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AN ANALYSIS OF THE INTERFACIAL BOND BETWEEN POLYPROPYLENE REINFORCING FIBER AND CEMENT MATRICES

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An analysis of the interfacial bond between

polypropylene reinforcing fiber

and cement matrices

by

Norbert Lee Lovata

A Dissertation Submitted to the

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CHAPTER 1. INTRODUCTION

The technology of fiber-reinforced building materials can be traced back to antiquity, when straw was used to make bricks. This statement about fiber reinforcement comes from Exodus 5:7, "Ye shall no more give the people straw to make brick, as heretofore: let them go and gather straw for themselves." This technique is still widely used today. All that is necessary is to travel to the American southwest of New Mexico or Arizona and view the modern adobe houses and buildings. In the last century, horse hair was used as a fiber reinforcing for plaster. One of the best preserved examples of this construction technique is the dome ceiling in the Morman Tabernacle located in Salt Lake City, Utah.

Fibers have not only been used in plaster and brick but also in concrete. A review of patent records by Ramachandran et al. (1981) verifies, "Several patents pertaining to steel fiber-reinforced concrete were granted between 1920 and 1935." Ramachandran et al. (1981) goes on to report that, "In recent years, intensive research has resulted in the technology of fibers such as glass, polypropylene and carbon." It appears to date that more research has been published relating to glass and steel fibers than with polypropylene fibers (PPF).

Polypropylene is an organic polymer of low modulus composed of the isotactic (fiberforming) methyl group. The physical properties of this material are: (1) lightweight and (2) has very high tensile strength. Two of the weaknesses of this material identified by research are: (1) lack of interfacial bonding between the fiber surface and the cement matrix, commonly referred to as chemical surface bonding, and (2) susceptibility to creep under tension. If one or both of these identified weaknesses can be improved or eliminated, there could be more extended areas of application for use of this material in the concrete industry.

Preliminary research conducted by this investigator, within the area of interfacial bonding, has clearly revealed that crystalline surface growth can be achieved when polypropylene fibers are first subjected to an oleic acid saturated water bath. This early indication has been identified through the use of the Scanning Electron Microscope. A second chemical, Basic H detergent, has also revealed initial positive results from this preliminary research. Oleic acid and Basic H detergent each revealed higher strength readings in both the compression and flexural tests performed. It should be stated that this preliminary research is not conclusive and complete. Certainly much more should be accomplished in this area before defendable results are published. However, the results of this preliminary research have identified two chemicals, which indicate possible directions in which this research should proceed in relation to surface bonding enhancement.

Problem of the Study

The problem of this study was to demonstrate the importance of research in developing methods to improve the interfacial bond between polypropylene fiber and Type I Portland cement and to also investigate the improved qualities of the interfacial bond.

Purpose of the Study

The purpose of this study was to demonstrate the importance of quality control by improving a secondary reinforcing material, which would ultimately improve construction productivity.

Objectives of the Study

The objectives of this study were:

1. To investigate the interfacial bond between polypropylene secondary reinforcing fiber and the concrete matrix.

2. To determine if the chemical surface treatments of the PPF did in fact improve the strength capabilities of the concrete samples.

3. To determine if crystalline growth was responsible for bond improvement on the PPF due to the bathing process.

4. To analyze the significance of variability in concrete material control tests.

Need for the Study

Polypropylene reinforced fibers have been used in concrete only since 1974. The product was originally designed to be used as a secondary reinforcement for slab on grade application purposes. This product, first produced in Switzerland, has been marketed in the United States since 1978. This synthetic product is relatively new when compared to other structural materials used in building construction. This researcher has been unable to identify any published research indicating an attempt to use chemicals to improve the bonding interface of this low modulus reinforcing material. It is important to note, however, Ramachandran et al. (1981) stated, "The interfacial bond between bond fibre and matrix is one of the most

Hypotheses

Research hypothesis 1:

It is hypothesized there will be no significant difference in the strength capabilities of the control group, which contains no polypropylene fiber reinforcement, when compared to the samples containing untreated polypropylene fibers.

$$H0:\ \mu 1 = \mu 2 \qquad HA:\ \mu 1 \neq \mu 2$$

Research hypothesis 2:

It is hypothesized there will be no significant difference in the strength capabilities of the control group, when compared to the samples containing polypropylene fibers treated with oleic acid.

$$H0:\ \mu 1 = \mu 3 \qquad HA:\ \mu 1 \neq \mu 3$$

Research hypothesis 3:

It is hypothesized there will be no significant difference in the strength capabilities of the control group, when compared to the samples containing polypropylene fibers treated with Basic H detergent.

$$H0:\ \mu 1 = \mu 4 \qquad HA:\ \mu 1 \neq \mu 4$$

Research hypothesis 4:

It is hypothesized there will be no significant difference in the strength capabilities among the treatment group samples, when compared to the control group samples.

$$H0:\ \mu 1 = \mu 2 = \mu 3 = \mu 4 \qquad HA:\ \mu 1 \neq \mu 2 \neq \mu 3 \neq \mu 4$$

where:

HO: = Null hypothesis
HA: = Tested hypothesis
$\mu 1$: = Group means

Assumptions

The study was conducted under the following assumptions:

1. Each material used in the concrete design mix was taken from one randomized source of supply.

2. Chemical additives used in the treated fiber groups were kept constant by batch as was the time that the fibers were soaked in the solution.

3. All samples produced were cured for the same period of time before being subjected to any testing.

Limitations of the Study

1. This study was limited to the use of bagged Type I Portland cement as the primary cementation material in the concrete design.

2. This study was limited to the use of one type of commercially selected polypropylene fiber.

3. The concrete samples produced in this study were limited to concrete cylinders, concrete beams, and tensile briquettes.

Procedure of the Study

The procedure used in this investigation was divided into two parts. The first part of this investigation was to design a statistical matrix for the analyzation of the data, which would then determine the minimum number of concrete samples needed for statistical and actual analysis. Also included in this initial decision was the need to consider the equipment and machines to be utilized when testing and measuring the samples.

The procedures used in determining what actual materials that were included in these test samples were determined by the recommended practices of the American Society for Testing and Materials Part 14 manual and the Concrete Design Manual of the Portland Cement Association.

The concrete design mix that was utilized in this investigation was from the Portland Cement Association 1981 Manual. All aggregates and sand used to cast the samples came from the same source to insure randomization and homogeneity. The Type I Portland cement used was bagged in 94 pound sacks and was selected from the same batch run. Each bag was opened and used when needed during the mixing period. It should be noted all of the sacks of cement were not mixed together to completely insure a homogenously mixed cement.

The second part of this investigation included the actual casting of the samples, the testing of these samples, and the analysis of the data. All samples were then tested according to the recommended procedures of the ASTM Part 14 Manual.

The factor of time was held constant in the manufacture of all test samples. All concrete was mixed in a drum mixer for a duration of ten minutes. Care was taken to use all fresh concrete before initial set took place. Any concrete not placed in the sample molds before the specified time limit of one hour and thirty minutes was discarded. Temperature of the test samples was held constant between 68 and 72 degrees room temperature. All manufacturing and curing of the concrete samples took place indoors to insure the specified constant temperature. The samples were cured in water for a full 28-day cycle before testing. All polypropylene fibers when treated were immersed in their respective chemical baths for a period of ten minutes.

The polypropylene fibers were separated into three groups. The first group of fiber was placed directly into the concrete mixer without any chemical surface treatment. The second group was exposed to the oleic acid treatment and after treatment was placed into the concrete mixer in the same manner as the untreated fibers. The third group was exposed to the Basic H detergent treatment. Its placement into the concrete mixer was the same as the other fiber groups. The fourth group was the control group and did not contain any fiber reinforcing. All materials needed for each treatment group were placed into the concrete mixer at the beginning of each individual mixing cycle.

All bulk materials used in the concrete design were weighed by scale to the nearest pound before being placed into the concrete mixter. All chemicals used in the surface treatment of the fibers were mixed in the proportion of 5 milliliters of chemical to 50 milliliters of distilled water. The polypropylene fibers were mixed into the concrete as recommended by the manufacturer. Manufacturer specifications list the weight of each bag as 750 grams. Manufacturer's specifications called for one bag of fiber to be added with each cubic yard of concrete. Since the laboratory concrete drum mixers are of 5 cubic feet or less, it was more accurate to use the method where each cubic foot of concrete contained 27.77 grams of reinforcing fiber.

The maximum aggregate size for all samples was 3/8 inch as specified by ASTM-39, when using 3-inch by 6-inch compression cylinders. All sand was washed and screened to be free from any foreign debris. Care was taken when selecting aggregate from the stock pile. The rotating method of extraction was used to insure that all samples extracted from the stock pile contained a randomized and homogenious cross section of small and large aggregate. The rotating method of extraction is a method where aggregate is removed from around the base of a pile of aggregate, in a clockwise direction, by use of a shovel.

The water used in this experiment was normal city tap water which was not being processed through a water softener system. Vibration by mechanical means was limited to a 1-second duration per lift for concrete cylinders of 3-inch by 6-inch design. A 2-second maximum vibration duration was recommended by the PCA. Since the flexural beam samples were not of a standard size, the same mechanical vibration durations were used as in the concrete cylinders. This vibration period was chosen because there is approximately the same volume of concrete in the test cylinders as there are in the flexural beams.

The statistical procedure followed in this investigation was a fully randomized split plot factorial design. The control group did not contain any polypropylene fiber reinforcement. The three treatment groups contained polypropylene fibers added as a secondary reinforcement material. Two of the fiber treatment groups contained fibers pre-treated with either oleic acid or Basic H detergent. The third fiber treatment group contained fibers with no chemical interface enhancement. There were seven samples cast for each treatment group or control group. To increase reliability, each test set was replicated. Each concrete test unit was designed to contain 56 concrete cylinders, 56 flexural beams, and 56 tensile briquettes.

The four types of measurements employed were: (1) compression, (2) three-point flexure, (3) tensile, and (4) Scanning Electron Microscopic visual inspection. Each concrete cylinder was tested according to ASTM-39. Each beam was tested according to ASTM-78, three-point flexural testing. Each briquette was tested according to the ASTM C190 alternate method for tensile testing. The Scanning Electron Microscope was utilized to inspect fibers from test samples. The standard procedures used in the Iowa State University Material Analysis and Research Laboratory for selecting and mounting SEM samples were followed throughout this investigation. This visual inspection utilized the comparative analysis technique to ascertain if surface primary crystalline growth was evident. The visual inspection technique was also utilized to determine if any interfacial bonding enhancement between the fiber surface and the cement matrix was present.

The data were analyzed by calculating the mean, standard deviation, and variance for the control group and the treatment groups. The Statistical Analytical Systems (SAS) linear regression ANOVA package model was utilized to calculate the F-statistic and to also calculate any significant interaction between treatment groups.

Definition of Terms

1. Oleic acid (Merck Index of Chemicals, Drugs and Biologicals, 1983) is obtained by the hydrolisis of vegetable fats, primarily from olive oil. It is sepatated from the olive oil by the double fractionation urea adducts process. Its chemical makeup is C 76.54%, H 12.13%, and 11.33%.

2. Basic H (Brookside Farms Laboratory Association, 1976) is a nutrient release containing mostly crude protein, Plus K, K_2O, Na. Ca.

3. There are three possible forms of polypropylene polymer. These are Isotactic, Syndiotactic, and Atactic. The Atactic is not fiber forming or amorphous. Isotactic (fiber forming): methyl groups are all on the same side of plane of zig-zag carbon atom chain. Syndiotactic: methyl groups are on alternate sides of plane of carbon atom chain.

4. Type I Portland Cement (Nasser and Kenyon, 1984), in its simplest form, is made up of four basic compounds: A. tetra-ciumaluminoferrite (celite) 6-9%, B. tri-calcium aluminate 7-14%, C. tri-calcium silicate (alite) 33-35%, D. di-calcium silicate (felite) 18-35%. Type I cement is used for general purpose construction both for above-grade and below-grade applications.

5. Interfacial bonding is simply the bonding that takes place where two materials join one another in a mechanical or chemical state.

6. Crystalline growth is the chemical bonding of two materials at the surface interface. Chemical bonding is evident when a crystalline matrix is observed at the material interface.

CHAPTER 2. LITERATURE REVIEW

This review of literature is organized in chronological order. It is documented by the use of published articles related to reinforcing materials in building construction. This literature review then delineates to specific research relating directly to polypropylene reinforcing fiber (PPF) in concrete and cement matrices.

Historically, reinforcing fibers used in building construction have been of the vegetable origin. These includes straw, grass, and reeds which were used to reinforce the mud in ancient brickwork. The ziggurat or temple pyramid of Agar Quf located near modern Baghdad was built in 1400 B.C. and was constructed with every sixth course or brick containing reeds. This was to facilitate drying and to evenly reduce and distribute the drying process in the mud. According to Cook (1980), the advent of fired clay brick replaced this ancient construction process.

Archeological records indicate gypsum was the first manufactured and commonly used cementious material. This material has been widely used in different forms of masonry, mortar, and plaster. Gypsum plasters, utilizing animal hair as a reinforcing material, were widely used in Europe during the renaissance. This building practice was brought to America and used by the early pilgrim builders, as well as the Spanish plasterers of the American southwest. Horsehair was the most widely utilized reinforcing material in this type of plaster. There are well-preserved examples of this reinforcing application throughout the western world.

Asbestos Cement

At the turn of the twentieth century, asbestos became a commonly used reinforcing material. This was primarily due to what has become known as the Hatschek process of 1900. This was the inclusion of asbestos in a cement matrix. Many applications came about by the mixing of the mineral fiber asbestos and cement. It has been used as a fire retardant to cover steel columns and beams. After it was discovered that asbestos had good insulating value, it was used as a membrane which was wrapped around steam and boiler pipes. Perhaps the most common worldwide application of asbestos has been in the area of cement roofing tiles. This abundant material, when mixed with cement, becomes pliable and easily formed into various roof tile shapes. The European colony countries used these roof tiles from Africa to Southeast Asia.

