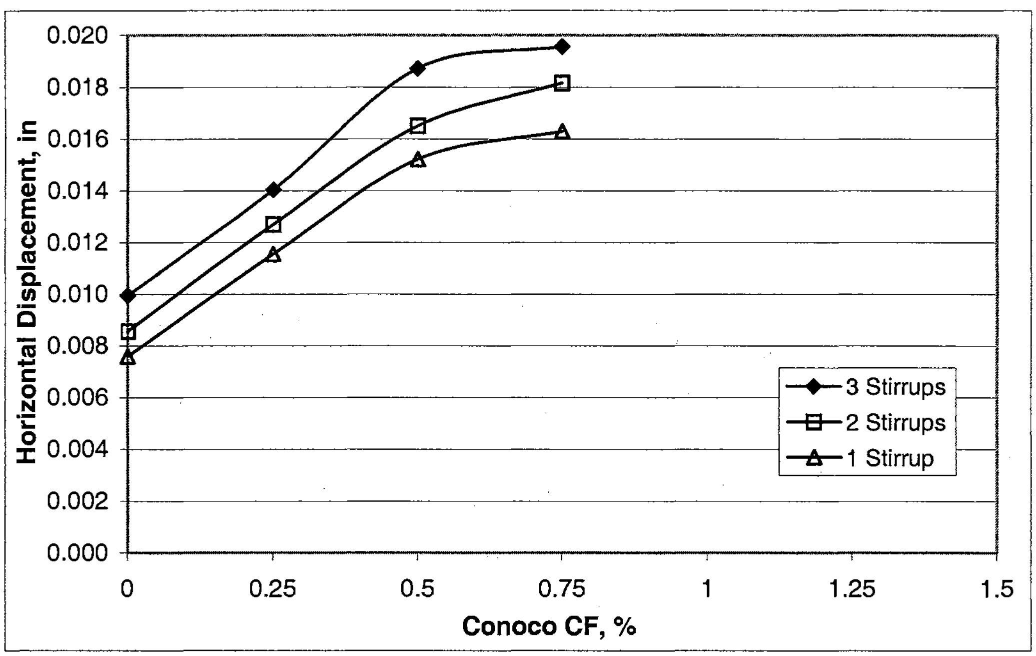

Figure 4-18. Increase in Separation at Maximum Load with Increase in Dosage of Conoco CF for 1, 2 or 3 Stirrups Crossing The Shear Plane

Conoco CF, respectively, for 1, 2 or 3 stirrups crossing the shear plane. For the same percentage of CF, separations across shear plane for specimens with Conoco CF were higher than that for specimens with Mitsubishi CF.

<u>Post Failure Behavior:</u> Specimens with CF exhibit gradual decrease in shear capacity with increase in slip or separation after reaching the maximum shear load as opposed to sudden decline in shear-slip and shear-separation curves for observed for specimens without CF. The post failure behavior was mostly observed in specimens with higher percentage of CF. This result can also be seen from Figures 4-11 and 4-12 as the curves became more flat with increase in CF dosage. This was due to the bridging of individual fibers over the cracks and acted as many small reinforcements in the specimens. The amount of shear reinforcement crossing the shear plane did not appear to have an effect on the post failure behavior of the specimens.

<u>Ultimate Shear Transfer Strength:</u> The values for ultimate shear transfer strength, V_u, and shear reinforcement ratio, ρF_y, are shown in Table 4-3 for several dosages of Mitsubishi and Conoco CF. The ultimate shear transfer strength is expressed as a nominal ultimate shear stress:

$$V_u = \frac{\text{Maximum shear}}{\text{Area of shear plane}} \tag{4-15}$$

Figures 4-19 and 4-20 show the relation between ultimate shear strength and shear reinforcement ratio for several dosages of Mitsubishi and Conoco CF, respectively.

For Mitsubishi CF, Figure 4-19, the ultimate shear strength increased as the shear reinforcement ratio increased for 0 percent and 0.25 percent dosages of CF. For a higher dosage of CF, the shear strength increased to a value of 528 psi of shear reinforcement ratio (2 stirrups crossing the shear plane) and decreased thereafter (3 stirrups crossing the shear plane). The decrease in shear strength was higher at higher dosages of CF. The ultimate shear strength decreased as the CF dosage increased.

Table 4-3

Average Ultimate Shear Strength for Push-Off Specimens

Ultimate Shear strength in psi for Mitsubishi CF Specimens:

Number of Stirrups	ρF_y (psi)	CF%					
		0	0.25	0.5	0.75	1.0	1.25
1	277	1520	1220	1070	760	730	510
2	554	1550	1410	1400	1160	940	740
3	832	1590	1590	1420	1140	890	870

Ultimate Shear strength in psi for Conoco CF Specimens:

Number of Stirrups	ρF_y (psi)	CF%			
		0	0.25	0.5	0.75
1	277	1520	1150	970	780
2	554	1550	1340	1060	1070
3	832	1590	1610	1220	1210

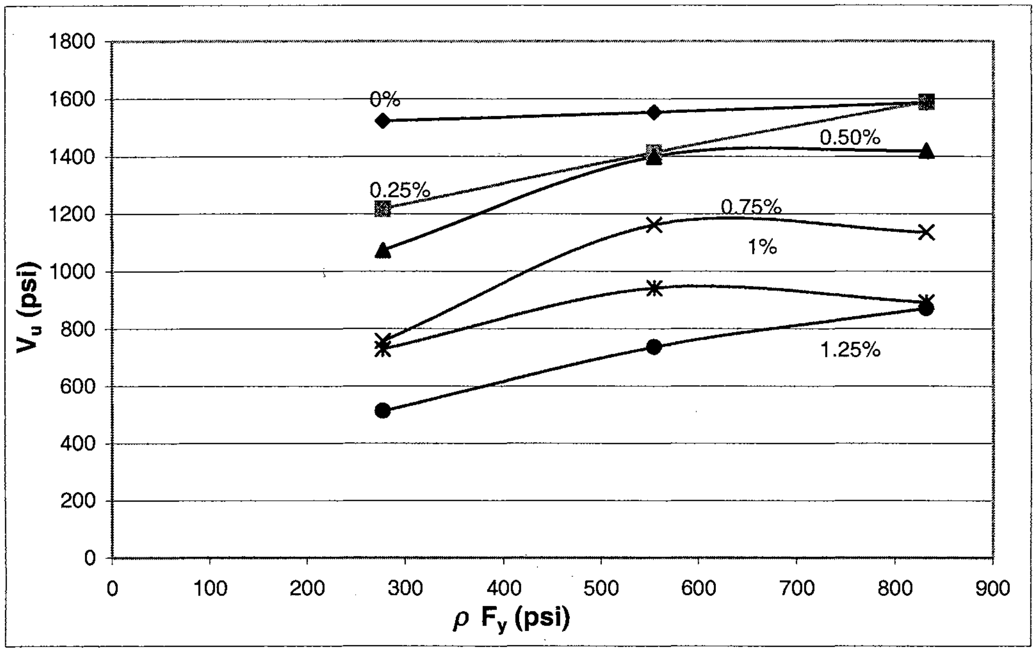

Figure 4-19. Ultimate Shear Stress With Shear Reinforcement Parameters for Specimens With Mitsubishi CF.

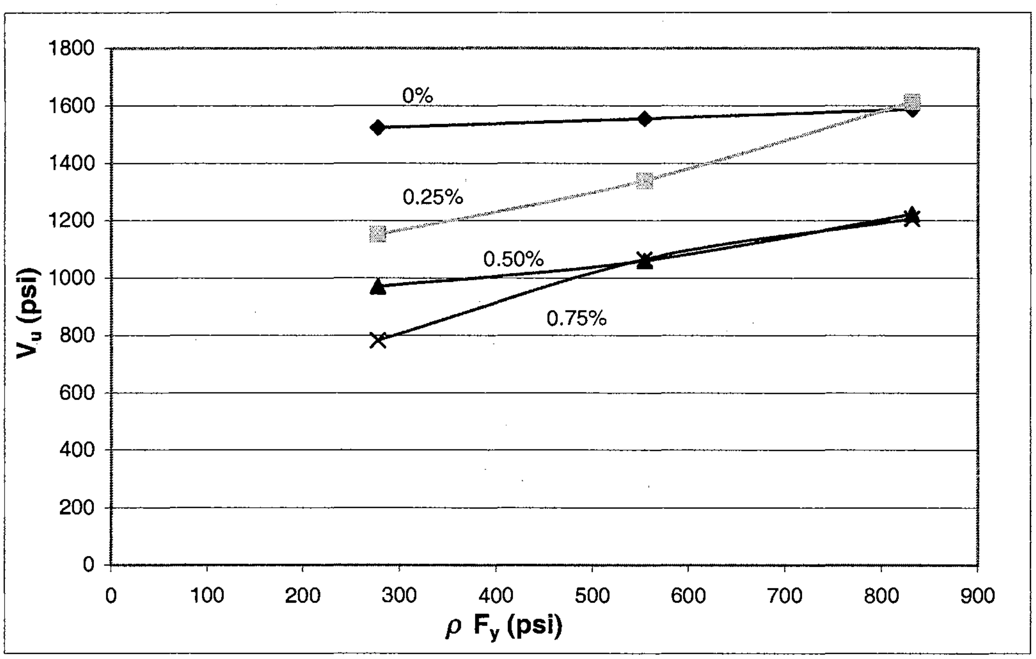

Figure 4-20. Ultimate Shear Stress With Shear Reinforcement Parameters for Specimens With Conoco CF.

For Conoco CF, Figure 4-20, ultimate shear strength increased as the shear reinforcement ratio increased for all percentages of CF. Also, ultimate shear strength decreased as the CF dosage increased.

CHAPTER V

SUMMARY AND CONCLUSIONS

5.1 Summary

The research investigated mechanical and structural properties of carbon fiber reinforced sand-lightweight concrete. The mechanical properties include compressive strength, splitting tensile strength, modulus of rupture and modulus of elasticity. The structural property investigated was the direct shear transfer capacity of push-off type specimens. Several volumetric percentages of CF manufactured by Mitsubishi and Conoco were used in the investigation. Eighty-three push-off specimens were used to study direct shear transfer of CF reinforced concrete. Steel reinforcement in the form of one, two or three closed stirrups crossing the shear plane of the push-off specimens was used. All CF reinforced concrete has approximately the same slump. Information obtained during earlier stages of this research project and are presented in Appendices A, B and C.

5.2 Findings and Conclusions

The presence of CF in the concrete mix increased the total surface area of the mix components for the cement particles to cover and provide the required adhesion in concrete. Also, the presence of CF decreased the concrete workability. To counteract this trend the water/cement ratio was increased as the CF dosage increased. The increase in surface area and water/cement ratio of the mix reduced the compressive strength of concrete, which in turn affected other mechanical properties of the concrete that are related to the compressive strength.

On the other hand, the presence of fibers in the concrete acted as individual reinforcement bridging over cracks and improved the tensile characteristics of concrete. For design, the concrete splitting tensile strength, modulus of rupture, and modulus of elasticity are often assumed proportional to the square root of the compressive strength of concrete. The constants of proportionalities were determined by experimental data. The modulus of elasticity for concrete with CF can be determined using ACI building code section 8.5.1 using the equation:

$$E_c = 33\,(w^{1.5})\,\sqrt{f_c'} \tag{5-1}$$

For design purposes, the splitting tensile strength and modulus of rupture for CF concrete can still be assumed proportional to the square root of compressive strength, but the constants of proportionalities can be assumed linearly related to the CF volumetric percentage, V_f. The suggested design equations for sand-lightweight specimens with Mitsubishi CF are:

$$f_{ct} = (5.7 + 0.6\,V_f)\,\sqrt{f_c'} \tag{5-2}$$

$$f_r = (\,6.4 + 4.3\,V_f)\,\sqrt{f_c'} \tag{5-3}$$

The suggested design equations for sand-lightweight concrete specimens with Conoco CF are:

$$f_{ct} = (5.7 + 2.2\,V_f)\,\sqrt{f_c'} \tag{5-4}$$

$$f_r = (\,6.4 + 2.4\,V_f)\,\sqrt{f_c'} \tag{5-5}$$

Concrete specimens made with Mitsubishi CF had better performance than specimens made with Conoco CF. Specimens with Mitsubishi CF had higher Compressive strength, splitting tensile strength, modulus of rupture and modulus of elasticity. Conoco CF uses smaller quantities of the sizing material, polyvinyl alcohol (PVA), and thus has lower bulk density than Mitsubishi CF. This decreased the bulk density of the Conoco CF concrete specimens and decreased the mechanical properties.

The shear transfer capacity in the push-off specimens decreased as the percentage of Mitsubishi or Conoco CF in concrete increased. The decrease in shear capacity was not directly related to CF presence in concrete but occurred as a result of the decrease in compressive strength and the increase in total surface area of concrete components. The ratio between shear strength and compressive strength of specimens increased as CF percentage in the concrete increased. Also, the shear transfer capacity increased as the reinforcement area crossing the shear plane increased.

Vertical and horizontal displacements at peak load for push-off specimens increased as the CF percentage in the concrete increased. The CF presence in the specimens provided similar behavior as shear reinforcement by bridging over the cracks allowing the shear load to distribute over larger area of concrete and increasing the aggregate interlock capacity. As the percentage of CF increased, and compressive strength decreased, specimens exhibited an increase in vertical and horizontal displacements at peak load, and the shape of the shear-slip and shear-separation curves after reaching peak load become flatter. The number of shear cracks increased and the crack widths decreased as the CF percentage increased.

5.3 Future Research Needed and Recommendations

Investigations are required to study the effect of CF length, diameter, strength, efficiency and orientation in the specimens on the mechanical and structural properties of CFRC. Those factors greatly affect the fiber performance in concrete such as the ability to bridge over cracks without reaching fracture load and tensile force transfer through bond between fibers and concrete components. Also, crack width measurement needs to be investigated for several CF percentages.

This research needs to be repeated keeping the compressive strength almost equal for all specimens with different CF percentages. Several trial batches need to be tried to achieve a mix design with pre-specified compressive strength for every CF percentage. Some of the suggested methods of changing mix design are increasing the cement content in concrete and/or adding admixtures to the mix (for example, fly ash, silica fume, Methyl-Cellulose, and metakaoline). Research to study the effect of adding CF on the shear capacity of normal weight and all-lightweight concrete is needed.

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APPENDIXES

APPENDIX A

Initial Investigation of CFRC Usage

A.1 Purpose and Scope

The main goals of this initial study were to achieve adequate dispersion of CF throughout mortar and concrete mixes and investigate several types and dosages of additives that help fiber dispersion and easily incorporated into mortar and concrete CF mixes. To achieve those goals, the scope of this phase was divided into three sections.

Effect of various aqueous solutions on fiber dispersion

Incorporation CF in mortar mixes

Incorporation CF in concrete mixes

A.2 Materials

The materials used in this phase were:

Cement: type I portland cement was used in this phase.

Carbon fibers: Mitsubishi CF was used in this phase.

Aggregates: Sand was obtained locally for this research and had a fineness modulus of 2.77, specific gravity of 2.62, and absorption of 0.4%. Coarse aggregate was ASTM C33 size No. 8 crushed limestone with a specific gravity of 2.67. Aggregate gradation is presented in Table A-1.

Methyl-cellulose: As an admixture to cement, methyl-cellulose serves to increase the bond strength between cement and steel and, in the case of cement with CF, it also serves to help disperse the fibers in the mix [1]. On the other hand, the addition of methyl-cellulose to cement decreases the thermal stability and the apparent coefficient of thermal expansion [88]. The methyl-cellulose used was K15M from Dow Chemical, Midland, MI.

Metakaoline: The project sponsors suggested this new additive to be used in this phase. Metakaolin is obtained by calcination of kaolinitic clay at a temperature between 650 and 850°C. It is ground to a fineness of 700 to 900 m2/kg and exhibits high pozzolanicity. Metakaolin, which is sometimes used as a finishing agent in the concrete, was used both as a pozzolan and to study its effect on CF dispersion in the mixes.

Defoamer: This additive decreases the amount of entrapped air in concrete specimens. Defoamer used was Colloid 770DD or Colloid 775DD from Rhône-Poulenc Inc.

Superplasticizer: Table A-2 shows the different types of superplasticizer used in the research with the manufacturer's maximum recommended dosage for each one.

A.3 Water Solution

A series of simple tests involving several types and temperatures of water mixtures were conducted to determine a simple and effective method to separate Mitsubishi chips into individual fibers. The following types of water mixtures were used in these tests:

Tap water

Distilled water

Table A-1

Aggregate Gradation Used at OSU

Screen	Individual % Retained	Accumulated % Retained	Individual. % Passing	ASTM C-33 Passing
Sand				
No. 4	2.42	2.42	97.58	95 to 100
No. 8	10.44	12.86	87.14	80 to 100
No. 16	17.44	30.30	69.70	50 to 85
No. 30	20.18	50.48	49.52	25 to 60
No. 50	32.18	82.67	17.33	5 to 30
No. 100	16.01	98.67	1.33	0 to 10
Pan	1.33			
Fineness Modulus	2.77			
Coarse Aggregate				
3/8"	1.06	1.06	98.94	85 to 100
No. 4	67.31	68.37	31.63	10 to 30
No. 8	29.36	97.73	2.27	0 to 10
No. 16	0.90	98.63	1.37	0 to 5
No. 30	0	100	0	0 to 3
No. 50	0	100	0	0 to 2
Pan	1.37			
Fineness Modulus	5.64			

Table A-2

Types and Recommended Dosages for Superplasticizers

Manufacturer	Product Name	Type	Manufacturer Recommended Dosage*
W. R. Grace	Daracem 100	SNF	3.25-13.0
W. R. Grace	Melment 330	SMF	3.75-16.0
W. R. Grace	Daracem ML500	SMF	3.75-16.0
Master Builders	Rheobuild 1000	SNF	6.50-16.0
Master Builders	Pozzolith 400N	SMF	2.00–6.0

*Ml/kg of cement.

Lime saturated water

Tap water with various percentages of methyl-cellulose K15M

Tap water with various percentages of Grace-Daracem 100 (superplasticizer)

Tap water with combinations of K15M and Daracem 100.

The effect of water temperature on fiber dispersion was studied for tap water only. Observations were recorded for liquid temperatures of 20, 30, 50, 70 and 90°C. Methyl-cellulose/water and fiber/water ratios were also based on previous research [1, 2, 3]. Methyl-cellulose/water ratios used were 0.25, 0.375, 0.5 and 0.625%.

The test procedure involved dispersing an amount of fiber, in wafer form, using a 5-qt Hobart mixer. Two grams of Mitsubishi fibers in wafer form were mixed for 2 min with 800 ml of water. Visual observations were made on the breakdown of wafers into individual fibers. After the initial mixing period and visual examination, the fiber/water mixture was stirred occasionally and examined Normally this was continued for about 20 min, but in some cases the mixture was examined several hours after mixing.

<u>Results of Water Mixture Tests:</u>

There was no correlation between degree of fiber separation and type of water mixture. In various water mixtures, approximately 20% of the fibers appeared to remain in the original chip or wafer form—undispersed. There was little improvement in fiber dispersion after 5 min. It was also observed that liquid temperature did not have a noticeable effect on wafer breakdown at this level of agitation.

Of the various water mixtures, the best dispersion was obtained using distilled water and 0.5% methyl-cellulose K15M by water weight. This methyl-cellulose/water ratio was later used in mortar mixes. Viscosity of this water mixture, which was slightly greater than tap water, allowed CF to remain in suspension. It was observed that when methyl-cellulose exceeded 0.5% by water weight, liquid viscosity had an adverse effect on fiber dispersion.

In conclusion, when Mitsubishi CF are used in mortar and concrete, the standard mix water will permit breakdown of the wafer; no special pretreatment with a special water solution is needed. Results indicate that approximately 0.5% methyl-cellulose K15M by weight of water promotes dispersion of CF in cement and water.

A.4 Mortar Mixes

Small-size batches

In this phase of the project, Mitsubishi CF was incorporated into mortar to investigate a number of variables. Initial work involved small batches made with a 5-qt Hobart mixer. Each mortar batch yielded a single 4 x 8-in. cylinder that was compacted in 3 lifts using a vibrating table. Batches were standardized to maintain a cement-to-sand ratio of 1:2 and a water-to-cement ratio of 0.4. Superplasticizer (Daracem 100) was used in this phase. Mix variables were:

Fiber content	0.2, 0.5 or 1% by total volume of the mix
Superplasticizer	10 or 15 ml/kg of cement.
Methyl-cellulose	0.0, 0.2, 0.4 or 0.6% by weight of cement.
Dry mixing duration	1, 1.5 or 2 min
Wet mixing duration	4, 6 or 8 min

After a 7-day curing period (23°C, 100% R.H.), cylinders were tested in compression according to ASTM Method C39, Standard Test Method for Compressive Strength of Cylindrical

Concrete Specimens. The failure surfaces of the cylinders were examined visually to determine the degree of fiber dispersion and individual fiber length breakage.

The following results were observed for small mortar batches:

Fiber dispersion: No fibers remained in wafer form after mixing. The aggressive agitation action of the Hobart mixer resulted in the breakdown of fiber chips into individual fibers and significant fiber breakage with all mixes.

Effect of fiber content: Increasing fiber content from 0.2 to 1% by total volume resulted in increasingly stiffer mixes. There was also an increase in compressive strength from 2.4 to 3.7 ksi with increasing fiber content.

Effect of superplasticizer: Superplasticizer was added to the mortar mix to determine if superplasticizer had an effect on fiber dispersion. As the amount of superplasticizer was increased, the mortar became more workable which had a positive influence on fiber dispersion.

Influence of methyl-cellulose: While methyl-cellulose improved fiber dispersion, it increased mix viscosity and entrapped air in the mix, which lowered compressive strength. The optimum methyl-cellulose dosage was approximately 0.2 to 0.3% by weight of cement. At a lower dosage, there was insignificant improvement in fiber dispersion; at a higher dosage, there was less workability and excessive entrapped air. Early tests indicated that adding methyl-cellulose to the mix in a dry powdered form was as effective as predissolving the admixture in water (which was recommended by the manufacturer); the admixture was subsequently mixed in the powdered form.

Effect of dry and wet mixing duration: The duration of dry mixing had little influence on fiber dispersion, but increasing the duration of wet mixing had a positive effect on fiber dispersion. Although longer mixing times appeared to be responsible for more fiber breakage, this conclusion was not verified using detailed tests. Table A-3 summarizes all results for small-size batches.

Table A-3

Summary of Results for Small-Size Mortar Batches

General Mix Characteristics: Cement/Sand = 1:2; Water/cement = 0.4; Super plasticizer type: Daracem 100 from Grace												
		Methocel		Mixing Duration		Fresh Mix Properties			Hardened Mortar Properties			
Fiber Content	Superplasticizer ml/kg cmt	Dosage %wt cmt	Mixing Method	Dry min	Wet min	Fiber Dispersion	Workability	Finishing	Settling Time	Weight lb/ft^3	Compressive Strength (psi)	Fiber Dispersion
0.2	10	0.2	wet	1	4	good	good	good	normal	121	2690	good
0.2	10	0.2	wet	1.4	4	good	good	good	normal	118	2280	good
1	10	0.2	wet	1	4	good	stiff	good	normal	124	3920	good
1	10	0.2	wet	1	4	good	stiff	good	normal	122	3360	good
1	10	0.2	wet	1	4	good	stiff	good	normal	125	3630	good
0.5	10	0.2	wet	2	4	good	average	good	normal	124	3220	good
0.5	10	0.2	wet	1	4	good	average	good	normal	123	3880	good
0.5	10	0.2	wet	1	4	good	average	good	normal	124	3690	good
1	10	0	-	1.4	4	poor	watery	good	normal	137	4720	fair
1	10	0	-	1	4	poor	watery	good	normal	137	4790	fair
1	15	0	-	1	4	poor	v. watery	average	normal	135	4720	fair
1	15	0	-	1	4	poor	v. watery	average	normal	134	4960	fair
1	10	0.2	dry	1	4	good	good	good	normal	123	3970	ave
1	10	0.2	dry	1	4	good	average	good	normal	123	3880	good
1	10	0.4	dry	1	4	good	stiff	good	normal	120	3470	good
1	10	0.4	dry	1	4	good	stiff	good	normal	119	3370	good
1	10	0.6	dry	1	4	v.good	v. stiff	good	normal	113	2750	good
1	10	0.6	dry	1	4	v.good	v. stiff	good	normal	114	2750	good
1	10	0.2	dry	1	6	good	good	good	normal	121	3670	v.good
1	10	0.2	dry	1	6	good	good	good	normal	121	3680	v.good
1	10	0.2	dry	1	8	v.good	good	good	normal	122	3880	v.good
1	10	0.2	dry	1	8	v.good	good	good	normal	121	3830	v.good
1	15	0.4	dry	1	4	good	sticky	good	normal	118	3220	good
1	15	0.4	dry	1	4	good	sticky	good	normal	117	3110	good

Medium-size batches

After completing tests using the Hobart mixer, the batch size was increased to prepare several specimens for a drum mixer. A tilting drum-style concrete mixer with a capacity of 3 ft^3 was used to prepare the mortar. The same materials used in the Hobart mixer were also used in this phase. Additional admixtures and mix procedures are described below. All batches maintained the following characteristics: cement-to-sand ratio of 1:2, water-to-cement ratio of 0.47, and dry mix duration of 1 min.

Other mix variables and their range and/or type were: fiber content (0 or 1% by volume of mix); methyl-cellulose (0, 0.2 or 0.4% by weight of cement); defoamer (0 or 0.1% by weight of cement); and wet mixing duration (12 or 24 min). Four types of superplasticizer were used: Daracem 100, Melment 330, Rheobuild 1000 and Pozzolith 400N. The manufacturers' maximum recommended dosages for all types of superplasticizer were used.

Control cylinders were made using 4 x 8-in. plastic molds. Initially, prisms were cast using 3 x 4 x 16 in. steel molds. ASTM Method C1018, Standard Test Method for Flexural Toughness and First Crack Strength of Fiber-Reinforced Concrete, endorses 4 x 4 x 14-in. specimens. Wooden molds were soon constructed for this specimen size and used during the remainder of the research.

Six cylinders and three beam specimens were prepared from each batch. A laboratory-vibrating table was used to consolidate the cylinder and beam specimens. Test specimens were removed from molds after 1 day and cured in a moist room for an additional 6 days. At 7 days, compressive strength, splitting tensile strength, and flexural strength of the mortar were determined in accordance with ASTM Methods C39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, C496 Standard Test Method for Splitting Tensile Strength of

Cylindrical Concrete Specimens, and C78 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam With Third-Point Loading), respectively. Project personnel visually rated fiber dispersion on failure surfaces of the test specimens. Good fiber dispersion was considered to be the absence of fibers in wafer form. The following results were obtained:

General observations: The agitation action of the drum mixer was less aggressive than the Hobart mixer and there was slight fiber breakage. However, some fibers remained in wafer form and were easily seen in the fresh concrete and on the formed and fracture surfaces of specimens. Low power magnification was required to identify individual fibers in the fresh and hardened concrete.

Effect of fiber content on strength: Mortar mixes containing 1% fiber by volume had lower compressive strength (approximately 5 to 10%) and higher tensile strength (approximately 20%) than mixes without fibers. The specimens with fibers were approximately 15 to 35 pcf lighter than specimens without fibers. It is believed the presence of voids in the fiber-reinforced mortar is responsible for the observed loss in compressive strength and lower density.

Effect of superplasticizer: Superplasticizer increased the fluidity of a cement paste, and seemed to indirectly improve carbon fiber dispersion by improving workability of the mortar. Four types of superplasticizer were used; Melment 330 from Grace gave the best fiber dispersion and improvement in tensile and flexural strength.

Effect of methyl-cellulose dosage: Results using Hobart and drum mixers were the same; the optimum amount of methyl-cellulose is approximately 0.2 to 0.3% by cement weight. However, any quantity of methyl-cellulose stiffened the wet mix considerably, decreased workability, and increased the amount of air entrapped in the mortar which lowered compressive strength of the cylinders.

Effect of defoamer: The defoamer increased the density of the mortar, thus increasing compressive, tensile, and flexural strengths.

Effect of method of adding the defoamer: Adding the defoamer after 6 min of wet mixing gave better results by achieving good fiber dispersion and less air entrapped in the mix.

