EFFECT OF FIBER AND RESIN TYPE ON THE AXIAL AND CIRCUMFERENCIAL TENSILE STRENGTH OF FIBER REINFORCED POLYESTER PIPE

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EFFECT OF FIBER AND RESIN TYPE ON THE AXIAL AND CIRCUMFERENCIAL TENSILE STRENGTH OF FIBER REINFORCED POLYESTER PIPE

submitted by **NESLİHAN GÖKÇE** in partial fulfillment of the requirements for the degree of **Master of Science in Polymer Science And Technology Department, Middle East Technical University** by,

Prof. Dr. Canan Özgen
Dean, Graduate School of **Natural and Applied Sciences** ________

Prof. Dr. Cevdet Kaynak
Head of Department, **Polymer Science and Technology Dept., METU** ________

Prof. Dr. Ülkü Yılmazer
Supervisor, **Chemical Engineering Dept., METU** ________

Examining Committee Members:

Prof .Dr. Erdal Bayramlı,
Chemistry Dept., METU ________

Prof. Dr. Ülkü Yılmazer,
Chemical Engineering Dept., METU ________

Prof .Dr. Teoman Tinçer,
Chemistry Dept., METU ________

Prof. Dr. Cevdet Kaynak,
Metallurgical and Materials Engineering Dept., METU ________

Assoc. Prof. Göknur Bayram,
Chemical Engineering Dept., METU ________

Date: 03/09/2008

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all materials and results that are not original to this work.

Name, Last Name : Neslihan Gökçe

Signature :

ABSTRACT

EFFECT OF FIBER AND RESIN TYPE ON THE AXIAL AND CIRCUMFERENCIAL TENSILE STRENGTH OF FIBER REINFORCED POLYESTER PIPE

Gökçe, Neslihan

M.S., Department of Polymer Science and Technology

Supervisor: Prof. Dr. Ülkü Yılmazer

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In this study, the aim is to investigate the stiffness, longitudinal tensile strength and circumferential tensile strength of short fiber reinforced polyester composite pipes produced by centrifugal casting production method. To achieve this aim, theoretical calculation of modulus of elasticity of pipes was done and then test program was carried out on pipe samples produced with three different resin types which were orthophthalic, isophthalic and vinyl ester resin and three different fiber types which were E glass fiber, ECR glass fiber and basalt fiber. The tests were performed according to ISO (International Organization for Standardization) standards.

When resin type and fiber type effect on the fiber reinforced polyester pipe samples were evaluated, calculated elastic modulus values were in accordance with the test results.

According to the experimental test data, which were used to evaluate the effect of resin type on fiber reinforced polyester pipe properties, there is not a significant difference was observed in the stiffness, longitudinal and circumferential tensile strength test results of pipes having different resin types. In other words, there was not a significant effect of resin type on the stiffness, longitudinal tensile strength and circumferential tensile strength of short fiber reinforced pipes produced by centrifugal casting method.

According to the experimental test data, which were used to evaluate the effect of fiber type on the properties of fiber reinforced polyester pipe, basalt fiber reinforced pipe samples showed higher mechanical performance over E glass fiber and ECR glass fiber reinforced pipes. However, the test results of basalt reinforced polyester pipe were not as good as the individual properties of basalt fiber.

Finally, by comparing the basalt fiber reinforced pipe samples having almost the same stiffness and tensile test results as E glass fiber reinforced pipe samples, the gain in fiber and resin amount were investigated. Basalt fiber reinforced pipes were slightly lighter and thinner than E glass fiber reinforced pipes. However, the decrease in the amount of the fiber and resin in basalt reinforced pipe did not result in an overall cost reduction.

Key Words: Composite, Fiber Reinforced Polyester Pipe, Centrifugal Casting, Longitudinal Tensile Strength, Circumferential Tensile Strength

ÖZ

ELYAF VE REÇİNE TİPİNİN ELYAF TAKVİYELİ POLYESTER BORUNUN EKSENEL VE ÇEMBERSEL MUKAVEMETİNE ETKİSİ

Gökçe, Neslihan

Yüksek Lisans , Polimer Bilimi ve Teknolojisi Bölümü

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Bu çalışmada, amaç santrifüj savurma üretim yöntemi ile üretilmiş olan kısa elyaf takviyeli polyester kompozit borularının rijitlik, boyuna çekme dayanımı ve çembersel çekme dayanımının araştırılmasıdır. Bu amaca ulaşmak için, boruların elastisite modülünün teorik hesaplaması yapılmış ve daha sonra test programı ortoftalik, izoftalik, vinilester reçine olan üç farklı reçine tipi ve E cam elyaf, ECR cam elyaf, bazalt elyaf olan üç farklı elyaf tipi ile üretilen boru numuneleri üzerinde yürütülmüştür. Testler ISO'ya (Uluslararası Standardizasyon Organizasyonu) uygun olarak yapılmıştır.

Reçine tipi ve elyaf tipinin elyaf takviyeli polyester boru numunelerindeki etkisi değerlendirildiğinde, hesaplanan elastisite modülü değerleri test sonuçlarını doğrulamıştır.

Reçine tipinin elyaf takviyeli polyester boru üzerindeki etkisini değerlendirmek için kullanılan deneysel verilere göre, farklı reçine tiplerine sahip boruların rijitlik, boyuna çekme dayanımı ve çembersel çekme dayanımı test sonuçlarında kayda değer bir fark gözlenmemiştir. Sonuç olarak, reçine tipinin santrifüj savurma yöntemi ile üretilmiş olan

kısa elyaf takviyeli polyester boruların rijitlik, boyuna çekme dayanımı ve çembersel çekme dayanımında kayda değer bir etkisi olmamıştır.

Elyaf tipinin elyaf takviyeli polyester boru üzerindeki etkisini değerlendirmek için kullanılan deneysel verilere göre, bazalt elyaf takviyeli boru numuneleri E cam elyaf ve ECR cam elyaf takviyeli borulara göre daha yüksek performans göstermiştir. Fakat bazalt elyaf takviyeli polyester borularının bu test sonuçları bazalt elyafının özellikleri kadar iyi değildir.

Son olarak, E cam elyaf takviyeli boru numuneleri ile hemen hemen aynı rijitlik ve çekme test sonuçlarına sahip bazalt elyaf takviyeli boru numuneleri kıyaslanarak elyaf ve reçine miktarındaki kazanç araştırılmıştır. Bazalt elyaf takviyeli borular E cam elyaf takviyeli borulardan daha hafif ve ince olmuştur. Fakat bazalt elyaf takviyeli borunun elyaf ve reçine miktarındaki azalma toplamda maliyet azalmasına yol açmamıştır.

Anahtar Kelimeler: Kompozit, Elyaf Takviyeli Polyester Boru, Santrifüj Savurma, Boyuna Çekme Dayanımı, Çembersel Çekme Dayanımı

To My Family

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b	: Width of the circumferential tensile test piece, mm
b_G	: Width of the longitudinal tensile test piece, mm
d_e	: External diameter of the test piece, m
d_m	: Mean diameter of the test piece, m
DN	: Nominal diameter of the pipe, mm
e	: Wall thickness of the test piece, m
$e_{average}$	: Average wall thickness of the test piece, mm
E	: Modulus of elasticity, in MPa
E_c	: Modulus of elasticity of composite, MPa
E_f	: Modulus of elasticity of fiber, MPa
E_m	: Modulus of elasticity of matrix, MPa
E_{pipe}	: Modulus of elasticity of pipe, MPa
E_S	: Modulus of elasticity of sand filler, Mpa
f	: Deflection coefficient
F	: Load, N
F_{ult}	: Ultimate force, N
HDT	: Heat distortion temperature, ºC
I	: Second moment of area in the longitudinal direction per meter length, mm^3
K	: Fiber efficiency factor

L : Average length of the test piece, m

l_g : Distance between the test apparatus' grips, mm

m : Mass, kg

m_f : Mass of fiber, kg

m_m : Mass of matrix, kg

m_s : Mass of sand, kg

PN : Nominal pressure class of the pipe, bar

S : The specific ring stiffness, in N/m^2

S_0 : Initial specific ring stiffness, in N/m^2

SN : Stiffness class of the pipe, N/m^2

V : Volume, dm^3

V_i : Volume of the layer, dm^3

v_m : Volume fraction of matrix

v_f : Volume fraction of fiber

v_S : Volume fraction of sand

V_c : Volume of the composite, dm^3

y : Deflection, m

(y/d_m) : Initial relative deflection

ρ : Density, kg/dm^3

ρ_C : Density of the composite, kg/dm^3

ρ_f : Density of fiber, kg/dm^3

ρ_i : Density of the layer, kg/dm^3

ρ_m : Density of matrix, kg/dm^3

ρ_s	: Density of sand, kg/dm^3
$\sigma_{CD}*$	: Initial circumferential tensile strength, N/mm
$\sigma_{LA}*$	: Initial longitudinal tensile strength, N/mm
S	: Estimated standard deviation
$\overline{X}$	**:** Arithmetic mean of the set of observations
X	: Value of single observation
n	: Number of observations

CHAPTER 1

INTRODUCTION

Engineers need new materials with improved combination of properties. Composites offer a number of advantages over traditional engineering materials. These beneficial characteristics have enabled the rapid incorporation of composites within a wide range of industries like automotive, construction, wind energy and also pipe sector. Composites combine tremendous durability and high specific strength with an ability to be formed easily.

Pipes are a good example of the successful application of composites. Pipes can be made out of a variety of materials as steel, iron, polyethylene, and yet most pipes today are fiber reinforced polyester pipes (FRP pipes).

Fiber reinforced polyester composite pipe products have been used for municipal water and sewage applications. These pipes combine the benefits of durability, strength and corrosion resistance, thus eliminating the need for interior linings and exterior coatings. These pipe systems also offer great design flexibility with a wide range of standard pipe diameters and fittings available, as well as an inherent ability for custom fabrication to meet special needs. There are few countries in world where FRP pipe has not been used.

The design flexibility inherent with FRP pipes and the range of manufacturing processes used precludes the simple listing of FRP pipe mechanical properties. For this reason, FRP pipe standards are based on performance and detailed product performance requirements rather than thickness-property tables. The broad range of mechanical properties depends on the amount, type, and orientation of the reinforcement as well as the manufacturing process. This situation enables improvement in performance properties. By selecting the proper combination of resin, fibers, fillers, and design, one can create a product that offers a broad range of properties and performance characteristics [1].

FRP pipes have been categorized by the particular manufacturing processes. The latest processes are continuous filament winding or centrifugal casting process in which the improved technology is used to produce FRP pipes. There are many experimental, analytical studies in literature on performance properties of filament winding composite pipes produced by using continuous fibers and resin matrix, but not much on centrifugal casting composite pipes.

In centrifugal casting process, only cut (chopped) fibers are used, whereas in filament winding process, both chopped and continuous fibers are used. Owing to the fully automatic system of feeding raw materials layer by layer and very good compacted structural wall of product are produced in centrifugal casting, this process is one of the most common techniques for production of FRP pipes. In sections below, the process details, advantages of the centrifugal casting process will be explained.

In this study it is aimed to improve the tensile properties and stiffness of fiber reinforced polyester composite pipes which are produced by centrifugal casting process by using different types of resin matrix and fiber reinforcement. The effects of orthophthalic, isophthalic, vinyl ester resin types and E glass fiber, ECR glass fiber, basalt fiber types on mechanical properties of centrifugal cast FRP pipes are evaluated and compared.

CHAPTER 2

LITERATURE SURVEY

2.1 Theoretical Studies

Composites are the result of embedding high strength, high stiffness fibers of one material in surrounding matrix of another material. The fibers of interest for composites are generally in the form of either single fibers about the thickness of a human hair or multiple fibers twisted together in the form of a yarn or tow. Fiber reinforced composite materials consist of fibers of high strength and modulus embedded in or bonded to a matrix with distinct interfaces (boundaries) between them. In this form, both fibers and matrix retain their physical and chemical identities, yet they produce a combination of properties that cannot be achieved with either of constituents acting alone [2]. The classification of composites processing techniques are shown in Figure 2.1.

FRP pipe is made from glass fiber reinforcements embedded in, or surrounded by, cured thermosetting resin. This composite structure may also contain aggregate fillers, thixotropic agents, and pigments or dyes. The term fiber reinforced polyester pipe (FRP) is widely used to describe such materials with glass reinforced polyester pipe (GRP) when the reinforcement is glass fiber [3].

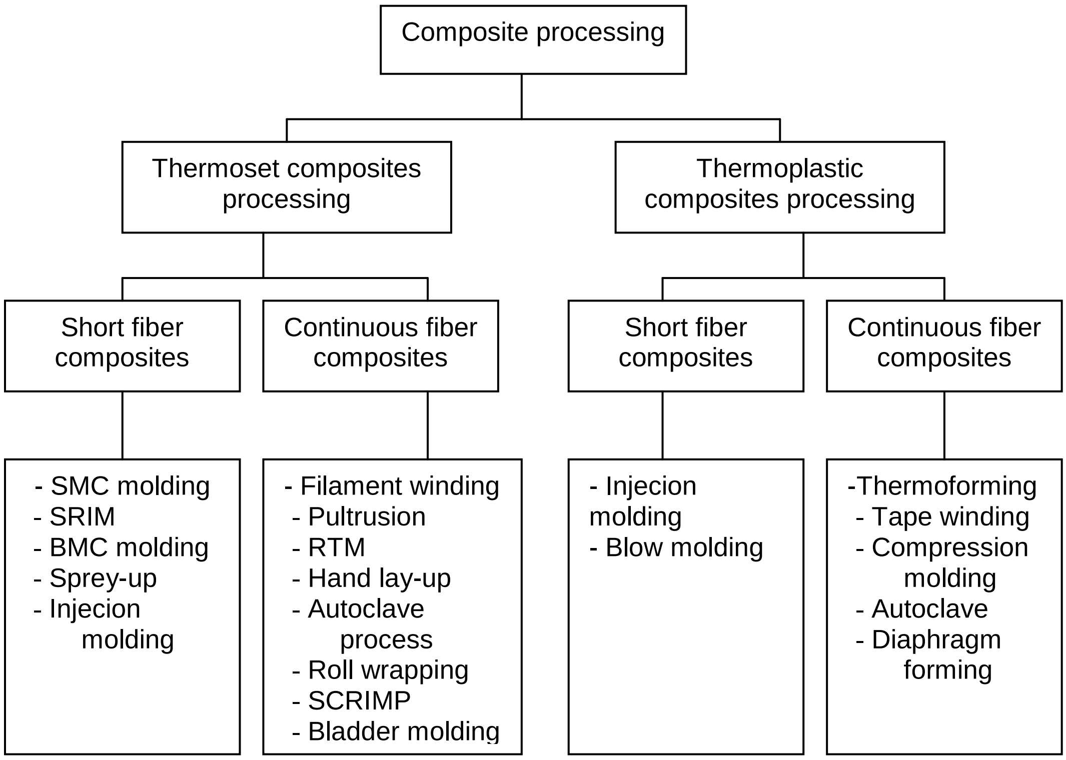


Figure 2.1 The classification of composites processing techniques [4]

The characteristics of FRP pipe and fittings are mainly: corrosion resistance, high strength-to-weight ratio, light weight, dimensional stability and low maintenance cost. Also, hydraulic characteristics of pipe and fittings are very good. The smooth interior of these products result in low fluid resistance, which could lower horsepower requirements for pumped systems. Because the interior pipe surface typically remains smooth over time, in most fluids resistance does not increase with age. In addition, the smooth interior allows the pipe diameter to be reduced while maintaining the desired flow. Today, the productions of composite materials grow approximately by 10% in the world.