Chrysotile is a natural mineral which constitutes more than 90% of the world's asbestos reserves and is used to a large extent in the manufacture of asbestos cement. As Hannant (1978) points out:

> Asbestos is a general name for several varieties of naturally occurring crystalline fibrous silicate minerals which possess a rather unique range of physical and chemical properties. The two main groups are the serpentines and the amphiboles.

Hannant goes on to explain that the amphibole group is crocidolite or blue asbestos ($Na_2O \cdot Fe_2O_3 \cdot 3FeO \cdot 8SiO_2 \cdot H_2O$) and is the strongest of the fiber groups. Crocidolite is considered to be the most dangerous form of asbestos from a health viewpoint. Unfortunately, this has been one of the most widely used reinforcing fibers until it was linked with specific forms of cancers.

Welded Wire Fabric

At the present time, steel welded wire mesh is the most commonly utilized secondary reinforcing material in concrete. It is also referred to as welded wire fabric (WWF). It is of the mild steel family with a tensile strength of 60,000 pounds per square inch. Higher tensile strengths can be specified in special applications. The configuration of the mesh is usually a 6-inch square pattern of either six-gage (.1920") or ten-gage (.1350") diameter steel. Other common configurations that can be specified by the structural designer are a 10-inch by 10-inch square or 6-inch by 10-inch rectangle pattern. The ten-gage material is fabricated in rolls. The six-gage heavier stock is delivered in flat mat form. Steel mesh is fabricated from the same drawn wire stock as the smaller diameter reinforcing rod, which is utilized in primary structural concrete design.

In the 1920s, steel mesh began to appear as an experimental material in concrete. However, not until the building boom of the late 1940s did WWF become the largest single secondary reinforcing material in concrete. In the last three decades, WWF has become a specified product in floor slabs, drive approaches to parking lots, and part of interior concrete floor deck systems.

Steel Fibers in Concrete

According to Ramachandran et al. (1981), a review of the U.S. Patent Office during the 1920s revealed several applications for steel fibers to be used as a reinforcing material in concrete. There have been several tests conducted with steel fibers and various fiber configurations.

Since the bonding process that takes place between steel and concrete is only of a mechanical nature, the steel is usually processed with some type of disfigurement to enhance mechanical bonding.

There are three common types of fiber disfigurement commonly employed in steel fibers. The first is the thread or depression of the steel fibers. The second is the bending of the steel fiber ends to create a lugging action. The third is a swagging process to swell the ends of the steel fiber to enhance mechanical bonding. In reviewing the research literature, all three processes work equally well with steel fibers. There have been many successful research projects involving steel fibrillated concrete. There are also several time tested projects utilizing this material.

It has been generally accepted by many in the concrete industry that steel fibers have the best compression capability of the fiber reinforced concretes. Part of this belief is because there are many time tested projects to examine which have steel fibrillated concrete.

There have been many field applications of fibrous concrete pavements, according to Yrjanson and Halm (1973). In 1973, there were three lanes of the Tampa, Florida International Airport paved with steel fibrillated concrete overlay. The overlays were 25 feet wide and 175 feet long, respectively.

In 1972, there were two fibrous concrete pavement projects in the State of Iowa, according to the American Concrete Association's records. One was at the Cedar Rapids Airport taxiway. The second project included several streets and a bridge in a downtown Cedar Rapids residential area.

Also, in late 1972, the most ambitious experimental fibrillated research project completed of that time was in Greene County, near Jefferson, Iowa. The county engineer, Mr. C. Arthur Elliot, reported there was 3.3 miles of surfacing completed as part of a research paving project. There were 41 test sections, including 10 duplicated sections for control. Each section was 400 feet in length. Variables in the project included type, size, and quantity of steel fibers; cement content; and overlay thickness. Research projects of the 1970s have provided information for Yrjanson and Harold J. Halm (1973), Executive Director of the American Paving Association, to make this statement:

> Fibrous concrete is a composite material consisting of a concrete matrix containing a random dispersion of small fibers. The fibers, being closely spaced at random angles, reinforce the concrete matrix in all directions. The fibers not only compensate for the relatively low tensile strength and brittle character of concrete, but also improve other properties of the composite material.

Laboratory research has indicated that among the important changes in the fibrillated properties are a substantial increase in flexural and tensile strength of the concrete. There is also evidence of an increase in the fatigue endurance limit. There is a higher resistance to abrasion and spalling in fibrillated concrete. One of the most important discoveries is the higher impact resistance of fibrillated concrete.

Over a period of time, empirical evidence has revealed that fibrillated concrete has excellent resistance to cracking. In Figure 1 is an example of how fibers work as crack arrestors in concrete.

In the use of steel fibrillated concrete, there are three important aspects involved in the concrete design mix. The first is the aspect ratio

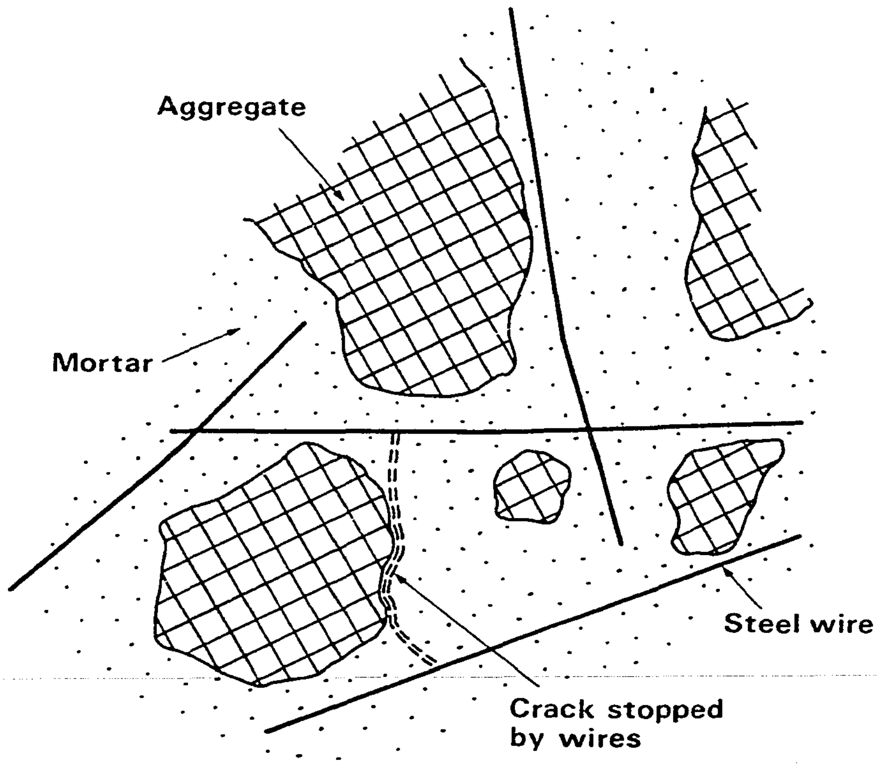


Figure 1. Possible crack-stopping mechanism of steel fibers in concrete

in relationship to aggregate size. Aspect ratio is the length of the steel fiber divided by its diameter. The American Concrete Institute Committee 544 (fibrillated concrete) recommends an aspect ratio of between 30-150. Therefore, the aggregate size will determine the aspect ratio or size of the steel fiber to be used in the concrete design mix.

The second consideration is the concrete to fiber ratio. Hannant (1978) states that 3 to 7% is the recommended weight per cubic yard allowed for acceptable workability and placement of fibrillated concrete.

The third consideration is the need to include additional cement to the concrete design mix as the percent of steel fiber increases. This additional cement is needed to coat the surface area of the added steel fibers.

Hannant (1978) presents an equation which is used to estimate the approximate amount of steel fiber for aggregates of normal density. The equation is:

$$W_f = < \frac{600(1-A_g)}{1/d}$$

where

W_f = weight of fibers as a percentage of the concrete mix which can be compacted with normal site techniques

$A_g = \dfrac{\text{Weight of aggregate greater than 5 MM}}{\text{total weight of concrete}}$

$\dfrac{1}{d} = \dfrac{\text{length}}{\text{diameter}}$ of fiber

The equation is designed to be concerned with only larger aggregate because sand and small aggregate do not affect the workability of the concrete when using fibers in concrete.

There is a host of research reports published relating to the positive effects of steel fibrillated concrete. Conversely, there are also drawbacks to the use of this product. Steel fibers are bulky and require special care during the mixing cycle. It is labor intensive to add steel fibers to the concrete during the mixing cycle. If the fibers are not mixed properly, the concrete will form into balls. Referred to as balling, coarse aggregate and groups of steel fibers form large balls in the wet concrete. This condition causes aggregate separation and places the fibers into an unrandomized pattern, which is precisely what is not wanted in concrete.

With the use of many admixtures in concrete, care must be taken to be sure the steel fibers are not affected by the chemical composition of these admixtures. One example is calcium chloride, which is a common admixture used in concrete. This salt base admixture attacks the steel fibers and causes corrosion to form around the fibers. Edgington (1973) has presented evidence that over a period of time, these fibers fail structurally. As cracks appear in concrete with age, moisture works into these cracks. In cases where salt is used on highways, as in the midwest or along ocean fronts, salt erosion causes the fibers to fail. In some conditions, steel fibers were used in concrete for cosmetic needs. After the steel fibers began to rust and bleed through the concrete, the cosmetic look sought by the architect was lost.

If structural loading is a consideration in the design where steel fibers are to be incorporated, care must be taken to consider the weight added by the steel fibers. This weight differential can be from 40 pounds to 250 pounds per cubic yard of concrete, depending on structural design.

Glass Fibers

Glass fibers have been widely investigated by experimentation but have not been employed in many actual construction building projects. In Britain, some very limited applications of E glass fibers led to structural problems over a short period of time. During the 1950s, the Soviet Union conducted a large-scale investigation as to the potential use of E-glass fibers in concrete. One of the biggest problems originally found with certain types of borosilicate glass fibers in concrete was that the alkaline environment of the cement attacked the glass fibers and eroded them away. Since then, researchers have developed different configurations of glass compositions to combat this characteristic in glass fibers. Majumdar (1983) at the Building Research Institute in England developed alkali resistant fibers containing zirconium.

Two groups of glass fibers, which were investigated and reportedly revealed wide promise, were beryllium oxide and alumina oxide. These fibers proved to be satisfactory in testing but proved to be far too expensive to produce. One pound of brellium oxide cost $113,000.00 to manufacture. In the case of the alumina, the cost was $10,000 per pound. Initial attempts at using nylon and rayon as fiber reinforcements have not proved successful, therefore, research in these areas has received little recent attention.

Polypropylene Fibers

Polypropylene fibers (PPF) have been used in concrete since 1965. Goldfein (1965) suggested to the U.S. Corps of Engineers the inclusion of polypropylene as an admixture in concrete for use in blast-resistant buildings. Early research conducted in this area was through Shell International Chemical Ltd. A British patent was registered in 1968, giving this product the name of Caricrete. One of the early researchers in the field of PPF was J. J. Zonsveld, who published his early research in October, 1970.

PPF, which is used in concrete as a secondary reinforcement, is manufactured in the isotactic configuration. It is extruded through a flat die and then is slit into tape form. It is then monoaxially stretched, which is referred to as "draw ratio." The draw ratio is a measure of the extension which is applied to the fiber during fabrication, and draw ratios of about 8 (eight times its original length) are common for polypropylene film. A molecular orientation results from the stretching and is the cause of the high tensile strength. Consequently, it may be noted that PPF is at its strongest state when designed and placed in concrete with tension as the primary concern.

The raw material, polypropylene, derived from the monomeric C2 H6, is a pure hydrocarbon. According to Zonsvield (1976), its mode of polymerization, its highly molecular weight, and the way it is processed into fibers combine to give PPF many useful properties.

PPF has a sterically regular atomic arrangement in the polymer molecule with high crystallinity. Its regular structure gives it the name isotactic polypropylene. This material has a high melting point of 165 degrees C and has the ability to withstand temperatures over 100 degrees C for short periods of time. This temperature durability is important as a secondary reinforcing material in concrete. Polypropylene is chemically inert, which makes the fibers resistant to most chemicals. If the fibers are exposed to aggressive chemicals, the concrete will be the first to deteriorate.

Since PPF has a hydrophobic surface, no additional water is needed in the concrete design mix. Also, because of this slick surface, there is less chance for balling during the mixing process as compared to steel fibers. Since PPF is drawn or stretched during fabrication, the polymer chain molecules are placed into a parallel orientation which gives it high tensile strengths. Stated in textile terms, its capabilities are 5g/denier, which is equivalent to 400 MN/m squared. Zonsveld (1976) goes on to state that this orientation leaves the film weak in the lateral direction. This opening allows for the wet cement matrix to wrap around the fibers during mixing, which in turn forms a mechanical bonding with the concrete matrix.

PPF has an advantage of being light in weight. Major American PPF suppliers specify its use at approximately one and a half pounds per cubic yard or about 1% by volume per cubic yard of concrete. There is no special mixing requirement necessary for PPF when mixed in the traditional over-the-road concrete mixing truck. Forta Corporation specifies that PPF can be added at the batch plant or on-the-job site prior to the placing of the concrete in its forms.