Effect of wet mixing duration: Visual observations for fiber dispersion were made during the first 10 min of wet mixing for each mix. In general, fiber dispersion improved by increasing wet mixing duration. However, the rate of improvement was minor for wet mixing duration more than 6 min.

Methyl-cellulose and superplasticizer contributed to improved dispersion of the fibers but tended to cause entrapment of air as evidenced by reduced densities and compressive strength. As mentioned above, use of a defoamer helped to increase mortar density and strength. Test personnel concluded that fiber dispersion was a self-limiting process. As more fibers became dispersed in the paste, the workability of the paste was reduced which restricted additional fiber dispersion. Table A-4 summarizes all results for medium-size mortar batches.

A.5 Concrete Mixes

The drum mixer used for mortar batches was also used to prepare concrete batches. Only one type of superplasticizer was used for concrete batches—Melment 330. Several ratios of cement-to-sand-to-coarse aggregate were used. Benchmark mixes with 0% fiber content were prepared for each aggregate ratio. The fiber content was fixed at 1% by total volume for all but the benchmark batches. The dry and wet mixing durations were 1 and 12 min, respectively, for all mixes. Mix variables and their dosages were:

Water/Cement ratio: 0.45, 0.47, 0.48, 0.5 or 0.6

Superplasticizer: 4, 8 or 16 ml/kg of cement

Table A-4

Summary of Results for Medium-Size Mortar Batches

General Mix Characteristics: Cement/Sand = 1:2 Water/cement = 0.47

Fibers =1% by volume Dry Mix Duration = 1 min. Wet Mix Duration = 12 min.

Mix	K15M Dosage %wt cmt	Superplasticizer		Fresh Mix Properties					Hardened Mortar Properties					
		Type [1]	Dosage ml/kg cmt	Fiber Dispersion			Workability	Finishing	Settling Time	Weight lb/ft³	Strength(psi) [2]			Fiber Dispersion
				6 min.	10 min.	12 min.					C	T	F	
1	0.2	G - D100	13	poor	poor	poor	average	average	normal	111	2130	370	575	poor
2	0.4	G - D100	13	poor	average	average	average	average	normal	109	2240	355	535	poor
3	0.2	MB - R1000	16	v. poor	poor	poor	average	good	slow	104	1460	275	380	v. poor
4	0.4	MB - R1000	16	poor	poor	poor	stiff	good	slow	115	2380	420	500	poor
5	0.2	MB - R1000	16	poor	average	average	average	v. good	normal	108	1350	280	315	poor
6	0.2	G - M33	16	poor	average	average	good	poor	normal	104	1870	320	510	average
7	0.4	G - M33	16	poor	average	average	stiff	average	normal	110	2060	375	565	poor
8	0.2	MB - P400N	6	average	average	average	average	average	fair	104	1360	260	450	poor
9	0.2	MB - P400N	6	poor	average	average	poor	poor	normal	114	2040	230	525	v. poor
10 [3]	0	G - M33	16	N/A	N/A	N/A	watery	N/A	normal	143	5360	590	790	N/A
11	0.2	G - M33	16	fair	average	average	good	good	normal	98	1200	215	415	poor
12 [4]	0.2	G - M33	16	N/A	N/A	average	good	good	normal	96	1150	180	365	v. poor
13 [3]	0	N/A	0	N/A	N/A	N/A	good	good	normal	140	4870	455	830	N/A
14 [5]	0.2	G - M33	16	poor	poor	poor	good	good	normal	134	4250	630	865	average
15 [6]	0.2	G - M33	16	fair	fair	fair	good	good	normal	133	3930	555	820	fair
16 [6]	0.2	G - M33	16	fair	fair	fair	average	good	normal	127	3490	590	775	fair
17 [6]	0.2	G - M33	16	fair	fair	fair	average	average	normal	135	4305	590	805	average
18 [6,7]	0.2	G - M33	16	fair	fair	fair	average	average	normal	131	4030	580	850	fair

[1] **Types of Superplasticizer:** **G** = **Grace** — **D100** = Daracem 100; **M33** = Mel 33. **MB** = **Master Builders** — **R1000** = Rheobuild 1000; **P400N** = Pozzolith 400N

[2] **Strength :** C= compression test; T= Split cylinder test; F= Third-point flexural test

[3] **No fibers added**

[4] **Duration for wet mix was 24 minutes and fiber dispersion was checked after 12, 16, and 24 minutes.**

[5] **Defoamer was added to the dry mix with dosage 0.1% by wt of cement**

[6] **Defoamer was added to the mortar after 6 minutes of wet mixing with dosage 0.1% by wt of cement**

[7] **Half the amount of cement was added after 6 minutes of wet mixing**

Methyl-cellulose: 0, 0.1, 0.2 or 0.25% by wt of cement

Defoamer: 0, 0.1, 0.15 or 0.2% by wt of cement

Metakaolin: 0 and 10% by wt of cement

For several batches, CF was pretreated to determine if removal of some of the polyvinyl alcohol (PVA) would improve fiber dispersion. Carbon fibers used in some batches were preheated in an oven at 250 to 280°C for approximately 3 hr before using them in the concrete batches. The result from this process was a reduction in the PVA that held the fibers together in chip form. Fibers were batched at room temperature. For other batches, fibers were soaked in tap water for 24 hr, drained, and then dried at 150°C before batching.

Several mixing techniques were used for those batches to improve Mitsubishi fiber dispersion: sand, metakaolin, and defoamer were added after 6 min of wet mixing; one-half of the sand, metakaolin, and defoamer were added after 6 min of wet mixing; sand was added after 4 min of wet mixing; defoamer was added after 8 min of wet mixing; and metakaolin and defoamer were added after 8 min.

Concrete specimens were made using 4 x 8-in. cylinder molds and 4 x 4 x 14-in. beam molds. Samples were demolded at 24 hrs and cured for an additional 6 days in a moist room at 100% humidity before testing. Fiber dispersion on the failure surfaces of the test specimens was visually rated. The following results were obtained:

Fiber dispersion: Better fiber dispersion was obtained in concrete than in mortar, and in batches that were moist and workable. This improvement was attributed to the presence of coarse aggregate particles that were able to break up fiber chips during the mixing process. However, some fibers in the original wafer form were visible in the freshly mixed concrete and on the formed and fracture surfaces of specimens.

Effect of fiber content: Adding fibers lowered compressive strength by 5 to 10% and increased tensile and flexural strengths by as much as 20 to 30%.

Effect of preheating fibers: Preheating of fibers was considered because of the Mitsubishi fiber format. Preheating fibers to reduce the PVA improved fiber dispersion and consequently increased tensile and flexural strengths by 30 to 40%, decreased compressive strength by 10 to 15%, and increased the amount of entrapped air.

Effect of soaking/drying fibers: This method was not successful; during mixing, the fibers formed larger clumps than the original chips. Many fiber clumps were observed on the failure surface of the samples after breaking.

Effect of water/cement ratio: As water-to-cement ratio increased from 0.45 to 0.6, the resulting mixes were more fluid and fiber dispersion was improved. However, there was a reduction in tensile and flexural strengths when the water-to-cement ratio was increased from 0.5 to 0.6.

Effect of superplasticizer: Increasing the amount of superplasticizer increased mix workability and wetness, which improved fiber dispersion.

Effect of methylcellulose amount: Again, an optimum amount of methylcellulose was determined to be 0.2 to 0.3% by weight of cement (see phase 2 results for more details).

Effect of defoamer: Adding defoamer decreased the amount of entrapped air in the concrete, which reduced the fluidity of the fresh concrete. With a reduction in entrapped air, the density and strength of concrete were increased. The two types of defoamer gave the same results for all mixes. The optimum amount of defoamer is 0.15% by weight of cement. If a defoamer was mixed with dry materials, the defoamer action was present during the entire wet mixing period; reduction of entrapped air resulted in a less workable mix and less efficient fiber dispersion. When defoamer was added after 6 min of wet mixing, the higher volume of entrapped air and increased workability during the initial mixing period improved fiber dispersion.

Effect of metakaolin: Fiber dispersion is easier to accomplish in fluid, highly workable mixes. After adding metakaolin to the mix, a reduction in slump and workability occurred. To take advantage of this "thirsty" property, metakaolin was added near the end of the wet mixing period. Most fiber dispersion took place while the mix was fluid and metakaolin was then used to reduce slump to normal level. If metakaolin was dry-mixed with other materials, it did not appear to improve fiber dispersion. Specimens were tested before the pozzolanic characteristics of metakaolin would be fully realized.

Effect of adding all or part of the sand in a later stage of wet mixing: When sand was withheld during the initial wet mixing period, there was greater fluidity of the mix--a mix characteristic favorable to fiber dispersion. However, until the sand was added to the mix, CF occupied more than 1% of the volume--a mix characteristic detrimental to good fiber dispersion. The overall influence of withholding sand lowered fiber dispersion and promoted clumping of fibers that had been separated from the wafer chips. Table A-5 summarizes all results for concrete batches.

A.6 Summary and Conclusion

When Mitsubishi CF are used in mortar and concrete, the standard mix water permitted breakdown of the wafer; no special pretreatment with a special water solution was needed. Results indicate that approximately 0.5% methyl-cellulose K15M by weight of water promotes dispersion of CF in cement and water. Adding CF to mortar mixes increased the tensile strength by 20% and decreased the compressive strength by 5 to 10%. The presence of dispersed fibers in mortar increased the amount of entrapped air, which is responsible for the observed loss in compressive strength. A defoamer can be used to decrease the amount of entrapped air mortar, thus increasing compressive and tensile strengths. The presence of superplasticizer in mortar increased mix fluidity and consequently increased fiber dispersion.

Table A-5

Summary of Results for Concrete Batches

General Mix Characteristics:

Fibers =1% Dry Mix Duration = 1 min. Wet Mix Duration = 12 min.

Batch	Cement	Sand by wt. of cement	Coarse by wt. of cement	Water/Cement Ratio	Metakaolin by wt. Of cement	Defoamer %wt of cement	K15M %wt of cement	Superplasticizer ml/kg of cement	Fresh Mix Properties: Fiber Dispersion 6 min	Fiber Dispersion 10 min	Fiber Dispersion 12 min	Workability	Finishing	Hardened Mortar Properties: wt. / Air lb/ft^3	wt. / Air %	Strength[3] (psi) C	Strength[3] (psi) T	Strength[3] (psi) F	Fiber Dispersion
1	1	2.5	3	0.45	0	0	0	0	NO FIBERS			good	fair	152	0.0	4260	505	735	-
2[2]	1	2	2	0.48	0.1	0	0	0	NO FIBERS			v.good	v.good	145	2.1	5490	475	790	-
3[2]	1	1.5	1.5	0.47	0.1	0	0	0	NO FIBERS			watery	v.good	146	0.0	6620	605	1030	-
4[2]	1	1.5	2	0.47	0.1	0	0	0	NO FIBERS			v.good	fair	148	0.0	6580	620	1090	-
5[2]	1	1	1	0.48	0.1	0	0	0	NO FIBERS			watery	good	142	0.0	5980	605	1015	-
6	1	3.5	2	0.45	0.1	0	0	8	NO FIBERS			good	good	149	0.5	6620	595	1010	-
7	1	2.5	3	0.45	0	0	0	16	v. poor	poor	poor	dry-stiff	fair	146	4.0	3265	500	585	v. poor
8	1	2.5	3	0.5	0	0.1	0.1	16	poor	poor	poor	< fair	< fair	147	1.9	3180	450	645	v. poor
9	1	2.5	3	0.5	0.1	0.1	0.1	16	v.poor	poor	poor	dry-stiff	< fair	147	2.4	6160	745	985	v.poor
10	1	2.5	3	0.45	0.1	0.1	0.2	16	v. poor	poor	poor	dry-stiff	v. poor	147	2.9	6760	830	975	v.poor
11	1	2.5	3	0.6	0.1	0.1	0.25	16	fair	fair	fair	fair	fair	142	3.6	4270	530	765	v.poor
12[2]	1	2	2	0.47	0.1	0.15	0.2	16	< fair	fair	fair	stiff	poor	144	3.1	6440	740	1005	poor
13[2]	1	1.5	1.5	0.47	0.1	0.15	0.2	16	fair	fair	fair	fair	fair	136	5.8	4850	570	815	fair
14[2]	1	1	1	0.48	0.1	0.15	0.2	16	fair	fair	fair	v.good	fair	136	2.6	5095	645	850	fair
15[2]	1	1.5	2	0.47	0.1	0.15	0.2	16	fair	fair	fair	< fair	fair	142	3.6	6700	680	1055	fair
16[2]	1	1.5	2	0.47	0.1	0.2	0.1	16	fair	fair	fair	good	fair	144	1.6	6830	725	1040	poor
17[2]	1	1.5	3	0.45	0.1	0.2	0.1	16	v.poor	poor	poor	fair	poor	144	4.7	3730	520	660	poor
18[3]	1	3.5	2	0.45	0.1	0.2	0.1	16	fair	fair	fair	dry-stiff	poor	146	2.7	6120	730	875	v. poor
19[3]	1	3.5	2	0.45	0.1	0.2	0.1	4	poor	poor	poor	dry-stiff	poor	146	2.9	5950	730	915	v. poor
20[3,4]	1	3.5	2	0.45	0.1	0.2	0.1	16	v.poor	poor	poor	dry-stiff	poor	145	3.1	5350	700	818	poor
21[5,6]	1	2	2	0.45	0.1	0.15	0.15	16	fair	ave.	ave.	< fair	< fair	146	1.6	6410	820	990	poor
22[5,7]	1	2	2	0.45	0.1	0.15	0.15	16	good	good	good	stiff	fair	146	1.4	7470	870	1120	fair
23[5,7]	1	2	2	0.45	0.1	0.15	0	16	good	good	good	stiff	fair	147	0.8	7470	815	1135	fair

[1] **Strength :** C= compression test; T= Split cylinder test; F= Third-point flexural test
[2] **Sand, Metakaolin, and Defoamer were added after 6 min of wet mixing**
[3] **1/2 of the sand, Metakaolin, and Defoamer were added after 6 min of wet mixing**
[4] **Fibers were soaked into tab water and then dried in the oven before adding to the dry mix**
[5] **Fibers were pre heated to 250c for 3 hrs, cooled then added to the dry mix.**
[6] **add the sand after 4 min. Add defoamer after 8 min.**
[7] **add metakaolin and defoamer after 8 min.**

Results indicate that the optimum mix ingredients for using fibers in mortar mixes include: methyl-cellulose at a dosage of 0.2% by weight of cement, the maximum recommended dosage of superplasticizer (16 ml/kg of cement for Grace Melment 330), and a defoamer (e.g Rhône-Poulenc Inc. type Colloid 770DD in the amount of 0.15% by weight of cement). Variations in cement-to-sand ratio, water/cement ratio, fiber content, and dry mix duration were not studied. These values were kept at 1 to 2, 0.47 and 1% by volume and 1 min, respectively.

Although the sequence and duration of mixing procedures were not investigated, it appears the procedures employed were suitable to produce mortar reinforced with CF. That is, cement, sand, fibers, and methyl-cellulose are initially added to the mortar mixer and dry mixed for 1 min, after the addition of water and superplasticizer, materials are mixed for 3 to 4 min. At this time, defoamer was added and the mortar mixed for an additional 2 min.

In concrete mixes with CF, good fiber dispersion was accompanied by a loss in compressive strength (5 to 10%) but a gain in splitting tensile strength and flexural strength (20 to 30%). Factors which lead to improved fiber dispersion include use of methyl-cellulose (a dispersing agent), breakdown of the PVA coating on fibers by preheating, and any action that increased mix fluidity. The use of methyl-cellulose led to the need for a defoamer to counteract the air entrapped by the action of methyl-cellulose.

As indicated above, increasing fluidity of the mix was achieved in several ways: using superplasticizer, allowing air to be entrapped and later removing it with a defoamer, using mix proportions which result in high slump and reducing slump after fiber dispersion with metakaolin, and increasing paste fluidity by increasing the water-to-cement ratio. Use of a defoamer or metakaolin that is added after a period of wet mixing might not be preferred in the field. Of these, the use of superplasticizer was probably the most practical.

APPENDIX B

Application of CFRC in Pipe Production

B.1 General

This phase of the project focused on a field study conducted at the North Star Concrete Company in Apple Valley, MN. The field study produced reinforced concrete pipe using CF as a replacement for steel stirrups and welded wire mesh. In research conducted at OSU, concrete mixes containing various percentages of CF were developed that would be suitable for use in concrete pipe.

OSU and DuPont personnel visited the North Star facility; information obtained during this visit allowed OSU to obtain materials and equipment for mixing and curing which simulated production conditions at the pipe plant. Because research continued while equipment and supplies were being purchased and installed, experimental procedures were adjusted many times, as described below, during this phase of the project.

B.2 Purpose and Scope

This phase objective was to produce CFRC mixes containing 1.0 to 2.5% CF (by volume) which would have the requisite workability and mechanical properties, and allow partial or total replacement for conventional steel reinforcement in precast concrete pipe production. The test program included development and characterization of zero-slump concrete mixes, similar to those used in pipe production, in laboratory-scale tests, followed by large-scale tests at a precast concrete plant in Oklahoma City, OK. Demonstration tests were performed involving limited pipe production runs at the North Star pipe plant in Apple Valley, MN.

Laboratory work at OSU modified one of North Star's mixes to incorporate CF while retaining workability characteristics of the original mix. This mix, AMX-5, is used to produce 72-in. ID pipes with 6.75-in wall thickness. North Star mix proportions for AMX-5 are presented in Appendix D. CFRC mixes developed by OSU would have the following characteristics: (1) a dry, stiff, cohesive mix that was essential since pipes demolded immediately after casting; and (2) a compressive strength of at least 3500 psi after 24 hr including 5 to 7 hr of steam curing. The 7-day compressive strength was to be at least 5000 psi.

The program proposed by DuPont and OSU included the following activities:

1. Continuation of previous laboratory work on incorporation of CF into specified concrete mixes. Laboratory tests would evaluate methods to improve fiber dispersion and optimization of relevant CFRC physical and mechanical properties.
2. Examination of the following parameters: fiber format (sizing, methods of fiber introduction into mix, etc.), various types of mixers (pan, drum, etc.), type of coarse aggregate (crushed rock or river gravel), aggregate gradation, fiber percentage, methods of consolidation, and methods of curing.
3. Evaluation of mechanical properties, including compressive, tensile, and flexural strengths, stress-strain relations, first crack stress, and shear stress.
4. After successful completion of laboratory tests, large-scale field trials of mixes would be performed using Coreslab precast plant production facilities. These tests evaluated scaling factors and any needed adjustments to ensure that mixes developed in the laboratory can be used in full-scale pipe production trials at North Star.
5. At the completion of laboratory work and field test at Coreslab, limited pipe production runs would be made at the North Star pipe plant in Apple valley, MN.

B.3 Materials

Adjustments to laboratory facilities, equipment, and materials to better simulate production conditions at the North Star pipe plant required approximately two months. Results obtained during this time reflect the variable experimental procedures involved with this work.

Aggregate: North Star uses sand with a fineness modulus of 2.65 and pea gravel coarse aggregate. Sand was obtained locally for this research and had a fineness modulus of 2.77, a specific gravity of 2.62, and absorption of 0.4%.

River gravel with a specific gravity of 2.65 quarried from the Arkansas River, near Sand Springs, OK, was used at OSU. The coarse aggregate gradation was significantly different than the North Star coarse aggregate gradation. To obtain similar coarse aggregate gradation, the coarse aggregate was separated into materials retained on the 3/8-in., No. 4 and No. 8 sieves. At the time of batching, these sizes were recombined to conform to the Minnesota coarse aggregate. Gradation charts for fine and coarse aggregates used at North Star and OSU are shown in Figures B-1 and B-2, respectively.

Cement and fly ash: Type I cement and a blend of types C and F fly ashes were used at the North Star pipe plant. Type I cement and type C fly ash were used in laboratory work at OSU. The fly ash/cement ratio was kept constant in all laboratory mixes and was equal to 0.277, the same ratio used in North Star pipe mixes.

Carbon fibers: Both Mitsubishi CF and Conoco CF were used at a dosage of 1% by volume of total mix.

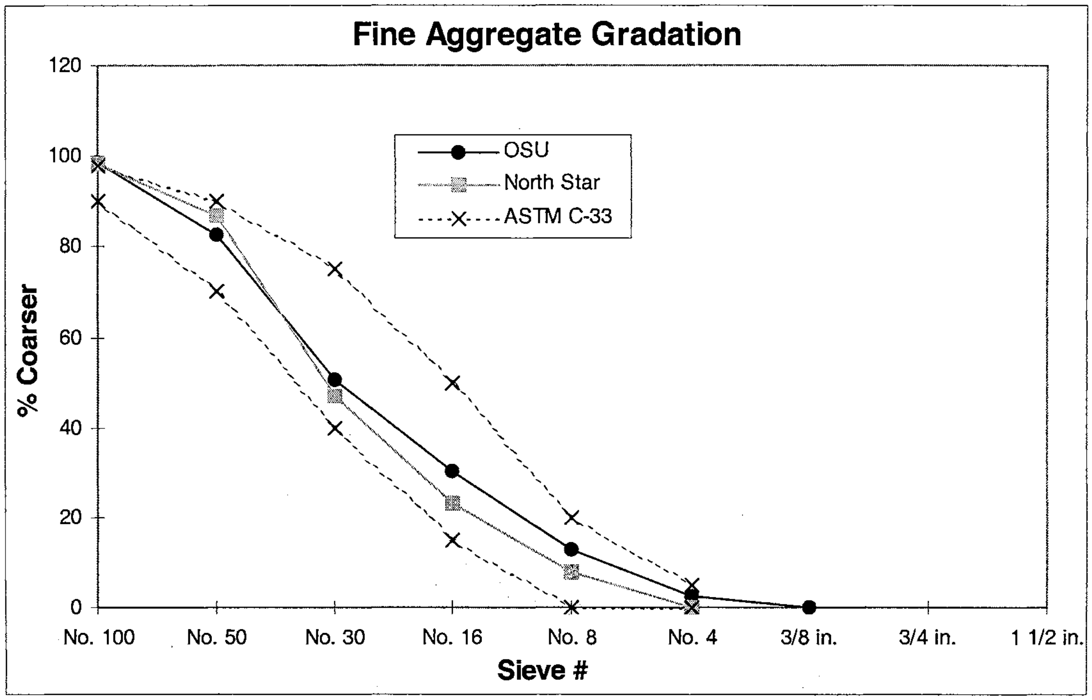

Figure B-1. Fine Aggregates Used at North Star and OSU with ASTM Limits

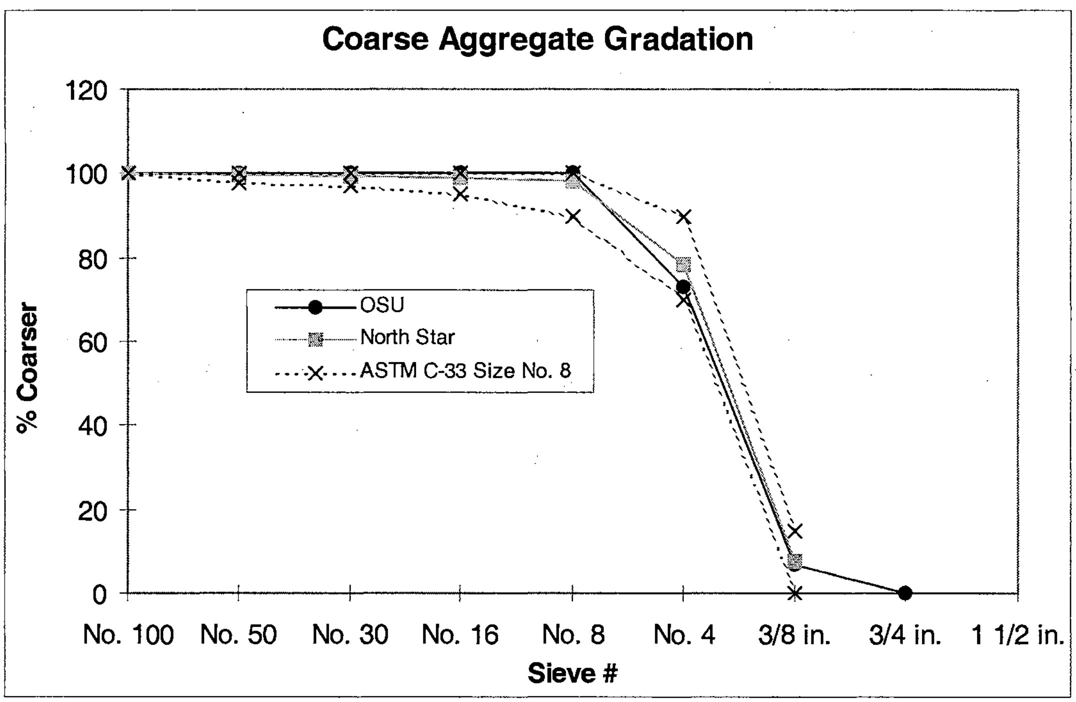

Figure B-2. Coarse Aggregates Used at North Star and OSU with ASTM Limits

Water Reducer: The North Star mix employed Sitka PL90, a water reducing agent developed specifically for the concrete pipe, at a dosage of 3 ml/kg of cement. In order to be comparable to batches produced at North Star, a dosage of 3 ml/kg of cement of PL90 was used in the control batches and all batches with CF that contained PL90.

Superplasticizer: A superplasticizer, Daracem ML500, manufactured by Grace was used in this phase, alternatively with water reducer. The manufacturer's maximum recommended dosage for the superplasticizer, 16 ml/kg of cement, was used in all the batches that contained the superplasticizer.

B.4 Initial Laboratory Work at OSU

Experimental Approach: In adjusting mix proportions, it is convenient to present various mix components as weight per unit volume (1 yd^3) of concrete. In the North Star mix, the unit volume was the sum of cement, sand, gravel, fly ash, water, and air content volumes. For the North Star mix, the volume of sand was 1.6 times the volume of pea gravel. Two control batches, based on mix AMX-5, were cast with the adjustment in aggregate weights due to the differences between the specific gravity of sand and pea gravel used by North Star and OSU laboratory. The volume of each mix component per 1 yd^3 remained the same as mix AMX-5 and proportions were:

	Weight (lb)	Specific Gravity	Volume (ft^3)	Percent of Mix (by wt)	Ratio toCement (by wt)
Cement	564	3.15	2.87	13.94	1.000
Fly Ash	156	2.5	1.00	3.85	0.277
Sand	1928	2.62	11.79	47.63	3.418
Rock	1225	2.67	7.35	30.26	2.171
Water	175	1	2.80	4.32	0.310
Fibers	0	1.9	0.00	0.00	0.000
Air Content	4.5%		1.22		
Σ	4047		27.03		

The results from those two mixes were similar to those obtained at earlier stages of the project from the same mix design; thus no additional control batches were cast. A total of 30 batches were cast for six different mix proportions.

Two CF mix designs were used in the laboratory work at OSU for this phase. The first mix was based on the mix used during the field test at North Star plant and the second mix was developed at the OSU concrete laboratory during earlier stages of the project that gave the best results for workability and mechanical properties.

