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POLYPROPYLENE FIBER REINFORCED CONCRETE:

EVALUATION OF MATERIAL PROPERTIES AND COMPOSITIONS

presented by

Faiz Abdullah Mohammed Mirza

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Parviz Soroushian
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POLYPROPYLENE FIBER REINFORCED CONCRETE: EVALUATION OF MATERIAL PROPERTIES AND COMPOSITIONS

By

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ABSTRACT

POLYPROPYLENE FIBER REINFORCED CONCRETE: EVALUATION OF MATERIAL PROPERTIES AND COMPOSITIONS

By

Faiz Abdullah Mohammed Mirza

This research has adopted statistically sound methods of experimental design and analysis in order to evaluate polypropylene fiber reinforced concrete as an engineering material which has found broad popularity in spite of the limited technical data available on its performance characteristics. The effects of collated fibrillated polypropylene fibers in the following properties of concrete materials were investigated: compressive and flexural strength and toughness, impact resistance, chloride permeability, and plastic shrinkage cracking. Different concrete matrix compositions and polypropylene fiber volume fractions and lengths were considered. Factorial design of experiments together with sufficient replications of tests were adopted in order to generate data for deriving statistically reliable conclusions.

polypropylene fibers showed no statistically significant effects on the compressive strength and toughness or flexural strength; flexural toughness, however, was improved with the addition of polypropylene fibers.

Polypropylene fibers were found to increase the impact resistance of concrete materials. Due to the positive interaction between polypropylene fibers and pozzolans (in the sense that fibers were more effective in the presence of pozzolans) the combined effects of pozzolans and fibers were found to be more than additive. A similar conclusion could be derived regarding the interaction between polypropylene fibers and latex polymer.

the permeability of the concrete materials was not affected by the addition of polypropylene fibers. The generally positive effects of pozzolans and latex on permeability could be observed in plain and fibrous concretes to a similar extent.

Polypropylene fibers significantly reduced the plastic shrinkage cracking of concrete materials. The construction operations (scrreding and finishing) also affected the plastic shrinkage cracking of both plain and fibrous concretes. Plastic shrinkage cracking was practically eliminated when polypropylene fiber reinforced concrete was properly finished. Different polypropylene fiber volume fractions (0.05%-0.20%) were found to have statistically comparable effects on the plastic shrinkage cracking, and longer fibers (o.75 in., 19 mm) performed better than shorter fibers (0.5 in., 13 mm) in controlling the plastic shrinkage cracks.

In The Name of Allah The Most Merciful, The Most Compassionate
"O my Lord! Advance me in Knowledge"

To My Lord "Allah"

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CHAPTER I

INTRODUCTION

Many aspect of our daily lives depend directly or indirectly on concrete; we may live, work, study, or play in concrete structures, and drive over concrete roads and bridges. Our planes land over concrete airport runways, the water we drink is stored behind concrete dams and flow to our houses through concrete pipes. The reasons for the popularity of concrete are varied, but among the most important are the economy and widespread availability of its constituents, its versatility (as evident by the many types of construction in which it is used), and its minimal maintenance requirements during service life.

Concrete is a brittle material with very low tensile strength compared to its compressive strength. Thus, concrete by itself should generally not be subjected to tension and impact loads. The volume instability of concrete must also be allowed for in design and construction. These shortcoming of concrete should be compensated for by suitable design, and should be controlled in part by a suitable choice of materials and construction practices. The reinforcement of concrete by fibers is an effective method of resolving the problems with the brittleness and dimensional instability of the material.

The use of fibers for reinforcing brittle materials can be traced back to ancient biblical times when straw was used to reinforced sunbaked bricks, and horse hair to reinforce plaster. It has, however, been only 40 years since a rigorous approach to the production of modern cement composite reinforced with fibers has been reported. New developments have enabled engineers to design fibers and concrete matrices for particular applications. Design decisions regarding the compatibility between fiber, matrix, and the environment have been improved by the intensive research efforts in the last decade.

A great variety of fibers in different sizes and shapes have been developed for use in fiber reinforced concrete. Many of these fibers are commercially available for use in construction (e.g. steel, polypropylene, glass, and carbon fibers). Polypropylene fibers have gained popularity in concrete application mainly due to their effectiveness, at low volume fractions, in controlling plastic shrinkage cracking, and also due to their relatively low cost, alkali resistance and high elongation.

Successful field work have prompted the growth in polypropylene fiber applications in concrete. While control of shrinkage cracking by polypropylene fibers provides the key motivation for the popularity of these fibers, there remain many uncertainties regarding the effects of polypropylene fibers on various aspects of the engineering properties of concrete. The primary goal of this research was to develop a comprehensive experimental data base for driving statistically reliable conclusions regarding the effects of polypropylene fibers on the plastic shrinkage cracking and other critical properties (flexural and compressive strength and toughness, impact resistance, and permeability) of concrete materials.

Polypropylene fiber with different lengths and volume fractions were considered, and their interaction with different matrix compositions popularly used with these fibers were investigated. The effects of different construction (finishing) techniques on the plastic shrinkage cracking of plain and polypropylene fiber reinforced concretes were also studied.

In regard to the organization of the research, Chapter II present a review of the literature. Chapter III covers the methodology used in conducting this study; in this chapter the factorial analysis of experiments is discussed, along with the process of selecting the sample size and designing the experimental program. The three subsequent chapters present the experimental results. Chapter IV covers some key mechanical properties of polypropylene fiber reinforced concrete, such as compressive and flexural strength and toughness, and impact resistance. Chapter V presents the effects of polypropylene fibers and their interaction with the concrete matrix composition on the permeability of concrete, and Chapter VI reviews the plastic shrinkage cracking characteristics of the material. A summary and conclusions of the research as well as recommendations for further research are presented in Chapter VII.

CHAPTER II

POLYPROPYLENE FIBER REINFORCED CONCRETE :

State of The Art

2.1 INTRODUCTION

Research and development in fiber reinforced concrete materials has evolved steadily, with most notable progress having been made through the periodic introduction of new fiber types. The last two decades of worldwide development in fibrous concrete proved that no one fiber material, fiber system production process, and fibrous composite system has emerged to dominate the marketplace. In general, one can say that each newly developed fiber type or technology has led to new applications. Therefore, a problem arises in matching the performance of various fiber types and systems with appropriate applications.

A wide variety of fibers have been used with hydraulic cement: conventional fibers such as steel and glass; new fibers such as carbon and kevlar; and low modulus fibers, either man-made (polypropylene, nylon) or natural (cellulose, sisal, jute). These types of fiber vary considerably in properties, effectiveness, and cost. Some common fibers, and their typical properties, are listed in Table 2.1.[22] In addition to their mechanical properties, fibers may also differ widely in their geometry.

Synthetic fibers, in general, and polypropylene fibers in particular are not new to the world of fiber reinforced concrete. Polypropylene in the form of continuous fibers was introduced in early 1960's to replace the fibers in asbestos cement sheets and other continuous reinforced products such as flat sheets for roofing, cladding panels, pile capping,etc. More recently research and application projects have also emphasized the use of discrete polypropylene fibers in concrete. The properties of discrete polypropylene fibers have been improved through stretching the film sheets which are then slitted into tapes and twisted along their lengths to form fiber bundles of lower cross sectional dimensions and slenderness ratios. These bundles are then cut into different lengths; they can be conveniently dispersed in fresh concrete mixtures and the mixing open the bundles to form into connected individual filaments, fibrillated polypropylene fibers have been chosen for reinforcement of cementitious materials for a number of desirable properties, including:

1. The network structure of fibrils leading to bi-directional action of fibers and desirable mechanical bonding of the matrix.
2. The fibrils, after being filamentized by the shearing action of aggregate particles during mixing, have higher tensile strength and modulus of elasticity than polypropylene films.
3. Potentials exist for surface treatment of fibers in order to improve their wettability and adhesion to cementitious matrices.

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Mixing of polypropylene fiber reinforced concrete is almost as simple as conventional concrete and does not require any special equipment or causes any critical slump modifications when used at low dosages. There is no special technical requirement for mixing and adding the fibers; polypropylene fibers can be added to the mix all at once at the low volume percentages typically used in practice. At the typically low volume fraction of polypropylene fibers used in concrete, there is less than 10% increase in the price of concrete.

Tests have indicated that polypropylene fiber improves many aspects of production and performance of concrete materials. Polypropylene reinforced concrete process desirable shrinkage cracking characteristics, impact resistance and toughness. There are also potentials for achieving improved flexural strength, tensile strength, abrasion and shattering resistance, freeze-thaw durability, deicing scaling resistance, permeability, fatigue, and fire resistance in concrete through the use of polypropylene fibers.

Control of plastic shrinkage cracks and improvement of concrete properties at early ages seem to play a key role in encouraging current commercial applications of polypropylene fibers in concrete. Many concrete structures may be subjected to their most severe loading at early ages during construction. Microscopic investigations of concrete structures have revealed that cracks can form in concrete shortly after casting or even before the formwork is removed. These types of crack are often called plastic shrinkage cracks, since polypropylene fibers cause tremendous improvements in controlling plastic shrinkage cracking, polypropylene fiber reinforced concrete can be used where early age strength and performance are required. Past experiments, however, have reported conflicting data concerning the effects of relatively low volume fractions of polypropylene fibers on the properties of concrete. Evaluation of the reported plastic shrinkage test data is further complicated by the fact that many of the testing methods used by different investigators have not been standardized.

The main thrust of this part of the research is to comprehensive background of polypropylene fiber reinforced concrete based on literature review. The discussion will be more emphasized on collated fibrillated polypropylene fibers at low volume fraction. This type of polypropylene fibers has been used in this study at low volume fractions.

2.2 POLYPROPYLENE FIBERS

Polypropylene fibers were suggested for use in concrete in early 1960's by Goldfein.[44] The development of stronger polypropylene materials, produced commercially in the 1960's, offered a potentially low priced polymer capable of being converted into useful textile fibers. Several forms of polypropylene fibers have been used in cement matrices; these are listed in Table 2.2 along with references describing their use.[20] A polypropylene film can be modified to produce Collated Fibrillated Polypropylene (CFP) fibers, as discussed below. Melt intrusion and stretching of polypropylene produces thin films with molecular orientation and consequent mechanical strength in the direction of stretching.

When a film is slit in a controlled an regular pattern and expanded transversely, a mesh of fine fibers is produced (Figure 2.1).[51]

The advantages of polypropylene fibers which encourage their concrete applications include:

1. high chemical resistance, particularly to alkalis,
2. high strength after stretching,
3. high resistance to oxidation when properly stabilized,
4. high melting point when compared with other synthetics fibers,
5. easy fibrillation, and
6. can be used in conventional mixing of concrete; no modifications is required with short fibers at the typically low volume contents.

Some concerns have been raised regarding the potential reinforcing efficiency of polypropylene fibers in concrete materials. It has been argued that the poisson effect in this low modulus fiber would prevent the development of sufficient bond, unless some shrinkage of the matrix also occurs. In addition, there are concerns if effective bonding is at all feasible because of the difference in the physico-chemical nature of polypropylene and cement-based matrix. The development of CFP fibers was successful in overcoming these difficulties.

Collated fibrillated polypropylene (CFP) fibers are produced by drawing or stretching thin film sheets, which are then slitted to produce CFP. These film sheets are slit conjugationally into tapes and then further distressed to produce fine fibers which are collated or held together by cross linking along their length. The fibrillated stretched tape is twisted along its length to form a fiber bundle of lower aspect (length-to-diameter) ratio, which can be conveniently mixed into concrete. The monofilament fibers within the bundle, however, have a very high aspect ratio, which helps with enhancing the reinforcement properties of fibers in concrete. The cross linking of fibrillated fibers in concrete also leads to improved mechanical bonding of fibers to the matrix. The network structure of fibrillated polypropylene fibers prior to mixing (Figure 2.2) consists of oriented fibrils cross linked together. After mixing with concrete, the fibrils will filamentize into multi-filament strands due to the tumbling forces (shear) exerted by the aggregates during mixing.[24]

Table 2.3 presents typical physical and chemical properties of collated fibrillated polypropylene fibers which are used nowadays in the construction of polypropylene fiber reinforced concrete.

Some fiber treatment techniques have also been tried to enhance the reinforcing action of polypropylene fibers in concrete. It has been suggested that the ultimate shear bond strength of monofilament polypropylene fiber is very low (approximately=29 psi, 0.2 MPa). When polypropylene fiber is subjected to a high voltage electrical treatment on both surfaces just before mixing with concrete, the ultimate shear bond strength is raised more than double.[68] An addition of an inorganic filler material with the polypropylene could also increase bond strength to about 580-725 psi (4-5 MPa).[68]

Some shortcomings of polypropylene fibers in concrete applications include:

1. Combustibility: A fire will leave the concrete with an additional porosity equal to the volume percentage of fibers; this is not necessary applicable if polypropylene fibers used strictly to control early age shrinkage cracking.
2. The low modulus of elasticity means that fibers can not effectively increase cracking strength of the composite, and relatively large strains might be resulted before the reinforcing action of fibers is fully utilized.

2.3 MIX PROPORTIONING

The Proportioning of concrete mixtures is a process by which one arrives at the right combination of cement, aggregates, water, and admixtures for making concrete according to given specifications. One purpose of mix proportioning is to obtain a product that will perform according to predetermined requirements, an essential requirement being the workability of fresh concrete at a specific age. Workability is defined as the property that determines the ease with which a concrete mixture can be placed, compacted, and finished. Durability is another important property, but it is generally assumed that under normal exposure conditions durability will be satisfactory if the concrete develops the necessary strength. Special attention will be required, of coarse, when proportioning concretes exposed to severe conditions such as freeze-thaws cycles or sulfate attack.

Another purpose of mix proportioning is to obtain a concrete mixture satisfying requirements at the lowest possible cost. The overall objective of proportioning concrete mixtures can be therefore summarized as selecting the suitable ingredients among the available materials and determining the most economical combination that will produce a concrete with certain minimum performance characteristics.

Wide ranges of mix proportions have been used for polypropylene fiber reinforced concrete (PPFRC) materials with relatively low fiber volume fractions. Conventional Concrete mix ingredients are used to produce PPFRC including: cement, coarse aggregate, fine aggregate, water and polypropylene fibers. Some mixtures may contain other binding materials such as fly ash, silica, slag, etc. Admixtures commonly used in PPFRC include water reducing, high-range water reducing and air entraining agents. Table 2.4 presents a list of the mix proportions used in the past for PPFRC. One may conclude from this table that with polypropylene fiber used at relatively low volume fractions, it is possible to use relatively high loading of aggregates with relatively larger particle sizes.

2.4 CONSTRUCTION

Polypropylene is chemically inert and thus can be added with impunity to an alkaline environment.The large increase in internal resistance makes fiber-mixes very interesting from the point of stiffening rate, lateral pressure on form-work and early stripping.

2.4.1 Conventional Concrete:

Polypropylene fiber reinforced concrete can be patched in a conventional concrete mixer, with addition of pre-packed bags measured for every cubic yard of concrete to give the target volume fraction (e.g. 0.1%) depending on job requirements. Polypropylene fiber at relatively low volume fractions (e.g. 0.1%) can be simply added to the mix, with a reasonably uniform dispersion of fibers achieved through regular mixing. To reduce any damage to fibers, the plain concrete may be mixed initially until a homogeneous mixture is achieved and then, after addition of fibers, an additional period of mixing would ensure uniform dispersion of fibers.[111]

The addition of polypropylene fibers to a concrete has an effect on its flow characteristics; this is an important factor from the construction point of view. However, the V-B consistometer (a British Standard) and slump tests still show reasonable mobility and compatibility of polypropylene fiber reinforced concretes incorporating relatively low fiber volume fractions; using the compacting factor as a measure of workability may lead to wrong conclusion.[111]

It has been reported that polypropylene fibers tend to act as a lubricant at the outside concrete surfaces; this lubricating effect may have some significance if fiber mixtures are used in conjunction with sliding shuttering, or in concrete pumping.[111]

Different mixing procedures have been utilized depending on the equipment and mix ingredients. Mindess and Vondran (1988) conducted PPFRC mixing in a pan mixer. After the plain concrete ingredients were patched and mixed, the fibers were added, and the following mixing sequence was followed: mix for 3 minutes, rest for 2 minutes, and mix for another 2 minutes.

Zollo (1984) performed their mixing in a drum mixer. Sand, gravel, and 1/3 of the mixing water were mixed with fibers for five minutes; cement and the remaining water were then added and mixed for another five minutes.

Some researcher performed following this method: plain concrete was mixed initially for two minutes, and then, after the addition of fibers, mixing was continued for one minute. Mixing was accomplished in Ref. 12 in a forced action mixer as follows: 2 minutes dry mixing of cement, aggregate, and fibers, and then 3 minutes of wet mixing with the addition of silica slurry and water.

2.4.2 Ready Mixed Concrete:

In the case of ready mixed concrete, if the job-site is closer than a 30-minute drive from the concrete plant, the fiber can be added at the plant with the cement and aggregate. If the job-site is farther than a 30-minute drive, the fibers should be added at the site. When mixed in turbine mixers, additional mixing time may be necessary.

2.4.3 Shotcrete:

For sprayed concrete (shotcrete), the dry method seems to reduce the potential problems with mixing and spraying of polypropylene fiber reinforced shotcrete. When balling of fibers during batching is observed, they could be removed by hand before entering the gun. Due to the presence of fibers on the surface of sprayed concrete, a flash coating with plain shotcrete is required when the unevenness of the finished surface is a concern. It was reported that 0.75% by volume of 12 mm (0.47 in.) polypropylene fiber appears to exceed the maximum useful dosage.[14]

2.4.4 Continuous Polypropylene Sheets:

Depending on the thickness of the cement sheets required and the fiber volume percentage needed, polypropylene networks could be used, in 12-16 elementary layers, to reinforce the cement sheets. Two different precesses have been developed for continuous production of the sheeting by Vittone (1987). In the first process, thin layers of the matrix paste are deposited on a continuous, porous belt, alternating with layers of the reinforcing networks. Each layer of polypropylene is carefully compacted into the cement, and excess water is removed through the belt with vacuum. A continuous final pressing controls the sheet thickness and provides the correct surface finish. The volume percent of reinforcement is controlled by the speed of the network feeders, the speed of the belt and the clearance between the matrix dosing boxes and the belt.

The second process differs from the first mainly in the method of impregnating the reinforcement. In this process, the cement mix is sprayed into the networks as they advance horizontally along a porous support. Excess water is removed by suction, and the sheet is continually compacted.

2.5 FRESH MIX PROPERTIES

Table 2.4 also presents a summary of fresh mix properties of polypropylene fiber reinforced concrete found by previous investigators. They studied many aspect of workability characteristics of polypropylene fiber reinforced concrete. The material is reported to respond well to vibration. It flows satisfactorily when kept moving, and segregation is reduced in the presence of fibers.[141] Zollo et al (1986) observed that collated fibrillated polypropylene fibers at 0.1% volume fraction reduce slump by approximately 50% but do not cause any significant loss in the actual workability of fresh mix during mixing and casting. Contractors are cautioned not to add water to restore the lost slump, because the addition of water will not improve workability and may reduce strength and increase shrinkage.[68] Even at the lower slump, workability of polypropylene fiber reinforced concrete is said to be adequate for placing, compacting, and finishing operations. Although it has been suggested that the loss of slump in the presence of polypropylene fibers is increased by increase of fiber length, recent laboratory and field tests indicate that there is little correlation between slump reduction and fiber length (Table 2.5).[79]

Although slump of the concrete will be somewhat different with polypropylene fibers, as mentioned earlier this stiffer appearing concrete is still quite workable and pumpable. Tests were conducted on fresh concrete mixtures by Ritchie and Mackintosh (1979) in which the mobility and compatibility of polypropylene fiber reinforced concrete were recorded using slump, compacting factor and Ve-Be consistometer tests. It can be seen from slump test results (Figure 2.3-a)[111] that the addition of 0.125% of polypropylene fibers reduces the slump to approximately half the original value in all cases studied by Ritchie and Mackintosh. Using the slump classification for workability is good as long as the addition of fibers do not add to the stiffness of the mix. When it is so the extra stiffness is not detected by the slump test, but is clearly illustrated by the V-B consistometer test (Figure 2.3-b).[111] Using the compacting factor test could lead to the wrong conclusion that there is little difference in the workability of plain concrete and concrete reinforced with 0.125% of Polypropylene fibers (Figure 2.3-c).[111]

2.6 MECHANICAL AND PHYSICAL PROPERTIES

A considerable amount of research has been performed on the mechanical properties of polypropylene fiber reinforced concrete. Past work in this area has been concerned mainly with the compressive, flexural and tensile strengths, and fatigue life of polypropylene fiber reinforced concrete. Test data has been compiled for composites reinforced with polypropylene fibers at volume fractions ranging from 0.1-10%, with the higher volume fractions corresponding to the usage of continuous fibers. The material properties of polypropylene fiber reinforced concrete depend greatly on the fiber content and the form of the fiber used as well as the construction techniques.

2.6.1 Strength and Toughness:

Contradictory test results have been reported by different investigators regarding the effects of polypropylene fibers on the compressive, flexural and tensile (direct and splitting) strengths of concrete materials.[6,14,37,54,74,87,93,110,133,142] Differences in results may have been caused by the differences in matrix composition, polypropylene fiber type and volume fraction, and manufacturing conditions. Table 2.6 presents a summary of the reported test results on the compressive, flexural and tensile strengths of polypropylene fiber reinforced concrete.

Zollo et al (1984) performed tests to determine compressive strength (ASTM C-39), splitting tensile strength (ASTM C-496), and flexural strength (ASTM C-78) for both plain and polypropylene fiber reinforced concretes. Fiber contents in these tests ranged from 0-0.3% by volume. The results (see Table 2.7)[142] indicated that the presence of fibers had negative effects on compressive strength, while splitting and flexural strengths increased slightly with increasing fiber content. In other tests the results generally agree with the earlier findings reported above.[6,37,74] Some researchers also reported evidence of small but favorable effects of fiber addition on toughness.[13,63,79] Mindess and Vondran (1988) reported that the compressive strength was found to be increased by about 25% at 0.5% volume fraction of polypropylene fibers. Test results reported by Hughes and Fattuhi (1976), suggest that compressive strength decreases but flexural properties are improved with increasing fiber content.

Several investigators have shown that the incorporation of continuous polypropylene fibers into cement based materials at higher fiber volume fractions (0.5%-8.0%), regardless of the difference in manufacturing technique and mixture proportions, leads to improved ductility and toughness of the composite material.[14,34,54,93,133] Test results indicate that such composites, when produced under certain optimized conditions, display excellent post-cracking behavior (see Figure 2.4).[93] Other test programs have shown that composites reinforced with continuous polypropylene fibers can sustain loads beyond the first cracking load.[133,34] Higher fiber contents were shown to result in reduced first cracking strength and increased ultimate strength of the composites in flexure (see Figure 2.5).[34]

Test results have indicated that fiber volume fractions necessary to obtain significant post-cracking load carrying capability and ductility with continuous fiber network are less than those required when discontinuous fibers are used. [51,70]

2.6.2 Impact and Shattering Resistance:

Concrete materials are subjected to impact loading in various fields of application, including pile driving, hydraulic structures, airfield pavements, protective shelters and industrial floor overlays. Impact loading resistance represents the ability of concrete to withstand repeated blows and absorb energy. The number of blows that concrete can withstand before reaching the debonding condition is of particular interest because this stage represents a definite state of damage. Since plain concrete is a brittle material, it has a relatively low energy absorption capacity under repeated impact loads.

Different test procedures have been developed for the measurement of the impact resistance of concrete. Due to the variable nature of such testing and the need to apply specialized analytical techniques to each test arrangement, cross test comparisons can not be made. Some reports indicate an increase in impact strength using polypropylene fibers,[43,77,87,110] while others show no improvement.[142] Impact strength improvements were reported to be 50% in the flexural mode by Mindess and Vondran (1988), and the increase fracture energy with polypropylene fiber reinforcement was reported to be between 33 and 1000%.[24,87] The effects of polypropylene fiber reinforcement on beams subjected to impact loading indicate an improvement in impact fracture energy of 2-10 times those of plain concrete.[87,128,133] Tests using ACI committee 544 recommendation (drop-hammer method) have indicated that the number of blows required to obtain the first crack and the ultimate failure was increased by the addition of polypropylene fibers.[4,44,128] The shattering resistance of concrete is also improved substantially by the addition of polypropylene fibers.[128]

2.6.3 Fatigue Resistance:

Polypropylene fibers reported by increase the fatigue life of concrete. It has been noticed that during the crack propagation in a polypropylene fiber reinforced concrete, there is a stress redistribution along the fibers which slows down the propagation of cracks, test results are shown in Table 2.8.[110]

2.7 PERMEABILITY

There is a growing awareness of the important role of permeability with regard to the long-term durability of concrete structures. If an aggressive substance (water, sulfates, chloride ions, etc) can be kept out of concrete by virtue of low permeability, then the associated problems, such as freeze-thaw deterioration, corrosion of reinforcement, and formation of expansive components may be mitigated. Therefore, there has been an interest both in determining the permeability of conventional concrete, and in the development of improved concretes with lower permeability.

Permeability is defined as the ease with which a particular substance (liquid, gas, ions, etc.) can flow through a solid. Alternatively, the ability of a given concrete to resist penetration of a particular substance represents its impermeability. Primary factors influencing concrete permeability have been found to be w/c ratio and the age of concrete (see Figure 2.6 and Table 2.9).[87] Tests on concrete permeability could be performed by measuring the permeation of liquids, gases, or ions. Some of these tests are described below:

1. Hydraulic Permeability: permeability to liquid water could be determined using several methods:

   a. Initial Surface Absorption Test (ISAT, British Standard 1881): Movement of water into dry concrete via capillary attraction can be quite rapid and approach fluid flow rates in saturated concrete brought about by applying hydraulic pressures close to 400 psi (2.8 MPa)

b. High Pressure Water Permeability Test: This test method was developed at King Fahd University of Petroleum and minerals (KFUPM); other versions of this test are also available. The test is performed by forcing water into 2.75 in. diameter x 4.0 in high (70 mm x 100 mm) cylindrical concrete specimen at a pressure of 1000 psi (6.90 MPA) in a pressure vessel.[5]

c. Von Test method: In this test the amount of water that permeates through a 2" thick layer of concrete in 24 hours is measured.

2. Air Permeability: Flow of air through concrete would be measured using one of the following methods:

a. EGG Method: A relatively new test procedure which uses an air pressure drop method.[14]

b. Standard API Method: The test is carried out using 4 x 8 in. (100 x 200 mm) concrete cylindrical specimens which seal into a cell. Air is then introduced to the upstream force of the sample. After a steady state condition is achieved, the upstream and downstream pressures are recorded. Flow rate is determined by measuring the pressure drop across a calibrated orifice. Permeability, in darcys (in.^{2}), is then calculated using the following equation:

$$K_g = \frac{2\mu Q_g P_b L}{A(P_2^2 - P_1^2)}$$

Where: K_g = gas permeability in days (in.^{2}),

μ = gas viscosity, in (Pa.S)

Q_g = gas flow rate, in (cm^2/sec. cm^2/s)

P_b = barometric pressure, in (pa)

P_1 = inflow pressure, in (Pa)

P_2 = outflow pressure, in (Pa)

A = Ave. cross-sectional area perpendicular to line of flow, in (cm^2)

L = length of flow path, in (cm).

3. Chloride Ion Permeability:

a. Rapid test for permeability to chloride ions: In this method, a potential of 60 is applied across a 4 in. diameter x 2 in. thick cylindrical specimen of concrete which has been conditioned by vacuum saturation. After six hours of test, the total charge passed through the specimen (in Coulombs) is obtained by integration of the current passed through the specimen during the test period. This test has been adopted by AASHTO (Designation No. T 277-83).

b. Chloride Ion Penetration Method: In this method, a concrete slab 12 x 12 x 3 (300 x 300 x 75 mm) is pounded with sodium chloride for a period of 90 days. The amount of chloride ion penetrating into the test specimen is measured according to the AASHTO T 259-8 procedure.

Defects such as those caused by settlement in fresh concrete, plastic and drying shrinkage cracks, thermal cracks, structural cracking, segregation or ho

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honeycombing of the concrete will increase the permeability rates, which in turn lead to less durable concrete. Plastic shrinkage cracks substantially increase the net permeability of concrete and expose greater surface areas of concrete to the detrimental effects of the environment, thus prematurely aging the concrete and shortening its performance life. The utilization of polypropylene fibers in concrete reduces the potentials for shrinkage cracking and is thus expected to reduce permeability.

Tests conducted to study the effects of polypropylene fiber reinforcement on permeability have been performed using the "Von test" method and water permeability test procedure mentioned earlier. Test results by the "Von" method indicated reductions of 34% to 75% in water migration due to the inclusion of 0.1% and 0.2% volume fraction of polypropylene fibers, respectively (see Figure 2.7).[135] The results obtained by high pressure method indicate that the effect on permeability due to the addition of 0.2% polypropylene fibers is negligible (see Figure 2.8).[5]

2.8 DURABILITY

Concrete is inherently a durable material, when properly designed for the environment to which it will be exposed, and if carefully produced with good quality control. However, concrete is potentially susceptible to aging in various environments (see Table 2.10)[87] unless certain precautions are taken. A major difficulty in studying durability is predicting concrete behavior several decades in the future on the basis of short-term tests.

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The reported test data on durability characteristics of polypropylene fibers reinforced concrete under severe exposure conditions (see Table 2.10) are summarized in this section.

2.8.1 Scaling:

Concrete that is adequately air-entrained for freeze-thaw resistance may nevertheless be damaged by repeated application of de-icing salts, whether these salts contain chloride that causes corrosion or not. Even properly air-entrained high-quality concrete may be damaged directly by de-icing chemicals that contain no chloride. These determinant effects of de-icing salts occur on flat surfaces; when cracks are present, the same mechanisms tend to work along the plane of cracks.[135]

Polypropylene fibers improve the resistance of concrete to cracking; this is expected to reduce deteriorations associated with salt scaling.[128]

2.8.2 Corrosion:

Concrete is generally reinforced with mild steel bars which are susceptible to corrosion under specific exposure conditions. The formation of rust is an expansive reaction that will lead to cracking and spalling of the concrete above the rusted bars.

The effect of polypropylene fiber reinforcement on corrosion of reinforcing steel in concrete has been investigated by different investigators, who reported contradictory conclusions. Preliminary test results using a short-full method show that polypropylene fibers resist corrosion damage of reinforcing steel in concrete in a salty environment.[128] On the other hand, tests on corrosion resistance of polypropylene reinforced concrete conducted by Al-Tayyib and Al-Zahrani (1990), using accelerated corrosion, and half-cell potential test procedures indicated no noticeable effects of the polypropylene fibers on the corrosion of the corrosion of reinforcement (see Figures 2.9 and 2.10).[5]

2.8.3 Freezing and Thawing:

When concrete is subjected to repeated cycles of freezing and thawing, the freezing and consequent expansion of pores water tend to damage the concrete. Air entrainment has proven to be an effective and reliable means of protecting concrete against frost attack. Polypropylene fibers are compatible with the entrained air in concrete, that is necessary to ensure the freeze-thaw durability of concrete with or without fibers.[128]

2.8.4 Fire Resistance:

Concrete has excellent fire-resistant properties compared to steel and wood. Concrete has a lower thermal conductivity and a higher specific heat than metals. However, it has been found that concrete is damaged by exposure to high temperatures which cause loss of strength, cracking and spalling.

Fire resistance tests were conducted on a 36 x 36 x 6 in. (914 x 914 x 152 mm) Concrete slabs of both normal and light-weight concrete, with or without collated fibrillated polypropylene (CFP) fibers; standard procedures of UL 263

"Fire Test of Building Construction and Materials" (ASTM E-119) were followed. Results showed that the fire resistance periods for both normal weight and light-weight concrete slabs were increased with the use of CFP fibers as compared with control slabs.[128]

2.8.5 Abrasion and Wear Resistance:

Abrading effects are a major cause of deterioration and reduced service life of concrete slabs. The abrasion phenomenon in roadways is a very complex dynamic force that is caused by small impacts of studs and studded tires. Some test data indicated that the utilization of polypropylene fibers in concrete improves the resistance of concrete to abrasion. Limited tests conducted following ASTM C-994-82 method [with double the load (20 kg) and three times abrasion time (6 minutes)] indicated that abrasion resistance doubles with the use of CFP fibers at 0.1% volume fraction.[128]

2.9 SHRINKAGE CHARACTERISTICS

2.9.1 General:

Volumetric changes in hardened and plastic concrete are significant in magnitude and have a serious influence on the performance and durability of concrete structures. Inadequate allowance for the effects of shrinkage in concrete can lead to cracking or warping of concrete slabs.[142] Shrinkage, the reduction in the bulk volume of concrete, is only a fraction of the volume of the water loss with larger part of released water coming from the pores in the concrete.

Furthermore, the shrinkage dose not depend on water loss alone, but also on the actual deformability of concrete.

The duration of shrinkage in concrete could be divided into three phases (Figure 2.11).[66] During the first phase, the concrete adopts itself to the mold (low resistance to deformation), it does not shrink at all in this phase (except in the vertical direction, see Figure 2.11) and does not suffer serious cracking. In the second phase, the evaporation of water causes rapid shrinkage. Thus, the danger of cracks arises as long as the tensile strength of concrete increases more slowly than the induced stresses. Then, in the third phase, the rapidly increasing resistance against deformation, see Figure 2.11, will be accompanied by a retardation in shrinkage and faster increase of the tensile strength. By the combination of both effects, the danger of cracking at early ages ceases in the third phase.

