FIBER REINFORCEMENT OF CONCRETE STRUCTURES

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16. Abstract

Deterioration of concrete structures due to steel corrosion is a matter of considerable concern since the repairing of these structures proved to be a costly process. Repair and rehabilitation of the civil structures needs an enduring repair material. The ideal durable repair material should have low shrinkage, good thermal expansion, substantial modulus of elasticity, high tensile strength, improved fatigue and impact resistance. Reinforcing the concrete structures with fibers such as polypropylene is one of the possible ways to provide all the criteria of the durable repair material. This type of reinforcement is called Fiber Reinforcement of Concrete Structures. There is an increasing worldwide interest in utilizing fiber reinforced concrete structures for civil infrastructure applications.

The bonding between the fibers and the concrete has to be good and the plastic has to withstand the changing environment of freeze and thaw as well as a high PH of 12.5 and a low of PH 6.5 when saturated with sodium chloride. With these brand new materials, little is known about the effect of fiber percentage on fracture properties under hot and cold conditions and when saturated with seawater. This information is necessary to be able to study the freeze-thaw durability of the fiber reinforced concrete structures under different environmental conditions and also in the marine environment.

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1. INTRODUCTION:

Civil structures made of steel reinforced concrete normally suffer from corrosion of the steel by the salt, which results in the failure of those structures. Constant maintenance and repairing is needed to enhance the life cycle of those civil structures. There are many ways to minimize the failure of the concrete structures made of steel reinforce concrete. The custom approach is to adhesively bond fiber polymer composites onto the structure. This also helps to increase the toughness and tensile strength and improve the cracking and deformation characteristics of the resultant composite. But this method adds another layer, which is prone to degradation. These fiber polymer composites have been shown to suffer from degradation when exposed to marine environment due to surface blistering. As a result, the adhesive bond strength is reduced, which results in the de-lamination of the composite(1).

Another approach is to replace the bars in the steel with fibers to produce a fiber reinforced concrete and this is termed as FRC. Basically this method of reinforcing the concrete substantially alters the properties of the non-reinforced cement-based matrix which is brittle in nature, possesses little tensile strength compared to the inherent compressive strength.

The principal reason for incorporating fibers into a cement matrix is to increase the toughness and tensile strength, and improve the cracking deformation characteristics of the resultant composite. In order for fiber reinforced concrete (FRC) to be a viable construction material, it must be able to compete economically with existing reinforcing systems.

Only a few of the possible hundreds of fiber types have been found suitable for commercial applications (2,21). This project deals specifically with the concrete reinforced with the 'polypropylene fibers'. The objective of this research is to explore the properties of polypropylene fibers in specific environments to which the commercial FRCs are exposed.

2. SIGNIFICANCE OF POLYPROPYLENE FIBER REINFORCED CONCRETE

2.1 Background of Fiber Reinforced Concrete.

Portland cement concrete is considered to be a relatively brittle material. When subjected to tensile stresses, non-reinforced concrete will crack and fail. Since mid 1800's steel reinforcing has been used to overcome this problem. As a composite system, the reinforcing steel is assumed to carry all tensile loads.

The problem with employing steel in concrete is that over time steel corrodes due to the ingress of chloride ions. In the northeast, where sodium chloride de-icing salts are commonly used and a large amount of coastal area exists, chlorides are readily available for penetration into concrete to promote corrosion, which favors the formation of rust. Rust has a volume between four to ten times the iron, which dissolves to form it. The volume expansion produces large tensile stresses in the concrete, which initiates cracks and results in concrete spalling from the surface. Although some measures are available to reduce corrosion of steel in concrete such as corrosion inhibitive admixtures and coatings, a better and permanent solution may be replace the steel with a reinforcement that is less environmentally sensitive.

More recently micro fibers, such as those used in traditional composite materials, have been introduced into the concrete mixture to increase its toughness, or ability to resist crack growth.

FRC is Portland cement concrete reinforced with more or less randomly distributed fibers. In FRC, thousands of small fibers are dispersed and distributed randomly in the concrete during mixing, and thus improve concrete properties in all directions. Fibers help to improve the post peak ductility performance, pre-crack tensile strength, fatigue strength, impact strength and eliminate temperature and shrinkage cracks(13).

Several different types of fibers, both manmade and natural, have been incorporated into concrete. Use of natural fibers in concrete precedes the advent of conventional reinforced concrete in historical context. However, the technical aspects of FRC systems remained essentially undeveloped. Since the advent of fiber reinforcing of concrete in the 1940's, a great deal of testing has been conducted on the various fibrous materials to determine the actual characteristics and advantages for each product.

Several different types of fibers have been used to reinforce the cement-based matrices. The choice of fibers varies from synthetic organic materials such as polypropylene or carbon, synthetic inorganic such as steel or glass, natural organic such as cellulose or sisal to natural inorganic asbestos. Currently the commercial products are reinforced with steel, glass, polyester and polypropylene fibers. The selection of the type of fibers is guided by the properties of the fibers such as diameter, specific gravity, young’s modulus, tensile strength etc and the extent these fibers affect the properties of the cement matrix(2).

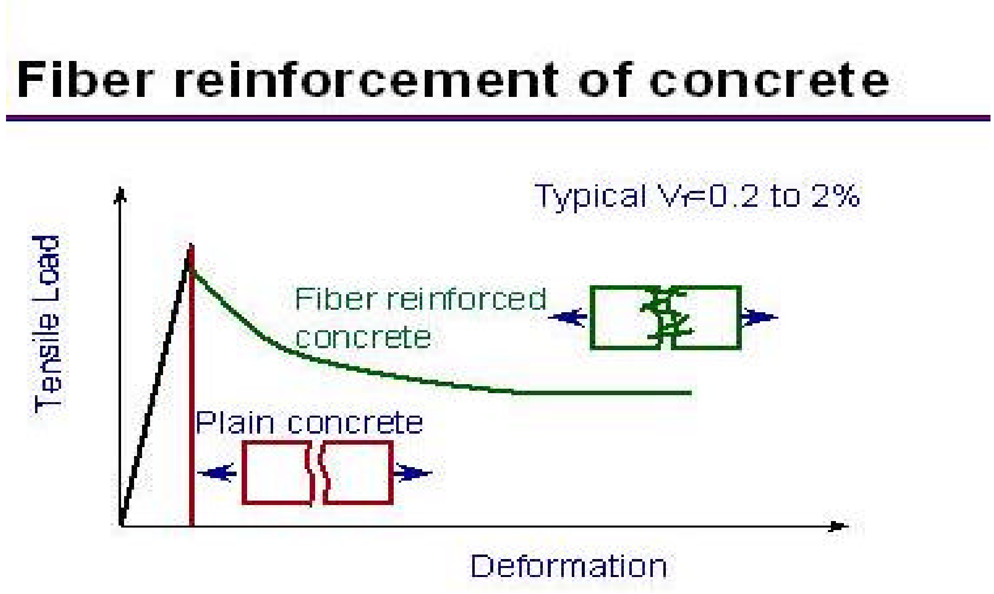


Figure 1. Tensile Load versus Deformation for Plain and Fiber Reinforced Concrete.

2.2 Behavior of Polypropylene Fibers in a Cement Matrix:

This research is oriented towards concrete reinforced with polypropylene fibers, so it is most important to understand how polypropylene fibers behave in the cement composite matrix. The study of this mechanism helps model the behavior of the composites in a real world environment.

The behavior of FRC under loading can be understood from the Figure 1. The plain concrete structure cracks into two pieces when the structure is subjected to the peak tensile load and cannot withstand further load or deformation. The fiber reinforced concrete structure cracks at the same peak tensile load, but does not separate and can maintain a load to very large deformations. The area under the curve shows the energy absorbed by the FRCs when subjected to tensile load. This can be termed as the post cracking response of the FRCs.

The real advantage of adding fibers is when fibers bridge these cracks and undergo pullout processes, such that the deformation can continue only with the further input of energy from the loading source.

Reinforcing fibers stretch more than concrete under loading. Therefore, the composite system of fiber reinforced concrete is assumed to work as if it were non-reinforced until it reaches its "first crack strength." It is from this point that fiber reinforcement takes over and holds the concrete together. With reinforcing, the maximum load carrying capacity is controlled by fibers pulling out of the composite. Reinforcing fibers do not have a deformed surface unlike larger steel reinforcing bars which have a non smooth surface which helps mechanical bonding. This condition limits performance to a point far less than the yield strength of the fiber itself. This is important because some fibers pull out easier than others when used as reinforcing and will affect the toughness of the concrete product in which they are placed.

Toughness is based on the total energy absorbed prior to compete failure. The main properties influencing toughness and maximum loading of fiber reinforced concrete are based on the type of fibers used, volume percent of the fiber, the aspect ratio and the orientation of the fibers in the matrix.

The other factors that control the performance of the composite material are physical properties of the reinforced concrete and matrix, the strength of the bond between fibers and matrix. The chemical properties of the fiber in terms of their inertness or reactivity with the surrounding environment plays an important role in determining the bonding characteristics of the fiber and the composite as they may or may not from a chemical bond between the fiber and matrix.

The environmental effects on the polypropylene fibers used for reinforcement need to be studied to understand the changes in the behavior of FRCs when placed in various environments. It has been understood that the change in the properties of the polypropylene fibers over a period of time when subjected to similar environments also affects the bonding characteristics of the fibers with the matrix, which subsequently alters the performance of the FRC loaded conditions,(2).

The objective of this research is to determine the environmental properties of the polymer fibers and how that affects the performance of the fiber reinforced composite. The environmental properties under investigation are the effect of temperature, and the effect of a marine environment on the tensile strength of the fibers. By studying the change in the tensile properties of the polypropylene fibers by themselves, these effects can be separated out from any general change in properties of the fiber reinforced concrete. Therefore matrix effects can be separated from fiber effects.

2.3. Fabrication of Polypropylene Fiber Reinforced Concrete.

Polypropylene fibers are added to the concrete in several different forms and by using various techniques. The fibers can be incorporated into concrete as short discrete chopped fibers, as a continuous network of fibrillated film, or as a woven mesh(2). The form of the available fiber decides the method of fabrication. Each and every method has its own limitations. The choice of the method is guided by the volume percentage of the fibers that can be obtained during fabrication using a particular technique.