2.1.1 Continuous Filament Winding (FW) Process and GRP FW Pipes

Figure 2.2 GRP pipes produced by continuous filament winding process [5]

GRP pipes which are produced by filament winding (FW) have a pipe wall which contains chopped and continuous glass fiber, resin and silica sand filling material. GRP pipes produced by continuous filament winding process are shown in Figure 2.2.

In continuous filament winding process, raw materials like resin, short chopped roving, continuous roving and silica sand (if needed) in pre-determined proportions are fed on to the steel tape. Before applying the raw materials, a special polyester film, aiming to protect the surface and to make extraction of GRP pipe easier, is wound on the mandrel. Then, a surface tissue of chemically resistant glass, impregnated with resin, is applied. Being rich in resin, this layer forms the chemical resistant wall of the pipe. The external layer also has the same characteristics as this inner layer.

Between the inner and outer layers, there are several mechanically resistant layers that consist of resin, continuous roving and chopped roving. The chopped rovings, 50 mm in length, supply axial mechanical resistance which is the sum of the axial resistance of each yarn. Continuous rovings supply the required circumferential resistance of the pipe. Such roving, coming from the feeding systems through suitable tensioning device are wound circumferentially and continuously on the pipe wall.

The middle layer called the core layer consists of chopped rovings, silica sand and small amount of continuous roving. Silica sand which is used as the filler material has the ability to increase the wall thickness, and therefore the pipe stiffness without using a quantity of glass fiber higher than foreseen by the design. The thickness and composition of the layers depend on the operating conditions that pipe shall withstand.

Continuous Filament Winding process is shown in Figure 2.3. The main machine is composed of a cylindrical mandrel which is supported by a steel band moving longitudinally with a speed depending upon the tape width and the cam plate. The steel band is elliptically wound on supporting beams placed along the grooved discs which are fixed on the mandrel shaft.

Figure 2.3 Continuous filament winding process [5]

As the steel tape moves forward longitudinally, the raw materials are measured in exact quantities under the direction of programmable logic controller and computer. The programmable logic controller and computer modules ensure integrated process control based on pre-programmed instructions. Firstly, the pipe data such as diameter, pressure and stiffness class need to be entered to the computer which calculates all the machine settings. The steel tape moves forward through four different heating zones having radiant heating units where the laminate gets cured. For each area, the heat to be supplied is controlled to maintain the required values of gel time and thermal peak.

The resin is applied by means of two basins providing the suitable distribution through gauged holes. The resin delivered to the distribution basins is already mixed with the required catalyst. The distribution of the resin, catalyst and other raw materials is controlled by a numerical controller in accordance with the mandrel speed.

Curing of resin is carried out by using induction and infrared lamps. It is possible to control the power supplied to each area in order to set the gel time, the isothermal peak and the post curing process according to the theoretical curing curve.

The production line is equipped with gauging and automatic cutting devices. The complete process is computer controlled. The pipe is cut to the required length by means of a diamond disc tool following the motion of the product. The saw unit ensures a clean perpendicular cut of the GRP pipe, and it is synchronized with the continuous longitudinal movement of the laminate.

After passing the cutting station, the cured pipe is supported on lifting tables that are specially designed for receiving the pipes. The pipe is then moved by conveyor to the chamfering and calibration unit. Both pipe ends with specific width are calibrated in this calibration unit to the specified diameter to have a smooth surface and to be able to connect the coupling. Pipes are then sent to the hydrostatic pressure test unit. All the pipes are tested to a pressure which is twice the pressure of their pressure class.

Finally, tested pipes are connected to the GRP couplings at the coupling connectors.

Marking labels prepared by a special printer and paper, are stuck on the pipe at the both ends of the pipe.

2.1.2 Centrifugal Casting (CC) Process and GRP CC Pipes

Centrifugal cast GRP pipes have a pipe wall which is made of chopped glass fiber, polyester and silica sand filler. GRP pipe picture produced by centrifugal casting process is shown in Figure 2.4.

Figure 2.4 GRP pipe produced by centrifugal casting process [5]

GRP pipes produced by Centrifugal Casting (CC) Process are manufactured by building up the pipe wall from the outside surface. The raw materials are fed into a rotating mold by a completely automated and electronically controlled process. There are eleven layers in a GRP CC pipe, and five of them can be seen by visually. The schematic representation of GRP CC pipe wall is shown in Figure 2.5.

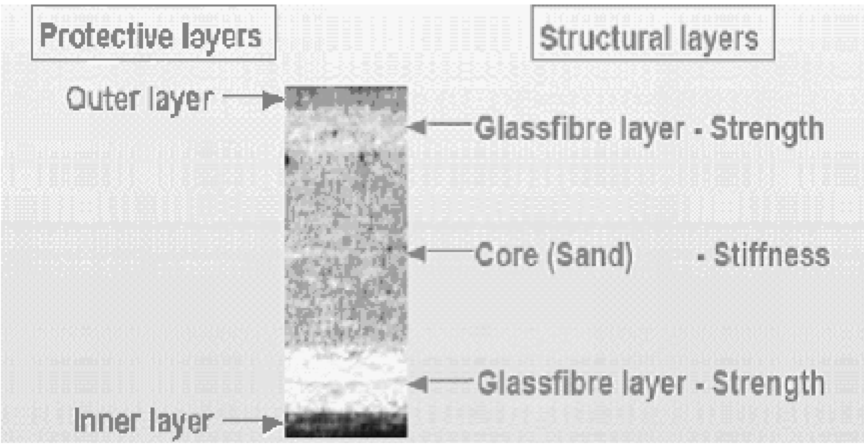


Figure 2.5 Schematic representation of GRP CC pipe wall [5]

The CC production process uses the latest developments in computer technology that ensure the control of the raw material distribution within the pipe wall as well as the control of the raw material consumption. The programmable logic controller supported process computers report the theoretical and actual raw material consumption. After the pipe class and diameter inputs are entered into the program, process control is made during the production. Curing behavior is shown as “time-temperature” graph on computers. Also, mold temperatures are measured by sensors. This pre-programmed repetitive process precisely measures the amount of the raw materials, the speed of rotation of the mold, the building up of the pipe wall layer by layer, and the internal heating of the mold.

Centrifugal Casting process is shown in Figure 2.6. In this process, a feeder arm deposits the raw materials at the pre-determined quantities into the mold. The resin is specially formulated not to polymerize during the filling process and glass fiber is chopped into its design length at the end of the feeder arm. The organization of the fiber is controlled to give the required circumferential and longitudinal design strength. The mold initially rotates at relatively low speed until all the raw materials are in position. The spinning speed is then increased to increase the compaction forces. The increase in speed ensures the complete compaction, creating a void-free pipe wall construction. The GRP Pipe wall is built up with each pass of the arm, feeding the raw materials into the mold in layers with progressive transitions from layer to layer. The reinforcing fibers are positioned on both sides of the neutral axis of the pipe wall and the intermediate space is filled with progressive mixture of sand and resin with glass fiber as reinforcement.

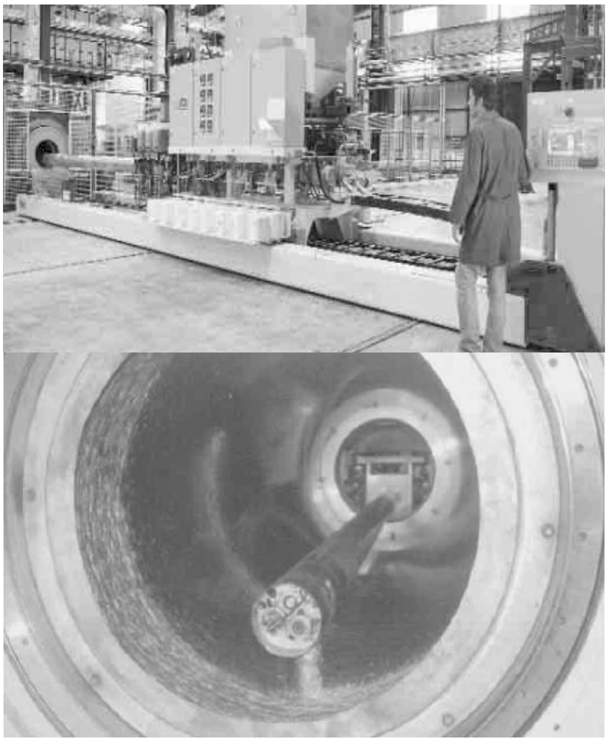


Figure 2.6 Centrifugal Casting Process [5]

After the pipe is taken from the mold, the cured pipe is supported on lifting tables that are specially designed for receiving the pipes. The end parts which consist of excess raw materials are cut by the cutting devices on these lifting tables.

Owing to the smooth outer surface of GRP CC pipes, there is no need for calibration of the pipe ends. All the pipes are tested to a pressure which is twice the pressure of their pressure class. Finally, tested pipes are connected to the GRP couplings at the coupling connectors.

Marking labels, prepared by a special printer and paper are stuck on the pipe at the both ends of the pipe.

2.1.3 Types of Materials Used in GRP Pipes

Fiberglass composites are polymer matrix composites (PMCs). PMCs are the most developed class of composite materials in that they have found widespread application, can be fabricated into large, complex shapes, and have been accepted in a variety of aerospace and commercial application. These reinforced plastics are synergistic combination of high performance fibers and matrices. The fiber provides the high strength and modulus, whereas the matrix spreads the load as well as offering resistance to weathering and corrosion [2].

2.1.3.1 The Resin Matrix

The use of a specific resin matrix will determine which properties are the strongest and the range of conditions over which the final product can be used. Properties of resins vary greatly and determine the conditions under which fabrication or molding a particular mixture can be done. Resin matrix selection will provide the physical and chemical properties (e.g. the glass transition temperature, a measurement of resistance to heat; and softening or plasticization by solvents and gases). Table 2.1 gives representative properties of some polymeric matrix materials.

Table 2.1 Representative properties of some polymeric matrix materials [6]

Property	Epoxy	Phenolic	Poly-carbonate	Vinyl ester	Polyimide
Density , kg/m^3	1200	1300	1200	1150	1400
Elastic-Modulus, MPa	4500	3000	2400	3300	4000-19000
Tensile Strength, MPa	130	70	60	75	70
Elongation, %	2	2.5	-	4	1
Coefficient of thermal expansion, 10^{-5} ºC^{-1}	11	1	6	5	8
Useful Temperature Limit, ºC	90 to 200	120 to 200	120	>100	250 to 300

The role of matrix in a fiber-reinforced is: to transfer stresses between fibers, to provide barrier against an adverse environment, and to protect the surface of the fibers from mechanical abrasion. The matrix plays a minor role in the tensile load-carrying capacity of a composite structure. The matrix provides lateral support against the possibility of fiber buckling under compression loading, thus influencing to some extent the compressive strength of the composite material. The interaction between fibers and matrix is also important in designing damage-tolerance structures. Finally, the process ability and defects in a composite material depends strongly on the physical and thermal characteristics, such as viscosity, melting point and curing temperature of the matrix [7].

The most common used matrix material in FRP products is unsaturated polyester resins. Unsaturated polyesters are macromolecules that are prepared by the condensation polymerization of difunctional acids or anhydrides with difunctional alcohols. The unsaturation in the polyester is usually supplied by the inclusion of maleic anhydride or fumaric acid as one component. In addition, a saturated acid or anhydride is often used, such as phthalic anhydride, adipic acid or isophthalic acid. A higher proportion of unsaturated acid gives a more reactive resin, with improved stiffness at high temperatures, while more of the saturated components give less exothermic cures and less stiff resins, particularly if the aliphatic acids are used. Ethylene and propylene glycols are perhaps most popular dihydric alcohols and styrene is by far the most widely used monomer in these systems [8].

The general chemistry of unsaturated polyesters can be illustrated by the following representation of the synthesis of a general purpose propylene glycol, maleic anhydride, phthalic anhydride polyester in Figure 2.7.