Here are some of the many factors that influence the shrinkage of concrete, which will consequently affect cracking:

1. Material composition;
2. Mix design;
3. Construction Methods;
4. Temperature and relative humidity of the construction environment;
5. Steel Reinforcement;
6. Curing practices of conditions;
7. Rate of evaporation;

8. Size of the structure;

9. Age of the concrete;

10. Structural loads;

11. Capillary stresses;

12. Desiccating pressure; and

13. Changes in surface pressure.

Recent investigations of concrete structures have revealed that cracking can occur inside the bulk of concrete structures with or without any visible sign on the outer surfaces. It is also indicated that under certain conditions both micro- and macro-cracks can form shortly after or even before the formwork is completely removed. It is more probable that micro-cracks will widen further due to both mechanical and environmental stresses. To lengthen the service life of a concrete structure it will be necessary to avoid the formation of the early cracks as much as possible. The relevant literature has divided the driving mechanisms of the processes that may cause crack formation at early ages of concrete structure into two broad classes:[28]

A. Crack formation due to desiccation: This can be further divided into:

i) Loss of water to the environment; and

ii) Fixation of liquid water, i.e. self-desiccation. Crack formation due to water loss to the environment is what we call shrinkage cracking, which also could be known as plastic shrinkage cracking (at early ages) or drying shrinkage cracking (when concrete hardens).

B. Crack formation due to the temperature difference:

This would occur during setting and hardening wherever the temperature differences between the bulk of the structure and its surfaces exceed approximately 20 ^{o}C.

Un-restrained (free) shrinkage in typical concrete structure is rarely found. Restraints are always present, either internal or external, resulting from support conditions, reinforcement, or due to non-uniform drying. These restraints induce tensile stresses which approach the tensile strength of concrete and cause cracking.

Shrinkage is a time-dependent phenomenon; if it takes place during the early age, it is called "plastic shrinkage". If it occurs after the concrete has hardened it is called "Drying shrinkage". Other identifiable types of shrinkage, such as carbonation shrinkage and autogenous shrinkage, while not caused by the same mechanisms, are similar in effects to drying shrinkage.

Plastic shrinkage cracks occur during the first few hours after casting the concrete while the material is still in a semi-fluid or plastic state. The study of plastic shrinkage cracking is complicated because the material properties that determine whether such cracks will form are time-dependent and change rapidly during the first few hours. In order to develop reliable means of preventing this type of damage to the concrete, it is desirable to know the physical or chemical origins of plastic shrinkage. Since plastic shrinkage takes place within the first few hours after placing the concrete, it can be shown that chemical shrinkage does not contribute to plastic shrinkage to a significant extent. Mainly because not much hydration takes place within the first two hours. One common observation, which is recorded in nearly all of the relevant papers, is that plastic shrinkage-induced cracks are created as soon as the surface of the fresh concrete dries. In other words, mean that plastic shrinkage is likely to occur when the rate of evaporation exceeds the rate at which the bleeding water raises to the surface.[138] It is also believed that plastic shrinkage cracking occurs at the exposed surfaces of freshly placed concrete due to consolidation of the concrete mass and rapid evaporation of water from the surface. This leads to open water channels that produce tensile stress in surface tears and cracks which destroy surface integrity and impair durability.

Drying shrinkage of concrete is due to loss of free water from the matrix gel. Some drying shrinkage is reversible upon rewetting. When the restraint against drying shrinkage movements causes tensile stresses which exceed the tensile and flexural strength achieved by concrete, surface cracks will occur. At the beginning and during the period of initial hardening (i.e., in green concrete), the fracture stress of concrete is going through a minimum, while the tensile strength is low (Figure 2.12).[33] As a result, concrete cracks easily.

In the presence of fibers, concrete exercises an additional restraint to drying shrinkage (to that produced by the aggregate particles). Since fibers are randomly distributed in concrete, they will offer resistance to volumetric changes in all directions. In fiber reinforced concrete the stress distributing properties of fibers and their ability to transfer tensile stresses over cracks are very important. When concrete reinforced with steel bars is subjected to tension, it has been shown that the predominant parameter determining the crack spacing and the crack width is the specific surface of the reinforcement (the surface area of reinforcement per unit volume of concrete). It can be shown that fiber reinforced concrete has higher volume of Specific Surface of Reinforcement than conventionally reinforced concrete.[68] Hence, when fiber reinforced concrete is subjected to restrained shrinkage, the resulting strains can be distributed over several cracks of limited width instead of a few cracks with unacceptably large widths, as is the case in unreinforced concrete.

There are currently no standard tests to assess cracking due to restrained shrinkage. Some difficulties with existing tests can be summarized here. One problem with the ASTM C-157 method is the lack of agreement between laboratory and field test results. The shrinkage observed in ASTM tests is much higher than the shrinkage results obtained from a structure containing the same concrete. Kraai (1984) believes that this difference is due in part to the size of the test specimen (Figure 2.13).[65] Another reason is that ASTM test conditions require saturation before drying shrinkage measurements, while in the field concrete drying starts immediately after placing (provided that no surface curing was made). ASTM C-157 and C-827, however, are used to determine the free drying and plastic shrinkage movements, respectively. ASTM C-157 recommends a prismatic specimen 11.25 in. (285 mm) long with 1, 3, or 4 in (25, 76, or 102 mm) square cross sections to measure the free drying shrinkage of the specimen along its length. This test specimen, if restrained at both ends, could present information on restrained drying shrinkage cracking. It is, however, found to be difficult to provide sufficient restraint to produce cracking with linear specimens as it is difficult to conduct a tensile test on concrete.

Table 2.11 presents a summary of the shrinkage test methods and conditions reported by different investigators. Some researchers tried to use long specimens with flared ends (Figure 2.14-a) that were restrained, and used small cross-sectional dimensions 2.75 x 4 in. (71 x 102 mm) to produce shrinkage cracking. Two main other types of specimen have been used by other investigators for restrained shrinkage tests, namely plate-type specimens (rectangular) and ring-type specimens. (Figures 2.14-b, 2.14-c and 2.14-d).[45,68] In the case of plate specimens, when the restraint against shrinkage movement is provided in two directions, a biaxial state of stress is produced. The results obtained from this type of test may depend on the specimen geometry in addition to the material properties. The restrained shrinkage tests using steel rings were conducted as early as 1939 to 1942 by Carlson.[45] The ring type restrained shrinkage test apparatus has been found to provide a high and nearly constant degree of restraint, producing consistent results with cement paste, and mortar. In this test a concrete ring is cast directly around a heavy steel ring. As concrete dries, the concrete ring tends to shrink, but the steel ring provides the restraint and prevents the shrinkage movements. The steel ring also serves as a sensitive dynamometer to compute the induced tensile stresses in concrete by measuring the steel strains using strain gages.

2.9.2 Shrinkage Characteristics of Polypropylene Fiber Reinforced Concrete:

The use of polypropylene fibers at low fiber volume fractions improves many aspects of the production and application of fiber reinforced concrete including shrinkage and crack control. Many parameters govern the performance of polypropylene fiber reinforced concrete subjected to restrained shrinkage. These include the potential extent of shrinkage, the degree of restraint, time-dependent constitutive properties of concrete, and fiber to matrix interfacial bond characteristics.[32,44,45] As mentioned earlier, the surface area of reinforcement per unit area of cement (specific reinforcement surface) has important effects on the spacing and width of cracks, polypropylene fibers can be split into very fine fibers (strands) at relatively small costs, producing fibers with specific surface areas of about 25.4 $in.^2/in.^3$ (10 cm^2/cm^3), which is 20 times the typical value for steel fibers.[68]

When plastic shrinkage forces are applied to concrete in the presence of polypropylene fibers, the fibers resist early shrinkage cracking and increase the capacity of concrete at the initial and early set stages, thus causing the material to l

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to be less susceptible to settlement cracking and to adverse vibration effects at the same time.

There is currently no standardized procedure for quantifying the effect of polypropylene, or any other synthetic fibers, on plastic or drying shrinkage cracking which results from volume changes under restrained conditions.

Unrestrained (free) drying shrinkage tests have indicated reductions of 14, 40 and 25% at fiber volume fractions of 0.1, 0.2 and 0.3% when curing was done for 7 days under water.[141] Higher reductions in unrestrained drying shrinkage were obtained with extended moist curing periods under water. Grzybowski and Shah (1990), however, suggest that the addition of polypropylene fibers does not substantially alter the unrestrained drying shrinkage movements at a fiber volume fractions as high as 1.0%. Tests following ASTM C-827 preceding on plastic volume change (shrinkage)[141] indicates reductions in total shrinkage at 3 hours of 15, 17 and 25% for fiber volume fractions of 0.1, 0.2 and 0.3%, respectively, when compared with plain concrete. During the test, it was noticed that the quantity of surface bleed water was significantly reduced by the addition of polypropylene fibers. It was suggested that fibers caused a reduction in consolidation, thus eliminating the damaging capillary bleed channels and causing an increase in inter-granular pressure in the plastic concrete.[141]

Although unrestrained shrinkage tests do provide some information about the shrinkage characteristics of fiber reinforced cement composites, results of these tests may not provide any useful information on how composites respond to sh

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shrinkage-induced stresses in restrained conditions when shrinkage strains translate into tensile stresses in concrete. After cracking, polypropylene fibers are believed to transfer the tensile stresses across cracks and to arrest or interrupt crack tip extensions so that many fine (hairline) cracks occur instead of fewer larger cracks.[45,117,141]

Some investigators have used a holographic technique to detect the presence of micro-cracks is specimens subjected to restrained shrinkage. In this approach, the specimens are illuminated with a laser beam. Two pictures were taken within a few days of when displacements in the micro-cracks were supposed to occur. The fringes in the first picture represent the undeformed state of the body, while the fringes in the second picture include the deformations in the specimen. By superimposing these two pictures, one can obtain discontinuity in fringes with micro-cracks are present. Holographic results can recall cracks which generally can not be detected by observation under optical microscope. The accuracy of the holographic observations is about 0.25 micron, whereas it is generally difficult to detect cracks less than 20-30 microns wide under optical microscope.

A theoretical model has been developed by Grzybowski and Shah (1989) to predict the cracking response in fiber reinforced concrete members subjected to restrained shrinkage. The model was used to predict the shrinkage cracking development of the ring type specimen.

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2.10 FIBER-MATRIX INTERACTIONS

Fibers are effective in enhancing the mechanical properties of brittle cementitious matrices. This characteristic of fibers is controlled by the method by which load is transferred from the matrix to the fibers, the arrest and deflection of micro-cracks by fibers, and the bridging affect of fibers across cracks.

The nature of the interface zones in cement-based materials is rather complicated; the structure of interface zone is also time-dependant. The geometry of fibrillated polypropylene fibers after mixing in concrete, and the nature of the fiber interface zones in the hardened composite have been investigated by several investigators in efforts to understand the bonding mechanisms in polypropylene fiber reinforced concrete materials. Earlier investigators suggested that the poisson effect in the low-modulus polypropylene fibers would prevent the development of sufficient bond, unless shrinkage movements of cement compensate for the poisson effect; in addition, doubts have been expressed as to whether effective bonding is at all feasible between polypropylene fibers and cementitious matrices due to the differences in the physico-chemical nature of polypropylene and cement paste.

The development of fibrillated polypropylene fibers for the reinforcement of cemetitious matrices was successful in overcoming these difficulties. The reinforcing unit in this case is in the form of a network (Figure 2.15)[23] that may be subjected to surface treatment for improved bonding with the cementitious matrix; improved bonding may also be achieved be adding buttons at ends of fibers or by twisting the fibers (Figures 2.16-a and 2.16-b).[93] Polypropylene may also be subjected to a high-voltage electrical treatment just before casting; this almost doubles the ultimate shear bond strength between polypropylene fibers and hardened cement paste.[68]

Bond stress values for polypropylene fiber reinforcement as determined by several investigators, are given in Table 2.12[(20)] and range from 2.0-22.75 ksi (0.3-3.4 MPa), depending on fiber characteristics, geometry, and method of determination. The nature of the bonding of a continuous fibrillated network was discussed by Hannant et al (1978) who suggested that a mechanical keying is obtained due to the nature of the net and the presence of matrix in the openings of the net. Baggott and Ghandhi (1981) suggested that, for continuous monofilament polypropylene reinforcement, enhanced bonding is obtained due to the lateral displacement of crack surfaces relative to the fiber array, and some misalignment in the fiber orientation. Majumdar (1975) stated that, since a low bond strength is generally associated with large impact resistance but poor tensile strength of the composite, there is some advantage in trying to reinforce cement by a mixture of fibers (e.g. glass together with polypropylene) forming both good and poor bonds with the matrix.

Walton and Majumdar (1975) have suggested that pull-out experiments aimed at measuring the fiber-to-matrix bond strength give widely variable results and in many cases the polypropylene fibers tend to break rather than pull out of the matrix. Their bond test results have indicated that the bond between polypropylene fibers and cementitious matrices is entirely frictional.[133] The bond strength was observed to be only slightly affected be changes in the environment in which the composite was placed.

Holographic interferometry was used to investigate micro-cracking in continuous polypropylene fiber reinforced cement-based composites under tension.[91] Formation of micro-cracks was verified to occur prior to bend-over point (the point at which the composite response first deviated from linearity). Holographic interferometry observations indicated that:

1. Cracking initiates from one side of the specimen and propagates to the other side. The bend over point is characterized by the cracks crossing the entire width of the specimen.
2. The average spacing of the cracks at bend over point is 0.5 in. (13 mm) for $V_f=12\%$, and 2.1 in. (54 mm) for $V_f=8\%$.
3. The toughening effect of fibers hinders unstable propagation of cracks, thus preventing localization.
4. After the bend over point, the spacing of the cracks decreases.
5. The distribution of active micro-cracks can be related to the state of deformation of the specimen.

Polypropylene fiber cement composites cured in an autoclave [at 0.4 MPa and 284 °F (140 °C) for 24 hours] and then oven-dried [at 241 °F (116 °C) for 24 hours] do not show any improvement in fractural toughness over the cement matrix, because of thermal oxidation degradation of the polypropylene fibers;

Scanning Electron Microscope (SEM) pictures (see Figure 2.17)[77] display distinct characteristics of brittle fracture after autoclaving. The major mechanism of fiber degradation is suggested to be a thermal oxidation effect due to the loss of antioxidants which are either leached out and/or deactivated during the autoclaving process. The solution to the problem was suggested by Mai et al (1980) to involve the reduction of oven drying temperature to about 65 °C (149 °F), or substituting oven-drying with air-drying after the composites are autoclaved.

The nature of bond of a continuous fibrillated network may not necessarily be the same in discontinuous polypropylene fiber reinforced concrete, where the fiber volume is much smaller and the composite is produced by conventional mixing techniques. Although the short fibers are fibrillated and have a network structure (see Figure 2.2),[22] they are designed to filamentise into multifilament strands when mixed with the concrete ingredients, due to the tumbling forces exerted be the aggregates during the mixing process.

The nature of the interaction between polypropylene fibers and the matrix in short collated fibrillated polypropylene fiber reinforce concrete at low fiber volume frictions was studied using Scanning Electron Microscope (SEM) and Energy Dispersive X-ray (EDX) techniques by different investigators. Their results are presented here.

Rice et al (1988) tested polypropylene fiber reinforced concrete in direct tension using 0.75 in. (19 mm) long fibers at 0.2% volume fraction. The fracture of polypropylene fiber-hydrated cement interface was studied by SEM and EDX methods. The results revealed that:

1. The bond between fibrillated polypropylene fibers and cement paste is both adhesion and mechanical (see Figures 2.18, 2.19, and 2.20).[109]
2. The bond is as strong as the cement paste at the time of the test, and may cause rupture of fibers prior to pull at. Bentur et al (1989) studied the effects of concrete strength and polypropylene fibers on the failure modes in polypropylene fiber reinforced concretes subjected to impact loading.[24] Two types of commercial polypropylene fibers, namely FTF and FBM, were used with lengths ranging from 0.5-2.0 in. (13-51 mm), at volume fractions ranging from 0.1-0.7%.

The structure and mode of fracture of two polypropylene fiber types under impact loading were investigated using Scanning Electron Microscopy.[24] The results indicated that:

1. The polypropylene fibers tend to fracture in high-strength concrete, while they pull out in normal strength concrete (Figures 2.21-a and 2.22-a).[24]
2. The different structures of the two polypropylene fiber types produced different structures in concrete, with greater preservation of the fibrillated network structure in the FTF (Figure 2.23-a)[24] and the separation into individual filaments of the FBM fibers (Figure 2.23-b).[24]

3. In all systems, on intimate contact at the fiber-matrix interfaces was observed, and the matrix adjacent to the fibers was quite dense (see Figures 2.21-b and 2.22-b).

In another study, Bentur et al (1989) investigated the nature of the polypropylene fiber matrix interaction in fiber reinforced concrete. The matrix was conventional, air entrained concrete reinforced with 0.1, 0.3 and 0.5% fibrillated polypropylene fibers by volume. Observations were done on fibers washed out of fresh concrete and on the fracture surfaces of hardened concrete (split under impact loading). The structure of the washed out fibers in fresh mix was characterized by multifilament strands (Figure 2.24-a)[22] and cross-linking fibrils (Figure 2.24-b).[22] Optical microscopy of the fractured surfaces suggested that there was a tendency in the polypropylene fibers to accumulate in the vicinity of the coarse inclusions such as steel bars, coarse aggregate, air voids...etc. (Figure 2.25-a and 2.25-b).[22,26] they also suggest that two bonding mechanisms may occur in polypropylene fiber reinforced concrete:

1. Interfacial adhesion: Here there is very tight contact between the fiber and the matrix at the interface (Figure 2.26).[22]
2. Mechanical anchoring: due to the fiber-matrix interlocking which was identified there. In this case, two levels of anchoring may be distinguished: a) The cement matrix was present between the branches of the fibrillated fiber [Figure 2.27-a].[22]

b) On a smaller scale, there may have been some contribution from the small fibers which separated from the fiber surface [Figure 2.27-b].[22]

Tests on bond of treated short polypropylene fibers were performed by Naaman et al (1984), and Fahamy and Lovata (1990). Naaman et al treated the fibers mechanically by adding buttons at their ends (Figure 2.16-a) and twisting the fibers (Figure 2.16-b).[93] Pull-out tests were performed on mortars reinforced with 1 in. (25.4 mm) polypropylene fibers at relatively high volume fractions (2-6%). The test results presents in Figures 2.28-a, and 2.28-b[(93)] are indicative of substantial improvement in bond strength (up to 5 times) with the addition of end buttons or the twisting of polypropylene fibers.

Fahamy and Lovata (1990) investigated the effects of mechanical treatment of polypropylene fibers on their performances in concrete. The fibers were surface treated before mixing it in the concrete. A mild linear alcohol base solution was chosen as the agent of this chemical treatment. The chemical was diluted by volume fraction with distilled water into two denominations 1:2 and 1:5, for each treatment groups. The chemical treatments were prepared first. The polypropylene fibers were then weighed and soaked in the chemical both for 10 minutes. Then, the fibers were removed and allowed to air dry. Four groups were studied: one was control group (no fiber) and three groups contain fiber as follows.

-Group A: Untreated polypropylene fibers.

-Group B: Polypropylene fibers treated with a diluted solution of 1:2.

-Group C: Polypropylene fibers treated with a diluted solution of 1:5.

Scanning Electron Microscopic (SEM) observation of the failed specimens indicated that CH crystals with sharp edges were seen to be the major precipitates on the fiber surface (see Figure 2.29).[37] The chemical treatment reported improved the wettability of the polypropylene fibers. The addition of the alkali solution up to a 1:5 ratio promote the formation of the CH crystals on the fiber surface which resulted in more CH crystal density on the fiber, hence increasing the mechanical bonding between the fiber and the matrix.[37]

2.11 APPLICATIONS:

Polypropylene fibers were introduced to the market in early 1960's. Most commercial applications of polypropylene fiber reinforced concrete involve the use of low-denier, law volume fraction fibrillated or monofilament fibers. These fibers have been generally used for non-structural applications, where polypropylene fiber provide concrete with reduced plastic shrinkage cracking, enhanced toughness characteristics, and improved impact and shattering resistance. Specific discussions on some common applications of polypropylene reinforced concrete are presented in this section.

Discrete polypropylene fiber have been used in a variety of cast-in-place and precast applications, are discussed below. Pictures of some of these application are presented in Appendix I.

2.11.1 Cast-in-Place

Floor systems: polypropylene fiber reinforced concrete is widely used for floor systems as micro-reinforcement to control cracking in many projects around the world, some of these projects are summarized here:

1. Multi-level shopping center in Mexico was constructed using polypropylene fiber reinforced concrete in the floor systems, columns, and parking areas.
2. Sixty-story steel framed Dallas Tower used polypropylene fiber as an alternate to wire mesh in composite floor system, where pumping helped reduced construction time and costs.
3. Chicago's McCormick palace used polypropylene fiber in the heavy duty concrete floor system in it's new Annex facility. The main reason behind this application was that polypropylene fiber increase impact and shatter resistance while reducing permeability in the critical crate handling areas.
4. Parking structures have been constructed recently using polypropylene fiber reinforced concrete. Polypropylene fibers helped extend the service life and reduce maintenance of parking structure, since they have the ability to reduce plastic shrinkage cracking and permeability (Examples of parking garages and desks that were constructed in Virginia and Cincinnati are shown in appendix I).
5. A power plant in Italy has use polypropylene fibers as micro-reinforcement to reduce plastic shrinkage cracking and permeability, which help protect rebars in the floor systems against corrosion.

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6. The State Mosque in Altor Setar, Malaysia has a huge area in front of the Mosque that was paved with polypropylene fiber reinforced concrete.

7. The chattanooga industrial plant has constructed heavy-duty floor systems with polypropylene reinforced concrete overlay along with a dry shake surface hardener for impact and abrasion resistance.

8. The Craig power plant roadway was constructed with ppfrc pavement to protect against abrasion from truck traffic.

9. Slabs on grade: polypropylene fibers have been used widely in slabs-on-grade (both interior and exterior). Some of those project are present:

9.1 Hanes converting company, conover, north Carolina has used over 200,000 ft^2 (18,580 m^2) of polypropylene fiber reinforced slabs-on-grade for an industrial manufacturing facility.

9.2 A Boston, Massachusetts area condo developer saved time and hassle by replacing wire mesh with polypropylene fibers in slab-on-grade, balconies, and walkways.

9.3 Hawaii Island residence have used polypropylene fiber reinforced concrete in slab-on-grade, floor, driveway and sidewalks to reduce shrinkage cracking.

10 Highway overlay: polypropylene fiber reinforced concrete has been used in highway pavements as well as overlays all over the nation. Examples of these projects are presented here:

10.1 In Pennsylvania, on a highway near Hershey, the passing lane was overlaid with 2 in. (51 mm) thin bonded PPFRC overlay. After several years the PPFRC continues to demonstrate superior performance over plain concrete on adjacent lane.

10.2 The Marine receiving dock (in Louisiana) for steel scrap needed fast restoration due to wear and impact damage. The problem was solved by a 2 in. (51 mm) overlay of PPFRC made with early-strength cement.

10.3 Budgetal Motels in Pidgeon Force, Texas used a 1.5 in (76 mm) overlay over precast floors to serve a very economical alternative to wire mesh.

11 Airport ramps are paved using PPFRC. Parking ramps for British Airways Concords at Heathrow Airport are made more resistant to fuel spills with more impermeable and shatter resistant PPFRC. Another project used PPFRC for crack-control in over 9,000 $yd.^3$ (8190 m^3) of concrete aprons and taxiway surrounding Lambert - St. Louis International Airport, St. Louis, Missouri, starting as early as 1983.

12 Water tanks: The lower water permeability of PPFRC proved useful in the construction of a water tank near Toronto, Canada.

13 Waste water treatment plant: PPFRC was specified to reduce plastic shrinkage cracking and permeability as protection against rebar corrosion in waste water treatment plants in Washington. In New Jersey, a sanitary sewer tunnel was constructed utilizing PPFRC as replacement for temperature steel bars to prevent corrosion and improve durability.

14 Highway barriers in Georgia have been made with PPFRC because it helps fresh concrete more self supporting to reduce sag in slip-formed barrier construction. Other benefits increased impact and shatter resistance of hardened concrete.

15 Retaining walls: In 1985 a waste processing containment wall was constructed using PPFRC. The wall dimensions were 320 ft (97.5 m) long by 4 ft (1.2 m) high and 12 in. (305 mm) thick .

16 Sidewalks and curbs: One of the first residential uses of polypropylene fibers in the U.S. was March of 1979 in west Pennsylvania. Since then, polypropylene fibers have been in many residential concrete projects throughout the country. For instance, one concrete contraction and home-builder in Minneapolis, Minnesota, has used PPFRC to control cracking in more than 300 custom-built homes. PPFRC was also used in more than 100 $yd.^3$ ($76\ m^3$) of curbs, sidewalks, walkways, and steps for the multi-family Harbor Homes project in Erie, Pennsylvania .[24]

2.11.2 Shotcrete:

Extensive laboratory and field studies have been conducted with shotcrete (wet method) reinforced with polypropylene fibers at 0.44 - 0.66% volume fractions. This study and a subsequent field applications have demonstrated that 1.5 in. (38 mm) polypropylene fibers can be added directly to the back of ready mix concrete truck at 0.66% volume fraction, and be thoroughly mixed, dispersed and applied by the wet-mix shotcrete process, using a common shotcrete pump. The 2.5 in. (57 mm) long fibers was readily mixed and applied by the wet-mix shotcrete process at 0.44% volume fraction, but proved difficult to pump and shoot. Some of shotcrete applications that were performed are presented in the following:

1. Repair of Budbrooke water tower, a victorian brick structure located in Warwickshire, England, in 1988: The repair consisted of a 1.4 in. (35 mm) layer of PPFRC at 0.5% polypropylene fibers by weight and length of 0.5 in. (12 mm) with non-fibrous flash coat to finish.[14] Manual site-batching and mixing using a simple drop weight concrete mixer; the use of a damp sand; and a standard piccolo type rotating barrel gun without an auger feed. Some balling of fibers did subsequently occur during batching, which was part of the rebound fibers (rebound quantities were ranging from 0-40% of the total fiber used). Some of these were removed by hand before entering the gun. Based on a thorough inspection, the structure was found to be generally in good condition with minor hairline shrinkage cracking at construction joints.[14]
2. Cedar Point amusement park: The famous Thunder Canyon water slide amusement ride utilized a three layer polypropylene fiber reinforced shotcrete (wet process) to create man-made landscapes and water falls.
3. In Arizona, miles of canals were shotcreted using PPFRC to prevent erosion. Projects were completed faster with less rebound and cracking.
4. U.S. Army Corps of Engineers used PPFRC shotcrete for coating deteriorated concrete surfaces in 1984. A dry-mix shotcrete gun was used

for application of PPFRC shotcrete. Polypropylene fibers showed very little rebound during application. It is found that polypropylene fibers appears to reduce cracking.

2.11.3 Precast Concrete:

1. West's Piling and Construction Co. (U.K.) used a technique of driving down a string of cylindrical shells threaded on steel or mandrel. The mix used for shell incorporated 0.5% volume fraction of 1.75 in. (40 mm) polypropylene fibers.[51] The satisfaction with this product raised the Manufacturing volume up to half a million shells annually.
2. Flotation units for marines were made by encasing of expanded polystyrene in PPFRC shell. The units measured 30 ft (0.9 m) deep with a top surface of 3-6 ft (1-2 m) by 5 ft (1.5 m).[51]
3. Precast slabs and walls: A construction company in Texas built a home on Padre Island using PPFRC in foundation slabs, all interior walls and center walls.[85] and floors of 3 in. (76 mm) thick. The polypropylene fibers were selected because the intrusion of salt-laden moisture into concrete member was a concern.
4. Window units: The precast window units that were built using PPFRC in Bahrain. The units were 0.6-1.0 in. (15-25 mm) thick.[69] These units were used to carry air condition units and at the same time provide shade in the house.

5. Art wall for exhibition:The wall with it's 13 ceramic statues was used first at the Solomon R. Gughenheim Museum in New York (1952), later at museums in Philadelphia and Los Angeles (1983) and lately in front of the Royal Museum of Fine Art in Copenhagen (June 1984). The wall thickness 1.2 in. (30 mm) and consist of 40 curved and 4 plain elements, each about 1.6 ft by 4.1 ft (0.50 m by 1.25 m).[69]

6. Other precast products include: flower boxes units for keeping cattle water tanks, and complete bathroom units.[69]

2.11.4 Continuous Network Polypropylene Film:

The main application areas are in cement mortars in thin sheet products where layers of continuous films are placed on top of each other bonded by the matrix.[51] Such applications are possible in: corrugated sheet roofing, cladding, troughs, rain water goods, tunnel lining, pipes crash barriers and ventilation shafts.

Table 2.1 Typical properties of fibers.[22]

Fiber Type	Diameter (μm)	Specific Gravity	Modulus of Elasticity (GPa)*	Tensile Strength (GPa)	Elongation at Break (%)	Interfacial Bond	Alkali Stability
Steel	5-500	7.84	200	0.5-2.0	0.5-3.5	Poor	Poor
Glass	9-15	2.60	70-80	2.0-4.0	2.0-3.5	Good	Poor
Asbestos	0.02-0.4	2.6-3.4	164-196	3.1-3.50	2.0-3.0	Good	Good
Fibrillated Polypropylene	20-200	0.90	5-77	0.5-0.75	10-20	Poor	Good
Kevlar	10	1.45	65-133	3.6	2.1-4.0	Poor	Sufficient
Carbon	9	1.90	230	2.6	1.0	Poor	Good
Nylon	---	1.10	4	0.9	13-15		
Cellulose	---	1.20	10	0.3-0.5	---		
Polyethylene	---	0.95	0.3	0.0007	10		
Cement Matrix (for Comparison)	---	2.50	10-45	0.00037	0.02	---	Poor

*GPa x 0.145 = 10^6 lb/in.^{2}

Table 2.2 Various forms of polypropylene fibers used to reinforce cementitius.[20]

Polypropylene Type	Reference
Smooth Monofilaments*	Dave and Ellis (1979)
Fibrillated Monofilaments*	Baggott (1983)
Fibrillated film-woven mesh	Hannant et al (1978)
Fibrillated tapes	Hannant (1981)
Smooth yarn	Goldfein (1965)
Fibrillated yarn* *	Hughes and Fattuhi (1977)
Twisted ribbon yarn	Naaman et al (1984)
Collated fibrillated mesh	Zollo (1984)
Woven fabric	Gardner et Currie (1983)

* generally up to 1500 denier; 30-150 μm diameter and 50 mm long.
** 1000-12,000 denier. 1 denier = mass in g of 9000 m of yarn.

Table 2.3 Typical properties of collated fibrillated polypropylene fibers.

Melting Point	320-340 °F (160-170 °C)
Maximum Use Point	275 °F (135 °C)
Ignition Point	1094 °F (590 °C)
Brittleness Point	32 °F (0 °C)
Tensile Strength	70-110 Ksi (550-760 MPa)
Young's Modulus	500-700 Ksi (3.5-4.8 GPa)
Thermal Conductivity	Low
Electrical Conductivity	Low
Transparency	Transluc
Specific Gravity	0.9
Ultimate Elongation at Rapture	~ 10%
Water Absorption	<0.02%
Chemical Resistance: -Acids, dilute or weak -Acids, strong & concentrated -Bases -Oxidizing Agent, Strong -Hydrocarbon, halogenated	 No Damage after 30-day No Damage after 30-day No Damage after 30-day Some Effect after 7-day Some Effect after 7-day

Table 2.4 Mix proportions and fresh mix properties of polypropylene fiber reinforced concrete from reported data.

Ref. No.	V_f (%)	L_f (in.)	Water Binder	Sand Binder	Gravel Binder	Max. Agg. Size (in.)	Slump (in.)	Air Content (%)	Unit Weight (kg/m^3)
7	0.10 0.30 0.50	0.75	0.66	3.75	3.0	0.75	7.0 5.1 2.0	2.5 5.4 4.2	2381 2345 2381
9	0.10	0.75	0.65	2.4 2.7	2.4 2.7	0.375 1.0	---	---	---
14	0.10	2.0	0.58 0.65	3.0 4.5	3.7 5.0	---	5.0	---	---
19	0.125-1.0	1.5	0.38-0.66	1.5, 3.0	1.5, 3.0	---	---	---	---
32	0.15-1.5	0.5-2.0	0.64	2.7, 3.5	1.3				
38	0.20	0.75	0.45 0.55 0.65	2.0	1.2	0.75	0.20 2.75 5.50	---	---
39	0.10	0.75	0.5	2.0	2.0				
128	0.10	2.0	0.44 0.44*	2.11	2.83	1.0	3.0 2.75	5.1 4.4	2310 2360
133	0.10	2.25	0.47	1.5	1.5	0.75	---	---	---
142	0.10 0.20 0.30 0.40 0.50		0.50 0.52 0.41-.54 0.45 0.50	1.5-2.5	1.0-4.5	0.75	2.0-3.0 3.25 2.0-4.0 3.5 3.5	2.50 2.25 2.0-2.5 3.0 4.5	---
151	0.50 1.00	2.25	---	---	---	---	0.75-1.5 1.5-3.0	7.0 4.5, 7.5	--- 2384
155	0.10	0.75	0.52 0.54	3.0	3.4	1.5	3.75 2.75	2.5 5.7	--- ---
157	0.06 0.06 0.08	0.75 2.0 2.0	0.46	3.3	2.4	---	2.5 2.5 2.0	2.4 2.2 2.5	2387 2403 2387
162	0.10	0.75	0.65	2.0	3.0	1.0	---	---	---
168	0.10	0.75	0.42* 0.50*	2.0 3.2	3.0 4.2	1.0	1.25 0.75	2.4 2.6	--- ---

V_f = Fiber Volume Fraction; L_f = Fiber length.