Daniel, Roller and Anderson (2) state that Walton and Majumdar produced concrete panels reinforced with chopped mono-filament polypropylene fiber by a '*spray-suction de- watering*' technique. Fiber volume content up to 6% can be achieved by using the spray suction de-watering techniques. Composites incorporating chopped mono-filament and chopped fibrillated polypropylene film are produced using a mixing, de-watering and pressing technique (2). Fiber volumes up to 11% have been obtained by mixing chopped fiber directly into the matrix at high water-cement ratios and then removing the excess water through suction and pressing(2).

A hand lay-up technique was used to produce composites with continuous networks of polypropylene fibrillated films (3). Woven polypropylene mesh can be incorporated into a cement matrix using a hand lay-up technique. High volume percentage of fibers (up to 12%) in the cement matrix can be obtained by using continuous polypropylene film networks or woven mesh with the hand lay-up technique(2).

When chopped polypropylene fibers are incorporated into conventional ready mix concrete, volume percentages of fibers must be kept relatively low. This indicates that special mixing conditions are needed for high fiber volumes. The practical implication of this is that low fiber volumes should be specified for placement. Several researchers have acknowledged that the addition of polypropylene fiber to concrete has a marked effect on the concrete slump, which is a measure of how concrete flows. A low slump rate is undesirable as molds will not fill efficiently leaving voids. Fiber reinforced concrete slump is dependent on fiber length and fiber concentration(2).

Because polypropylene fibers are hydrophobic and non-polar, they can be mixed ahead of time to ensure uniform dispersion in the concrete mix. In the case of fibrillated film or tape fibers, mixing should be kept to a minimum to avoid unnecessary shredding of the fibers(2). Polypropylene fibers are usually added to ready mixed concrete after all the normal ingredients are completely mixed. When placing concrete the workability of the concrete is affected as the addition of polypropylene fibers has a definite negative impact on the slump, workability and finishability of the concrete. An optimum quantity of superplasticizer while mixing helps avoid the problem of reduction in workability(18)

Ready mixed concrete containing polypropylene fibers can be placed using conventional methods. To ensure maximum performance all entrapped air must be expelled from the concrete to achieve optimum density. Also during the process of incorporating of polypropylene fibers more compaction must be done than for the plain concrete. Generally, polypropylene fibers, when mixed with concrete, respond well to conventional compaction techniques and fibers do not easily segregate from the mix(2).

2.4 Properties of Polypropylene Fiber Reinforced Concrete.

The use of polypropylene fibers has successfully increased the toughness of concrete (3). Although polypropylene fibers are characterized by low elastic modulus and poor physiochemical bonding with cement paste, it is quite apparent that the load carrying ability of a structure under flexural loading is considerably increased (3). A substantial amount of research has been done to evaluate the properties of the fiber reinforced concrete. Test data have been classified for concrete reinforced with polypropylene fibers at volume percentages ranging from 0.1%-10.0%. The material properties of polypropylene fiber reinforced concrete are somewhat variable, depending greatly of fiber concentration and the form of the fiber reinforced(2).

The other major inherent factor that affects the properties of the fiber reinforced is the bond strength of the polypropylene fiber with cement composite. The effectiveness of the polypropylene fiber as concrete reinforcement depends on the bond between fiber and the matrix. The chemical bond between polypropylene fiber and the cement paste is very poor(2). In fact, concrete forms are commonly made of polypropylene because of the ease of release after hardening(3). The bundles of polypropylene fibers added to concrete are separated into millions of individual strands due to the abrasive action of the aggregates. The fibers are distributed throughout the entire matrix, providing support to concrete in all possible directions (3). This also explains the mechanism of how the interface is formed between the fibers and the cement matrix after incorporating the fibers into concrete.

"Polypropylene fibers in the form of fibrillated films and tapes or woven meshes provide better bond with the cement matrix than chopped monofilament fibers"(2). However, the improved bond is almost entirely physical and is a direct result of cement matrix penetration into the network of individual fiber filaments created by fibrillation(3) The fiber diameter and length also can have a direct effect on post-peak ductility behavior of FRC(17).

When chopped and twisted fibrillated polypropylene fibers with their open structure were used the interfacial adhesion was increased by the wedge action at the slightly disturbed fiber(3). The bond strength can only roughly be estimated by conducting pullout loads of twisted defibrillated fibers. The accurate calculation of the bond strength is not possible, because the surface area of the fiber content in contact with the cement matrix cannot be estimated(3).

In specimens that are at least one year old, the fibers break instead of being pulled out, in contrast to new specimens where fibers pullout rather than break(3). The evaluation of the tensile properties kin this research will help to understand the change in properties as a function of time. The approach is to measure any the change in tensile properties of fibers when exposed to different environments. The change of properties will be compared to the changes noted for FRC fiber behavior.

2.5 Advantages and Disadvantages of Fiber Reinforced Concrete.

Fiber reinforced concrete has started to find its place in many areas of civil infrastructure applications where the need for repairing, increased durability arises. Also FRCs are used in civil structures where corrosion can be avoided at the maximum.

Fiber reinforced concrete is better suited to minimize cavitation /erosion damage in structures such as sluice-ways, navigational locks and bridge piers where high velocity flows are encountered. A substantial weight saving can be realized using relatively thin FRC sections having the equivalent strength of thicker plain concrete sections. When used in bridges it helps to avoid catastrophic failures. Also in the quake prone areas the use of fiber reinforced concrete would certainly minimize the human casualties. In addition, polypropylene fibers reduce or relieve internal forces by blocking microscopic cracks from forming within the concrete(20)

The main disadvantage associated with the fiber reinforced concrete is fabrication. The process of incorporating fibers into the cement matrix is labor intensive and costlier than the production of the plain concrete. The real advantages gained by the use of FRC overrides this disadvantage.

3. POLYPROPYLENE AND POLYPROPYLENE FIBERS - STRUCTURE AND PROPERTIES.

3.1. Polypropylene

3.1.1. Introduction and Structure:

Polypropylene (PP) is a versatile thermoplastic material, which is produced by polymerizing monomer units of polypropylene molecules into very long polymer molecules or chains in the presence of a catalyst under carefully, controlled heat and pressure. Propylene is an unsaturated hydrocarbon, containing only carbon and hydrogen atoms:

$$CH_2{=}CH$$
|
$$CH_3$$

(Propylene)

There are many ways of polymerization of the monomer units, but PP as a commercially used material in its most widely used form is produced with catalysts that produce crystallizable polymer chains. With Ziegler-Natta or metallocene catalysts, the polymerization reaction is stereo-specific. Propylene molecules add to the polymer chain only in a particular orientation, depending on the chemical and crystal structure of the catalyst, and a regular, repeating three-dimensional structure is produced in the polymer chain. Propylene molecules are added to the main polymer chain, increasing the chain length, and not to one of the methyl groups attached to alternating carbon atoms that are termed as pendant methyl groups(4,6)

A typical structure of polypropylene chain is shown below,

$$----CH_2 ---- CH ---- CH_2 ---- CH ---- CH_2 ---- CH ----$$
| | |
$$CH_3 \quad CH_3 \quad CH_3$$

Polypropylene is one of the fastest growing classes of commodity thermoplastics, with a market share growth of 6-7% per year and the volume of polypropylene produced is exceeded only by polyethylene and polyvinyl chloride. The moderate cost and favorable properties of polypropylene contribute to its strong growth rate. Polypropylene is one of the lightest of all thermoplastics (0.9 g/cc). The reason for the popularity of the polypropylene fibers is because of the versatility of the material. It has a good combination of properties, cheaper than many other materials that belong to the family of polyolefins and it can be manufactured using various techniques. These benefits are derived from the very nature and the structure of polypropylene (4)

Many forms of commercial polypropylene are available. One form of PP is a semi-crystalline solid with good physical and mechanical and thermal properties. Another form of PP, produced in much lower volumes as a byproduct of semi-crystalline PP production and having very poor mechanical and thermal properties. The crystallizable form of PP is termed as "*isotactic*" PP and the non-crystallizable form is termed as "*atactic*" PP (5).

In "*isotactic*" polypropylene, the most common commercial form, pendant methyl groups are all in the same configuration and are in the same side of the polymer chain. The regular and repeating arrangement of the pendant methyl groups gives PP the high degree of crystallinity. In "*atactic*" PP, pendant methyl groups have a random orientation with respect to the polymer backbone. There is another form called "*Syndiotactic*" polypropylene that is now produced using metallocene catalysts. In this type of PP, the pendant methyl groups are on opposite sides of the polymer backbone. The amounts of isotactic, atactic and syndiotactic segments in a formulation are determined by the catalyst used and the polymerization conditions (4).

3.1.2 Polypropylene Morphology and Properties:

Polypropylene is a semi-crystalline polymer with varying degrees of crystallinity and with various types of crystal structures (4). The rate and manner in which the crystals have been formed influence the crystal structures. This in turn largely determines both physical properties and processing characteristics of the polymer. Nucleation agents are added in amounts below 0.1% to provide additional crystallization sites and the formation of smaller and more numerous polymer crystals. This controlled morphology of polymer termed to as 'high crystallinity PP' results in higher bulk properties of the material such as softening point, stiffness, tensile strength, modulus and hardness (14).

Crystallinity arises from the stereo-regularity in the molecular structure. Occasional irregularities such as branching or tail-to-tail addition during polymerization or the presence of copolymers limit the extent of crystallization. Atactic PP with its random, irregular molecular structure, is predominantly amorphous. Isotactic polymers are termed as 'Semi-Crystalline polymers' and characterized by high strength, stiffness, density and sharp melting points. Semi-crystalline materials are more opaque and can be used at high temperatures, while amorphous materials are generally more transparent and have greater toughness and ductility (4).

Polypropylene is an extremely hard, stiff, but brittle material at very low temperature, gradually becomes softer, more flexible, and tougher as the temperature increases and finally softens beyond the range of usefulness. It is also stated that the stiffness of polypropylene varies with temperature (7). This transition can be explained in a more relevant way in terms of melting point temperature (T_m) and glass transition temperature (T_g).