During the field trial at North Star, plant personnel chose to add 1% by volume of 1 yd^3 of CF to the mix components of AMX-5. This amount of CF was 32 lb according to the following calculation:

$$\text{Volume of CF} = 0.01 \times 1\ yd^3 \times 27\ ft^3/yd^3 = 0.27\ ft^3$$

$$\text{Weight of CF} = 0.27\ ft^3 \times (S.G = 1.9) \times 62.4\ pcf = 32\ lb$$

The mixing personnel at North Star then decided that the batch was sufficiently dry to form concrete pipe, so they added more water to the mix until they reached the required workability and wetness for pipe casting. The total amount of water added was about 57 lb/yd^3, which increased the total amount of water to 237 lb/yd^3 and the water/cement ratio to 0.42. The total volume of the mix was altered after adding CF and extra water to the batch. In addition, the average air content of the samples taken from the batch was found to be 6.0% which was more than the air content of the original AMX-5 provided by North Star (4.5%). Air content was calculated using the gravitational method. The mix proportions of this batch were altered and became as follows:

	Weight (lb)	Specific Gravity	Volume (ft³)	Percent of Mix (by wt)	Ratio to Cement (by wt)
Cement	564	3.15	2.87	13.73	1.000
Fly Ash	156	2.50	1.00	3.80	0.277
Sand	1965	2.67	11.79	47.82	3.484
Rock	1155	2.52	7.35	28.11	2.048
Water	237	1.00	3.80	5.77	0.420
Fibers	32	1.90	0.27	0.78	0.057
Air Content	6.0%		1.73		
Σ	4109		28.80		

In order to calculate the weight of each mix component per 1 yd³, the volume of each component (except percentage of air content) should be scaled down to give a final total volume of 27 ft³. The scaled factor is calculated as follows:

$$\text{Scaled factor} = \frac{27.00\,\text{ft}^3 - (\text{Air content at } 6.0\% = 1.62\,\text{ft}^3)}{28.80\,\text{ft}^3 - (\text{Air content at } 6.0\% = 1.73\,\text{ft}^3)} = 0.938$$

Thus the components of this mix were as follows:

	Weight (lb)	Specific Gravity	Volume (ft³)	Percent of Mix (by wt)	Ratio to Cement (by wt)
Cement	529	3.15	2.69	13.73	1.000
Fly Ash	146	2.5	0.94	3.80	0.277
Sand	1842	2.67	11.05	47.80	3.482
Rock	1084	2.52	6.89	28.12	2.048
Water	222	1.00	3.56	5.77	0.420
Fibers	30	1.90	0.25	0.78	0.057
Air Content	6.0%		1.62		
Σ	3853		27.00		

At the OSU laboratory, the specific gravity of the sand and pea gravel was different from those at the North Star plant. The weight of sand and gravel per 1 yd³ used in the first mix was altered to give the same volumetric percentage as in the mix used in the field test at the North Star plant. The components of the first mix used at OSU were as follows:

	Weight (lb)	Specific Gravity	Volume (ft^3)	Percent of Mix (by wt)	Ratio to Cement (by wt)
Cement	529	3.15	2.69	13.73	1.000
Fly Ash	146	2.50	0.94	3.80	0.277
Sand	1807	2.62	11.05	46.91	3.417
Rock	1148	2.67	6.89	29.80	2.171
Water	222	1.00	3.56	5.77	0.420
Fibers	30	1.90	0.25	0.78	0.057
Air Content	6.0%		1.62		
Σ	3883		27.00		

During earlier stages of the project, it was found that increasing the cement content of mixes with CF gave better results for workability and mechanical properties. For the second mix at OSU the weight of cement per 1 yd^3 increased by 27 lb over the AMX-5 mix to 591 lb/yd^3. The water/cement ratio was also increased to 0.42 and the fiber content was 1% by total volume of the mix. The ratio of fly ash/cement was kept the same as the AMX-5 mix at 0.277. Since the volume of the mix increased, the volume of some components had to decrease to have the same unit volume. The approach was to compute the volumetric contribution of the nonaggregate components, then provide the necessary aggregate to achieve the unit volume of 1 yd^3. Thus the volumetric sum of air, cement, fly ash, water, and CF was computed and subtracted from 1 yd^3 to give the combined volume of sand and pea gravel. The volume of sand and pea gravel was then determined according to the ratio 1.6 (the same volumetric ratio of sand to pea gravel used by North Star). With the correction in aggregate specific gravity, the second mix components used at OSU were as follows:

	Weight (lb)	Specific Gravity	Volume (ft^3)	Percent of Mix (by wt)	Ratio to Cement (by wt)
Cement	591	3.15	3.01	15.36	1.000
Fly Ash	164	2.50	1.05	4.26	0.277
Sand	1720	2.62	10.52	44.70	2.910
Rock	1093	2.67	6.56	28.40	1.849
Water	248	1.00	3.97	6.45	0.420
Fibers	32	1.90	0.27	0.83	0.054
Air Content	6.0%		1.62		
Σ	3847		27.00		

The batches made at OSU concrete laboratory were as follows:

- Two control batches
- Six using the first mix design with Mitsubishi CF and 3 ml/kg of PL90
- Six using the first mix design with Conoco CF and 3 ml/kg of PL90
- Six using the first mix design with Conoco CF and 16 ml/kg of ML500
- Four using the second mix design with Conoco CF and 3 ml/kg of PL90
- Six using the second mix design with Conoco CF and 16 ml/kg of ML500

Concrete Mixing Equipment, Batching, and Casting: A mortar mixer with a capacity of 3 ft^3 was used. The mixer was portable and was used outside the laboratory to reduce problems with airborne CF. The dry mixing duration was kept at 10 sec for all batches; the wet mixing duration was 2 min for control batches and 4 min for batches with CF. A total of 12 cylinders (4 x 8 in.) and 6 prisms (4 x 4 x 14 in.) were sampled from each batch.

Consolidation: Conventional rodding or internal vibration cannot consolidate concrete used to make pipe. It was learned that North Star fabricates control cylinders using a vibration table. Consolidation is achieved by applying firm downward pressure on each lift while the vibration table is operated. A similar vibration table was constructed for OSU research.

Curing: North Star employs a 5-hr atmosphere steam cure at 49°C followed by a gradual cool-down to ambient temperature. At OSU, immediately after molding, specimens were placed in a steam chamber maintained at 49°C and removed from the curing atmosphere after about 22 hr.

Test Methods: Cylinders and prisms were tested after 1, 7 and 28 days. Compressive strength, modulus of elasticity, splitting tensile strength, and flexural toughness of the concrete were determined in accordance with ASTM Methods C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, C469, Test Method for static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression, C496, Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, and C1018, Test Method for Flexural Toughness and First-Crack Strength of Fiber Reinforced Concrete (Using Beam With Third-Point Loading), respectively. Figure B-3 shows a setup for the ASTM C469 test on cylinder. Figure B-4 shows the ELE test machine used for splitting tensile test. Figure B-5 shows a setup for the ASTM C1018 test on beams.

Several batches were made for each different mix proportions. Statistical analysis was performed to get the final results for each mix. Project personnel visually rated fiber dispersion on failure surfaces of the test specimens. Good fiber dispersion was considered to be the absence of fibers in wafer form for Mitsubishi fibers and the absence of clumps of fibers for Conoco fibers.

Experimental Results: Table B-1 presents summary of results obtained for the initial laboratory work at OSU. Each line in the table represents one mix design and contains mix proportions, number of batches for each mix, average fiber dispersion for fresh concrete, and average hardened mix properties. Air content was calculated using the gravitational method. The control mix presented in the first line had a water/cement ratio of 0.31 while all the mixes with CF had a water/cement ratio of 0.42 to give the same texture and wetness as the concrete produced at the North Star pipe plant. Following is a discussion of the results:

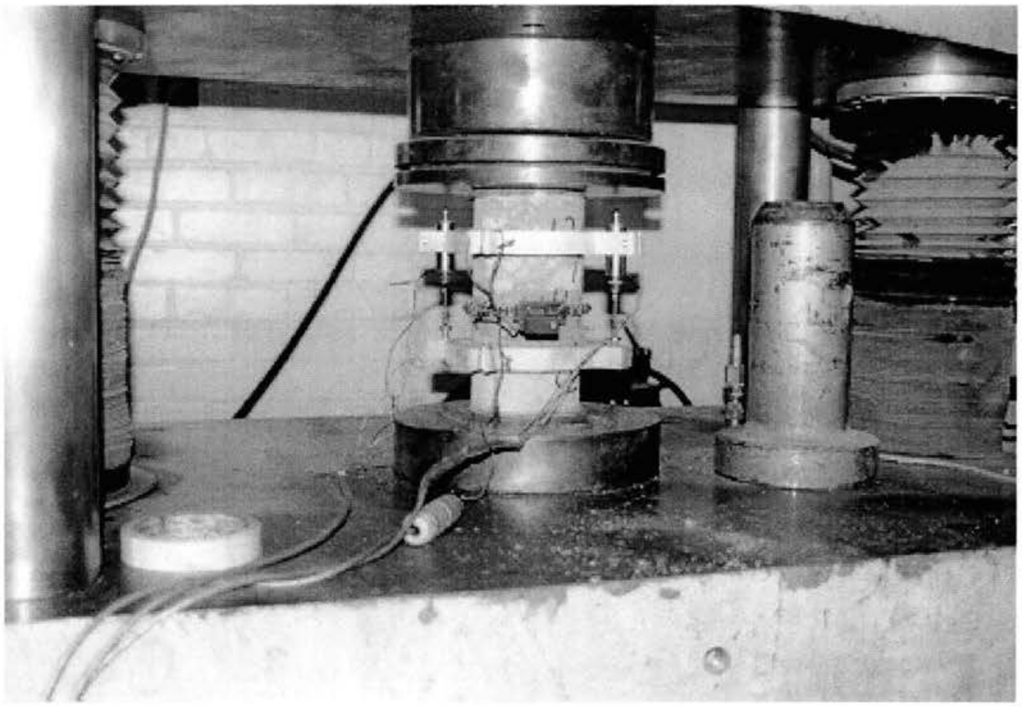

Figure B-3. Testing Machine Used for Static Modulus of Elasticity by ASTM C469

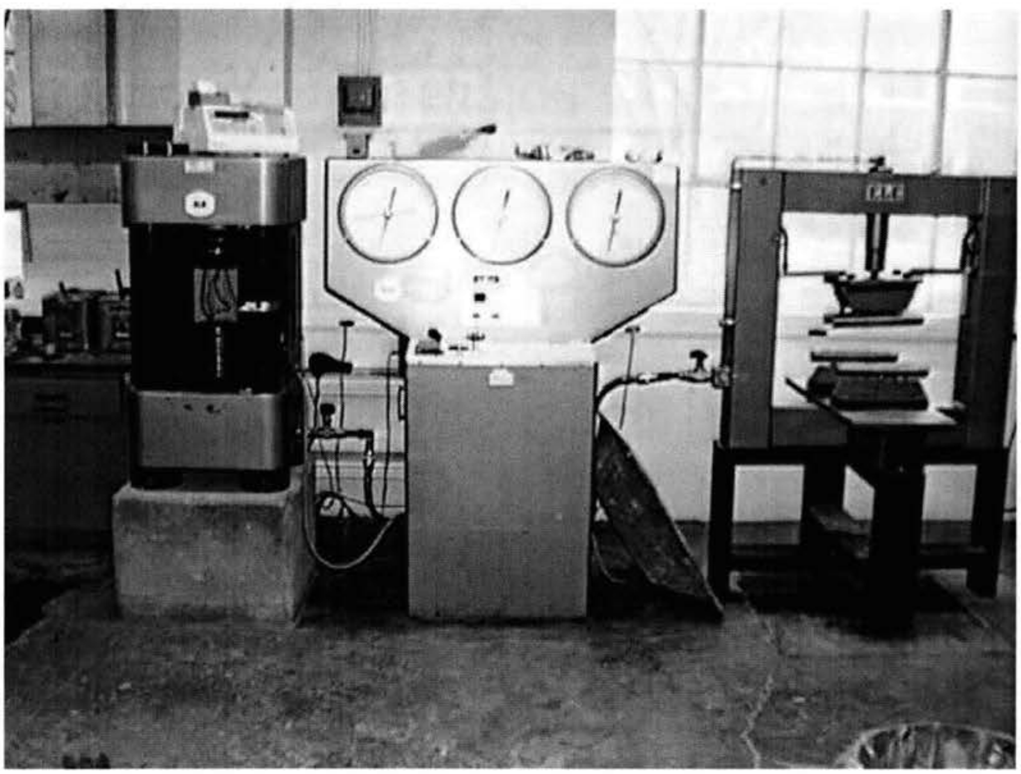

Figure B-4. Testing Machine Used for Cylinder Splitting Tensile Strength by ASTM C496

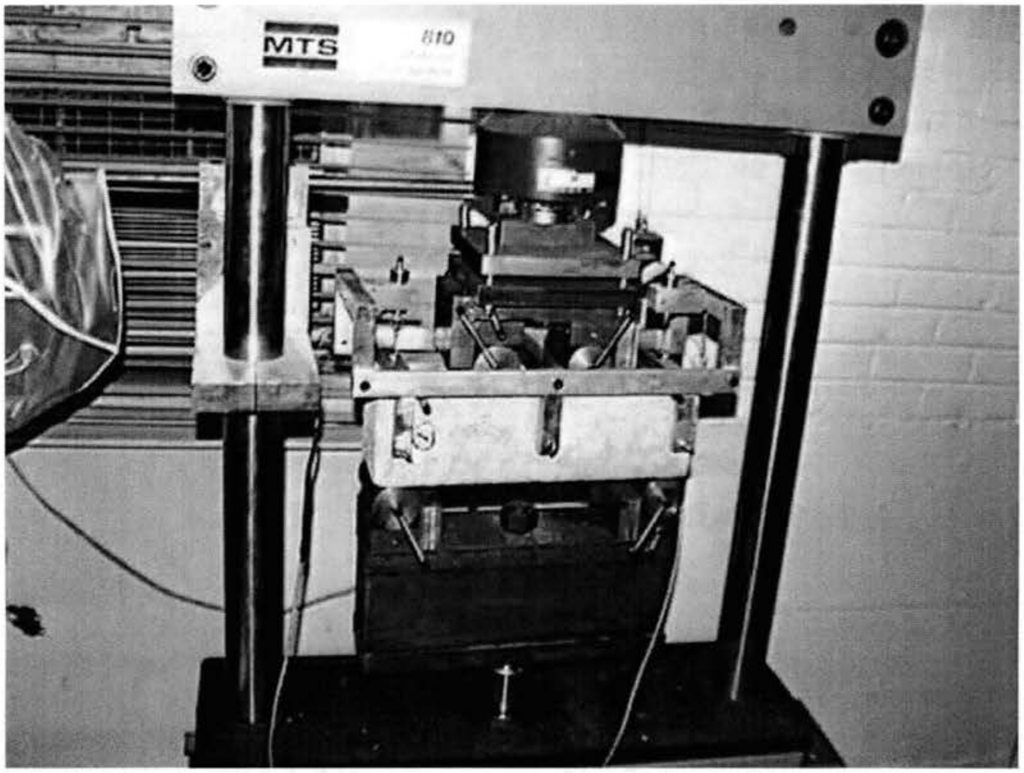

Figure B-5. Apparatus Used for Tests of Beams by ASTM C1018

Table B-1

Summary of Results for Initial Laboratory Work at OSU

General Mix Characteristics:

Mix	No. of Batches	Cement	Sand by wt of cement	Coarse Aggregate by wt of cement	Fly Ash by wt of cement	Fibers % by Volume	Type of Fiber [1]	Water/Cement Ratio	Superplasticizer, ml/kg of cement	PL 90, ml/kg of cement	Fiber Dispersion for Fresh Concrete	Unit Weight	Entrapped Air	Hardened Properties												
														1-Day				7-Day				28-Day				Fiber Dispersion
														Strength [2] (psi)			E	Strength [2] (psi)			E	Strength [2] (psi)			E	
												lb/ft^3	%	C	T	F	(ksi)	C	T	F	(ksi)	C	T	F	(ksi)	
1	2	1	3.418	2.171	0.277	0	-	0.31	-	3	-	148	4.0	3380	435	360	3800	4910	465	410	3670	4580	525	480	3390	-
2	6	1	3.417	2.171	0.277	1	M	0.42	-	3	< avg.	144	6.8	3260	470	605	3110	4610	660	695	2900	4450	500	770	2900	avg.
3	6	1	3.417	2.171	0.277	1	C	0.42	-	3	poor	144	6.5	3260	385	615	3373	3790	490	670	3780	4190	500	700	3640	< avg.
4	6	1	3.417	2.171	0.277	1	C	0.42	16	-	> avg.	143	6.3	3010	410	540	3885	3710	505	680	3640	4035	490	720	3610	> avg.
5	4	1	2.91	1.849	0.277	1	C	0.42	-	3	> avg.	146	4.7	2630	425	660	3180	2630	425	660	4070	4200	510	710	3950	> avg.
6	6	1	2.91	1.849	0.277	1	C	0.42	16	-	< avg.	143	5.5	3050	405	580	3665	3410	530	620	2930	4090	535	620	3550	< avg.

[1] M= Mitsubishi; C= Conoco

[2] **Strength :** C= compression test; T= Split cylinder test; F= Third-point flexural test

Effect of Entrapped Air, as a Result of CF Presence in Concrete, on strength: A direct correlation between fiber content and density of the concrete samples was observed. Higher fiber content and dispersion resulted in lower density and more entrapped air in the concrete. Figures B-6, B-7 and B-8 show the effect of entrapped air percentage on compressive, splitting tensile and flexural strengths after one day, respectively. Compressive and flexural strengths decreased as the percentage of entrapped air increased. Percentage of entrapped air did not affect the splitting tensile strength. The average air content for control mix samples was 4% and the average air content for samples with CF was approximately 6%.

Effect of Adding CF on Compressive Strength of the Concrete: Figure B-9 demonstrates the average compressive strength values after 1, 7 and 28 days for the control mix and mixes with Mitsubishi and Conoco CF using PL90 as a water reducer. The compressive strength standard deviation for samples from control mix, mixes with Mitsubishi CF, and mixes with Conoco CF were approximately 4, 8 and 10%, respectively. Samples from all three mix designs had similar compressive strength after 1 day; however, the compressive strength of control mix samples and samples with Mitsubishi CF had better performance than the compressive strength of samples with Conoco CF after 7 and 28 days. The control mix compressive strength had overall higher values than samples with Mitsubishi and Conoco CF.

Effect of adding CF on static Modulus of Elasticity: Figure B-10 presents the average static Modulus of Elasticity values after 1, 7 and 28 days for the control mix and mixes with Mitsubishi and Conoco CF using PL90 as a water reducer. The standard deviations for static Modulus of Elasticity values were 4, 6 and 9 percent for control mix, Mixes with CF, and mixes with Mitsubishi CF, respectively. The control mix and mixes with Conoco CF had similar average modulus of elasticity. Mixes with Mitsubishi CF had a lower modulus of elasticity than the control mix and mixes with Conoco CF.

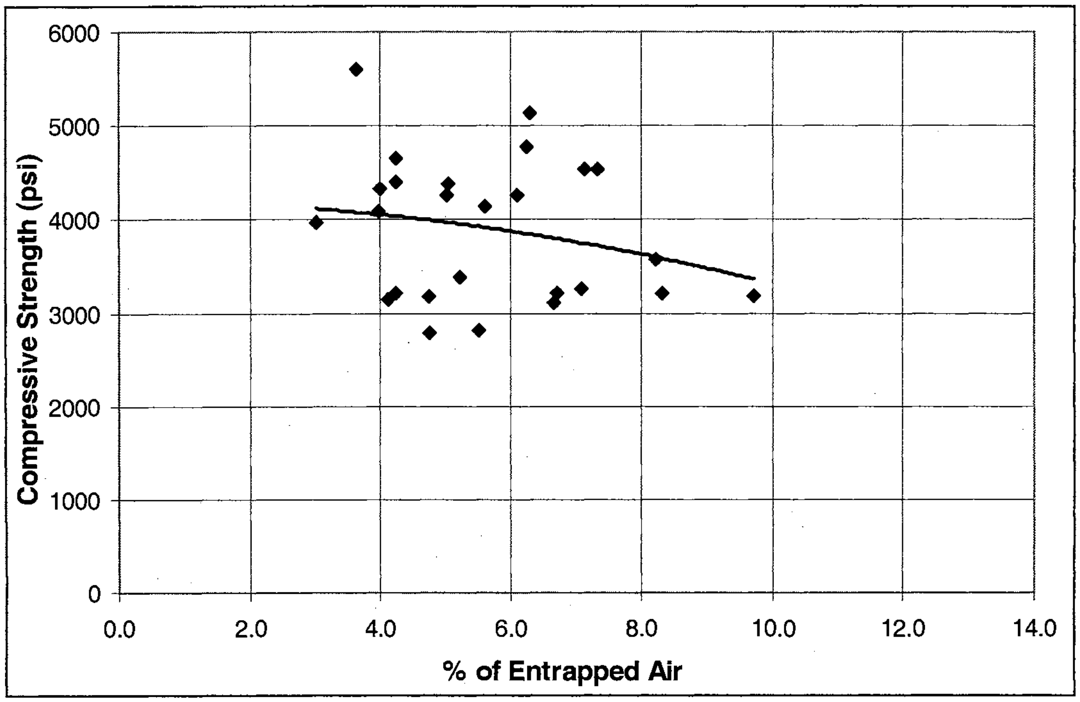

Figure B-6. Decrease in Compressive Strength with Increase in Percentage of Entrapped Air

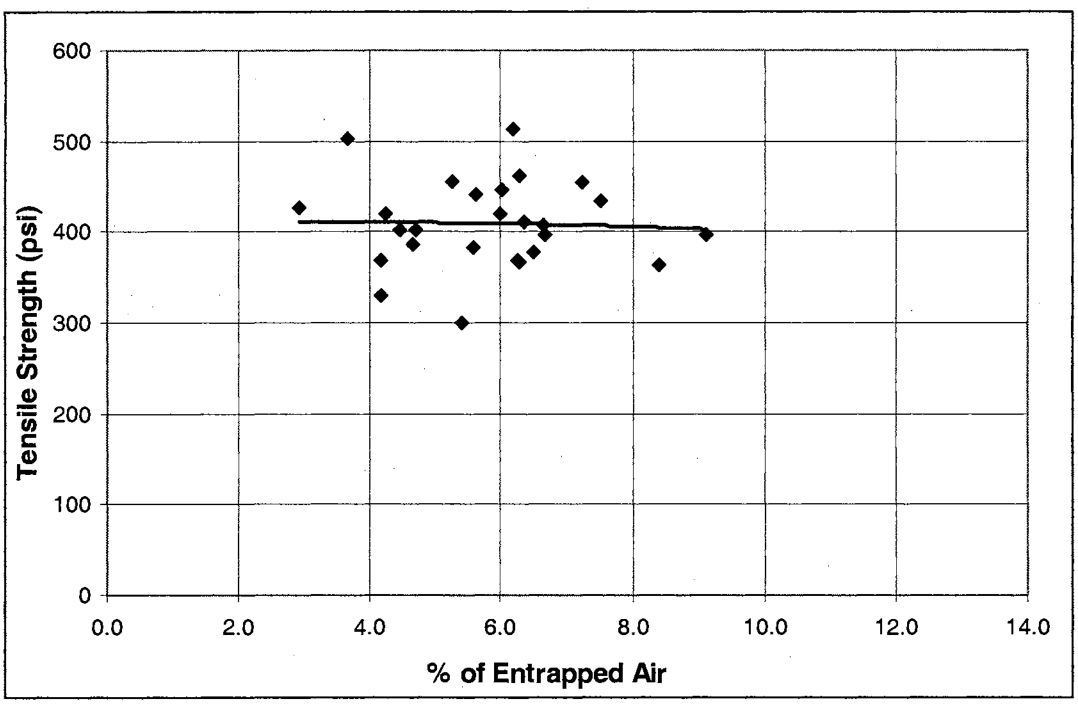

Figure B-7. No Effect on Splitting Tensile Strength for different Percentages of Entrapped Air

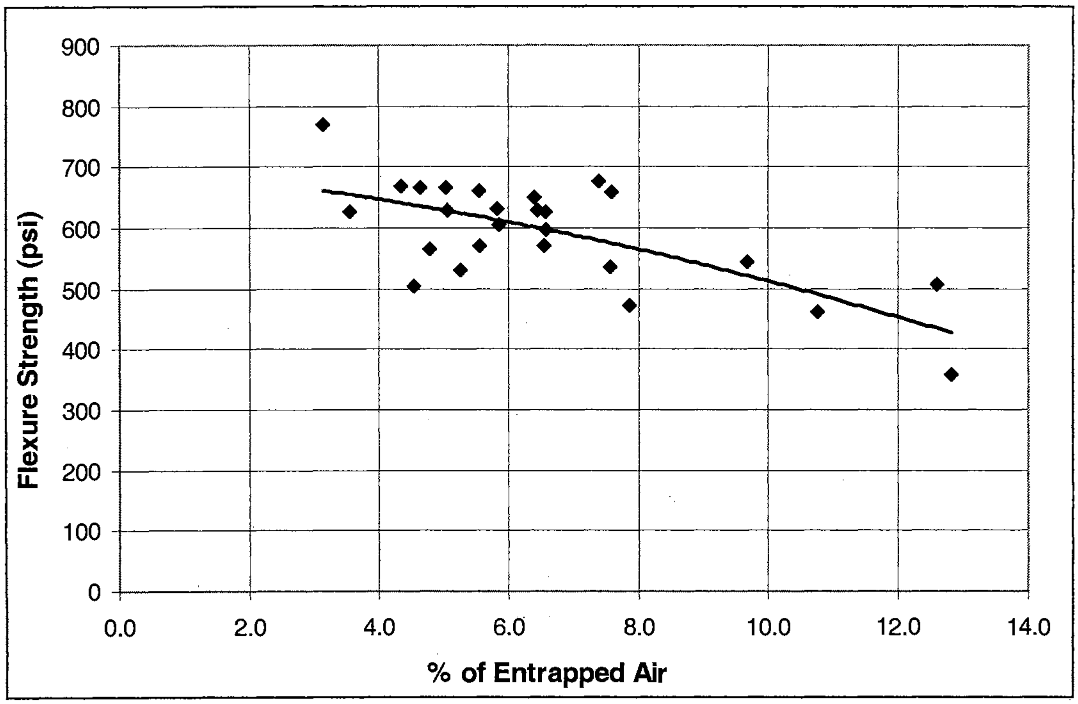

Figure B-8. Decrease in Flexural Strength with Increase in Percentage of Entrapped Air

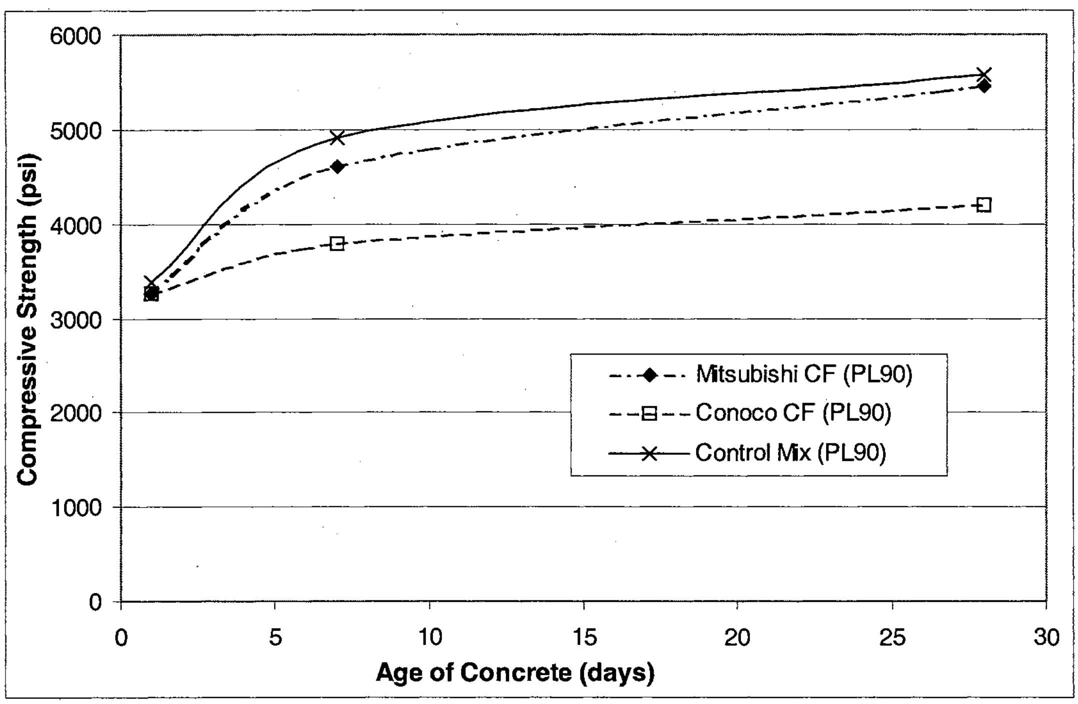

Figure B-9. Decrease in Compressive Strength by Adding Mitsubishi or Conoco CF

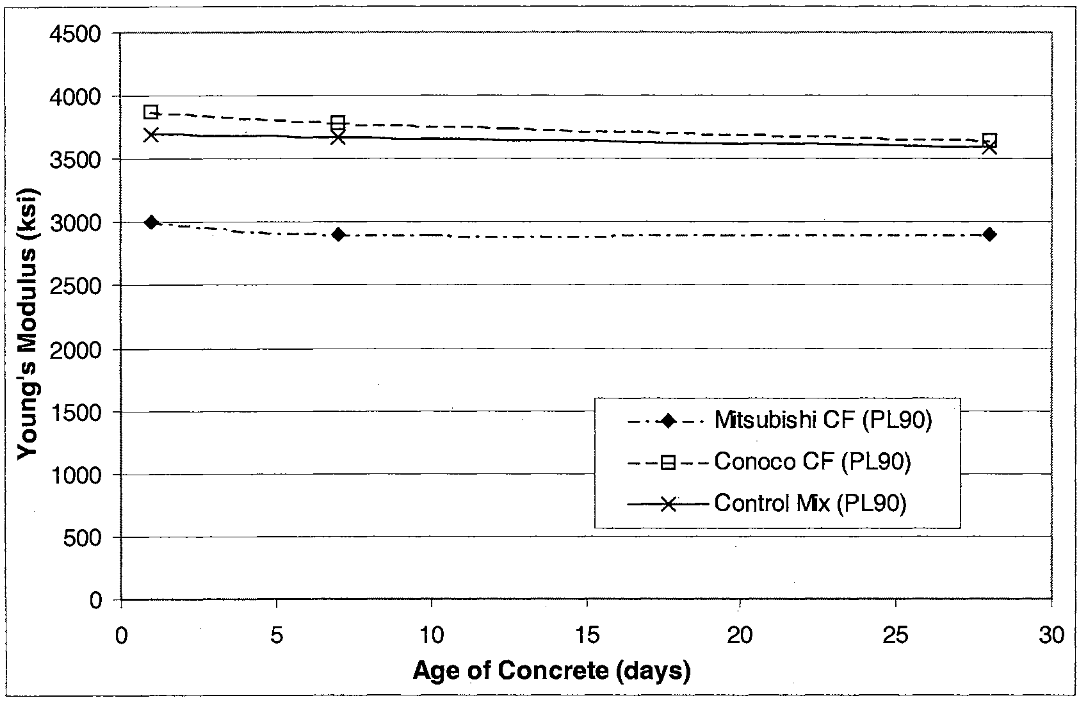

Figure B-10. Static Modulus of Elasticity for Mitsubishi and Conoco CF Specimens

Effect of Adding CF on Strain at Failure of Concrete: Figure B-11 shows the average values for longitudinal strain at failure for cylinder compression tests. Concrete with CF had more deformation at failure than concrete without CF. This behavior is probably the result of carbon fibers bridging cracks and providing limited ductility. Batches with Mitsubishi CF had a higher strain at failure than batches with Conoco fibers. The original length and diameter of Mitsubishi fiber (18-mm and 18-μm, respectively) were larger than the average length and diameter of Conoco fiber (10-mm and 7-μm, respectively) which may account for this increase.