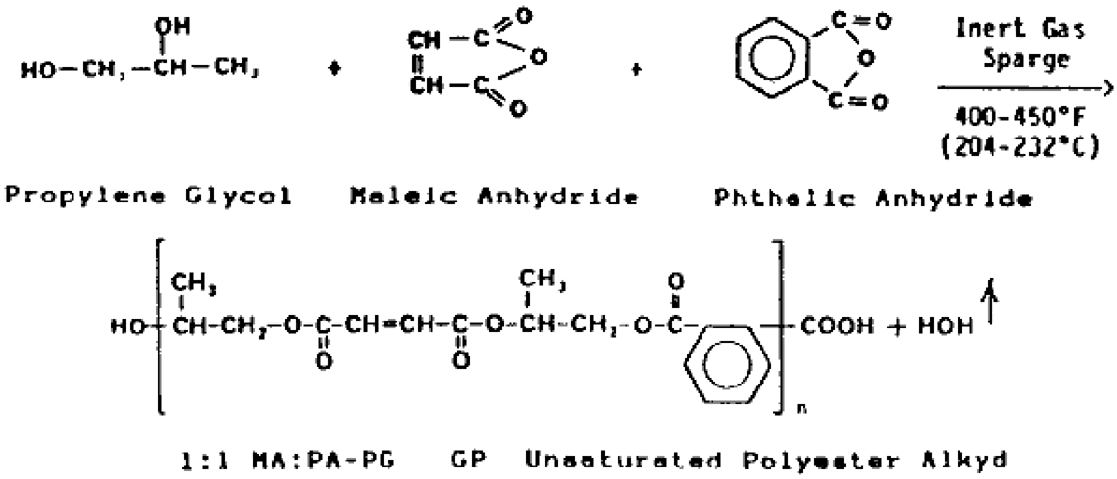


Figure 2.7 Synthesis of a general purpose unsaturated polyester [9]

Unsaturated polyester resins are relatively low in molecular weight, and are viscous, pale colored liquids consisting of a solution of polyester in a monomer, which is usually styrene. The addition of styrene in amounts of up to 50% helps to make the resin easier to be handled by reducing its viscosity. Styrene also performs the vital function of enabling the resin to be cured from a liquid to a solid by cross linking the molecular chains of the polyester, without the evolution of any by-products. These resins can therefore be molded without the use of pressure and are called “contact” or “low pressure” resins. Polyester resins have a limited storage life as they will set or gel on their own over a long period of time. Often small quantities of inhibitor are added during the resin manufacture to slow this gelling action. Table 2.2 gives some important properties of polyester.

Table 2.2 Some important characteristics of polyester [10]

Density g/cm^3	**Strength MPa**	**Modulus GPa**	**Poisson’s ratio**	**CTE $10^{-6}K^{-1}$**	**Cure Shrinkage %**	**Use Temp ºC**
1.1-1.4	30-100	2-4	0.2-0.33	50-100	5-12	80

General purpose polyester resins based on orthophthalic anhydride comprise the largest group of polyester resins which is widely used in FRP industry resulting in moderate strength and corrosion resistance, and are used at room temperature curing. The glycol generally controls the required performance: the phthalic-maleic anhydride ratio is adjusted to modify the reactivity according to physical properties required for fabrication needs. By using special alcohols, such as a glycol, in a reaction with di-basic acids, a polyester and water will be produced. This reaction, together with the addition of compounds such as saturated di-basic acids and cross linking monomers, forms the basic process of polyester manufacture. As a result there is a whole range of polyesters made from different acids, glycols and monomers, all having varying properties.

Isophthalic resins are based on isophthalic acid and maleic anhydride. The incorporation of isophthalic acid creates a high-molecular-weight resin with good chemical and thermal resistance and good mechanical properties. The use of nonpolar glycols contributes to improved aqueous resistance, which is required to protect the fiberglass. Isophthalic resins tend to show higher tensile and flexural properties than orthophthalic resins. This may be because isophthalics usually form more linear, higher- molecular-weight polymers than orthophthalics [11].

Vinyl ester resin is the common name for a series of unsaturated resins that are prepared by the reaction of a monofunctional unsaturated acid, typically methacrylic acid, with an epoxy resin. The resulting polymer, which contains unsaturated sites only in the terminal positions, is mixed with an unsaturated monomer, generally styrene. At this point, the appearance, handling properties, and curing characteristics of vinyl ester resins are the same as conventional polyester resins. However, the corrosion resistance and mechanical properties of vinyl ester composites are much improved over standard polyester resin composites. These improved properties have enabled vinyl ester resins to become the workhorse of the polyester custom corrosion industry. However, the properties of vinyl ester resins are not as easily tailored to a specific application as are standard unsaturated polyester resins. This combined with the use of higher-cost raw materials has somewhat limited the ability of vinyl ester resins to penetrate the unsaturated polyester resin market [12].

Vinyl ester resins are similar in their molecular structure to polyesters, but differ primarily in the location of their reactive sites, these being positioned only at the ends of the molecular chains. As the whole length of the molecular chain is available to absorb shock loadings this makes vinyl ester resins tougher and more resilient than polyesters. The vinyl ester molecule also features fewer ester groups. These ester groups are susceptible to water degradation by hydrolysis which means that vinyl esters exhibit better resistance to water and many other chemicals than their polyester counterparts, and are frequently found in applications such as pipelines and chemical storage tanks.

The starting material for a vinyl ester matrix is an unsaturated vinyl ester resin produced by the reaction of an unsaturated carboxylic acid, such as methacrylic or acrylic acid, and an epoxy resin. Figure 2.8 below shows the chemistry of a vinyl ester resin. With the reduced number of ester groups in a vinyl ester as compared to polyester, the resin is less prone to damage by hydrolysis. The material is therefore sometimes used as a barrier or “skin” coat for a polyester laminate that is to be immersed in water, such as in a boat hull. The cured molecular structure of the vinyl ester also means that it tends to be tougher than polyester, although to achieve these properties the resin usually needs to have an elevated temperature post cure [7].

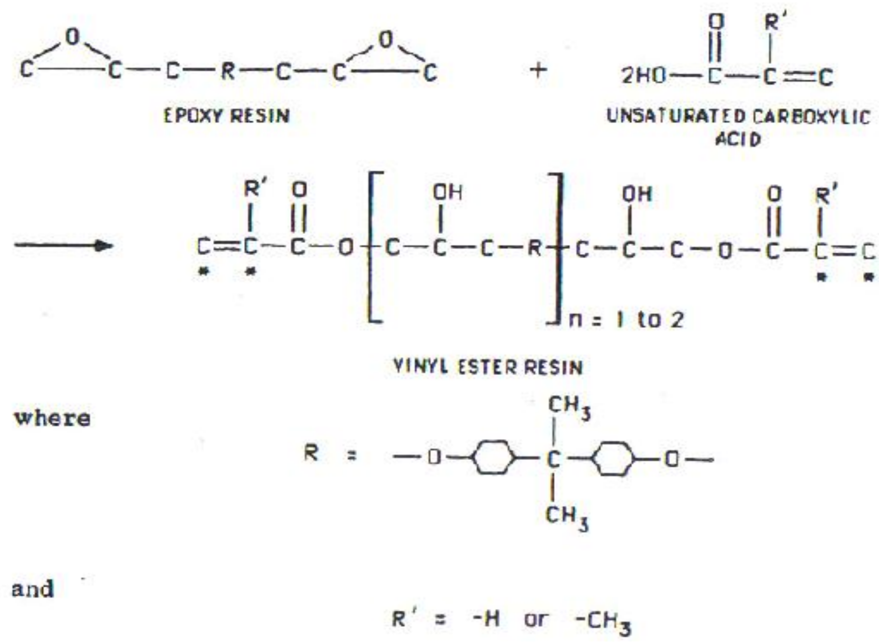


Figure 2.8 The chemistry of a vinyl ester resin. The asterisk (*) denotes unsaturation points (reactive sites) [7]

2.1.3.1.1 Cross-Linking Mechanism

The “curing” is a cross-linking chain reaction, converting the low-viscosity solution into a three- dimensional thermoset plastic. This is referred to as the cure. [13]

When the polymerization reaction takes place, after it has progressed to a certain point, gelation occurs. This well defined change during polymerization is known as the gel point. At this point reaction mixture changes from a viscous liquid to an elastic gel. Before gelation the polymer is soluble and fusible. After gelation, it is neither soluble nor fusible. This is a result of restraining effects of three dimensional space networks. Another classification of polymers is also possible. It is based on whether the material can form cross linked or gelled networks. The polymers that eventually reach gelation are called thermosetting. Such polymers are also called “crosslinkable polymers” [14].

The polyester resin is then said to be “cured”. It is now a chemically resistant (and usually) hard solid. It is a non-reversible chemical reaction. The “side-by-side” nature of this cross-linking of the molecular chains tends to mean that polyester laminates suffer from brittleness when shock loadings are applied.

The polymerization takes place by the opening up of the double bonds in the styrene, and double bonds in the polyester chain are also involved in this reaction, leading to molecular network where the polyester chains are cross linked by polystyrene ones, as shown in Figure 2.9.

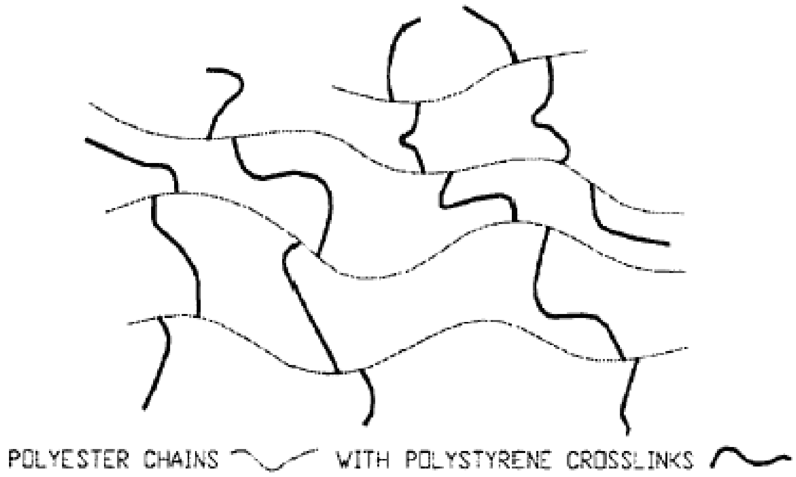


Figure 2.9 Schematic representation of thermosetting polymer [7]

Since it is advantageous to polymerize (cure) the unsaturated linear polyesters at room temperature, reducing agents and initiators are usually added to accelerate the production of free radicals. The general reactions involved in the production of the polyester-polystyrene networks are shown in Figure 2.10 [15].

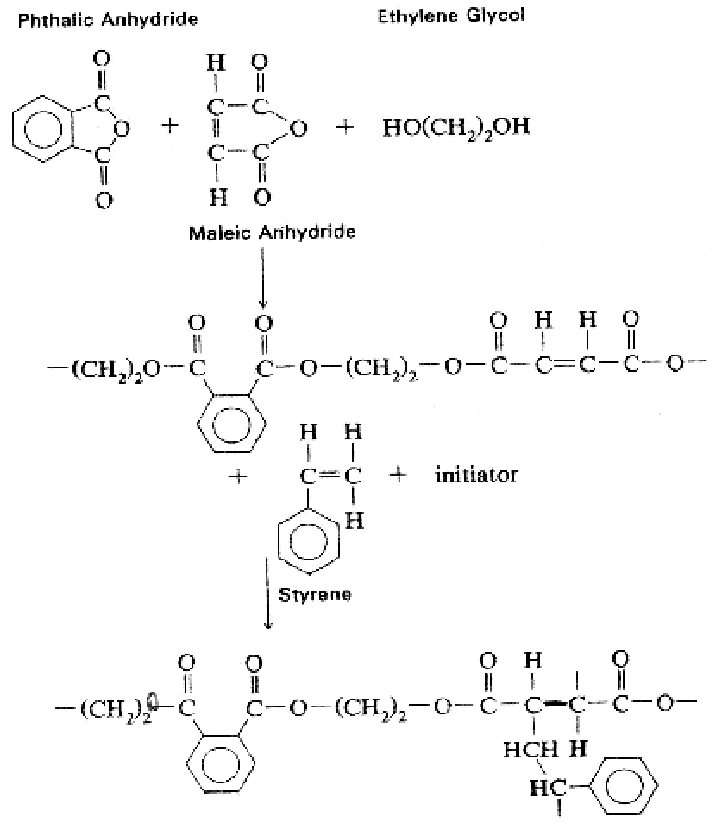


Figure 2.10 Synthesis of polyester-polystyrene networks [15]

Commercial phthalic and isophthalic resins usually have fumarate levels in excess of 95% and demonstrate full hardness and property development when catalyzed and cured. The addition polymerization reaction between the fumarate polyester and styrene monomer is initiated by free-radical polymerization. Commercially, benzoyl peroxide (BPO) and methyl ethyl ketone peroxide (MEKP) are the most common initiators used to cross-link unsaturated polyester and styrene. The initiators can be dissociated by heat or redox metal activators into peroxy and hydroperoxy free radicals.

The free radicals initially formed are neutralized by the quinone stabilizers, temporarily delaying the cross-linking reaction between the styrene and the fumarate sites in the polyester. This temporary induction period between catalysis and the change to a semisolid gelatinous mass is referred to as “gelation time” and can be controlled precisely by varying stabilizer and catalyst levels. As the quinone stabilizer is consumed, the peroxy radicals initiate the addition chain propagation reactions through the formation of styryl radicals. Then the soft gel is transformed into a hard, rubbery transition stage that demonstrates low physical strength before the onset of the exotherm of polymerization. As the temperature subsides, the resulting cross-linked thermoset solid develops superior properties characteristic of the polymer.

The low resin viscosity and ambient temperature cure systems developed from peroxides have facilitated the expansion of polyester resins on a commercial scale, using relatively simple fabrication techniques in open molds at ambient temperatures. The dominant catalyst systems used for ambient fabrication processes are based on metal (redox) promoters used in combination with hydro peroxides and peroxides commonly found in commercial MEKP and related perketones [16]. Promoters such as styrene-soluble cobalt octoate undergo controlled reduction–oxidation (redox) reactions with MEKP that generate peroxy free radicals to initiate a controlled cross-linking reaction. These reactions are shown in Figure 2.11. Cobalt is not built in the polymer.

$$ROOH + Co^{+2} \rightarrow RO\bullet + OH^{-} + Co^{+3}$$

$$ROOH + Co^{+3} \rightarrow ROO\bullet + Co^{+2}$$

$$2\ R\text{--}O\text{--}O\text{--}H \rightarrow RO\bullet + ROO\bullet + H_2O$$

Figure 2.11 Redox system at room temperature cure

The cross-linking reaction between the unsaturated polymer and styrene results in a spontaneous change from liquid to a solid state with the onset of the exotherm. The exothermic heat generated is proportional to the fumarate level in the polymer, but increasing styrene levels can enhance it further. Although some exotherms can be tolerated in molding processes, these can lead to excessive shrinkage, warpage, and cracking in large moldings. The cure exotherm can be suppressed in a number of ways to afford a more controllable fabrication system, without adversely affecting the final cure or structural performance.