The crystalline structure of the semi-crystalline polymer undergoes a major change at the melting point T_m. At T_m, physical properties of the PP change abruptly, as the material becomes more viscous. Here again the T_m, varies with the amount of crystallinity (4). Theoretically semi-crystalline isotactic polypropylene resin has a maximum T_m value of 176 ^{0}C (348.8 ^{0}F) under normal processing conditions (6). Melting points of commercial isotactic polypropylene resins normally range from 160-166 ^{0}C (320 – 331 ^{0}F) due to the presence of atactic material and non-crystalline regions also melting points decrease dramatically with lower crystallinity. The high melting point of polypropylene provides resistance to softening at elevated temperatures. Standard grades of polypropylene can withstand continuous service temperatures of over 107 ^{0}C (225 ^{0}F) and over 121^0 C (250 ^{0}F) for short periods of time (7).

Amorphous regions of the PP undergo a transition a glass transition (T_g) at a temperature between -35 and 26 ^{0}C (-31 and 79 ^{0}F). This transition depends on the heating rate, thermal history and microstructure. Molecules and segments of polymer chains above the glass transition temperature vibrate and move in non-crystalline polymer regions. Motions include diffusion, rotation about bond axes, and translation under mechanical stresses. At the glass transition temperature free volume is restricted and only low amplitude vibrations occur. This movement continues down to absolute zero, at which point all movement ceases (4).

The normal temperature range within which PP is most commonly used is limited by the crystalline melting point T_m on the high side and by the glass transition temperature T_g on the low side (7).

3.1.3: Mechanical, Thermal Properties and Chemical resistance:

(a) Mechanical Properties.

Traditional materials tend to be relatively little affected by temperature and time within the normal service conditions. But thermoplastics exhibit a different behavior. Stresses and strains that a thermoplastic can withstand when they are applied slowly may be quite sufficient to shatter when they are applied rapidly. A stress that creates no problem for a short period may cause the material to deform or creep over a longer period of time. These are instances of the time-dependency of plastics.

The mechanical properties of polypropylene are strongly dependent on time, temperature and stress. Furthermore, it is a semi-crystalline material, so the degree of crystallinity and orientation also affects the mechanical properties. Also the material can exist as homopolymer, block copolymer and random copolymer and can be extensively modified by fillers, reinforcements and modifiers. These factors also affect the mechanical properties (4).

A summary of the mechanical properties are given below,

Tensile Strength: 25-33 Mpa

Flexural Modulus: 1.2-1.5 Gpa

Elongation at break: 150-300%

Strain at yield: 10-12%

(b) Thermal properties.

Polypropylene is a thermoplastic and hence softens when heated and hardens when cooled. It is hard at ambient temperatures and this inherent property allows permits economical processing techniques such as injection molding or extrusion. The softening point or resistance to deformation under heat limits its service temperature range. Melting point and the glass transition temperature control the operating range. If the product has a wide working temperature range, then the co-efficient of linear expansion becomes significant. The coefficient of linear expansion of polypropylene is higher than most commodity plastics but is less than that of polyethylenes. Its coefficient of linear expansion varies with temperature, unlike those of metals that are substantially independent of temperature (4).

"When polypropylene is exposed to high temperatures within its maximum operating temperatures a gradual deterioration takes place. This effect is known as thermal ageing (4). It is an oxidation process and hence it is related to weathering. Polypropylene is more susceptible to oxidation by oxidizing agents and by air at elevated temperatures (14). Normally all polypropylenes are stabilized against oxidation by adding stabilizers. Copper, manganese, cobalt and carbon black additives decrease resistance of polypropylene to heat ageing (4,6,7).

Thermal ageing resistance is measured using an "induction" technique. In this method samples are held at a particular temperature for some days to degrade the samples to a particular extent. Ageing temperature varies from 70 ^{0}C to 135 ^{0}C were used, depending upon the degree of stability of the fiber and the expediency of the test. A 50 percent loss in fiber strength and elongation or the toughness factor is generally taken as the end of the induction period and is considered as a relative measure of polymer stability at test temperature (8).

The resulting data make it possible to estimate the service life of polypropylene at elevated temperatures. For example, a polypropylene with an induction period of 20 days would have a service life of about 6 years at 80 ^{0}C, while one with an induction period of 10 at the same temperature days would have a life of about 1,000 days (4).

(c) Chemical resistance.

Chemical resistance refers to inertness and compatibility with other ingredients present within the compounded polymer as well as resistance to external environment. It is often associated with heat stability because reaction may take place during high-temperature processing (8). Polypropylene has a high resistance to chemical attack due to its non-polar nature. The term non-polar refers to the bond between atoms. The atoms of each element have specific electro-negativity values of the atoms in a bond. If the electro-negativity value is greater the polarity of the bond will be higher. When this difference is small the material is said to be non-polar. In other words, the solubility of a polymer is related to the forces holding the molecule together, and one measure of this is the solubility parameter. Vulnerability is said to occur when the solubility parameter of the polymer and solvent are similar. It is understood that lower the value of the solubility parameter, the more resistant will be the polymer (4,7). Normally in chemical solutions polymers are not dissolved outright but soften and also may swell. These changes can be reversible when the chemical is driven off, but changes that are caused by chemical reaction are irreversible. Many chemical attacks are more severe at higher temperatures and at higher concentrations of the chemical reagent.

In general, polypropylene is resistant to alcohols, organic acids, esters and ketones. It is swollen by aliphatic and aromatic hydrocarbons, and by halogenated hydrocarbons but is highly resistant to most inorganic acids and alkalis. However, it is readily attacked by strong, oxidizing acids and halogens. Contact with copper and copper alloys accelerates oxidation, particularly in the presence of fillers and reinforcements. Also the water absorption is very low and this is again because of the non-polar nature of the material. (4,6,7,8).

3.2 POLYPROPYLENE FIBERS.

3.2.1: Introduction.

Polypropylene is widely used in the production of fibers, for use in carpeting, rope and twine, automobile interiors, textiles and in other applications (4). Production of polypropylene in U.S. during 1994 reached 2688 million lbs. for fibers. Consumption reached to 1,000,000,000 lbs per year for non-woven fabric application with staple fiber product showing about 475,000,000 lb. and spun-bond fabrics about 400,000,000 lb (19). Fibers are one of the most important applications for polypropylene homopolymer. Due to its melt flow properties, fiber formation is easier when compared to other polymers. Its low density results in a higher yield of fiber per pound of material (4).

Polypropylene chips can be converted to fiber/filament by traditional melt spinning processing, though the operating parameters need to be changed depending on the final products. Spun-bonded and melt-blown are also very important fibers producing techniques for non-wovens (19). Melt spinning is a process in which the molten polymer is forced through a spinneret, a metal plate that contains as many as 100-200 holes or capillaries, each with a diameter less than 0.008 inches. The molten polymer emerges from the spinneret as continuous strands of fiber that are cooled or quenched using water or current of air. The fibers are then drawn by heating to a temperature close to the melting point and stretched. This process reduces the cross-section and produces orientation in fibers, resulting in increased tensile strength (4). The mode of polymerization, its high molecular weight and molecular orientation and the process that is adopted for manufacturing determines the properties of the polypropylene fibers (3).

Polypropylene demonstrates an interesting example of the need for regularity of structure to secure crystallization in a polymer. During polymerization, the successive chain sequences of $--CH_2--CH(CH_3)$ can be added on in either a right-handed or a left-handed screw direction, owing to the stereochemistry of the chain. If these forms occur at random, the chain will have an irregular shape and will not crystallize. This is *atactic* PP that is unsuitable for making fibers. But if successions of units are added on to give the isotactic form the molecular will be regular and will crystallize. It was the discovery of means of controlling the polymerization that led to the production of *isotactic* polypropylene fibers (10).

During crystallization of polymer, in the absence of external forces, the polymer chains are arranged randomly in no preferred direction. When the polymer is subjected to external stress such as flexing immediately after crystallization the polymer chains align in the direction of the external stress. This process is called 'Orientation', which is common in the production of polypropylene fibers. Normally uniaxial orientation is used for the production of fibers (4,8).

Polypropylene fibers are available in two different forms; Monofilaments and Multi-filaments. Monofilaments are ribbons of polypropylene composed of a single extruded filament produced by melt spinning followed by water quenching. Sizes of monofilaments range from 75-5000 denier (1 denier = weight in grams of 9000 m of fiber) (3,4). Monofilaments are used in weaving stiffer products such as rope or twine. Ropes thus produced have high wear resistance, do not absorb water, float due to the low density and they retain strength when they are wet. Monofilament fibers are characterized by highly reflective and translucent surface, limited absorption capacity, high stiffness and good tensile strength (4,8).

Several individual monofilaments that are ≤ 75 denier are grouped into a single continuous bundle to produce Multifilaments. Filaments that are of size ≤ 30 denier are air quenched. Slow cooling results in the very highly ordered crystal structure and hence fibers possess high thermal stability and low creep. Larger filaments cool more slowly and air quenching is not economically and hence water quenching is used instead. Due to this rapid cooling, enough time is not available for the formation of crystalline structures. Consequently water quenched fibers are tough with high tenacity. Multifilament fibers are characterized by flexibility, lightweight and hydrophobic nature.

Polypropylene fibers are also produced as continuous cylindrical monofilaments that can be chopped to specified lengths or as films and tapes that can be fibrillated to form the fibrils of rectangular cross-section (2). Fibrillated means the polypropylene film is slit so it can be expanded into an open network of fibers (3).

3.2.2 Properties of Polypropylene Fibers.

Polypropylene fibers are composed of crystalline and non-crystalline regions. The spherulites developed from a nucleus can range in size from fractions of micrometer to centimeters in diameter. Each crystal is surrounded by non-crystalline. Fiber spinning and drawing may cause the orientation of both crystalline and amorphous regions. If the extension is less than 0.5%, the spherulite deformation is elastic and no disruption of the structure occurs, otherwise spherulites are highly oriented in the direction of the force and finally are converted to microfibrils. These highly anisotropic microfibrillar structures lead to anisotropic fiber properties (19).