Just as every material has useful applications, when utilized in a large variety of settings, shortcomings can exist. The same holds true for polypropylene fiber. Even though PPF has a high melting temperature compared to other polymers, it does not withstand heat from fires in structures. When exposed to extremely high temperatures, which is common in fires, PPF melts away and leaves a void in the concrete equal to the volume of the original mixture when produced. In addition, the PPF voids left after a fire create a porosity in the concrete equal to the volume of PPF originally added.

Since PPF has a low modulus of elasticity, a high strain rate occurs before multiple cracking appears. When compared to steel, which has a higher modulus of elasticity, PPF does not react in the same manner as steel. Between steel and concrete, there is a close coefficient of expansion and contraction. Once cracks occur in concrete, the steel reinforcing assumes the total load for the concrete mass. This creates a safety net, so to speak. PPF and concrete react very differently. Because of its low modulus of elasticity, the polypropylene fibers directly assume the load until a pullout occurs on the surface of the fibers. At this point, known as modullus of rupture (MOR), ultimate failure occurs. In some testing, MOR in PPF is higher than in secondary steel reinforcing. It should be noted that there is a larger coefficient of expansion and contraction between PPF and concrete than there is between steel and concrete, which accounts for some of the changes in the behavior of this material.

In Figure 2 is a drawing which depicts the classification of fiber arrangements. As can be viewed in specimen 1D, the fibers are aligned in a single plane, are parallel to the longest side, and are centered in the object. Specimen 2D depicts the fibers in a random pattern but in a single plane at the center of the object. A matting arrangement is presented in specimen 2D. This is a newer configuration of PPF, which has been recently field tested. In the cube marked 3D, or three dimensional, is a specimen which shows how PPF is mixed throughout the concrete matrix. When random fibers are mixed throughout the concrete, a three directional reinforcing matrix develops.

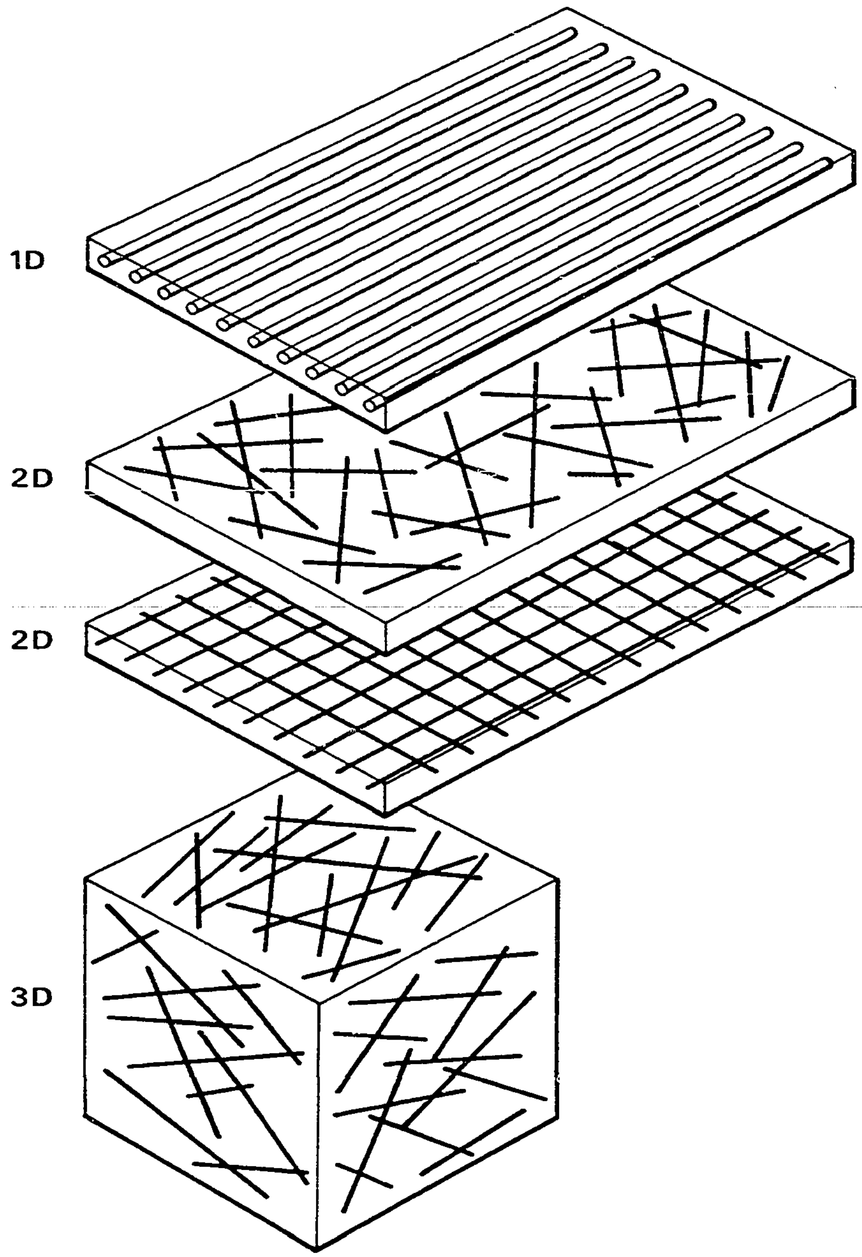


Figure 2. Classification of fiber arrangements

Crack propagation

The subject of crack propagation in concrete matrices utilizing PPF has been investigated. The two most common forms of test procedures employed have been impact testing and fracture toughness testing. It has been proven that polypropylene fibers do work as a crack arrestor in concrete. One of the conclusions of a research project completed by Fattuhi (1983) indicated that after impact testing there is less hairline cracking in polypropylene reinforced concrete as compared to steel fiber reinforced concrete.

In June 1971, the Corps of Engineers conducted a concrete flexural toughness test on airstrip pavements. A 50-foot square, 10-inch thick plain concrete pad was constructed. After 950 passes using the weight of a C5A transport landing gear, the test pad failed. A 4-inch concrete steel fiber reinforced overlay was laid over the failed pavement section. Nine hundred additional repetitions were completed before the first visible cracks appeared in the 4-inch overlay. According to the Corps of Engineers report, after 6,900 additional load repetitions, the test was discontinued. The only cracks that developed were directly over cracks from the initial pavement tested.

In a study conducted by Shah (1983), PPF fiber reinforced concrete beams were tested in a drop-weight, instrumented impact testing machine. The MOR values at high strain rates obtained in impact loading were up to twice that observed at low strain rate (static loading). Shah (1983) goes on to report that the energy absorbed by long steel fiber (2 1/2") reinforced beams was as much as 100 times that as compared to unreinforced beams. Short steel fibers adsorbed 14 times as much impact loading as compared to unreinforced concrete specimens. The PPF reinforced beams absorbed 31 times the impact loading as compared to unreinforced concrete beams.

Initially much of the research and testing of fibers in concrete and cement matrices were involved with compressive testing. It is generally viewed that PPF in concrete is accepted for slab on grade applications. As more empirical evidence has been accumulated in this area, research and field testing have now shifted. Areas of research which are now being addressed are the poor mechanical bonding properties of PPF and the behavior of PPF in flexural situations such as floor systems, beams, and thin concrete sheets.

Flexural behavior

Testing of polypropylene materials in concrete and cement matrices has expanded into many areas of application. Polypropylene has been manufactured into fibers, tapes, and mats. The many variables of this material have led to many avenues of research. The one common important variable that has prevailed throughout this phase of research has been the behavior of PPF in flexural testing and the reactions of this material in field testing.

Since asbestos fibers were found to cause health hazards in some of its applications, PPF now looks like an attractive alternative. Comparative testing has been completed by Hannant (1983) in regard to the use of fibrillated polypropylene networks. This three-year study was conducted to determine the effects of time weathering in relation to the tensile stress of thin sheets of cement composites. The samples tested were strips cut from larger squares. The sample thickness of these test specimens was 6 millimeters. Hannant's 1983 study concluded that the coloring agent used in the PPF mat was not necessary because the cement worked well as a shield against the sun's ultraviolet rays. A second conclusion indicated the tensile stress-strain curves of the composites showed significant differences between the natural weathered samples and the samples stored inside. The modulus of elasticity of the weathered samples increased by 26% in three years, whereas the stored samples did not reveal this change. The weathered pre-cracked samples had also undergone autogenous healing (or a self healing with time). These effects were not noted in the stored samples with the passage of time.

An investigation of the flexural behavior of corrugated composite cements was conducted by Gardiner and Currie in 1983. This investigation included woven polypropylene fabric in a warp and weft configuration to simulate the flexural effects of roofing tiles. Their finding indicated that polypropylene fabric will produce equal to or stronger flexural strengths when compared to open networks of fibrillated fibers. After a period of seven months, there was found to be no deterioration in flexural strength of the composites. This evidence is important from the standpoint of construction. PPF fabric is easier to handle and place when utilized in a free formed concrete form.

According to Nichols (1982), the use of polypropylene fabric for reinforcing in concrete structures is very feasible. In this investigation, there was reported evidence about five different structures that Nichols had constructed utilizing PPF fabric. The structures included a spherical shell, three types of domes, and a rectangular dome. The medium utilized for raising the structures was the use of a balloon system with air pumped into the balloon to support the fabric. Once the structure was inflated, the PPF fabric which was impregnated with cement was moistened and allowed to reach initial setting. After the initial set of the cement composite, the air bag was deflated, and the dome stood on its own. Nicholls also reported the largest dome had a diameter of 17 meters. For farm grain storage, this method of construction can be very competitive with other estimated temporary storage facilities.

Fibrillated concrete applications

There have been reports of several applications utilizing PPF in concrete and cement matrices. Research conducted in Great Britain reports concrete window jambs incorporating PPF have found satisfactory use. According to Krenchel and Shah (1984), corrugated roofing plates using PPF as the main reinforcing material have been produced in Aalborg, Denmark. In Bahrain, there is a single story pre-cast building totally constructed from PPF concrete. Shah also reported that a 101-foot clear span fiber-reinforced shell has been constructed in Stuttgart, West Germany. The average thickness of this structure is 3/8 of an inch. It is thought that this span-to-thickness-ratio holds the world's record for this application.

Summary

Polypropylene fiber (PPF) as a reinforcing material has been researched extensively. There have been efforts to overcome the poor mechanical bonding properties of this material by use of altering the actual fibers through manufacturing techniques. To some extent, this drawback has been overcome. From research efforts to improve the mechanical bonding properties of this material, a stronger fiber has been developed for field applications. There is a broad base of information published regarding the compressive, flexural, and impact behavior of this material.

The construction industry is one which accepts change slowly. Being an independent group, the industry is slow to accept new techniques or materials that cannot be proven safe or cost effective within a short period of time. The research conducted with PPF has followed a traditional route and for the most part has been led by those in the civil and construction engineering disciplines. Those researchers in these disciplines have been given the task to inform the construction industry as to the uses of PPF.

During this investigation of the literature review, it should be noted that not one piece of research was cataloged pertaining to the chemical enhancement of the interfacial bond between PPF and the cement matrix.

CHAPTER 3. METHODOLOGY

Four primary means of investigation were used in this research. Since this research was of an experimental design, testing was conducted utilizing compression, three-point flexural bending, tension, and visual inspection employing the Scanning Electron Microscope (SEM).

The first measure was the compression cylinder test. This provided a quantitative measurement of the effects of the chemical treatment among the three fiber treatment groups and specifically the two chemically treated fiber groups. The purpose of this test was to measure the chemical bonding effects of the polypropylene (PPF).

The second measure was the three-point flexural test using concrete beams. This test utilized both compression and tension differences to measure the modulus of rupture (MOR). The purpose of this test was to measure the flexure or bonding effect of the PPF in both a compression and tensile mode.

The third method of measure was the test of tension. This test was used to measure the creep behavior of the PPF.

The fourth test was a visual inspection using the Scanning Electron Microscope (SEM). This photographic scanning process was utilized to determine if a crystalline growth took place, at the interfacial bond, between the PPF and the concrete matrix.

Method of Measurement

The method of measurement was determined by incorporating three factors, the American Society for Testing and Materials (ASTM) part 14 manual, the equipment available for measuring the samples, and the actual measurement capabilities of the equipment. Working within these parameters, three types of specimen design were chosen. These were compression cylinders, flexural beams, and tensile briquettes. In the case of the flexural beams, 2-inch by 2-inch (4 square inch cross sectional area) by 12-inch length samples were chosen. Due to recent trends of using smaller concrete cylinders, and the equal reliability of smaller cylinders (Nasser and Kenyon, 1984), the 3-inch by 6-inch cylinders were chosen for this experiment. The tensile briquettes tested were of the ASTM standard size with a 1-square inch cross sectional test area.

Determination of Sample Size

ASTM specifications require a minimum of six samples to be cast from a batch and a minimum of two of the samples be tested. This ASTM requirement does not fit minimum requirements for a factorial design statistical model. Therefore, it was decided to cast five samples for each test and to replicate each batch. This procedure was chosen to exceed the minimum requirements for the ASTM specification and also to improve the precision of the statistical and SEM analysis.

Selection of Materials

Steps were taken at the time of procuring concrete materials to insure the quality and grade of the materials utilized in this study. The aggregates chosen for casting came from a Department of Transportation approved gravel and sand pit in Black Hawk County, Iowa. The sand and aggregate were furnished free of charge by Shirey Concrete Co. of Waterloo, Iowa. The type I bagged cement selected for the research came from one single supplier. The local retail supplier confirmed a delivery date of within 30 days before use in this experiment. Upon delivery, all materials needed for the project were moved indoors to protect them from the natural elements.