Polyester resins undergo a rapid transformation from a viscous liquid to a solid plastic state that comprises a three-dimensional cross-linked polymer structure. The level of polyester unsaturation determines essential performance characteristics. The cross-linked polymers form a thermoset plastic which cannot be changed or returned to its original condition by heating, as it can with thermoplastics. This thermoset characteristic is beneficial in providing high temperature properties, good solvent and chemical resistance, and high flexural modulus. Cross-linked polyester resins are rigid materials and are highly sensitive to brittle fracture. The strength of all polyester resins is enhanced significantly by glass and other fibrous reinforcements.

The three-dimensional cross-linked network resists penetration and attack by most corrosive chemicals and nonpolar solvents, although weak alkalies and especially polar solvents such as lower ketones, chlorinated aliphatics, and aromatics readily attack orthophthalic, isophthalic, and dicyclopentadiene resins. Water has wide-ranging effects on different resin compositions as it penetrates into the plastic network. Cross-linking density and the presence of steric constituents local to the ester groups can enhance water resistance. Isophthalic resins have better water absorption characteristics than corresponding orthophthalic resins.

2.1.3.2 The Fiber Reinforcement

Fibers are the principal constituent in a fiber reinforced composite material. They share the major portion of the load acting on a composite structure. Proper selection of the type, amount, and orientation of fibers is very important, since it influences the following characteristics of a composite laminate: specific gravity, tensile strength and modulus, compressive strength and modulus, fatigue strength as well as fatigue failure mechanism, electrical and thermal conductivities, cost [7].

Advantages of fibers are: high tensile modulus and tensile strength, high impact resistance, high stiffness and high dimensional stability (low coefficient of expansion). The use of fibers as high-performance engineering materials is based on three main important characteristics. First one is small diameter with respect to its grain size. This allows a higher friction of the theoretical strength to be attained than is possible in its bulk form. Second one is a high aspect ratio (length/diameter), which allows a very large fraction of the applied load to be transferred via the matrix to the stiff and strong fiber. The third one is a very high degree of flexibility, which is really a characteristic of a material that has a high modulus and small diameter. A comparison of some important characteristics of reinforcement fibers is made in Table 2.3 [10].

Table 2.3 Properties of reinforcement fibers [10]

Characteristic	Unit	Kevlar 49	E Glass	Al_2O_3	Boron
Diameter	µm	12	8-14	20	100-200
Density	g/cm^3	1.45	2.55	3.95	2.6
Young's modulus (Parallel to fiber axis)	GPa	125	70	379	385
Tensile Strength	GPa	2.8-3.5	1.5-2.5	1.4	3.8
CTE (Parallel to fiber axis)	$10^{-6}K^{-1}$	-2 - -5	4.7	7.5	8.3

Glass fibers have good properties both in an absolute sense and relative to weight. They have very good processing characteristics and they are inexpensive. Glass fiber is a generic name like carbon fiber or steel. A variety of different chemical compositions is commercially available. Common glass fibers are silica based (~50-60% SiO_2) and contain a host of other oxides of calcium, boron, sodium, aluminum, and iron, for example. Table 2.4 gives the compositions of some commonly used glass fibers.

Table 2.4 Composition of glass used for fiber manufacture [17], [18], [19]

Composition	ECR Glass	S Glass	E Glass	C Glass	Basalt
SiO_2	58.2	64.4	52.4	64.4	48,8-51
Al_2O_3, Fe_2O_3	11.7	25.0	14.4	4.1	21,3-28,9
CaO	21.7	-	17.2	13.4	10
MgO	2	10.3	4.6	3.3	6,2-16
Na_2O, K_2O	1.2	0.3	0.8	9.6	1,9-2.2
B_2O_3	-	-	10.6	4.7	-
BaO	-	-	-	0.9	-
TiO_2	2.5	-	-	-	0,9-1,6
MnO	-	-	-	-	0.1-1.16
ZnO	2.9	-	-	-	-

The secret of the strength of glass fibers, and of their ability to bond to polymeric matrices is the size which is applied to the surface of the fibers in the form of an aqueous solution shortly after the fibers emerge from the bushings. The size contains a polymeric binder which coats the glass surface to protect it and lightly binds together the individual fibers in each fiber tow to prevent them rubbing against one another during subsequent handling and processing. The size also contains a coupling agent which is a reactive component, usually an organosilane, which is a multi-functional molecule.

Chemical coupling agents are used with glass fibers to (1) improve the fiber/matrix interfacial strength through physical and chemical bonds and (2) protect the fiber surface from moisture and reactive fluids. Common coupling agents used with glass fibers are organo functional silicon compounds, known as silanes. Their chemical structure is represented by $R'\text{-}Si(OR)_3$, in which the functional group R' must be compatible with the matrix resin in order for it to be an effective coupling agent. The glass fiber surface is treated with silanes in aqueous solution. When a silane is added to water, it is hydrolyzed to form $R'\text{-}Si(OH)_3$;

$$R'\text{-}Si(OR)_3 + 3H_2O \rightarrow R'\text{-}Si(OH)_3 + 3HOR$$

Before treating glass fiber with a coupling agent, its surface must be cleaned from the size applied at the time of forming. The size is burned away by heating the fiber in an air circulating oven at 340˚C for 15-20h. As the heat cleaned fibers are immersed into the aqueous solution of a silane, chemical bonds (Si – O – Si) as well as physical bonds (hydrogen bonds) are established between the (OH) groups on the glass fiber surface (which is hydroscopic owing to alkaline content) and $R'\text{-}Si(OH)_3$ molecules as shown in Figure 2.12 [7].

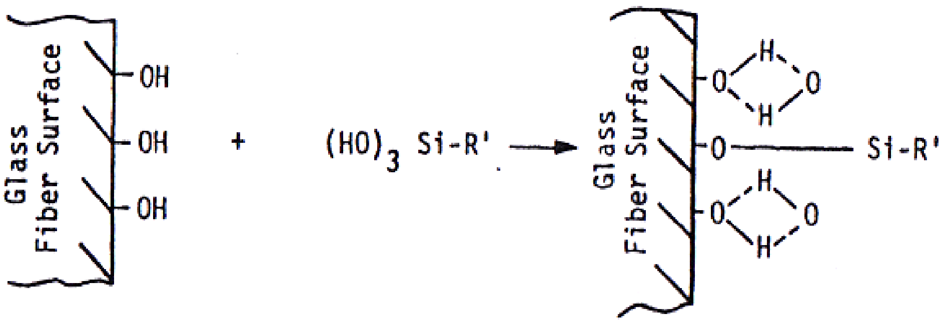


Figure 2.12 Treating glass fiber with a coupling agent [7]

When treated glass fibers are incorporated into a resin matrix, the functional group R’ in the silane film reacts with the resin to form a chemical coupling between fibers and matrix as shown in Figure 2.13.

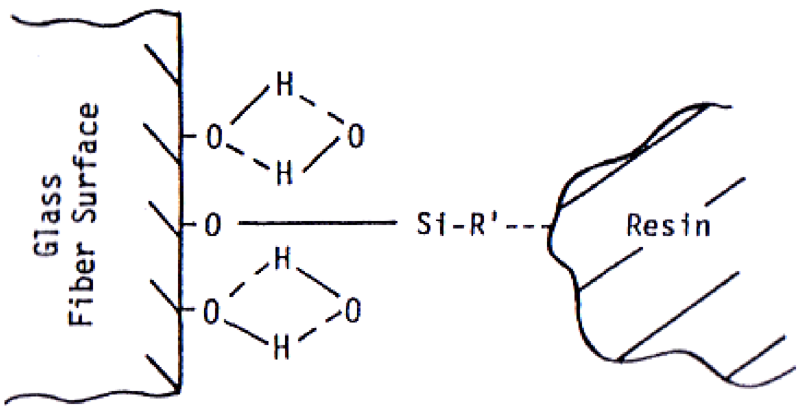


Figure 2.13 Chemical coupling between fibers and matrix [7]

Fiberglass is manufactured from a number of materials that are largely composed of silicone dioxide that are cooled below their melting points (super cooled liquids) without crystallizing. Other oxides are included giving glass fibers with differing characteristics. Table 2.5 contains a brief description of the most important glass fiber types. The glass fibers are pulled from the melted glass, forming fibers that typically range from 2 to 25 μm in diameter. This pulling acts to orient the overall three dimensional structure, producing a material with greater strength and stiffness along the axis of the pull [20].

Table 2.5 Types of glass fibers [20]

Designation	General properties
C-glass	Chemical Resistant
E-glass	“Typical” glass fiber
R-glass and S glass	Stiffer and stronger than E-glass

C -glass was developed to resist attack from chemicals, mostly acids which destroy E-glass. Mainly used in the form of surface tissue in the outer layer of laminates used in chemical and water pipes and tanks. S glass stands for the high silica content that makes S glass withstand higher temperatures than other glasses. S-glass is a high strength formulation for use when tensile strength is the most important property.

E-glass have good insulation properties. The letter E is used because it was originally for electrical applications. E-glass (electrical) - lower alkali content and have good tensile and compressive strength and stiffness, good electrical properties and relatively low cost, but impact resistance relatively poor.

There is range of glassy reinforcements of alternative composition, designed to give either superior mechanical performance or resistance to certain types of environment. These types of glass reinforcement are more expensive than E glass, depending upon the material. ECR glass offers enhanced resistance to certain types of corrosive environment. ECR glass fibers offer enhanced long-term acid resistance and short-term alkali resistance [21].

Basalt fibers are produced from basalt rock using single component raw material by drawing and winding fibers from the melt. Basalt fibers show higher tensile strength and modulus, better chemical resistance, extended operating temperature range, better environmental friendliness than regular E glass. Basalt fibers are ideally suited for demanding applications requiring high temperatures, chemical resistance, durability, mechanical strength and low water absorption.

The strength of fibers affects the strength of composites in a very direct manner. Any reduction in fiber strength will result in the lowering of the composite strength. A high strength composite will be obtained when all the fibers are uniform in their strength values. Orientation of fibers with respect to loading axis is also an important parameter. Fiber orientation directly affects the distribution of load between the fibers and the matrix. The contribution of the fibers to the composite properties is maximum only when they are parallel to the loading direction. Composite strength and stiffness will be reduced when the fibers are not parallel to the loading direction. The extent to which the strength and stiffness may be reduced depends on the angle of the fibers to the loading axis or the number of fibers that are not parallel to the loading direction. In practice, all the fibers cannot be aligned perfectly while making composites [22].

2.1.3.3 The Fillers

By using various additives, liquid resin systems can be made suitable to provide specific performance. Filler materials are used extensively with polyester resins for a variety of reasons including to increase rigidity, to reduce the cost of the molding, to facilitate the molding process and to impart specific properties to the molding.

Fillers are often added in quantities up to 50% of the resin weight, although such addition levels will affect the flexural and tensile strength of the laminate. The use of fillers can be beneficial in the laminating or casting of thick components where otherwise considerable exothermic heating can occur. Addition of certain fillers can also contribute to increasing the fire-resistance of the laminate.

Fillers are mostly inorganic materials, which may yield economic, appearance, or performance advantages in fiberglass pipe. The most commonly used fillers are calcium carbonate, alumina silicate (clay) and silica sand. Calcium carbonate is primarily used as a volume extender to provide the lowest-cost-resin formulation in areas in which performance is not critical. Silica sand is used to improve stiffness of the pipe and also to decrease resin consumption and cost. If proper amounts are used, they can reduce curing shrinkage and improve water resistance and weathering properties.

One of the oldest composite pipe was asbestos reinforced cement (A/C) pipe. Its strength is very good and it is a cost effective pipe. The price of portland cement, the main ingredient in A/C pipe, has remained relatively stable over the years. A highly competitive market has ensured that price increases have been minimal. The price of asbestos has also remained relatively stable, but fluctuations in its price have less of an impact on final costs because it comprises no more than 15% to 20% of the raw materials used. But asbestos is very hazardous to health, it is cancerous. Thus, way asbestos is forbidden in many countries, and GRP pipe is designed as alternative.

Silica is the most abundant mineral found in the crust of the earth. It forms an important constituent of practically all rock-forming minerals. It is found in a variety of forms, as quartz crystals, massive forming hills, quartz sand (silica sand), sandstone, etc., and in with numerous other forms depending upon color. The most common use of quartz and glass-sand, also referred to as silica-sand, is in the manufacture of glass. Great advancement has been made in the manufacture of translucent, transparent, colored and clear glass in sheets or in glassware.

The size of the sand grains is important in glass industry. It should be of high purity containing a minimum of 98% SiO_2.

2.2 Experimental Studies

Most of studies reported in the literature were basically focused on filament wound composite tubes. Most of them are about multi axial filament winding of tubular composites. There are also some studies present on centrifugal casting of FRP composite pipes. Some of the studies on FRP pipes and composites are summarized below:

Ha, S.K. and Jeong, J.Y. [23] studied the effects of winding angles on through-thickness properties and residual strains of thick filament wound composite rings. In their study, they produced thick composite rings with wet impregnation of E-Glass fibers in an epoxy resin, and the through thickness properties were measured. The residual strains in the radial and hoop directions were also measured using a split-ring method. They observed significant decrease in the radial residual strains and increase in Young's moduli, as the winding angle decreased.

Kaynak, C.and Erdiller, E.S. and Parnas, L. and Senel, F. [24] studied process parameters of continuous fiber reinforced epoxy composite tubes produced by filament winding. Split disk tests were performed for the specimens produced with two different epoxy resin systems, five different fiber materials and five different winding angles. The effects of resin type, fiber type and winding angle were evaluated. They noticed that different epoxy resin systems have no significant effect, but carbon fibers increase the performance of composite tubes when compared to glass fibers, at winding angles greater than 60º.