Polypropylene fibers are produced in a variety of types with different tenacities designed to suit varying market requirement. Fibers for general textile uses have tenacities in the range of 4.5-6.0 g/den. High tenacity yarns up to 9.0 g/den are produced for the use in ropes, nets and other similar application(18). Polypropylene fibers are characterized by lightweight, good resilience, good thermal stability, high strength, and favorable elongation properties (13).

The physical properties of the PP fibers are summarized as follows (4,18).

Thermal conductivity	0.95 Btu-in/$ft^{2}\cdot hr\cdot {}^{o}F$
Coefficient of linear thermal expansion	4.0 x $10^{-5}/^{o}F$
Decomposition temperature range	328-410^{0} C
Specific gravity	0.9

The properties of monofilament and multifilament fibers vary considerably. Depending on the diameter the Young's modulus of the monofilaments will be up to 725 ksi and for the fibrillated multifilaments, it will be up to 500 ksi. The tensile strength of the monofilaments will be up to 65 ksi whereas the multifilaments have the tensile strength within the range of 80 to 110 ksi (2).

Chemical resistance is excellent at room temperature. They don't absorb water because of hydrophobic nature. It has excellent abrasion resistance due to the surface smoothness. The fibers do not react to any substances that can form stains and they have good washability. The growth of microorganisms does not affect the mechanical properties of fibers (2,3,4,9). They also exhibit very good chemical inertness but they degrade from exposure to UV Light (4,9). Typical fibers are shown in figure 2.

3.2.3 Application of Polypropylene Fibers in Concrete.

Several manufacturers currently produce polypropylene fiber specifically for use in concrete as a form of reinforcement as they possess many properties that make them particularly adaptable for use in concrete (2). Polypropylene has ,for polymers, a high melting point (165 ^{0}C) and it is chemically inert. The chemical inertness makes the fibers resistant to

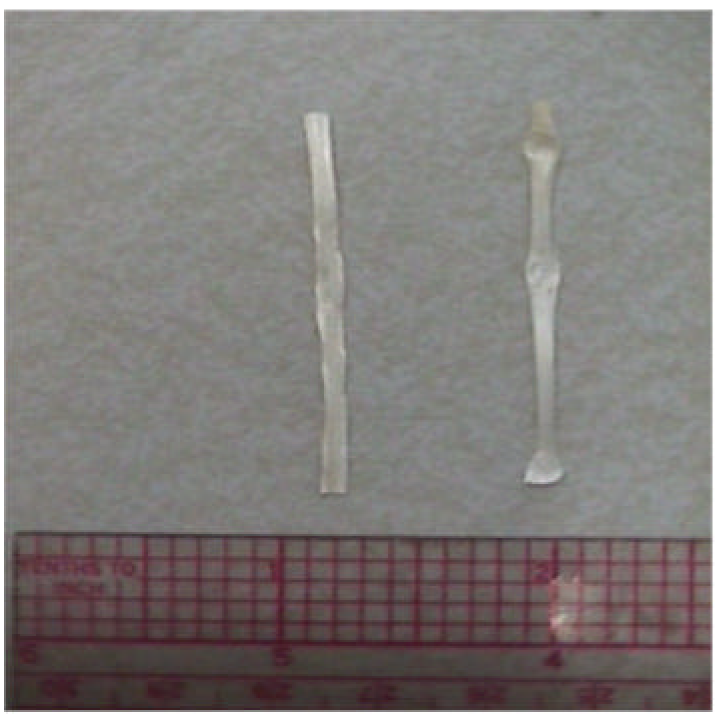


Figure 2. Polypropylene fibers used for reinforcing concrete.

most chemicals. Any chemical that will not attack the concrete will have no effect on the fiber either (3). Polypropylene has a hydrophobic surface that prevents it from being wetted by the cement paste. Since they are non-polar the bundles of polypropylene fibers do not cling or ball together (3). The hydrophobic nature of the polypropylene fiber does not affect the mixing water requirements of the concrete (2). Another type of fiber called Collated Polypropylene Fiber (CFP) is used for reinforcement of concrete. CFP fibers are produced by slitting film sheets in the longitudinal direction and then further distressed to produce fine fibers which are collated or held together by cross linking along their length (11). The orientation of the fibers while manufacturing leaves the fibers weak in the lateral direction, which facilitates fibrillation. The cement matrix can therefore penetrate in the mesh structure between the individual fibrils and create a mechanical bond between fiber and matrix.

The shortcomings are low combustibility and attack by sunlight and oxygen. Because of low combustibility a fire will leave the concrete with an additional porosity equal to the volume percentage of the fibers (3).

The tensile strength of the polypropylene fiber samples used for the experiments in this research ranges from 45-65 ksi. The samples have an average cross-sectional area of 0.0006 inch with an average length of 2 inches. These types of polypropylene fibers are produced by continuously welding monofilaments.

4. PROJECT DESCRIPTION AND EXPERIMENTAL PROCEDURES:

4.1 Background.

Polypropylene fibers that are added to the concrete for reinforcement contributes for the post peak ductility of the FRCs. If fiber contribution to ductility of hardened concrete is the reason for use of PP fibers then enough information about the long-term performance of these fibers should be ascertained. Most studies on high performance fiber reinforced cement composites have addressed only short-term properties (3). However, in civil engineering applications, durability is the matter of greatest concern. Durability covers service life, long-term performance, and resistance to thermal and environmental effects (16). Need for information on time-dependent properties or durability with time is very important to estimate the service life.

The vital parameters that are to be estimated are the durability of polypropylene fibers in concrete environment, durability of fibers that are exposed to elements either due to cracking or partial deterioration of concrete. Durability can be defined as the length of time during which early-age performance expressed in terms of tensile, compressive, shear and flexural strength and also impact resistance, fatigue resistance. Durability is influenced by many factors such as normal ageing, variations in temperature including high and low temperatures, resistance to freezing and thawing, chemical and biological attack and also mechanical wear (15). It is understood that if the fibers deteriorate the FRC will behave like a plain concrete. Subsequently, the void or channels left by the deteriorated will also affect the long-term durability of the concrete (3,4).

The fibers exposed to the environment should be durable in order to sustain composite action. Although the fibers are actually protected inside the concrete, the durability of the fibers is susceptible to the exposed environment due to the cracking of the concrete sections.

The objective of this research is to identify the long time effect of the elevated temperature and the effect of low temperature on the tensile properties of the polypropylene fibers. The parameter chosen for evaluating the durability is 'tensile strength' of the polypropylene fibers. The tensile strength of any material is a measure of its performance limit. It shows the breaking point of the brittle material or the yield point of the ductile material.

To test the durability of fibers for high and low temperatures, a normal service condition was determined. It is already mentioned in the previous chapter that the normal temperature range within which polypropylene fibers are used are limited by the glass transition temperature Tg (-35^0 to 26 ^{0}C) and the melting point Tm (260 ^{0}C). So it has been decided to keep the limit of testing within the normal service conditions. The lower temperature to which the polypropylene fibers are exposed was fixed at 20 ^{0}F and the higher temperature exposure was fixed at 160 ^{0}F. The actual goal of this project is to study the long-term properties of the fiber reinforced concrete. The first phase of the experimental research is limited to six month. However, the research project is scheduled for three years. The baseline data that will be established from the experimental data will help to model the properties of the polypropylene fibers and the fiber reinforced concrete. The tensile data obtained at the upper and lower limit temperatures of 20 ^{0}F and 160 ^{0}F will help to model the long-term properties over a wide range of conditions.

Hence the polypropylene fibers that are used for the commercial production of the fiber reinforced concrete will be held at 160 ^{0}F to determine the effect of an elevated temperature on their tensile properties. To determine the effect of the low temperature properties the samples are held at 20 ^{0}F. To study the effects in the salt or ionic environment on fibers they are placed in salt water at high (160 ^{0}F) and at low (20 ^{0}F) temperatures.

To study the effect of a marine environment, fibers are placed in a salt spray chamber at 100 ^{0}F. This temperature is maintained in the salt spray chamber to accelerate the effect of marine environment.

The samples were removed from simulated environments at regular intervals such as the end of the each month for 6 months and the tensile properties measured using an Instron tensile test machine. The samples were extended until failure and the failure load recorded. Although a three-year time limit is proposed for this research, the first phase was limited to collection of the data for only six months.

4.2. Resources Used.

The resources needed for this research included the Instron tensile test machine model type-1101 shown in figure 3, furnace manufactured by 'BLUE M ELECTRIC COMPANY' (Model No. 0V-18A - Serial No. 0V1-9513) to simulate the high temperature environments, refrigerator manufactured by Acme to place the samples at low temperatures and a salt spray chamber manufactured by the Singleton Corporation, model No. 20-16621, shown in figure 4. Considerable literature survey was done using the books in the University of Rhode Island library and in the library of University of

Massachusetts at Lowell. W.G.Grace Company, a well-known commercial producer of fiber reinforced concrete, supplied the polypropylene fibers.

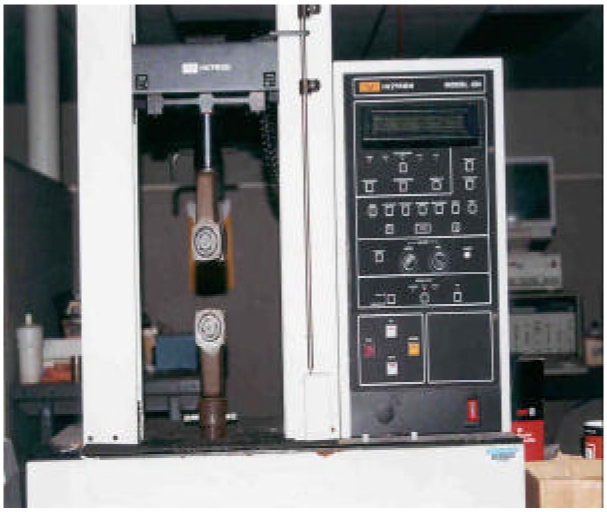


Figure 3. Instron Tensile Tester

Figure 4. Salt spray chamber.