Fiber Treatment Preparation

The bundles for the three fiber treatment groups were weighed to the nearest 1/10 gram before being treated in their respective baths. The American Concrete Institute (ACI) concrete laboratory mix chosen for this experiment yields .81 cubic feet of concrete. Therefore, according to the PPF manufacturer's specifications, each concrete test batch required 22.43 grams of fiber for each treatment group. This is one-tenth of 1% by volume of the total concrete mix. Prior to batch mixing, the two fiber groups were soaked in their respective mixed liquids for a period of 10 minutes and then dried. They were then re-weighed to determine if there had been any change in the fiber weight due to the chemical treatment. There was no measurable difference in either fiber batch weight after being exposed to the chemical treatments.

The first fiber treatment group used fiber as it was delivered directly from the manufacturer. The fiber supplier for this research project was Forta-Fibre Inc. of Grove City, PA. The second fiber treatment group had fiber soaked in a solution of 1 part Basic H detergent to

10 parts distilled water. The weighed fibers were then soaked in this solution for ten minutes, removed, and air-dried. The drying process time took approximately two hours. The fibers were then reweighed. There was no measurable difference in the fiber weight due to the soaking process. The third treatment fiber group contained fibers soaked in an oleic acid bath.

It should be noted, however, that the oleic acid was processed by use of a separatory funnel. The oleic acid was mixed in a solution of 1 part oleic acid to 10 parts of distilled water. The two liquids were mixed vigorously in the separatory funnel and allowed to stand till a clear solution settled in the bottom of the funnel. The clear diluted oleic acid solution was then drained off and later used as one of the treatment chemicals.

Concrete Design

The concrete design mix chosen is one widely used by the Portland Cement Association and recommended by the ASTM-C31. The batch design is listed in Table 1. The concrete mix chosen for this experiment was of a low water to cement ratio design. One slump test was performed in a control group test batch and was found to be satisfactory, yielding a 2-inch concrete slump test.

Sample Inspection

Each batch of concrete samples was inspected upon removal from the forms and prior to the 28-day curing period. This procedure was utilized to insure there was no honeycombing or visible surface cracking. From each

Table 1. Concrete design mix

Water	5.46 lbs
Cement	16.50 lbs
Coarse aggregate	58.65 lbs
Fine Aggregate	38.73 lbs
Total Weight	119.34 lbs

concrete batch, additional samples were cast to insure that the minimum number required for testing were met. All additional samples, in all treatment groups, passed the pre-test inspection, so it was arbitrarily determined to increase all sample groups to seven. This procedure improved the statistical test reliability, increased actual number of samples for testing, and increased the number of samples for visual inspection with the use of the Scanning Electron Microscope (SEM) equipment.

Equipment Calibration

Two machines were used to analyze the samples. The first was the soiltest tensile machine Veratester Model 30-M. The manufacturer recommends this machine be calibrated once a year. This tensile machine was calibrated two months prior to being used in this experiment. This machine is designed primarily for compression testing.

The second machine used was the Vega tensile machine Model 10-K. This machine does not have a recommended calibration period but was calibrated within the last 12 months.

Instrumentation

The soil test machine comes equipped with two dials. The first is a low level dial with measurement lines at 50 pound intervals, starting from 0 to 10,000. The second dial is a 100 pound dial interval, starting at 0 and continuing to 60,000 pounds.

Compression Cylinder Test

The compression cylinder test is generally accepted as the test method for determining the bond strength between type I cement and the aggregates within concrete. The test requirements and procedures are covered in detail in ASTM-31. All specified requirements and procedures were rigorously adhered to throughout this investigation.

The purpose of this portion of the investigation was threefold: namely, to give this investigator an indepth experience with the procedures involved in concrete testing, to obtain results consistent with other researchers, and to obtain data pertaining to the effects of various treatments of PPF in concrete matrices.

A photograph of the compression machine with a cylinder being tested is shown in Figure 3. In the photo is a 3-inch by 6-inch concrete cylinder being tested. After the concrete cylinders had been cured and capped, they were individually placed between the compression plates, and a constant load was applied to each cylinder. The average load rate of the compression cylinders was 40 psi per second. ASTM Part 14 specifies a maximum of

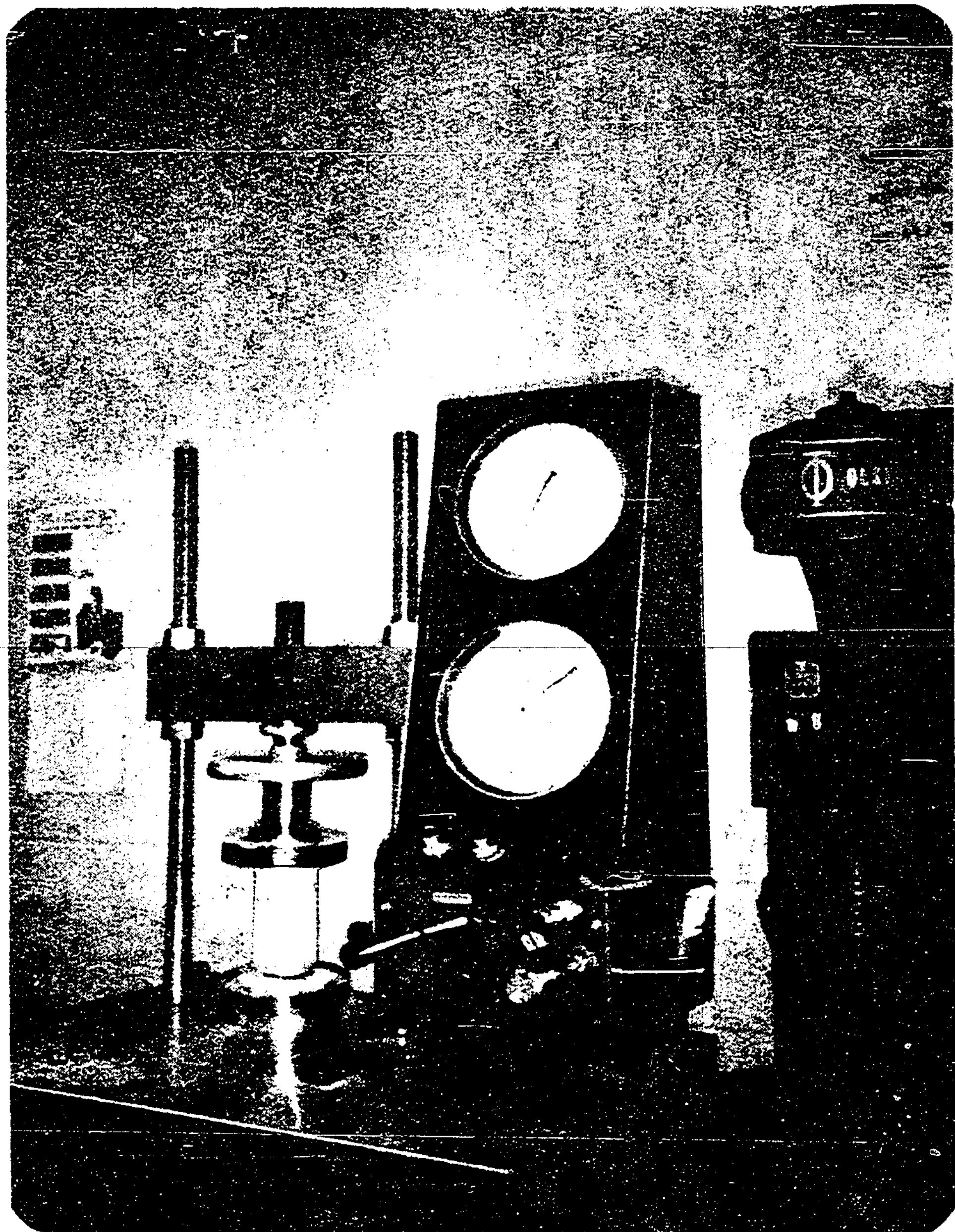


Figure 3. Soil test cylinder testing machine

50 psi per second loading rate for concrete samples. This researcher checked the loading rate every hour throughout the test. The compressive strengths of each cylinder were calculated from the relationship in psi

$$S = P/A$$

where:

P = total applied load in lbs.

A = cross sectional area of the cylinder by $in.^2$

Listed in Table 2 is the 28 day compressive strength for each treatment group of compression cylinders.

Table 2. Compression cylinder in PSI

Control group	Plain fiber group	Basic H group	Oleic acid group
PSI	PSI	PSI	PSI
3,064	▪ 5,662	▪ 4,359	▪ 4,246
2,930	5,775	5,350	4,345
2,972	▪ 6,185	▪ 4,940	▪ 5,152
3,001	5,803	4,699	4,812
3,213	▪ 5,704	4,812	4,515
3,482	5,860	▪ 4,444	▪ 4,275
3,623	▪ 5,945	4,459	4,713
3,482	6,115	5,237	4,798
3,255	6,016	▪ 5,195	▪ 5,209
3,156	▪ 6,185	5,336	4,812
2,392	5,874	5,308	▪ 4,699
3,213	5,860	▪ 5,364	5,011
3,156	6,001	▪ 5,449	4,912
3,439	5,916	5,265	4,275
3,169	5,921	5,015	4,698[a]
295.8	158.5	374.8	312.5[b]

[a] Means.
[b] Standard Deviations.
▪ Samples chosen for SEM visual analyzation.

Flexural Testing

Three point flexural testing is a widely utilized method to test concrete composition in both the compression and tension mode. In this portion of the research, 2-inch by 2-inch (4 square inch cross sectional area) by 12-inch long beams were cast for flexural testing.

The purpose of this test was to determine the modulus of rupture and the modulus of elasticity. These measurements would later be compared among the three treatment groups of PPF (polypropylene fiber) and then compared to the control group concrete batches.

Upon curing, the flexural beams were placed in the Vega testing machine. The lower flexural points were positioned 1 inch in from each end of the beam. The upper flexural pressure bar was placed midpoint between the lower flexural bars. The flexural load was then applied to the beam. The loading rate for the flexural beams was held constant at a level below the ASTM recommended 50 pounds per second loading rate. There are two measuring devices on the Vega tensile tester. The first is a dial indicator which measures readings in psi. This dial is calibrated before each test by indexing the dial indicator to zero. The second measurement device is the mechanical crank which calculates deflection by turns. The user first sets the beam in the machine, and as soon as pressure is exerted, a zero point is established. To improve the precision of results, this researcher calculated and recorded all deflections to the nearest one-quarter turn. The dial indicator on this machine is designed to measure at 10 pound intervals. The formula listed next was used to calculate the MOR of the samples.

Modulus of rupture is calculated from the relationship

$$R = \frac{3Pl}{2bd^2}$$

where:

R = modulus of rupture, psi, or MPa,

P = maximum applied load indicated by the testing machine, lbf or N,

l = span length, in. or mm,

b = average width of specimen, at the point of fracture, in. or mm, and

d = average depth of specimen, at the point of fracture, in. or mm.

In Table 3 are the flexural beam data samples as recorded by treatment group.

Tension Test

Cement briquettes are commonly used as a means of testing the tensile strength of cement mortars. In Figure 4 is a diagram of a tensile briquette mold similar to the type fabricated for this research project.

The purpose of this portion of the research was twofold. The first was to determine the strain rate of the concrete samples. The second was to compare statistically the interaction of treatment groups of PPF with the control group samples.

In order to test the tensile briquettes, this researcher fabricated a set of steel tensile jaws to test the strain rate of the samples. On these jaws, a second dial indicator was attached to directly measure the modulus of elasticity of the tensile samples. With this second dial, both strain rate and modulus of elasticity were measured simultaneously. In Figure 5 is a diagram of a set of tensile briquette jaws.

Table 3. Flexural beam readings by modulus of rupture/deflection in E

Control group		Plain fiber group		Basic H group		Oleic acid group	
MOR	E	MOR	E	MOR	E	MOR	E
788	4.25	938	5.00	825	3.50	844	4.75
750	5.25	769	3.25	713	3.25	844	4.50
806	4.50	806	4.00	806	4.00	825	5.25
788	4.25	713	3.00	844	3.50	806	4.75
750	4.75	750	3.0	788	3.25	863	3.75
844	5.50	806	3.25	769	3.50	750	4.00
844	4.25	994	4.75	788	5.50	713	5.50
806	4.50	806	4.00	900	5.25	731	5.25
769	4.25	788	4.25	900	5.75	788	3.75
731	4.75	1050	5.00	994	4.50	675	4.25
788	4.50	900	3.75	1069	5.00	713	3.50
900	5.00	956	4.50	994	4.25	713	4.00
788	4.50	900	5.00	956	5.50	713	3.50
788	4.50	900	4.50	1069	5.00	713	3.50
796.0	4.6	862.6	4.1	886.7	4.4	763.4	4.30[a]
42.3	.375	96.4	7.17	110.3	.884	60.3	.456[b]

[a] Means.
[b] Standard Deviations.