Wang, Y.C. and Kodur, V. [25] studied the variation of strength and stiffness of fiber reinforced polymer bars with temperature. They used two different types of FRP reinforcement bars with carbon fiber and glass fiber reinforcement. Results from strength tests were used to show that temperatures of about 325º and 225º appear to be critical in terms of strength for glass fiber reinforced polyester bars and carbon fiber reinforced polyester bars respectively.

Parnas, R. and Shaw, M. and Liu, Q. [26] investigated basalt fiber reinforced polymer composites and compared them with glass fiber reinforced polymer composites. They performed strength and stiffness tests and found no significant differences basalt fiber reinforced polymer composites and between glass fiber reinforced polymer composites. They also found that the fatigue life of basalt fiber reinforced polymer composites is longer.

Farshad, M. and Necola, A. [27] investigated the effects of aqueous environment on the long term behavior of glass fiber reinforced plastic pipes. The research was made by long term tests on GRP pipes with unsaturated polyester resin produced by centrifugal casting process. The ring samples were subjected to a range of radial compression forces, in creep conditions. Radial deflection of samples was measured and the time to failure of each sample was recorded. Long term extrapolation was made from the experimental data. The long term tests showed that, for the pipes tested, the strength corresponding to 1000 hours of testing was about 60% of the short term strength. 50 years extrapolation showed a reduction of strength by about 55% of the short term strength.

CHAPTER 3

SAMPLE PREPARATION AND TESTING

3.1 Material Selection

Test samples were produced from three different types of resins and three different types of fibers. Information about these raw materials is given in the following sections.

3.1.1 Resin Systems

Thermoset polymers, especially polyesters and vinyl esters are used extensively as the matrix in composites, mainly owing to the ease of processing with these materials.

All the tested pipes were produced by Centrifugal Casting (CC) Process. Two different resins are used in the Centrifugal Cast GRP pipes. One of them is used in the outside cover layer and structural layers and it is called as “body resin”. The other is used in the inside cover layer and barrier layer of the Centrifugal Cast GRP pipe and it is called as “liner resin”. This method of production and layers of GRP pipe is explained in section 3.2.

In this study, in the outside cover layer and structural layers for all the pipes produced; three different resin types were used as the body resin which are orthophthalic resin, isophthalic resin and vinyl ester resin. These resins were BOYTEK BRE 310 (orthophthalic resin), BOYTEK BRE 311 (isophthalic resin) and DSM ATLAC E NOVA 1045 (vinyl ester resin). BOYTEK BRE 820 was used as the liner resin in the inside cover layer and barrier layer of all the pipes produced. The properties of these resin systems, given by their manufacturers, are shown in Tables 3.1 to 3.4.

Table 3.1 Mechanical properties of cast non-reinforced BRE 310 resin

Property	Unit	Value	Test Method
Tensile Strength	MPa	70	ISO 527
Elongation at Break	%	2	ISO 527
Tensile Modulus	MPa	3800	ISO 527
Flexural Strength	MPa	110	ISO 178
Flexural Modulus	MPa	3700	ISO 178
HDT	ºC	80	ISO 75A
Density	kg/dm^3	1.2	
Hardness	Barcol	45	DIN EN 59
Curing schedule	The curing characteristics are obtained by using 1% accelerator Cobalt Octoate and 1.5% hardener Curox M300. All test samples were post cured for 3 h/80ºC and 1h/100ºC		

Table 3.2 Mechanical properties of cast non-reinforced BRE 311 resin

Property	Unit	Value	Test Method
Tensile Strength	MPa	70	ISO 527
Elongation at Break	%	3.5	ISO 527
Tensile Modulus	MPa	3600	ISO 527
Flexural Strength	MPa	120	ISO 178
Flexural Modulus	MPa	3700	ISO 178
HDT	ºC	90	ISO 75A
Density	kg/dm^3	1.2	
Hardness	Barcol	40	DIN EN 59
Curing schedule	The curing characteristics are obtained by using 1% accelerator Cobalt Octoate and 1.5% hardener Curox M300. All test samples were post cured for 3 h/80ºC and 1h/100ºC		

Table 3.3 Mechanical properties of cast non-reinforced Atlac E-Nova 1045 resin

Property	Unit	Value	Test Method
Tensile Strength	MPa	85	ISO 527
Elongation at Break	%	5-6	ISO 527
Tensile Modulus	MPa	3300	ISO 527
Flexural Strength	MPa	140	ISO 178
Flexural Modulus	MPa	3500	ISO 178
HDT	ºC	125	ISO 75A
Density	kg/dm^3	1.2	
Hardness	Barcol	45	DIN EN 59
Curing schedule	The curing characteristics are obtained by using 0.3% accelerator NL51P, 0.2% accelerator NL 63-10P, 1.5% hardener Butanox M50. All test samples were post cured for 3 h/100ºC and 3h/150ºC		

Table 3.4 Mechanical properties of cast non-reinforced BRE 820 resin

Property	Unit	Value	Test Method
Tensile Strength	MPa	15	ISO 527
Elongation at Break	%	30-40	ISO 527
Tensile Modulus	MPa	850	ISO 527
Flexural Strength	MPa	N/A	ISO 178
Flexural Modulus	MPa	N/A	ISO 178
HDT	ºC	N/A	ISO 75A
Density	kg/dm^3	1.2	
Hardness	Barcol	N/A	DIN EN 59
Curing schedule	The curing characteristics are obtained by using 1% accelerator Cobalt Octoate and 1.5 % hardener Curox M300. All test samples were post cured for 16 h/80ºC		

3.1.2 Fiber Reinforcements

Different types of reinforcement affect mechanical properties of composites. The most important property of the fiber is its elastic modulus. The reinforcement must be significantly stiffer than the resin matrix. This allows it to pick up the stress applied to the composite. Since the fiber is attempting to carry the stress it must have sufficient strength available so that it does not fail.

In this study, three different fibers were used which are E glass fiber, ECR glass fiber and basalt fiber. These fibers were VETROTEX P219 (E glass fiber), OWENS CORNING Advantex (ECR glass fiber) and BPG Basalt fiber (Basalt fiber). The properties of these fiber reinforcements, given by their manufacturers, are shown in Table 3.5.

Table 3.5 Properties of VETROTEX P219 (2400 tex), OWENS CORNING CCR 520 (2400 tex) and BPG basalt fiber (2400 tex).

Property	Unit	VETROTEX P219 – 2400 tex	OWENS CORNING CCR 520 – 2400 tex	BPG BASALT fiber - 2400 tex
Linear Density	Tex	2400	2400	2400
Tensile Strength	MPa	3100-3800	3300-4000	3000-4840
Tensile Modulus	GPa	73	75	85
Elongation at break	%	4.7	5.0	3.1
Specific Density	kg/dm^3	2.54	2.54	2.7

3.1.3 Sand Filler

In this study, the same sand filler is used for all the pipes produced. This product was KUMSAN silica filler given by the manufacturer, as shown in Table 3.6.

Table 3.6 Properties of KUMSAN silica filler product

Property	Unit	KUMSAN SILICA SAND
Moisture Content	%	Max. 0.5
Modulus of elasticity	MPa	6400
Specific Gravity	kg/dm^3	2.67
Particle size distribution	%	Min. 90% between 0.15 mm - 0.6 mm
SiO_2 content	%	Min 98%

3.2 Test Specimen Fabrication

GRP pipes produced by Centrifugal Casting (CC) Process are manufactured by building up the pipe wall from the outside surface. The raw materials are fed into a rotating mold by a completely automated and electronically controlled process according to the recipe which is loaded to the process computer. Because of feeding raw materials into a rotating mold; outside diameter of the pipe is fixed to the inner side of mold. Thus, outer diameters of the pipes are fixed. Outer diameter of GRP pipes are specified according to the International Standards [28].

The raw materials in each layer are controlled by the process computer. The peak exotherm temperature of pipe during curing is recorded. The detail of the process is given in section 2.1.2. There are eleven layers in the GRP CC pipes, produced in the plant; five of them can be seen by naked eye. The position of these layers is shown in Figure 3.1.

The layer e_1 consist of body resin and sand. This layer is called "outside cover layer". The layers e_2 to e_9 are "structural layers".

Each of the e_2, e_3, e_8, e_9 layers consist of body resin and long fibers.

Each of the e_4, e_5, e_6, e_7 layers consist of body resin, sand filler and short fibers.

The layer e_{10} consist of body resin, short fibers, and it additionally contains a small amount of liner resin. The layer e_{10} is called "barrier layer".

The layer e_{11} consist of liner resin only. The layer e_{11} is called "inside cover layer".

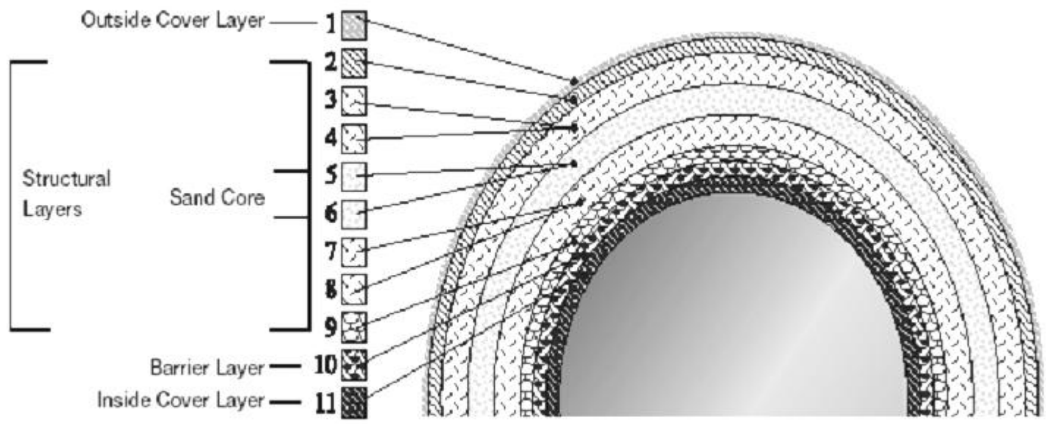


Figure 3.1 Definition of GRP CC pipe layers [5].

The inside cover layer is minimum 1mm thick, glass fiber free, flexible resin layer. This flexible resin layer ensures good hydraulic properties of pipe as well as a very high abrasion resistance. Behind the inside cover layer, there is a barrier layer consisting of chopped glass fibers and flexible resin. The inside cover layer and the barrier layer together ensure that no fluid media can penetrate into the structural layers of the pipe. Behind the barrier layer, there are structural layers, which consist of chopped glass fibers. These chopped glass fibers are cut into two different lengths (25 mm & 50 mm). Shorter chopped fibers are distributed randomly in the layers, and longer chopped fibers are aligned in the layers of pipe. These glass fibers provide longitudinal and circumferential tensile strength to the pipe to withstand the working pressure. A model of aligned long fibers and randomly distributed short fibers are shown in Figure 3.2 below.

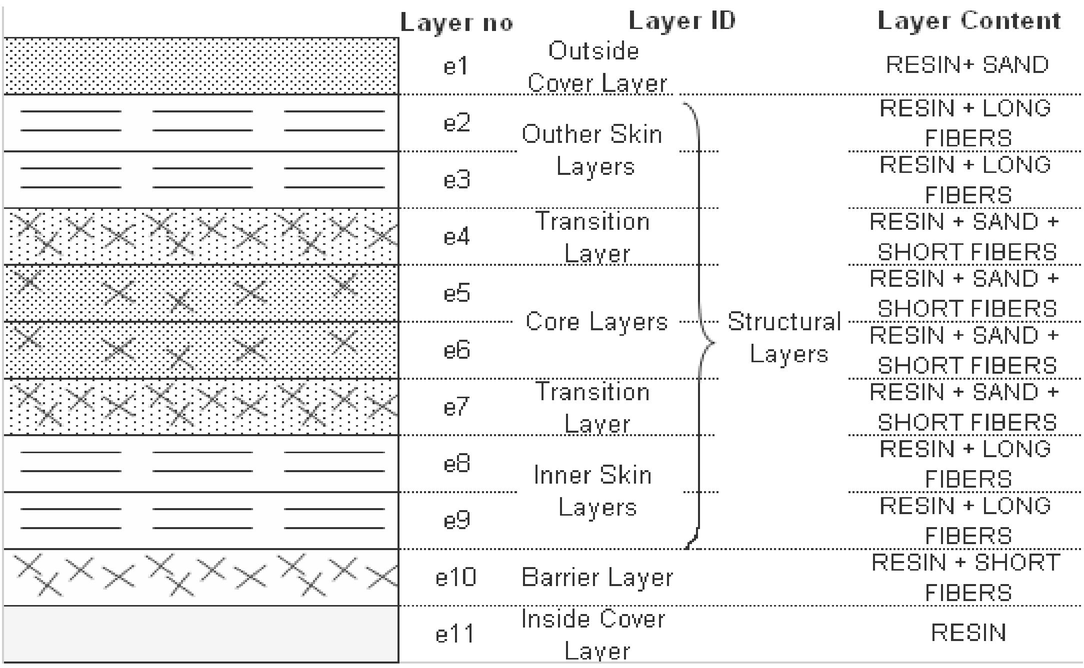


Figure 3.2 Model of aligned long fibers and randomly distributed short fibers in GRP CC pipe test samples.

Silica sand provides the required stiffness to the pipe. Amount of raw materials varies according to pipe pressure class and pipe stiffness. The final, outside cover layer is scratch resistant layer, which makes the pipe easier to be handled during installation. It consists of sand and resin. This layer prevents the UV effects.

In this study, resin matrix and fiber reinforcements were separately evaluated. To evaluate the effect of resin matrix on pipe properties; firstly, three different recipes were used to produce pipes with orthophthalic resin. Then the same three recipes were used to produce pipes with isophthalic resin matrix and finally the same three recipes were used to produce pipes with vinyl ester resin matrix. For all the recipes and resin types nine test groups were obtained and for each test group five samples were tested.