4.3. Impact of the Research.

The results of the experiments were then interpreted to study the tensile properties of the fibers when they are exposed to various environmental conditions. The interpretation of the tensile properties indirectly shows how the fiber performs at these conditions. The change in the properties of the PP fibers definitely reflects the bonding characteristics of the fiber with the matrix. It has been emphasized previously in this report that for a satisfactory performance of the FRC structures there must be a good bond between the fiber and the cement matrix. Although the production of the fiber reinforced concrete structures are commercialized not much research has been done in the area studying the long-term properties of the reinforcing fibers and also the fiber reinforced concrete structures. The structures thus produced are sold to different users who place the FRCs in a particular environment varying from low temperatures to aggressive environments. Clear baseline data are not available to provide a clear specification for the users. The baseline data thus gathered in this research will help to improve the standardization of the commercial production of polypropylene fiber reinforced concrete structures.

The extended research would be to find the mechanical properties of the FRC structures when they are exposed to similar environments. The baseline data will assist this extended research by providing the fiber-only properties under the same exposed conditions.

5. EXPERIMENATAL RESULTS AND ANALYSIS:

5.1 Experimental Specifications and Results.

The objective of the experiment is to generate the baseline tensile data for the polypropylene fibers for the short-time effects of low temperature and high temperatures for a period of 6 months for the specific environments. The evaluation of short-term properties forms the first phase of the proposed research, which is to evaluate the long-term properties of the polypropylene fibers. The polypropylene fibers were placed in the following simulated environments.

Environment 1: 160 degree Fahrenheit.

Environment 2: 160 degree Fahrenheit in salt water.

Environment 3: 20 degree Fahrenheit.

Environment 4: 20 degree Fahrenheit in salt water.

Environment 5: 100 degree Fahrenheit in salt spray chamber.

As per the objective the samples were taken from the specified environments and tested in the Instron machine. All tests were conducted at room temperature of 65 °F. The load range was set to 100 lbs. The speed of the grip movement was set at 0.25 inches/min. The chart speed of the chart plotter, which plots the tensile strength of the polypropylene fibers, was set at 0.5 inches/min.

The typical plot for the tensile strength of the polypropylene fiber is as shown in Figure 5. The initial offset in the graph shown as region A indicates the pre-load on the fiber exerted by the machines grips. As the top grip moves upwards the curve moves upwards. The region B indicates that there is a slip between the grips and fiber as a result a smooth slanting line appears. When the top grip of the machine moves upwards the orientation of the curve changes to reach a peak point at C in Figure 5, which indicates the peak tensile force. The load rapidly decreased when the fiber failed after reaching the peak load.

Five similar samples taken from the same environment were tested to failure. All samples were given one hour to equilibrate to the 65 °F temperature prior to testing. The average was calculated and taken as the force exerted on the fiber. The average cross sectional area was calculated by measuring the width and thickness of the fiber bundle

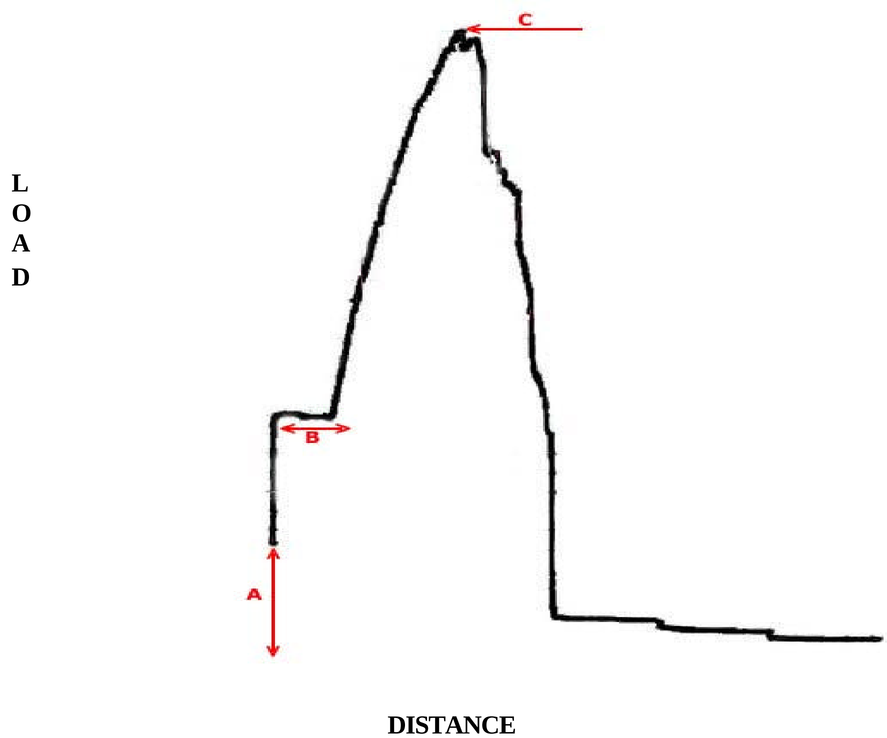


Figure 5. Load against distance curve for polypropylene fibers.

with a micrometer. The individual fiber width was measured in a scanning electron microscope. By assuming diametral contact, the number of individual fibers in the bundle was calculated. The cross sectional area of the bundle of fibers was then calculated by multiplication of the number of fibers and their individual cross sectional area. The ratio of the peak force to the average cross-sectional area of the fiber gives the ultimate tensile strength of the fiber subjected to the respective environment. This procedure was done for the polypropylene fibers taken from all the environments described above. The data thus obtained from the experiments were then tabulated as shown in the Appendix.

5.2 Analysis of the Results.

For making any valid interpretations, the data obtained from the experiments are analyzed by various methods. The following methods of analysis are done for the tensile data of the polypropylene fibers.

- 'Error bar' chart with 95% Confidence interval.
- Trend-line chart to find the trend of the tensile strength.
- Control chart to provide the baseline data.
- Paired T-Test to find the significance on the differences among the various environments followed by the 'Normal Probability Plot' to check the adequacy of the model.

5.2.1. Analysis by Error Bar Charts.

The basic method for representing a data set is by plotting the 'Error Bars'. Error bars graphically express potential error amounts relative to each data point in a group of related data points plotted in a chart. The charts of error bars with 95% confidence interval for the tensile data of the polypropylene fibers placed in the environments 160^0 F, 160^0 F in salt water, 20^0 F, 20^0 F in salt water and in salt spray chamber are respectively shown in Figures 6,7,8,9,10. These charts are plotted with the help of MS Excel software. Tensile data for polypropylene fibers at room temperature of 65 °F is plotted with the tensile test data.

FIGURE 6: ERROR BAR CHART FOR TENSILE DATA OF POLYPROPYLENE FIBERS AT 16 DEGREE FAHRENHEIT

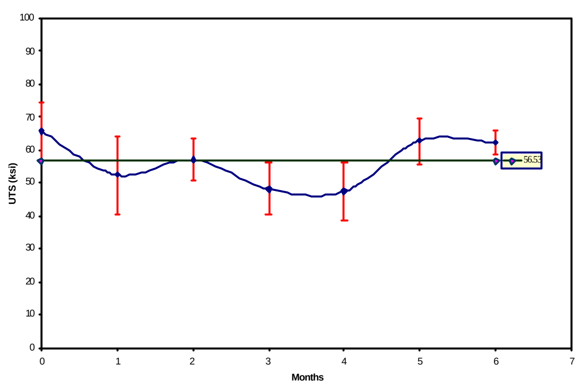


FIGURE 7: ERROR BAR CHART FOR TENSILE DATA OF POLYPROPYLENE FIBERS IN SALT WATER AT 160 DEGREE FAHRENHEIT

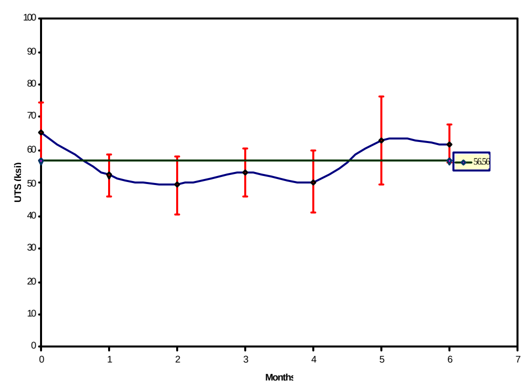


FIGURE 8: ERROR BAR CHART FOR TENSILE DATA OF POLYPROPYLNE FIBERS AT 2 DEGREE FAHRENHEIT

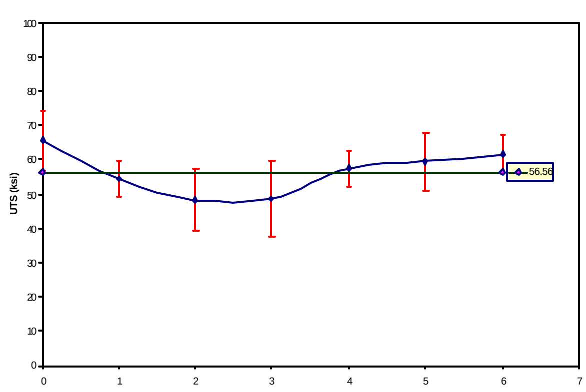
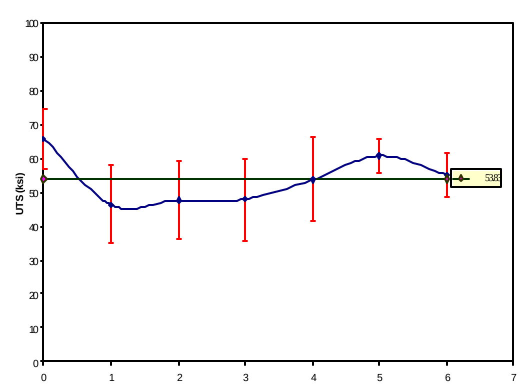
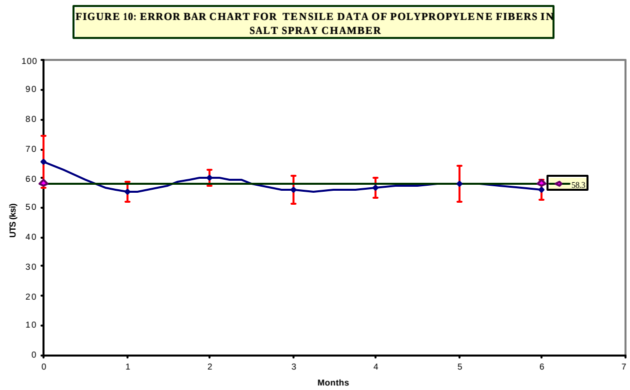


FIGURE 9: ERROR BAR CHART FOR TENSILE DATA OF POLYPROPYLNE FIBERS IN SALT WATER AT 20 DEGREE FAHRENHEIT





The standard deviations of the each month's tensile data were calculated at of 95% confidence interval.