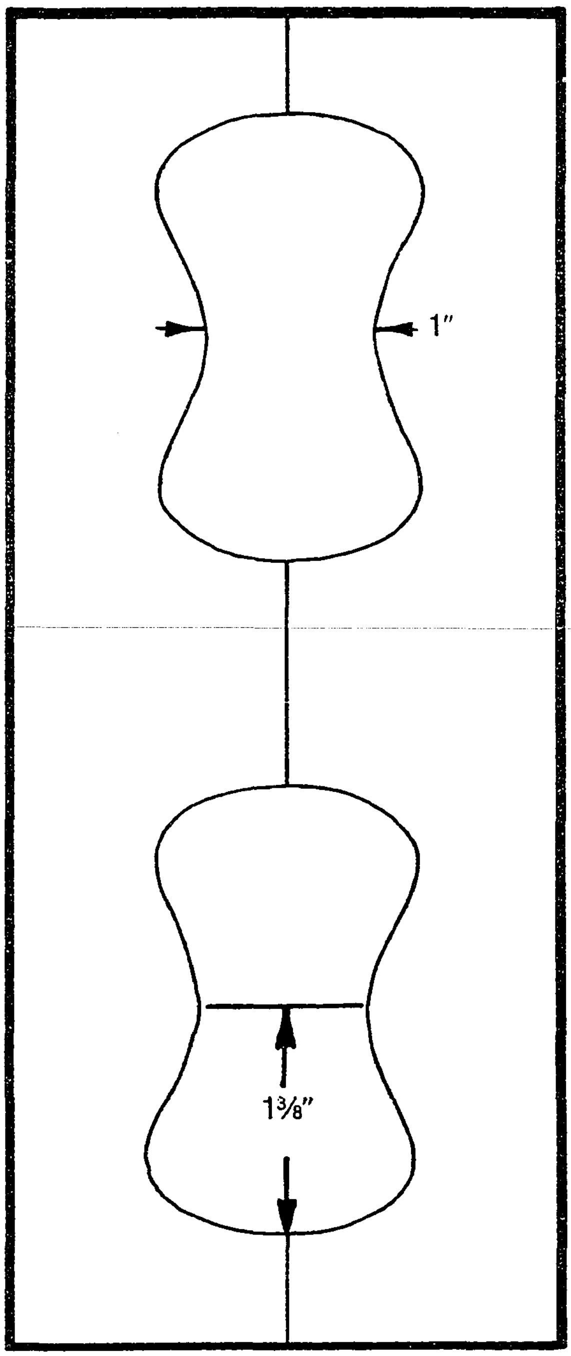


Figure 4. Diagram of a tensile briquette mold

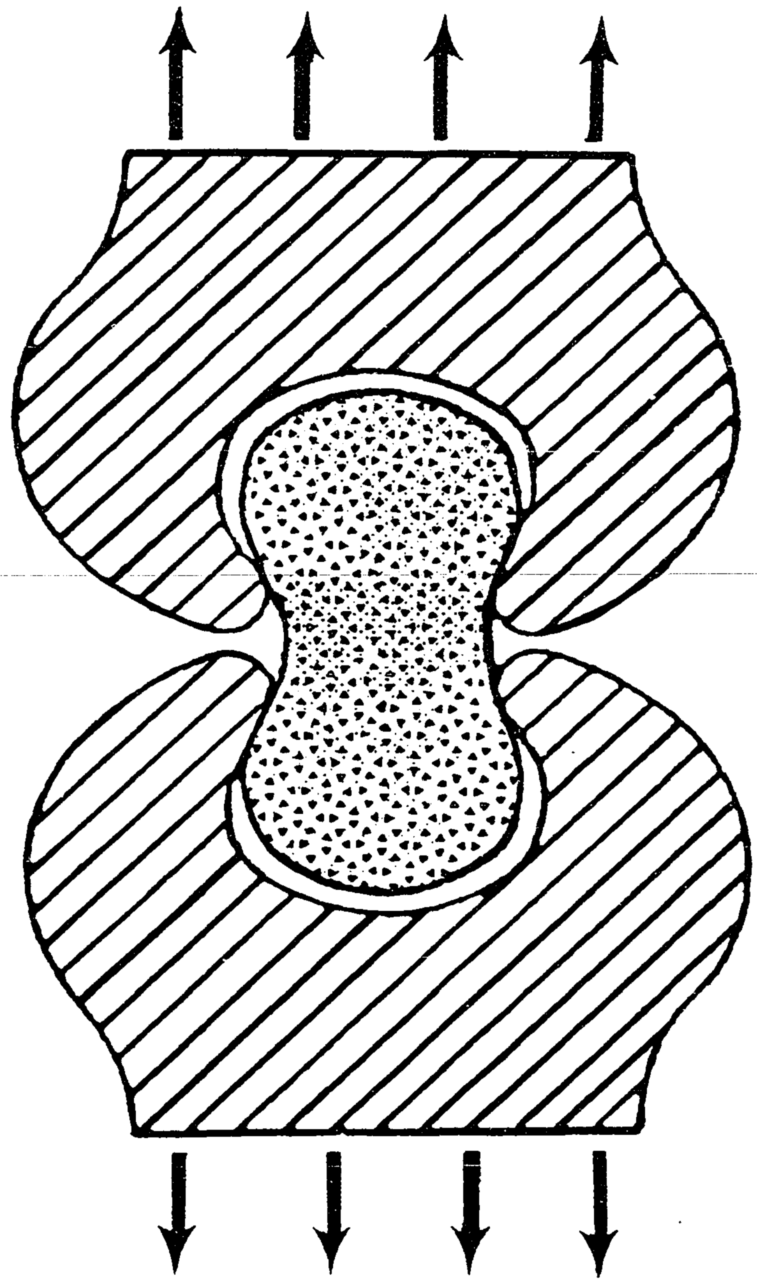


Figure 5. Diagram of a set of tensile jaws

Since the standard tensile briquettes are designed with a 1 square inch cross sectional area, no calculations were necessary to convert the actual readings to psi. By adding the second dial indicator to the tensile jaws, the strain rate was measured directly. By employing a second dial indicator in this test, the precision and measurement reliability of this test were appreciably increased. In Table 4 are the raw scores and means gathered by treatment group for all tensile briquettes tested.

Table 4. Tensile briquette data

Control group		Plain fiber group		Basic H group		Oleic acid group	
PSI	E	PSI	E	PSI	E	PSI	E
210	40	570	64	310	40	320	50
260	36	340	78	450	71	210	43
220	40	550	86	290	34	340	50
190	38	380	39	300	70	280	47
270	46	500	55	550	90	310	45
300	52	500	52	450	32	310	45
241.6	42.0	473.3	62.3	391.6	56.1	295.0	46.6[a]
38.0	5.4	84.7	15.8	97.7	21.9	41.9	2.6[b]

[a] Means.
[b] Standard Deviations.

Scanning Electron Microscope Procedures

The purpose of using the Scanning Electron Microscope (SEM) was to visually examine the interfacial bond and crystalline growth between the PPF and the concrete matrix. In addition, the (SEM) photographs provided a basis to compare interfacial bonding of the PPF between different treatment groups.

The SEM currently being used by the Material Analysis and Research Laboratory (MARL) at Iowa State University is a (JEOL) Japanese Electron Optical Laboratory, Model JSM-3, which was installed in 1971. This piece of research equipment is also interfaced with a Tracor Northern TN-2000 energy dispersive X-ray analyzer that is capable of performing elementary quantitative analysis. This researcher has been able to obtain clear resolution in photographs at 5,000X which were very acceptable for the requirements of this investigation.

During the pilot study portion of this research, it was determined that (SEM) photographs gave the best representation of the interfacial bond at 400-500X, at 1,200-1,400X, and at 3,000X magnification. Therefore, it has been determined to standardize all SEM photographs for analysis into these three magnification groups. These are 100X, 1,000X, and 3,000 magnification. In Figure 6 is a photograph of the SEM currently in operation in the Material Analysis and Research Laboratory at Iowa State University, Ames, Iowa.

Due to the extreme cost in analyzing all of the samples in this study, it was determined to complete a thorough analysis of the compression cylinders only at this time using the Scanning Electron Microscope. Each treatment group had six samples picked for analysis by their respective

Figure 6. Scanning electron microscope

compressive psi rankings. In each treatment group, samples were selected by their rank order of: first, second, sixth, seventh, thirteenth, and fourteenth. By choosing these samples in rank order from each batch, an opportunity was provided to view the strongest samples, the weakest samples, and the samples at mid-point. Marked with an asterisk on Table 2, titled Compression cylinders, are the samples chosen for visual analysis utilizing the SEM.

Preparation of SEM Samples

After the compression cylinders were tested, they were identified and marked for future analysis. The cylinders chosen for the SEM were first separated from the total sample sets. Failed fibers were carefully brushed off to remove dust and concrete particles before being severed from the failed sample. The failed fibers were removed at random from the cylinders by using a pair of tweezers and small scissors. These fibers were then catalogued and stored for future mounting.

The 1-inch metal discs chosen for scanning in the electron microscope were first prepared for mounting by having double-stick tape applied to the mounting surface. Next, individual fibers that were taken from each marked sample container were then mounted on a tagged metallic disc. The coating process is one where the samples were individually placed in a decompression chamber. They were then flushed with argon gas to clean all surfaces not directly touching the mounting surface. The final step of this procedure was the actual gold coating process, which was accomplished through a sputtering process. The coating applied over the entire fiber surface area was 300 angstroms thick. The sputter machine used to complete the gold coating process was the Polaron Model Number E 5100.

The final step in this process was the actual analysis of the selected samples. The first procedure employed in this process was to view the sample at magnifications of 100 to 500. This magnification enabled the analyst to become familiar with each sample and determine where higher magnification would be most useful. The final step was to visually inspect at high magnification levels all surfaces which revealed crystalline growth.

CHAPTER 4. PRESENTATION OF DATA

Measurement Analysis

The results of this research are presented in this chapter. Each of the null hypotheses listed at the outset of this research were tested at the 95% confidence level. The data gathered from this research project are listed in analytical, graphic, and photographic sequence.

Descriptive data compression cylinders

The average strength of the compression cylinders tested was 4,701.2 with a standard deviation of 991.6 psi. There were seven samples tested in each treatment group, and each treatment group was replicated. In the compression cylinder group, there were 56 cylinders. The cylinders were divided into treatment groups, with treatment one being the control group. This set of cylinders contained only the concrete design mix with no additional polypropylene fiber (PPF) reinforcing. Treatment group two contained PPF as supplied by the manufacturer and was not subjected to a chemical treatment. Treatment group three contained PPF that was treated with oleic acid. Treatment group four contained PPF that was treated with Basic H detergent. All groups referred to in the analysis chapter will be designated as: CG for control group, PPF for plain polypropylene fiber as a treatment group, OA for oleic acid treatment group, and BH for Basic H as a treatment group. All samples, regardless of their sample configuration (cylinders, beams, briquettes), were all cast from their respective concrete batch and treatment group.

Table 5 represents the descriptive statistics for the compression cylinder tests. They are listed by batch, by treatment, and by the number of samples in each set. In Figure 7 is the scatter plot of the compression cylinders. The lowest strength values were identified as the control group. This was expected, for there was not any reinforcing material placed in the control group. The highest strength values were found to be in the plain polypropylene fiber group.

Statistical analysis compression cylinder samples

The Statistical Analytical Systems (SAS) General Linear Model (GLM) computer package at Iowa State University was utilized to calculate the Analysis of Variance (ANOVA) results for all the statistical tests conducted in this research project. The ANOVA schedule in Table 6 was one of the measures utilized in determining whether to accept or reject the research hypotheses tested in this chapter.

In Figure 7, the compression cylinder scatter plot reveals a linear relationship. The control group provided the lowest strength values when compared to the plain fiber group, which had the highest strength values.

Descriptive data three-point flexural beams

The average measurement at the moment of rupture (MOR) for the flexural beams was 827.1 psi with a standard deviation of 22.6 psi. There were 56 samples measured in this test. Each treatment group contained 14 samples per set. As can be viewed in Figure 8, the weakest beam failed at 675 psi and was a sample from the oleic acid treatment group. The strongest beam failed at 1,069 psi and was a sample from the basic H fiber

Table 5. Descriptive data compression cylinders

Batch	Number	Mean Y
1	28	4583.6
2	28	4818.9

Treatment	Number	Mean Y
CC	14	3169.8
OA	14	4698.1
BH	14	5015.5
PF	14	5921.5

Batch	Treatment	Number	Mean Y
1	CC	7	3183.6
1	OA	7	4579.7
1	BH	7	4723.3
1	PF	7	5847.7
2	CC	7	3156.1
2	OA	7	4816.6
2	BH	7	5307.7
2	PF	7	5995.3

Table 6. ANOVA Procedure compression cylinders

Dependent Variable: Y

Source	DF	Sum of Squares	Mean Square
Model	7	56531773.07	8075967.58
Error	48	3442047.43	71709.32
Corrected Total	55	59973820.50	

Source	DF	Type I SS	F Value	PR F
Batch	1	775501.76	10.81	0.0019
TRT	3	55061116.07	255.95	0.0001
Batch*TRT	3	695155.21	3.23	0.0304

F Value 112.62

Contrast	DF	SS	F Value	PR F
Batch 1 vs. Batch 2	1	775501.79	10.81	0.0019
TRT 1 vs. TRT 2	1	16349600.57	228.00	0.0001
TRT 1 vs. TRT 3	1	23844782.89	332.52	0.0001
TRT 1 vs. TRT4	1	53000768.89	739.11	0.0001

PSI	CC	OA	BH	PFF
6200				2
6100				1
6000				2
5900				5
5800				2
5700				2
5600				
5500				
5400			3	
5300			3	
5200		2	2	
5100				
5000		1		
4900		1	1	
4800		3	1	
4700		2	1	
4600				
4500		1	1	
4400			2	
4300		3		
4200		1		
4100				
4000				
3900				
3800				
3700				
3600	1			
3500	2			
3400	1			
3300	1			
3200	4			
3100	1			
3000	2			
2900	1			
2800				
2700				
2600				
2500				
2400	1			
2300				
2200				
2100				
2000				

The number on the plot indicates the number of observations at each measurement.