Table 2.4 Continued.

Ref. No.	V_f (%)	L_f (in.)	Water Binder	Sand Binder	Gravel Binder	Max. Agg. Size (in.)	Slump (in.)	Air Content (%)	Unit Weight (kg/m³)
173	0.1 0.2 0.3	2.25	0.4*	2.4	2.4	0.75	3.13 3.25 2.75	9.2 6.5 6.4	2291 2355 2355
179	0.1, 0.15	0.5-1.5	0.64	2.35	1.13	0.75	---	---	---
181	0.1 0.15	1.5	0.74	2.7	1.3	0.75	4.72 4.33	--- ---	2310 2360

V_f = Fiber Volume Fraction; L_f = Fiber length.

Table 2.5 Effect of polypropylene fibers in concrete slump.[79]

Initial Slump (in)	Final Slump (in)	Fiber Length (in)	Reference
3.50	3.00	2	2
5.25	2.75	2	2
6.75	4.75	1 1/2	3
5.00	1.90	2	4
4.90	2.10	2	4
4.25	2.50	3/4	6

Table 2.6 Relative material properties of polypropylene fiber reinforced concrete versus plain concrete.

Fiber volume content, %	Compressive strength.* psi(MPa)	Splitting tensile strength.* psi(MPa)	Flexural strength.* psi(MPa)
0	5700(39.3)	408(2.8)	866(6.0)
0.1	5268(36.3)	408(2.8)	889(6.1)
0.2	5165(35.6)	411(2.6)	842(6.5)
0.3	5226(36.0)	508(3.5)	900(6.2)

*Strength values based on average of at least three tests.

Table 2.7 Mechanical properties of polypropylene fiber reinforced concrete of reported researches.[142]

Ref. No.	V_f (%)	L_f (in.)	W/C	Compressive Strength (psi)		Flexure Strength (psi)		Tensile Strength(psi)	
				P.C.	PPFRC	P.C.	PPFRC	P.C.	PPFRC
7	0.5	0.75	0.64	3000	3600	---	---	---	---
9	0.1	2.0	0.65	4800 5300 4000	4400 5000 4250	--- 640 785	--- 770 775	--- 450 ---	--- 460 ---
14	0.1	2.0							
142	0.1 0.2 0.3 0.4 0.5	0.75	0.5	5300	4800 4350 5650 3800 5500	350	570 600 650 610 500	---	---
125	0.2	0.75	0.45 0.55 0.65	6155 5128 4116	6091 5116 4090	961 814 710	967 826 725	787 636 503	800 662 526
128	0.1	2.0	0.44* 0.44	5623 6420	6464 6696	696 ---	783 ---	420 420	449 493
133	0.1	2.25	---	5038	4403	752	820	492	469
151	0.5 1.0	2.25	---	---	---	681	623 671		
152	0.5	0.75	0.58	2900	2610	720	725	---	---
155	0.1	0.75	0.52* 0.54	5137 5370	5250 5570	--- ---	--- ---	--- ---	--- ---
168	0.1	0.75	0.42 0.50	10,903 ---	11921 10467	1366 ---	1279 1075	--- ---	--- ---
173	0.1 0.3 0.5	2.25	0.40*	5160	5440 5990 6000	725	720 730 745	--- --- ---	--- --- ---
181	0.10 0.14	1.5	0.74	7536 7100	7217 6957	--- ---	--- ---	--- ---	--- ---

V_f = Fiber Volume Fraction; L_f = Fiber length; W/C = Water Cement ratio; P.C = Plain Concrete; PPFRC = Polypropylene Fiber Reinforced Concrete.

Table 2.8 Fatigue resistance of plain and collated fibrillated polypropylene fiber reinforced concrete at 28 days.[110]

Concrete Type	Estimated Load at Rupture (K)	Applied Load % of Est. Load	No. of Cycles at Failure
Plain	16.0	60.6	54,850
	16.0	60.6	150,000
	16.0	60.6	165,800
Average	16.0	60.6	123,550
PPFRC	17.9	58.6	370,360

Table 2.9 Effect of age of cement paste on its permeability coefficient (w/c = 0.5).[87]

Age (day)	K_p (m/s)	
Fresh Paste	10^{-5}	Independent of w/c
1	10^{-8}	
3	10^{-9}	
4	10^{-10}	Capillary Pores
7	10^{-11}	Interconnected
14	10^{-12}	
28	10^{-13}	
100	10^{-16}	Capillary Pores
240 (Maximum Hydration)	10^{-18}	Discontinuous

Table 2.10 Causes of concrete deterioration.[87]

Chemical Attack	Leaching and Efflorescence (P)* Silica Attack (P) Alkali-Aggregate Reaction (A) Acids and Alkalis (P) Corrosion of Metals (R)
Physical Attack	Freezing and Thawing (P, A) Wetting and Drying (P) Temperature Changes (P, A) Wear and Abrasion (P, A)

* Letter(s) in parentheses indicates the concrete component most affected, in order of importance: A, aggregate; P, paste; R, reinforcement.

Table 2.11 Summary of the shrinkage test methods and conditions reported by different investigators.

Ref. #	Shrinkage Test Type	Specimen		Mix Proportions						Curing Conditions
		Type	Dimension	V_f(%)	L_f(in.)	C	W	S	G	
9	Free (Dry)	Prism	1.5 x 3.0 18 in. long	0.1	2.25	1	0.65	2.65	2.7	100 °F, 40% R.H. up to 20 days
13	Restrained (Dry)	Ring	6.7/9.8 in. 1.6 in. thick	2.0	0.5	1	0.47& 0.64	2.4	2.6	Moist cured for 1-2 weeks then ambient atmosphere
14	Free (Dry)	Prism	3.0 x 3.0 11.3 in. long	0.1	2.0	1	0.58& 0.84	3.0& 4.5	3.7& 5.0	7-day at 75 °F, 40% R.H. then at 73 °F, 40% R.H.
20	Restrained (Plastic)	Panel	24 x 36 in. 0.75 in. thick	---	---	1	0.50-0.7	2.2-3.3	---	77-95 °F, 10-25% R.H. fan speed=7-8 mph
21	Restrained (Dry)	Ring	6.0/7.36 in. 5.5 in. thick	0.25 0.1-1.0	0.75	1	0.5	2.0	2.0	68 °F, 100% R.H. for 2.5 hrs. then dry at 40% R.H.
22	Free (Plastic)	Cylinder	6.0 in. dia.	0.1	0.75	1	0.6	3.0	3.0	No Curing
	Free (Dry)	Prism	4.0 x 4.0 in. 14 in. long	0.1-0.3	1.0	1	0.6	3.0	3.0	70 °F water bath after 24 hr.
24	Restrained (Plastic)	Panel	24 x 36 in. 0.75 in. thick	0.7		1	0.7	4.0	---	68 °F, 40% R.H. air speed 10-12 mph
32	Restrained (Plastic)	Ring	11.0/22.8 in. 3.15 in. thick	0.1, 0.15	1.5	1	0.74	2.7	1.3	68 °F, 40% R.H. air speed 10 mph
		Ring	11.0/22.8 in. 3.15 in. thick	0.1,0.15, 1.5 0.1, 0.15	0.75 1.50	1	0.74	3.5	---	Same
34	Restrained (Dry)	Ring	20/23 in. 4.0 in. thick	2.0	2.0	1	0.42	1.8	---	61 °F, 50% R.H. (chamber)

V_f = Fiber Volume Fraction; L_f = Fiber length; C =Cement; W = Water; S = Sand (fine aggregates); G = Gravel (coarse aggregates).

Table 2.12 Bond stress of polypropylene fibers with cementitius materials reported by different investigators.[20]

Bond stress (MPa)	Type of polypropylene	Matrix	Test method	Investigation
τ = 0.11-0.23	Fibrillated film	cement mortar	calculation using ACK model for crack spacing	Hannant, Zonsveld and Hughes (1978)
τ = 0.10	Monofilaments 49μm diameter	cement paste W/C = 0.40	Pull-out tests	Dave and Ellis (1979)
τ = 0.70-1.39	150 μm diam. monofilaments, fibrillated yarn	Cement past W/C = 0.40	Pull-out tests	Walton and Majumdar (1975)
τ = 0.68-3.40	Monofilament 1 play twisted yarn, 2 play twisted yarn	Cement mortar W/C = 0.32-0.50	Pull-out tests	Naaman, Shah and Throne (1984)
τ = 0.30-0.40	Fibrillated film networks	Fly ash-cement mortar w/c = 0.34	Calculation, ACK model	Hannant (1983)
τ_s= 0.6-0.98 τ_i= 0-0.34	Fibrillated monofilaments	Cement paste	Calculation using pull-out model	Laws (1982)
τ= 1.84	Fibrillated monofilaments	Polyethyl-acrylate modified mortar	Calculation using force balance eqn.	Kubota (1967)

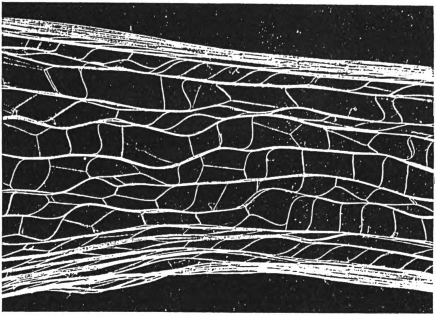


Figure 2.1 Fibrillated polypropylene film split into mesh of line fibers.[51]

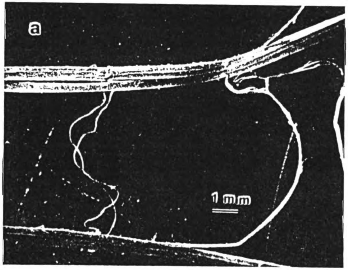
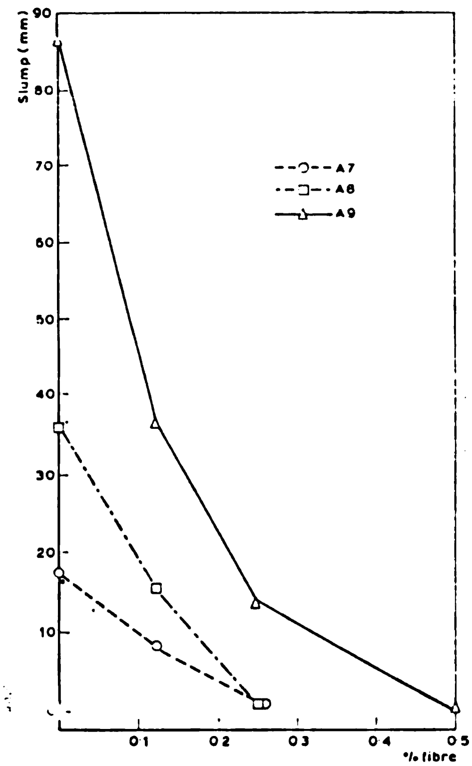
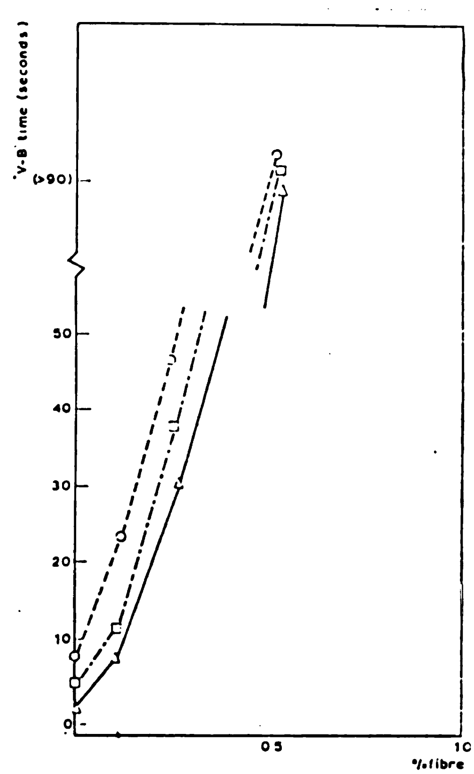


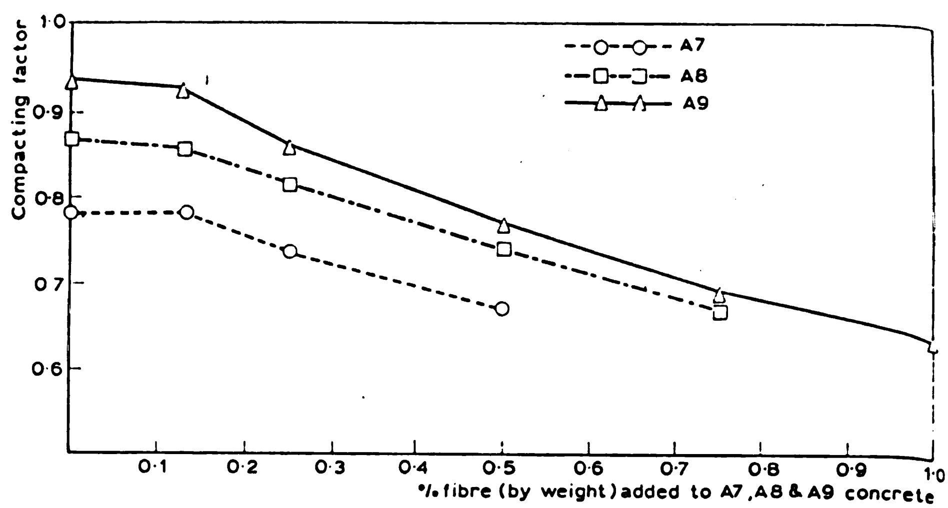
Figure 2.2 The network structure of Collated fibrillated polypropylene fibers prior to mixing.[22]



(a) Slump test result.



(b) Ve-Be test result.



(c) Compacting factor test result.

Figure 2.3 Polypropylene fiber reinforced concrete workability tests.[111]

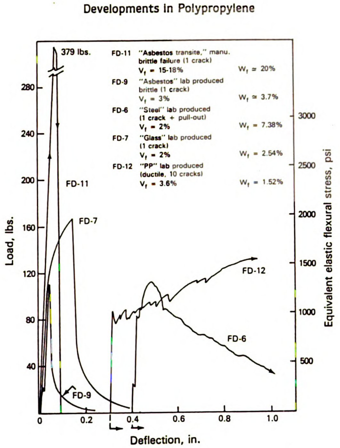


Figure 2.4 Comparison of the load-deflection curves of various fiber reinforced cementitious composites.[93]

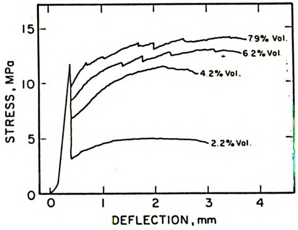


Figure 2.5 Typical flexural load-deflection curves of continues polypropylene fiber reinforced composites.[34]

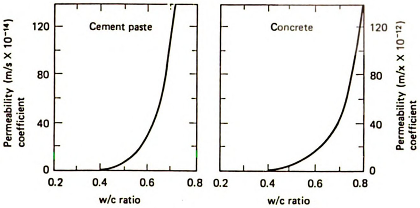


Figure 2.6 Effects of w/c ratio on the permeability of: (a) cement paste; (b) concrete.[87]

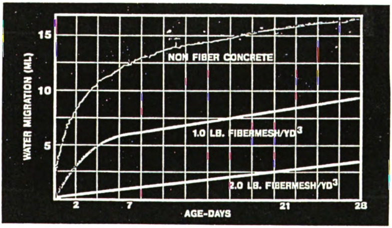


Figure 2.7 Effect of polypropylene fibers on concrete permeability (water migration).[135]

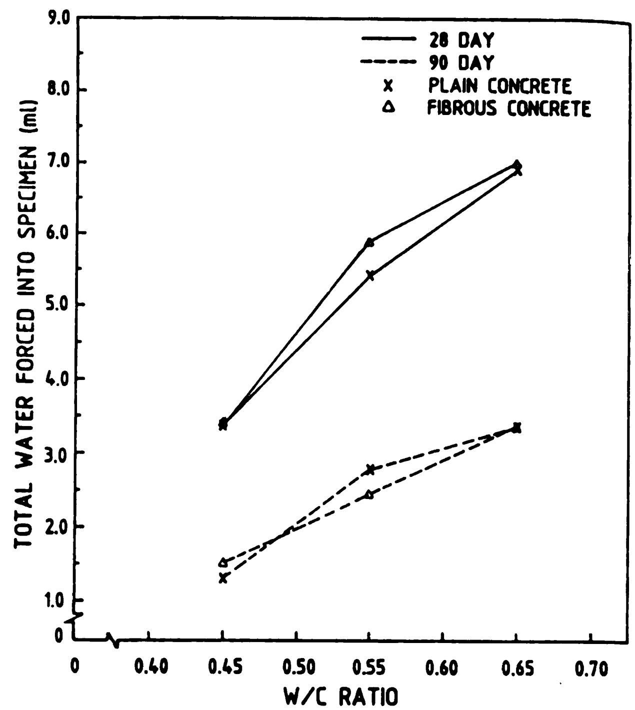


Figure 2.8 High-pressure permeability results of PPFRC and PC at 28 and 90 days.[5]

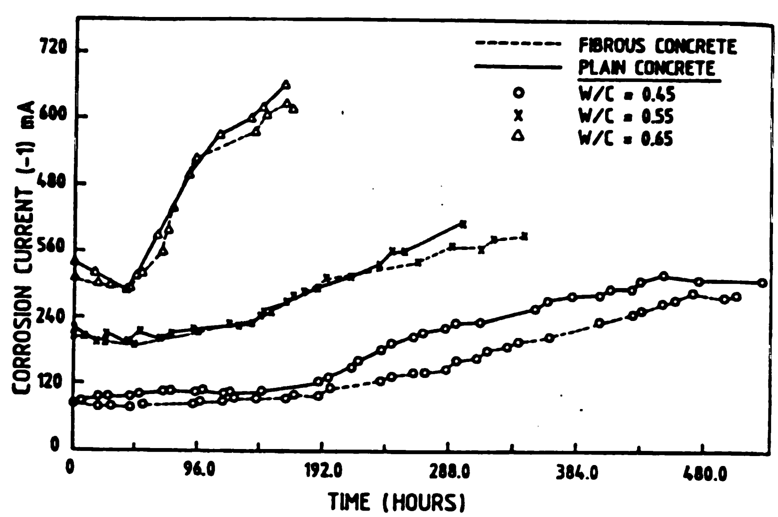


Figure 2.9 Variation of corrosion current with time in PPFRC and PC.[5]

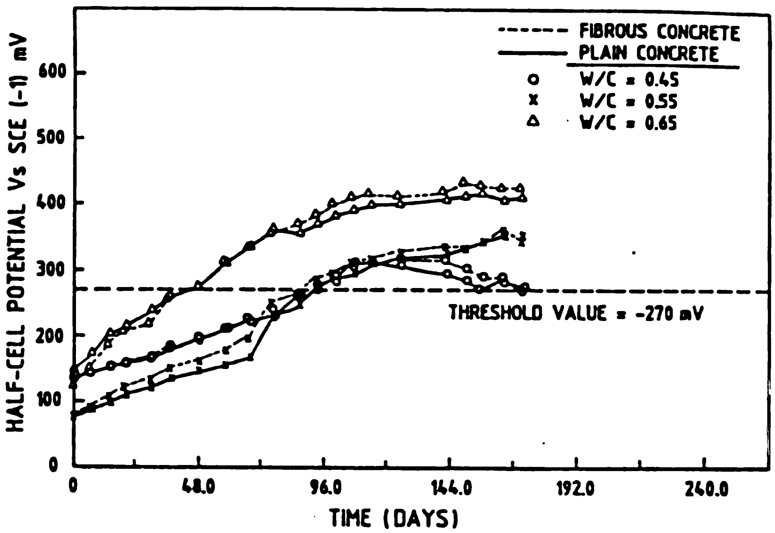


Figure 2.10 Variation of half-cell potential (corrosion) with time of PPFRC and PC slabs subjected to seawater pounding.[5]

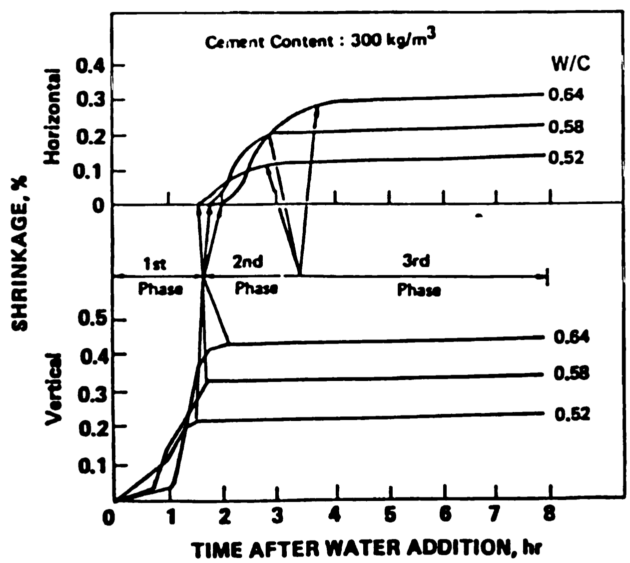


Figure 2.11 Effect of water-cement ratio on vertical and horizontal shrinkage.[66]

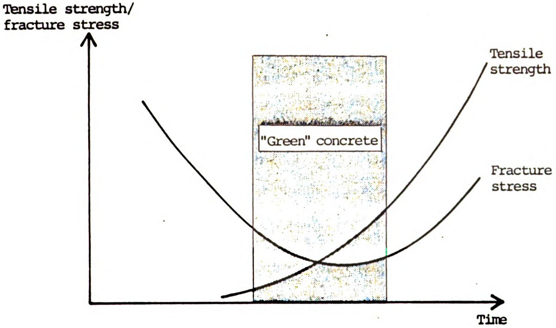


Figure 2.12 Principle of stress and tensile strength development of concrete at early stage.[33]

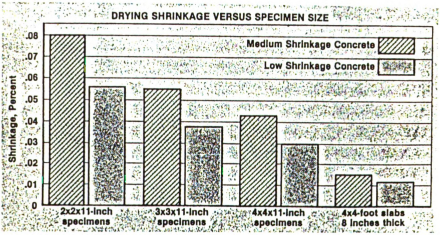


Figure 2.13 Size effects on drying shrinkage test results.[65]

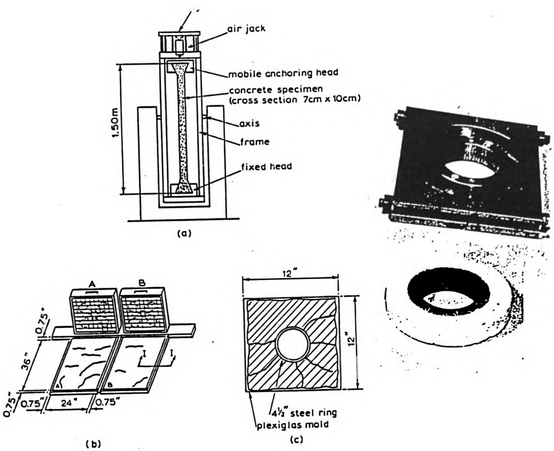


Figure 2.14 Restrained shrinkage test specimen types; (a) Flared ends, (b) Plate (panel), (c) Plate with steel ring, (d) Ring type.[45,68]

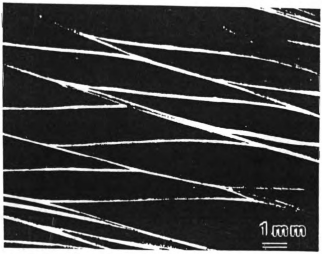


Figure 2.15 Polypropylene fiber network showing cross-links.[23]

(a) Monofilament fibers with end buttons.

(b) Two-ply twisted fibers.

Figure 2.16 Physical treatment of polypropylene fiber surfaces to improve matrix bonding.[93]

Figure 2.17 Delamination fracture in polypropylene fiber heat treated at 140°C for 24 hrs.[77]

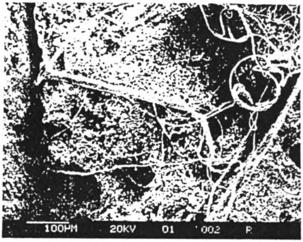


Figure 2.18 Fibrillation of collated fibrillated polypropylene fibers into small fibrils and curling of fibrils.[109]

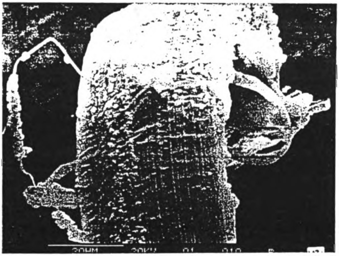
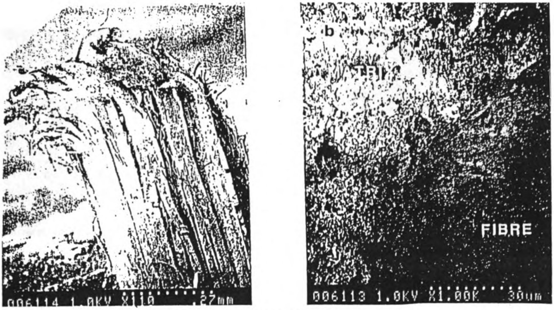


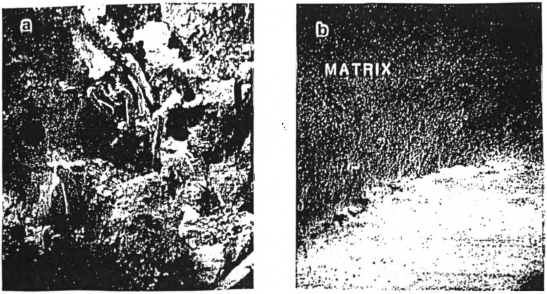
Figure 2.19 Adhesion of calcium silicate hydrate (C-S-H) to the surface of polypropylene fibers.[109]

Figure 2.20 The fracture interface between polypropylene fiber and concrete.[109]



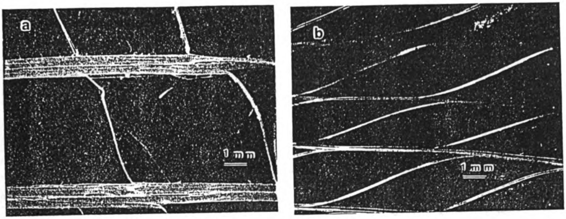
(a) The fibrillated structure. (b) The intimate contact with the matrix.

Figure 2.21 Scanning electron micrograph (SEM) observation of FTF fibers in high strength silica fume concrete.



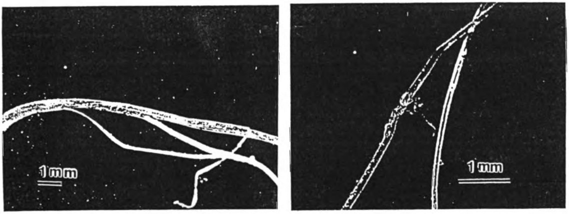
(a) individual filament surrounded by matrix. (b) The intimate contact with the matrix.

Figure 2.22 Scanning electron micrograph (SEM) observation of FBM fibers in high strength silica fume concrete.



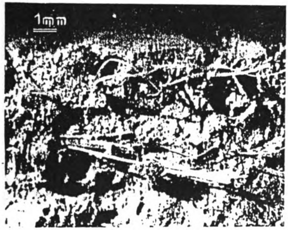
(a) FTF fiber. (b) FBM fiber.

Figure 2.23 The network structure of the fibrillated polypropylene fibers after mixing with silica fume.[24]

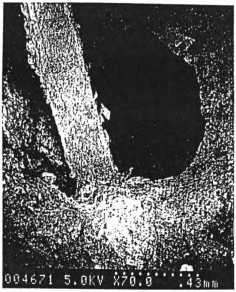


(a) Multifilament strands. (b) Cross-linking.

Figure 2.24 Optical microscopy of filamentized fibers washed out of the concrete mix showing two fibers interconnected by a thin fibril.[22]



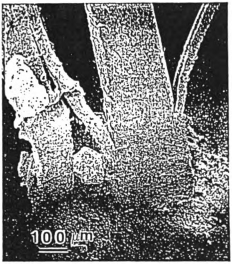
(a) The accumulation of fibers near a reinforcing bar.[22]



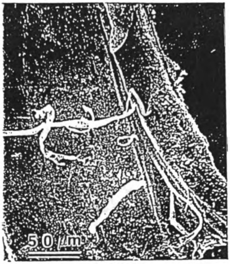
(b) And in the vicinity of an air void.[26]

Figure 2.25 Optical microscopy of a fractured surface in polypropylene fiber reinforced concrete.

Figure 2.26 Interfacial adhesion between polypropylene fibers and cement matrix.[22]



(a) Two embedded filaments.



(b) Fibrils of polypropylene fibers.

Figure 2.27 Scanning electron micrograph observation of polypropylene fiber in concrete matrix at 0.5% fiber volume fraction.[22]

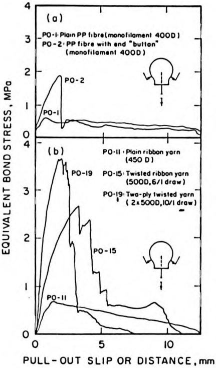


Figure 2.28 Bond (Pull-out) test result of physically treated monofilament polypropylene fiber; (a) Effect of end botton, (b) Effect of twisting.[93]

Figure 2.29 Scanning electron micrograph (SEM) of Chemically treated polypropylene fiber surface morphology of a failed fiber from the splitting tensile test.[37]

CHAPTER III

EXPERIMENTAL PROGRAM METHODOLOGY

3.1 INTRODUCTION

The key factors (variables) in this experimental study were the percentage and the length of polypropylene fibers, to be studied at different levels. A two-way factorial design of experiments (see Table 3.1) was traced in order to investigate these two variables.

Replicated tests were conducted in this investigation in order to:

1. Provide an estimate of experimental error by generating several observations on experimental units receiving the same treatment;
2. Increase precision by reducing standard error;
3. Broaden the base for making inference.

The completely randomized design adopted in this investigation is very easy to lay out and its analysis is simple to perform; however, it should be used only when the number of treatment combinations is small and the experimental material is homogeneous. The number of replications in this completely randomized design should be decided to yield a relatively high power in the analysis of variance of the test results.

The objective of this chapter is to introduce the general experimental design of this research along with the variables and their levels of investigation. The materials, mix proportions and the construction methods are presented. Finally, the tests procedures for all the experiments used in this investigation are reviewed in this chapter in order to avoid repetitions in the proceeding chapters.

3.2 EXPERIMENTAL DESIGN

The effects of polypropylene fiber reinforcement were investigated in three phases. In the first phase, the effects of fiber length and volume fraction were studied; three fiber lengths and five volume fractions were considered and the interactions between fiber length and volume fraction were also assessed. Table 3.2 presents the 3 x 5 factorial design of experiments used in this phase.

Unless otherwise mentioned, the following set of variables were used in different mixtures of the study (it should be understood that each phase of the investigation may involves some variation in these variables) :

Aggregate/Cement Ratio	= 4.5
Gravel / Sand Ratio	= 1.25
Fiber Volume Fraction	= 0.1 %
Fiber Length	= 0.75 in. (19 mm)

In the second phase, the effects of pozzolonic materials (fly ash, silica fume and slag) and latex were investigated. A 2^2 factorial design provided the basis for this phase of the experimental program. The variables studied in this phase were polypropylene fiber volume fraction (0% and 0.1%) and pozzolan or latex content (0% and 25% by weight of cement substituted with fly ash or blast furnace slag; 10% by weight of cement substituted with silica fume, or 10% latex by the weight of cement added). Table 3.3 summarizes the experimental design used in this second phase.

The third phase consisted of two parts concerned with comparing different fiber types. First, Comparisons were made between two types of collated fibrillated polypropylene fibers (Fibermesh and W.R.Grace & Co.) at 0.1% volume fraction for a fiber length of 0.75 in. (19 mm). Thereafter, the performance of polypropylene fibers was compared with that of hooked end steel fibers at 0.1% fiber volume fraction and similar fiber lengths of approximately 0.75 in. (19 mm). Table 3.4 summarizes the experimental design used in the third phase.

3.3 MATERIALS, MIX PROPORTIONS AND CONSTRUCTION

3.3.1 Materials

The basic mixture ingredients of polypropylene fiber reinforced concrete (PPFRC) were: Portland cement type I, coarse aggregate, fine aggregate, water, and collated fibrillated polypropylene fibers. An air entraining agent was added to provide for freeze-thaw resistance. Superplasticizer was added to unworkable mixtures in order to maintain certain limits on water/cement ratio and slump.

The matrix composition in some mixtures was adjusted through partial substitution of Portland cement with a pozzolonic material (fly ash, slag, or silica fume), or by the addition of latex. Two different types of polypropylene fibers and one type of steel fiber were used at different stages of the investigation.

A brief description of all the materials used in this research are give in the following:

Portland Cement: Type I Portland cement (ASTM C 150-89) was used, with the chemical compositions and physical properties given in Tables 3.5 and 3.6, respectively.