These confidence interval values and y-error bars are presented in Figures 6,7,8,9,10. The straight line running across the error bars in each plot for the respective environments shows the overall mean population of the collection of tensile data of all the months.

The tensile data for polypropylene fibers were not consistent. The polypropylene fibers shown in Figure 2 have welds at some locations. These fail at the low range of measured failure forces. These are termed poorly welded mono-filaments of polypropylene fibers. The polypropylene fibers that do not have welds fail at much higher loads. The experiments were conducted with random sampling of the fibers and therefore a batch of testing for a particular month can consist of both types of fibers. Hence the tensile data for the polypropylene fibers do not show a constant value but a range of values.

The error bars with 95% confidence interval for the environment of 160 ^{0}F, shown in Figure 6, overlap consistently for each months. The overlapping can be confirmed by referring to the overall mean population line. The overall mean population line passes between all error bars except for the sixth month. But this difference is not statistically significant. Hence it can be stated that the tensile property of the polypropylene fibers do not change under the environment of 160 ^{0}F.

Similarly for all the other environments shown in Figures 7,8,9 and10, the error bars with 95% confidence interval overlap consistently. The overall mean population line crosses all the error bars respectively in all the environments. For the environment of the polypropylene fibers placed in salt water at 20 ^{0}F there is a slight deviation of the overall mean population line occurs during the 5th month's data. However this is not significant as the overall mean population line crosses the 6th month's error bar satisfactorily.

It is inferred from all the charts that are no statistically significant differences among the tensile data of each month's for respective environments. Hence it can be concluded that there is no significant change in the tensile properties of the polypropylene fibers and they remain constant when they are placed in all the specified environments.

5.2.2. Analysis By Plotting Trend-Lines.

Trend lines are used to analyze the problem of predictions and also to show the behavioral trend of the actual data. The trend lines actually smoothes out the fluctuations in the data and shows the pattern or trend clearly. The trend-line charts for the tensile data of the polypropylene fibers placed in the environments at 160^{0} F, 160^{0} F in salt water, 20^{0} F, 20^{0} F in salt water and 100^{0} F in salt spray chamber are respectively shown in Figures 11,12,13,14 and 15. The linear trend-line is plotted by calculating the least squares fit for a line by the given equation y = mx + b, where m is the slope and b is the intercept. The equation of the trend-line is also displayed in all the charts. These trend-line charts are plotted using MS Excel software.

The trend-line chart for the tensile data of the polypropylene fibers placed in the environment of 160^0 F is shown in Figure 11. The trend-line moving across the tensile data of each month's exhibits straight-line behavior with a negligible slope of 0.0482. The trends that can be inferred from this chart is that the tensile strength of the polypropylene fibers when they are placed at 160 ^{0}F does not change and remains constant.

FIGURE 11: TRENDLINE CHART FOR TENSILE DATA OF POLYPROPYLENE FIBERS AT 160 DEGREE FAHRENHEIT

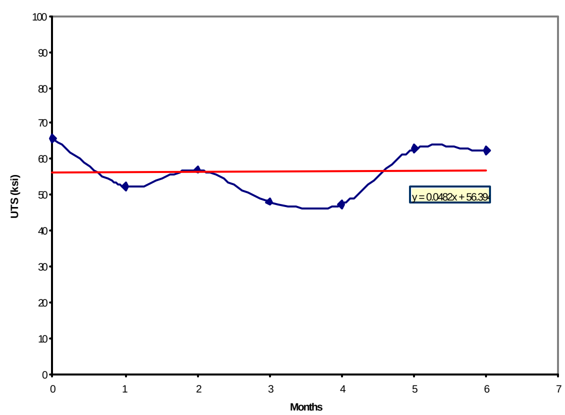


FIGURE 12: TRENDLINE CHART FOR TENSILE DATA OF POLYPROPYLENE FIBERS IN SALT WATER AT 160 DEGREE FAHRENHEIT

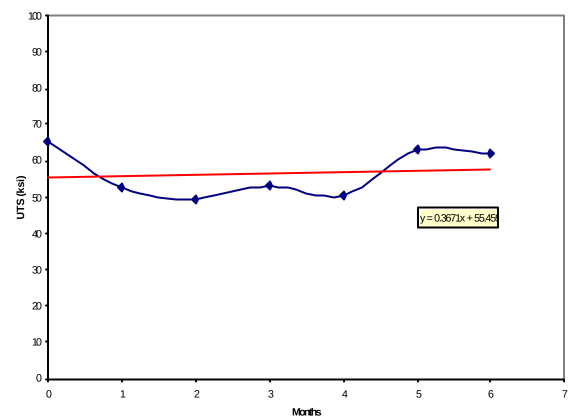


FIGURE 13: TRENDLINE CHART FOR TENSILE DATA OF POLYPROPYLENE FIBERS AT 20 DEGREE FAHRENHEIT

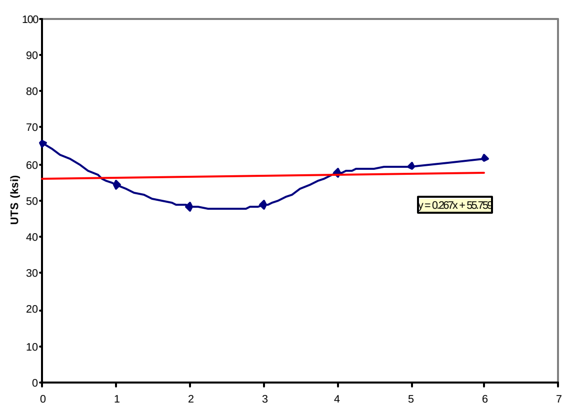


FIGURE 14: TRENDLINE CHART FOR TENSILE DATA OF POLYPROPYLNE FIBERS IN SALT WATER AT 20 DEGREE FAHRENHEIT

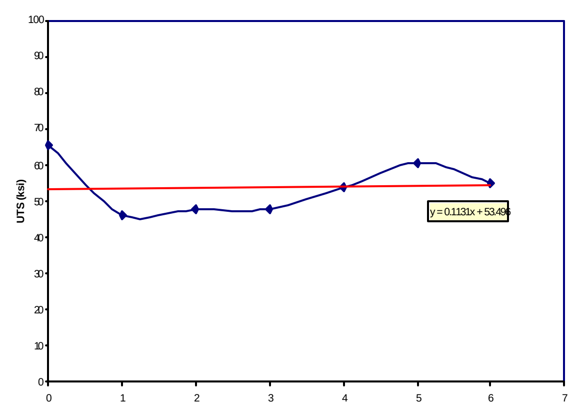
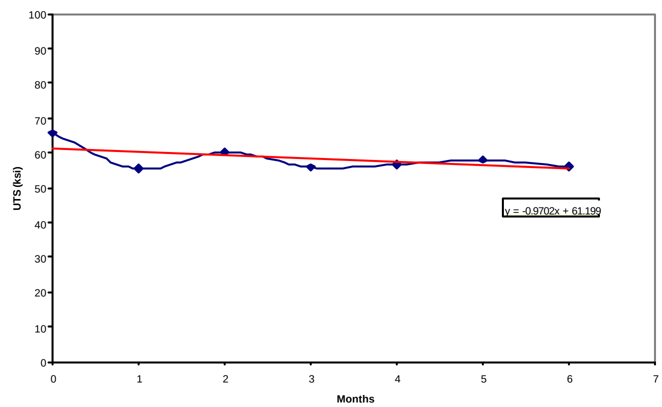


FIGURE 15: TRENDLINE CHART FOR TENSILE DATA FOR POLYPROPYLENE FIBERS IN SALT SPRAY CHAMBER



The same type of behavior is apparent in all the charts of the respective environment. The slopes of the trend-line equation for the tensile data of the polypropylene fibers placed in saltwater at 160 ^{0}F in salt water, 20 ^{0}F in salt water and 95 ^{0}F in salt spray chamber are respectively 0.3671, 0.267, 0.1131 and -0.9702. All these values are approximately equal to the slope of a straight line. Hence a common pattern is exhibited by the tensile strength of the polypropylene fibers when they are placed in all the specified environments.

The analysis of trend-line charts for the tensile data of the polypropylene fibers placed in all the specified environments helps us to deduce that the tensile strength of the polypropylene fibers are not affected and remains constant.

5.2.3. Control Chart to Establish Baseline Data.

A control chart is an important statistical tool used for the study and control of repetitive process and also to establish a baseline data. Use of control charts is a very common in manufacturing industries. Manufacturers often need to monitor the variation of the critical parameters. A graphical approach, called a control chart, is recommended to record the variation in data for this purpose because it allows for the visual inspection of outliers and trends. It adds a centerline and control limits to the plot and helps to identify unusual observations. To construct a control chart the following steps are followed.

1. Plot the observations versus time.
2. Add a solid line centerline at the level of sample mean x.
3. Add dashed line for the control limits at x-3σ and x+3σ, where σ = standard deviation.

The x-3σ and the x+3σ limits are termed as upper and lower control limits respectively. The upper and lower control charts help to identify unusually low or unusually high observations. It allows distinguishing between typical variation that is especially large and could be due to special causes. Any time an observation falls outside of the control limits, an effort should be made to search for the reason.

The control charts for the tensile data of the polypropylene fibers placed in the environments at 160^0 F, 160^0 F in salt water, 20^0 F, 20^0 F in salt water and 100^0 F in salt spray chamber are respectively shown in Figures 16,17,18,19,20. The software 'MINITAB' generated these Control Charts [21].