Figure 7. Compression cylinder plot

Table 7. Flexural beam treatment comparison

Alpha = 0.05 Confidence = 0.95 DF = 48 MSE = 4188.89

Critical Value of T = 3.76

Least Significant Difference = 65.10

Comparisons significant at the 0.05 level are indicated by *

TRT Comparison		Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	
3	−4	−40.89	24.21	89.32	
3	−1	26.01	91.11	156.21	*
3	−2	58.04	123.14	188.24	*
4	−3	−89.32	−24.21	40.89	
4	−1	1.79	66.89	131.99	*
4	−2	33.83	98.93	164.03	*
1	−3	−156.21	−91.11	−26.01	*
1	−4	−131.99	−66.89	−1.79	*
1	−2	−33.07	−32.04	−97.14	
2	−3	−188.24	−123.14	−58.04	*
2	−4	−164.03	−98.93	−33.83	*
2	−1	−97.14	−32.04	33.07	

PSI	CG	OA	PPF	BH
1,069				2
1,050			2	
1,032				
1,013				
994			1	2
975				
956			1	1
938			1	
919				
900	1			
882				
863		2		
844	2	2		1
825		1		1
806	2	1	2	1
788	5	1	1	2
769	1		1	2
750	2	1	1	
731	1	1		
713		5	1	1
694				
675		1		

Figure 8. Flexural beam plot

The number on the plot indicates the number of observations at each measurement.

treatment group. When plotted, the averages from the sample groups revealed a linear relationship. Those batches which did not reveal a significant difference were the oleic acid and Basic H batches plus the plain fiber and Basic H batches. This procedure was utilized to ascertain the significance difference among all groups.

Statistical analysis flexural beams

The SAS multiple regression analysis procedure was utilized in calculating the data relating to three point flexural beams. For each sample, there were two observations measured. The first measurement was modulus of rupture the moment of failure. The second measure was the modulus of elasticity.

The statistical model developed for the dual measurement of the flexural beams and the tensile briquettes is listed as:

$$Yij = \mu i + \beta i + \tau i + \Sigma ij.$$

where:

μi = treatment

βi = psi measure

τi = modulus of elasticity

Σij = unexplained error term

The SAS statistical model included the treatment, the psi measure, the modulus of elasticity measure, and the treatment by interaction.

Descriptive data tensile briquettes

There were 24 briquettes tested in this experiment. Within the four concrete groups, there were six samples tested from each treatment group.

The mean average of the samples was 357.5 psi. The weakest specimen failed while sustaining a stress of 190 psi with a strain value of .038 in./in. The modulus of rupture (MOR) of the strongest sample was recorded while sustaining a stress of 550 psi with a strain value of .096 in./in. In Figure 9, tensile briquette plot reveals a linear relationship with plain polypropylene having the highest strength values of all groups tested. There is over a 200% difference in tensile strength between the lowest control group sample and the highest treatment group sample. Listed in Table 8 are the results by mechanical measure of the tensile briquettes. The tensile strength of concrete can be enhanced by the addition of polypropylene fiber as a secondary reinforcing member.

Statistical analysis tensile briquettes

The multiple regression analysis procedure from SAS was utilized to calculate the ANOVA for the tensile characteristics of the briquettes. Each sample was measured twice while under tensile load at the modulus of rupture (MOR). The strain rate and psi at MOR were recorded simultaneously. The ANOVA results revealed an alpha level of .05, with 20 degrees of freedom and a mean square error of 239.175. The statistical partitioning results of SAS revealed a least significant difference of 18.62 among the four groups.

Scanning Electron Microscope Analysis

Photomicrographic analysis by means of the Scanning Electron Microscope (SEM) has been limited to compression cylinders only. The control group and all treatment group compression cylinders were analyzed using the SEM visual inspection process of highly magnified fiber samples.

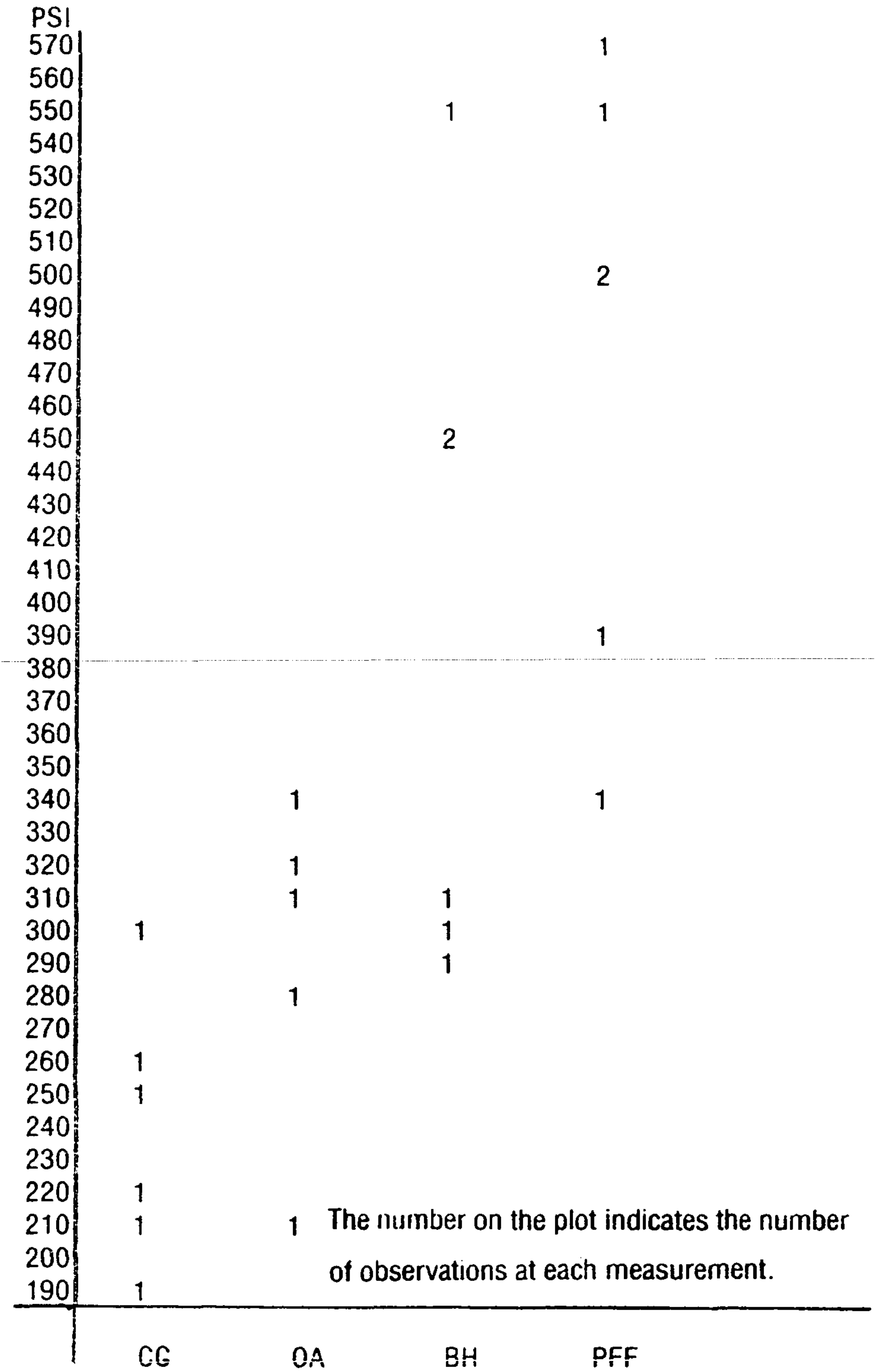


Figure 9. Tensile briquette plot

Table 8. Tensile briquette readings

Control group		Plain fiber group		Basic H group		Oleic acid group	
PSI	E	PSI	E	PSI	E	PSI	E
210	40	570	64	310	40	320	50
260	36	340	78	450	71	210	43
220	40	550	86	290	34	340	50
190	38	380	39	300	70	280	47
270	46	500	55	550	90	310	45
300	52	500	52	450	32	310	45
241.6	42.0	473.3	62.3	391.6	56.1	295.0	46.6[a]
38.0	5.4	84.7	15.8	97.7	21.9	41.9	2.6[b]

[a] Means.
[b] Standard Deviations.

Upon reviewing the PSI data from the compression cylinder groups, it was decided to analyze six cylinders from each treatment group. Two cylinders from each treatment group were chosen that had achieved the highest compressive strengths. The second set of cylinders chosen for inspection came from readings at the mean of each treatment group. The last set of cylinders chosen were those generating the lowest compressive strengths. By utilizing this technique, cylinders from all treatment groups at different levels of compressive strengths were analyzed.

Each cylinder was microscopically inspected at three magnification levels using the SEM. These were at 100X, 1,000X, and 3,000X. The decision to analyze the PPF at these magnification levels resulted from the pilot study conducted prior to this research. These magnification ranges revealed the best visual inspection of the PPF during the pilot study.

Scanning Electron Microscope Inspection Results

Oleic acid compression cylinder visual examination

The Scanning Electron Microscope (SEM) revealed that the amount of surface interfacial crystalline growth was directly proportional to the strength values (PSI) of the oleic acid compression cylinders. The interfacial growth was consistent with all samples, taken at all levels, from the oleic acid compression cylinder treatment group. Therefore, the crystalline growth on the interfacial bond visually indicates a positive correlation and was linear in nature. In Figures 10 and 11 are the SEM photographs revealing the interfacial crystalline growth on the failed oleic acid fibers. As can be observed on the SEM photographs, the oleic acid fibers with the highest compressive strength values, as shown in Figures 10-1, 10-4, and 11-1, revealed the most crystalline growth on the fiber surface area.

An attempt was made to ascertain the type of crystalline growth present on the oleic acid fiber surfaces. When this researcher compared the crystalline growth in Figure 11-2 to research published by others, there was strong evidence this crystalline growth is a type II calcium silicate hydrate.

Basic H compression cylinders

The Basic H SEM photographs revealed a high degree of fly ash present on the fiber surface area. There was a high degree of fly ash in the

Figure 10. Crystalline growth on oleic acid fibers

10-1 and 10-4 are SEM magnified views from the high strength fibers

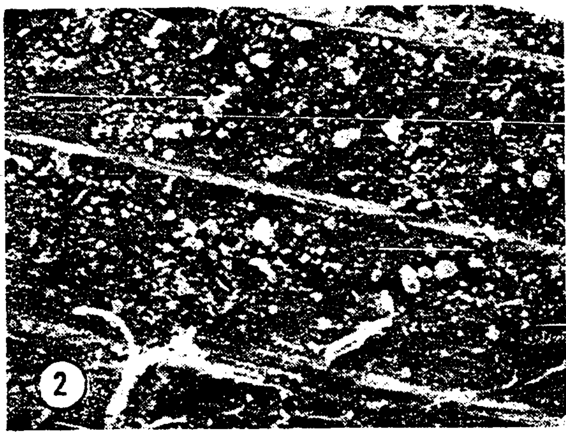
10-2 and 10-5 are SEM magnified views from the mean strength fibers

10-3 and 10-6 are SEM magnified views from the low strength fibers

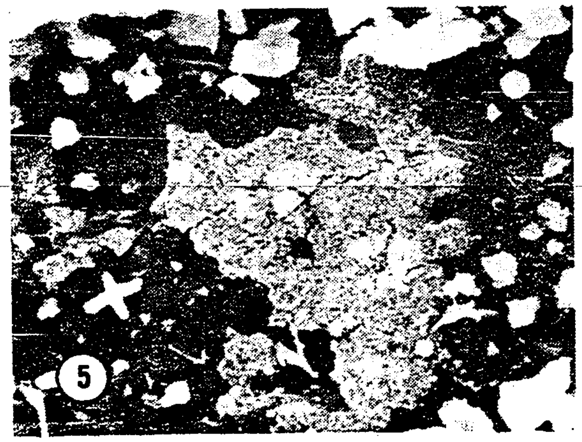
OLEIC ACID

100x 200 Microns

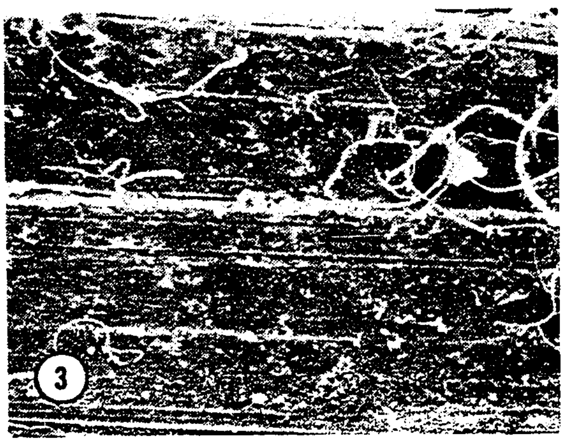
1,000x 20 Microns



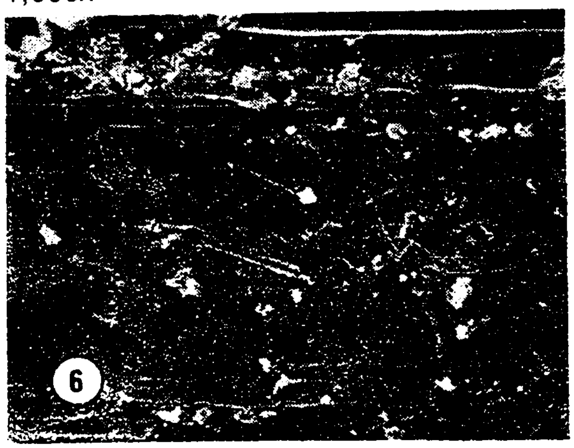
100x 200 Microns



1,000x 20 Microns



100x 200 Microns



1,000x 20 Microns

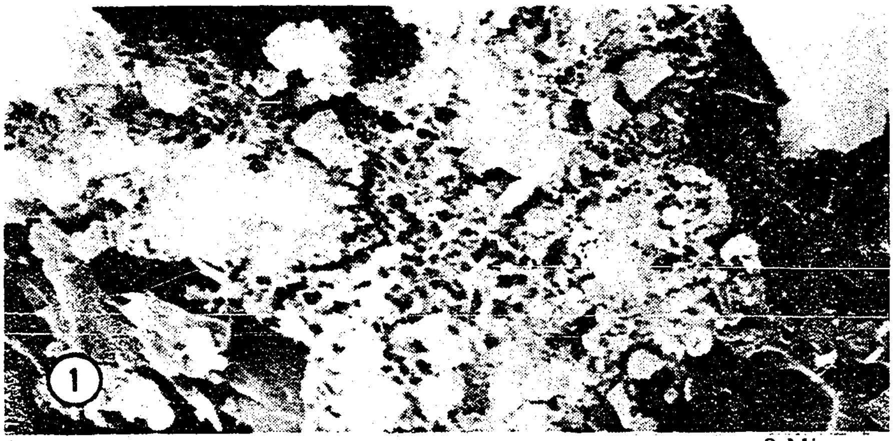
Figure 11. Crystalline growth on oleic acid fibers at high magnification