Fly Ash: Class F fly ash (ASTM C 618-89) was used, with the chemical compositions and physical properties presented in Tables 3.5 and 3.6, respectively.

Silica Fume: Condensed silica fume was used in this research. Its chemical compositions and physical properties presented in Tables 3.5 and 3.6, respectively.

Blast Furnace Slag: Ground granulated blast furnace slag was used, with the chemical compositions and physical properties presented in Table 3..5 and 3.6, respectively.

Latex: Styrene-butadiene dispersion latex was used in this investigation. Its properties are given in Table 3.7.

Coarse Aggregate: Crashed lime stone with maximum aggregate size of 0.75 in. (19 mm) was used; Table 3.8 presents the gradation which met the ASTM C 33 requirements. The specific gravity of coarse aggregate was 2.55, and its absorption capacity was 1.0%.

Fine Aggregate: Natural sand with fineness modulus of 3.0 was used in this research. Its gradation, meeting the ASTM C 33 requirements, is given in Table 3.8. The specific gravity of fine aggregate was 2.50, and its absorption capacity was 3.5%.

Polypropylene Fibers: Two types of collated fibrillated polypropylene fibers were used in this research. The main one (manufactured by Fibermesh company) was used in three different lengths, namely: 0.5 in. (13 mm), 0.75 in. (19 mm), and 1.5 in. (38 mm) at different volume fractions of 0.05%, 0.1%, 0.2%, and 0.3%. The other type (manufactured by W.R.Grace & Co.) was used in the third phase of this investigation at a length of 0.75 in. (19 mm) and volume fraction of 0.1%. Table 3.9 presents the physical properties of these fibers. The appearance of these fibers is shown in Figures 3.1(a) and 3.1(b).

Steel Fiber: Hooked end steel fibers with a length of ≈ 0.75 in (19 mm) and diameter of 0.01 in (1.3 mm) were used in phase 3 of this project at 0.1% volume fraction; the tensile strength of the steel fibers was 170 ksi (1175 MPa). Figure 3.1(c) present the appearance of this fibers.

Air Entraining Agent: A completely neutralized vinsol resin solution air entraining agent was used in this research.

Superplasticizer: A naphthalene-based superplasticizer was used in some mixtures of this study.

3.3.2 Mix Proportioning

It was decided that the concrete mixture should provide a slump of 3.5±0.5 in. (89±13 mm) for ease of handling, placing and consolidation, and an air content of 8±1% for frost resistance. The basic mix proportions used in this investigation were as follows (air entraining agent was added at required dosages for achieving the target air content):

Aggregate / Binder Ratio	= 4.5
Coarse Aggregate / Fine Aggregate Ratio	= 1.25
Water / Cement Ratio	≤ 0.45*

* Superplasticizer was added, if necessary, to achieve the specified slump without exceeding the limit on water / cement ratio; in shrinkage tests this limit was exceeded and no superplasticizer was used.

In some cases, where pozzolans were used, a fraction of cement was substituted with a pozzolan on equal mass basis. The cement-pozzolan binder in these mixtures had one of the following composition by weight:

1. 75% Cement + 25% Fly Ash
2. 75% Cement + 25% Blast Furnace Slag
3. 90% Cement + 10% Silica Fume

Latex modified mixtures were also used in phase II; they had 10% latex by weight of cement added to the concrete mixture with the proportions introduced earlier in this section.

3.3.3 Construction:

All mixtures were mixed in a conventional rotary drum concrete mixer with a capacity of 0.04 m^3 (1.41 ft^3). The mixing procedure for the concrete mixture basically followed ASTM C 192-90. The mixer was first loaded with the coarse aggregate and a portion of the mixing water; after starting the mixer, the fine aggregate, cement (and pozzolan, if any), and the rest of water were added and mixed for 3 minutes. This was followed by 3 minutes of rest and then 2 minutes of final mixing. The fibers, in the case of fibrous mixtures, were added following the addition of all mix ingredients. The admixtures (air entraining agent and/or superplasticizer, if any) were added to the mixing water. latex, when used, was also added to the mixing water.

All the specimens (except for the plastic shrinkage test panels; see section 3.6.6) were covered with wet burlap and plastic 30-45 minutes after casting, and demolded after 24 hours, and then moist cured at 73$\pm$3 °F (23$\pm$1.7 °C) and 97$\pm$3% relative humidity (R.H.) for three days. They were then exposed to the interior laboratory conditions at 73$\pm$3 °F (23$\pm$1.7 °C) and 40$\pm$5% R. H. until the test age of 28 days.

3.4 SELECTION OF MIX PROPORTIONS (Optimization of Mix Proportions)

A trial and error approach was used to select the water-cement ratio and dosage of air entraining agent required to achieve the target workability [3.5 ± 0.5 in. (89 ± 13 mm) slump] and air content ($8 \pm 1\%$) for all the mixtures to be used in the three phases of this investigation. Whenever the maximum limit on water/cement ratio (0.45) was reached, superplasticizer was used to increase slump. Table 3.10 presents a summary of the selected mix proportions. At slump of 3.5 ± 0.5 in. (89 ± 13 mm), the measured Ve-Be time and inverted slump cone time (two measures of workability under the effects of vibration) were not affected by the addition of different polypropylene fiber volume fractions; however, the fiber length had some effect on the workability of the concrete materials (see Figure 3.1, noting that increased time of Ve-Be or Inverted slump cone are indication of reduced workability).

3.5 PRELIMINARY STUDY AND SELECTION OF SAMPLE SIZE

A preliminary investigation was conducted to: (1) establish if polypropylene fiber reinforcement (at conventionally low volume fractions) has any significant effects on abrasion resistance in order to make a decision on the inclusion of abrasion studies in this project; and (2) assess the variations in impact strength test results in order to select the sample size (number of replications) for deriving statistically reliable conclusions; the same concepts (with relevant variations) were used throughout the study to select sample size.

Concrete mixtures with 0.0% and 0.1% volume fractions of 3/4 in. (19 mm) polypropylene fibers were used in this preliminary study. Table 3.11 summarizes the experimental program for this preliminary study. Thirty specimens were tested for impact and abrasion resistance at each level of fiber volume fraction (0.0 and 0.1%). The impact tests were carried out following the ACI committee 544 recommendation (see section 3.6.3). The abrasion test was carried out following the ASTM C 944-80 procedure.

The impact and abrasion test results are presented in Table 3.12. A statistical summary of results is presented in Table 3.12. Figures 3.2, 3.3 and 3.4 present the mean impact and abrasion test results, respectively with the corresponding 95% confidence intervals.

One-way analysis of variance of the test results at 95% level of confidence showed that:

1. The mean first-crack impact resistance of plain and polypropylene fiber reinforced concretes are not significantly different.
2. The mean failure impact resistance of polypropylene fiber reinforced and plain concretes are significantly different. Polypropylene fibers with length of 0.75 in. (19 mm) at 0.1% volume fraction increased the mean ultimate impact resistance of the concrete used in this study by 49%.
3. The abrasion resistance of plain and polypropylene fiber reinforced concretes are not significantly different.

Based on the preliminary test results, noting that polypropylene fiber reinforcement had insignificant effects on abrasion resistance, further studies on abrasion resistance were excluded from this research program.

In the analysis of the ultimate impact resistance test results, considering the observed polypropylene fiber effects and the random experimental errors, decision was made on the required number of tests in later impact tests, as discussed below. The remaining impact tests, in this research, were concerned with the effects of polypropylene fiber length and volume fraction (in a 2-variable factorial design of experiments) and also the effect of binder composition and fiber volume fraction (in an other 2-variable factorial design) for power of statistical analyses of test results at high confidence levels. The selection of sample size was based on the relationships between the number of replications and the power of statistical analysis of variance in different experimental designs.

The power of analysis of variance was calculated for the ultimate impact test results using the following formula:

$$\Phi = \sqrt{\frac{n\Sigma\alpha_j^2}{J\sigma_\epsilon^2}}$$

Where n = Number of replications;

j = Number of treatment;

α_j = The effect of the j^{th} treatment;

σ_ϵ^2 = The error variance.

In the analysis of the ultimate impact resistance, standard deviation of the error was used as an unbiased estimation of the variance, Φ from the above equation was found to be equal to 1.86. Using power charts, the power $(1-\beta)$ was found to be 0.76 at 0.05 level of significance, noting that β is the probability of committing type II error. This power could be acceptable; however, an increase in the number of replications to n = 35 gave a desirable power of $(1-\beta) = 0.82$.

Using estimates of polypropylene fiber effect and standard deviation of the error based on the preliminary study, typical fictitious values for ultimate impact resistance were chosen for the 3 x 5 experimental program of the phase 1 (Table 3.2) concerned with the effects of polypropylene fiber length and volume fraction (the effect of fiber length was estimated using the data reported in the literature). These fictitious test results were used to determine the number of replications of tests needed to provide a desirable two-factors power in the analysis of actual results.

Fictitious test results were also assumed in a 2 x 2 factorial design (Table 3.3, Phase 2 of this project) aimed at investigating the effect of binder composition on the impact resistance of plain and polypropylene fiber reinforced concretes.

Table 3.14 summarizes the effects of the number of replications on the power of analysis of variance; it also presents powers for alternative experimental designs. Fiber percentage (factor B) is assumed, based on the reported data and those generated in the preliminary study, to have larger effects on the ultimate impact resistance than fiber length. Judgement on the required number of tests is thus based on the effects of fiber volume fraction. It can be see from table 3.12 that smaller number of replications could be required for larger factorial designs (i.e., those with more levels of variables included) to achieve the same power. In the 3 x 5 factorial design of this investigation, three replications of tests are observed in Table 3.14 to give a very desirable power of 0.93. In the case of 2 x 2 factorial design, 10 replications would be needed (see Table 3.14) to give an acceptable power of 0.77. These number of replications were used later in the impact resistance test programs.

3.6 TEST PROCEDURES

A brief description of the test procedure used in this project is presented in this section. Some of these test follow ASTM standards or the guidelines given by the American Concrete Institute, while some are not yet standardized and have been devised to reproduce some critical conditions relevant to the performance characteristics of polypropylene fiber reinforced concrete. some standard tests were also modified to better suit some specifics of the polypropylene fiber reinforced concrete behavior.

3.6.1 Aggregate Tests:

These were preliminary tests that are required in order to determine the type and the quality of the aggregates used in concrete mixtures.

3.6.1.1 Sieve Analysis:

This test method covers the determination of the particle size distribution of fine and coarse aggregates by sieving. The test was performed following ASTM C 136-84 Standard Method. A specified weighed sample of dry aggregate is separated in this test through a series of sieves of progressively smaller openings for determination of particle size distribution.

3.6.1.2 Specific Gravity and Absorption Test:

3.6.1.2.1 Coarse Aggregate:

In this test the specific gravity and absorption of coarse aggregate is determined. The specific gravity may be expressed as the bulk specific gravity (SSD, Saturated-Surface Dry), or apparent specific gravity. The bulk specific gravity (SSD) and absorption are based on measurements made on aggregates soaked in water for 24 hours. The test was performed following ASTM C 127-88 Standard Test Method. A sample of coarse aggregate is immersed in water for approximately 24 hours to essentially fill the pores. It is then removed from the water, the particles surfaces were dried, and the aggregate were weighed. Subsequently, the sample is weighed while submerged in water. Finally, the sample is oven-dried and weighed a third time. Using the weights thus obtained, the specific gravity and absorption can be calculated.

3.6.1.2.2 Fine Aggregate:

This test method covers the determination of bulk and apparent specific gravity and absorption of fine aggregate. The test was performed following ASTM C 128-88 Standard Test Method. A sample of fine aggregate is soaked in water for 24 hours. The excess water is then removed avoiding loss of fines. It is then spread on a flat non-absorbent surface and exposed to gentle dry air. This is continued until the sample approaches a free-flowing condition (saturated-surface dry), using a specific mold (cone). Using a pycnometer (special flask), The weight of fine aggregate immersed in water is found. The specific gravity and absorption are then calculated.

3.6.2 Fresh Mix Tests:

This section describe the test procedures used with plain and polypropylene fiber reinforced concretes at the fresh stage.

3.6.2.1 Slump Test:

This test determines the workability characteristics of fresh concrete mix. The test was performed following ASTM C 143-90 standard test method.

3.6.2.2 Unit Weight:

The method determines the weight per unit volume of freshly mix concrete. The test was performed following ASTM C 138-81 standard test method.

3.6.2.3 Air Content:

This method covers the determination of the air content of freshly mixed concrete from observation of the changes in the volume of concrete with a change of pressure. The test was performed following ASTM C 231-91 (Air meter B) guidelines.

3.6.3 Abrasion Test:

This test determines the resistance of concrete to abrasion. The test was performed following ASTM C 944-80 Standard Test Method. The test is performed on 6 in. (152 mm) diameter concrete surfaces. The average loss in mass (gram) after 2 minutes of abrasion is recorded. The apparatus consists of a drill press device with rotation cutter operating at a speed of 200 r/m and exerting a constant force of 10 kgf (98 N) on the test specimen.

3.6.4 Impact Test:

The test set-up is shown in Figure 3.5 (ACI Committee 544, 1989).[140] The test is performed on a cylindrical specimen 6 in. (152 mm) in diameter and 2.5 in. (64 mm) high. The test simply consists of repeatedly dropping a hammer from a height of 18 in. (457 mm) on a steel ball supported by the specimen, while observing the formation of cracks and failure of the specimen. the number of blows required to cause the first visible crack on the top and the ultimate failure are both recorded.

3.6.5 Compressive Strength and Toughness Test:

This test was performed on 6 x 12 in. (152 x 305 mm) cylindrical specimens following ASTM C 39-86 procedures. The stress-strain curves were monitored throughout the test using a computer-based data acquisition system.

The compressive toughness was calculated following the JCI-SF guidelines (area underneath the stress-strain curves up to a strain of 0.0075).[57]

3.6.6 Flexural Strength and Toughness Test:

This test was performed on prismatic specimens with dimensions of 4 x 4 x 14 in. (102 x 102 x 356 mm) using the third point loading procedure of ASTM C 78-84; the test was conducted in a displacement-controlled manner, and deflections were measured at the center of the specimen using the Japanese JCI-SF specifications.[57] The stress-strain curves in flexural tests were obtained using a computer-based data acquisition system.

Flexural toughness of polypropylene fiber reinforced concrete was calculated following the JCI-SF guidelines (area underneath the flexural load-deflection curves up to a mid-span deflection equal to span length divided by 150).[57]

3.6.7 Permeability Test:

The chloride ion permeability was performed following AASHTO T-277 (Rapid Determination of The Chloride Permeability of Concrete). The test is based on a relationship between the electrical conductance and the resistance to chloride penetration. A cylindrical specimen 4 in. (102 mm) in diameter and 2.0 in. (51 mm) high is used in this test. The sides of this specimen are sealed and it is dried under vacuum. The specimen is subsequently saturated by immersion in water and then connected to a cell with chloride and sodium solutions applied to the negative and positive charge surfaces, respectively (see Figure 3.6). After six hours, the total ampere-seconds (Coulombs) of charge passed during the test period is recorded. The test results are then evaluated using the qualitative classification of Table 3.15.

3.6.8 Plastic Shrinkage Cracking Test:

The test procedure proposed by Kraii (1985)[24] and refined by Shaeles and Hover (1988)[20] was used for evaluating the effects of polypropylene fibers on plastic shrinkage cracking of concrete. The test procedure was slightly modified so that it compiles with the specifics of polypropylene fiber effects on plastic shrinkage cracking of concrete.

Two 21 x 33 in. (533 x 838 mm) slabs with a thickness of 1.5 in. (38 mm) (one plain and the other fibrous concrete) were casted side by side and exposed to identical finishing processes and environmental conditions (temperature, humidity, and wind velocity). A vertical partition was used between the two panels to prevent non-uniformities arising from interference effects between the two fans and slabs. To monitor the weight of water lost from concrete during the test, two 6 in. (152 mm) diameter by 2.5 in. (64 mm) high cylinders filled with concrete were placed adjacent to the panels and weighed during the test. Open pans of water were similarly placed and weighed to monitor the rate of evaporation from a free water surface (see Figure 3.7). The fans were started 25 minutes after the addition of water to the mixer for all test slabs in order to have identical conditions. The temperature, relative humidity, and wind velocity were measured during tests on each pair of panels.

The leveling operation after placing the concrete into forms, known as striking off or screeding, has been found to be a critical factor.[20] Thus the effects of the rate and direction of screeding, and also the effects of the finishing operations on plastic shrinkage cracking were investigated in this research. Placing and finishing of concrete slabs were performed according to the procedures described in the Portland Cement Association (PCA) publication entitled "Design and Control of Concrete Mixtures," Chapter 9 (1988) by Kosmatka, S.H. and Panarese, W.C.[63] The finishing procedures used in this project are summarized in the following:

1. Screeding (Strike off): Screeding of the slab surface was done immediately after pouring the concrete in the forms using a wood straightedge that is moved across the concrete surface with a sawing motion and advanced forward a short distance with each movement (see Figure 3.8-a).

2. Bullfloat or Darby: Immediately after strike off, bullfloat was applied to eliminate high and low spots and embed large aggregate particles using an aluminum bullfloat. Bullfloat application was completed before bleed water accumulated on the surface of the slab (see Figure 3.8-b).

3. Finishing operations: These operations include floating, trowelling, and (in some field application, not considered in this study) also edging and jointing. When the bleed water sheen evaporates and concrete can sustain pressure with very low indentation, the surface is judged to be ready for continued finishing operations, as discussed below:

a) Floating: Floating was done using an aluminum hand float held flat on the slab surface and moved with a slight sawing motion in a sweeping arc so that holes were filled, bumps were cut off and ridges were made smooth (see Figure 3.9-a).

b) Troweling: Troweling was performed after floating in order to produce a smooth and dense surface. Using a steel trowel, the slab was finished in same manner as floating was performed. The final pass should make earring sound as the trowel moves over the hardening surface (see Figure 3.9-b).

3.6.9 Setting Time Test:

This test method is concerned with the determination of the time of setting of concrete by means of penetration resistance measurements on a mortar specimen sieved from the concrete mixture. The test was performed following ASTM C 403-90 Standard Test Method. A mortar sample is obtained by sieving a representative sample of fresh concrete. The mortar is placed in a container and stored at a specified ambient temperature. At regular time intervals, the resistance of the mortar to penetration by standard needles is measured. From a plot of penetration resistance versus elapsed time, the times of initial and final setting are determined.

3.6.10 Bleeding Test:

In this test the relative quantity of mixing water that will bleed from a sample of freshly mixed concrete is determined. The test was performed following ASTM C 232-87 Standard Test Method (Procedure A). A sample of freshly mixed concrete is placed in a specified container and stored at a specified ambient temperature. At given time intervals, the accumulated water on the surface is drawn off and measured. The volume of bleeding water per unit area of surface and the accumulated bleeding water, expressed as a percentage of the net mixing water contained within the test specimen, are calculated.

Table 3.1 Two-way factorial design.

Factor A (e.g. Fiber Length)	Factor B (e.g. Fiber Percentage)
1	y_{11} y_{12} ---------------- y_{1b}
2	y_{21} y_{22} ---------------- y_{2b}
.	
.	
.	
.	
.	
.	y_{a1} y_{a2} ---------------- y_{ab}
a	

Table 3.2 First experimental program.

Fiber Length (in.)	Fiber Volume fraction (%)				
	0.00	0.05	0.10	0.20	0.30
0.50	*	*	*	*	*
0.75	*	*	*	*	*
1.50	*	*	*	*	*

* 2-compression, 3-flexure, 4-impact tests for each cell.

Table 3.3 Second Experimental Program.

Binder Type	Fiber Volume Fraction (%)	
	0.0	0.1
Cement	*	*
75% Cement + 25% Fly Ash	*	*
90% Cement + 10% Silica Fume	*	*
75% Cement + 25% Slag	*	*
Latex (10% of Cement)	*	*

* 2-compression, 3-flexural, 10-impact, and 6-permeability tests for each cell.

Table 3.4 Third experimental program.

Fiber Type	Fiber Volume Fraction (%)	
	0.0	0.1
Polypropylene Type 1	*	*
Polypropylene Type 2	*	*
Hooked Steel	*	*

* 40-impact tests for each cell.

Table 3.5 Chemical compositions of binders.

Binder Type	CaO	Sio_2	Al_2O_3	Fe_2O_3	So_3	MgO	K_2O	C	Na_2O
Cement	63.24	21.14	5.76	2.93	2.46	2.06	0.79	---	---
Fly Ash	2.6	47.00	22.10	23.40	---	0.76	2.00	4.30	---
Silica Fume	---	96.50	0.15	0.15	---	0.20	0.04	1.40	0.20
Slag	---	35.40	11.40	0.60	1.02	13.00	0.34	---	0.10

Table 3.6 Physical properties of binders.

Binder Type	Specific Gravity	Specific Surface m^2/Kg	Fineness (% retained in # 325 sieve
Cement	3.15	160	10.7
Fly Ash	2.25		19.6
Silica Fume	2.30		
Slag	2.90		1.3

Table 3.7 Latex polymer properties.

Total Solid, wt. %	47
Specific Gravity	1.01
pH, °C	10
Surface Tension, m N / m	38
Weight / Volume, lb/U.S.gal (Kg / l)	8.3 (1.01)

Table 3.8 Aggregates gradations.

Sieve Size mm (in.)	19.0 (3/4)	12.5 (1/2)	9.5 (3/8)	4.75 (No.4)	2.36 (No.8)	1.18 (No.16)	600 μm (No.30)	300 μm (No.50)	150 μm (No.100)
Coarse Aggregate	100	94	70	11	5	---	---	---	---
Fine Aggregate	---	---	100	100	90	72	46	18	4

Table 3.9 Physical properties of polypropylene fibers.

Property	Polypropylene Fiber Manufacture	
	Fibermesh Co.	W.R.Grace & Co.
Tensile Strength	80-110 Ksi (628-760 MPa)	
Young's Modulus	500 Ksi (3.5 GPa)	500 Ksi (3.5 GPa)
Specific Gravity	0.9	0.91
Melting Point	320-340 °F (160-170 °C)	320 °F (160 °C)
Ignition Point	1100 °F (590 °C)	1100 °F (590 °C)
Thermal Conductivity	Low	
Electrical Conductivity	Low	
Acid and salt Resistance	High	High
Absorption	Nil	Nil

Table 3.10 Summary of the selected mix proportions.

Mix No.	No. of Trial	Variable Parameter			Water Cement Ratio	AEA	Sup.	Slump	Inv. Slump	Ve-Be Time	Air Content	Unit Weight
		Matrix	V_f (%)	L_f (in.)		(%)	(%)	(in.)	(sec.)	(sec.)	(%)	(g/cm^3)
1	3	P.C	---	---	0.40	0.08	---	3.5	8	5	8.9	2274
2	5	PPFRC	0.05	0.50	0.41	0.05	---	3.5	8	3	8.5	2284
3	4	PPFRC	0.10	0.50	0.42	0.05	---	3.8	8	3	8.8	2245
4	2	PPFRC	0.20	0.50	0.45	0.05	---	3.0	11	5	7.2	2299
5	2	PPFRC	0.30	0.50	0.45	0.05	0.1	3.0	9	5	7.4	2301
6	4	PPFRC	0.05	0.75	0.42	0.05	---	3.5	8	4	8.5	2280
7	2	PPFRC	0.10	0.75	0.45	0.05	---	4.0	8	5	7.4	2295
8	1	PPFRC	0.20	0.75	0.45	0.05	0.15	3.0	11	5	7.2	2287
9	2	PPFRC	0.30	0.75	0.45	0.06	0.25	3.0	10	6	8.4	2207
10	2	PPFRC	0.05	1.50	0.45	0.05	---	3.0	10	5	7.0	2340
11	1	PPFRC	0.10	1.50	0.45	0.05	---	3.0	11	5	7.0	---
12	2	PPFRC	0.20	1.50	0.45	0.05	---	3.0	10	6	8.5	2257
13	2	PPFRC	0.30	1.50	0.45	0.06	---	3.0	11	4	7.7	2271
14	3	SFRC	0.1	0.75	0.43	0.07	---	3.0		3	7.5	2238
15	2	PPFRC*	0.1	0.75	0.43	0.05	---	3.5		3	7.5	
16	3	L (P.C)	0.0	---	0.28	---	---	4.0	5		8	
17	2	L(PPFRC)	0.1	0.75	0.30	---	---	3.25	4	15	7	
18	3	SF(P.C)	0.0	---	0.45	0.15	0.30	3.0		11	7.5	2197
19	3	SF(PPFRC)	0.1	0.75	0.45	0.15	0.4	3.0	5		7.4	2176
20	3	FA(P.C)	0.0	---	0.45	0.22	---	4.0	5		8.0	2346
21	3	FA(PPFRC)	0.1	0.75	0.45	0.20	0.1	3.5	6		7.0	2329
22	3	S(P.C)	0.0	---	0.40	0.13	---	3.75	6	11	7.9	2211
23	2	S(PPFRC)	0.1	0.75	0.41	0.10	---	3.0	4	9	8.0	2202

V_f = Fiber Volume Fraction; L_f = Fiber Length; AEA = Air Entraining Agent; Sup. = Superplasticizer; P.C. = Plain Concrete; PPFRC = Polypropylene Fiber Reinforced Concrete; SFRC = Steel Fiber Reinforced Concrete; PPFRC* = PPFRC With Other Polypropylene Fiber Type; L = Latex Polymer; FA = Fly Ash; SF = Silica Fume; S = Blast Furnace Slag. --- = Not applicable; Missing values are left vacant.

Table 3.11 Preliminary experimental program.

Test Type	Fiber Volume Fraction (%)	
	0.0	0.1
Impact	30 Specimen	30 Specimen
Abrasion	30 Specimen	30 Specimen

Table 3.12 Impact and abrasion test results for preliminary study.

Impact Resistance (No. of Drops)				Abrasion (g/cm^2) x 100	
V_f = 0.0%		V_f = 0.1%		V_f = 0.0%	V_f = 0.0%
1st Crack	Failure	1st Crack	Failure		
50, 15, 33,	51, 16, 34,	23, 45, 31,	45, 53, 54,	4.93, 13.24, 4.96,	6.58, 11.90, 9.23,
32, 21, 42,	34, 22, 43,	29, 38, 37,	51, 40, 51,	9.88, 14.71, 5.65,	9.64, 13.05, 5.04,
32, 29, 24,	31, 33, 25,	33, 24, 28,	45, 54, 40,	6.51, 12.20, 5.91,	7.60, 11.12, 6.79,
35, 41, 71,	35, 42, 73,	23, 26, 34,	39, 37, 44,	7.35, 12.74, 6.66,	8.97, 10.23, 6.10,
13, 45, 25,	15, 46, 27,	75, 49, 19,	81, 64, 35,	4.93, 12.08, 8.00	6.48, 10.62, 6.00
47, 20, 15,	48, 21, 17,	26, 29, 42,	36, 49, 58,	8.78, 10.72, 9.35,	3.95, 11.09, 7.86,
40, 90, 20,	41, 92, 27,	24, 29, 104,	46, 43, 113,	8.12, 12.88, 8.96,	7.69, 10.37, 4.33,
17, 29, 48,	35, 18, 29,	40, 35, 109,	55, 48,125,	7.76, 7.27, 9.90,	5.83, 5.01, 8.22,
14, 34, 125,	15, 49,126,	38, 27, 121,	54, 56, 138,	6.17, 7.25, 5.23,	7.23, 7.84, 7.51,
34, 28, 107,	36, 29,109,	29, 44, 130	45, 58, 145,	6.35, 4.04, 5.05	6.51, 5.71,7.30

$g/cm^2 = 1.42 \times 10^{-2}$ lb/in^2.

Table 3.13 Statistical summary of the preliminary results.

Test Type	V_f (%)	Mean	Variance	Standard Deviation	Standard Error	Confidence Interval	
						Lower Limit	Upper Limit
Impact First-Crack	0.0	39.4	713.4	25.7	4.88	29.4	49.4
	0.1	44.7	935.7	30.6	5.58	33.3	56.1
Impact at Failure	0.0	40.4	725.8	26.9	4.92	30.4	50.5
	0.1	60.7	890.3	29.8	5.45	48.9	71.2
Abrasion	0.0	8.26	8.55	2.92	0.534	7.17	9.36
	0.1	7.87	5.40	2.32	0.424	6.89	8.74

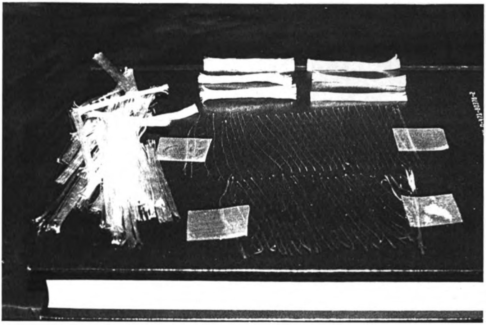
Table 3.14 Effects of number of replications on the power of analysis of variance.

Factorial Design	No. of Replications	Φ_α	1-β	Φ_β	1-β
3*5	2	0.4	---	1.17	0.40
	3	0.7	---	2.00	0.93
	5	1.1	0.34	3.10	0.99
3*3	3	0.23	---	0.90	---
	5	0.40	---	1.40	0.53
	7	0.50	---	1.80	0.79
2*5	3	0.42	---	1.44	0.73
	4	0.52	---	1.75	0.84
	5	0.66	---	2.26	0.98
2*3	5	0.22	---	1.00	0.28
	8	0.33	---	1.46	0.57
2*2	5	0.17	---	1.18	---
	7	0.23	---	1.58	0.55
	10	0.30	---	2.00	0.77

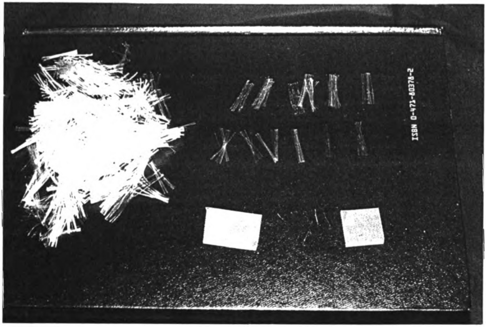
Φ_α = Power Parameter For Factor A ; Φ_β = Power Parameter For Factor B;
1-β = Power of The Analysis of Variance.

Table 2.15 Chloride permeability classifications.

Charged Passed (Coulombs)	Chloride Permeability	Typical of
> 4,000	High	High water-cement ratio (>0.6), conventional PCC.
2,000-4,000	Moderate	Moderate water-cement ratio (0.4-0.5), conventional PCC.
1,000-2,000	Low	Low water-cement ratio (<0.4), conventional PCC.
100-1,000	Very Low	Latex-modified concrete, internally sealed concrete.
<100	Negligible	Polymer impregnated concrete, polymer concrete.

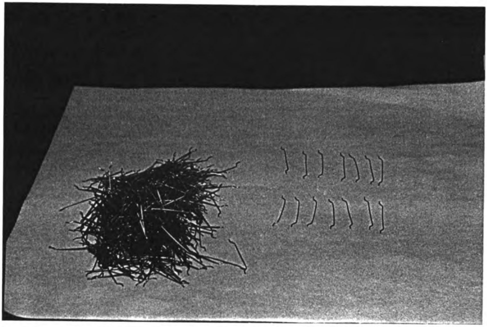


(a) Fibermesh collated fibrillated polypropylene fibers.



(b) W.R.Grace & Co. collated fibrillated polypropylene fibers.

Figure 3.1 Appearance of different polypropylene fibers.



(c) Steel fibers.

Figure 3.1 Continued.

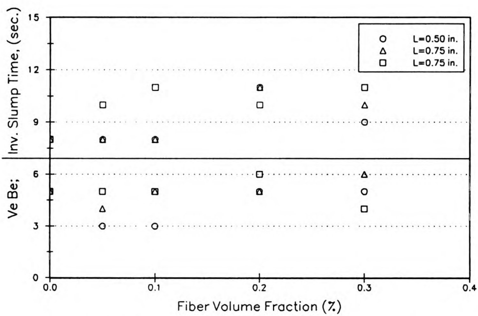


Figure 3.2 Effects of the content and length of polypropylene fibers on the consistency of concrete.

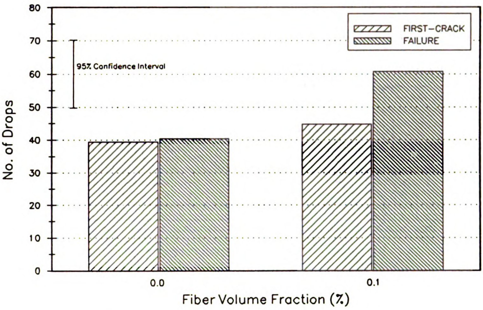


Figure 3.3 Impact test results for preliminary study.

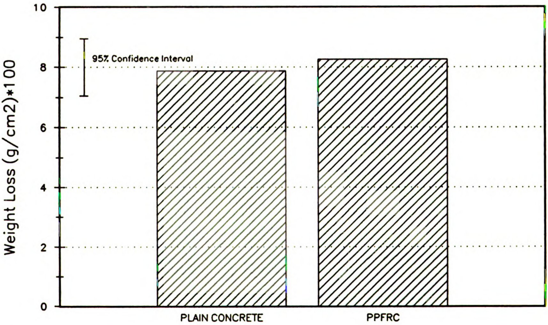


Figure 3.4 Abrasion test result for preliminary study.