These control charts provide a baseline data by recording the trend of the tensile data over a period of six months. The upper and lower control limits of the control charts for the tensile data of the polypropylene fibers placed in the specific environments were calculated at 3 sigma level. The centerline was drawn at a level marked by overall mean of the tensile data of all the months for a particular environment. It was observed from all the control charts that the data points connected by the straight lines remained well within the upper and lower control limits.

Hence these control charts help to deduce that the data obtained from the experiments remained well within the control limits. Also these control charts provide a clear baseline data about the behavior of the tensile strength of the polypropylene fibers when they are exposed to the specific environments, which satisfy the one of the major objectives of this research.

5.2.4. Paired T-Test and Normal Probability method:

In this analysis the tensile data results from various environments were compared with a particular base environment to find if there is any significant change or a deviation in the

FIGURE 16: CONTROL CHART FOR TENSILE DATA OF POLYPROPYLENE FIBERS AT 160 DEGREE FAHRENHEIT

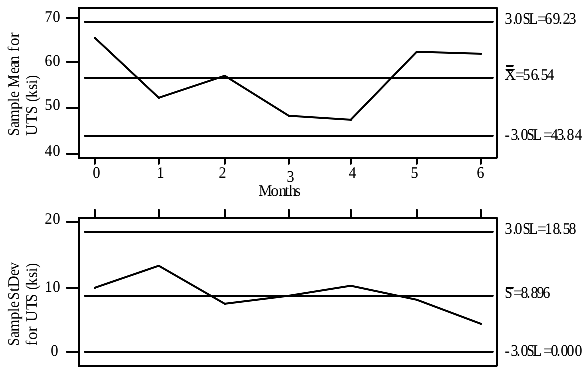


FIGURE 17: CONTROL CHART FOR TENSILE DATA OF POLYPROPYLNE FIBERS IN SALT WATER AT 160 DEGREE FAHRENHEIT

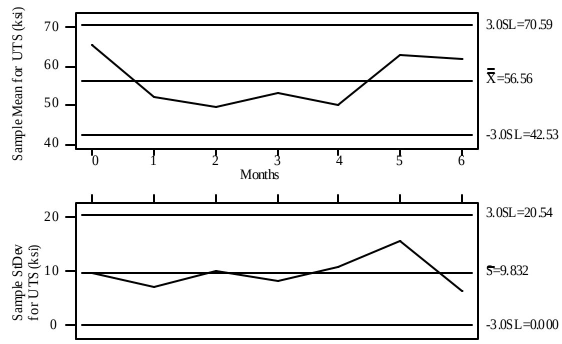


FIGURE 18: CONTROL CHART FOR TENSILE DATA OF POLYPROPYLENE FIBERS AT 20 DEGREE FAHRENHEIT

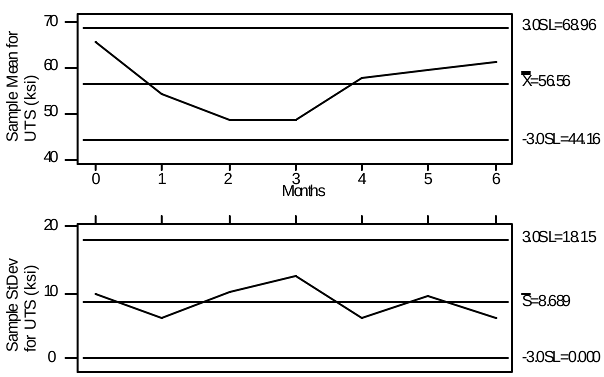


FIGURE 19: CONTROL CHART FOR TENSILE DATA OF POLYPROPYLENE FIBERS IN SALT WATER AT 20 DEGREE FAHRENHEIT

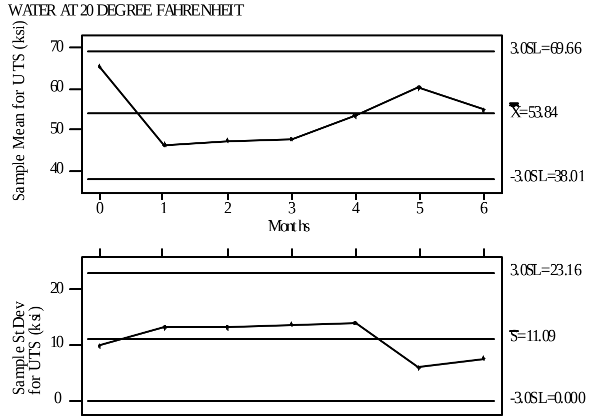
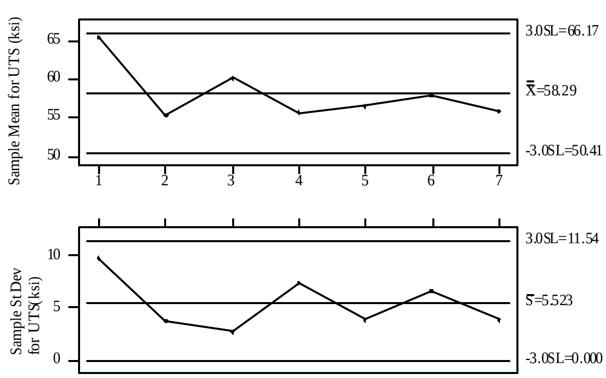


FIGURE 20: CONTROL CHART FOR TENSILE DATA FOR POLYPROPYLENE FIBERS IN SALT SPRAY CHAMBER AT 100 DEGREE FAHRENHEIT



tensile strength of the polypropylene fibers with respect to a particular environment. It intends to determine appropriate intervals to contain allowable differences between the tensile data between various environments. Data retrieved from all the environments were transferred to MS Excel and MINITAB for certain statistical analysis. The 95% prediction interval on the difference between the individual test results was obtained under the assumption that the data followed a normal distribution.

Determination of 95% prediction interval can be expressed mathematically as:

$$\{m -(Z_{a/2})s \ , m + (Z_{a/2})\, s\ \}$$

Where a = 0.05 for 95% interval, μ = mean & σ =standard deviation

The statistical software MINITAB was employed in determining the adequacy of the analytical model and in conducting the hypothesis testing. Paired t-tests were conducted to determine if there are any significant differences exist between the two test results and also to check the adequacy of the model. The hypothesis (H_o) that no difference existed between the two results was tested against the alternate hypothesis (H_1) that differences did exist. The hypothesis can be expressed as follows:

H_o: $D = 0$

H_1: $D \neq 0$

Where D is the difference between the two test results, H_o is null hypothesis and H_1 is the alternate hypothesis. The t-test was conducted using a P value of 0.05. The conclusion of the hypothesis testing will be:

reject H_o, there is a difference if P £ *0.05*

fail to reject H_o, there is no difference if P > *0.05*

If there is no significant difference, the suggested 95% prediction limits will be re-centered at 0 (zero), otherwise the limits will be centered at the calculated average difference.

The environment of 160^0 Fahrenheit was selected as the base model and the other environments are paired with this base model to run the paired-t tests. The selection for the paired t-test is modeled is given below.

- 160 Degree Fahrenheit Vs 160 Degree Fahrenheit in Salt Water
- 160 Degree Fahrenheit Vs 20 Degree Fahrenheit
- 160 Degree Fahrenheit Vs 20 Degree Fahrenheit in Salt Water
- 160 Degree Fahrenheit Vs 100 Degree Fahrenheit in Salt Spray Chamber

The results generated by the 'MINITAB' software are given in the following tables:-

Table 1. Paired T-Test and Confidence Interval for Selected Pair 1, 160 ^{0}F Vs 160 ^{0}F in Salt Water

	N	Mean	StDev	SE Mean
Tensile	35	56.54	10.92	1.85
Tensile	35	56.56	11.19	1.89
Difference	35	-0.02	11.11	1.88

95% CI for mean difference: (-3.84, 3.79)

Test of mean difference = 0 (Vs not = 0): T-Value = -0.01, P-Value = 0.990

Table 2. Paired T-Test and Confidence Interval for Selected Pair 2, 160 ^{0}F Vs 20 ^{0}F

	N	Mean	StDev	SE Mean
Tensile	35	56.54	10.92	1.85
Tensile	35	56.56	10.2	1.72
Difference	35	-0.02	12.96	2.19

95% CI for mean difference: (-4.47, 4.43)

T-Test of mean difference = 0 (Vs not = 0): T-Value = -0.01, P-Value = 0.991

Table 3. Paired T-Test and Confidence Interval for Selected Pair 3,160 ^{0}F Vs 20 ^{0}F in salt water.

	N	Mean	StDev	SE Mean
Tensile	35	56.54	10.92	1.85
Tensile	35	53.84	12.49	2.11
Difference	35	2.7	13.56	2.29

95% CI for mean difference: (-1.96, 7.36)

T-Test of mean difference = 0 (Vs not = 0): T-Value = 1.18, P-Value = 0.247

Table 4. Paired T-Test and Confidence Interval for Selected Pair 4,160 ^{0}F Vs 100 ^{0}F in Salt Spray Chamber.

	N	Mean	StDev	SE Mean
Tensile	35	56.54	10.92	1.85
Tensile	35	59.19	6.53	1.1
Difference	35	-2.65	9.87	1.67

95% CI for mean difference: (-6.04, 0.74)

T-Test of mean difference = 0 (Vs not = 0): T-Value = -1.59, P-Value = 0.121

It can be noted that the P-Values for all the selection of the paired-t tests are greater than 0.05, which clearly indicates that there is no significant difference between tensile strength of the polypropylene fibers placed under the specific environments. But before making any conclusions the normal probability plots for each environment are checked for normality. Since the prediction interval on the difference between the individual test results is determined under the assumption that the data followed a normal distribution, plotting the normal probability plot on the difference of the test results checks the adequacy of the model.

The normal probability plots for the tensile data of the polypropylene fibers placed in the environments at 160 ^{0}F, 160 ^{0}F in salt water, 20 ^{0}F, 20^{0} F in salt water and 100 ^{0}F in salt spray chamber are respectively shown in Figures 21,22,23,24 and 25. These normal probability plots were generated by software 'MINITAB and show the data to be within the 5% limits.