Effect of Adding CF on Splitting Tensile Strength of Concrete: Figure B-12 demonstrates average tensile strength values for control mix, mixes with Mitsubishi CF, and mixes with Conoco CF after 1, 7 and 28 days. The standard deviations for splitting tensile strength were 5, 8 and 11% for control mix, mixes with Mitsubishi CF, and mixes with Conoco CF, respectively. The average tensile strength of the concrete increased slightly with age for the control mix and mixes with Conoco CF. Mixes with Mitsubishi fibers exhibit higher splitting tensile strength and had better performance after 7 and 28 days than both control mix and mixes with Conoco CF.

Effect of adding CF on flexural strength of the concrete: Figure B-13 presents the influence of CF in the average flexural strength of concrete prism samples after 1, 7 and 28 days for control mix, mixes with Mitsubishi CF, and mixes with Conoco CF. All samples used PL90 as a water reducer. The standard deviations for flexure strength values were 3, 5 and 6% for control mix, mixes with Mitsubishi CF, and mix with Conoco CF, respectively. Mixes with Mitsubishi and Conoco CF had higher average flexural strength than the control mix. While mixes with Mitsubishi and Conoco fibers had similar flexural strength at 1 day, mixes with Mitsubishi CF had a slightly higher flexural strength than mixes with Conoco fibers at 7 and 28 days.

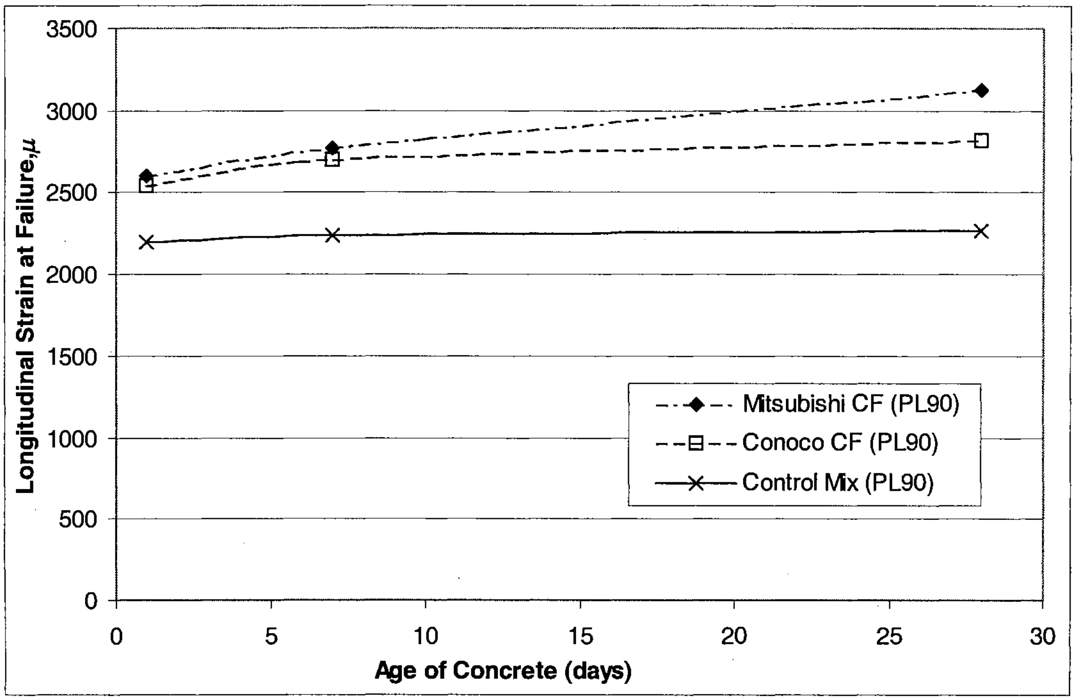

Figure B-11. Increase in Longitudinal Strain at Failure by Adding CF

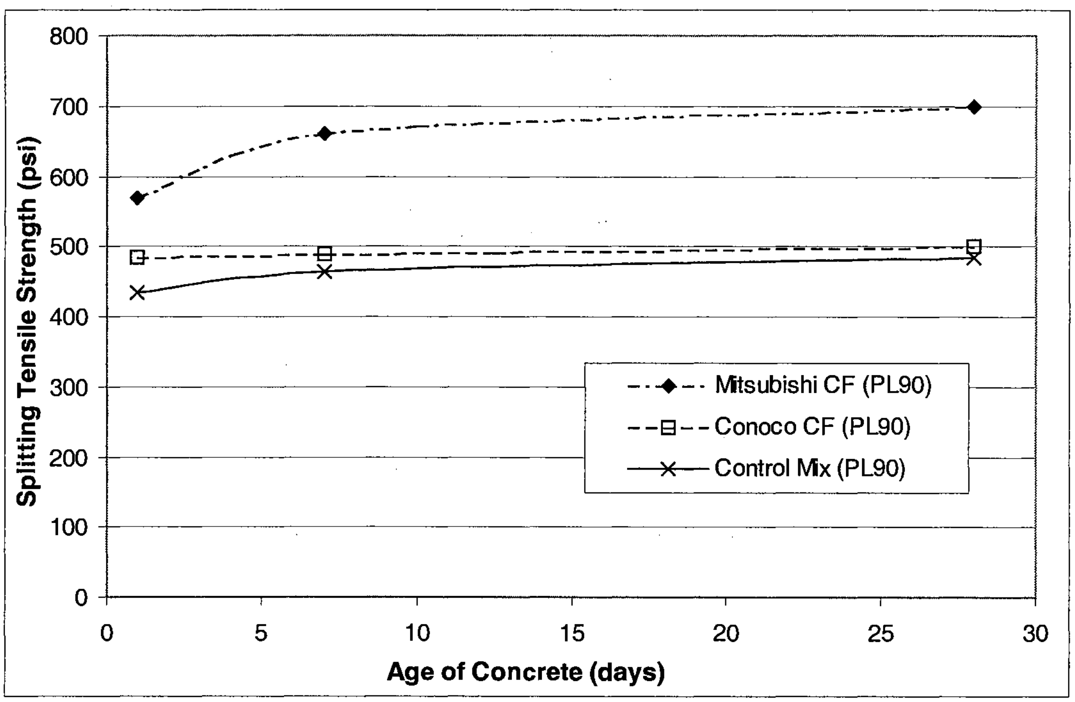

Figure B-12. Increase in Splitting Tensile Strength for Specimens with Mitsubishi CF

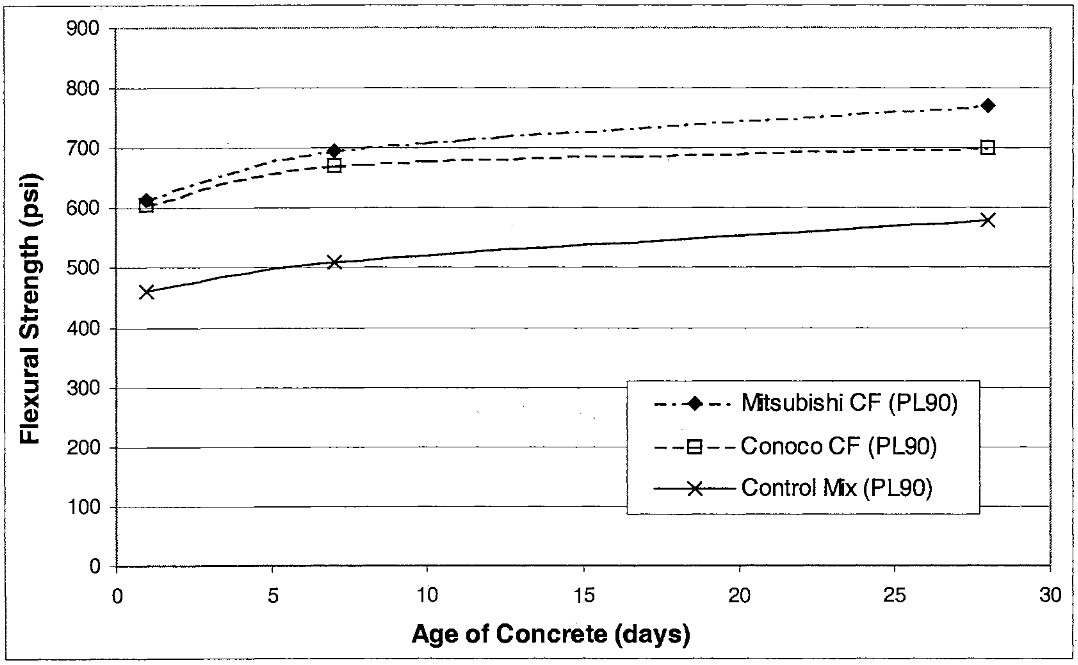

Figure B-13. Increase in Flexural Strength for Specimens with Mitsubishi or Conoco CF

Type of Additive: Figures B-14 to B-18 compare average mechanical properties of concrete samples made with Conoco CF and either PL90 water reducer or ML500 superplasticizer to the control mix made with PL90. As discussed earlier in the experimental detail section of this report, PL90 was added at a dosage used at North Star plant of 3 ml/kg of cement while ML500 was used at the manufacturer maximum recommended dosage of 16 ml/kg of cement. The average compressive strength values, shown in Figure B-14, for mixes with PL90 and ML500 were less than the average values for control mix especially at 7 and 28 days. Mixes with ML500 had slightly better performance than mixes with PL90. No significant compressive strength differences appeared to be for cylinders made with the two types of water reducer.

Figure B-15 presents the effect of type of additives on the average value for longitudinal strain at failure for cylinder compression tests for control mix, mixes with Conoco CF and PL90, and mixes with Conoco CF and ML500. The type of additive did not affect the strain at failure for samples with Conoco CF.

Figure B-16 presents the average static Modulus of Elasticity for control mix, mixes with Conoco CF and PL90, and mixes with Conoco CF and ML500. No significant differences in modulus of elasticity between the three mix designs.

Figure B-17 presents the average splitting tensile strength for control mix, mixes with Conoco CF and PL90, and mixes with Conoco CF and ML500. Mixes with ML500 had better performance than the other two mix designs after 7 and 28 days. Figure B-18 presents the average flexure strength for control mix, mixes with Conoco CF and PL90, and mixes with Conoco CF and ML500. Mixes with Conoco CF and either type of additives had higher flexure strength values than the control mix. Although mixes with Conoco CF and ML500 had lower average flexural strength than mixes with Conoco CF and PL90 after 1 day, ML500 mixes had better performance than PL90 mixes after 7 and 28 days.

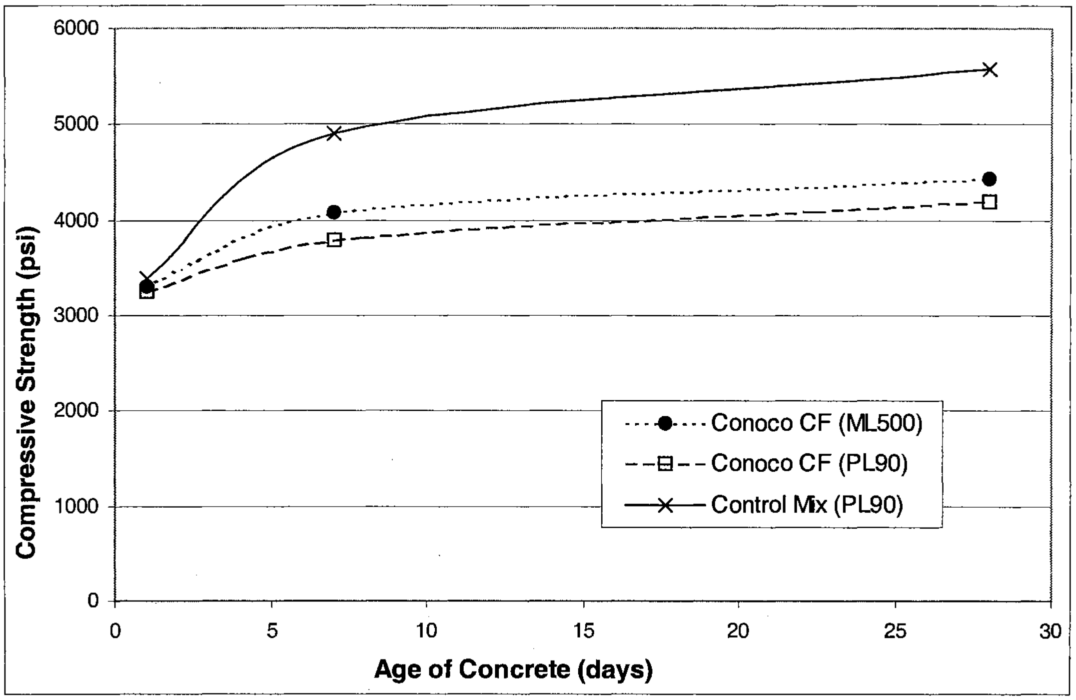

Figure B-14. Compressive Strength for Specimens with Superplasticizer (ML500) or Water Reducer (PL90)

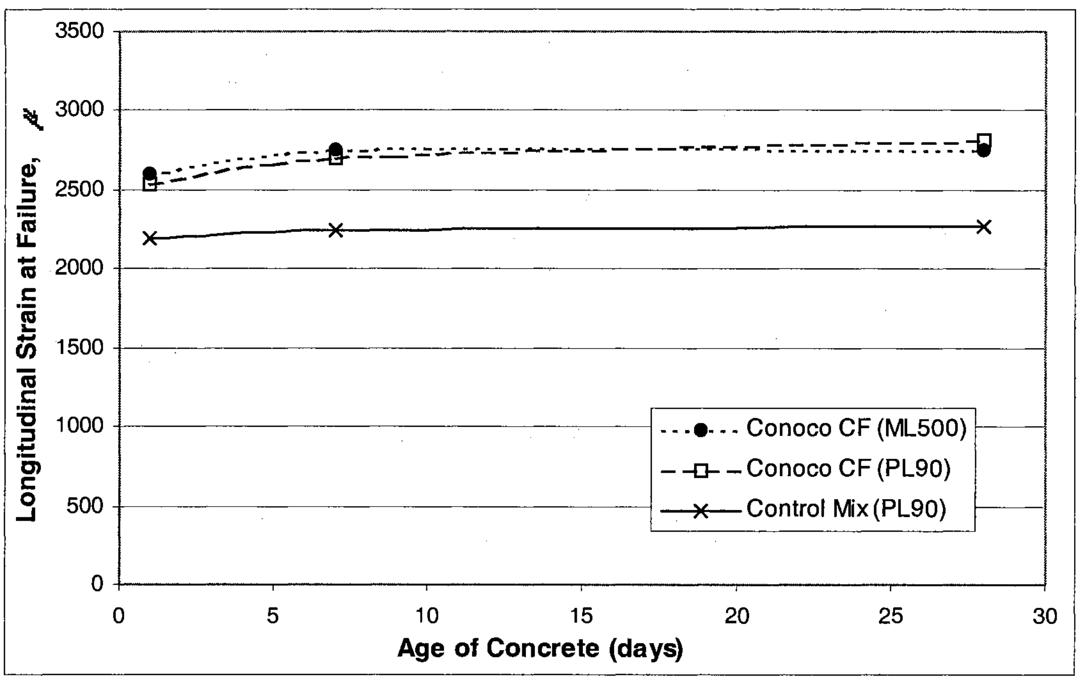

Figure B-15. Longitudinal Strain at Failure for Specimens with Superplasticizer (ML500) or Water Reducer (PL90)

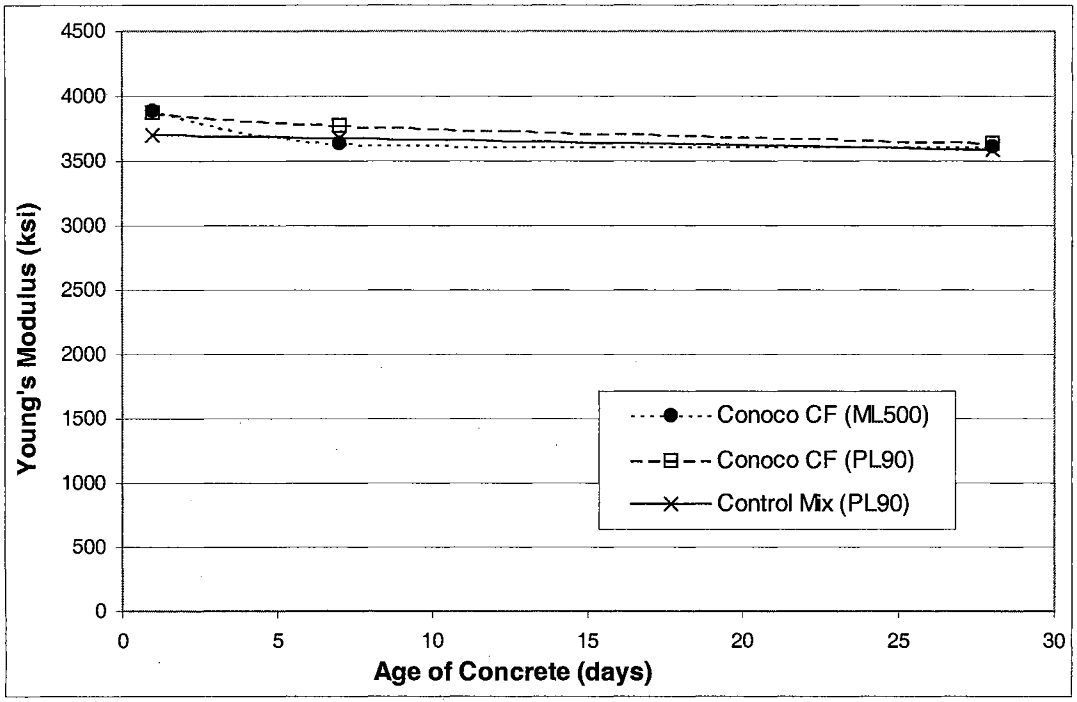

Figure B-16. Static Modulus of Elasticity for Specimens with Superplasticizer (ML500) or Water Reducer (PL90)

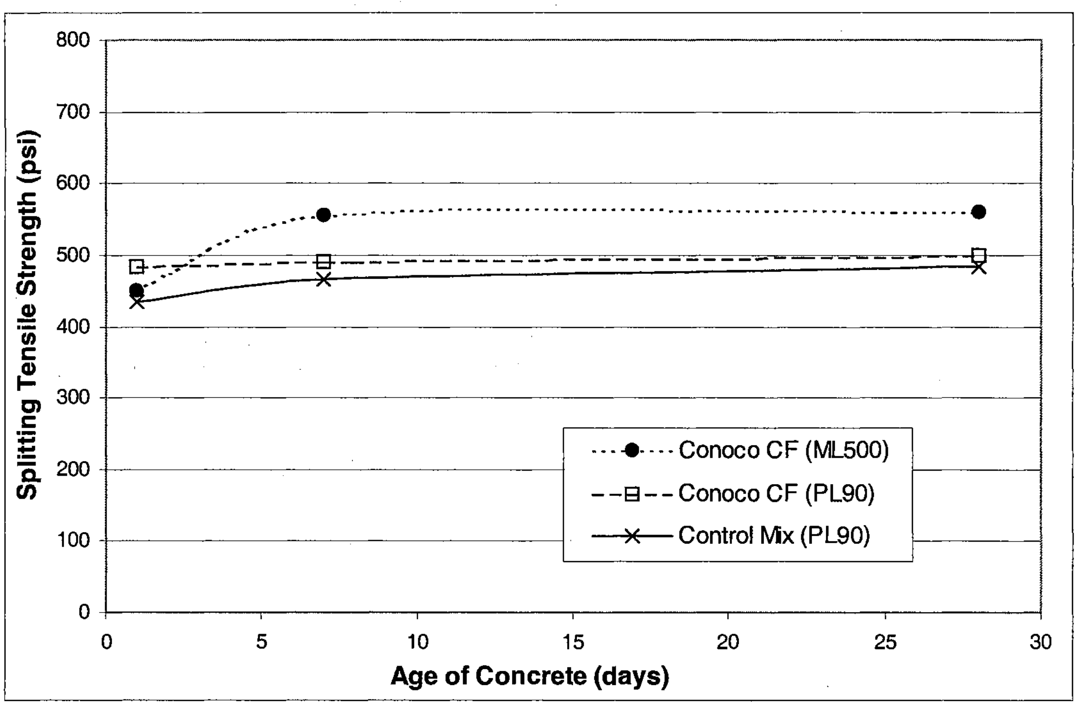

Figure B-17. Splitting Tensile Strength for Specimens with Superplasticizer (ML500) or Water Reducer (PL90)

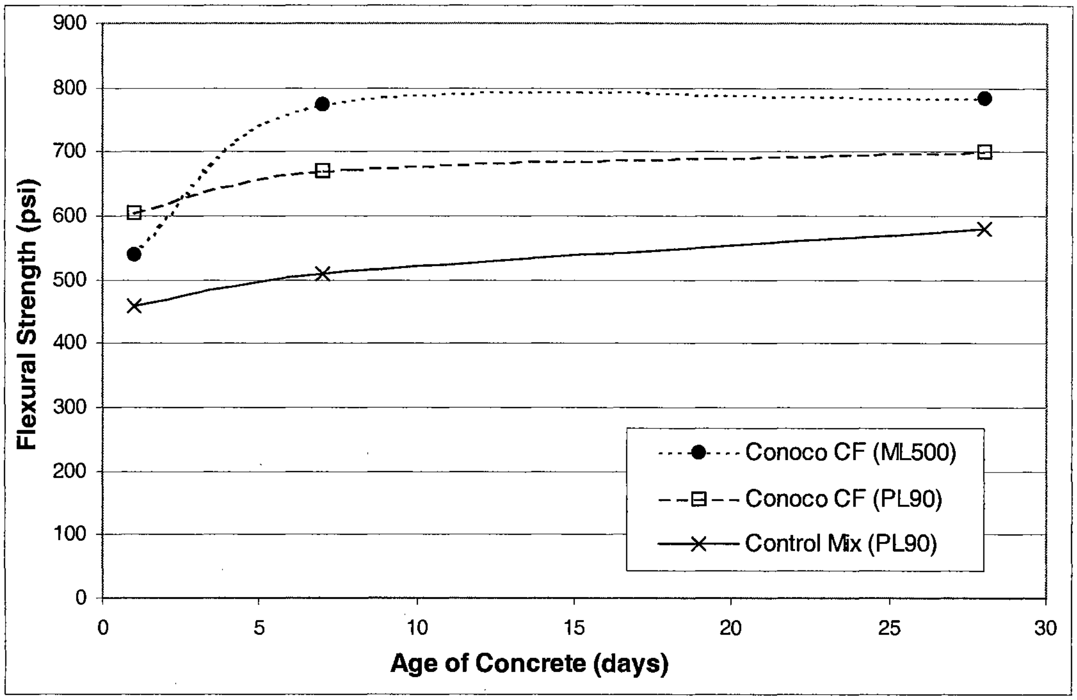

Figure B-18. Flexural Strength for Specimens with Superplasticizer (ML500) or Water Reducer (PL90)

Use of extra cement per unit volume and the effect on CF concrete: Figures B-19 through B-22 show results from using an extra 27-lb-per-yd^3 of concrete. Results in the figures are for mixes with Conoco CF and PL90 water reducer and control mixes made with PL90. Figure B-19 shows the average compressive strength values for the three mix designs. Mixes with Conoco CF and extra cement had slightly higher average compressive strength than mixes with Conoco CF without extra cement. However, mixes with Conoco CF and extra cement had lower compressive strength than the control mix after 7 and 28 days. Figure B-20 shows that the modulus of elasticity for mixes with Conoco CF and extra cement was slightly higher than the modulus of elasticity for the other two mixes. Figure B-21 shows that mixes with Conoco CF and extra cement had slightly higher average splitting tensile strength than mixes with CF without extra cement especially after 7 and 28 days. Both mixes with Conoco CF had slightly higher splitting tensile strength than the control mix. Figure B-22 shows that mixes with Conoco CF and extra cement had similar average flexure strength as mixes with CF without extra cement. Both mixes with Conoco CF had slightly higher flexure strength than the control mix.