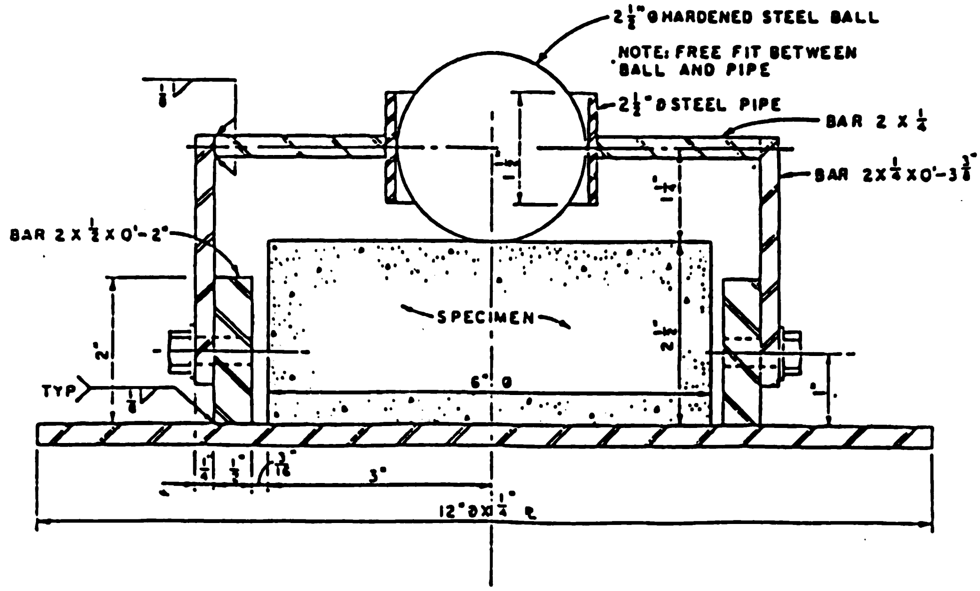


Figure 3.5 Schematic of impact test apparatus.

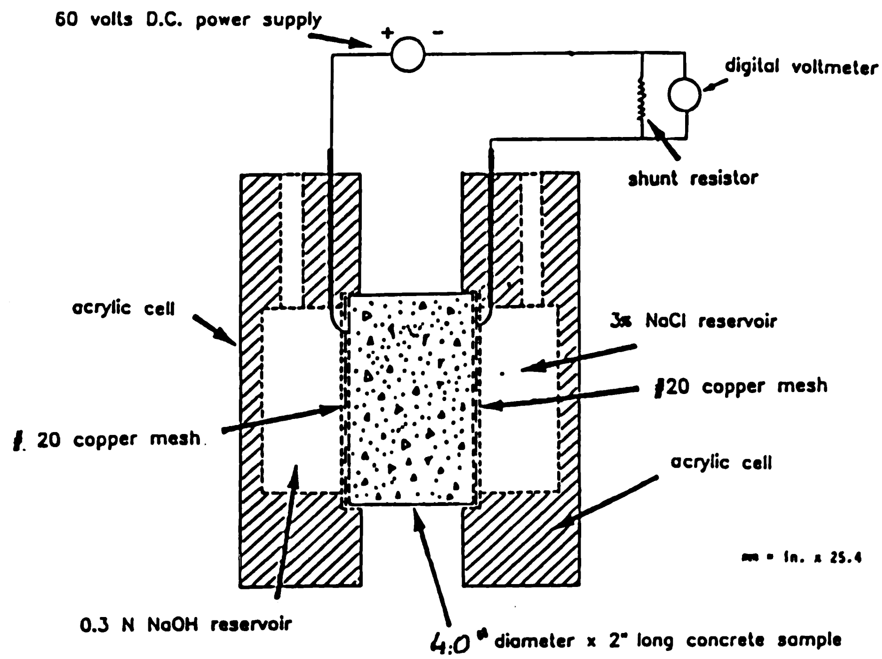


Figure 3.6 Schematic of rapid chloride permeability test apparatus.

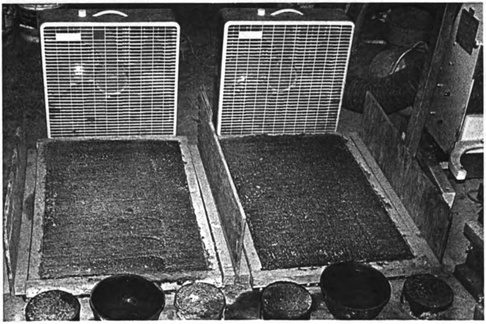
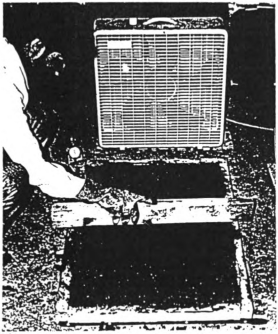
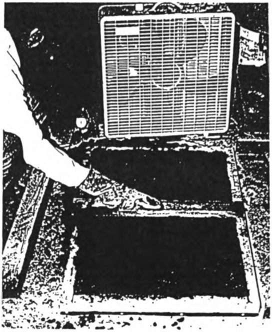


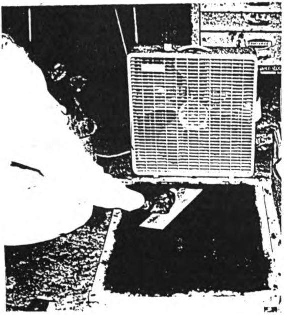
Figure 3.7 Plastic shrinkage cracking test arrangement.



(a) Screeding



(b) Bullfloating



(c) Floating

(d)Troweling

Figure 3.8 Construction operations for plastic shrinkage cracking test panels.

CHAPTER IV

MECHANICAL PROPERTIES

4.1 INTRODUCTION

The compressive strength of concrete is considered to be its most important characteristic, although in many practical cases other properties, such as durability, impermeability, and volume stability, may ply important roles. In general, improvements in concrete strength will improve other properties of concrete as well. Strength as well as durability and volume stability of hardened concrete appear to depend not so much on the chemical composition as on the physical structure of the hydration products of cement and other ingredients of concrete, and on their relative volumetric proportions.

Fibers in general and polypropylene fibers in particular have gained popularity in the recent years for use in concrete, mainly to enhance the toughness and shrinkage cracking resistance of plain concrete. Polypropylene fibers are not expected to increase the strength of concrete, but to improve its ductility and toughness, shattering resistance, and particularly resistance to shrinkage cracking at early ages. Polypropylene fibers are commercially utilized at relatively low volume fractions to control plastic shrinkage cracking of concrete. At low dosages, however, the fiber effects on concrete strength properties and impact resistance are relatively small, and careful statistical analysis of sufficiently large number of tests would be required to distinguish between the actual fiber effects and the random variations in experimental results.

This chapter presents a comprehensive experimental data and powerful statistical analyses which produce conclusions, at high levels of confidence, regarding the effects of low volume fractions of collated fibrillated polypropylene fibers on the compressive and flexural strength and toughness, and impact resistance of polypropylene fiber reinforced concrete materials.

4.2 EXPERIMENTAL PROGRAM

The mechanical properties of polypropylene fiber reinforced concrete (PPFRC) were investigated experimentally. First the effects of collated fibrillated polypropylene fibers on compressive and flexural strength and toughness were considered, and then the impact resistance of polypropylene fiber reinforced concrete was assessed experimentally.

Two experimental programs were designed for studying the compressive and flexural properties of polypropylene fiber reinforced concrete. In phase one the effect of polypropylene fiber volume fraction was investigated in a one-variable experimental design with five different volume fractions (0.0%, 0.05%, 0.1%, 0.2%, and 0.3%), as presented in Table 4.1. In the second experimental design, the effects of pozzolanic materials and latex polymers in polypropylene fiber reinforced concrete were assessed experimentally (see Table 3.2 in Chapter 3).

The effects of polypropylene fibers on impact resistance were studied in three phases. First, the effects of fiber length and fiber volume fraction were investigated (Phase I), then the effects of pozzolanic materials and latex polymers were studied (Phase II), and finally the effects of different fiber types were assessed experimentally (Phase III). These three phases of the experimental investigation of impact resistance are presented in Tables 3.1, 3.2 and 3.3 (see Chapter 3).

The basic mix constituents used to construct the specimens are described in section 3.3.1. The mix proportions are presented in Tables 4.2, 4.3 and 4.4 for different phases of this study (notice that in compression and flexure, a part of Table 4.2 fiber length=0.75 in., 19 mm, and the whole Table 4.3 were used). All concrete mixtures were mixed in a conventional rotary drum mixer; the mixing procedure basically followed ASTM C 192-90 (see section 3.3.3). All the specimens were covered with wet burlap and plastic sheet 30-45 minutes after casting, and demolded after 24 hours. The specimens were then moist cured for three days at 73±3 °F (23±1.7 °C) and 97±3% R.H. They were then exposed to interior laboratory conditions at 73±3 °F (23±1.7 °C) and 50±5% R.H. until the test age of 28 days.

The flexural strength tests were performed on 4 x 4 x 14 in. (102 x 102 x 356 mm) prisms by third-point loading following ASTM C 78-84 and C 1018-89 methods and the Japanese JCI-SF Code[57] (the Japanese method of deflection measurement was used). The compression strength tests were performed using 6 x 12 in. (152 x 305 mm) cylinders following ASTM C 39-86 method (with compressive strains monitored following the Japanese JCT-SF code.[57] The impact tests were performed on 6 x 2.5 in. (152 x 64 mm) cylindrical concrete disks following the ACI Committee 544 recommendations as described in section 3.6.3. The number of specimens for impact test was chosen using the prescribed method in section 3.5, in order to generate sufficient data for powerful statistical analyses.

4.3 TEST RESULTS AND DISCUSSION

The experimental data for compressive and flexural strength and toughness, and impact resistance are presented in this section along with the statistical analysis of the data. The number of specimens used for compression and flexure tests were two and three, respectively. In case of impact resistance, the number of specimens was based on the preliminary study presented earlier in section 3.5; this number was chosen to be large enough for statistical analysis at 95% level of confidence with a reasonable power of ≥ 0.76 in the statistical analysis of variance.

4.3.1 Compression Test Results

Tables 4.5 and 4.6 present the raw test data for the compressive strength and toughness, respectively, of polypropylene fiber reinforced concretes considered in this investigation. Compressive toughness is defined here, following the definition of the Japanese Concrete Institute, as the area underneath the stress-strain curve up to a strain of 0.0075.

Typical stress-strain curves for different conditions are shown in Figures 4.1 through 4.5. the average compressive strength and toughness test results, together with the corresponding 95% confidence intervals are presented in Figures 4.6 and 4.7, respectively, for different fiber volume fractions (Phase I of this Experimental Program). One-way analysis of variance of the test data revealed that the effects of polypropylene fiber volume fraction on compressive strength and toughness of concrete is not statistically significant at 95% level of confidence.

The average values and 95% confidence intervals of the compressive strength and toughness test results for concrete materials incorporating pozzolanic admixtures (Phase II of Experimental Program) are presented in Figures 4.8 and 4.9, respectively. The results were analyzed by the factorial analysis of variance technique. The two factors in the analysis were the volume fraction at two levels (0.0% and 0.1%), and the binder composition at four levels (cement, fly ash, silica fume, and slag). Table 4.7 presents a summary of statistical analysis of variance of the compressive strength data. It could be seen that compressive strength was influence by the binder composition at 95% level of confidence, while the fiber volume fraction did not have statistically significant effects on compressive strength at the same level of confidence. On the average, there were 21% and 23% increase in compressive strength with the addition of silica fume to plain and polypropylene fiber reinforced concretes, respectively. compressive toughness was not significantly affected by neither the binder composition nor the fiber volume fraction at 95% level of confidence.

The average values and 95% confidence interval for the compressive strength and toughness of latex modified concrete are presented in Figures 4.10 and 4.11, respectively. The results were analyzed through factorial analysis of variance; it was concluded that both compressive strength and toughness were significantly affected by the addition of latex polymer at 99% level of confidence. There were, on the average, 19%, and 21% increase in compressive strength with the addition of latex to plain and polypropylene fiber reinforced concretes, respectively; the corresponding improvements in toughness were about 40% in both plain and fibrous concretes.

4.3.2 Flexural Test Results

The raw flexural strength and toughness test data are presented in Tables 4.8 and 4.9, respectively for polypropylene fiber reinforced concrete. Flexural toughness is defined here, following the Japanese definition,[57] as the area underneath the flexural load-deflection curve up to a mid-span deflection equal to the span length divided by 150. Typical load-deflection curves for different conditions used in this study are shown in Figures 4.12 through 4.16. The average values and 95% confidence intervals for the flexural strength and toughness test results in phase I of this part of the research are shown in Figures 4.17 and 4.18, respectively. One-way analysis of variance of test data revealed that the polypropylene fiber volume fraction did not affect the flexural strength of the co

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concrete materials at 95% level of confidence. The flexural toughness, however, was significantly affected at 99% level of confidence by the addition of polypropylene fibers. The increases in flexural toughness due to the addition of 0.1, 0.2 and 0.3% polypropylene fibers were 44, 271, and 386% over the plain concrete, respectively. Multiple comparison of results indicated that the increase in flexural toughness at 0.05% fiber fraction was not statistically significant.

The average values and 95% confidence intervals for the flexural strength and toughness of plain and polypropylene fiber reinforced concretes with different binder compositions are shown in Figures 4.19 and 4.20,respectively. Factorial analysis of variance [2 x 4 factorial design; two fiber volume fractions (0.0 and 0.1%) and four binder compositions (cement, fly ash, silica fume, and slag)] indicated that polypropylene fibers at 0.1% volume fraction do not affect the flexural strength (at 95% level of confidence), but the binder composition influences flexural strength at 99% level of confidence. Analysis of variance of the flexural toughness test results indicated that both polypropylene fiber volume fraction and binder composition have significant effects at 99% level of confidence. There was also a significant interaction between fibers and binder composition in the sense that the flexural toughness of, for example, silica fume and fly ash concretes improved, by 79 and 28% over that of the conventional fibrous concrete (without silica fume or fly ash), respectively.

The average flexural strength and toughness test results of latex modified plain and fibrous concretes along with the corresponding 95% confidence intervals i

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are presented in Figures 4.21 and 4.22, respectively. The results were analyzed through factorial analysis of variance, which revealed that, at 99% level of confidence, flexural strength was affected by the addition of latex but not fibers. The flexural strengths of plain and polypropylene fiber reinforced concrete were increased by 34 and 26%, respectively, due to the addition of latex polymer. Flexural toughness was not significantly affected, at 95% level of confidence, by the addition of polypropylene fibers or latex polymer, noting that the conclusion regarding the fiber effects is made here based on a relatively small experimental design.

4.3.3 Impact Rsistance Test Results

In this section, the impact resistance test data will be presented together with the results of statistical analyses of the data. Due to the large variations in impact test results (which is a problem with the measurement technique), and in order to derive statistically reliable conclusions, all the data were carefully studied and the outlier were removed following the Shapiro-Wilk Normality test method.[43]

4.3.3.1 Effect of Fiber Volume Fraction and Fiber Length

The impact test data are presented in Tables 4.10 (a) and 4.11 (a) for first-crack and failure conditions, respectively. The average first crack and failure impact resistance test results are presented in Figures 4.23 and 4.24, respectively. Analysis of variance of the data revealed that polypropylene fibers affect the first-crack and failure impact resistance at 95% and 99% levels of confidence, respectively.

Multiple comparison of means of the data showed that only at 0.2% fiber volume fraction the first-crack impact resistance was different from that of plain concrete, at 95% level of confidence, for fiber lengths of 0.5 and 0.75 in. (13 and 19 mm); the impact resistance at failure was significantly different from plain concrete only with the addition of: (1) 0.1% and 0.2% fiber volume fractions, at 95% level of confidence, for the same fiber lengths; and (2) 0.2% and 0.3% fiber volume fractions for the fiber length of 1.5 in. (38 mm).

4.3.3.2 Effects of Pozzolanic Materials

The first-crack and failure impact test data are presented in Tables 4.10 (b) and 4.11 (b), respectively. The average values and 95% confidence intervals for the first-crack and failure impact test results are shown in Figures 4.25 and 4.26, respectively. Analysis of variance of the data indicated that, at 99% level of confidence, polypropylene fiber at 0.1% volume fraction improved both the first-crack and failure impact resistances of concrete, while pozzolanic materials damaged the impact resistance. A positive interaction was also found between the fibers and pozzolans effects, in the sense that fibers produced a larger increase in the impact resistance of pozzolan concrete when compared with plain concrete. On the average, polypropylene fibers increased the first-crack impact resistance of fly ash, slag and silica fume concretes by 151%, 78% 91% respectively; and the corresponding improvements in failure impact resistance were 202%, 145%, and

164%, respectively. Pozzolans damaged the impact resistance of plain concrete; fly ash, slag and silica fume reduced the failure impact resistance of plain concrete by 40%, 42%, and 28%, respectively.

4.3.3.3 Effects of Latex Polymer

The raw test data on the impact resistance of latex modified plain and fibrous concretes are presented in Tables 4.10 (b) and 4.11 (b). The average values and 95% confidence intervals of the these impact test results are shown in Figure 4.27. Factorial analysis of variance indicated that latex polymers affect the first-crack and failure impact resistance, at 99% level of confidence, of both plain and fibrous concretes. A positive interaction was also found between the fiber and latex effects on impact resistance, in the sense that fibers produced a larger increase in the impact resistance of latex modified concrete when compared with conventional concrete. On the average, the latex polymer increased the first-crack impact resistance of plain and fibrous concretes by 42% and 259%, respectively; the impact resistance at failure was increased with the addition of latex by 38% and 158% in plain and fibrous concretes, respectively. The positive interaction between latex polymer and polypropylene fibers may be attributed to the improved bonding of latex modified matrices to polypropylene fibers.

4.3.3.4 Effects of Different Fiber Types

Tables 4.10 (c) and 4.11 (c) present the first-crack and failure impact test data, respectively. The average impact test results and the 95% confidence intervals are shown in Figure 4.28. One-way analysis of variance indicated that all the three fiber types have statistically comparable first-crack and failure impact resistance at 95% level of confidence.

4.3.4 SUMMARY AND CONCLUSIONS

The effects of collated fibrillated polypropylene fibers on the compressive an flexural strength and toughness, and impact resistance of conventional concrete materials and concretes incorporating different pozzolanic and polymeric admixtures were investigated experimentally. Sufficient replicated test data were produced in order to confirm the validity of the conclusions at 95% (or higher) level of confidence:

1. Polypropylene fibers have no statistically significant effects on the compressive strength and toughness of conventional concrete at the volume fractions used in this investigation. The presence of silica fume and latex polymer, however, increased the average compressive strength of plain concrete by 17% & 19%, respectively, and that of fibrous concrete by 23% and 21%, respectively. Latex was also able to increase the compressive toughness by an average of 40% in both plain and conventional polypropylene fiber reinforced concrete.
2. While polypropylene fibers have no effects on flexural strength at the volume fractions used in this study, the positive interaction between fibers and latex tends to increase the flexural strength by an average of 26% when compared with conventional polypropylene fiber reinforced concrete.

3. Polypropylene fibers affect the flexural toughness significantly at 95% level of confidence. On the average, the addition of 0.1%, 0.2%, and 0.3% volume fraction of fibers increases the flexural toughness by 44%, 271% and 387%, respectively. Silica fume increases the flexural toughness by 48% and 79% in the case of plain and fibrous concretes, respectively. Latex modification has no effects on flexural toughness in both plain and fibrous concretes.

4. Polypropylene fibers increase the first-crack and failure impact resistance of concrete reinforced with different fiber volume fractions used in this study. The impact resistance at failure is increased by 48%, 62%, 171% and 90% with the addition of 0.05, 0.1, 0.2 and 0.3% fiber volume fraction, respectively, for fiber length of 0.75 in (38 mm).

5. While pozzolans generally reduce the impact resistance of concrete, the positive interactions between polypropylene fibers and pozzolans (fibers are more effective in the presence of pozzolans) leads to enhanced the impact resistance of fibrous concrete with pozzolans. The impact resistance at failure of conventional fibrous concrete was increased by 82%, 42% and 90% with the addition of fly ash, silica fume and slag, respectively.

6. The failure impact resistance of latex modified concrete is increased by 158% with the addition of polypropylene fibers at 0.1% volume fraction.

7. Different Polypropylene Fiber types behave similarly in affecting impact resistance at 0.1% fiber volume fraction. Other fiber types such as steel fibers also have comparable impact resistance at 0.1% fiber volume fraction.

Table 4.1 One-way experimental program for compression and flexural tests; phase I.

Fiber Volume Fraction (%)				
0.0	0.05	0.10	0.20	0.30
*	*	*	*	*

2-compression and 3-flexure tests for each cell.

Table 4.2 Mix proportions, phase I (lb/yd^3)*

V_f (%)	L_f (in.)	Cement	Coarse Agg.	Fine Agg.	Water	AEA	Sup.
0.0	---	676	1691	1353	271	0.541	---
0.05	0.50	673	1683	1347	276	0.337	---
0.1	0.50	671	1677	1342	282	0.336	---
0.2	0.50	662	1654	1323	298	0.331	---
0.3	0.50	661	1652	1322	297	0.330	0.661
0.05	0.75	671	1676	1341	282	0.335	---
0.1	0.75	668	1671	1336	301	0.334	---
0.2	0.75	662	1654	1323	298	0.331	0.993
0.3	0.75	661	1653	1322	297.5	0.397	1.653
0.05	1.50	663	1657	1326	298	0.332	---
0.1	1.50	662	1656	1325	298	0.331	---
0.2	1.50	662	1654	1323	298	0.331	1.323
0.3	1.50	661	1653	1322	297.5	0.397	1.719

* 1 lb/yd.^{3} = 1.685 kg/m^3; V_f = Fiber volume fraction; L_f = Fiber Length; AEA = Air entraining agent; Sup. = Superplasticiezer.

Table 4.3 Mix proportions, phase II (lb/yd³)*

Matrix Composition	V_f (%)	Cement	Coarse Agg.	Fine Agg.	Water	Pozzolan Latex	AEA	Sup.
Cement	0.0	676	1691	1353	271	---	0.541	---
	0.1	668	1671	1336	301	---	0.334	---
Cement + 25 % Fly Ash	0.0	493	1232	985	296	164.1	1.084	0.345
	0.1	492	1230	984	295	163.9	0.984	0.394
Cement + 25 % Slag	0.0	506	1265	1012	270	168.4	0.658	---
	0.1	504	1260	1008	276	167.8	0.504	---
Cement + 10 % Silica Fume	0.0	595	1488	1191	298	66.1	0.893	1.786
	0.1	595	1487	1190	297	66.0	0.891	0.952
Latex (10 % of Cement)	0.0	684	1711	1369	192	68.4	---	---
	0.1	678	1695	1356	203	67.8	---	---

* 1 lb/yd.³ = 1.685 kg/m³; V_f = Fiber volume fraction; AEA = Air entraining agent; Sup.=Superplasticiezer;

Table 4.4 Mix proportions, phase III (lb/yd³)*

Fiber Type	V_f (%)	Fiber	Cement	Coarse Agg.	Fine Agg.	Water	AEA
PP-1	0.10	1.52	668	1671	1336	301	0.334
PP-2	0.10	1.52	668	1669	1335	287	0.334
Steel	0.10	13.14	665	1662	1330	286	0.465

* 1 lb/yd.³ = 1.685 kg/m³; V_f = Fiber volume fraction; AEA = Air entraining agent.

Table 4.5 Compression strength test results (ksi).
(a) Phase I

Fiber Volume Fraction (%)				
0.0	0.05	0.10	0.20	0.30
4.934, 5.285	4.775, 4.637	5.441, 5.373	5.492, 5.677	4.959, 5.007

(b) Phase II

V_f (%)	Matrix Compositions				
	Cement (C)	C + Fly Ash	C + Silica Fume	C + Slag	Latex
0.0	4.934, 5.285	4.025, 5.392	6.020, 6.335	5.371, 6.614	6.159, 6.040
0.1	5.441, 5.375	4.570, 4.530	6.700, 6.603	3.895, 5.458	6.571, 6.525

Table 4.6 Compression toughness test results (k-in.).
(a) Phase I

Fiber Volume Fraction (%)				
0.0	0.05	0.10	0.20	0.30
2.339, 3.332	3.750, 3.560	3.907, 3.830	4.000, 4.169	4.003, 3.470

(b) Phase II

V_f (%)	Matrix Compositions				
	Cement (C)	C + Fly Ash	C + Silica Fume	C + Slag	Latex
0.0	2.339, 3.332	3.289, 4.799	4.160, 3.477	2.839, 3.378	4.449, 3.452
0.1	3.907, 3.830	3.985, 3.496	3.404, 3.275	3.223, 3.752	5.585, 5.230

Table 4.7 Summary of statistical analysis of variance in two-way factorial design.

Factor	Sum-of-Squares	D.F.	Mean-Square	F-Ratio	F-Prob.
V_f	0.001	1	0.001	0.004	0.953
BT	7.858	3	2.619	8.287	0.011
V_f* BT	0.412	3	0.137	0.434	0.735
Error	2.213	7	0.316		

V_f = Fiber volume fraction; BT = Binder type.

Table 4.8 Flexural strength test results (psi).
(a) Phase I

Fiber Volume Fraction (%)				
0.0	0.05	0.10	0.20	0.30
623, 639, 710	690, 619, 624	709, 692, 774	676, 634, 695	693, 681, 667

(b) Phase II

V_f (%)	Matrix Compositions				
	Cement (C)	C + Fly Ash	C + Silica Fume	C + Slag	Latex
0.0	623, 710, 639	639, 629,602	763, 718, 766	672, 667, 695	842, 888,910
0.1	709, 692, 774	633, 742, 609	693, 697, 745	587, 567, 576	988, 954, 805

Table 4.9 Flexural toughness test results (lb-in.)
(a) Phase I

Fiber Volume Fraction (%)				
0.0	0.05	0.10	0.20	0.30
9.6, 10.1, 10.5	7.2, 10.7, 10.5	15.6, 15.4, 12.4	41.8, 30.8, 39.4	46.8, 48.9, 51.2

(b) Phase II

V_f (%)	Matrix Compositions				
	Cement (C)	C + Fly Ash	C + Silica Fume	C + Slag	Latex
0.0	9.6, 10.1, 10.5	9.6, 8.6, 11.1	14.9, 14.5, 15.4	9.0, 10.6, 10.9	9.6, 11.1, 15.2
0.1	15.6, 15.4, 12.4	11.4, 18.5, 25.4	21.4, 31.8, 24.4	11.4, 11.3, 11.3	17.4, 10.5, 12.1

Table 4.10 First- Crack impact test results.

(a) Phase One

Fiber Length	Fiber Volume Fraction (%)				
	0.0	0.05	0.10	0.20	0.30
0.50"	36, 26, 26, 39, 72, 51, 26, 18, 17, 54	21, 44, 93	60, 69, 51	74, 112, 44	18, 85, 29, 39
0.75"		54, 69, 39, 30	see Table 4.7 (c)	44, 83, 74	31, 60, 29, 38
1.50"		39, 61, 38, 19	32, 38, 43, 40	28, 35, 42, 53	60, 71, 40, 55

(b) Phase Two

V_f (%)	Matrix Compositions				
	Cement (C)	C+Fly Ash	C+Silica Fume	C + Slag	Latex
0.0	36, 26, 26, 39, 72, 51, 26, 18, 17, 54	34, 34, 14, 14, 29, 11, 32, 11, 9	23, 24, 11, 20, 15, 28, 24, 15, 38, 9	26, 17, 22, 51, 40, 21, 15, 25, 14, 43, 29, 11, 33	25, 74, 25, 117, 41, 63, 25, 29, 69
0.1	see Table 4.7 (c)	64, 14, 26, 110, 22, 46, 27, 105, 23, 17, 71, 103	22, 78, 55, 39, 23, 16, 17, 82, 25, 12	12, 25, 16, 23, 25, 24, 54, 37, 65, 18, 39, 110, 127, 139	125, 162, 318, 165, 161, 134, 140, 62, 40, 79

(c) Phase Three

PPF (Fibermesh)	PPF (W.R.Grace&Co.)	Steel Fiber
31, 64, 15, 33, 15, 33,36, 26, 24, 34, 47, 50, 26, 39, 31, 26, 79, 47, 29, 24, 50, 65, 40, 36, 42, 52, 56, 33, 59, 55, 38, 21, 35, 23	48, 67, 67, 18, 44, 35, 32, 72, 48, 25, 20, 31, 36, 40, 41, 31, 41, 34, 54, 44, 36, 31, 16, 21, 71, 30, 42, 21, 75, 65, 30, 18, 41, 31	61, 81, 63, 69, 53, 41, 21, 113, 43, 35, 41, 59, 45, 22, 52, 33, 40, 13, 20, 20, 37, 27, 63, 23, 70, 17, 55, 38, 36, 14, 36, 17, 29, 27, 46, 90, 58, 25

Table 4.11 Impact test results at failure.
(a) Phase One

Fiber Length	Fiber Volume Fraction (%)				
	0.0	0.05	0.10	0.20	0.30
0.50"	40, 29, 29, 41, 74, 51, 26, 18, 18, 55	33, 59, 100	87, 82, 56	90, 129, 71	39, 100, 54, 55
0.75"		59, 74, 50, 43	see Table 4.8 (c)	80, 130, 100	73, 89, 58, 70
1.50"		45, 77, 54, 33	47, 57,65, 69	55, 67, 70, 88	90, 104, 65, 76

(b) Phase Two

V_f (%)	Matrix Compositions				
	Cement (C)	C + Fly Ash	C + Silica Fume	C + Slag	Latex
0.0	40, 29, 29, 41, 74, 51, 26, 18, 18, 55	39, 35, 18, 15, 30, 12, 34, 11, 13	23, 25, 13, 21, 16, 28, 28, 17, 40, 10	28, 17, 24, 52, 41, 22, 15, 26, 15, 43, 30, 11, 34	26, 75, 25, 117, 42, 64, 25, 29, 69
0.1	see Table 4.8 (c)	89, 26, 50, 132, 43, 80, 40, 114, 40, 26, 80, 114	39, 90,70, 60, 45, 30, 40, 92, 45, 30	32, 50, 37, 45, 45, 42, 77, 67, 81, 32, 49, 137, 136, 186	148, 177, 336, 178, 180, 157, 156, 78, 69, 102

(c) Phase Three

PPF (Fibermesh)	PPF (W.R.Grace&Co.)	Steel Fiber
54, 79, 41, 51, 29, 50, 56, 56, 51, 56, 74, 73, 34, 59, 52, 47, 108, 70, 57, 51, 77, 87, 74, 51, 61, 71, 72, 59, 85, 84, 76, 51, 57, 47	70, 89, 75, 37, 59, 56, 54, 92, 60, 51, 38, 51, 54, 57, 61, 40, 61, 64, 79, 70, 57, 52, 34, 46, 93, 58, 65, 60, 91, 84, 63, 43, 70, 52	78, 100, 80, 84, 73, 65, 128, 33, 58, 53, 58, 82, 58, 48, 61, 53, 53, 30, 32, 33, 51, 45, 70, 30, 78, 25, 65, 50, 51, 33, 55, 41, 47, 45, 61, 100, 84, 45

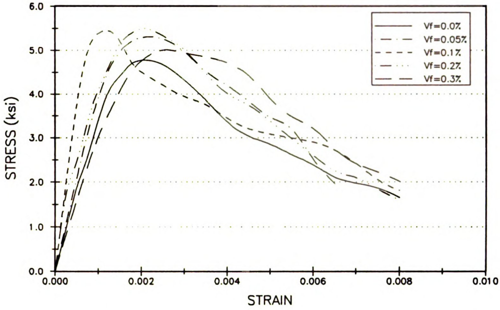


Figure 4.1 Typical compressive stress-strain at different fiber volume fractions.

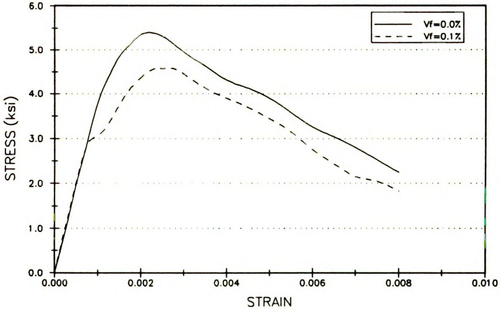


Figure 4.2 Compressive stress-strain curves for fly ash concrete at different volume fractions.