All of the other raw materials and their amounts were the same in each of the recipes. E Glass fiber was used as the reinforcement in these recipes. Test group used to evaluate the effect of resin matrix on pipe properties are given in Table 3.7.

Table 3.7 Test groups used to evaluate the effect of resin matrix on pipe properties

DN/PN/SN	Recipe No	Sample No	Resin	Fiber
600/10/5000	600-1	600-11	Orthophthalic (BRE 310)	E Glass (P219)
		600-12		
		600-13		
		600-14		
		600-15		
500/10/10000	500-1	500-11		
		500-12		
		500-13		
		500-14		
		500-15		
700/10/5000	700-1	700-11		
		700-12		
		700-13		
		700-14		
		700-15		
600/10/5000	600-2	600-21	Isophthalic (BRE 311)	
		600-22		
		600-23		
		600-24		
		600-25		
500/10/10000	500-2	500-21		
		500-22		
		500-23		
		500-24		
		500-25		
700/10/5000	700-2	700-21		
		700-22		
		700-23		
		700-24		
		700-25		
600/10/5000	600-3	600-31	Vinyl ester (ENova 1045)	
		600-32		
		600-33		
		600-34		
		600-35		
500/10/10000	500-3	500-31		
		500-32		
		500-33		
		500-34		
		500-35		
700/10/5000	700-3	700-31		
		700-32		
		700-33		
		700-34		
		700-35		

To evaluate the effect of fiber reinforcement on pipe properties; firstly, three different recipes were used to produce pipes with E glass fiber (This test group was in Table 3.7 and also had used to evaluate the effect of resin matrix on pipe properties). Then the same three recipes were used to produce pipes with ECR glass fiber. Finally, one of these recipes which is 600-5 was used to produce pipes with basalt fiber. For all the recipes and fiber types seven test groups were obtained and for each test group five samples were tested. All of the other raw materials and their amounts were the same and orthophthalic resin was used as the matrix in these recipes.

After evaluating the test results of basalt fiber reinforced polyester pipe, 600-5 recipe was revised as 600-5-rev recipe to evaluate the gain in fiber and resin amount. To be able to see the gain in fiber and resin amount, it was aimed to have similar experimental results of pipes having 600-5-rev recipe when compared to pipes having 600-1 recipe.

Test groups used to evaluate the effect of fiber reinforcement on pipe properties are given in Table 3.8.

In Tables 3.7 and 3.8; “DN” is nominal diameter of the pipe, expressed in mm, “PN” is nominal pressure class of the pipe, expressed in bar, and “SN” is stiffness class of the pipe, expressed in N/m^2.

Table 3.8 Test groups used to evaluate the effect of fiber reinforcement on pipe properties

DN/PN/SN	Recipe No	Sample No	Fiber	Resin
600/10/5000	600-1	600-11	E Glass (P219)	Orthophthalic (BRE 310)
		600-12		
		600-13		
		600-14		
		600-15		
500/10/10000	500-1	500-11		
		500-12		
		500-13		
		500-14		
		500-15		
700/10/5000	700-1	700-11		
		700-12		
		700-13		
		700-14		
		700-15		
600/10/5000	600-4	600-41	ECR Glass (CCR 520)	
		600-42		
		600-43		
		600-44		
		600-45		
500/10/10000	500-4	500-41		
		500-42		
		500-43		
		500-44		
		500-45		
700/10/5000	700-4	700-41		
		700-42		
		700-43		
		700-44		
		700-45		
600/10/5000	600-5	600-51	Basalt fiber (BPG)	
		600-52		
		600-53		
		600-54		
		600-55		
	600-5-rev	600-5r1		
		600-5r2		
		600-5r3		
		600-5r4		
		600-5r5		

3.2.1 Pipe Recipes Expressed by Weight of Raw Materials

Detailed information of the recipes used to produce the tested pipes is given in Tables 3.9 through 3.12.

In all these recipes, Cobalt octoate was used as the accelerator and MEKP (Curox M300) was used as the initiator. The percentage of accelerator cobalt octoate was 1% of the total resin amount and the percentage of the hardener Curox M300 was 1.5 % of the total resin amount.

Table 3.9 **600-1, 600-2, 600-3, 600-4, 600-5** recipes of DN 600 PN 10 SN 5000 pipe (length: 6 meter)

Pipe Layers	Body Resin kg	Liner Resin kg	Fiber kg	Sand kg	Total kg
e1	7.76	-	-	20.97	28.73
e2	3.88	-	8.64	-	12.52
e3	2.31	-	3.62	-	5.93
e4	3.80	-	5.35	17.59	26.74
e5	10.28	-	1.12	33.31	44.71
e6	9.66	-	1.13	34.35	45.14
e7	5.10	-	1.30	14.93	21.33
e8	7.32	-	7.17	-	14.49
e9	10.06	-	8.23	-	18.29
e10	5.90	4.99	6.36	-	17.25
e11	-	17.59	-	-	17.59
Total kg	66.07	22.58	42.92	121.15	252.72
wt %	26.14	8.94	16.98	47.94	100

Table 3.10 **600-5-rev** recipe of DN 600 PN 10 SN 5000 pipe (length: 6 meter)

Pipe Layers	Body Resin kg	Liner Resin kg	Fiber kg	Sand kg	Total kg
e1	7.76	-	-	20.97	28.73
e2	4.61	-	7.53	-	12.14
e3	2.37	-	3.71	-	6.08
e4	3.07	-	5.59	19.29	27.95
e5	9.05	-	1.05	32.00	42.10
e6	8.50	-	1.06	32.82	42.38
e7	4.60	-	1.34	16.07	22.01
e8	7.94	-	6.24	-	14.18
e9	10.45	-	7.88	-	18.33
e10	5.98	4.99	6.44	-	17.41
e11	-	17.59	-	-	17.59
Total kg	64.33	22.58	40.84	121.15	248.90
wt %	25.85	9.07	16.41	48,67	100

Table 3.11 **500-1, 500-2, 500-3, 500-4** recipes of DN 500 PN 10 SN 10000 pipe (length:6 meter)

Pipe Layers	Body Resin kg	Liner Resin kg	Fiber kg	Sand kg	Total kg
e1	7.02	-	-	16.39	23.41
e2	2.76	-	5.12	-	7.88
e3	1.83	-	2.74	-	4.57
e4	3.23	-	4.35	14.72	22.30
e5	11.84	-	1.16	33.42	46.42
e6	9.89	-	1.21	37.16	48.26
e7	3.02	-	1.08	11.38	15.48
e8	3.19	-	5.92	-	9.11
e9	7.87	-	7.87	-	15.74
e10	4.84	4.10	5.51	-	14.45
e11	-	14.38	-	-	14.38
Total kg	55.49	18.48	34.96	113.07	222.00
wt %	25.00	8.32	15.75	50.93	100.00

Table 3.12 **700-1, 700-2, 700-3, 700-4** recipes of DN 700 PN 10 SN 5000 pipe (length: 6 meter)

Pipe Layers	**Body Resin kg**	**Liner Resin kg**	**Fiber kg**	**Sand kg**	**Total kg**
e1	9.75	-	-	21.69	31.44
e2	5.86	-	11.13	-	16.99
e3	2.98	-	3.95	-	6.93
e4	4.52	-	5.42	20.18	30.12
e5	12.81	-	1.83	46.37	61.01
e6	11.75	-	1.86	48.24	61.85
e7	6.15	-	1.96	19.84	27.95
e8	11.60	-	10.29	-	21.89
e9	11.41	-	9.33	-	20.74
e10	6.66	5.63	7.37	-	19.66
e11	-	20.44	-	-	20.44
Total kg	83.49	26.07	53.14	156.32	319.02
wt %	26.17	8.17	16.66	49.00	100.00

3.2.2 Pipe Recipes Expressed by Volume Fractions of Raw Materials

As it can be seen from the recipes in section 3.2.1, each layer has different amounts of raw materials. So volume and density of each layer was calculated according to the formula (3.2) and (3.3) respectively.

$$\rho = m / V \tag{3.1}$$

$$V_i = (m_f / \rho_f) + (m_m / \rho_m) + (m_s / \rho_s) \tag{3.2}$$

$$\rho_i = m_i / [(m_f / \rho_f) + (m_m / \rho_m) + (m_s / \rho_s)] \tag{3.3}$$

where ρ is density, m is mass and V is volume,

V_i is the volume of the layer and ρ_i density of the layer,

ρ_f is density of fiber, ρ_m is density of matrix and ρ_s is density of sand,

m_f is mass of fiber, m_m is mass of matrix and m_s is mass of sand.

The recipes above are expressed with the volume fractions of the raw materials in Appendix A, Tables A.1 through A.5 by using the formulas (3.4), (3.5) and (3.6):

$$v_m = V_m / V_C = (m_m / \rho_m) / (m_C / \rho_C) \quad (3.4)$$

$$v_f = V_f / V_C = (m_f / \rho_f) / (m_C / \rho_C) \quad (3.5)$$

$$v_S = V_S / V_C = (m_S / \rho_S) / (m_C / \rho_C) \quad (3.6)$$

where v_m is the volume fraction of matrix,

v_f is the volume fraction of fiber,

v_S is the volume fraction of sand,

V_c is the volume of the composite and ρ_C density of the composite,

ρ_f is density of fiber, ρ_m is density of matrix and ρ_s is density of sand,

m_f is mass of fiber, m_m is mass of matrix and m_s is mass of sand.

Since the density of basalt fiber is slightly different from E glass fiber and ECR glass fiber; the volume fractions of the raw materials for DN 600 PN 10 SN 5000 pipe given in Table 3.9 is recalculated for recipe no 600-5 and given in Appendix A, Table A.2.

3.3 Experimental Techniques

3.3.1 Test Specimens

Except for recipes no 600-5 and 600-5-rev, all the recipes given in Tables 3.7 and 3.8, were produced by manufacturing five pipes. For 600-5 and 600-5-rev recipes, one pipe was produced.

Except for recipes no 600-5 and 600-5-rev, one stiffness ring was cut from each recipe in Tables 3.7 and 3.8. Since only one pipe was produced for 600-5 and 600-5-rev recipes, to be able to have more test results, five stiffness rings were cut from each of the pipes produced with these two recipes. The longitudinal and circumferential tensile test specimens were cut from the stiffness rings.

The cutting method of stiffness ring specimen from GRP pipe is drawn in Figure 3.3 and cutting method of tensile test specimens from stiffness ring is drawn in Figure 3.4. The cutting of stiffness ring from pipe was made by cutting devices on these lifting tables at the production line.

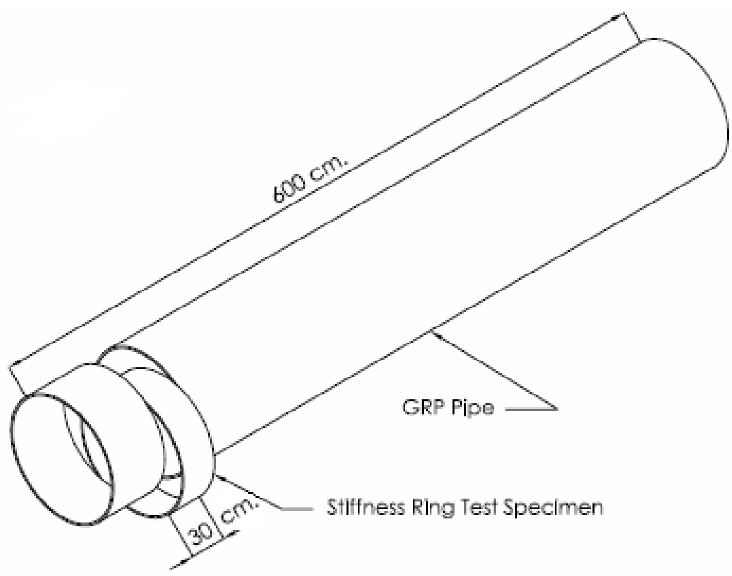


Figure 3.3 Cutting method of stiffness ring specimen from CC GRP pipe

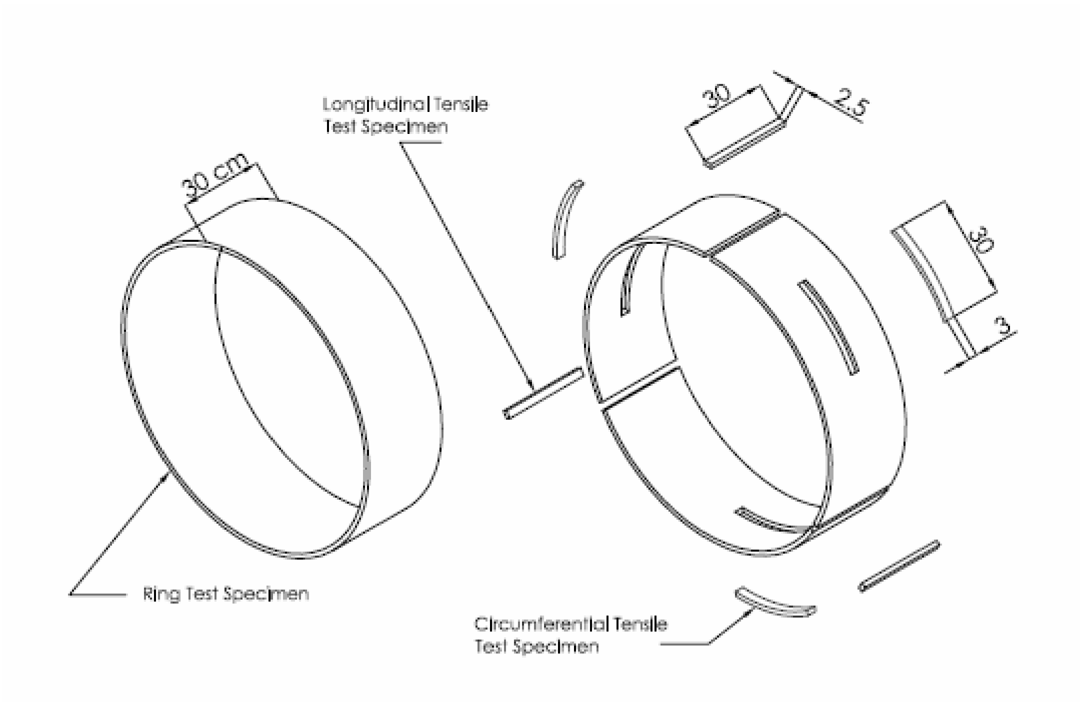


Figure 3.4 Cutting methods of tensile test specimens from stiffness ring

3.3.2 Mechanical Testing of GRP Pipes

In this study, there are three types of tests that have been carried out: stiffness test, longitudinal tensile strength test and circumferential tensile strength test. Details of these test methods are given in sections that follow.