Conclusions and discussion:

Based on the results presented in this report and the results obtained at earlier phases of the project, concrete with CF can be used in the production of concrete pipes. The main goal is to have a dry mix and dense concrete to withstand removing molds immediately after mixing and has suitable mechanical properties to resist induced stresses during operational life. At OSU laboratory, batches with lower dosage of water reducer, PL90, and batches with moderate dosage of superplasticizer, ML500, had suitable wetness for pipe production. In this report, only batches with high dosage of superplasticizer, 16 ml/kg of cement, were presented and those batches did

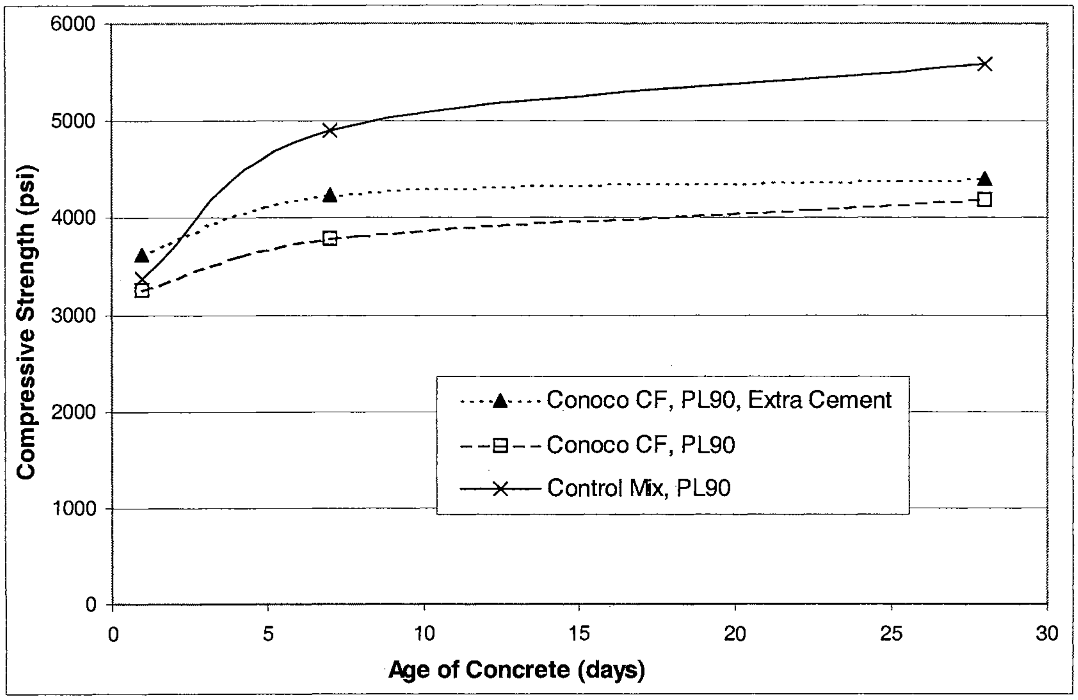

Figure B-19. Increase in Compressive Strength with Increase in Cement Content

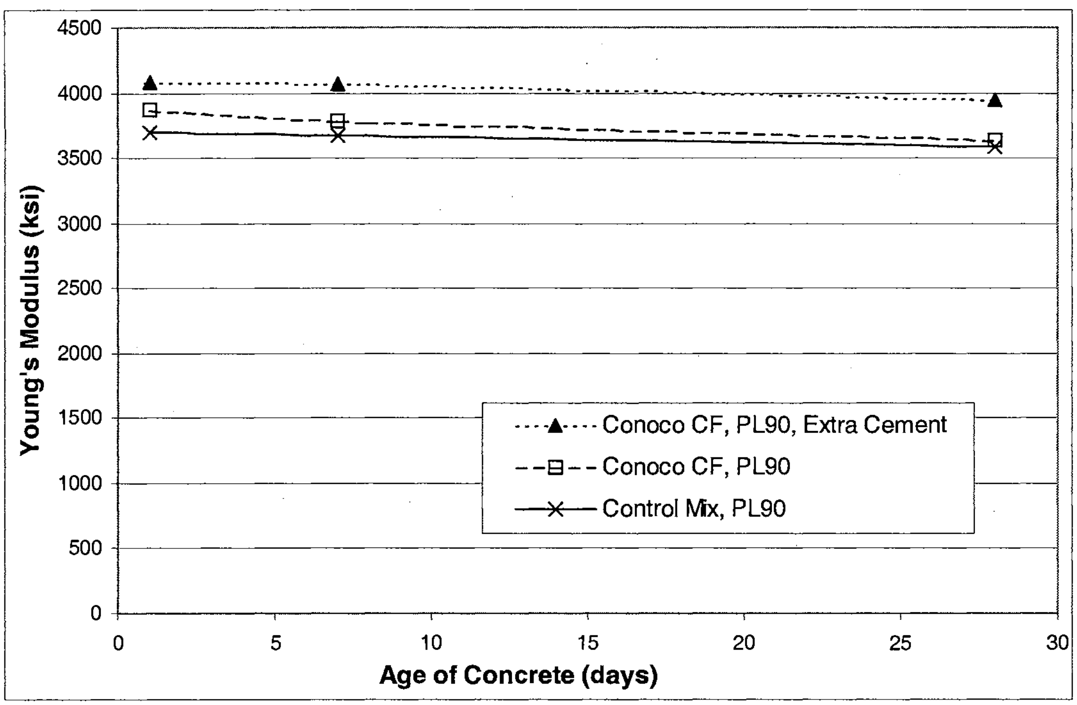

Figure B-20. Increase in Static Modulus of Elasticity with Increase in Cement Content

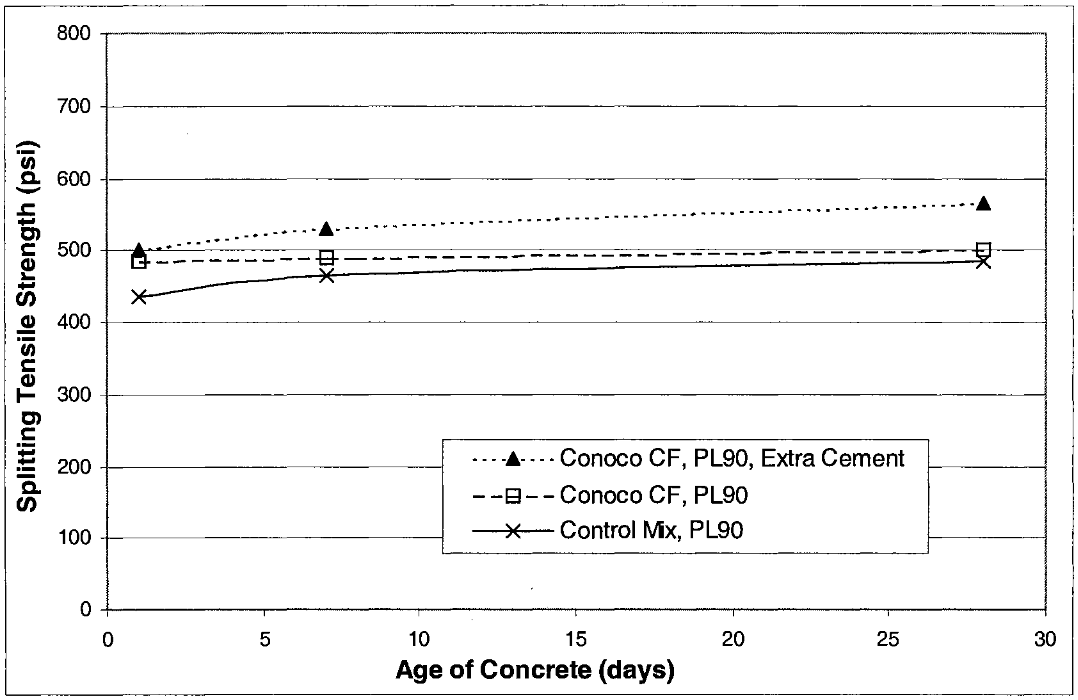

Figure B-21. Increase in Splitting Tensile Strength with Increase in Cement Content

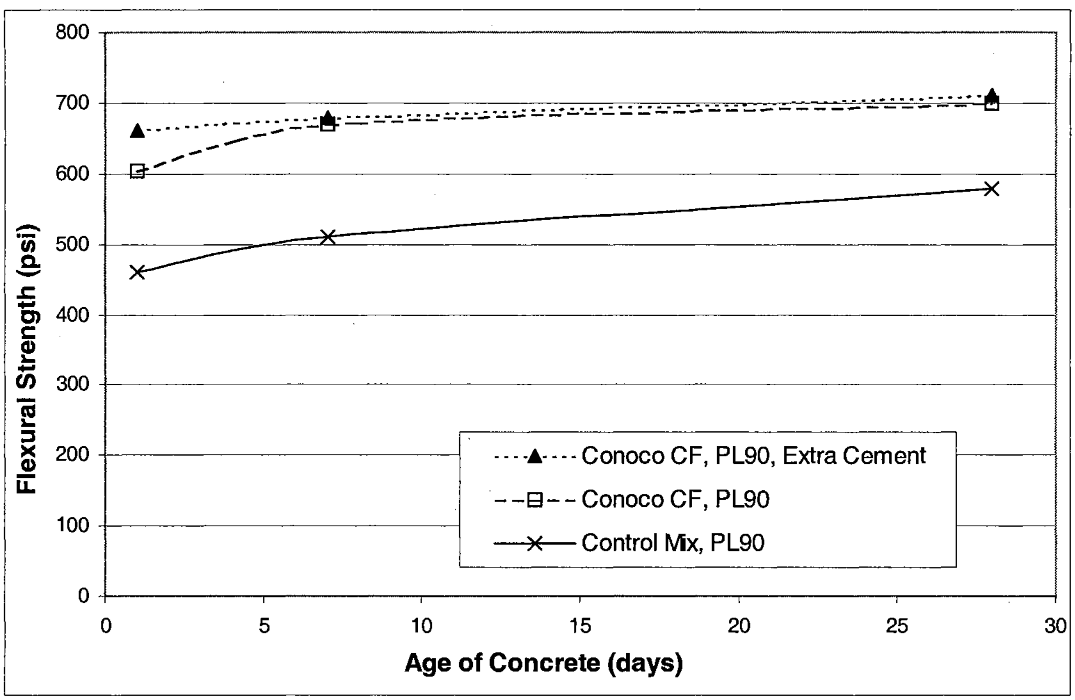

Figure B-22. Effect on Flexural Strength with Increase in Cement Content not have the dryness suitable for pipe production and was presented for comparison of fresh and hardened properties of concrete samples.

The consolidation method used in the OSU concrete laboratory did not provide the required dense concrete suitable for pipe production. This consolidation method was highly dependable on the physical characteristics of batching personnel and was not under good quality control as that provided at the North Star plant.

Carbon fiber concrete produced at OSU had a high percentage of air content and lower density, which was detrimental to mechanical properties of concrete samples. A high percentage of entrapped air in the samples resulted from the dispersed fibers that acted as mesh inside the concrete and prevented air bubbles to escape with the method of consolidation used at the OSU laboratory. High values of standard deviation for the mechanical properties of concrete samples could be lowered had a better method of consolidation been used, such as the one adopted by North Star.

Comparing the mechanical property results for CF concrete to concrete without CF was difficult since other factors, like air content and slight change in mix proportions, affected the results. The comparison will be summarized here for references.

Adding CF to concrete resulted in lowering compressive strength—5 and 15% in average for Mitsubishi and Conoco CF, respectively. The modulus of elasticity was not altered by the presence of Conoco CF; however, it was lower for Mitsubishi CF samples. Adding CF resulted in increasing the average value of longitudinal strain at failure for compression cylinder tests, 20 and 15% in average for Mitsubishi and Conoco CF, respectively. Adding CF resulted in increasing splitting tensile strength by 35 and 7% in average for Mitsubishi and Conoco CF, respectively. Also, the flexure strength increased by the presence of CF by 35 and 27% in average for Mitsubishi and Conoco CF, respectively.

Concrete samples with Mitsubishi CF had better performance than samples with Conoco CF. Samples with Mitsubishi CF had higher compressive strength, strain at failure, splitting tensile strength, and flexure strength than mixes with Conoco CF. Concrete with Mitsubishi CF had lower modulus of elasticity than concrete with Conoco CF.

The effect of using the two type of additives, water reducer PL90 vs. superplasticizer ML500, was not noticeable in the mechanical property results for concrete with Conoco CF. For mixes with Conoco CF, increasing the amount of cement by 5% slightly improved the average mechanical properties; 10% increase in compressive strength, 8% increase in splitting tensile strength, and 2% in flexural strength.

B.5 Field Trial at Coreslab

After reviewing the laboratory results, a field trial was undertaken at a local concrete plant. The main objective of the field trial was to determine if results obtained in the laboratory could be duplicated when concrete is produced under conditions similar to those at North Star. The Coreslab Structures plant in Oklahoma City, OK, was selected to run the field trial.

Test Description: The agreement with Coreslab was to cast two 2 yd^3 batches in their plant. Mix categories 4-1 and 4-2 were selected because of their overall good results for fiber dispersion and strength and the availability of all mix components in the required quantities. Both mixes have the same cement content (47 lb/yd^3 more than AMX-5), water-to-cement ratio, sand-to-coarse aggregate ratio, and fly ash-to-cement ratio. Category 4-1 has a 1% fiber content by volume while category 4-2 has a 2% fiber content by volume; the amounts of sand and coarse aggregate were adjusted accordingly to give the same batch volume for both mixes. The mix design for category 4-1 is as follows:

1% Fibers Cat. 4-1	Weight (lb)	Specific Gravity	Volume (ft^3)	Percent of Mix (by wt)	Ratio to Cement (by wt)
Cement	611	3.15	3.11	15.34%	1.000
Fly Ash	169	2.5	1.08	4.24%	0.277
Sand	1843	2.62	11.27	47.16%	3.016
Rock	1103	2.52	7.02	27.70%	1.805
Water	189	1	3.03	4.75%	0.309
Fibers	32	1.9	0.27	0.80%	0.052
Metakaolin	0	2.5	0.00	0.00%	0.000
Air Content	4.50%			1.22	
Σ	3982			27.00	

Aggregate Breakdown 63% sand and 37% rock

Superplasticizer was used in both mixes at a dosage of 10 ml/kg of cement. Melment 330 was used for the first batch. Because there was insufficient Melment 330 to prepare the second batch, a mixture of Melment 330 and Daracem 100 (a water reducer used at the Coreslab plant) was used for the second batch (approximately 40 and 60%, respectively).

Coreslab sand and coarse aggregate were used in this test; sand had a lower fineness modulus than North Star while the coarse aggregate was similar to North Star (pea gravel ASTM C33 size No. 8). Due to a lack of communication with Coreslab personnel, moisture content of sand and gravel were not considered when adding water to the first mix. The exact water-to-cement ratio was not determined for the first mix; nevertheless, it appeared to be wetter than the North Star mixes. For the second mix, water was added gradually to the mixer until the mix consistency was similar to North Star. Following are the results from the two batches:

Mix Category	Compressive Strength (psi)	Split Tensile Strength (psi)	Flexural Strength (psi)	Fiber	% of Entrapped Air Dispersion
4-1	6560	680	775	Fair	4.4
4-2	4780	685	675	Fair	9.9

Conclusions: There was agreement in results of the OSU concrete laboratory and Coreslab tests for fiber dispersion. After discussing the results with DuPont, it was agreed that the decrease in strength for the second mix was due to an increase in percentage of air entrapped (decrease in density).

B.6 Field Trial at North Star

An important objective in this phase was to manufacture pipes at the North Star concrete plant in Apple Valley, MN. Results and conclusions from laboratory work at OSU and from the field trial at Coreslab Structures gave a starting knowledge for the experiment at North Star. This experiment was conducted from November 18- 22, 1996.

Experimental Details: The plan was to cast several pipes using certain mix categories designed at OSU that gave the best overall results. North Star personnel suggested adding Mitsubishi CF to the existing mix design, AMX-5. After initial mixing of the first batch, North Star personnel determined that additional water was required to give acceptable cohesiveness. Three different fiber contents were used in these mixes: 1, 1.5 and 2% by volume. Two pipes with an 8-ft length and an inside diameter of 60 in. were made from each mix, a total of six pipes. Figure B-23 shows the pipes immediately after demolding and before entering the steam chamber. Figure B-24 shows a close-up of the outer surface of a pipe with fibers at 1.5% by volume.

An ASTM C-76, class V concrete pipe must carry 3000 lb/linear ft/ft of diameter at a crack width of 0.01 in. and 3750 lb/ft/ft at ultimate. North Star reported that if this size of pipe is fabricated without stirrups and with normal flexural reinforcement, the ultimate strength will be approximately 3000 lb/ft/ft. If they add their standard stirrups reinforcement, the ultimate strength is increased to approximately 5400 lb/ft/ft. They would desire a typical ultimate strength of about 3900 lb/ft/ft, somewhat greater than the ASTM minimum strength. To determine if CF can replace

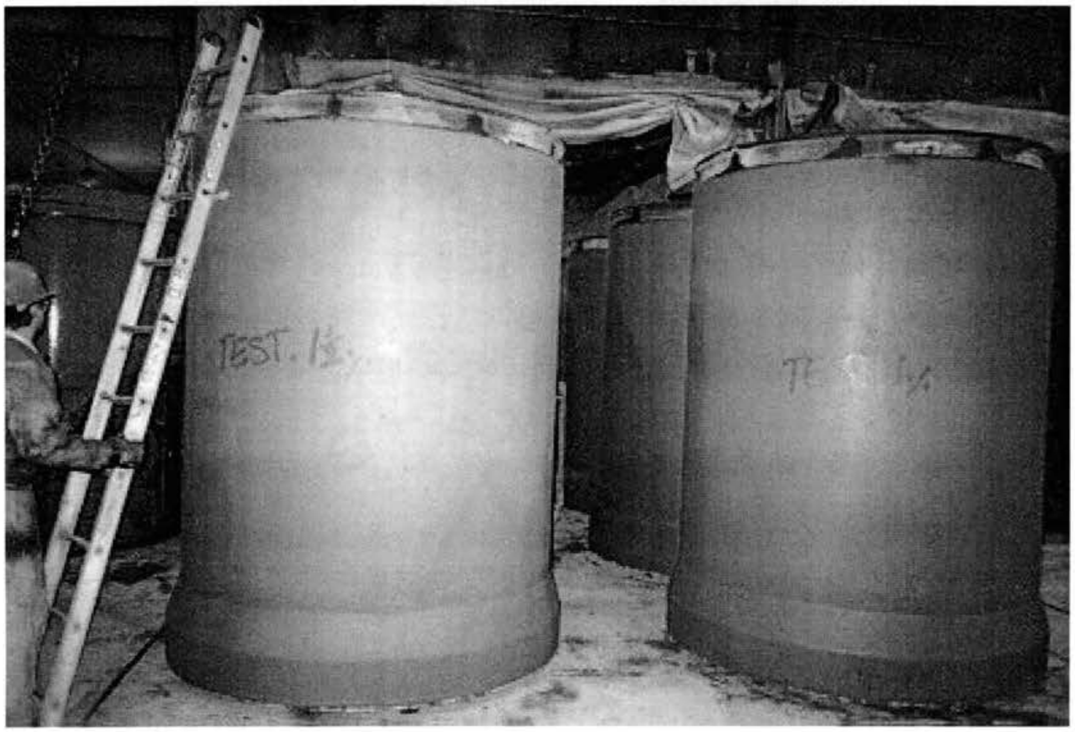

Figure B-23. Pipe Immediately After Demolding

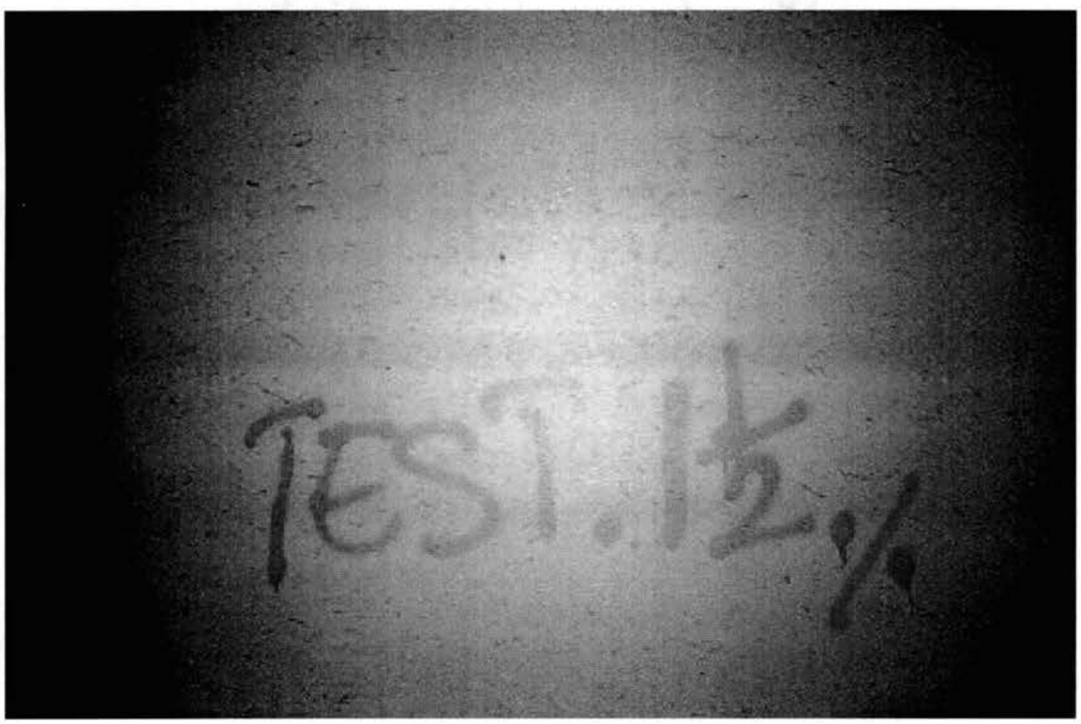

Figure B-24. Pipe Surface Showing Undispersed Fibers stirrups reinforcement, the pipe specimens were cast with standard flexural reinforcement and no shear reinforcement. Two 4 x 8 cylinders and two 4 x 4 x 14 in. prisms were taken from the mix containing 1.5% fiber by volume and consolidated using an air-driven vibration table. Several hours after fabrication, the pipes and control specimens were subjected to 49°C steam curing for 5 hr and allowed to gradually cool to ambient temperature.

One pipe section contains 1% CF was tested at an age of 2 days in accordance with ASTM C-497. Figure B-25 shows the pipe installed in the load frame. In the spring of 1997, North Star personnel removed cores from the pipe wall and shipped the concrete to OSU for evaluation. North Star personnel tested other pipes at later ages. North Star will present a full report to DuPont covering tests at the North Star plant.

Test Results: According to North Star personnel, finishing and demolding of all products manufactured using CF were acceptable from a handling and marketing point of view. The degree of fiber dispersion achieved by North Star mixing equipment was similar to that obtained at OSU.

The pipe tested at 2 days had a 0.01-in. crack and ultimate strength of 2930 and 3560 lb/ft/ft, respectively. Figures B-26 and B-27 show cracks formed in the pipe during the test. While the pipe did not meet ASTM strength requirements, the proof test is usually conducted several days after casting. North Star informed DuPont that another pipe tested several weeks later had an ultimate strength of 4200 lb/ft/ft, above the target strength of 3900 lb/ft/ft.

Cylinders and prisms made at the North Star plant were tested at an age of 5 months. The average Young's modulus and compressive strength was 3400 ksi and 5900 psi, respectively; Figure B-28 presents a stress-strain curve for one of the cylinders. The average values for first-crack toughness, toughness index I5, and flexural strength for prisms were 3.4 in.-lb, 2.1 and 715 psi, respectively.

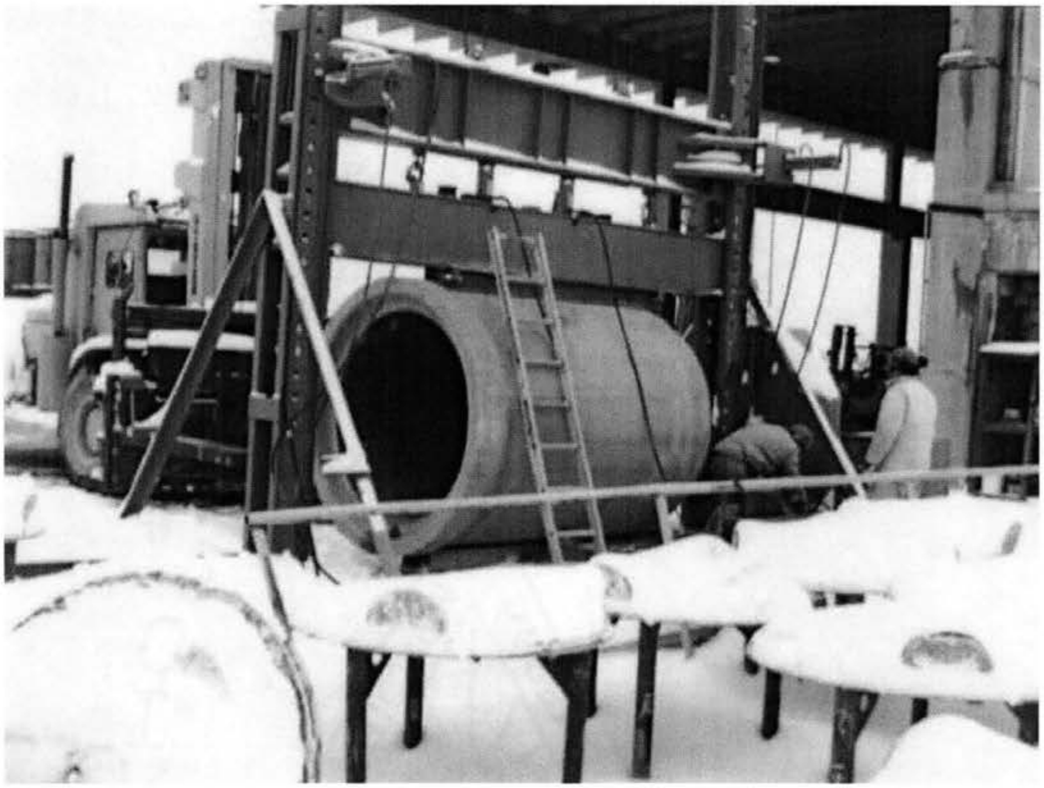

Figure B-25. Test Frame for ASTM C-497 Three-Edge Bearing Test

Figure B-26. Crack Formed at the Inner Surface of the Pipe

Figure B-27. Surface Crack Near Upper Load Point

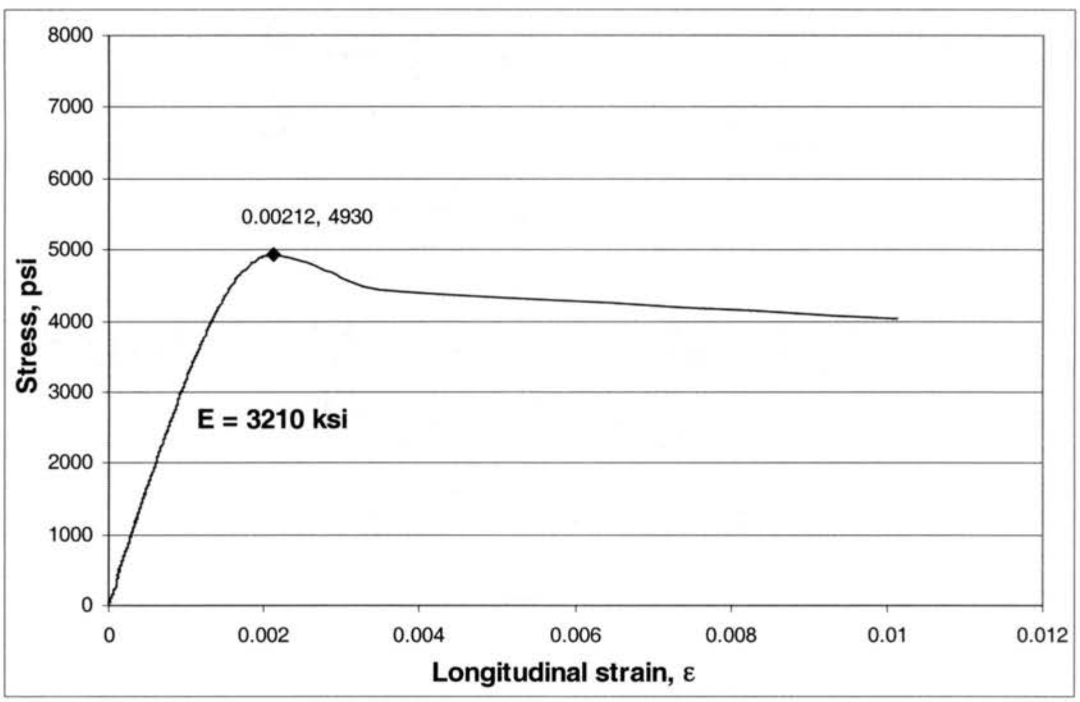

Figure B-28. Stress-Strain Curve for North Star Concrete Cylinder

Figure B-29 presents a load-displacement curve for one of the prisms in accordance with the ASTM C-1018 test method. The specimens had an average density of 142 lb/ft^3 which corresponds to an air content of 8.2%.