The prediction interval of 95% was assumed for running the paired-t tests and the all the resulting p-values were greater than 0.05 that was stipulated for the hypothesis made. The results of all the pair-t tests matched the prediction interval of 95% and hence as per the hypothesis if the p-values are greater than 0.05 then there is no difference between the

FIGURE 21: NORMAL PROBABILITY PLOT FOR TENSILE DATA OF POLYPROPYLENE FIBERS AT 160 DEGREE FAHRENHEIT

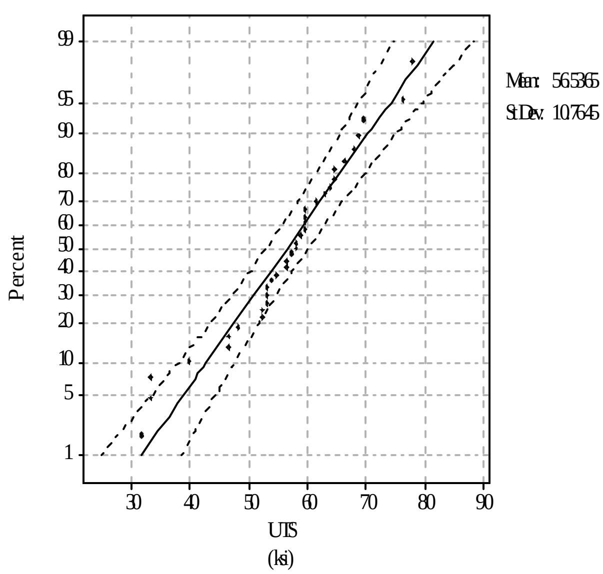


FIG 22 NORMAL PROBABILITY PLOT FOR TENSILE DATA OF POLYPROPYLENE FIBERS IN SALT WATER AT 160 DEGREE FAHRENHEIT

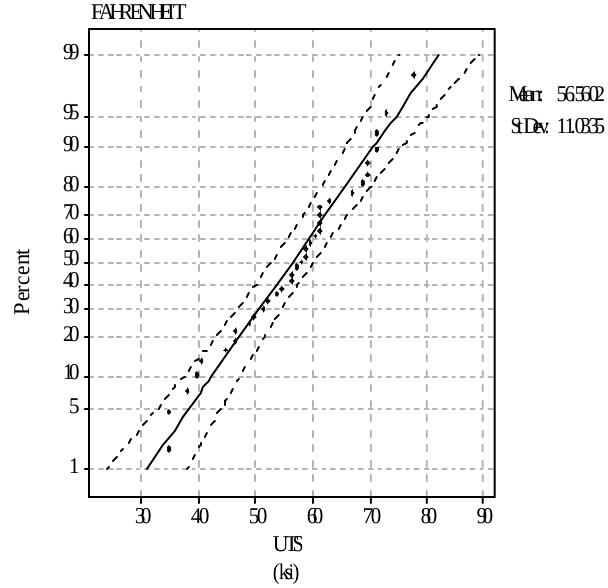


FIGURE 23: NORMAL PROBABILITY PLOT FOR TENSILE DATA OF POLYPROPYLENE FIBERS AT 20 DEGREE FAHRENHEIT

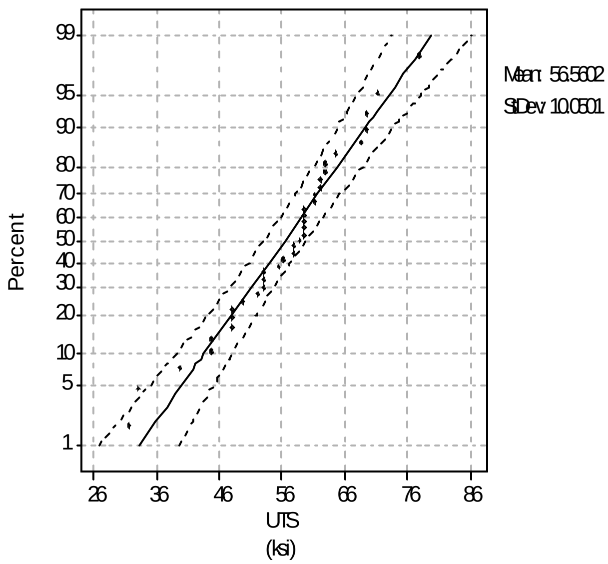


FIGURE 24: NORMAL PROBABILITY PLOT FOR TENSILE DATA OF POLYPROPYLENE FIBERS IN SALT WATER AT 20 DEGREE FAHRENHEIT

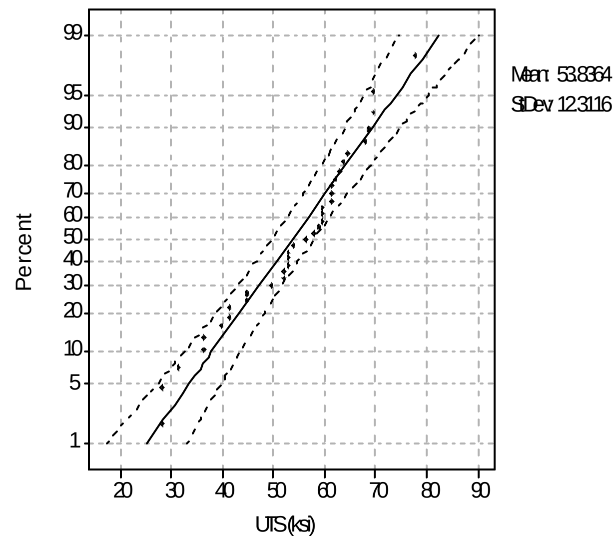
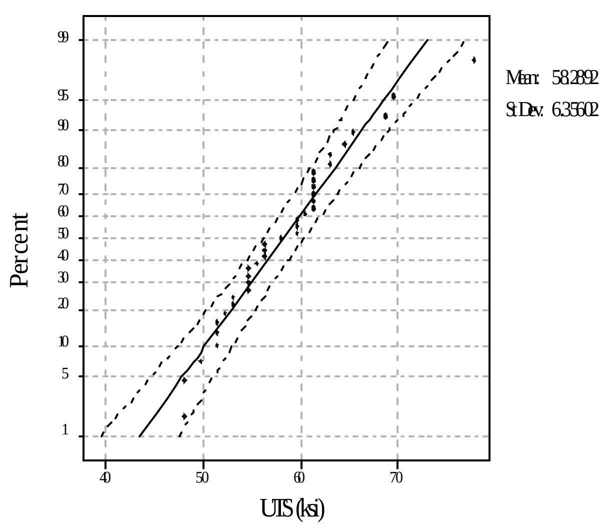


FIGURE 25: NORMAL PROBABILITY FOR TENSILE DATA OF POLYPROPYLENE FIBERS IN SALT SPRAY CHAMBER AT 100 DEGREE FAHRENHEIT



paired selections. From the normal probability plots for each environments it can be observed that all the tensile data points falls along the straight line and also within 5% limits.

Hence it can be concluded that the selected model of comparison is adequate. As there is adequacy in the model we can also validate the previous conclusions made in the analysis using 'Error bar charts' and 'Trend-line Charts' that there in no significant change in the tensile strength of the polypropylene fibers for a period of six months and it remains constant.

6. CONCLUSIONS AND FUTURE RESEARCH:

6.1 Conclusive Summary Of The Analysis:

Bar-chart analysis and Trend-line analysis contribute to the individual analysis for a particular environment. The results of these analyses show that the tensile properties of polypropylene fibers remain unchanged for a period of six months when exposed to all the specified environments. The results of the paired t-test followed by normal probability plot, which is for the overall comparison analysis, validate the fact that there is no change in the properties of the polypropylene fibers.

Although the melting temperature of the polypropylene fibers is much higher than one of the test conditions' temperature of 160 ^{0}F, maintaining this heat for a prolonged service period follows the path of the accelerated ageing techniques. A relatively more aggressive environment existed when the fibers where placed at 160 ^{0}F in salt water. The presence of salt water created an ionic environment of sodium and chloride ions. The mechanical properties of the polypropylene fibers were not affected by the accelerated ageing process during the presence of an ionic environment. It is also observed that fibers' properties do not change when they are subjected to the low temperature of 20 ^{0}F and at the same temperature in ionic environment. The same behavior is exhibited by fibers at 100 ^{0}F in the marine environment.

Hence, the analysis of the experimental results for the various environments under which the polypropylene are subjected, indicates that at high temperature and low temperature including during the presence of salt water and in a salt spray environment, the service conditions of the polypropylene does not change and remains constant within the normal range. But these experimental data are limited to only a period of six months.

The process of establishing a clear set of baseline data for the tensile properties of the polypropylene fibers would help to determine performance of the fiber reinforced concrete structures under simulated environmental conditions. The experiments conducted for this research project has yielded a clear set of reliable baseline data and these data would certainly help the commercial producers of the fiber reinforced concrete in carefully designing the structures for service applications.

6.2. Future Research:

The original scope of this research was to produce the data for the long-term effects of elevated and low temperatures and under a reactive environment. The actual schedule is to initially produce the data for a period of 6 months and then periodically continue with testing and producing the data till the end of three years. This research project has collected data for the initial period as per the plan and in future the research can be continued in collecting the data for the full three years.

Since FRC may be exposed to a wider range of temperatures in actual use the PP fibers should be exposed to much higher temperatures close to the melting point (Tm) and to below freezing temperatures within the glass transition temperature range (Tg). When the fibers are subjected to these extreme environments any acute changes of the extreme ductile behavior at low temperatures and loss of strength at high temperatures can be observed.

The present data indicates that there is no change in the tensile properties of the fibers over a six month period, but this cannot be extrapolated to a longer term without further study. When there is a significant change in the tensile properties of the fibers these fibers can be studied under the scanning electron microscope to understand the mode of deterioration.

The polypropylene reinforced concrete structures can also be subjected to similar environments and the data of maximum load carrying capacity under ultimate tensile load of the structures can also be produced. The tensile data of the FRCs that are subjected to the loading conditions under similar environments will be compared to the tensile data of the fiber only properties of the polypropylene fibers that are subjected to similar environments. These comparisons would yield many explanations and these interpretations would help to constitute a more robust service specification for the diverse applications of the fiber reinforced concrete.

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