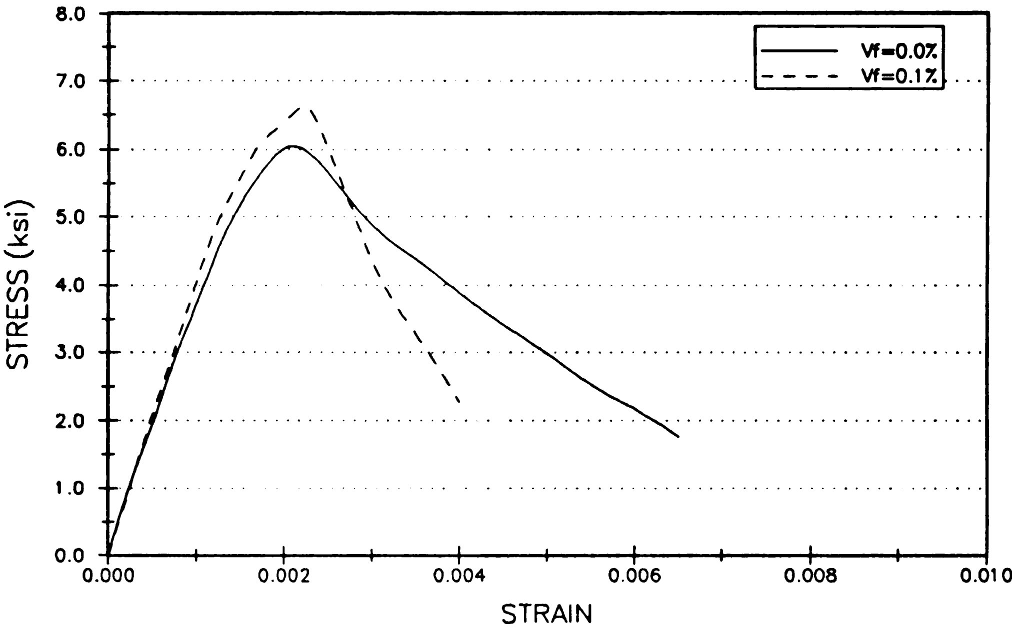


Figure 4.3 Compressive stress-strain curves for silica fume concrete at different volume fractions.

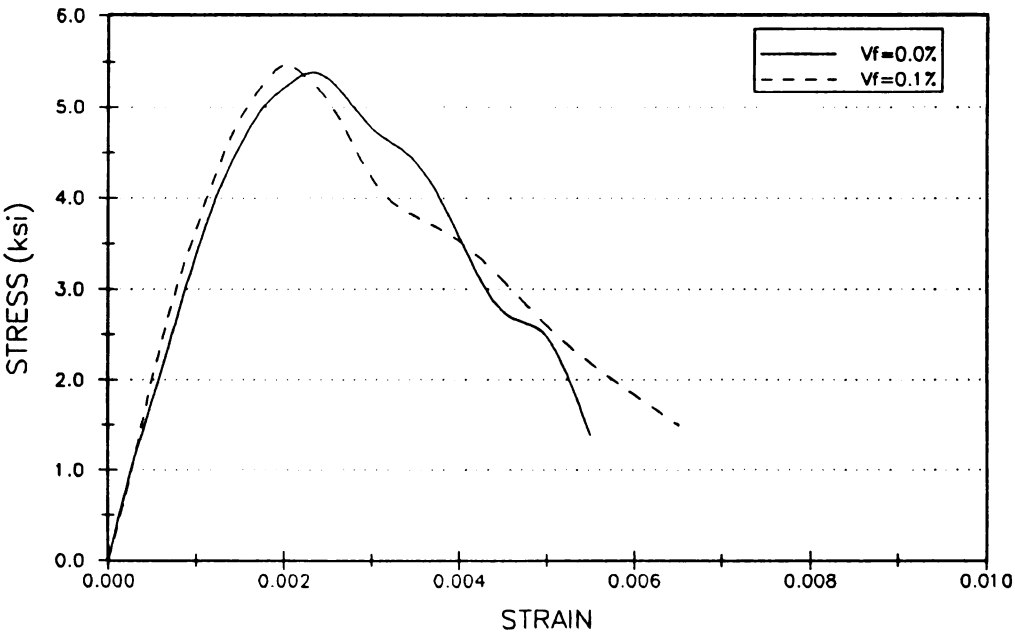


Figure 4.4 Compressive stress-strain curves for slag concrete At different volume fractions.

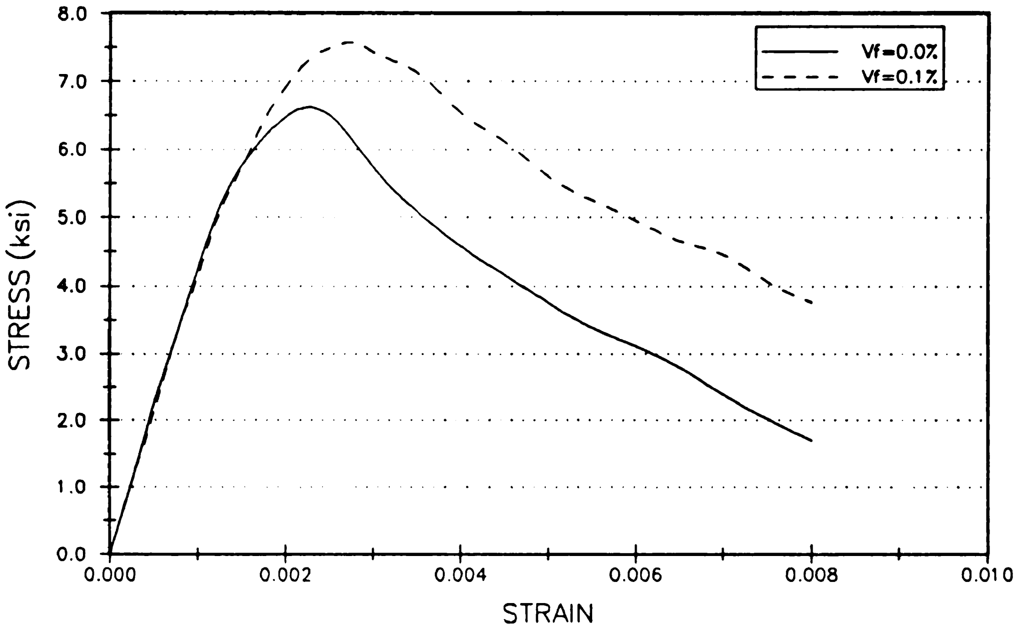


Figure 4.5 Compressive stress-strain curves for latex modified concrete at different volume fractions.

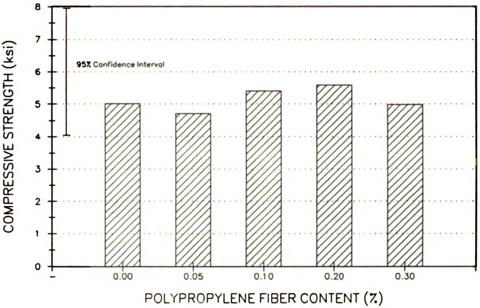


Figure 4.6 Compressive strength test results at different volume fractions.

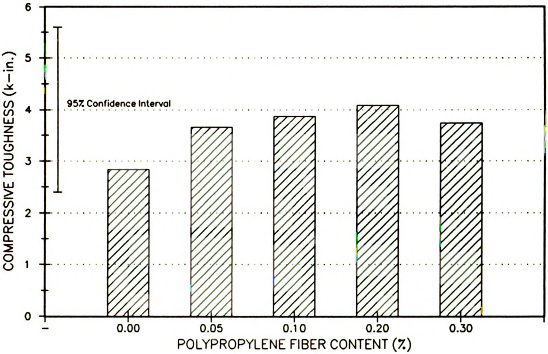


Figure 4.7 Compressive toughness test results at different Fiber volume fractions.

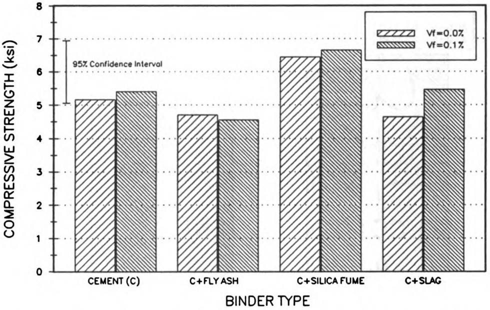


Figure 4.8 Compressive strength test results for plain and fibrous concrete materials with different binders.

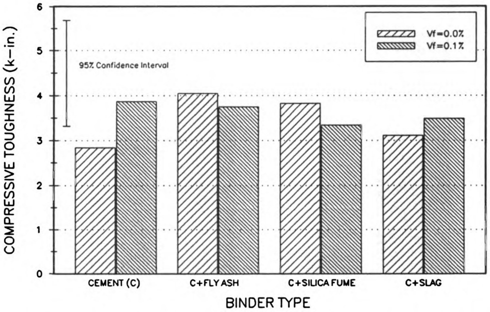


Figure 4.9 Compressive toughness test results for plain and fibrous concrete materials with different binders

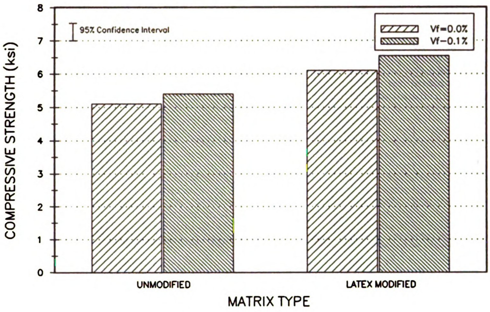


Figure 4.10 Compressive Strength test results for plain and fibrous latex modified concrete.

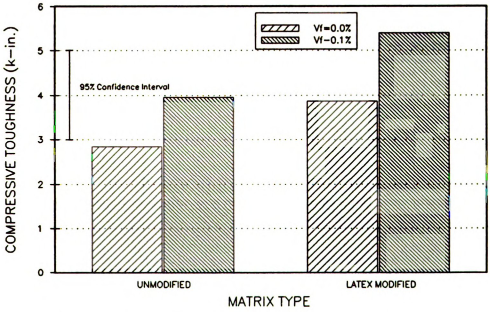


Figure 4.11 Compressive toughness for plain and fibrous latex modified concrete.

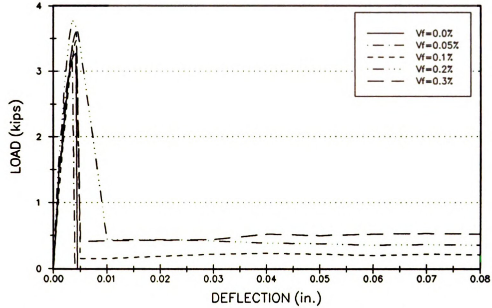


Figure 4.12 Flexural load-deflection curves at different volume fractions.

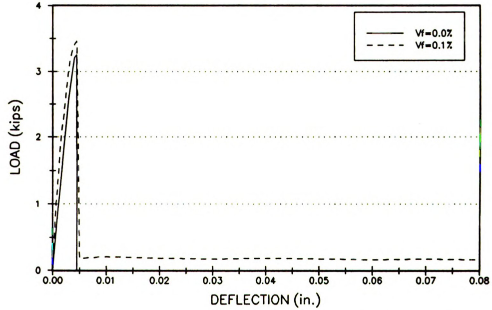


Figure 4.13 Flexural load-deflection curves for fly ash concrete at different volume fractions.

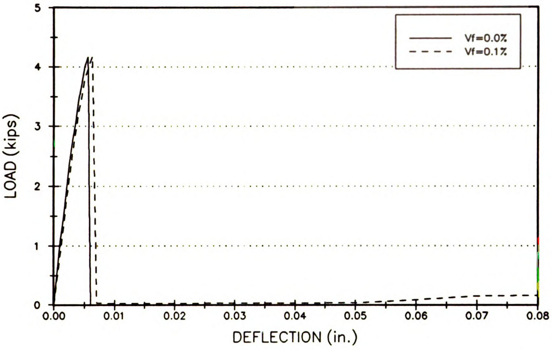


Figure 4.14 Flexural load-deflection curves for silica fume concrete at different volume fractions.

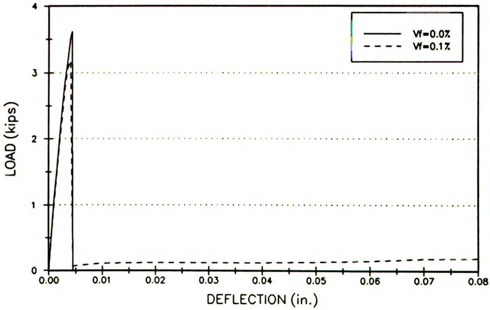


Figure 4.15 Flexural load-deflection curves for slag concrete at different volume fractions.

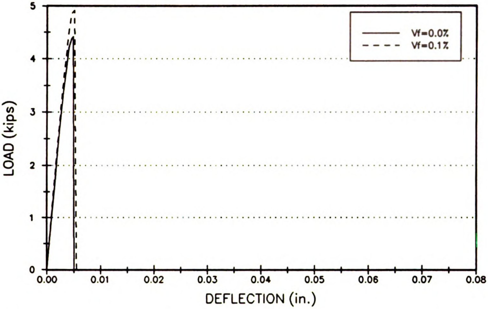


Figure 4.16 Flexural load-deflection curves for plain and fibrous latex modified concrete.

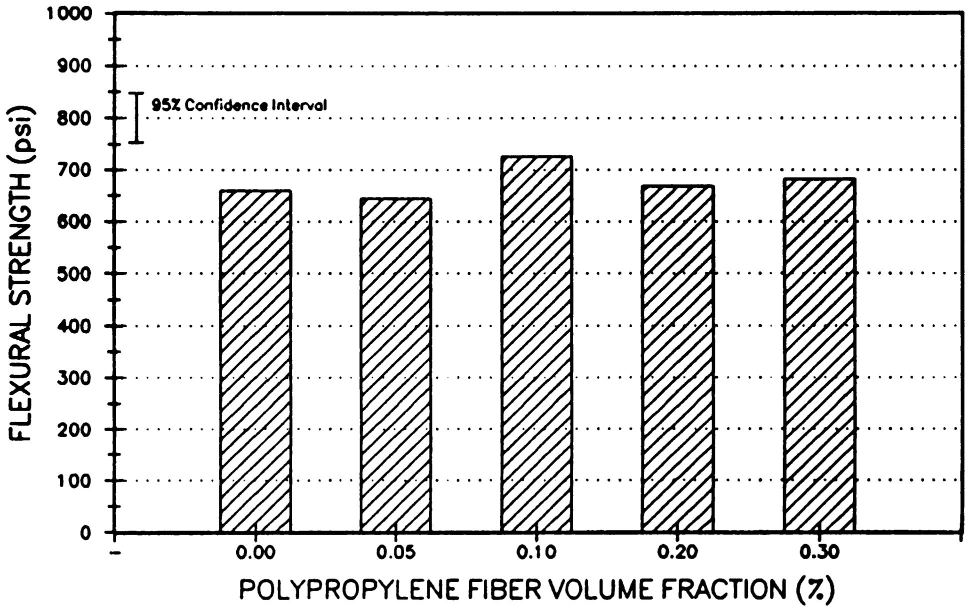


Figure 4.17 Flexural strength test results of concrete at different volume fractions.

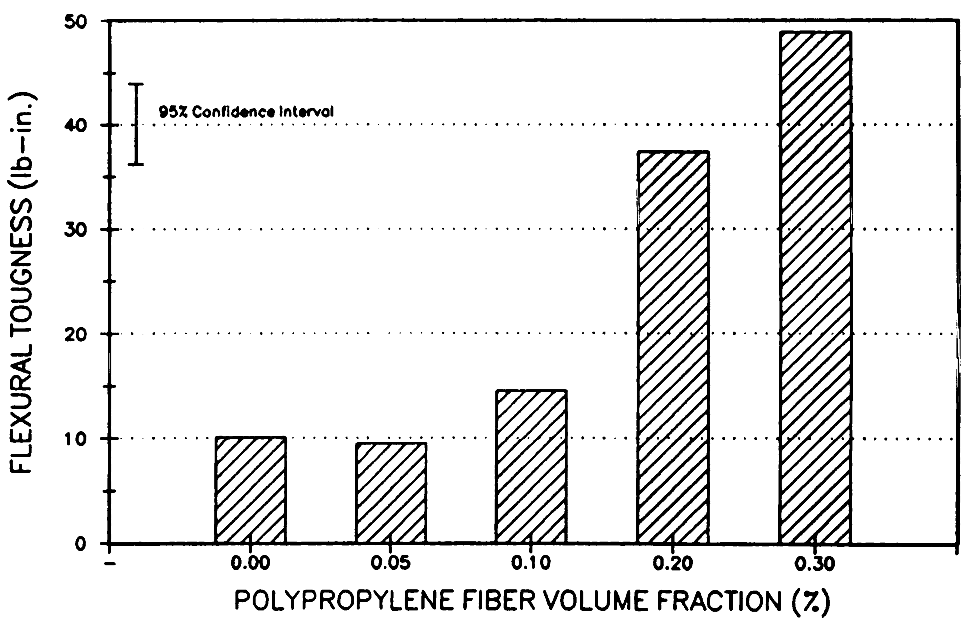


Figure 4.18 Flexural toughness test results of concrete materials at different volume fractions.

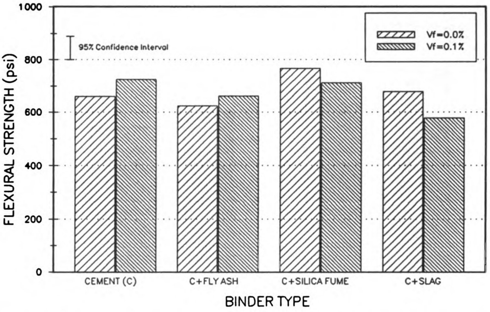


Figure 4.19 Effects of pozzolanic materials and fiber volume fraction on flexural strength.

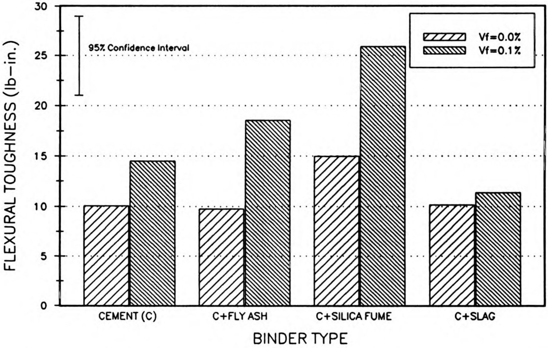


Figure 4.20 Effects of pozzoanic materials and fiber volume fraction on flexural toughness.

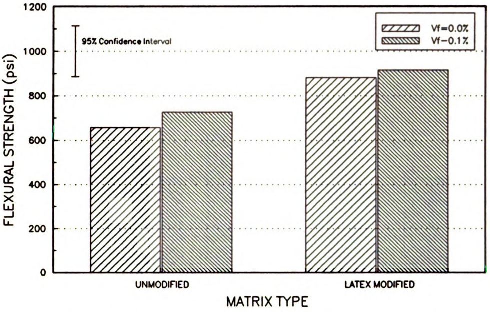


Figure 4.21 Flexural strength test results for plain and fibrous latex modified concrete.

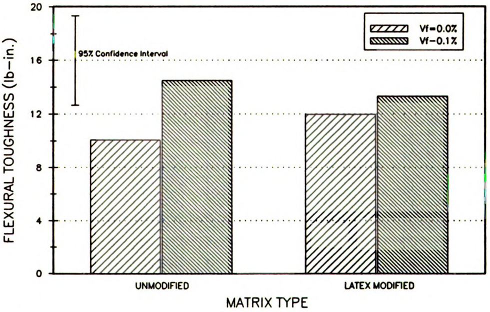


Figure 4.22 Flexural toughness test results for plain and fibrous latex modified concrete.

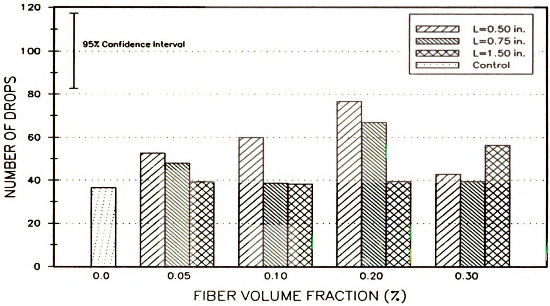


Figure 4.23 First-Crack impact resistance test results for different fiber volume fractions and lengths.

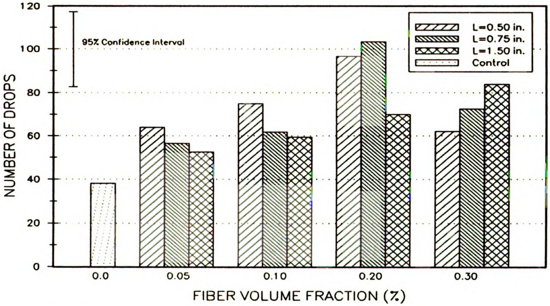


Figure 4.24 Failure impact resistance test results for different fiber volume fractions and lengths.

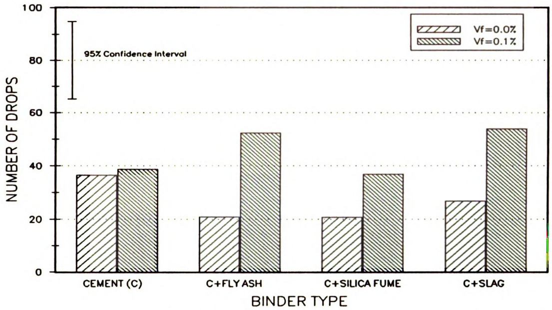


Figure 4.25 Effects of pozzolanic materials and fiber volume fraction on first-crack impact resistance.

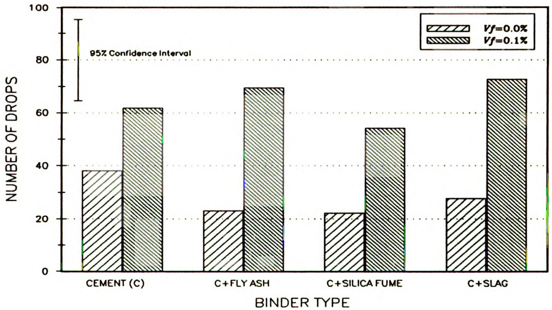


Figure 4.26 Effects of pozzolanic materials and fiber volume fraction on failure impact resistance.

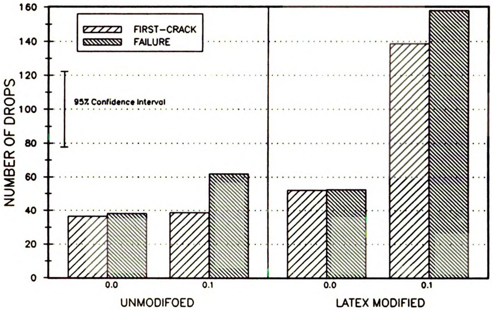


Figure 4.27 Effects of latex polymer and Fiber volume fraction on impact resistance.

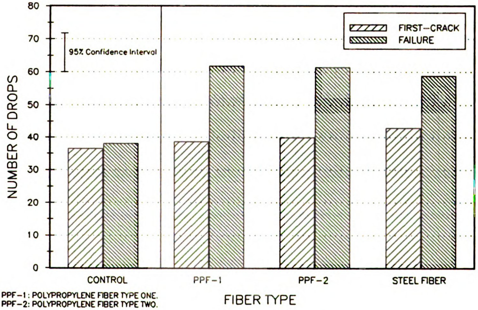


Figure 4.28 Effects of fiber types on impact resistance.

CHAPTER V

PERMEABILITY CHARACTERISTICS

5.1 INTRODUCTION

Permeability plays an important role in the long-term durability of concrete materials. Permeability of concrete generally refers to the rate at which particular aggressive substance (water, sulfates, chloride ions, etc.) can flow through the concrete.

Polypropylene fibers have gained popularity in the recent years for the use in concrete at relatively low volume fractions, mainly to reduce shrinkage cracking. The arrest of shrinkage cracks in young concrete by fibers could lead to reduced permeability of polypropylene fiber reinforced concrete when compared with plain concrete. Limited test results have been reported on the permeability characteristics of polypropylene fiber reinforced concrete, the available test results also have not generally been performed using standardize test methods, and mainly concern water or gas permeability. In light of the variations in test results, one may find it difficult to derive statistically reliable calculations based on the limited test data available regarding the permeability characteristics of polypropylene fiber reinforced concrete.

The main thrust of this phase of the project is to produce a comprehensive experimental data on chloride permeability of polypropylene fiber reinforced concrete in order to perform powerful statistical analyses which produce statistically sound conclusions regarding the effects of low volume fractions of collated fibrillated polypropylene fibers on the chloride permeability of concrete materials incorporating different types of pozzolanic materials and latex polymer.

5.2 EXPERIMENTAL PROGRAM

The effects of polypropylene fiber reinforcement on the chloride permeability of concrete materials was investigated experimentally. The interactions of fibers with pozzolanic materials and latex polymer in deciding the permeability of concrete were also assessed.

Experiments were conducting following a 2^2 factorial design in two phases. In phase one the two variables were polypropylene fiber volume fraction (0% and 0.1%) and pozzolan content (0% and 25% by weight of cement substituted with class F fly ash and blast furnace slag; and 10% by weight of cement substituted with silica fume). In phase two, the latex content (0% and 10% by weight of cement) was the other variable besides the volume fraction of polypropylene fibers (0% and 0.1%). Table 5.1 summarizes the experimental design used in this investigation. For each mix design, six permeability test specimens were casted and tested in order to provide sufficient data for powerful statistical analyses. (see section 3.5).

The materials used in this experimental study include: cement, class F fly ash, blast furnace slag, silica fume, latex polymer, coarse aggregate, fine aggregate, polypropylene fibers, air entraining agent and superplasticizer. These materials were introduced in section 3.3. The mix proportions for all the mixtures of this phase of the study are presented in Table 5.2.

All the specimens were demolded 24 hours after casting (see section 3.3.4 for construction method), and then moist cured at 73±3 °F (23±1.7 °C) and 100% R.H. for three days. They were then exposed to interior laboratory conditions at 73±3 °F (23±1.7 °C) until the test age of 28 days.

The chloride permeability test was performed following AASHTO T-277 (Rapid Determination of The Chloride Permeability of Concrete). The test procedure is briefly described in section 3.6.

5.3 TEST RESULTS AND DISCUSSION

The raw permeability test data are presented in this section together with the results of statistical analysis of the data. It is worth mentioning that the number of replications (6 specimens) of permeability tests were large enough for statistical analysis at 95% level of confidence with a relatively high power of 0.80 in the statistical analysis of variance.

Tables 5.3 and 5.4 present the raw permeability test data. The average permeability test results together with 95% confidence intervals are presented in Figures 5.1 and 5.2. Polypropylene fibers at 0.1% volume fraction did not influence the permeability of concrete at 95% level of confidence. Pozzolanic materials (except for the specific fly ash used in this investigation) are observed in Figure 5.1 to be effective in reducing concrete permeability; silica fume and blast furnace slag reduced permeability by 70% and 44%, respectively. Statistical analysis (2 x 2 factorial design; analysis of variance) indicated that , at 90% level of confidence, there was no interaction between the pozzolans and polypropylene fibers in deciding concrete permeability (see Figure 5.3). This indicate that fibers do not change the generally positive effects of pozzolans on permeability. It is worth mentioning that previous investigations indicate almost similar results of pozzolanic materials on plain concrete.

Latex is observed in Figure 5.2 to be very effective in reducing concrete permeability; this was confirmed statistically at 99% level of confidence. The reduction in permeability in the presence of latex was 83%, from highly permeable to low permeability (see Table 3.14). Analysis of variance of the test data indicated that there was no interaction between latex and polypropylene fibers in deciding concrete permeability. The fact that concrete permeability was not influenced in this specific program by the presence of polypropylene fiber may have resulted from the differences between the field and laboratory operations.

Certain field conditions encouraging shrinkage cracking may lead to reduced permeability in the presence of polypropylene fibers due to arrest the shrinkage cracking.

5.4 SUMMARY AND CONCLUSIONS

The effects of collated fibrillated polypropylene fibers, at 0.1% volume fraction, on the chloride permeability of concrete materials incorporating different types of pozzolans and latex were investigated experimentally. Sufficient replicated tests were performed to confirm the validity of the following conclusions at 95% level of confidence (with a power of 0.8 is the statistical analysis of variance):

1. While pozzolans generally reduce concrete permeability, polypropylene fibers have no statistically significant effects on the chloride permeability of concrete. Fibers also have no interaction with pozzolans in deciding concrete permeability, and thus the generally positive effects of pozzolan on permeability would be evident to a similar effect in plain and polypropylene fiber reinforced concretes.
2. Latex modified concrete is known for its very low permeability, polypropylene fibers have no statistically significant effects on the chloride permeability of latex modified concrete. Field conditions promoting shrinkage cracking could possibly provide conditions in which polypropylene fibers could reduce permeability by arresting the shrinkage cracks.

Table 5.1 Experimental design.

Binder Content	Fiber Volume Fraction (%)	
	0.0	0.1
0 %	6 Specimens	6 Specimens
B %	6 Specimens	6 Specimens

B = 25 for Fly Ash and Slag, 10 for Silica Fume, and 10% of weight of cement Latex.

Table 5.2 Mix proportions, (lb/yd^3)*

Matrix Composition	V_f (%)	Cement	Coarse Agg.	Fine Agg.	Water	Pozzolan or Latex	AEA	Sup.
Cement	0.0	676	1690	1351	271	---	0.339	---
	0.1	666	1663	1330	298	---	0.332	---
Cement + 25 % F A	0.0	492	1643	1314	295	164.3	1.083	0.345
	0.1	492	1641	1313	295	164.1	0.984	0.394
Cement + 25 % Slag	0.0	506	1685	1397	270	168.5	0.657	---
	0.1	504	1678	1390	276	167.8	0.504	---
Cement + 10 % S F	0.0	495	1655	1321	298	66.1	0.893	1.786
	0.1	495	1653	1321	297	66.1	0.893	0.952
Latex (10 % of Cement)	0.0	679	1698	1358	190	76.9	---	---
	0.1	679	1698	1358	204	76.9	---	---

* 1 lb/yd^3 = 1.685 Kg/m^3, V_f = Fiber Volume Fraction, AEA = Air Entrained Agent, Sup. = Superplasticizer, FA = Fly Ash, and SF = Silica Fume.

Table 5.3 Permeability test results; phase I.

V_f (%)	Matrix Composition			
	Cement	Cement + Fly Ash	Cement + Silica Fume	Cement + Slag
0.0	3770, 5231, 3133 4962, 3437, 4398	7338, 5069, 3727 6044, 6413, 7270	1164, 1184, 1492 1252, 1072, 1230	2064, 2634, 2329 2317, 2583, 2382
0.1	3770, 5231, 3133 4962, 3437, 4398	5078, 6460, 4821 7205, 7185, 6155	1274, 1089, 1971 1943, 1462, 1312	2404, 3261, 2942 2867, 2785, 2853

Table 5.4 Permeability test results; phase II.

Latex (%)	Fiber Volume Fraction (%)	
	0.0	0.1
0	3770, 5231, 3133, 4962, 3437, 4398	3770, 5231, 3133, 4962, 3437,4398
10	809, 780, 939, 790, 539, 815	748, 802, 872, 786, 777, 653

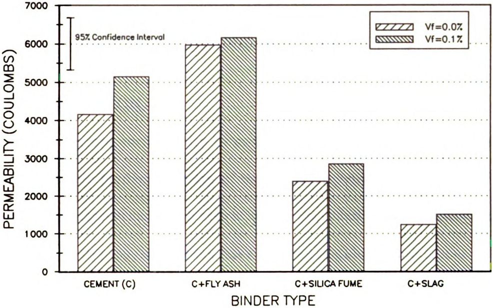


Figure 5.1 Effects of pozzolans on permeability of plain and fibrous concrete

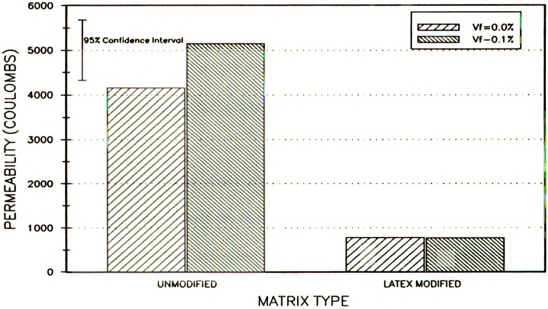


Figure 5.2 Effects of latex polymer on permeability of plain and fibrous concretes.

CHAPTER VI

PLASTIC SHRINKAGE CRACKING

6.1 INTRODUCTION

When concrete surfaces dry at early ages, plastic shrinkage cracks form before the concrete hardens. Drying of the surface occurs when the rate of water loss from the surface exceeds the rate at which the bleed water is made available to the surface. Polypropylene fibers have become popular in the recent years for the reinforcement of concrete materials, mainly due to their effectiveness in reducing cracking at early ages under the effects of restrained plastic shrinkage.

Reducing the rate of evaporation is the key approach to reducing the plastic shrinkage cracks during the construction of concrete slabs in dry conditions. It is likely, however, that under given evaporation conditions, the extent and severity of plastic shrinkage cracking may be increased by certain construction practice, namely finishing operations (screeding rate and direction, bullfloating, floating, and troweling).

The main thrust of this phase of research was to produce a comprehensive set of experimental data, based on the practice of concrete slab construction, in order to derive statistically reliable conclusions regarding the effects of low volume fractions of collated fibrillated polypropylene fibers on the plastic shrinkage cracking of concrete slabs finished by different construction methods.

This work was motivated by the limited test data reported on the plastic shrinkage cracking of concrete materials; the available test data generally deal with fine aggregate mortars which due to size effects may behave differently from course aggregate concrete materials.