Cores supplied by North Star had diameters of 7, 10 and 15 in and a length of 6-3/4 in, the pipe wall thickness. Since the pipe was reinforced with two cages of welded wire fabric (WWF), it was difficult to obtain plain concrete cylinders and prisms to test. Using a brick saw, it was possible to obtain two prisms with nominal dimensions of 4 x 4 x 14 in; these specimens were obtained from a 15-in. core and contained only small amounts of WWF which were placed at the compression face during ASTM C-1018 tests. To obtain cylinders for compression tests, the cores provided by North Star were recorded using a 3-in. bit.

Figure B-30 shows delamination present in the region of the WWF. It is not known if similar defects are present in the pipe manufactured without CF. A brick saw was used to remove the region near the WWF. Four cylinders with an outside diameter of 2.75 in. and an average length of 3.5 in. were obtained for tests. The cylinders and prisms had an average density of 146 lb/ft^3 which corresponds to an air content of 5.8%.

When tested at an age of approximately 7 months, the average compressive strength of the cores was 7940 psi. The average values for first-crack toughness, toughness index I5, and flexural strength of the prisms were 2.39 in-lb, 2.6 and 795 psi, respectively. A load-displacement curve for one of the prism specimens is presented in Figure B-31.

Discussion of North Star Results:

Experiments at North Star demonstrated that CF can be used in concrete pipe production. Pipes with CF produced in this test were satisfactory from demolding, handling, and appearance points of view. After allowing concrete to mature, pipe made with CF satisfied the strength

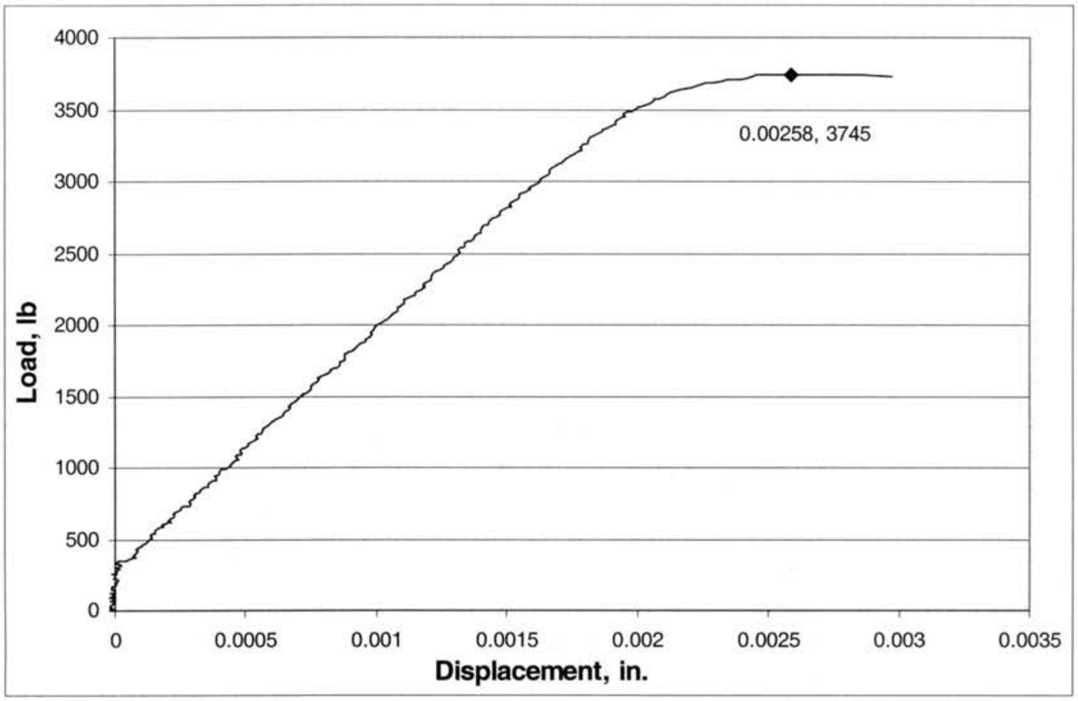

Figure B-29. Load-Displacement Curve for North Star Concrete Prism

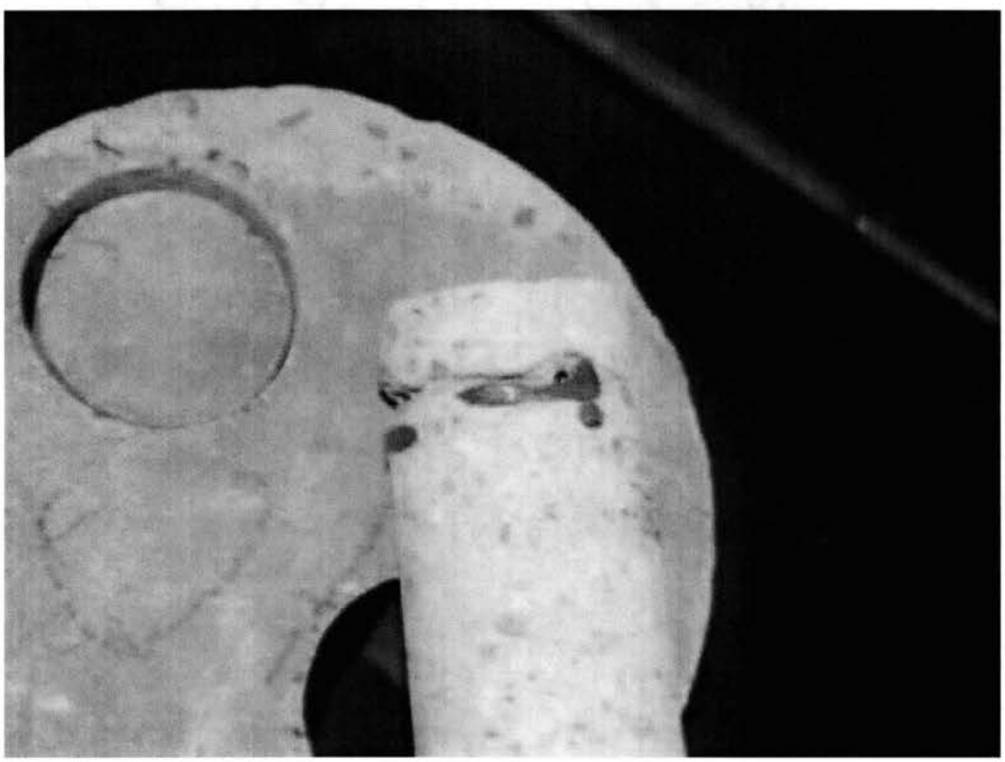

Figure B-30. Delamination Near WWF for Core Samples From North Star

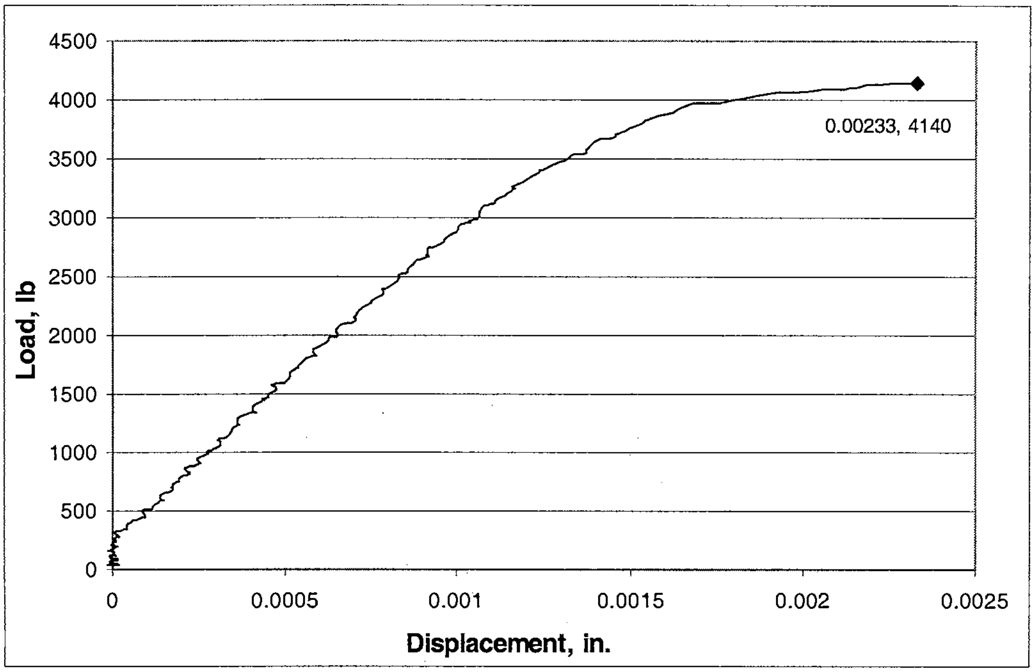

Figure B-31. Load-Displacement Curve for a Prism Sawed From North Star Core Samples requirements for ASTM C-76 class V pipes. Specimens made from cores taken from one of the pipe walls had a higher unit weight and greater strength than specimens consolidated using a vibration table. If future work is to accurately reflect the high compaction achieved during the manufacture of pipe, a different type of laboratory consolidation apparatus will be required. North Star personnel did not use mixes developed during the OSU laboratory work. If one of those mixes had been used for the field trial, the resulting concrete would have had greater strength and toughness.

B.7 Summary and Conclusion

The main objective for this phase of the project was to develop one or more concrete mixes suitable for production of concrete pipe. Based on results presented in this section, concrete with CF can be used in the production of concrete pipes. The main goal is to have a dry mix and dense concrete to withstand removing molds immediately after mixing and has suitable mechanical properties to resist induced stresses during operational life. At the OSU concrete laboratory, batches with a lower dosage of water reducer, PL90, and batches with moderate dosage of superplasticizer (ML500), 8 to 12 ml/kg of cement, had suitable wetness for pipe production.

The consolidation method used in the OSU laboratory did not provide the required dense concrete suitable for pipe production. This consolidation method was highly dependable on the physical characteristics of batching personnel and was not under good quality control as that provided at the North Star plant. Carbon fibers concrete produced at OSU had high percentage of air content, lower density, which was detrimental to mechanical properties of concrete samples. High percentage of entrapped air in the samples resulted from the dispersed fibers that acted as mesh inside the concrete and prevented air bubbles to escape with the method of consolidation used at the OSU concrete laboratory. The high values of standard deviation for the mechanical properties of concrete samples could be lowered had a better method of consolidation, as the one adopted by North Star, been used.

Comparing the mechanical property results for CF concrete to concrete without CF was difficult since other factors, like air content and slight change in mix proportions, affected the results. The comparison will be summarized here for reference.

Adding CF to concrete lowered compressive strength 5 and 15% in average for Mitsubishi and Conoco CF, respectively. The modulus of elasticity was not altered by the presence of Conoco CF; however, it was lower for Mitsubishi CF samples. Adding CF increased the average value of longitudinal strain at failure for compression cylinder tests, 20 and 15% on average for Mitsubishi and Conoco CF, respectively. Adding CF increased splitting tensile strength by 35 and 7% in average for Mitsubishi and Conoco CF, respectively. Also, the flexure strength increased by the presence of CF by 35 and 27% on average for Mitsubishi and Conoco CF, respectively.

Concrete samples with Mitsubishi CF had better performance than samples with Conoco CF. Samples with Mitsubishi CF had higher compressive strength, strain at failure, splitting tensile strength, and flexural strength than mixes with Conoco CF. Concrete with Mitsubishi CF had a lower modulus of elasticity than concrete with Conoco CF.

The effect of using two types of additives—water reducer PL90 vs. superplasticizer ML500—was not noticeable in the mechanical property results for concrete with Conoco CF. For mixes with Conoco CF, increasing the amount of cement by 5% slightly improved the average mechanical properties, 10% increase in compressive strength, 8% increase in splitting tensile strength, and 2% increase in flexural strength.

APPENDIX C

Application of CFRC in Precast Production

C.1 General

Precast members such as double-tee sections often experience cracking of flange elements during handling operations. Because flanges are typically reinforced with welded wire fabric (WWF), these cracks are seldom serious from a strength standpoint but can be aesthetically objectionable.

In this phase, research focused on the use of CF reinforced concrete to investigate cracking in the flange of precast members. The project was conducted with the cooperation of Coreslab Structures, a precast plant in Oklahoma City, OK. The plant produces prestressed beam and wall elements with single- and double-tee sections in addition to other prestressed structural elements.

C.2 Objectives and Scope

Objectives of this section of the research were: (1) develop one or more CF mixes with fresh and hardened concrete properties suitable to manufacture precast concrete double-tee sections; and (2) study the ability of CF to control flexural cracks in the cantilever flanges of double-tee sections.

To achieve these goals, OSU and DuPont agreed to begin this phase of the project with the development of precast concrete mixes containing CF. Coreslab uses two standard mixes to produce prestressed concrete—one with lightweight coarse aggregate and the other with normal weight coarse aggregate. The proportions of these mixes would be adjusted to permit the use of

CF in the concrete. After completion of laboratory work at OSU, field tests would be conducted at the Coreslab Structures plant with a higher batch volume (1 to 2 yd^3) to cast short double-tee beam specimens. Tests would be conducted at the OSU concrete laboratory on those samples to determine their mechanical properties and the effect of adding CF to precast mixes.

C.3 Laboratory Work at OSU

Experimental Details: Coreslab provided OSU with its mix proportions used to produce prestressed concrete as well as data on its aggregate. Type III portland cement was used by Coreslab and in OSU laboratory. While Coreslab employs steam to heat forms—there is no release of steam into the atmosphere—concrete at OSU was cured by atmospheric steam.

Before the laboratory work at OSU was completed, DuPont personnel asked to conduct field tests at the Coreslab plant (refer to Field Trial at Coreslab Structures, Appendix B, section B.5). During the field test, it was determined that the actual water reducer dosages were 1½ times the values supplied earlier by Coreslab; these new dosages were used in subsequent batches. The aggregate used in the field test was sand-lightweight. Laboratory work after the field test focused on mixes with sand-lightweight aggregate.

Aggregate: Coreslab uses sand with a fineness modulus of 2.55, specific gravity of 2.63, absorption of 0.6 percent, and normal and lightweight coarse aggregate. The normal weight coarse aggregate is limestone with a specific gravity of 2.69. The normal weight mix design in this work contained ASTM C-33, size No. 7 with a fineness modulus of 6.30. The lightweight coarse aggregate conformed to ASTM C-330, size 1/2 to No. 4, with a fineness modulus of 6.30 and a specific gravity of 1.89. The fine and coarse aggregate gradations supplied by Coreslab are shown in Table C-1:

Table C-1

Aggregate Gradation Used at Coreslab Structures

Screen	Ind. % Retained	Accum. % Retained	Ind. % Passing	ASTM C-33 Passing
Sand				
No. 4	1.2	1.2	98.8	95 to 100
No. 8	4.7	5.9	94.1	80 to 100
No. 16	14.0	19.9	80.1	50 to 85
No. 30	28.1	48.0	52.0	25 to 60
No. 50	41.8	82.8	17.2	5 to 30
No. 100	14.1	96.9	3.1	0 to 10
Pan	0.0			
Fineness Modulus	2.55			
Surface Moisture	6%			
Absorption	0.6%			
Lightweight Coarse Aggregate (ASTM C-330 Size ½ to No. 4)				
3/4"	0.0	0.0	100.0	100
1/2"	5.5	5.5	94.5	90 to 100
3/8"	33.1	38.6	61.4	40 to 80
No. 4	48.5	87.1	12.9	0 to 20
No. 8	11.9	99.0	1.0	0 to 10
Pan	1.0			
Fineness Modulus	6.3			

At OSU, sand used previously for the North Star phase of the project was also used in this project and had a fineness modulus of 2.77, specific gravity of 2.62 and absorption of 0.4 percent. The OSU sand gradation is presented in Figure B-1. Adjustments were made in mix proportions at OSU to reflect the differences between sand absorption at OSU and Coreslab. For laboratory work at OSU, normal weight coarse aggregate was obtained from Coreslab. Coreslab obtained lightweight coarse aggregate from Chandler materials; aggregate is metered from three storage bins producing a blend meeting ASTM C-330, size ½ to No. 4. For the work at OSU, lightweight coarse aggregate from Chandler materials was obtained in three separate sizes and later combined in proper proportions at the time of mixing. The gradations are presented in Figure C-1.

At Coreslab, the aggregate were delivered to the plant site with a moisture content of approximately 6 percent above SSD (saturated-surface dry) condition and then used in batching over a period of time which altered the moisture content at time of mixing. The Coreslab personnel adjusted the amount of mixing water at mixing time to achieve the target slump value. Also, the aggregates were added to concrete mixer by volume. At OSU laboratory, two different approaches were used to control the moisture content of the aggregates; one approach was used for sand and normal weight aggregates and the second approach was used for lightweight aggregate. The sand and normal weight aggregate were set in laboratory atmosphere to dry and then stored in bins where the moisture content of each aggregate was measured.

The lightweight aggregate were delivered at the OSU concrete laboratory and immediately stored in barrels. The lightweight aggregate were soaked in water for 24 hours and then set in covered containers to drain excess water for another 24 hours and then used in batching. At mixing time, the amount of mixing water was adjusted to reflect the differences between the actual moisture content of each type of aggregate and SSD condition.

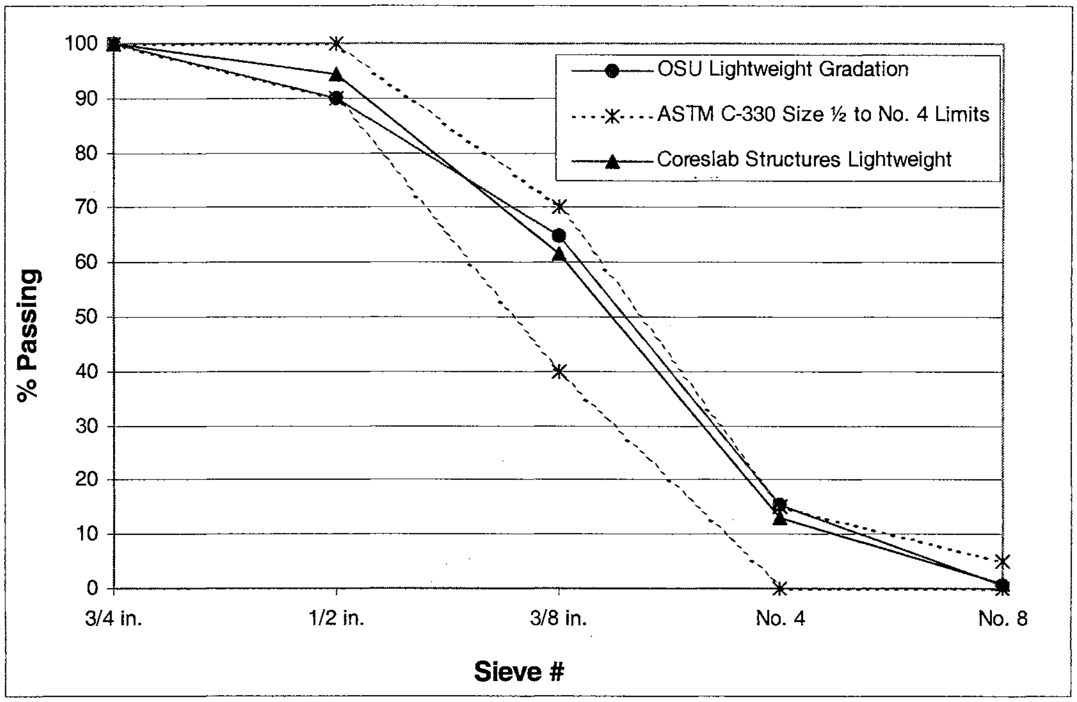

Figure C-1. Lightweight Aggregate Gradation Used at OSU and Coreslab

Carbon Fibers: Mitsubishi CF was used in laboratory work at OSU. For lightweight mixes, all the batches used a dosage of 1 percent by volume.

Defoamer: In an earlier phase of this project, when CF reinforcement was used in a workable mortar or concrete mix, large quantities of air were entrapped in the mix. These batches required a defoamer to decrease the amount of entrapped air. Defoamer (Colloid 770DD from Rhône-Poulenc Inc.) was used at dosages of 0.15 or 0.2 percent by weight of cement in some batches to determine its influence on the percentage of entrapped air in concrete samples.

Admixture: Coreslab uses two types of admixtures: a water reducer agent (Daracem 100 from W. R. Grace which conforms to ASTM C-494) and an air-entraining agent (Daravair 1000 from W. R. Grace which conforms to ASTM C-260). These two admixtures were also used in the OSU concrete laboratory work. Since CF entrapped air in the batches, the air-entraining agent was only used in control batches; did not contain CF. The manufacturer's recommended dosage for Daracem 100 is 6 to 16 ml/kg of cement.

Mix Proportions: Coreslab furnished mix proportions for sand-lightweight and normal weight mixes used to produce prestressed concrete. Those mix designs are presented in Appendix E. As mentioned earlier, the actual dosages of water reducer used by Coreslab are 1½ times the values shown in Appendix E; thus the water reducer dosages used at the plant are 103 and 154 oz/yd^3 (9.8 and 14.6 ml/kg of cement) for lightweight and normal weight mixes, respectively. In OSU mixes, several dosages of the water reducing agent were used (6.6, 9.8, 12 or 16 ml/kg of cement for both lightweight and normal weight mixes).

In adjusting mix proportions, it is convenient to present various mix components as weight per unit volume (1 yd^3) of concrete. In the Coreslab mix, the unit volume was the sum of cement, sand, coarse aggregate, water, and air content volumes. To better simulate the concrete mix produced in Coreslab, a control mix was designed at OSU laboratory. The control mix had the same volumetric contribution of each mix component as the mix design for Coreslab. Sand used at the OSU concrete laboratory had a slight different specific gravity than sand used at Coreslab, thus the control mix used in the OSU concrete laboratory had a different sand weight by yd^3 than the sand weight used in Coreslab mix design. The mix components for sand-lightweight control mix were as follows:

	Weight lb	Specific Gravity	Volume ft^3	Percent of mix (by wt.)	Ratio of cement (by wt.)
Cement	686	3.15	3.49	21.55	1.000
Sand	1001	2.62	6.12	31.45	1.459
Coarse	1200	1.70	11.31	37.70	1.749
Water	296	1.00	4.74	9.30	0.431
Air Content	5.00%		1.35		
Σ	3183	27.01			

Water Reducer	103 oz
Air Entraining	7 oz
Unit Weight:	118 pcf
Slump:	5 3/4 in

The approach used to design CF mixes at the OSU concrete laboratory was to have a target slump of 5 ¾ in. and adjust the amount of water/cement ratio for each dosage of water reducer used. After several trial batches it was found that the water/cement ratios were 0.59, 0.504, 0.497 and 0.487 with dosages of 6.6, 9.8, 12 or 16 ml/kg of water reducer, respectively, for sand-lightweight mixes. The air-entraining agent was not used in CF mixes since the presence of CF increased percentage of air content in concrete. The percentage of air content was calculated using the gravitational method and the average value was found to be 6 percent for CF mixes. The amount of CF added for each yd^3 was 32 pounds (1 percent by volume) and the mix design for sand-lightweight concrete with water reducer dosage of 9.8 ml/kg of cement and 0.504 water/cement ratio was as follows:.

	Weight lb	Specific Gravity	Volume ft³	Percent of mix (by wt.)	Ratio of cement (by wt.)
Cement	686	3.15	3.49	21.01	1.000
Sand	1001	2.62	6.12	30.66	1.459
Coarse	1200	1.70	11.31	36.75	1.749
Water	346	1.00	5.54	10.60	0.504
Fibers	32	1.90	0.27	0.98	0.047
Air Content	6.00%		1.71		
Σ	3265		28.45		

Water Reducer	103 oz
Air Entraining	0 oz
Unit Weight:	115 pcf
Slump:	5 3/4 in

In order to calculate the actual weight of each mix component per 1 yd³, the volume of each component (except the percentage of air content) should be scaled down to give a final total volume of 27 ft³. The scaled factor is calculated as follows:

$$\text{Scaled factor} = \frac{27.00\,\text{ft}^3 - (\text{Air content at } 6.0\% = 1.62\,\text{ft}^3)}{28.45\,\text{ft}^3 - (\text{Air content at } 6.0\% = 1.71\,\text{ft}^3)} = 0.949$$

Thus the components of this mix were as follows:

	Weight lb	Specific Gravity	Volume ft³	Percent of mix (by wt.)	Ratio of cement (by wt.)
Cement	651	3.15	3.31	21.01	1.000
Sand	950	2.62	5.81	30.66	1.459
Coarse	1139	1.70	10.74	36.75	1.749
Water	328	1.00	5.26	10.60	0.504
Fibers	30	1.90	0.26	0.98	0.047
Air Content	6.00%		1.62		
Σ	3098		27.00		

Water Reducer	103 oz
Air Entraining	0 oz
Unit Weight:	115 pcf
Slump:	5 3/4 in

The sand/cement and coarse aggregate/cement ratios for this mix were used in all the CF sand-lightweight mixes. Similar procedure were followed for normal weight concrete and the following mix design was used at OSU laboratory:

	Weight lb	Specific Gravity	Volume ft^3	Percent of mix (by wt.)	Ratio of cement (by wt.)
Cement	654	3.15	3.33	17.40	1.000
Sand	1066	2.62	6.52	28.36	1.630
Coarse	1677	2.69	9.99	44.65	2.566
Water	330	1.00	5.28	8.78	0.504
Fibers	30	1.90	0.26	0.81	0.047
Air Content	6.00%		1.62		
S	3757		27.00		

Water Reducer	154 oz
Air Entraining	0 oz
Unit Weight:	139 pcf
Slump:	5 3/4 in

Concrete Mixing Equipment and Casting: A masonry mixer was used for laboratory work at OSU. For normal weight and most sand-lightweight mixes, the mixer was equipped with normal paddles. For the some sand-lightweight batches, the paddles were replaced with an optional spiral blade assembly. All the solid mix component; cement, sand, coarse aggregate, CF if used, and defoamer if used, were combined in the dry mixing process that lasted for 10 sec for all mixes. The wet mixing duration was 2 min for control batches while for batches with CF the mixer operated for 1 min after adding water, stopped for slump test, operated for 2 more min while adding water reducer, and then stopped for slump test. If the slump was less than the target value, more water is added, the mixer operated for 1 more min, and slump test is performed again until the value became ±1/2 inch within the target value. The process of adding extra water to meet the target slump was very limited as the mixing personnel became more familiar with the mix and most of the batches did not require this process. If the slump value was higher than the target value, the batch was rejected.

Single use plastic molds were used for control cylinders and metal forms were constructed at the OSU concrete laboratory for prism specimens. A total of 8 cylinders (4 x 8 in.) and 4 prisms (4 x 4 x 14 in.) were made from each batch.

Consolidation: Cylinders and prisms were consolidated using vibration table. Forms for the cylinders were manually held in contact with the table while forms for the prisms were clamped to the table. For some CF mixes and high water/cement ratio, rodding was used in place of vibrating table in the consolidation process after observing some segregation in specimens.

Curing: For the OSU concrete laboratory work, after mixing, specimens were allowed to rest for about 5 hours and then subjected to 120° F steam curing for 24 hours.

Test Methods: Cylinders and prisms were tested after 1 and 7 days for normal weight and most of sand-lightweight concrete specimens and after 1, 7 and 28 days for some of sand-lightweight concrete specimens. The compressive strength, splitting tensile strength and modulus of rupture were determined in accordance with ASTM C-39, C-496 and C-78, respectively. For most of the sand-lightweight batches, special testing apparatus were available for determining static Modulus of Elasticity and ductility indices in accordance with ASTM C-469 and C-1018, respectively. Figure B-3 shows a setup for the ASTM C469 test on cylinder. Figure B-4 shows the ELE test machine used for splitting tensile test. Figure B-5 shows a setup for the ASTM C1018 test on beams. The target compressive strengths were 3000 and 4500 psi after 1 and 7 days, respectively, while no compressive strength target was set for 28-day-old specimens. The target value for slump was 5 ¾ in. after adding the water reducer admixture. Statistical analysis was performed on acceptable repetitive batches. Project personnel visually rated fiber dispersion on failure surfaces of the test specimens. Good fiber dispersion was considered to be the absence of fibers in wafer form.

Test Results and Discussion for Sand-Lightweight Mixes:

A summary of the test results for sand-lightweight is presented in Table C-2. Analysis and discussion of the results are presented below.