3.3.2.1 Stiffness Test

The stiffness value indicates the ability of the pipe to resist external soil, hydrostatic and traffic loads, and negative pressure. It is a measurement of resistance of a whole pipe body to the deflection.

In this study, to determine the initial specific ring stiffness of the pipe samples, Method B according to ISO 7685 was used. According to this method, a length of pipe was loaded throughout its length and compress radially. After applying the load necessary to give the initial relative deflection of (3±0.5) %, the deflection was kept constant for a one minute and the final load being applied was determined.

3.3.2.1.1 Test Pieces

Each test piece was a complete ring cut from the pipe to be tested. The cut ends of the test pieces were smooth. 6 straight lines were drawn on the outside along the length of the test piece around its circumference with equal distance intervals. One test piece was cut from each pipe.

The length of the test pieces along each reference line were measured and average lengths, L, in meters, of the test pieces from each of the 6 measured values were calculated. All the stiffness ring samples were cut from a pipe according to Figure 3.3 to a length of 300 mm. All the test pieces were stored for 24h at 23ºC before testing.

The wall thicknesses of the test pieces along each reference line were measured and average wall thicknesses, e, in meters, of the test pieces from each of the 12 measured values were calculated.

The external diameter of the test piece was measured at the mid point of the ring sample to be tested.

The mean diameter, d_m, of the test pieces were calculated by using the values obtained for wall thickness and the external diameter.

Test pieces were conditioned for 24 h at 23ºC ± 3ºC before testing.

Schematic diagram of the ring stiffness test arrangement is given in Figure 3.5

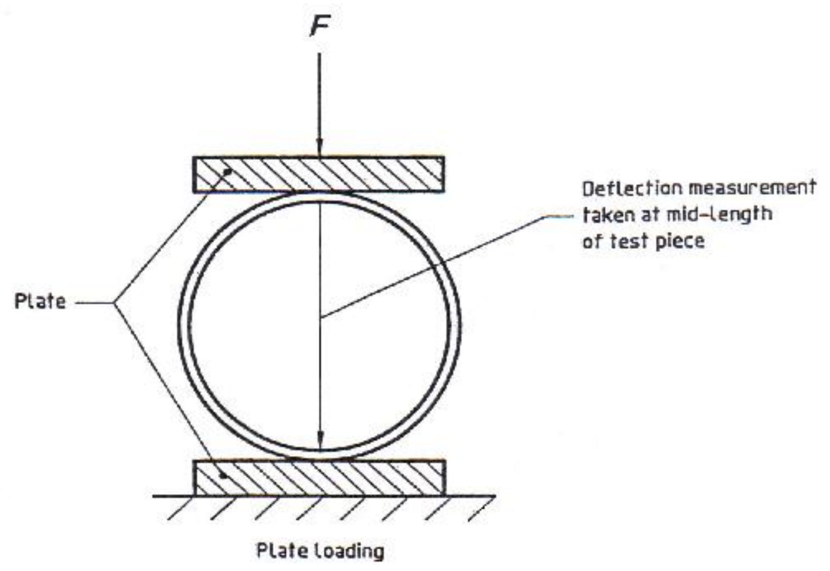


Figure 3.5 Schematic diagram of the ring stiffness test arrangement [29]

3.3.2.1.2 Apparatus

The main apparatus was a compressive loading machine applying a compressive force at a controlled rate through two parallel load application surfaces with their major axes perpendicular to and centered in the direction of the application of the load F. In this way, a horizontally oriented pipe test piece could be compressed vertically. These plates have a length which is longer than that of the test piece.

The compressive loading machine used in stiffness test is shown in Figure 3.6.

The testing machine has a load indicator with an accuracy of ±1% which is connected to the computer. The machine also had a deflection indicator which has an accuracy of ±1%.

The other apparatus used in stiffness test were dimension measuring instruments which were the digital calipers and circometer. Both of these measuring devices were capable of measuring thickness, length and diameters to an accuracy of within ±0.01 mm.

Figure 3.6 Stiffness test machine

3.3.2.1.3 Test Procedure

Test piece was placed in the apparatus with a pair of diametrically opposed reference lines in contact with the plates. The contact between the plates and the test piece was uniform.

To determine the initial specific ring stiffness of pipe samples according to Method B of ISO 7685 international standard, the pipe ring samples were loaded to give initial relative deflection of (3±0.5) %. The compressive load was applied at an approximately constant rate so that the relative deflection 3±0.5 % was reached in 60±10 seconds. The deflection was kept constant for a one minute and the final load being applied was determined. The applied load and the deflection were recorded.

Test was carried out at each pair of reference lines. The test piece was allowed to recover for approximately 15 minutes between each test.

3.3.2.1.4 Calculation of Stiffness

The specific ring stiffness, S, is a physical characteristic of the pipe, which is a measure of the resistance to ring deflection under external load. This characteristic is determined by testing and is defined, in Newton per square meter, by Equation 3.7:

$$S = E * I / d_m^3 \qquad (3.7)$$

where E is the apparent modulus of elasticity, in MPa;

I is the second moment of area in the longitudinal direction per meter length, expressed in meters to the fourth power per meter, i.e.

$$I = e^3/12 \qquad (3.8)$$

where e is the wall thickness of the test piece, in meters;

d_m is the mean diameter of the test piece, in meters, i.e.

$$d_m = d_e - e \qquad (3.9)$$

where d_e is the measured external diameter, in meters.

Initial specific ring stiffness, S_0 is the initial value of S obtained by testing in accordance with ISO 7685, International Standard. It is expressed in newton per square meter:

$$S_0 = F^* f / L * y \quad (3.10)$$

where f is the deflection coefficient, in accordance with ISO 7685 International Standard:

$$f = (1860 + (2500^*y/d_m))/100000 \quad (3.11)$$

L is the average length of the test piece, expressed in meters;

F is the applied load, expressed in Newton;

y is the deflection, expressed in meters;

d_m is the mean diameter, expressed in meters.

The averages of the three value of S_0 were recorded as the initial specific ring stiffness of the test piece.

3.3.2.2 Longitudinal Tensile Strength Test

The initial longitudinal tensile strength, σ_{LA}*, of the pipe sample is the maximum tensile force in the longitudinal direction per unit mean circumference at failure. The maximum longitudinal tensile stress, σ , is the maximum longitudinal tensile force per unit cross-sectional area at failure.

In this study, to determine the longitudinal tensile strength of the pipe samples, Method A according to ISO 8513 was used. According to this method, strip test pieces were cut longitudinally from the pipe walls and subjected to an increasing tensile force in the longitudinal direction at a constant rate until the failure occurred.

The tensile properties were determined by using the initial dimensions of the test piece and the tensile force.

3.3.2.2.1 Test Pieces

Test pieces were parallel sided strips cut in the longitudinal direction of the pipe as shown in Figure 3.7. These test pieces were cut from the rings which were previously used for the determination of the initial specific ring stiffness tests. Three test samples were cut for each pipe. The longitudinal and circumferential tensile test specimens' lengths were 300 mm, because they were cut from stiffness rings according to Figure 3.3. Test pieces were cut with widths of 25 mm.

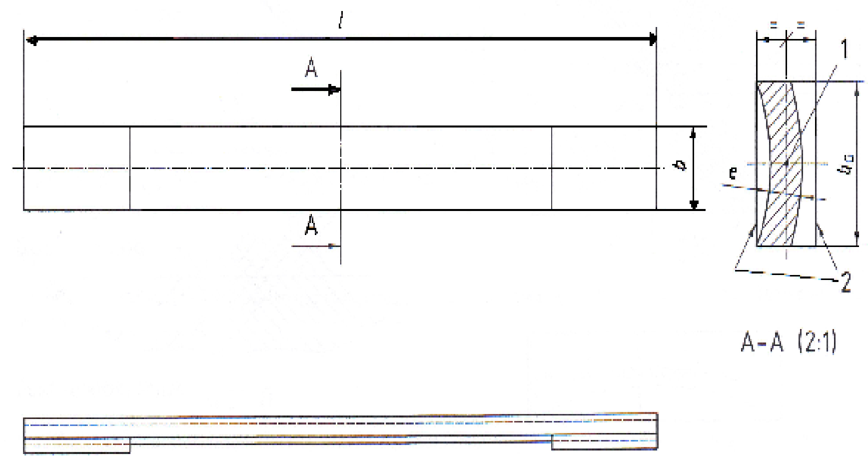


Figure 3.7 Parallel-sided strip test piece dimensions [30]

3.3.2.2.2 Apparatus

The main apparatus was a tensile testing machine that with a constant rate cross-head movement type, incorporating the fixed part, a drive mechanism and a force indicator. The fixed part was fitted with a grip to hold one end of the test piece without permitting any longitudinal movement and a movable part incorporating a grip to hold the other end of the test piece during extension.

The fixed and moving parts and their associated grips enabled the test pieces to be aligned when a force was applied so that its longitudinal axis coincides with the direction of this force.

The drive mechanism was capable of imparting a constant speed to the moving part.

The force indicator was capable of measuring the force applied to a test piece which was held in the grips. Each of the two grips was capable of holding one end of the test piece without slipping or crushing to an extent that would affect the results obtained.

The tensile testing machine used for both the longitudinal and circumferential tensile tests is shown in Figure 3.8. The maximum measurement capacity of it was 250000 N. The machine has a load indicator with an accuracy of ±1% and it is connected to the computer. The other apparatus used in tensile test were dimension measuring instruments was a digital caliper. This measuring device was capable of measuring thickness, length and width of the test pieces to an accuracy of within ±0.01 mm.

Figure 3.8 Tensile testing machine

The maximum measurement capacity of it was 250000 N. The machine has a load indicator with an accuracy of ±1% and it is connected to the computer. The other apparatus used in tensile test were dimension measuring instruments was a digital caliper. This measuring device was capable of measuring thickness, length and width of the test pieces to an accuracy of within ±0.01 mm.

3.3.2.2.3 Test Procedure

The length, L, the wall thicknesses, e, and the width, b_G, of the test pieces were measured.

Each the test piece was placed in the tensile testing machine so that the axial alignment coincided with the direction of pull. The grips were clumped uniformly and sufficiently tightly to prevent slipping of the test piece.

Test pieces were loaded by separating the grips at a constant speed. The maximum forces sustained by the test pieces were recorded.

3.3.2.2.4 Calculation of Longitudinal Tensile Strength

For each test piece, the initial longitudinal tensile strength, (σ_{LA}*), in Newton per millimeter of circumference, was calculated by using the following equation:

$$\sigma_{LA}^* = F / b_G \tag{3.12}$$

where F is the maximum force, in Newton;

b_G is the width of the strip test piece, in millimeters;

The average initial longitudinal tensile strength of the test pieces were calculated from three different samples for each pipe.

3.3.2.3 Circumferential Tensile Strength Test

The initial circumferential tensile strength, σ_{CD}*, of the pipe sample is the ultimate circumferential tensile force per unit length in the circumferential direction.

In this study, to determine the initial circumferential tensile strength of the pipe samples, Method D according to ISO 8521 was used. According to this method, strip test pieces, cut from the pipe walls in the circumferential direction, were subjected to an increasing tensile force until rupture occurred.

The tensile properties were determined by using the initial dimensions of the test piece and the tensile force.

3.3.2.3.1 Test Pieces

Test pieces were cut from the pipe walls in the circumferential direction and three test samples were cut for each pipe.

The faces of the test pieces in contact with the clamp were smooth and perpendicular to the axis of the pipe. In order to prevent shear failure, the distance between the test apparatus' grips, lg, was (15±5) mm. (See Figure 3.9)

The circumferential tensile test specimens were cut from stiffness rings according to Figure 3.4. Test pieces were cut to width of 30 mm.

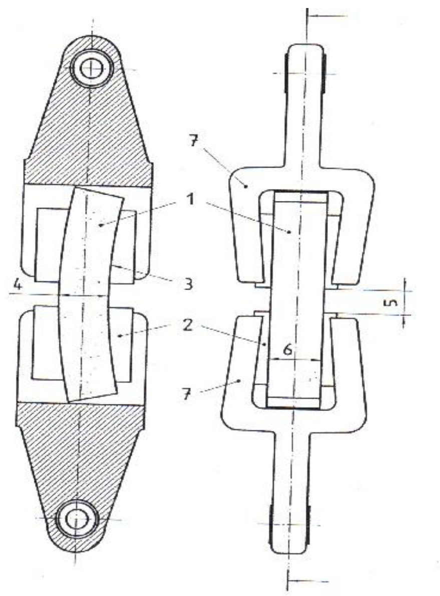
3.3.2.3.2 Apparatus

The apparatus had a fixed part with a grip to hold one end of the test piece, a movable part, a drive mechanism and a load indicator. The movable part had a second grip to hold the other end of the test piece. The grips were used for holding the ends of the test pieces without slipping.

The fixed and moving parts and their associated grips enabled the test pieces to be aligned when a force was applied so that its longitudinal axis coincided with the direction of this force.

The drive mechanism was capable of imparting a constant speed to the moving part, so that failure could be reached between 1 min and 3 min following the initial loading. Typical test arrangement for the modified strip test is given in Figure 3.9.

The tensile testing machine used for both of the longitudinal and circumferential tensile tests is shown in Figure 3.8. The other apparatus used in circumferential tensile test was dimension measuring instruments which was a digital caliper mentioned earlier.