6.2 EXPERIMENTAL PROGRAM

Plastic shrinkage cracking of polypropylene fiber reinforced concrete was investigated in two phases. In the first phase, four variables were considered each at two levels, in order to assess their effects on plastic shrinkage cracking of concrete. These four variables and their corresponding levels are given below:

a) Fiber Volume Fraction; V_f (%)	(1) 0.0	(2) 0.1
b) Screeding Speed; SS, ft/min (m/min.)	(1) 3 (2.74)	(2) 12 (10.97)
c) Finishing (Floating and Troweling); Fin	(1) Without	(2) With
d) Screeding Direction; SD	(1) Long Side	(2) Short Side

A 2 x 2 x 2 factorial combination of the first three variables was considered; the screeding direction (SD) was used as a blocking variable to form a randomized block design of experiments. The fact that screeding direction (based on the reported data which were also confirmed in this investigation) has only a secondary effect of simply changing the direction of cracking was the underlying reason to select it as a blocking variable in order to enhance the sensitivity of the statistical analysis. Table 6.1 presents the experimental design for this phase.

In phase II, the effects of polypropylene fiber volume fraction and length on plastic shrinkage cracking were assessed experimentally. Based on the phase I test results, the most critical conditions to produce plastic shrinkage cracking (higher-speed screeding without finishing) were chosen to be applied for phase II. A 2 x 3 fractional design of experiments (Table 6.2) with fiber length, 0.50 and 0.75 in. (13 and 19 mm), and fiber volume fraction, 0.05%, 0.10% and 0.20%, as the variables was adopted for this phase of the investigation.

The basic concrete mix constituents were cement, coarse aggregate with maximum aggregate size of 0.5 in. (13 mm), fine aggregate, and water. A brief description of the materials was given in section 3.3.1. The mix proportions for all panels are cement:coarse aggregate:fine aggregate:water of 1:2.5:2.0:0.47 (see Table 6.3). The designated water-cement ratio was selected to produce plastic shrinkage cracking in the specific conditions of this investigation [temperature of 75-80 °F (24-27 °C), humidity of 50$\pm$5%, and wind speed of 8 mile/hr (12.8 km/hr)]. The concrete mixtures were mixed using a conventional rotary drum mixer, and the mixing procedures basically followed ASTM C 192-91 (see section 3.3.3). All the panels were casted immediately after mixing, and the tests were conducted following the adopted restrained plastic shrinkage test procedure prescribed in section 3.6.6.

6.3 TEST RESULTS AND DISCUSSION

The formation of plastic shrinkage cracks was monitored by naked eyes; generally, the cracks begin to form within 40-120 min. after starting the fans. The fan was stopped after 5 hours. Subsequently, the crack widths and lengths were measured using optical lenses. Total crack area (TCA) was calculated by multiplying the width of each crack by its length. Characterizing the cracks by their total area, instead of their total length, helps account for the fact that some cracks are simply hairlines while others are much wider.

The rate of evaporation from concrete surfaces was found to range from 0.05-0.65 $lb/ft^2/hr.$ (0.5-0.65 $kg/m^2/hr.$), while the rate of free water evaporation was almost double that amount. The times of setting for plain and polypropylene fiber reinforced concretes are shown in Figure 6.1. The initial and final setting times were decreased by 9% and 27%, respectively with the addition of polypropylene fibers. This reduction is expected to reduce the period of exposure of fresh concrete (prior to setting) to the dry environment, which is responsible for plastic shrinkage cracking. The amount of bleed water for plain and fibrous concretes are shown in Figure 6.2. Due to the addition of polypropylene fibers, there was 18% decrease in the amount of bleed water of concrete; the fibers could be reducing the settlement of heavier mix constituents (e.g. aggregates), thereby reducing the up word movement (and bleeding) of concrete.

6.3.1 Effects Of Construction Operations:

The total crack area and the maximum crack width of plastic shrinkage test panels are presented in Tables 6.4 and 6.5, respectively. A heavily cracked panel (plain, unfinished concrete with high-speed screeding) is compared in Figure 6.3 with a typical fibrous concrete panel (with minimal cracking) after plastic shrinkage cracking test. Due to the relatively large range of the total crack area measurements, resulting form negligible crack widths of polypropylene fiber reinforced panels, transformation was necessary in order to perform a reliable statistical analysis of the total plastic shrinkage crack areas. Square root transformation was found to suitable transformation for the total crack area measurements.

The average values and 95% confidence intervals (in case of maximum crack width) of the total crack areas and maximum crack widths are shown in Figures 6.4 and 6.5, respectively. The average values are obtained from two test results (with two screeding directions), and the confidence intervals represent the random variation in all the transformed test data. Randomized block analysis of variance of the transformed data revealed that screeding speed and finishing (floating and troweling) had significant effects on plastic shrinkage cracking area and maximum crack width at 99% and 95% level of confidence, respectively. Polypropylene fibers were also highly significant in deciding the extent of plastic shrinkage cracking (at 99% level of confidence). There seemed to be significant interaction between construction operations (screeding speed and floating followed by troweling) and polypropylene fibers in deciding the total area of plastic shrinkage cracks. However, screeding speed had no interaction with fibers in deciding the maximum crack width.

Multiple comparison of the test data indicated that in all cases the total plastic shrinkage cracking area in fibrous concrete was significantly less than that of plain concrete. In fibrous concrete, finished panels had similar total crack areas when compared with the unfinished ones, while slow rate of screeding significantly reduced the total plastic shrinkage crack area in finished and unfinished fibrous concrete panels.

Since the plastic shrinkage cracks were hairline cracks in polypropylene fiber reinforced panels, the multiple comparison of the maximum crack widths revealed that maximum crack widths were statistically comparable in all cases in the presence of fibers (irrespective of the finishing operation or screeding speed). Multiple comparison of the maximum crack widths in plain concrete panels confirmed that slower screeding led to narrower maximum crack widths when no finishing was performed. With finishing, however, the screeding rate did not influence the maximum crack width in plain concrete. Finished plain concrete panels showed smaller maximum crack widths than unfinished ones, even at the high rate of screeding.

Polypropylene fibers reduced the total plastic shrinkage crack area by 95% at the most critical conditions (high screeding speed and without finishing). Fibers eliminated any detectable plastic shrinkage cracks at the best conditions (slow screeding speed and with finishing).

6.3.2 Effects of Fiber Volume Fraction and Fiber Length:

Tables 6.6 and 6.7 present the measured total crack area and maximum crack width in the plastic shrinkage tests, respectively. The corresponding average values and 95% confidence intervals (reflecting the random scatter of all test data) are shown in Figures 6.6 and 6.7. Factorial analysis of the test results indicated that fiber length affects the plastic shrinkage crack area and the maximum crack width at 99% and 95% level of confidence, respectively. On the other hand, the specific polypropylene fiber volume fraction (0.05, 0.1 or 0.2%) had no statistically significant effects on the total plastic shrinkage crack area or maximum crack width. Multiple comparison of means indicated that with 0.75 in. (19 mm) fibers the total plastic shrinkage crack areas were less than those obtained with 0.5 in. (13 mm) fibers only at 0.1% and 0.2% fiber volume fractions (but not at 0.05% fiber content). The maximum crack widths were not significantly different, based on the outcomes of multiple comparison; with the two fiber lengths at 0.1% and 0.2% fiber volume fractions; the longer fibers (0.75 in., 19 mm), however, at 0.05% fiber volume fraction had smaller crack widths than the shorter fibers (0.5 in., 13 mm).

On the average, 0.75 in. (19 mm) fibers had 13%, 57% and 55% less crack areas than 0.5 in. (13 mm) fibers at 0.05%, 0.1% and 0.2% fiber volume fraction, respectively. The maximum crack widths with 0.75 in. (19 mm) fibers were, on the average, 47%, 33% and 36% less than those for 0.5 in. (13 mm) fibers at 0.05%, 0.1% and 0.2% fiber volume fractions, respectively.

6.4 SUMMARY AND CONCLUSIONS

The effects of collated fibrillated polypropylene fibers, at 0.1% fiber volume fraction, and construction operations on plastic shrinkage cracking of concrete were investigated experimentally. Subsequently, the effects of different polypropylene fiber volume fractions and lengths were also assessed. Statistical analysis of the data were performed in order to confirm the validity of the following conclusions at 95% (or higher) level of confidence:

1. Polypropylene fibers reduce the total plastic shrinkage cracks and maximum crack width at 0.1% fiber volume fraction.
2. The construction operations (screeding rate and finishing) affect the total plastic shrinkage crack area in plain concrete. However, in the specific case of polypropylene fiber reinforced concrete, only the screeding rate influenced the total crack area, and the effects of finishing operations were not statistically significant.
3. Since polypropylene fiber reinforced concrete is characterized by fine hairline cracks, the maximum plastic shrinkage crack width was not influenced by any of the construction operations (screeding rate and finishing) in fibrous concrete. On the other hand, the maximum plastic shrinkage crack widths of polypropylene fiber reinforced concrete decreased significantly when compared with plain concrete. In plain concrete, higher screeding rates and lack of finishing led to statistically significant increase in the maximum crack width.
4. At the higher rate of screeding and without finishing, different polypropylene fiber volume fractions (0.05%, 0.1% and 0.2%) have statistically similar effects on the total plastic shrinkage crack area and the maximum crack width. Longer fibers (0.75 in., 19 mm), however, produce

less crack areas at 0.1% and 0.2% fiber volume fractions, and smaller maximum crack widths at 0.05% fiber volume fraction, when compared with the shorter (0.5 in., 13 mm) fibers.

Table 6.1 Experimental program phase I, randomized block design.

Screeding Direction (Block)	Fiber Volume Fraction (%)							
	0.0				0.1			
	Screeding Speed (ft/min.)				Screeding Speed (ft/min.)			
	3		12		3		12	
	Finishing		Finishing		Finishing		Finishing	
	Without	With	Without	With	Without	With	Without	With
Long	---	---	---	---	---	---	---	---
Short	---	---	---	---	---	---	---	---

Table 6.2 Experimental program phase II, 2 x 3 factorial design.

Fiber Length (in.)	Fiber Volume Fraction (%)		
	0.05	0.10	0.20
0.50	2 Panels	2 Panels	2 Panels
0.75	2 Panels	2 Panels	2 Panels

Table 6.3 Mix proportions; (lb/yd^3)*

Cement	Coarse Aggregate	Fine Aggregate	Water
650	1625	1300	306

* 1 lb/yd^3 = 1.685 kg/m^3.

Table 6.4 Total cracked area for plastic shrinkage cracking test results in experimental program I (in.^{2}).

Screeding Direction (Block)	Fiber Volume Fraction (%)							
	0.0				0.1			
	Screeding Speed (ft/min.)				Screeding Speed (ft/min.)			
	3		12		3		12	
	Finishing		Finishing		Finishing		Finishing	
	Without	With	Without	With	Without	With	Without	With
Long	0.484	0.039	1.225	0.262	0.001*	0.006	0.057	0.006
Short	0.302	0.031	0.987	0.229	0.023	0.001*	0.047	0.009

* = The actual value is zero, this number was chosen for analysis purposes; 1 in. = 25.4 mm.

Table 6.5 Maximum crack width for plastic shrinkage cracking test results in experimental program I (in.).

Screeding Direction (Block)	Fiber Volume Fraction (%)							
	0.0				0.1			
	Screeding Speed (ft/min.)				Screeding Speed (ft/min.)			
	3		12		3		12	
	Finishing		Finishing		Finishing		Finishing	
	Without	With	Without	With	Without	With	Without	With
Long	0.018	0.006	0.059	0.006	0.0001*	0.004	0.006	0.002
Short	0.014	0.003	0.003	0.004	0.004	0.0001*	0.004	0.003

* = The actual value is zero, this number was chosen for analysis purposes; 1 in. = 25.4 mm.

Table 6.6 Total cracked area for plastic shrinkage cracking test results in experimental program II (in.^{2}).

Fiber Length (in.)	Fiber Volume Fraction (%)		
	0.05	0.10	0.20
0.50	0.044 0.051	0.054 0.036	0.047 0.029
0.75	0.038 0.034	0.020 0.019	0.012 0.023

1 in. = 25.4 mm.

Table 6.7 Maximum crack width for plastic shrinkage cracking test results in experimental program II (in.).

Fiber Length (in.)	Fiber Volume Fraction (%)		
	0.05	0.10	0.20
0.50	0.008 0.007	0.008 0.004	0.006 0.004
0.75	0.004 0.004	0.004 0.004	0.003 0.003

1 in. = 25.4 mm.

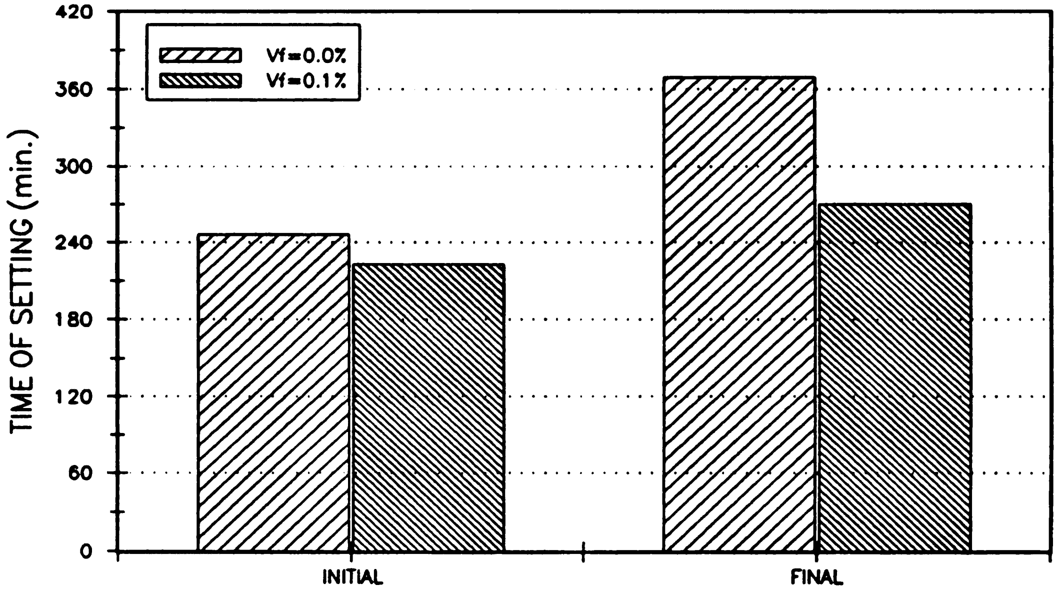


Figure 6.1 Time of setting for plain and fibrous concretes.

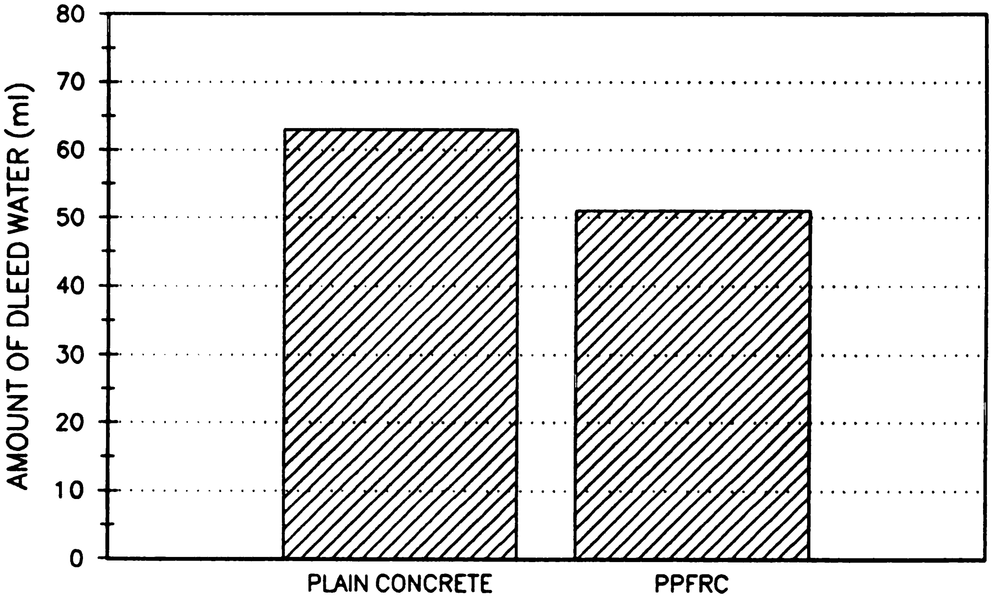
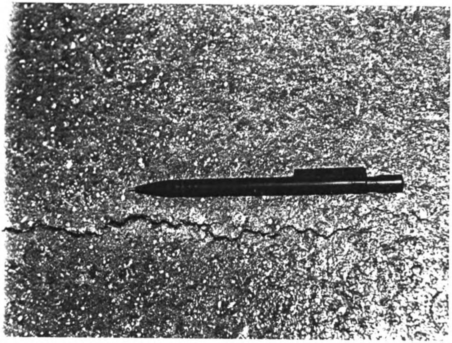
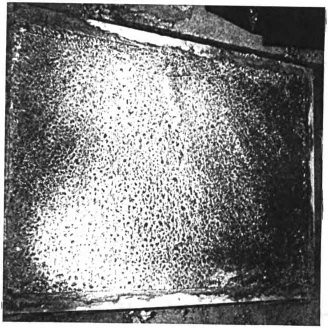


Figure 6.2 Bleeding test results.



(a) Plain Panel.



(b) Fibrous panel.

Figure 6.3 Comparison of a heavily cracked panel with a fibrous one.

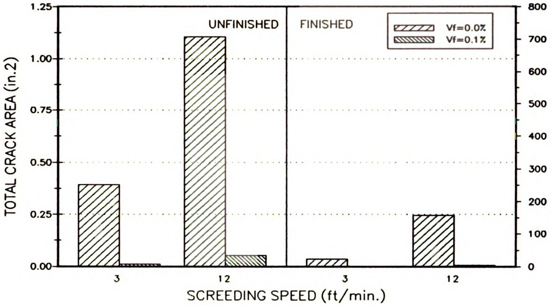


Figure 6.4 Effects of construction operations and fiber volume fraction on total plastic shrinkage crack area.

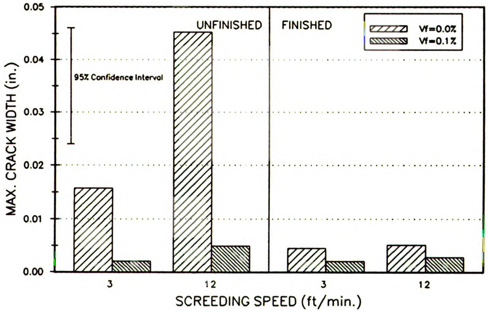


Figure 6.5 Effects of construction operations and fiber volume fraction on max. plastic shrinkage crack width.

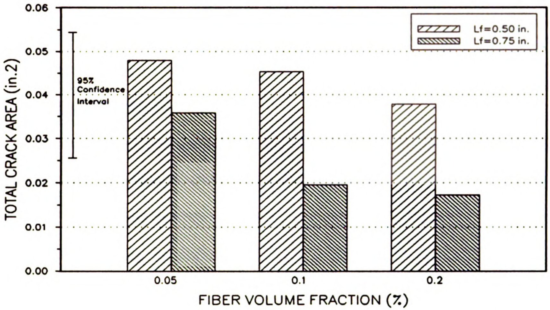


Figure 6.6 Effects of fiber volume fraction and length on total plastic shrinkage crack area.

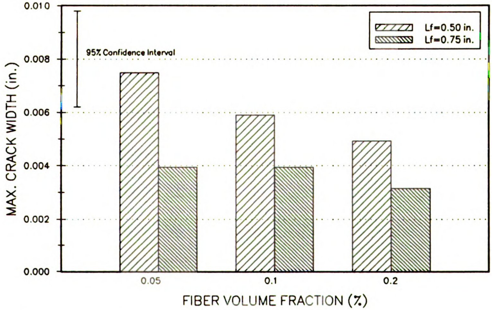


Figure 6.7 Effects of fiber volume fraction and length on max. plastic shrinkage crack width.

CHAPTER VII

SUMMARY AND CONCLUSIONS

7.1 INTRODUCTION

The effects of polypropylene fibers on some key properties of concrete materials were investigated. Different mix compositions, fiber volume fractions, and fiber lengths were considered. Factorial design of experiments was used as basis for investigating the effects of different variables on material performance. A summary of the topics dealt with in this research along with the conclusions derived based on analysis of variance on the statistical analysis of test results are presented in this chapter. Sufficient replicated test data were produced in order to (at high powers of analysis of variance) confirm the validity of the conclusions at 95% (or higher) level of confidence.

7.2 MECHANICAL PROPERTIES

The effects of collated fibrillated polypropylene fibers on the compressive and flexural behavior, and impact resistance of conventional concrete materials and concrete incorporating different pozzolanic and polymeric admixtures were investigated experimentally. Statistical analysis of variance revealed that:

1. Polypropylene fibers have no statistically significant effects on the compressive strength and toughness of conventional concrete at the volume fractions used in this investigation. The presence of silica fume and latex

polymer, however, improved the compressive strength of both plain, and polypropylene fiber reinforced concretes. Latex was also able to increase the compressive toughness in both plain and polypropylene fiber reinforced concretes.

2. Polypropylene fibers significantly improved the flexural toughness. Among the pozzolans, only silica fume increased the flexural toughness of plain and fibrous concretes. The positive effects of latex polymer on flexural toughness in both plain and fibrous concretes could not be confirmed statistically in this study.
3. Polypropylene fibers increased the first-crack and failure impact resistance of concretes reinforced with different fiber volume fractions. The impact resistance at failure was increased, on the average, by 48%, 62%, 171% and 90% with the addition of 0.05, 0.1, 0.2 and 0.3% fiber volume fraction, respectively, for fiber length of 0.75 in (38 mm).
4. While Pozzolans generally reduced the impact resistance of concrete, the positive interactions between polypropylene fibers and pozzolans (in the sense that fibers were more effective in the presence of pozzolans) lead to improved impact resistance of plain and fiber reinforced concretes.
5. The failure impact resistance of latex modified concrete was increased by an average of 158% with the addition of polypropylene fibers at 0.1% volume fraction.

6. Different commercially produced Polypropylene Fiber types behaved similarly in affecting the impact resistance at 0.1% fiber volume fraction. Steel fibers also had comparable impact resistance at 0.1% fiber volume fraction.

7.3 PERMEABILITY CHARACTERISTICS

The effects of collated fibrillated polypropylene fibers, at 0.1% volume fraction, on the chloride permeability of concrete materials incorporating different types of pozzolans and latex were investigated experimentally. Statistical analysis of variance indicated that:

1. While pozzolans generally reduce concrete permeability, polypropylene fibers have no statistically significant effects on the chloride permeability of concrete. The generally positive effects of pozzolans on permeability would be evident to a similar extent in plain and polypropylene fiber reinforced concretes.
2. Latex modified concrete is known for its very low permeability; polypropylene fibers have no statistically significant effects on the chloride permeability of latex modified concrete.

It is worth mentioning that the field conditions promoting shrinkage cracking could possibly provide circumstances in which polypropylene fibers could reduce permeability by arresting the shrinkage cracks.

7.4 PLASTIC SHRINKAGE CRACKING

The effects of collated fibrillated polypropylene fibers, at 0.1% fiber volume fraction, and construction operations on plastic shrinkage cracking of concrete were investigated experimentally. The effects of different polypropylene fiber volume fractions and lengths were assessed subsequently. Statistical analysis of the data were performed in order to confirm the validity of the following conclusions at 95% (or higher) level of confidence:

1. Polypropylene fibers reduce the total plastic shrinkage cracks and maximum crack width at 0.1% fiber volume fraction.
2. The construction operations (screeding rate and finishing) affect the total plastic shrinkage crack area in plain concrete. However, in the specific case of polypropylene fiber reinforced concrete, only the screeding rate influenced the total crack area, and the effects of finishing operations were not statistically significant.
3. Since polypropylene fiber reinforced concrete is characterized by fine hairline cracks, the maximum plastic shrinkage crack width was not influenced by any of the construction operations (screeding rate and finishing) in fibrous concrete. On the other hand, the maximum plastic shrinkage crack widths of polypropylene fiber reinforced concrete decreased significantly when compared with plain concrete. In plain concrete, higher screeding rates and lack of finishing led to statistically significant increase in the maximum crack width.

4. At the higher rate of screeding and without finishing, different polypropylene fiber volume fractions (0.05%, 0.1% and 0.2%) have statistically similar effects on the total plastic shrinkage crack area and the maximum crack width. Longer fibers (0.75 in., 19 mm), however, produce less crack areas at 0.1% and 0.2% fiber volume fractions, and smaller maximum crack widths at 0.05% fiber volume fraction, when compared with the shorter (0.5 in., 13 mm) fibers.

While improvements in flexural strength and permeability, in this laboratory study, could not be confirmed statistically, the elimination of plastic shrinkage cracks was confirmed at a high level of confidence. The impact resistance and flexural toughness were also improved at 95% level of confidence. In case of field applications where concrete is subjected to restrained plastic shrinkage, permeability is expected to improve by the addition of polypropylene fibers which arrest the plastic shrinkage cracks.

Considering the cost and performance of polypropylene fiber reinforced concrete, it is recommended to use polypropylene fibers at 0.1% volume fraction with fiber length of 0.75 in. (19 mm) for concrete flat work particularly in dry environments. Although slow rate of screeding followed by finishing (after bleeding) helped further reduce plastic shrinkage cracks, finishing operations (floating and troweling) could be eliminated in the presence of polypropylene fibers if theses operations are not necessary for other purposes. Concrete structures subjected to repeated impact loading should be designed using polypropylene fiber reinforced concrete; it is recommended to use 0.2% fiber volume fraction with fiber length of 0.50 in. (13 mm) or 0.75 in. (19 mm), provided that other engineering properties are satisfactory. In case of pozzolans, depending on the specific type, content and chemical composition, the addition of 0.1% fiber volume fraction was found to positively interact with pozzolans to produce better behavior in mechanical properties of concrete. Hence, the use of pozzolans in polypropylene fiber reinforced concrete is highly recommended.

LIST OF REFERENCES

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1. AASHTO T-277-83, "Standard Method of Testing for Rapid Determination of Chloride Permeability of Concrete," Standard Specification for Transportation Materials and Method of Sampling and Testing, Part II, Washington, D.C., 1987, pp.1229-1234.

2. ACI Committee 544, "Measurements of The Properties of Fiber Reinforced Concrete," (ACI 544-2R-88), American Concrete Institute, Detroit, 1988, 8 pp.

3. Ahmed, A.E., "Causes and Control of Cracking in Concrete in Saudi Arabia," Journal of Science Engineering, King Saud University, Vol. 14, No. 2, 1988, pp.329-341.

4. Aitcin, P.C., Laplante, P., and Palme, Y.L., "The Use of Fiber Reinforced Concrete for Highway Rehabilitation," Report # 231, National Research Council of Canada, Boucherville, Quebec, 1985, 78 pp.

5. Al-Tayyib, A.J., and Al-Zahrahi, M.M., "Corrosion of Steel Reinforcement in Polypropylene Fiber Reinforced Concrete Structures," ACI Material Journal, Vol. 87, No. 2, 1990, pp.108-113.

6. Al-Tayyib, A.J., Al-Zahrani, M.M., Rasheeduzzafar, A., and Al-Sulaimani, G.J., "Effect of Polypropylene Fiber Reinforcement on the Properties of Fresh and Hardened Concrete in the Arabian Gulf Environment," Cement and Concrete Research, Vol. 18, No. 4, 1988, pp.561-570.

7. Al-Tayyid, A.J., and Al-Zahrani, M.M., "Use of Polypropylene Fibers to Enhance Deterioration Resistance of Concrete Surface Skin Subjected to Cyclic Wet/Dry Sea Water Exposure," ACI Material Journal, Vol. 87, No. 4, 1990, pp.363-370.

8. Alwahab, R., and Soroushian, P., "Characterization of 'Fiberforce' Collated Fibrillated polypropylene Fibers and Their Application to Concrete," Report submitted to Collage of Engineering, Michigan State University, Dec. 1987,

61 pp.

9. Annual Book of ASTM Standard, Section 4, Vol. 4.02, ASTM, Philadelphia, PA, 1991, 824 pp.

10. Anon, "Fiber Reinforced Concrete," Indian Highways, Vol. 13, No. 12, December 1985, pp.3-5.

11. Anon, "Fiber Reinforced Concrete," from The ACI Library, Concrete International, Vol. 7, No. 3, 1985, pp.64-65.

12. Anon, "Elevated Temperature Study, Fibermesh Polypropylene Fiber Reinforced Lightweight Concrete," Schwein/Christengen Engineering, Ltd., Report # 1112, Feb.5, 1988, 14 pp.

13. Anon, "Polymeric Fiber Reinforced Concrete," Concrete Technology Today, Portland Cement Association, Vol. 10, No. 13, November 1989, pp.1-5.

14. Austin, S., and Robins, P., "A Repair Application of Polypropylene Fiber Reinforced Sprayed Concrete," Proceeding of International Conference on Recent Development on Fiber Reinforced Cement and Concrete, Cardiffe, U.K, September, 1989, pp.21-31.

15. Bailey, J.H., Bentley, S., Mayfield, B., and Pell, P.S., "Impact Testing of Fiber Reinforced Concrete Stair Treads," Magazine of Concrete Research, Vol. 27, No. 92, 1975, pp.167-170.

16. Barr, B., and Lin, K., "General Behavior of Polypropylene Fiber Concrete," Concrete (London), Vol. 16, No. 14, 1982, pp.33-35.

17. Barr, B., and Newman, P.D., "Toughness of Polypropylene Fiber Reinforced Mortar in Compression," Composite, Vol. 16, No. 1, 1985, pp.48-53.

18. Baston G.B., "Fatigue Strength Toughness Indices of Fiber Reinforced Concrete," International Conference on Durability of Concrete; Second CANMET/ACI, ACI Special Publication (SP 126-78), Vol. II, 1991, pp.715-728.

19. Bazomt, Z.P., and Panula, L., "Practical Prediction of Time-Dependant Deformations of Concrete," Part I: Shrinkage. Material and Structure, Vol. 11, No. 65, 1978, pp.307-316.

20. Beaudoin, J.J., Handbook of Fiber Reinforced Concrete, Noyes Publications, New Jersey, 1990, 332 pp.

21. Benthan, K., "Polypropylene Fiber Reinforced Concrete," First Canadian University-industry Workshop on Fiber Reinforced Concrete, Quebec, October 1991, pp.155-163.

22. Bentur, A., and Mindess, S., Fibre Reinforced Cementitious Composites, Elsevier Applied Science, New York, 1990, 449 pp.

23. Bentur, A., Mindess, S. and Vondran, G., "Bonding in Polypropylene Fiber Reinforced Concrete," Cement Composite and Light-Weight Concrete, Vol.11, No. 3, 1989, pp.153-158.

24. Bentur, A., Mindess, S. and Skalny, J., "Reinforcement of Normal and High Strength Concrete With Fibrillated Polypropylene Fibers," Proceeding of International Conference on Recent Development on Fiber Reinforced Cement and Concrete, Cardiffe, U.K, September 1989, pp.229-239.

25. Biddle, D.T., "Fiber Reinforcement in Residential Concrete," Concrete International, Vol. 13, No. 2, 1991, pp.46-47.

26. Carino, N.J., Jennings, H.J., and Snell, L.M., "Properties of Concrete at Early Ages," Cement, Concrete, and Aggregates, Vol. 11, No. 2, 1989, pp.129-131.

27. Carrasquillo, P., "Durability of Concrete Containing Fly Ash for use in Highway Applications," Concert Durability; Proceeding of the Catharine and Bryant Mather International Symposium, ACI Special Publication (SP 100-47), 1987, pp.843-861.

28. Chatterji, S., "Probable Mechanisms of Crack Formation at Early Ages of Concrete; A Literature Survey," Cement and Concrete Research, Vol. 12, 1982, pp.371-376.

29. Chern, J-Ch., and Young, Ch-H., "Study of Factors Influencing Drying Shrinkage of Steel Fiber Reinforced Concrete," ACI Material Journal, Vol. 87, No. 2, 1990, pp.123-129.

30. Clastres, P. and Debicki, G., "Shrinkage Cracking Test of a Cement Paste Reinforced by Synthetic Fibers," International Conference on Recent Development in Fiber Reinforced Cements and Concretes, September 1989, Cardiff, U.K., 10 pp.

31. Currie, B., and Gardiner, T., "Bond Between Polypropylene Fibers and Cement Matrix," The International Journal of Cement and Lightweight Concrete, Vol. 11, No. 1, February 1989, pp.3-9.

32. Dahl, P.A., "Influence of Fiber Reinforcement on Plastic Shrinkage Cracking," Proceeding of International Conference on Recent Development on Fiber Reinforced Cement and Concrete, Cardiffe, U.K, September 1989, pp.435-441.

33. Dahl, P.A., and Holand, I., "Plastic Shrinkage and Cracking Tendency of Mortar and Concrete Containing Fibermesh," Cement and Concrete Research Institute, report # STF65-A85309, September 1985, 14 pp.

34. Dave, N.J., and Ellis, D.G., "Polypropylene Fiber reinforced Cement," International Journal of Cement Composites, Vol. 1 No. 1, May 1979, pp.19-28.

35. Elvery, R.H., and Samari, M.A., "An Examination of the Behavior of Fibers in Reinforced Concrete," Composites, Vol. 7, No. 4, 1976, pp.180-184.

36. Erlin, B., and Holm, J., "Deicer Scaling Studies," Erlin, Holm Associates, Northbrook, Illinois, Report # 855030, September 1985, 8 pp.

37. Fahamy, M.F., and Lovata, N.L., "Chemical treatments of Polypropylene Fiber Surfaces Used in Fiber Reinforced Concrete," TRB, No. 1226, 1989, pp.31-35.