Influence of CF and Water Reducer Dosage on Compressive Strength: Figure C-2 shows the effect of adding CF with water reducer dosages of 6.6, 9.8, 12 or 16 ml/kg of cement on the average compressive strength of cylinder concrete samples after 1 and 7 days. The Figure also shows the average compressive strength after 1 and 7 days for control mix with 9.8 ml/kg of cement. The compressive strength increased with the increase of water reducer dosage.

Mixes with CF and water reducer dosage of 12 ml/kg of cement had similar average compressive strength values as the control mixes. Increasing water reducer dosage increased fiber dispersion and allowed cement particles to distribute almost evenly between individual CF and increase bond between CF and other mix components; thus increase the compressive strength.

Influence of CF and Water Reducer Dosage on Modulus of Elasticity: Figure C-3 shows the effect of adding CF with water reducer dosages of 6.6, 9.8, 12 or 16 ml/kg of cement on the average modulus of elasticity values for concrete samples after 1 and 7 days. The Figure also shows the average modulus of elasticity values after 1 and 7 days for control mix with 9.8 ml/kg of cement. Mixes with CF, at any dosage of water reducer, showed more elastic behavior than mixes without CF. The presence of CF in the concrete bridged over cracks and helped increase the elastic behavior of concrete until CF reached its failure strength.

Table C-2

Summary of Results for Lightweight Mixes of Coreslab Phase

Mix	No. of Batches	Cement	Sand, by wt of cement	Lt.Wt. Coarse Agg., by wt of cement	Fibers % by Volume	Water/Cement Ratio	Water reducer (D100),ml/kg of cement	Air Entraining, ml/kg of cement	Defoamer, % wt of cement	Fresh Mix Properties: Fiber Dispersion	Fresh Mix Properties: Slump (in)	Fresh Mix Properties: Workability	Hardened Properties: Unit Weight lb/ft^3	Hardened Properties: Entrapped Air %	1-Day Strength[1] (psi) C	1-Day Strength[1] (psi) T	1-Day Strength[1] (psi) F	1-Day E (ksi)	1-Day First crack load, lb	1-Day First crack deflection, μ in.	1-Day First crack toughness, in.-lb	1-Day Maximum load, lb	1-Day Deflection at max. load, μ in.	1-Day I_5	7-Day Strength[1] (psi) C	7-Day Strength[1] (psi) T	7-Day Strength[1] (psi) F	7-Day E (ksi)	7-Day First crack load, lb	7-Day First crack deflection, μ in.	7-Day First crack toughness, in.-lb	7-Day Maximum load, lb	7-Day Deflection at max. load, μ in.	7-Day I_5	Fiber Dispersion
1	3	1	1.459	1.749	0	0.431	9.8	0.7	-	-	5 3/4	good	118	4.8	3500	310	420	2590	2110	1000	0.8	2170	2800	5.5	4730	380	525	2940	2550	2300	3.1	2710	2700	5.6	-
2	2	1	1.459	1.749	1	0.590	6.6	-	-	poor	6	good	113	6.0	2750	425	510	2400	2220	1600	2.3	2640	3300	5.0	3650	475	545	2560	2200	2800	3.5	2690	3200	5.1	poor
3	2	1	1.459	1.749	1	0.504	9.8	-	-	poor	5 1/2	<avg	115	5.8	3410	460	540	2260	2900	1700	2.5	3050	3500	4.8	3740	465	615	2360	2950	3000	3.6	3490	3300	4.5	poor
4	3	1	1.459	1.749	1	0.497	12	-	-	avg	5 3/4	avg	115	5.7	4320	500	605	2210	2870	1700	2.8	3130	3600	4.1	5080	505	610	2310	2400	2900	4.1	3130	3500	4.0	avg
5	5	1	1.459	1.749	1	0.487	16	-	-	good	5 3/4	avg	114	6.6	3690	410	590	2130	2210	1900	3.0	2790	3900	3.6	4600	525	675	2480	2520	3200	4.6	3180	3700	3.7	good
6	2	1	1.459	1.749	1	0.487	16	-	0.15	good	5	<avg	119	4.0	3990	400	580	2110	2460	2000	3.2	3000	3800	3.5	5410	510	670	2450	2010	3100	4.5	2950	3500	3.5	good

[1] **Strength :** C= compression test; T= Split cylinder test; F= Third-point flexural test

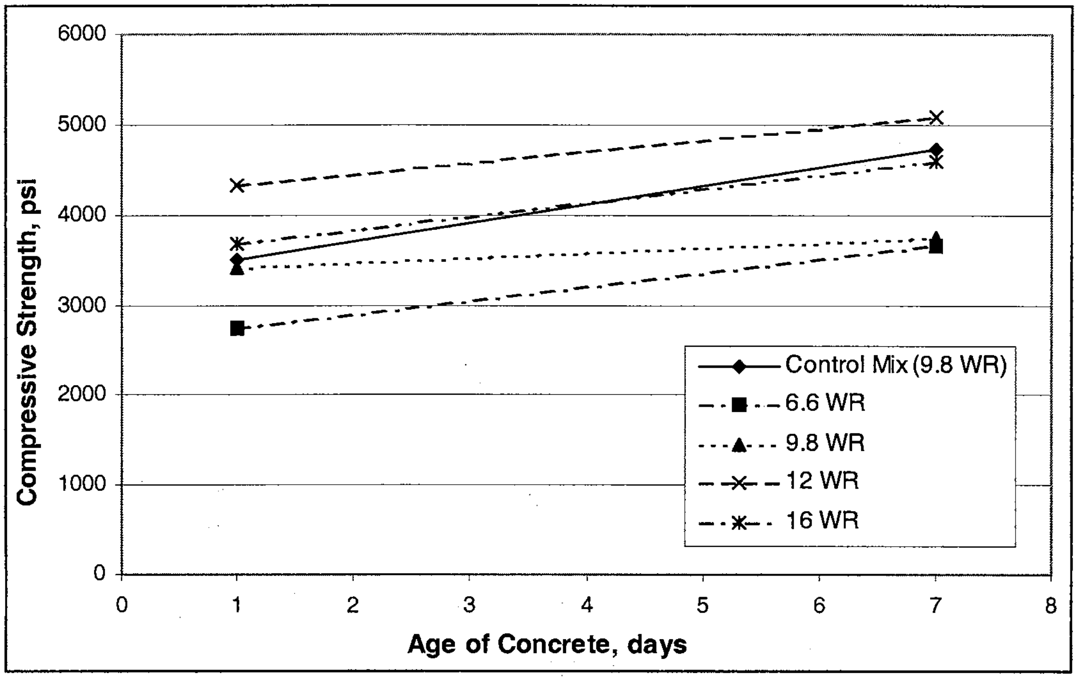

Figure C-2. Effect of CF and Water Reducer Dosage on compressive Strength for Sand-Lightweight Concrete

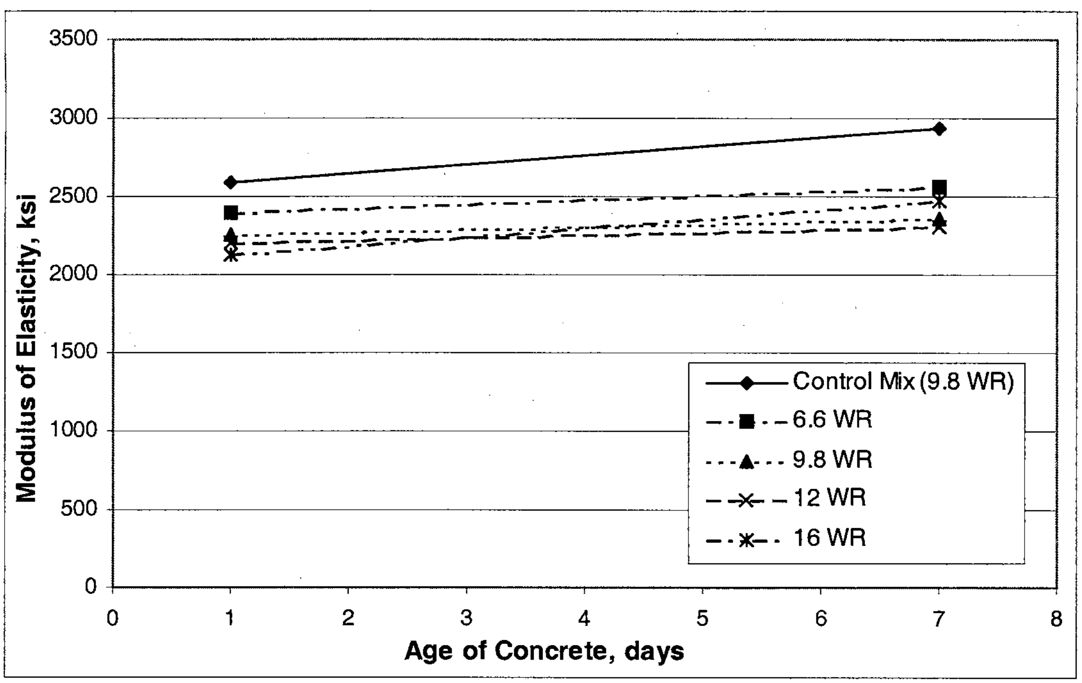

Figure C-3. Effects of CF and Water Reducer Dosage on Static Modulus of Elasticity for Sand-Lightweight Concrete

Figures C-4 and C-5 present the stress-strain curves for 1- and 7-day-old sand-lightweight prism samples, respectively. The figures represent three mix designs: mixes 1, 3 and 5 in Table C-2. It is noted that each curve in the Figures is a result of one cylinder test, while each value in Table C-2 is the average of several tests. Failure was sudden for control mix while samples with CF had post-cracking behavior and failed at much higher strain than control mix samples.

Influence of CF and Water Reducer Dosage on Splitting Tensile Strength: Figure C-6 shows the effect of adding CF with water reducer dosages of 6.6, 9.8, 12 or 16 ml/kg of cement on the average splitting tensile strength of cylinder concrete samples after 1 and 7 days. The Figure also shows the average splitting tensile strength after 1 and 7 for control mix with 9.8 ml/kg of cement. The Figure shows that mixes with CF and any dosage of water reducer had higher average splitting tensile than the average values for control mix. The increase in splitting tensile strength by adding CF to concrete is due to bridging of individual CF over concrete cracks. The performance of CF mix with a water reducer dosage of 16 ml/kg of cement was better than CF mixes with other water reducer dosages due to the good fiber dispersion obtained for this mix.

Influence of CF and Water Reducer Dosage on Flexural Strength: Figure C-7 shows the effect of adding CF with water reducer dosages of 6.6, 9.8, 12 or 16 ml/kg of cement on the average flexural strength of prism concrete samples after 1 and 7 days. The Figure also shows the average flexural strength after 1 and 7 for control mix with 9.8 ml/kg of cement. Mixes with CF had higher average flexural strength than control mix. Carbon fiber mix with water reducer dosage of 16 ml/kg of cement had higher performance than other CF mixes due to good fiber dispersion obtained at this high level of water reducer dosage.

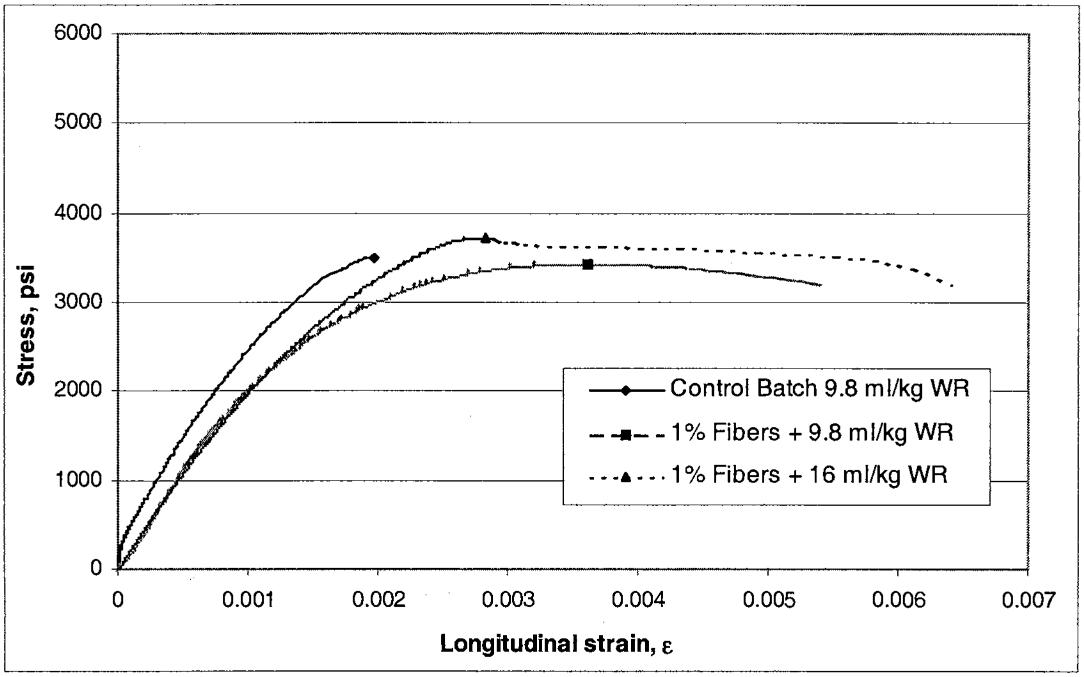

Figure C-4. Stress-Strain Curves for 1-Day-Old Lightweight Cylinder Samples

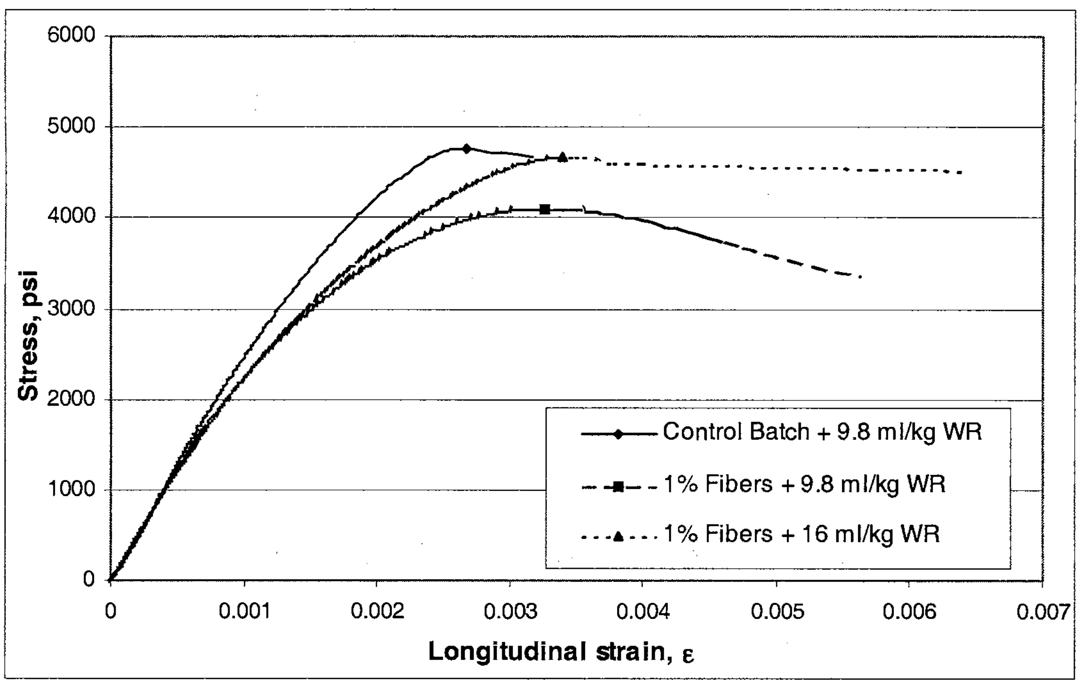

Figure C-5. Stress-Strain Curves for 7-Day-Old Lightweight Cylinder Samples

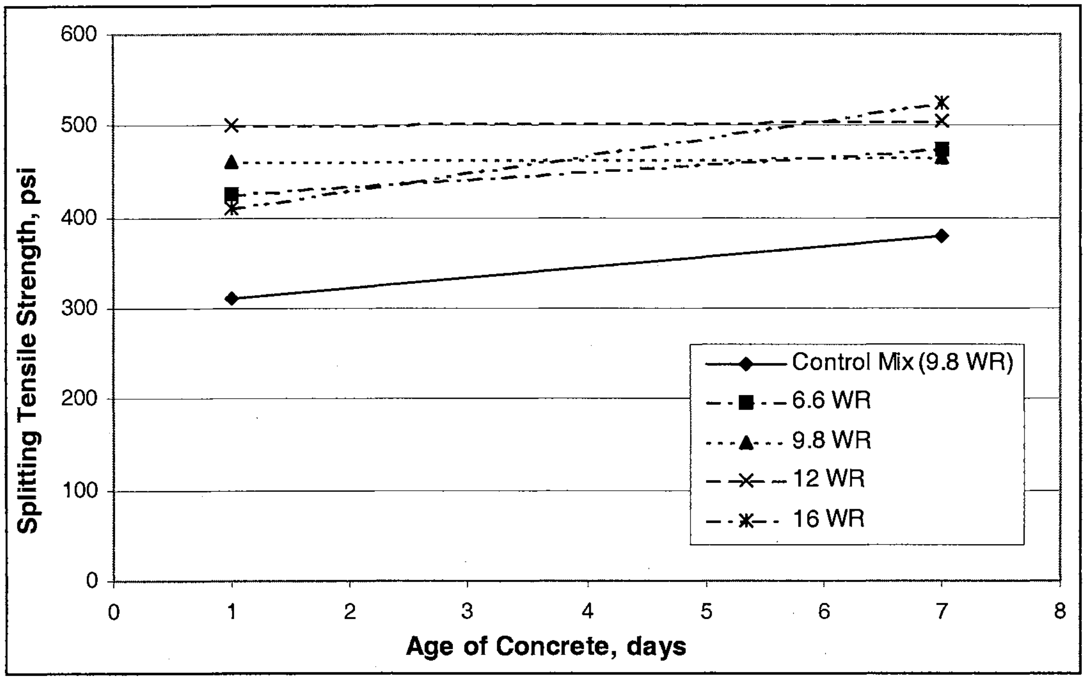

Figure C-6. Effects of CF and Water Reducer Dosage on Splitting Tensile Strength for Sand-Lightweight Concrete

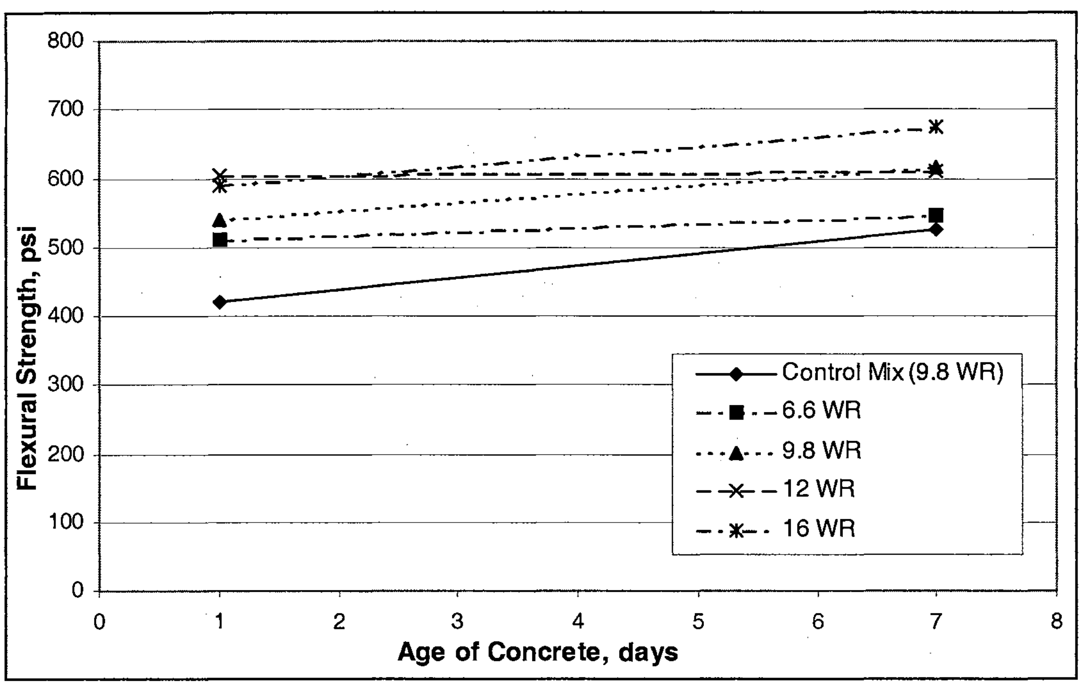

Figure C-7. Effects of CF and Water Reducer Dosage on Flexural Strength for Sand-Lightweight Concrete

Influence of CF and Water Reducer Dosage on Maximum Load Deflection: Figure C-8 shows the effect of adding CF with water reducer dosages of 6.6, 9.8, 12 or 16 ml/kg of cement on the average deflection at maximum load for prism concrete samples after 1 and 7 days. The Figure also shows the average deflection at maximum load after 1 and 7 for control mix with 9.8 ml/kg of cement. Deflection at maximum load is an indication for the ductility of samples, as it will be presented in the concrete toughness test discussion later this chapter. Mixes with CF had higher average deflection at maximum load than control mix. Deflection at maximum load increases as the water reducer dosage increases, as shown in Figure C-8. As water reducer dosage increased, fiber dispersion improved and concrete prism samples became more ductile.

Influence of Defoamer: Defoamer was only added to one CF mix design, with 16 ml/kg of cement as shown in Table C-2.. Adding defoamer decreased the amount of entrapped air in the samples and increased the compressive and flexural strengths over the values from the same batch without defoamer. The tensile strength was similar for batches with and without defoamer.

Concrete Toughness (ASTM C-1018): Prism samples for sand-lightweight mixes were tested in accordance with ASTM C-1018, and the summary of results is presented in Table C-2. The reported results are: first crack load (lb), first crack deflection (in.), first crack toughness (lb-in.), maximum load (lb), deflection at maximum load (in.), and toughness index I_5.

Ductility of prisms and deflection at failure increased with the addition of CF. The increase was more noticeable for prisms tested at 7 days than for those tested at 1 day. Figures C-9 and C-10 present the load-displacement curves for 1- and 7-day-old sand-lightweight prism samples, respectively. The figures represent three mix designs (mixes 1, 3 and 5 in Table C-2): control mix with 9.8 ml/kg of cement of water reducer dosage, 1 percent fibers by volume with 9.8 ml/kg of cement of water reducer dosage, and 1 percent fibers by volume with 16 ml/kg of cement of water reducer dosage. It is noted that each curve in Figures C-9 and C-10 is a result of one

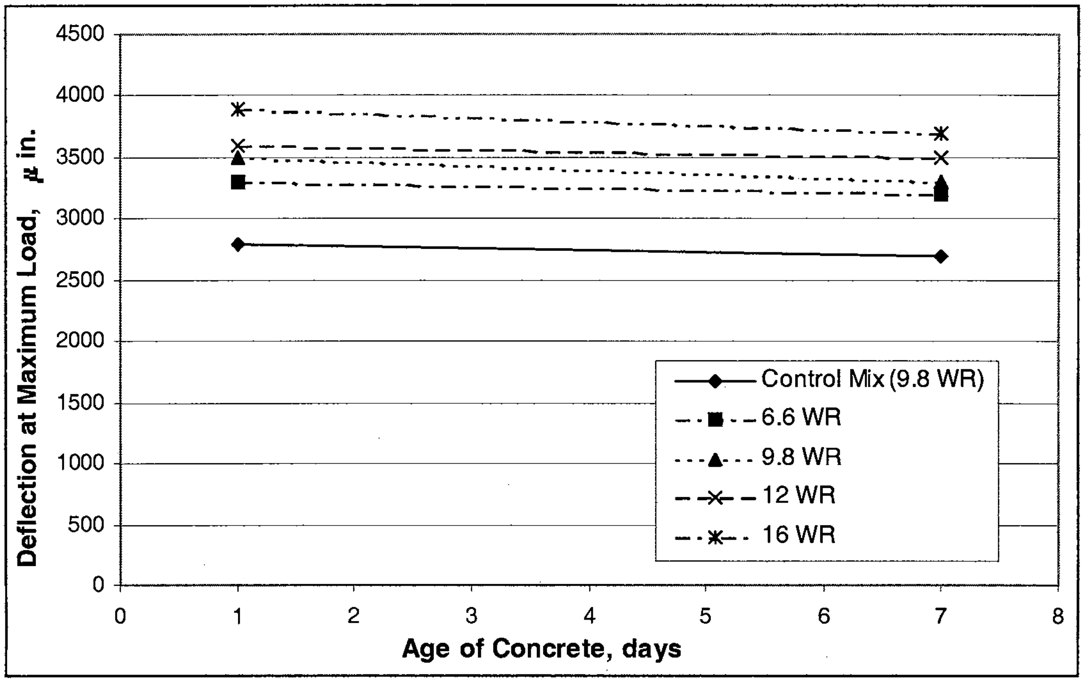

Figure C-8. Effects of CF and Water Reducer Dosage on Deflection at Maximum Load for Sand-Lightweight Concrete

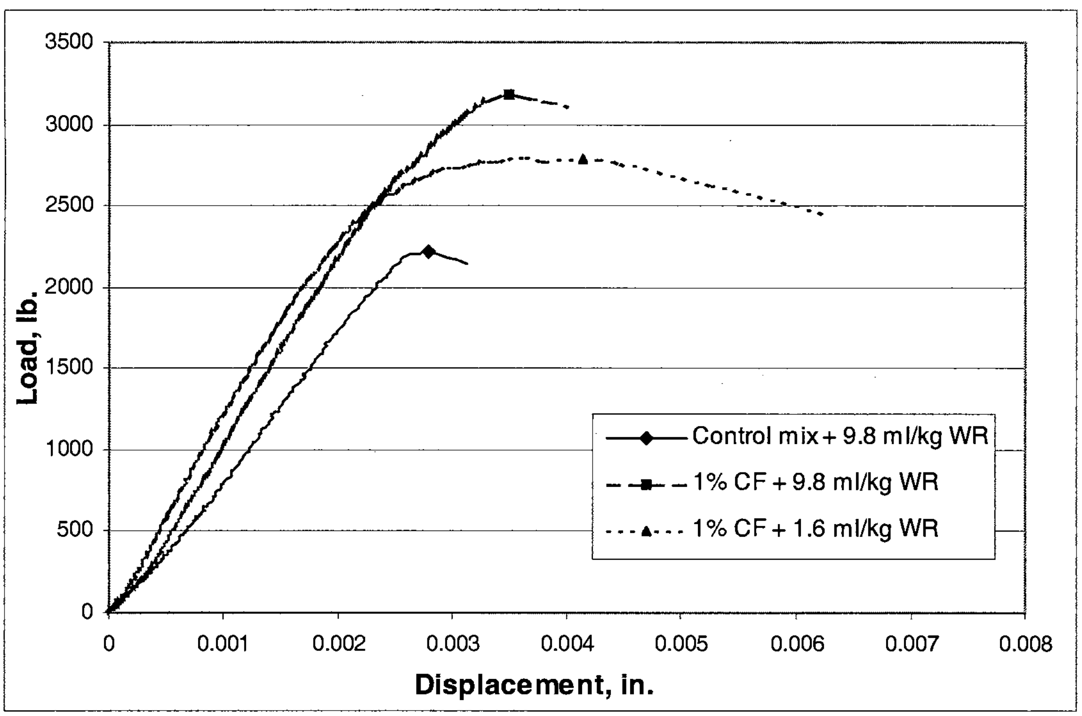

Figure C-9. Load-Displacement Curves for 1-Day-Old Prism Samples

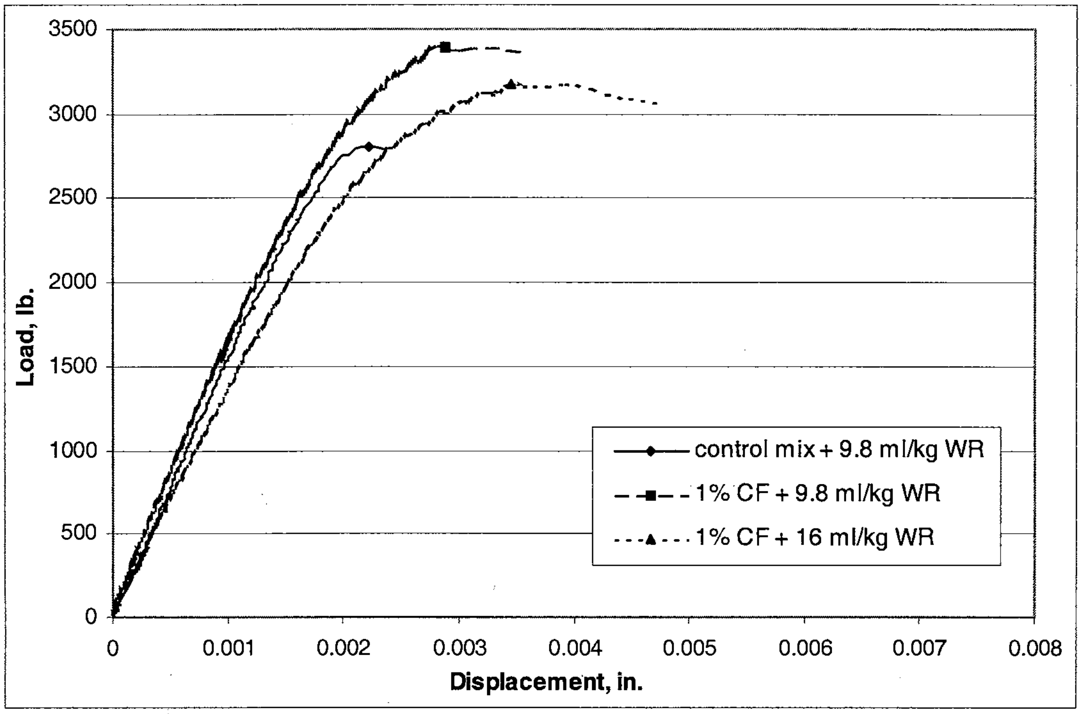

Figure C-10. Load-Displacement Curves for 7-Day-Old Prism Samples prism test, while each value in Table C-2 is the average of several tests. The ductility increased for batches with more water reducer agent; this trend is probably due to better fiber dispersion in batches with high dosages of water reducer. The toughness index I_5 increased by adding CF to the concrete as presented in Table C-2. The average toughness index I_5 for control mixes was 5.5 and 5.6 for 1- and 7-day-old prisms, respectively. For batches with CF, the value ranged from 3.5 to 5.0 for 1-day-old prisms and from 3.5 to 5.1 for 7-day-old prisms. The toughness index I_5 decreased as the water reducer dosage increased.