11-1 is a SEM magnified view from the high strength fibers

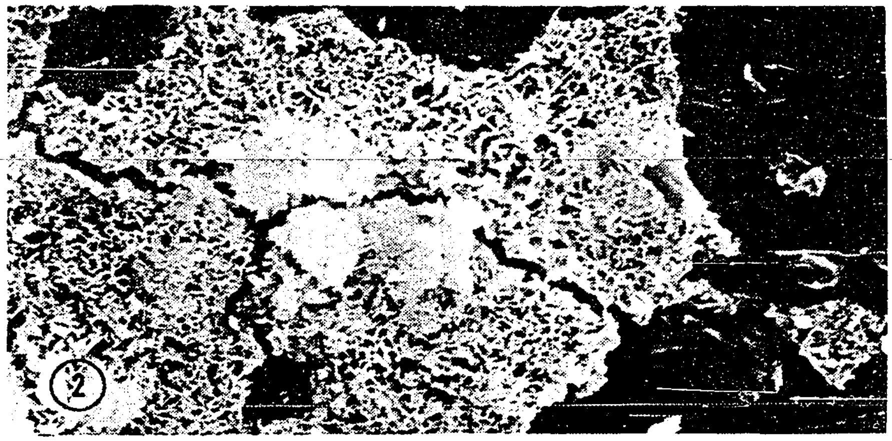
11-2 is a SEM magnified view from the mean strength fibers

11-3 is a SEM magnified view from the low strength fibers

OLEIC ACID



3,000x 6 Microns



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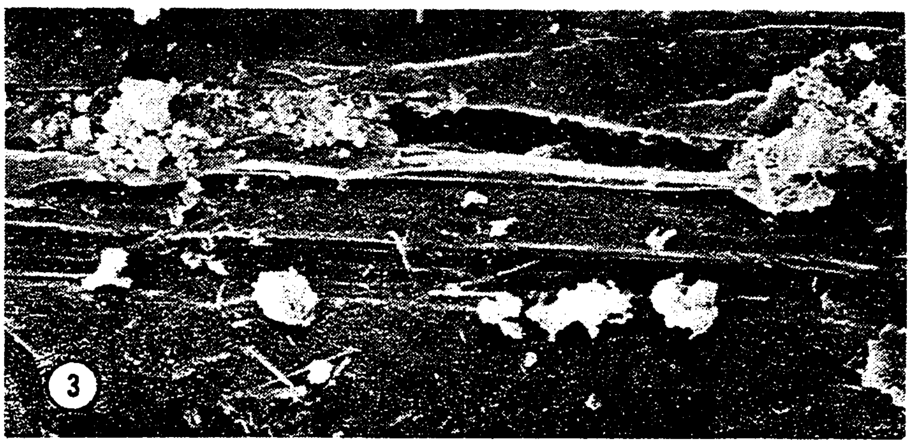


3,000x 6 Microns

cavities of the Basic H treatment group fibers. Fly ash is a pozzolan which improves the strength in cement matrices. All samples of Basic H fiber inspected under the SEM contained various levels of fly ash. It should be noted, however, that on three of the six Basic H samples examined, there appears to be particle agglomeration (balling together) of fly ash in the crevices. The degree of coalescence appears to be more consistent with the higher strength Basic H fibers. In Figures 12-2 and 12-5 are SEM photographs which lend support to this position.

None of the Basic H samples viewed under the SEM inspection revealed any crystalline growth. This phenomenon is unexplainable since there are crystalline growths on the fiber surfaces of the other two treatment groups. In Figure 12 are the SEM photographs of the Basic H fibers. The bonding process which occurred with these samples was assumed to be strictly of a mechanical nature.

Plain fiber treatment group

Upon SEM inspection, the plain fiber treatment group revealed mechanical bonding between the fibers and the cement matrix. In one of the six samples evaluated, there was some evidence of crystalline growth, as can be seen in Figure 13-2. In none of the other five untreated fiber samples were there any crystalline growth at the interface. There were only slight traces of fly ash on the fiber surface of the plain polypropylene fibers. The SEM results of the plain polypropylene fibers were consistent with extensive research published by other researchers and reviewed by this researcher.

Figure 12. Fly ash on Basic H fiber surfaces

12-1 and 12-4 are SEM magnified views from the high strength fibers

12-2 and 12-5 are SEM magnified views from the mean strength fibers

12-3 and 12-6 are SEM magnified views from the low strength fibers

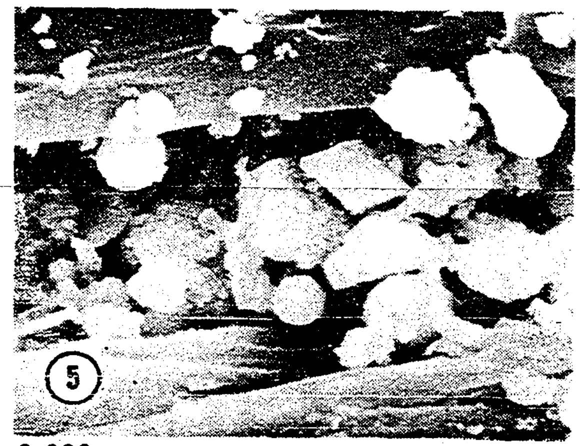
BASIC H

1,000x 20 Microns

1,000x 20 Microns

1,000x 20 Microns

3,000x 6 Microns



3,000x 6 Microns

3,000x 6 Microns

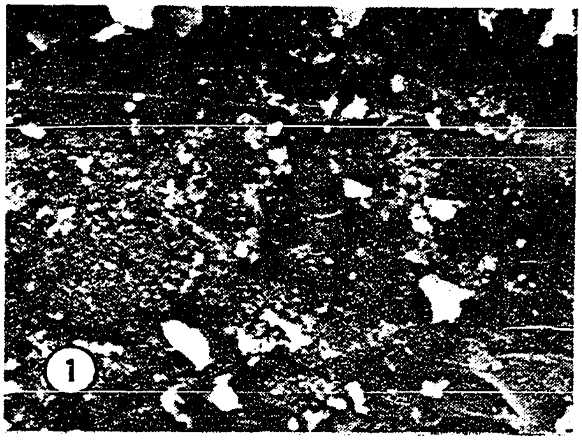
Figure 13. Plain polypropylene fiber surfaces

13-1 and 13-2 are SEM magnified views from the high strength fibers

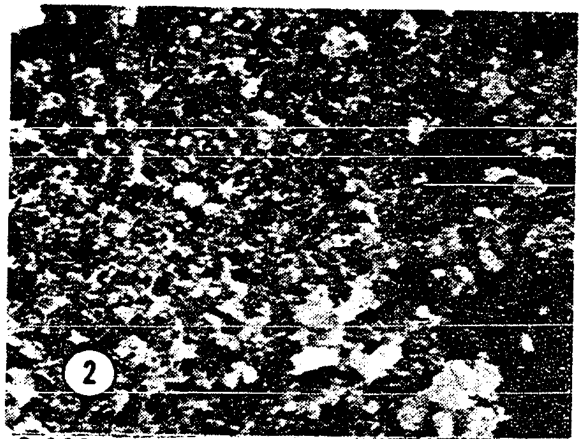
13-3 and 13-4 are SEM magnified views from the mean strength fibers

13-5 and 13-6 are SEM magnified views from the low strength fibers

PLAIN FIBER



1,000x 20 Microns



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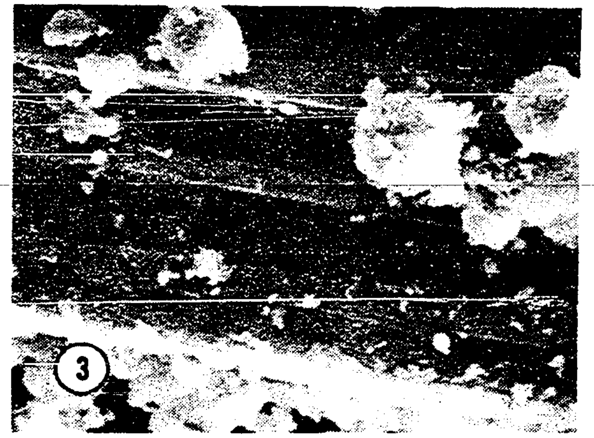
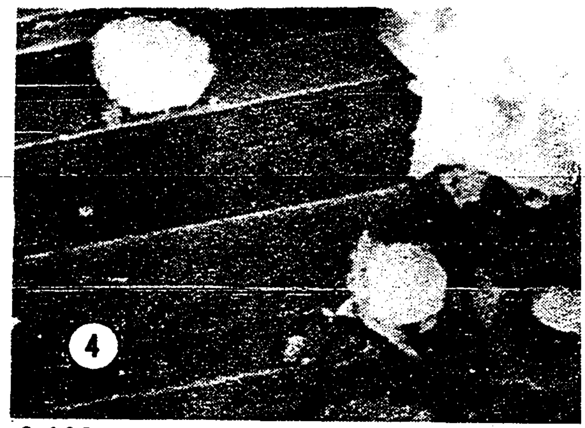
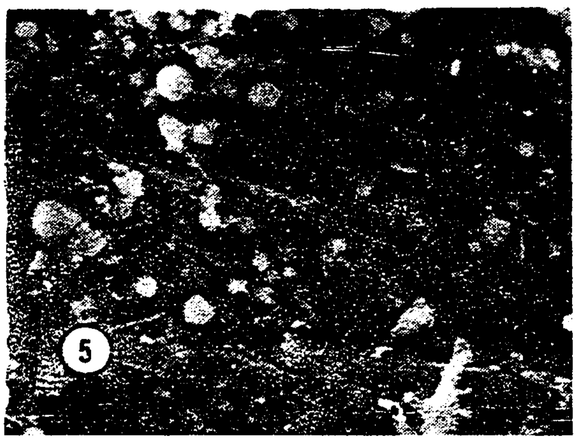


1,000x 20 Microns



3,000x 6 Microns



1,000x 20 Microns

3,000x 6 Microns

Testing of Hypotheses

It was determined at the start of this investigation to accept or reject these hypotheses by the statistical analysis of the mechanical measures. Specifically, these results were ascertained from the strength values of the treated polypropylene fibers in compression cylinders, flexural beams, and tensile briquettes. It was intended that the use of the SEM photographs would more clearly explain and reinforce the phenomenon of the crystalline growth observed at the interfacial bond between the polypropylene fibers and the cement matrix.

Research hypothesis 1: There will be no significant difference in the strength capabilities of the control group samples, when compared to the samples containing untreated polypropylene fibers.

By examining Table 9, the compression cylinder statistical results revealed there were significant differences between the control group samples and the untreated polypropylene fiber samples. The statistical results listed under the titles of flexural beams and tensile briquettes also indicated a significant difference between the control group samples and the untreated PPF samples. In all three measures (cylinders, beams and briquettes), there was a significant F statistic.

Therefore, hypothesis 1 was rejected without any qualifications.

Research hypothesis 2: There will be no significant difference in the strength capabilities of the control group samples, when compared to the samples containing polypropylene fibers treated with oleic acid.

Table 9. Plain fiber comparisons

Control group	Plain fiber group	Oleic acid group	Basic H group	Significant F group
Measure				
Compression test				
××	××			.001**
Flexural test				
××	××			.05*
Tensile test				
××	××			.05*

*p .05.

**p .01.

When examining Table 10, two of the three measures indicated that there were significant differences between the control group and the oleic acid treatment group. The tensile test data analyzed did not reveal a significant difference at the .05 level. Therefore, the data did not support a clear decision to reject the second hypothesis.

Research hypothesis 3: There will be no significant difference in the strength capabilities of the control group samples, when compared to the samples containing polypropylene fibers treated with Basic H detergent.

Table 10. Oleic acid comparisons

Control group	Plain fiber group	Oleic acid group	Basic H group	Significant F
Measure				
Compression test				
××			××	.05*
Flexural test				
××			××	.05*
Tensile test				
××			××	NONE

*p .05.

**p .01.

By statistically examining the results of the Basic H samples, and comparing them to the control group samples, there was not a significant difference in the flexural beams and the tensile briquettes. As can be viewed in Table 11, only the compression cylinder statistical results revealed a significant difference. Therefore, based on the results of two out of three measures, hypothesis 3 was accepted.

Research hypothesis 4: There will be no significant difference in the strength capabilities among the treatment group samples, when compared to the control group samples.

Table 11. Basic H comparisons

Control group	Plain fiber group	Oleic acid group	Basic H group	Significant F group
Measure				
Compression test				
××			××	.05*
Flexural test				
××			××	NONE
Tensile test				
××			××	NONE

*p .05.

**p .01.

The compression cylinder T-tests (least significant difference) for the *y* variable were calculated to ascertain the type 1 comparison error rate. The SAS general linear model procedure was utilized to calculate the contrasting differences among the control and treatment groups. As can be viewed from Table 12, the treatment comparisons among all groups were found to be significant at the .05 level.