38. Fairweather, A.D., "The Use of Polypropylene Film Fiber to Increase Impact Resistance of Concrete," Prospects for Fiber-Reinforced Construction Materials, An International Building Conference, November 1971, pp.41-44.

39. Fanella, D.A., and Naaman, A.E., "Stress-strain Properties of Fiber Reinforced Mortar in Compression," ACI Journal, Vol. 82, No. 4, 1985, pp.475-83.

40. Forta Fiber Inc., "Concrete Reinforced with Polypropylene Fibers," Concrete Construction, Vol. 28, June 1983, pp.468-470.

41. Gardiner, T., and Currie, B., "Flexural Behavior of Composite Cement Sheets Using Woven Polypropylene Mesh Fabrics," The International Journal of Cement Composite and Lightweight Concrete, Vol. 5, No. 3, 1983, pp.193-197.

42. Gill, J.L., Design and Analysis of Experiments, Vol.I, The Iowa State University Press, 1987, 409 pp.

43. Gjorv, O.E., Baerland, T., and Ronning, M.R., "Abrasion Resistance of High-strength Concrete Pavements," Concrete International, Vol. 12, No. 1,

1990, pp.45-48.

44. Goldfein, S., "Plastic Fibrous Reinforcement for Portland Cement," Technical Report # 1757-TR, U.S. Army Engineer Research and Development Laboratories, Fort Belvoir, Virginia, October 1963, 19 pp.

45. Grzybowski, M. and Shah, S.P., "Shrinkage Cracking of Fiber Reinforced Concrete," ACI Material Journal, Vol. 87, No. 2, 1990, pp.138-148.

46. Grzybowski, M. and Shah, S.P., "Model to Predict Cracking in Fiber Reinforced Concrete Due to Restrained Shrinkage," Magazine of Concrete Research, 1989, Vol. 41, No. 148, pp.125-135.

47. Grzybowski, M., Shah, S., and Karaguler, M.E., "A Model to Predict Restrained Shrinkage Cracking of Fiber Reinforced Concrete," Proceeding of International Conference on Recent Development on Fiber Reinforced Cement and Concrete, Cardiff, U.K, September 1989, pp.334-344.

48. Guirguis, S. and Potter, R.J., "Polypropylene Fibers in Concrete," Technical Report No. TR/F90, Cement of Concrete Association of Australia, May 1985, 22 pp.

49. Hannant, D.J., "The Effect of Changes in Matrix Properties With Time on the Measured and Predicted Long Term Properties of Fiber Reinforced Cement," International Conference on Durability of Concrete; Second CANMET/ACI, ACI Special Publication (SP 126-42), Vol. II, 1991, pp.783-797.

50. Hannant, D.J., "Durability of Cement Sheets Reinforced With Fibrillated Polypropylene Networks," Magazine of Concrete Research, Vol. 35, No. 125, 1983, pp.197-204.

51. Hannant, D.J., Fiber Cement and Fiber Concretes, John Willey & Sons Lit., New York, 1978, 219 pp.

52. Hoff, G., "Durability of Fiber Reinforced Concrete in a Severe Marine Environment," Concert Durability; Proceeding of the Catharine and Bryant Mather International Symposium, ACI Special Publication (SP 100-55), 1987, pp.997-1041.

53. Hughes, B.P., and Fattuhi, N.I., "Predicting the Flexural Strength of Steel and Polypropylene Fiber-Reinforced Cement-based Beams," Composites, Vol. 8, No. 1, 1977, pp.57-61.

54. Hughes, B.P. and Fattuhi, N.I., "Improving The Toughness of High Strength

Cement Paste With Fiber Reinforcement," Composite, Vol. 7, No. 4, 1976, pp.185-188.

55. Idorn, G.M. and Svensson, S.E., "Concrete; the Recent Oil Crisis and the Subsequent 'Durability Crisis' have Changed the Market Structure for Cement," The Construction Specifier, December 1989, pp.100-106.

56. Japanese Concrete Institute, "JCI Standard for Test Methods of Fiber Reinforced Concrete," Report No. JCI-SF-1984, 64 pp.

57. Kahlmann, L.A., "Cracks in Latex Modified Concrete Overlays," TRB Annual Meeting, January, 1991, 18 pp.

58. Kasai, Y. and Yokoyama, K., "Shrinkage and Cracking of Concrete at Early Ages," Canadian Journal of Civil Engineer, Vol. 18, No. 1, 1991 pp. 45-50.

59. Khajuria, A., Bohra, K. and Balagura, P., "Long-Term Durability of Synthetic Fibers in Concrete," International Conference on Durability of Concrete; Second CANMET/ACI, ACI Special Publication (SP 126-46), Vol. II, 1991, pp.851-868.

60. Komlos, k., Brull, L., "Early Age Shrinkage of Fiber Reinforced Cements and Mortars," Proceedings of the International Symposium on Fiber Reinforced Concrete, December 16-19, 1987, Madros, India, pp.4.41-4.50.

61. Kosa, K., Naaman, A.E., and Hansen, W. "Durability of Fiber Reinforced Mortar," ACI Material Journal, Vol. 88, No. 3, 1991, pp.310-19.

62. Kosmatka, S.H., and Panarese, W.C., Design and Control of Concrete Mixtures, Portland Cement Association, 1988, 225 pp.

63. Kraii, P.P., "A Proposed Test to Determine the Cracking Potential Due to Drying Shrinkage of Concrete," Concrete construction, Vol. 30, september 1985, pp.775-778.

64. Kraii, P.P., "Crack Control Methods Welded-Wire Fabric vs. CFP Fibers," Paul P. Kraii Consultant Engineering, Report No. KO21-072085, Los Gates, CA, July 1985, 10 pp.

65. Kraii, P.P., "Proposed Field Test for Drying Shrinkage of Concrete," Concrete Construction, Vol. 29, July 1984, pp.603-665.

66. Kral, S., and Geuaver, J., "Shrinkage and Cracking of Concrete at Early Ages," Advances in Concrete Slab Technology, International Conference,

Dundee, 1979, pp.414-420.

67. Krenchel, H., "Fiber Spacing and Specific Fiber Surface," RILEM Symposium on Fiber Reinforced Cement and Concrete, London, U.K, 1975, pp.69-79.

68. Krenchel, H., and Shah, S., "Restrained Shrinkage Tests With Polypropylene Fiber Reinforced Concrete," Fiber reinforced Concrete Properties and Applications, ACI Special Publication (SP 105), 1987, pp.141-159.

69. Krenchel, H., and Shah, S., "Application of Polypropylene Fibers in Scandinavia," Concrete International, Vol. 7, No. 3, 1985, pp.32-34.

70. Krenchel, H., and Jensen, H.W., "Organic Reinforcing Fibers for Cement and Concrete," RILEM Symposium in Fibrous Concrete, 1980, pp.87-98.

71. Krenchel, H., and Hnasen, A., "Durability of Polypropylene Fibers in Concrete," Concert Durability; Proceeding of the Catharine and Bryant Mather International Symposium, ACI Special Publication (SP 100-23), 1987, pp.143-153.

72. Laphante, P., Aitcin, P.C., and Vezina, D., "Abrasion Resistance of Concrete," Journal of Material in Civil Engineering, Vol. 3, No. 1, Feb. 1991, pp.19-28.

73. Lerch, W., "Plastic Shrinkage," ACI Journal, Vol. 54, No. 2, 1957, pp.797-802.

74. Litvin, A., "Properties of Concrete Containing Polypropylene Fibers," Report to Wire Reinforce Institute, January 1985, 5 pp.

75. Liu, T.C., "Abrasion Resistance of Concrete," ACI Journal, Vol. 78, No. 5, 1981, pp.341-351.

76. MacDonald, C.N., "Durability Comparisons of Fiber Reinforced Concrete in Chemical Plant Applications," International Conference on Durability of Concrete; Second CANMET/ACI, ACI Special Publication (SP 126-41), Vol. II, 1991, pp.773-782.

77. Mai, Y.W., Andonian, R., and Cotterell, B., "Thermal Degradation of Polypropylene Fibers in Cement Composites," International Journal of Cement Composite and Lightweight Concrete, Vol. 4, No. 3, 1980, pp.149-155.

78. Majumdar, A.J., "Properties of Fiber Cement Composite," RILEM

Symposium on Fiber Reinforced Cement and Concrete, London, U.K, 1975, pp.279-313.

79. Malisch, W.R., "How Well Do Polypropylene Fibers Control Cracking," Concrete Construction, Vol. 31, April 1986, pp.371-377.

80. Malisch, W.R., "Polypropylene Fibers in Concrete, What Do The Test Tell us," Concrete Construction, Vol. 31, April 1986, pp.363-368.

81. Malmberg, B. and Skarendahl, A., "Method of Studying the Cracking of Fiber Concrete Under Restrained Shrinkage," RILEM Symposium on Fiber-Reinforced Cement and Concrete, London, U.K, 1975, pp.173-79.

82. Mangat, P.S., Monarakis, G., and Azari, M.M., "Theory for Early Age Shrinkage of Fiber Reinforced Cement Composites," Proceedings of International Conference on Recent Development on Fiber Reinforced Cement and Concrete, Cardiffe, U,K, September 1989, pp.188-199.

83. Mangat, P.S. and Azari, M.M., "Shrinkage of Steel Fiber Reinforced Cement Composites," Materials and Structures, No. 21, 1988, pp.163-171.

84. Mehta, P.K., Concrete Structure; Properties and Materials, Prentice-Hall, New Jersey, 1986, 450 pp.

85. Miller, M.M., "Concrete Residence in Fiber Reinforced; A Home With a View," Concrete International, Vol. 11, No. 7, 1989, pp.28-29.

86. Mindess, S., and Young, J.F., Concrete, Prentice-Hall, New Jersey, 1986, 671 pp.

87. Mindess, S., and Vondran, G., "Properties of Concrete Reinforced with Fibrillated Polypropylene Fibers Under Impact Loading," Cement and Concrete Research. Vol. 18, 1988, pp.109-115.

88. Mindess, S., Banthia, N., and Bentur, A., "The Response of Reinforced Concrete Beams with a Fibre Concrete Matrix to Impact Loading," International Journal of Cement Composite & Light-Weight Concrete, Vol. 8, No. 3, 1986, pp.165-170.

89. Mobasher, B., and Mitchell, T.M., "Laboratory Experience With the Rapid Chloride Permeability Test," Permeability of Concrete, ACI Special Publication (SP 108-17), 1988, pp.117-144.

90. Mobasher, B., Stang, H., and Shah, S.P., "Micro-cracking in Fiber

Reinforced concrete," Cement and Concrete Research, Vol. 20, 1990, pp.665-676.

91. Mobasher, B., Castro-Motero, A. and Shah, S.P., "A Study of Fracture in Fiber-Reinforced Cement-Based Composites Using Laser Holographic Interferometry". Experimental Mechanics, September 1990, pp.286-294.

92. Morgan, D.R., McAskill, N., Richardson, B.W. and Zellers, R.C., "A Comparative Evaluation of Plain, Polypropylene Fibers, Steel Fiber, and Wire Mesh Reinforced Shotcretes," TRB, No. 1226, 1989, pp.78-87.

93. Naaman, A.E., Shah, S.P., and Throne, J.L., "Some Development in Polypropylene Fibers for Concrete," Fiber reinforced Concrete International Symposium, ACI Special Publication (SP 81-18), 1984, pp.375-396.

94. Nelson, R.L., and Kolahowski, J.A., "Freeze/Thaw Resistance of Fiber-Enhanced Concrete," H.H. Holmes Testing Laboratories, Inc., Weeling, Illinois, Report # 98377, June 1984, 4 pp.

95. Neter, J., Wasserman, W., and Kutner, M.H., Applied Linear Statistical Models, Third Edition, IRWIN, Homewood, IL, 1990, 1181 pp.

96. Neville, A.M., Properties of Concrete, Third Edition, Longman Scientific & Technical, U.K., 1981, 779 pp.

97. Neville, A.M., and Brook, J.J., Concrete Technology, Longman Scientific & Technical, U.K., 1987, 438 pp.

98. Ozyildrim, C. and Holstead, W., "Resistance to Chloride Ion Penetration of Concrete Containing Fly Ash, Silica Fume, or Slag," Permeability of Concrete, ACI Special Publication (SP 108-3), 1988, pp.35-61.

99. Padron, I., and Zollo, R.F., "Effect of Synthetic Fibers on Volume Stability And Cracking of Portland Cement Concrete and Mortar," ACI Material Journal, Vol. 88, No. 4, 1990, pp.327-332.

100. Pashina, K.A., "Some Comments on Cracking," Concrete Construction, Vol. 31, June 1986, pp.604-607.

101. Peterson, R.G., Design and Analysis of Experiment, Marcel Dekken Inc., New York, 1985, 429 pp.

102. Plante, P., and Biladean, A., "Rapid Chloride Ion Permeability Test: Data on Concrete Incorporating Supplementary Cementing Materials," Fly Ash, Silica

Fume, Slag, and Natural Pozzolans in Concrete, ACI Special Publication (SP 114-30), 1989, pp.626-643.

103. Pollock, D., "Are Concrete's Ills Fully Understood," A Consultant's View, Civil Engineering, Vol. 58, No. 7, 1988, pp.36-37.

104. Ramakrishnan, V., "Materials and Properties of Fiber-Reinforced Concrete," Civil Engineering, Vol. 58, No. 4, 1988, pp.29-40.

105. Ramakrishnan, V., Gollapudi, S., and Zellers, R., "Performance Characteristics and Fatigue Strength of Polypropylene Fiber-Reinforced Concrete," Fiber reinforced Concrete Properties and Applications, ACI Special Publication (SP 105-9), 1990, pp.159-177.

106. Ramakrishnan, V., Wu, G.Y., and Hosalli, G., "Flexural Fatigue, Strength, Endurance, Limit, and Impact Strength of Fiber Reinforced Concretes," TRB, No. 1226, 1989, pp.17-24.

107. Raouf, Z.A., Al Hassani, S.T., and Simpson, J.W., "Explosive Testing of Fiber Reinforced Cement Composites," Concrete, Vol. 10, No. 4, 1978, pp.28-30.

108. Rhodes, K.D., and Katz, J.M., "Small Scale Fire Tests of Fiber-Enhanced Concrete," Underwriters Laboratories Inc., Northbrook, Illinois, Test Report No. R11194/84, April 1985, 5 PP.

109. Rice, E.K., Vondran, G.L., and Kunbargi, H.O., "Bonding of Fibrillated Polypropylene Fibers to Cementitious Materials," Proceeding of Material Research Society Symposium, Vol. 114, 1988, pp.145-152.

110. Richardson, B.W., "High-Volume Polypropylene Reinforcement for Shotcrete," Concrete Construction, Vol. 35, January 1990, pp.33-35.

111. Ritchie, A.G.B., and Mackintosh, D.M., "Selection and Rheological Characteristics of Polypropylene Fibers," Concrete (London), Vol. 13, No. 3, 1979, pp.36-39.

112. Robins, P.J., and Galderwood, R.W., "Explosive Testing of Fiber Reinforced Concrete," Concrete, Vol. 12, No. 1, 1979, pp.26-28.

113. Sanjuan, M.A., Bacle, B., Moragues, A., and Andrade, C., "Plastic Shrinkage and Permeability in Polypropylene Reinforced Mortar," ACI Special Publication (SP 124-7), 1990, pp.125-136.

114. Schrader, E.K., "Impact Resistance and Test Procedure for Concrete," ACI Journal, Vol. 78, No. 2, 1981, pp.141-146.

115. Senbetta, E., and Bury, M.A., "Control of Plastic Shrinkage Cracking in Cold Weather," Concrete International, Vol. 13, No. 3, 1991, pp.49-53.

116. Shah, S.P., "Do Fibers Increase the Tensile Strength of Cement-Based Matrixes," ACI Material Journal, Vol. 88, No. 6, 1991, pp.595-602.

117. Shales, Ch. A., Hover, K.C., "Influence of Mix-Proportions and Construction Operations on Plastic Shrinkage Cracking in Thin Slabs," ACI Material Journal, Vol. 85, No. 6, 1988, pp.495-504.

118. Silmbas, A.S., "Abrasion Resistance of Fibermesh Entrained Concrete for Roads," Skarer, Norway, 7 pp.

119. Smoak, W.G., "Repair of Abrasion-Erosion Damage to Hydraulic Concrete Structures," ACI Convention 1989, Toronto, Canada, 17 pp.

120. Soviero, M.M., "Concrete That Bends," Popular Science, Feb. 1991, pp.82-85.

121. Spencer-Smith, J.L., "Microfibril-Matrix Theory of Drawn Polypropylene," Plastic and Rubber: Materials and Application, May 1976, pp.74-80.

122. Stang, H., Mobasher, B., and Shah, S.P., "Quantitative Damage Characterization in Polypropylene Fiber Reinforced Concrete," Cement and Concrete Research, Vol. 20, 190, pp.540-558.

123. Studinka, J.B., "Asbestos Substitution in the Fiber Cement Industry," The International Journal of Cement and Lightweight Concrete, Vol. 11, No. 2, 1989, pp.73-78.

124. Swamy, R.N., Theodorakopoulos, D.D., and Stavrides, H., "Shrinkage and Creep Characteristics of Glass Fiber Reinforced Cement Composites," International Congress on Glass Fiber Reinforced Concrete, Brighton, U.K, October 1977, pp.76-96.

125. Swamy, R.N. and Stavrides, H., "Influence of Fiber Reinforcement on Restrained Shrinkage and Cracking," ACI Journal, Vol. 76, Part I,No. 3, 1979, pp.443-460.

126. Turton, C., "Use Air on Fiber to Control Plastic Shrinkage," Concrete Construction, Vol. 34, February 1989, pp.233-234.

127. Vittone, A., "Fibrillated Polypropylene Reinforced Cement Based Products," Concrete International, Vol. 9, No. 9, 1987, pp.43-45.

128. Vondran, G., "Making More Durable Concrete With Polymeric Fibers," Concert Durability; Proceeding of the Catharine and Bryant Mather International Symposium, ACI Special Publication (SP 100-23), 1987, pp.337-396.

129. Vondran, G. and Ebster, T., "The Relationship of Polypropylene Fiber Reinforced Concrete to Permeability," Permeability of Concrete, ACI Special Publication (SP 108-5), 1988, pp.85-97.

130. Vondran, G.L., "Polypropylene FRC in Steel Deck Composite Slabs," Structural Material, pp.1-11.

131. Vondran, G.L., "Plastic Fiber Reinforced Concrete," Michigan State University, Concrete Seminar, 1989, pp.8.1-23.

132. Walpole, R.E., and Myers, R.H., Probability and Statistics for Engineers and Scientists, Third Edition, Macmillan Publishing Company, New York, 1985, 639 pp.

133. Walton, P.L. and Majumdar, A.J., "Cement-Based Composites with Mixtures of Different Types of Fibers," Composite, Vol. 6, No. 5, 1975, pp.209-216.

134. Wang, Y., Li, V.C., and Backer, S., "Tensile Properties of Synthetic Fiber Reinforced Mortar," Cement and Concrete Composites, Vol. 12, No. 1, 1990, pp.29-40.

135. Webster, T., "Polypropylene Fibers May Protect Bridge Decks," Road & Bridges Magazine, June 1987, pp.25-26.

136. Whiting, D., "Rapid Measurement of the Chloride Permeability of Concrete," Public Roads, Vol. 45, No. 3, 1981, pp.101-112.

137. Whiting, D., "Permeability of Selected Concretes," Permeability of Concrete, ACI Special Publication (SP 108-11), 198, pp.195-223.

138. Wittman, F.H., "On The Action of Capillary Pressure in Fresh Concrete," Cement and Concrete Research, Vol. 6, 1976, pp.49-56.

139. Yuan, R.L., and Chen, W.F., "Abrasion Test for Fiber Reinforced Concrete," RILEM Symposium on Fiber-Reinforced Cement and Concrete, London, U.K, 1975, pp.531-536.

140. Zellers, R.C., "High Volume Application of Collated Fibrillated Polypropylene Fiber," Proceedings of International Conference on Recent Development on Fiber Reinforced Cement and Concrete, Cardiffe, U,K, September 1989, pp.316-325.

141. Zollo, R.F., Allter, J. and Bouchacourt, G.B., "Plastic and Drying Shrinkage in Concrete Containing Collated Fibrillated Polypropylene Fibers," RILEM Third International Symposium on Development in Fiber Reinforced Cement and Concrete, Sheffield, U.K, Vol. I, July 1986.

142. Zollo, R.F., "Collated Fibrillated Polypropylene Fibers in FRC," Fiber reinforced Concrete International Symposium, Fiber reinforced Concrete International Symposium, Fiber reinforced Concrete International Symposium, ACI Special Publication (SP 81-19), 1984, pp.397-409.

143. Zonsveld, J.J., "Properties and Testing of Concrete Containing Fibers Other Than Steel," RILEM Symposium on Fiber-Reinforced Cement and Concrete, London, U.K, 1975, pp.217-226.

APPENDICES

APPENDIX A

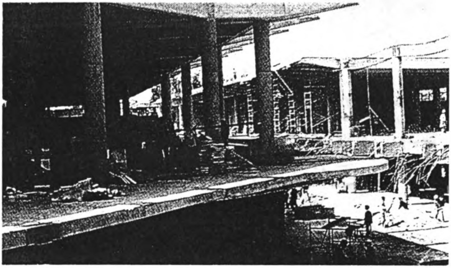

Figure A-1 Multi-level Shopping center, Mexico.

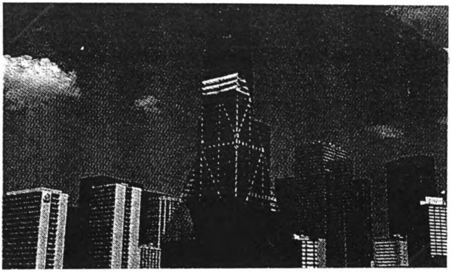

Figure A-2 Sixty-story steel framed Dallas tower, Texas.

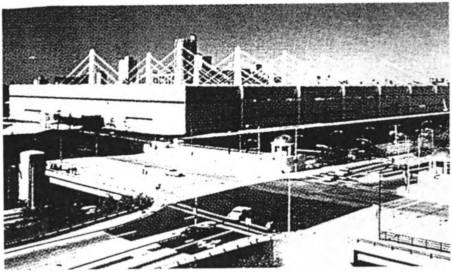

Figure A-3 Chicago's McCormic Annex cacility, Illinois.

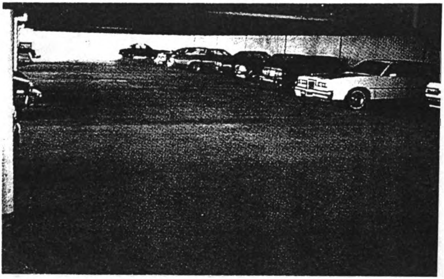

Figure A-4 Parking structure deck, Virginia.

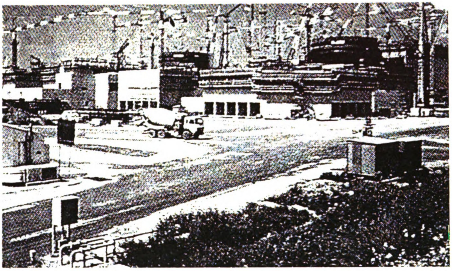

Figure A-5 Power Plant, Italy.

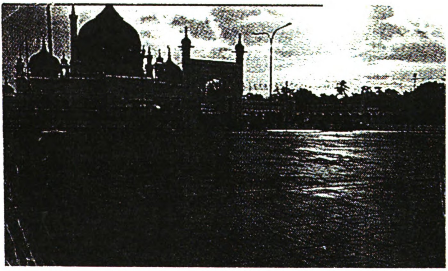

Figure A-6 State Mosque, Malaysia.

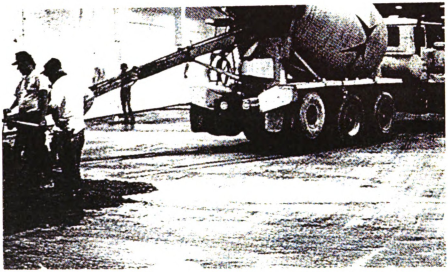

Figure A-7 Chattanooga industrial plant, Tennessee.

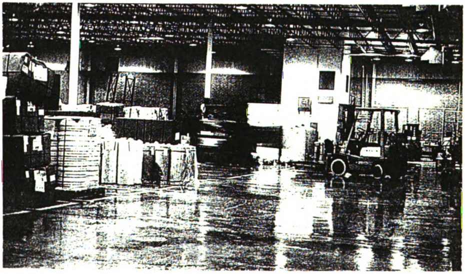

Figure A-8 Hanes Hosiery company, North Carolina.

Figure A-9 Boston area condo, Massachusetts.

Figure A-10 Hawaii island residancial homes, Hawaii.

Figure A-11 Passing lane of a highway near Hershy, Pennsylvania.

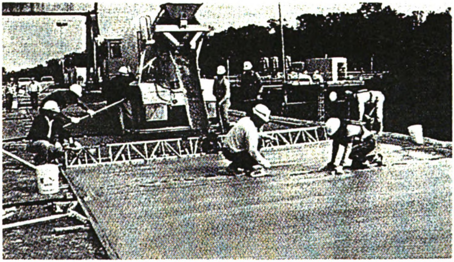

Figure A-12 Marine receiving dock, Louisiana.

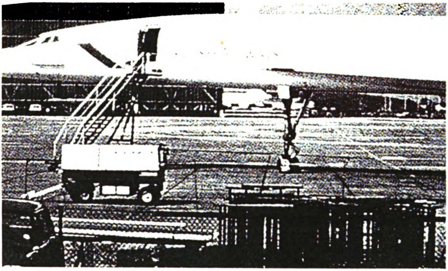

Figure A-13 Heathrow airport, United Kingdom.

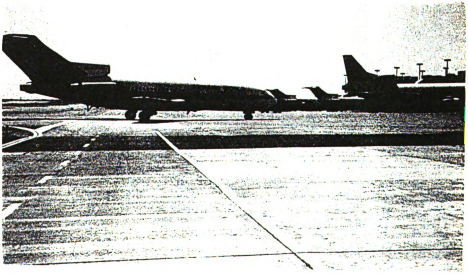

Figure A-14 Lambert-St. Louis international airport, Missouri

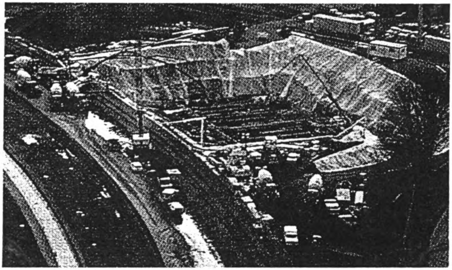

Figure A-15 Water and waste treatment Plant, Wasington.

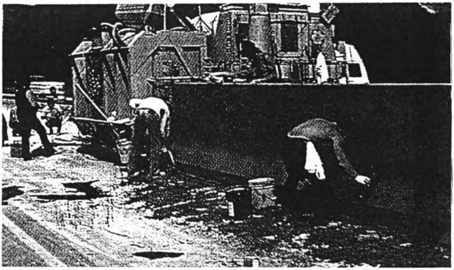

Figure A16 Highway concrete barrier construction, Georgia.

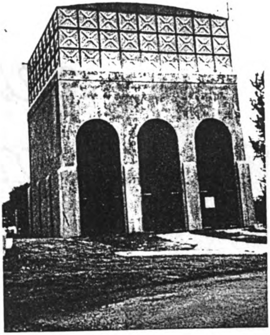

Figure A-17 Budbrooke water tower; warwickshire, England.

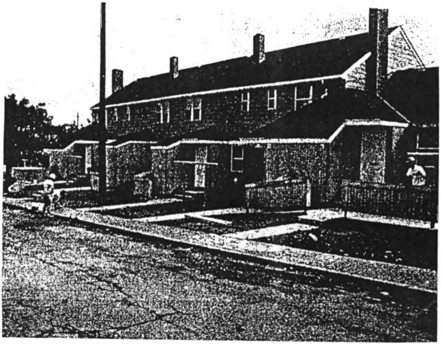

Figure A-18 Sidewalks and curbs in residensial area. Pennsylvania.

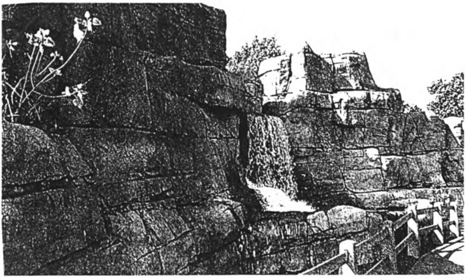

Figure A-19 Cedar Point amusement park, Ohio

Figure A-20 Shotcrete of a canal, Arizona.

Figure A-21 Cylindrical shells, United Kingdom.

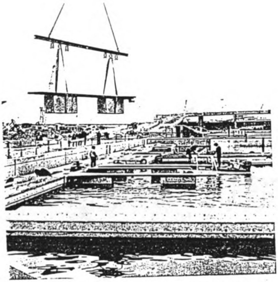

Figure A-22 Flotation units for marines.

Figure A-23 Precast walls construction, Texas.

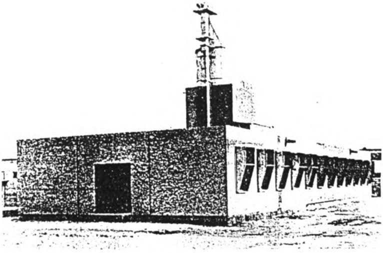

Figure A-24 Window units to carry air-condition units, Bahrain.

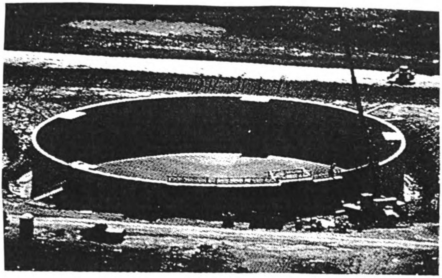

Figure A-26 Water tank construction, Canada.

APPENDIX B

DRYING SHRINKAGE

B.1 DRYING SHRINKAGE TEST

B.1.1 Restrained Drying Shrinkage:

This section describes the restrained shrinkage test procedure adopted in this investigation.

B.1.1.1 Test Specimen:

Ring type specimens have been used by different investigators for restrained drying shrinkage test on concrete or mortar. Depending on the aggregate size and other factors, different ring specimen dimensions have been used. The specimen adopted for use in this research has an internal and external diameter of 7 and 13 in. (178 and 330 mm), respectively, and a thickness of 4 in. (102 mm). Figure B.1 presents the specimen geometry. The concrete ring has a cross-sectional area of 3 x 4 in. (76 x 102 mm) which is sufficiently large to accommodate aggregates with maximum particle size up to 1 in. (25 mm), and fibers up to 2 in. (51 mm) long. The steel ring which has a thickness of 1.25 in. (32 mm) is sufficiently rigid to reduce shrinkage strains (which tend to reduce the ring diameter) to a minimum.

B.1.1.2 Test Procedure:

The specimens were casted in two equal layers, leveled by trowel, and then covered with plastic sheet for 150 minutes. The specimens were then transferred to a control chamber at 68 ± 3 °F (23 ± 1.7 °C) and 40 ± 3% R.H. (or sometimes other drying conditions). The upper and lower sides of the specimens were coated with silicon rubber sealer to prevent moisture loss from top and bottom surfaces and to allow for uniform shrinkage along the width of the specimens. Cracks were observed and measured at 3, 7, 14, 28, and 56 days after the start of drying.

B.2 EXPERIMENTAL PROGRAM

Several mixture at different mix compositions and water cement ratios were tried using the selected test specimen. Table B.1 presents all the mix proportions that were tried in this part of research. It was found that, under the given drying conditions, only the cement paste mix composition (with no aggregates to reduce shrinkage movements) cracked after 5 days; other specimens that contained fine or coarse aggregates did not crack. Several trials were also performed at different specimen hights and thickness, but they also were not successful in the present of aggregates. It is suggested that wider rings should be used for concrete specimens. Two mixes were conducted on 10.0 in. (254 mm) diameter steel ring with a concrete thickness of 1.5 in. (38.1mm), which also did not cracked under the drying conditions used on this investigation, i.e. 68 ± 3 °F (23 ± 1.7 °C) and 40 ± 3% R.H. It should be noted that the instrumentation used for creating the drying environment could maintain the desired levels of temperature and humidity for approximately 10 days. Better control of the drying envirnment over longer time periods could help the formation restrained shrinkage cracks.

Table B.1 Mix proportions (lb/yd^3)*

Cement	Fine Aggregate	Coarse Aggregate	Water
658	1316	1645	309-326
658	1481-1600	1300-1481	325
1011	1011-1517	1011	505.5
860	860-2365	---	344-473
3370	---	---	1618

* 1 lb/yd^3 = 1.685 kg/m^3.

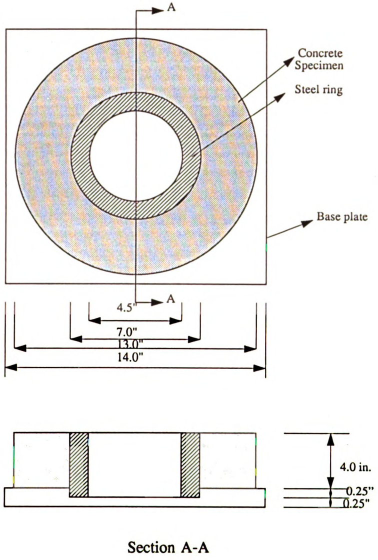

Figure B.1 Drying shrinkage test specimen.