Test Results and Discussion for Normal Weight Mixes:

Only nine batches were cast using normal weight concrete and repetitive data could not achieved. Future studies are required to study the effect of CF on the normal weight concrete.

C.4 Field Experiment at Coreslab (Double-Tee Girders)

Introduction

One goal of this phase has been to demonstrate that concrete reinforced with CF can be used in practical, real world applications. A potential application for CF is in the manufacture of prestressed concrete members such as double-tee sections. In conversations with Coreslab personnel, it was learned that flanges of double-tee members, which are lightly reinforced with welded wire fabric (WWF), are sometimes cracked during handling operations. Consequently, a field study was conducted to demonstrate that CF could be used to manufacture precast members and to research the possible advantages of CF for precast concrete.

Activities at Coreslab Structures Plant

An 8-ft wide double-tee section is a very common precast section. Normally the flange has a 2-in. thickness; the cross section of a typical member is shown in Figure C-11. Three specimens were cast at Coreslab Structures; each specimen was 8 ft in length and had a 2-in. flange thickness. The standard WWF used by Coreslab for this section has W2.5 wires at 6-in centers perpendicular to the web. This reinforcement, providing 0.05 in^2/ft, is placed at mid-depth in the flange. One specimen containing the standard WWF flange reinforcement was cast using standard sand-lightweight mix design from Coreslab. The proportions of this mix are given in Appendix E; at the time of the field study Coreslab had increased the water reducer dosage from 6.6 to 9.8 ml/kg of cement. The manufacturer maximum recommended dosage for water reducer is 16 ml/kg of cement. Two specimens were made using sand-lightweight CFRC: one contained the standard WWF flange reinforcement, as shown in Figure C-12; the other had no steel reinforcement in the flange, as shown in Figure C-13. The mix design for these specimens was based on the standard Coreslab mix design for sand- lightweight concrete discussed earlier with the following adjustments:

- The mix contained 31 lb/yd^3 of CF (~1% by volume)
- The water content was increased to 317 lb/yd^3 (w/c ratio = 0.462)
- Water reducer dosage was increased to 169 oz/yd^3 (16 ml/kg of cement)
- No air-entraining agent was used.

While the specimen made without CF consolidated and finished easily, the specimens with CF were cast with considerable difficulty. Simultaneous use of an external form vibrator and an internal vibrator were required to consolidate the concrete. Figure C-14 shows casting in progress for specimens containing CF.

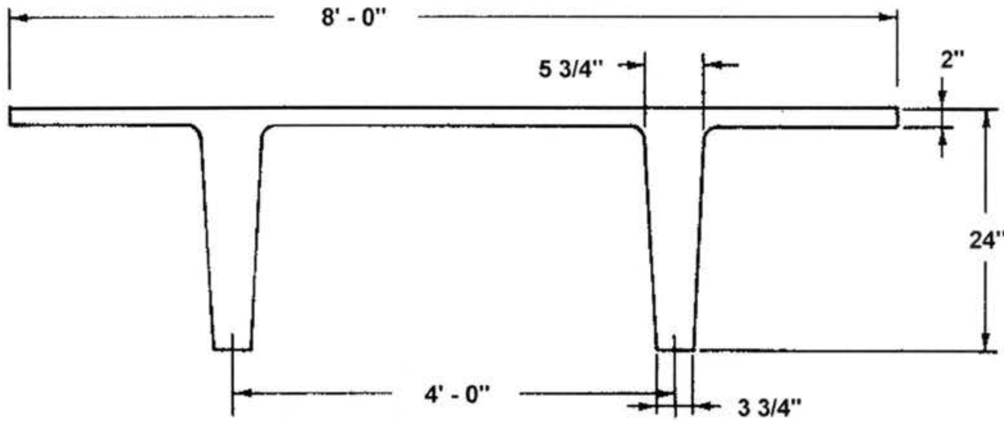

Figure C-11. Double-Tee Dimensions Produced at Coreslab Structures

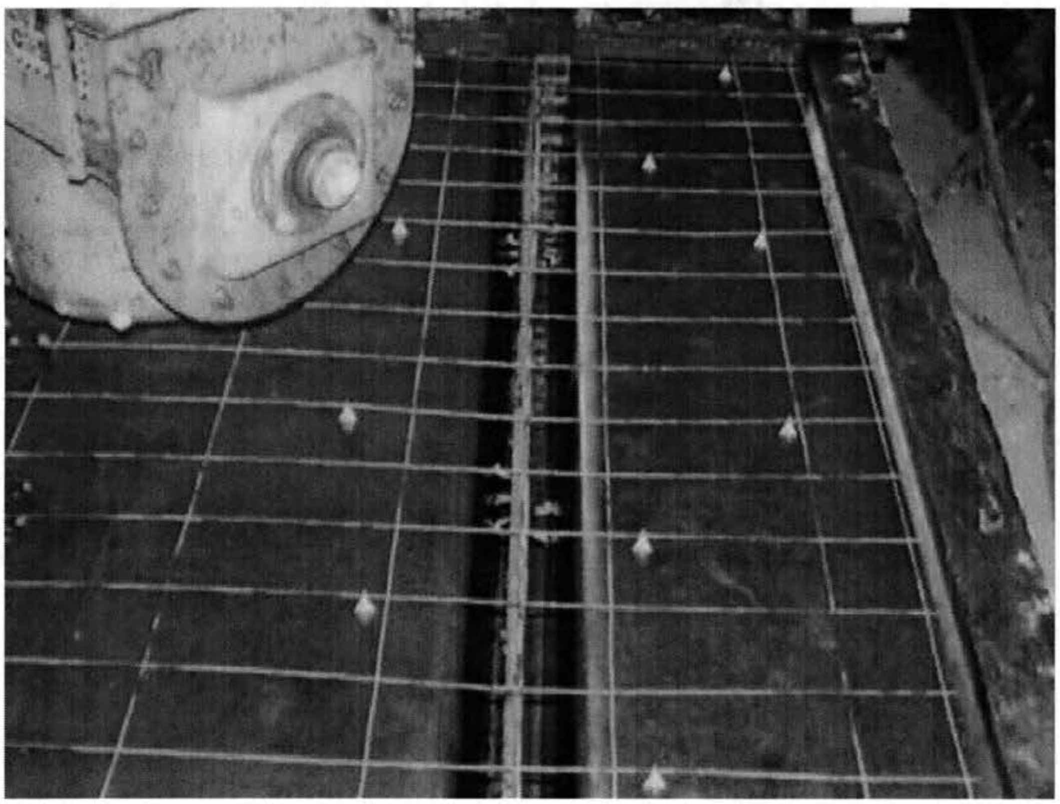

Figure C-12. Double-Tee Form With Slab Steel Reinforcement

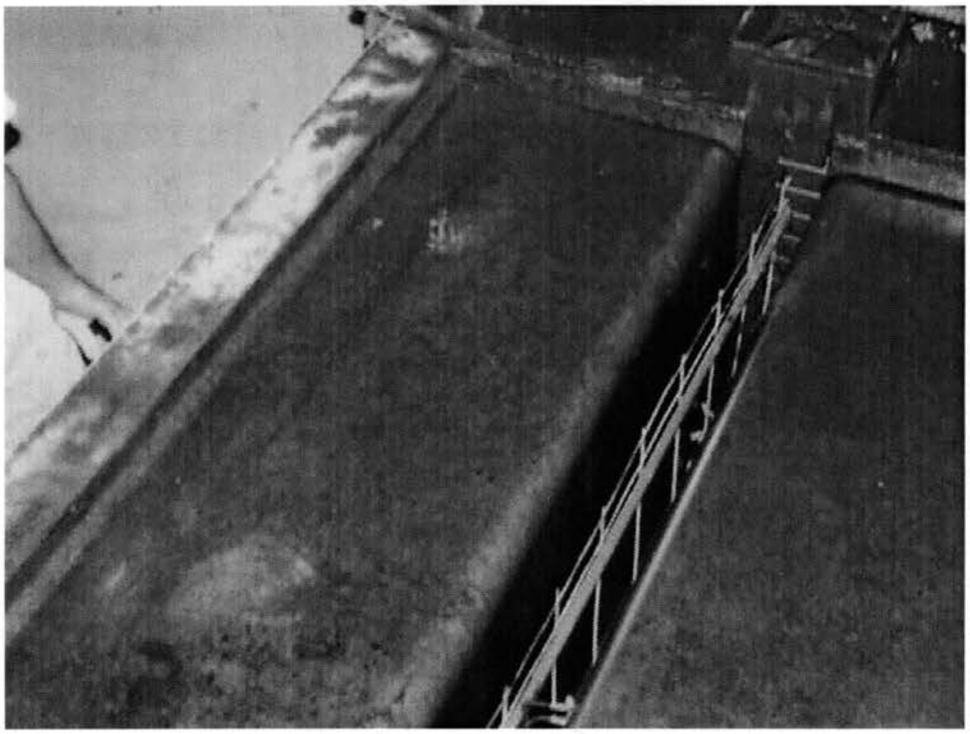

Figure C-13. Double-Tee Form Without Slab Steel Reinforcement

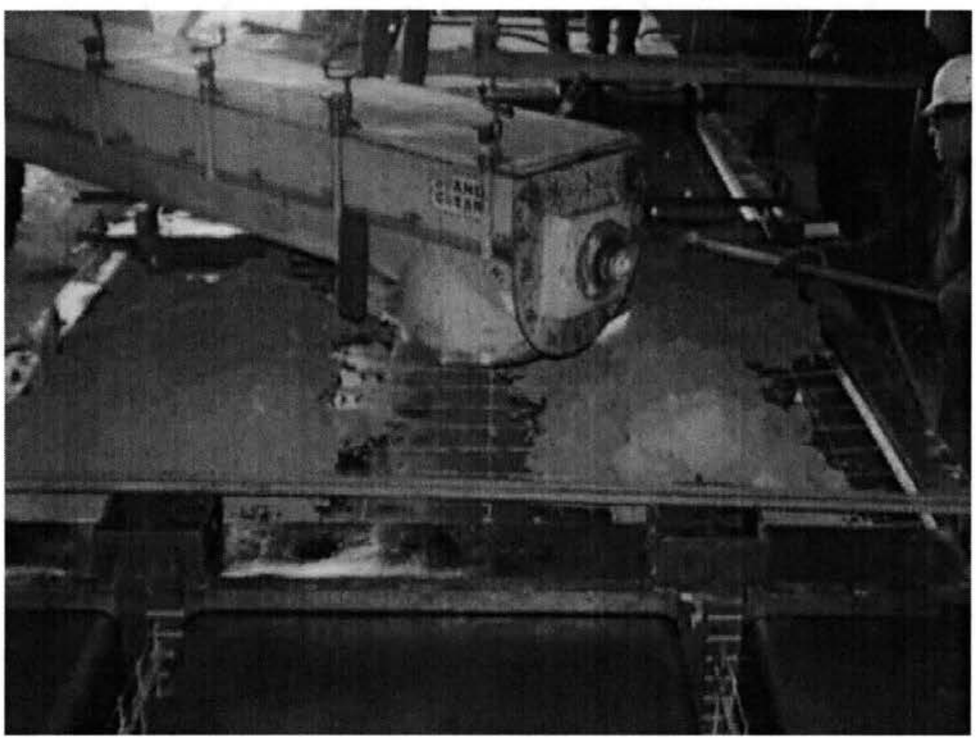

Figure C-14. Casting Process for the CF Mix

Six 4 x 8-in. cylinders and three 4 x 4 x 14-in. prisms were taken from each batch and were consolidated using the vibrating table from the OSU laboratory. The double-tee section, cylinder, and prism specimens were cured using the usual Coreslab method of curing; after a rest period of at least 3 hr, the covered forms were heated using steam lines attached to the forms.

After approximately 16 hr of accelerated curing, specimens were allowed to cool to ambient temperature and remained in the forms for 2 additional days. At an age of 3 days, the double-tee sections were removed from the forms and transported to OSU. Several cracks formed in the specimens during the demolding process. For the CF specimen with no WWF flange reinforcement, longitudinal cracks between the webs separated the specimen into several elements. Coreslab personnel noted that they experienced some difficulty in demolding the specimen from the form.

Test of Coreslab Specimens at OSU

Double-tee section, Cylinder, and prism specimens were tested at age of 28 days. The compressive strength, splitting tensile strength and modulus of rupture were determined in accordance with ASTM C-39, C-496 and C-78, respectively. Static Modulus of Elasticity and ductility indices were determined in accordance with ASTM C-469 and C-1018, respectively. Summery of the results is shown in Table C-3.

Initial plans had been to apply flexure to the cantilever regions of the flanges and torsion to the flange region between the webs. Because of extensive cracking caused by demolding, torsional tests were not conducted. Using concrete saw, kerfs were placed perpendicular to webs in the cantilever flanges. The kerfs at 12-in centers resulted in several beams that cantilevered approximately 19 in. from the web. For flanges reinforced with WWF, each cantilever contained two W2.5 wires at mid-depth.

Table C-3

Summary of Results for Coreslab Field Trial

General Mix Characteristics:

Mix	Hardened Properties										
	Unit Weight	Entrapped Air	Strength[1] (psi)					First crack load, lb	First crack deflection, μ in.	Maximum load, lb	Deflection at max. load, μ in.
	lb/ft^3	%	C	T	F	E (ksi)	ε, μ				
No CF	118	4.8	5200	360	550	2680	3120	2610	2850	2840	3150
1% CF	113	6.0	5480	480	725	2270	3780	2740	3120	3740	3810

[1] **Strength :** C= compression test; T= Split cylinder test; F= Third-point flexural test

A simple loading fixture shown in Figure C-15 was used to apply a concentrated load approximately 1-in from the free end of the cantilever; a DCDT transducer measured vertical deflection at the point of loading. To remove slack from the test apparatus, it was necessary to apply a small preload of approximately 30 to 50 lb to the cantilever. Displacement measurements were referenced to the deflection under the action of the preload. The raw data curves were extrapolated to zero load and shifted to a common origin. Figure C-16 shows typical load-deflection curves for cantilevers from each of the three specimens.

Test Results

Cantilever specimens containing CF and slab reinforcement had the highest load carrying capacity followed by specimens with CF and no slab reinforcement. Cantilever Specimens without CF but reinforced with slab mesh (regular Coreslab sand-lightweight double-tee sections) had the lowest load carrying capacity. For such specimens (contain no CF), a sudden drop in the load deflection curve (not shown completely in the Figure) was observed instantaneously after reaching maximum load and then the curve leveled out, and increased in some cases, as reinforcement started resisting flexural stresses. However, the moment capacity provided by the WWF was less than the cracking moment. In the case of specimens with CF, beams showed more ductile behavior after reaching maximum load. For specimens with CF and slab reinforcement, the load-deflection curves leveled out at the same load obtained for specimens without CF; at the load carrying capacity of the slab reinforcement. For specimens with CF but without slab reinforcement, failure was sudden shortly after reaching the maximum load and the cantilever collapsed as individual fibers crossing cracks near the tensile face experienced large elongation and reached its failure strength gradually.

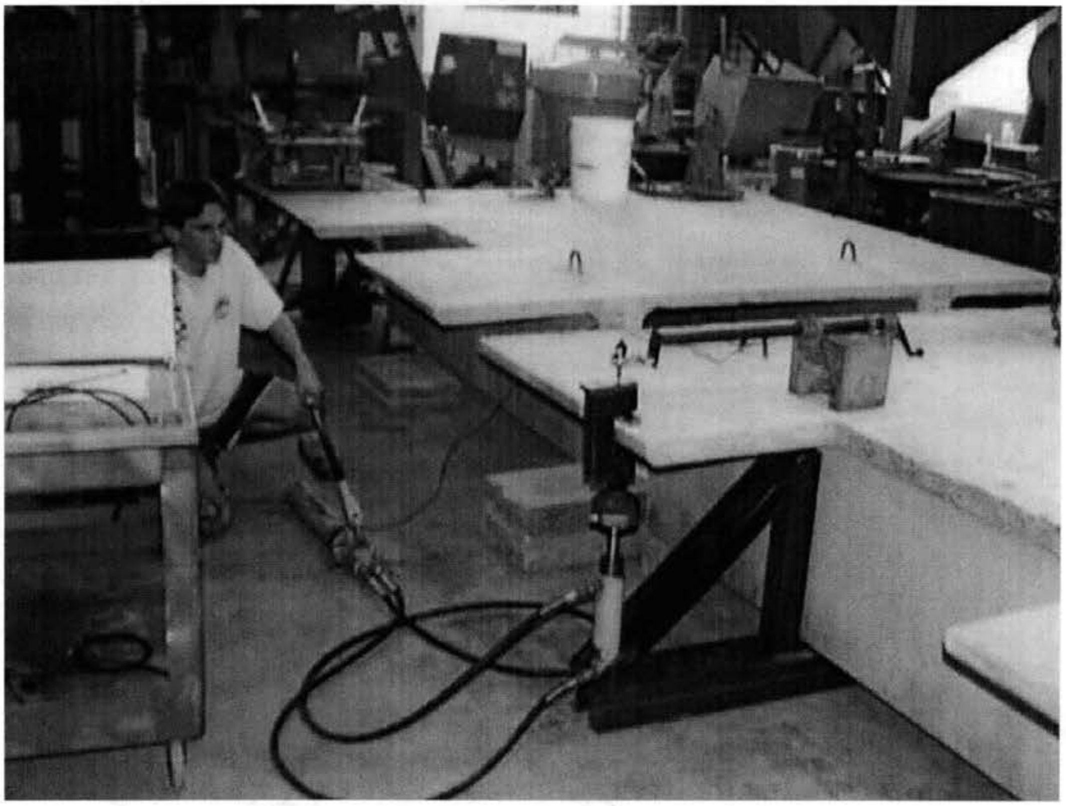

Figure C-15. Apparatus Setup for Double-Tee Cantilever Flexural Test

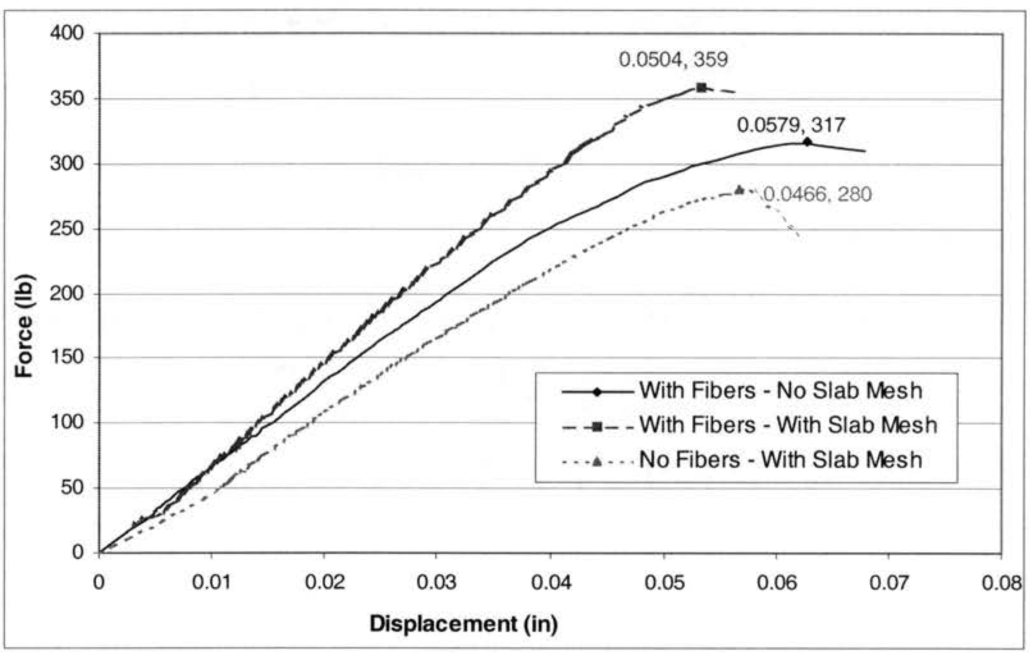

Figure C-16. Flexural Test Results for Cantilever Elements of Double-Tee Beams

Discussion of Coreslab Tests

The field trial at Coreslab was originally scheduled before starting of the OSU concrete laboratory work, but was postponed to accommodate DuPont's product development schedule. Consequently, mix design work at OSU was incomplete at the time of the field test. Laboratory work at OSU had focused on optimizing the CF mix using standard supplies at Coreslab; thus OSU mix development had considered only the water reducer employed by Coreslab. If additional mix development had occurred, the use of a superplasticizer would have been investigated.

The sequence of events created a useful observation for the field study. Working with the CF mix in the laboratory, a slump of approximately 2 in. was achieved using the maximum recommended dosage of water reducer. Test personnel at the OSU concrete laboratory believed the slump measurement was misleading, and the actual workability of the mix was greater than indicated by the slump. However, consolidation of the mix at Coreslab, while possible, required an impractical level of effort for a precast plant to employ in normal operations. Careful consideration must be given to the ability to place and finish CFRC in future research and development.

Information obtained from demolding operations and flexural tests on cantilever flanges also provides useful guidance for future research. During the design of the flange, flexural strength of the concrete is ignored and a small quantity of reinforcing is provided to carry the design loads on the member. The field trial revealed that cracks occur during the demolding process and the flexural strength provided by the slab reinforcement was lower than the cracking moment of the concrete. Higher concrete flexural strength can be obtained using CF, but strength is of little value if cracks develop. The flange failure of the specimen with CF but without slab reinforcement during demolding was dramatic evidence that ductility provided by conventional reinforcement is needed in most concrete members.

C.5 Summary and Conclusion

One of the objectives for this phase of the project was to develop one or more CF mixes with fresh and hardened properties suitable to manufacture precast concrete members. The research focused on using sand-lightweight concrete mixes used by Coreslab Structure. Adding CF to concrete decreased the workability that is required for precast production. To achieve the required workability for precast CF concrete production, the water/cement ratios and the water reducer agent dosage had to increase in the mix design. The slump test was used in measuring the workability of batches with and without CF. A comment from mixing personnel at the OSU concrete laboratory that batches with CF had an apparent stiffness in the matrix that the slump test was not the correct indication for workability. In some CF batches, the slump tests showed values 3 to 4 in. but the batches appeared to be able to consolidate as 5 to 6 in. slump for batches without CF. For consistency and remaining within the scope of this chapter, all the data presented are for batches with a slump value from 5 ½ to 6 in. The presence of CF and the increase in water/cement ratio in the mix increased the air content in the concrete and the air-entraining agent need not be used in the mix design.

The compressive strength of samples with CF varied with variation in water reducer agent dosage. Samples with water reducer dosage of 12 ml/kg of cement had the highest average compressive strength values. Modulus of elasticity for concrete with CF was lower than that for concrete without CF. Variation in water reducer dosage did not have effect on the modulus of elasticity of CF concrete. Cylinder samples with CF showed ductile behavior more than samples without CF. The energy released from samples at failure was sudden for concrete without CF while it was gradual for concrete with CF.

Concrete samples with CF had higher splitting tensile and flexural strengths than concrete samples without CF. Mixes with water reducer dosage of 12 ml/kg of cement had the best performance in splitting tensile strength and the highest average flexural strength values. Also adding CF to concrete increased the toughness and deflection at failure of prism samples.

There may be applications for CFRC where both CF and conventional reinforcement contribute to strength of the member. However, using CFRC and welded wire fabric in the flange of a double-tee section is not one of those applications—at least from the standpoint of flexural strength. Tests demonstrated that CF can contribute to flexural strength of concrete; but after cracks form, the CF fail and load is transferred to the welded wire fabric. Because the welded wire fabric is located at mid-depth of the flange, the transition from uncracked behavior to fully cracked behavior is dramatic.

If CF are to play a useful rule after the formation of tensile cracks in a member, this work indicates that crack widths must remain small. There are situations where this is the case. Some cracks have cleavage motion and shear displacement, and the ability of CF to bridge these modes of cracking will need to be investigated thoroughly.

APPENDIX D

North Star Mix AMX-5

Existing AMX-5 (PH-72)

	Weight lb	Specific Gravity	Volume Ft^3	Percent of mix	Ratio to cement	
Cement	564	3.15	2.87	14.05%	1.000	Aggregate
Fly Ash	156	2.5	1.00	3.89%	0.277	Breakdown
Sand	1965	2.67	11.79	48.94%	3.484	63%
Rock	1155	2.52	7.35	28.77%	2.048	37%
Water	175	1	2.80	4.36%	0.310	
PL90	25 oz					
Air Content	4.50%		1.22			
Σ	4015		27.03			

Desired Combined Fineness Modulus = 3.8

APPENDIX E

Coreslab Structures Mix Design

Lightweight 7.3 A

	Weight lb	Specific Gravity	Volume ft^3	Percent of mix (by wt.)	Ratio of cement (by wt.)
Cement	686	3.15	3.49	21.53	1.000
Sand	1004	2.63	6.12	31.51	1.464
Coarse	1200	1.7	11.31	37.66	1.749
Water	296	1	4.74	9.29	0.431
Air Content	5.00%		1.35		
Σ	3186		27.01		

Water Reducer	69 oz	Unit Weight:	118 pcf
Air Entraining	7 oz	Slump:	5 3/4 in

Normal Weight 7.3 A

	Weight lb	Specific Gravity	Volume ft^3	Percent of mix (by wt.)	Ratio of cement (by wt.)
Cement	686	3.15	3.49	17.80	1.000
Sand	1122	2.63	6.84	29.12	1.636
Coarse	1760	2.69	10.49	45.68	2.566
Water	285	1	4.57	7.40	0.415
Air Content	6.00%		1.62		
Σ	3853		27.00		

Water Reducer	103 oz	Unit Weight:	142 pcf
Air Entraining	7.5 oz	Slump:	5 3/4 in

VITA

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