The flexural beams T-test (least significant difference) indicated there was not a significant difference among all the control group samples when compared to all the treatment group samples. From the 12 possible

Table 12. ANOVA Compression cylinder contracts

Dependent Variable: Y

Source	DF	Sum of Squares	Mean Square
Model	7	56531773.07	8075967.58
Error	48	3442047.43	71709.32
Corrected Total	55	59973820.500	

Source	DF	Type I SS	F Value	PR F
Batch	1	775501.79	10.81	0.0019
TRT	3	55061116.07	255.95	0.0001
Batch*TRT	3	695155.21	3.23	0.0304

F Value 112.62

Contrast	DF	SS	F Value	PR F
Batch 1 vs. Batch 2	1	775501.79	10.81	0.0019
TRT 1 vs. TRT 2	1	16349600.57	228.00	0.0001
TRT 1 vs. TRT 3	1	23844782.89	332.52	0.0001
TRT 1 vs. TRT4	1	53000768.89	739.11	0.0001
Batch vs. TRT	0	Non-Est.		

treatment comparison configurations, which are listed on Table 13, there were four treatment comparison configurations which were found not to be statistically significant. These were the comparisons of the Basic H and plain fiber group and comparisons of the control group and oleic acid treatment group. By examining Table 11 under the flexural beam comparison, there is not a significant difference between the control group flexural beams and the flexural beams containing Basic H treated fibers.

The tensile briquettes T-test (least square difference) indicated there was not a significant difference among the control group samples, when compared to the treatment group samples. From the 12 possible treatment comparison configurations, only two treatment comparison groups were statistically significant. These were the control group and plain fiber group. In two out of the three measures (compression cylinders, flexural beams, and tensile briquettes), there was not a significant statistical difference. When viewing the statistical results in Tables 9, 10, and 11, under compression cylinders, the results indicate a significant difference in all treatment groups, when compared to the control group. By viewing these same three tables, there were found not to be clear significant differences in the flexural beams and tensile briquettes when compared to the control group. Therefore, research hypothesis 4 was accepted.

Table 13. Flexural treatment comparison

Alpha = 0.05 Confidence = 0.95 DF = 48 MSE = 4188.89

Critical Value of T = 3.76

Least Significant Difference = 65.10

Comparisons significant at the 0.05 level are indicated by *

TRT Comparison		Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	
3	−4	−40.89	24.21	89.32	
3	−1	26.01	91.11	156.21	*
3	−2	58.04	123.14	188.24	*
4	−3	−89.32	−24.21	40.89	
4	−1	1.79	66.89	131.99	*
4	−2	33.83	98.93	164.03	*
1	−3	−156.21	−91.11	−26.01	*
1	−4	−131.99	−66.89	−1.79	*
1	−2	−33.07	−32.04	−97.14	
2	−3	−188.24	−123.14	−58.04	*
2	−4	−164.03	−98.93	−33.83	*
2	−1	−97.14	−32.04	33.07	

CHAPTER 5. SUMMARY, DISCUSSION, AND RECOMMENDATIONS

The purpose of this study was to improve the interfacial bond, between polypropylene fibers and cement matrices in concrete, by means of crystalline growth. Crystalline growth is the result of the chemical bonding between concrete and polypropylene fibers. The preceding chapters in this research endeavor dealt with the review of literature, which specifically related to the use of polypropylene fibers (PPF) as a reinforcing material in cement matrices within concrete. The second part of this research was devoted to developing chemical treatment which would improve the interfacial bond between PPF and cement matrices. Upon completion of the pilot testing, the research methodology procedures and statistical analysis procedures were developed for this project. The third chapter in this research was devoted to the methods of analysis. These methods of measure were accomplished by mechanical, statistical, and microscopic analysis. After measuring and accumulating the data from the test samples by means of mechanical measures, the tests of significance were statistically calculated. In the final measure, a microscopic assessment was conducted utilizing the Scanning Electron Microscope.

Summary and Conclusions

This section provides a summary and the conclusions of the study, based upon the findings reported in the preceding chapter. The four research hypotheses are re-stated, followed by a brief description of the results.

Re-statement of the problem

The problem of this study was to develop a method to improve the interfacial bond between polypropylene fibers and Type 1 Portland cement. This study also investigated the improved qualities of the interfacial bond.

Research hypothesis 1

There will be no significant difference in the strength capabilities of the control group samples, when compared to the samples containing untreated polypropylene fibers.

The conclusions were:

(1) It was found that the plain polypropylene fibers in the compression cylinders produced the highest compressive strengths of all treatment groups tested.

(2) It was found that the plain polypropylene fiber treatment group was the only treatment group which produced a significant strength difference in all three measures. Those significant differences were found in compression, flexural, and tension measurements.

(3) It was found there was a significant difference between the strength values of the control group and the plain fiber treatment group. Therefore, the first hypothesis was rejected without any reservations.

Research hypothesis 2

There will be no significant difference in the strength capabilities of the control group, when compared to the treatment group containing polypropylene fibers treated with oleic acid.

The conclusions were:

(1) It was found there was a significant difference in the strength capacity of the control group when compared to the oleic acid treatment group.

(2) It was found that the strength values of the oleic acid treatment group has a direct correlation to the amount of interfacial crystalline growth on the fiber surface.

(3) It was found that there was crystalline growth at the interfacial bond between the polypropylene fiber surface and the cement matrix.

(4) It was found that there was a significant difference between the control group when compared to the oleic acid treatment group in two out of the three measures. There were significant differences in the compression and flexural test. There was not a significant difference in the tensile test results. Therefore, the data did not support a clear decision to reject the second hypothesis.

Research hypothesis 3

There will be no significant difference in the strength capabilities of the control group samples, when compared to the samples containing polypropylene fibers treated with Basic H detergent.

The conclusions were:

(1) It was found there was not a significant difference between the control group and the Basic H treatment group samples in two out of the three measures. The only measure which resulted in a significant difference was the compression test.

(2) It was found that there was not any crystalline growth on the surface of the polypropylene reinforcing fibers which were treated with Basic H detergent.

(3) It was found that there was a high degree of fly ash (pozzolan) deposits on the surface areas of the Basic H sample fibers. In only one out of three measures was there a significant difference. Therefore, hypothesis three was accepted.

Research hypothesis 4

There will be no significant difference in the strength capabilities among the treatment group samples and the control group samples.

The conclusions were:

(1) It was found there were no significant differences among the control group and the treatment samples in two out of the three measures. The flexure test and tensile test did not indicate a significant difference.

(2) It was found that only in the compression cylinder test was there a significant difference among the control group and the treatment samples. Therefore, the measures did not warrant a clear decision to reject the fourth hypothesis.

Discussion

A great deal of research has been conducted pertaining to the improvement of the mechanical bonding process between polypropylene fibers (PPF) and concrete. This researcher has found little evidence of research specifically relating to the chemical improvement of these two constituents, polypropylene and cement matrices.

Any published research relating to chemical mixtures utilized in concrete and PPF has been specifically targeted to admixtures. Among these are common chemicals referred to as accelerators and retarders. These admixtures specifically address the initial set time that takes place in the cement's hydration process.

The research methodology utilized in this investigation has been of a basic and traditional nature. The measures employed have been those basically utilized in traditional engineering research. There is clear evidence from this research that crystalline growth does have an effect on the strength of the PPF in the concrete matrix. To what extent the crystalline growth can be converted into any real increase in strength is yet to be determined. This investigation is hopefully just the beginning in research relating to the chemical bonding between PPF and cement matrices.

This limited investigation did meet the basic objective of improving the crystalline growth on the surface of PPF through the use of chemical enhancement. Extensive research will have to be completed and reported before the answer is known to what extent crystalline growth directly affects the strength characteristics of the chemical bonding in concrete. In this investigation, only two chemicals were tested to enhance the chemical bonding between the fibers and the cement matrix.

The SEM photographs revealed a high level of fly ash was present on the surface area. The cement manufacturer would not confirm nor deny the use of pozzolan in the cement product.

The Scanning Electron Microscope photographs taken of the Basic H samples did not reveal any crystalline growth at the interface. This indicates the need for more research in this area to ascertain why the Basic H samples had such high strength values without any crystalline growth.

It should also be pointed out that upon inspection of the plain untreated polypropylene fibers, one sample revealed some crystalline growth. These fibers were from the high strength compression samples. How the crystalline growth developed is not known. Nevertheless, the plain polypropylene fibers with some crystalline growth did in fact reveal high compressive strengths.

The choice to only analyze the compression cylinder samples by use of the Scanning Electron Microscope (SEM) was strictly made because of budget restrictions. The real strengths of the PPF are to be found in its flexural and tensile capabilities. These samples were not analyzed, so no assessment can be reported.

It is recommended that research continue in this field to improve the crystalline growth at the interface of PPF and cement matrices. Those researchers who have the expertise in the chemical and plastics industry should be consulted in the development of any future research pertaining to this research topic.

Further Chemical Developments in Research

Chemical additives and polypropylene fibers in concrete

This researcher wishes to discuss a recently completed research project which is not part of this dissertation. It is included to identify further chemical developments in concrete and polypropylene fiber (PPF) reinforcing. This latest piece of research included a chemical additive Basic H and PPF in concrete. Since there are numerous manufacturers of polypropylene fibers on the market, a comparison was made between two national brands of PPF. This investigation was limited to the use of PPF in compression cylinders. There was found to be no significant difference in the compressive strength values of the two major fiber brands tested. The research was of a factorial design. The compression cylinders were tested at 7, 14, 21, and 28 days. In one treatment group, the chemical Basic H was added to the concrete design in an attempt to improve its strength capabilities. There was a significant increase in the strength values of this chemical treatment group. The samples have not been microscopically inspected using the SEM. In Figure 14 is a 28-day plot of the control group and treatment groups tested.

The initial findings of this second investigation tend to indicate that the strength values of the PPF can be improved by the inclusion of chemicals in the concrete matrix.

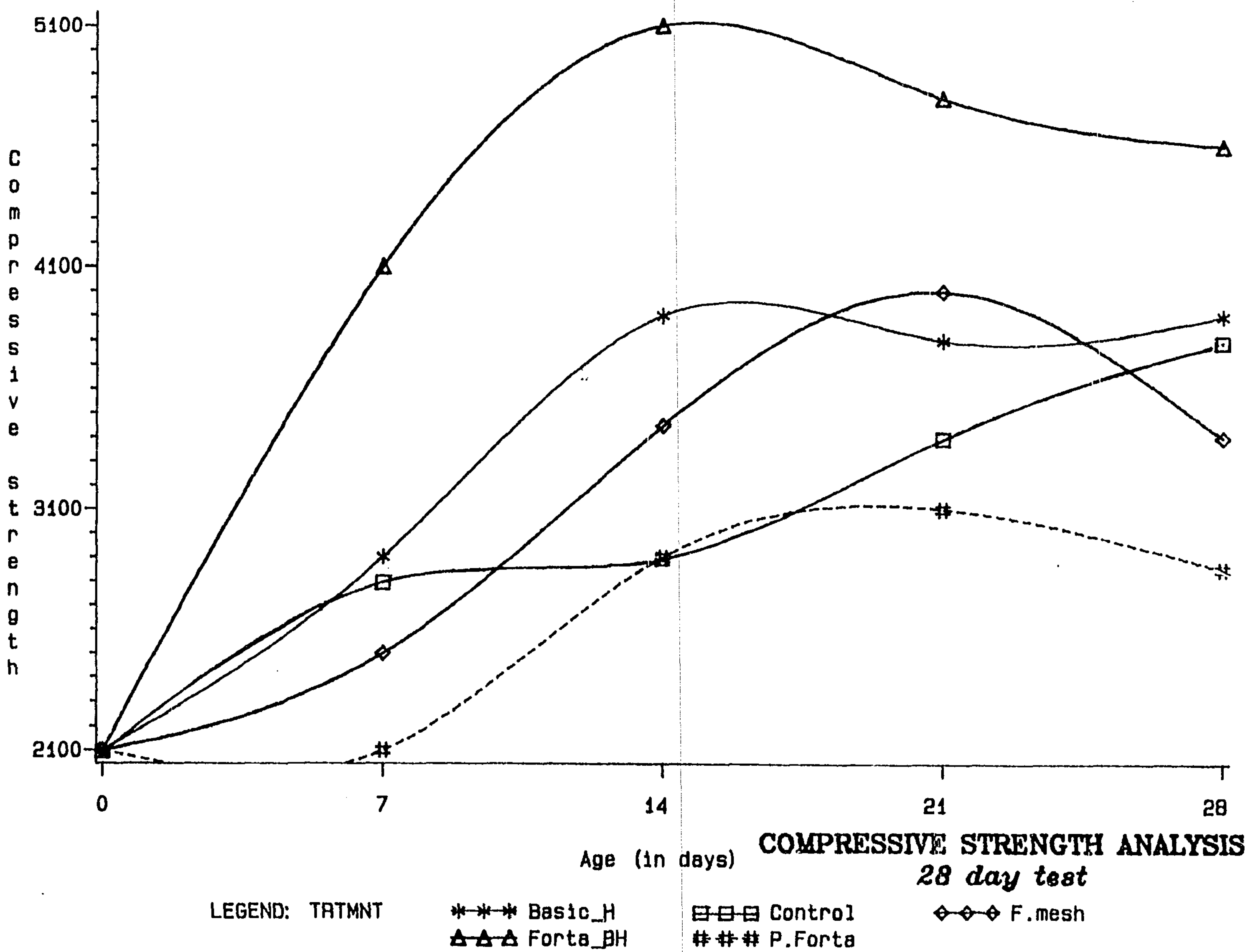


Figure 14. Compression cylinder plot

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