1- Test Piece
2- Tapered Clamp
3- Inside Diameter
4- Pipe wall thickness, e
5- Distance between Grips
6- Width of the test piece, b
7- Grip

Figure 3.9 Typical test arrangement for the modified strip test [31]

3.3.2.3.3 Test Procedure

The width, b, and the wall thickness, e, of the test pieces were measured.

Each of the test pieces was fixed in the grips so that the force was applied through the centerline of the test piece. The midpoint of the test pieces was located at approximately the midpoint of l_g.

A constant separating speed was applied to the grips so that failure occurred between 1 to 3 minutes. Maximum force was recorded.

3.3.2.3.4 Calculation of Circumferential Tensile Strength

For each test piece, the initial circumferential tensile strength, $\sigma_{CD}*$, in Newton per millimeter of circumference, was calculated by using the following equation:

$$\sigma_{CD}* = F_{ult} / b \tag{3.13}$$

where F_{ult} is the ultimate force, in Newton;

b is the width of the test piece, in millimeters;

The average initial circumferential tensile strength of the test pieces were calculated from three different samples for each pipe.

3.3.2.4 Calculation of Standard Deviation

After calculating stiffness, longitudinal tensile strength and circumferential tensile strength of each specimen, the arithmetic mean of these results and standard deviations were calculated with the following equation:

$$\bar{X} = \frac{1}{n}.\left(\sum_{i=1}^{n} X_i\right) \tag{3.14}$$

$$S = \sqrt{\frac{\sum_{i=1}^{n} X_i - n.X_i^2}{n-1}} \tag{3.15}$$

where:

S : Estimated standard deviation

$\bar{X}$**:** Arithmetic mean of the set of observations

X : Value of single observation

n : Number of observations

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Theoretical Calculation of Modulus of Elasticity and Stiffness from Pipe Recipes

From the raw material amounts in the specific recipes, theoretical calculations are made to foresee the pipe's modulus of elasticity and stiffness of the pipes. Rule of mixtures is a method of approach to estimate the properties of composite materials, based on the assumption that a property of the composite is the volume weighed average of the properties of phases.

According to generalized rule of mixtures, modulus of elasticity of composite materials is estimated as follows:

$$E_c = K\, E_f\, v_f + E_m\, v_m + E_S\, v_S \qquad (4.1)$$

where E_c is modulus of elasticity of a composite in fiber direction,

E_f, E_m, E_S is modulus of elasticity of fiber, matrix and sand filler respectively,

v_f, v_m, v_S are volume fractions of fiber, matrix and sand filler respectively.

K is fiber efficiency factor and its values [32] :

For short aligned fibers 1D: K = 1 (anisotropic)

For short random fibers 2D: K = 3/8 (2D isotropy)

For short random fibers 3D: K = 1/5 (3D isotropy)

In this study, fiber efficiency factor value “K” is taken as 1 for the long fibers in e_2, e_3, e_8, e_9 layers, because long fibers are aligned in the circumferential direction in these layers. K value is taken as 3/8 for the short fibers in e_4, e_5, e_6, e_7, e_{10} layers because short fibers are distributed randomly in these layers. The random distribution of short fibers and especially circumferential alignment of long fibers are not 100% realized in production. However, this theoretical calculation is necessary to have an opinion for the property of the pipe and to make comments on test results. So modulus of elasticity each eleven layers were calculated by using equation (4.1) for each recipe.

The modulus of elasticity of pipes was calculated according to formula (4.2); generalized rule of mixtures for modulus of elasticity of composite materials.

$$E_{pipe} = E_1 v_1 + E_2 v_2 + \ldots + E_{11} v_{11} \qquad (4.2)$$

where E_{pipe} is modulus of elasticity of a pipe,

E_1, E_2, …, E_{11} is modulus of elasticity of layer 1 to 11 respectively,

v_1, v_2,…, v_{11} is volume fractions of layer 1 to 11 respectively,

The theoretical calculation results of modulus of elasticity for each recipe as described above are shown in Tables 4.1, 4.2 and 4.3.

Table 4.1 Modulus of elasticity for the **600-1, 600-2, 600-3, 600-4, 600-5, 600-5-rev** recipes of DN 600 PN 10 SN 5000 pipe (length: 6 meter)

Pipe Layers	**Modulus of Elasticity MPa**					
	600-1	**600-2**	**600-3**	**600-4**	**600-5**	**600-5-rev**
e1	5226	5136	5001	5226	5226	5226
e2	39270	39172	39026	40295	44181	42316
e3	33206	33091	32918	34056	37099	40517
e4	9430	9377	9297	9563	9999	10779
e5	5793	5713	5593	5808	5853	5397
e6	5856	5781	5668	5872	5918	5360
e7	6371	6289	6166	6408	6519	5131
e8	25703	25566	25361	26336	28440	28098
e9	23092	22947	22731	23649	25453	26100
e10	7833	7748	7621	7995	8506	8545
e11	850	850	850	850	850	850
E of pipe	**10833**	**10752**	**10631**	**11026**	**11590**	**11672**

Table 4.2 Modulus of elasticity for the **500-1, 500-2, 500-3, 500-4** recipes of DN 500 PN 10 SN 10000 pipe (length: 6 meter)

Pipe Layers	**Modulus of elasticity MPa**			
	500-1	**500-2**	**500-3**	**500-4**
e1	5131	5033	4887	5131
e2	36140	36034	35874	37075
e3	32500	32383	32208	33330
e4	9314	9260	9178	9443
e5	5697	5610	5481	5712
e6	5893	5820	5711	5909
e7	6734	6664	6560	6779
e8	36140	36034	35874	37075
e9	26003	25867	25664	26645
e10	8072	7988	7862	8241
e11	850	850	850	850
E of pipe	**10409**	**10330**	**10213**	**10587**

Table 4.3 Modulus of elasticity for the **700-1, 700-2, 700-3, 700-4** recipes of DN 700 PN 10 SN 5000 pipe (length: 6 meter)

Pipe Layers	Modulus of elasticity MPa			
	700-1	**700-2**	**700-3**	**700-4**
e1	5100	5000	4850	5100
e2	36520	36415	36257	37466
e3	30448	30325	30141	31219
e4	8999	8943	8860	9118
e5	5960	5886	5775	5979
e6	6045	5977	5874	6065
e7	6613	6536	6420	6656
e8	24232	24091	23879	24822
e9	23092	22947	22731	23649
e10	7953	7869	7742	8119
e11	850	850	850	850
E of pipe	**10855**	**10773**	**10651**	**11047**

By using theoretical modulus of elasticity results, the specific ring stiffness, S of the each pipe were calculated by using formulas (3.9), (3.8) and (3.7). To calculate the specific ring stiffness values, outer diameter values of GRP pipes were specified according to the ISO 10639, International Standards, and the design wall thickness values of pipe samples were obtained as declared by the manufacturer.

The theoretical calculation results of specific ring stiffness values, modulus of elasticity, design wall thicknesses and outer diameters for each recipe as described above are summarized and shown in Table 4.4. Calculated theoretical values of modulus of elasticity and stiffness are compared in sections 4.2.1.1 and 4.2.2.1.

Table 4.4 The specific ring stiffness for the tested pipe recipes (length: 6 meter)

DN / PN / SN of pipe produced	Recipe No	Outside Diameter of pipe , d_m mm	Wall Thickness of pipe , e mm	Mean Diameter of pipe , d_e mm	Calculated The specific ring stiffness, S N/m^2	Calculated Modulus of elasticity of pipe, E MPa
600/10/ 5000	600-1	633.1	11.60	621.50	5870	10833
	600-2				5826	10752
	600-3				5760	10631
	600-4				5974	11026
	600-5				6280	11590
	600-5-rev		11.32	621.78	5870	11672
500/10/ 10000	500-1	530.1	12.02	518.08	10833	10409
	500-2				10751	10330
	500-3				10629	10213
	500-4				11018	10587
700/10/ 5000	700-1	718.3	12.82	705.48	5428	10855
	700-2				5387	10773
	700-3				5326	10651
	700-4				5524	11047

4.2 Experimental Results

In this section, the experimental test results are given. All the test results are discussed and the gain in resin and basalt fiber amount is compared when recipe 600-5 is compared to recipe 600-5-rev.

4.2.1 Test Group Used To Evaluate The Effect of Resin Matrix On Pipe Properties

As explained in section 3.2, the effect of resin matrix was investigated separately from the effect of fiber reinforcement on GRP pipe stiffness and tensile properties. Three different GRP pipe recipes were applied in the production and test samples were produced by changing only the type of resin in these three recipes. Five pipes were produced from each of the recipes (See Table 3.7).

The stiffness test was carried out at each pair of reference lines of each sample. The averages of these three values of S_0 were recorded as the initial specific ring stiffness of the test piece. The stiffness test, measurements and results for samples having recipes of 600-1, 600-2, 600-3, 500-1, 500-2, 500-3, 700-1, 700-2 and 700-3 are given in Appendix B, Tables B.1 to B.9.

The longitudinal and circumferential tensile strength test measurements and results are given in Appendix C, Tables C.1 to C.9.

Average test results are given in Appendix D, Table D.1 and summarized in Table 4.5, and finally the average test results are shown in Figures 4.1 to 4.4.

Table 4.5 Summarized average test results for the evaluation of type of resin

Recipe No	**Average Stiffness Test Results**			**Average Longitudinal Tensile Test**	**Average Circumferential Tensile Test**
	$e_{average}$ mm	**S_0 N/m^2**	**E MPa**	**σ_{LA}* N/mm**	**σ_{CD}* N/mm**
600-1	11.61	5875	10814	222.1	1237.5
600-2	11.63	5860	10741	227.5	1245.9
600-3	11.61	5787	10640	232.6	1287.1
500-1	12.02	10724	10304	208.1	1096.6
500-2	12.02	10697	10284	212.3	1100.2
500-3	12.02	10664	10257	217.1	1146.6
700-1	12.82	5425	10843	253.5	1574.3
700-2	12.82	5402	10802	255.8	1586.1
700-3	12.82	5380	10769	262.3	1622.0

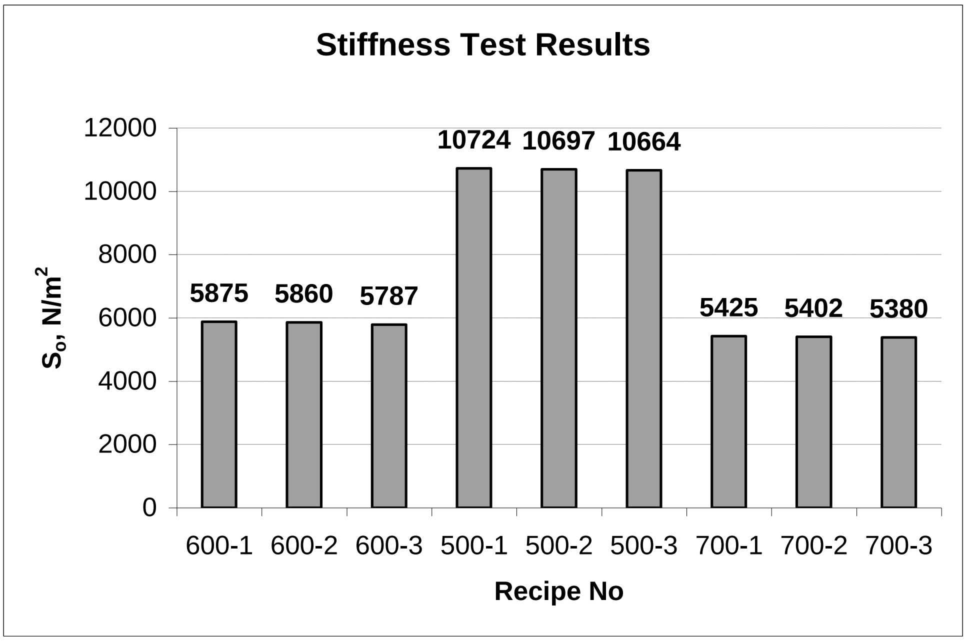


Figure 4.1 Average stiffness test results for the evaluation of type of resin

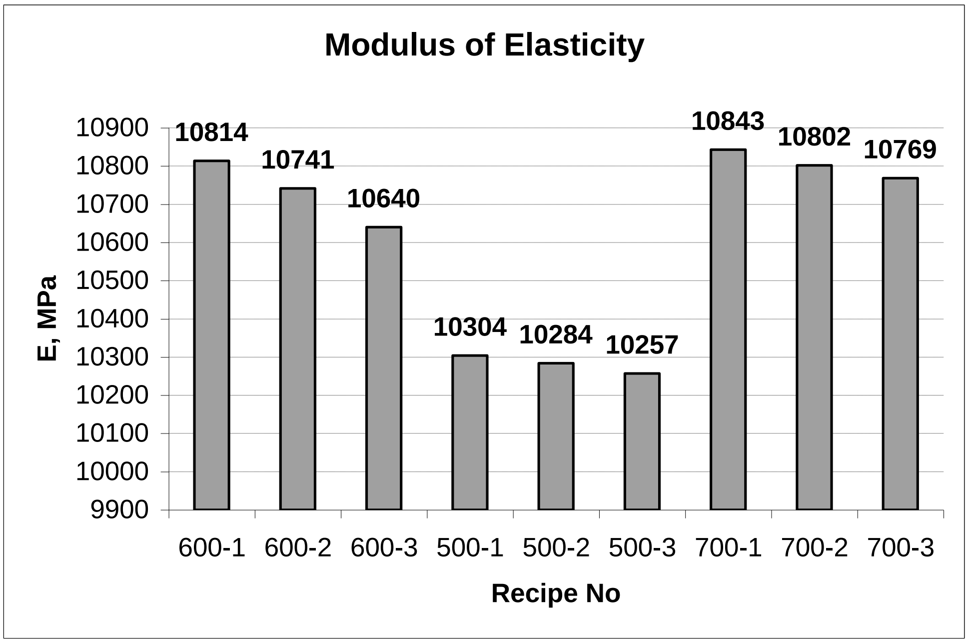


Figure 4.2 Average value of modulus of elasticity obtained from stiffness tests for the evaluation of type of resin

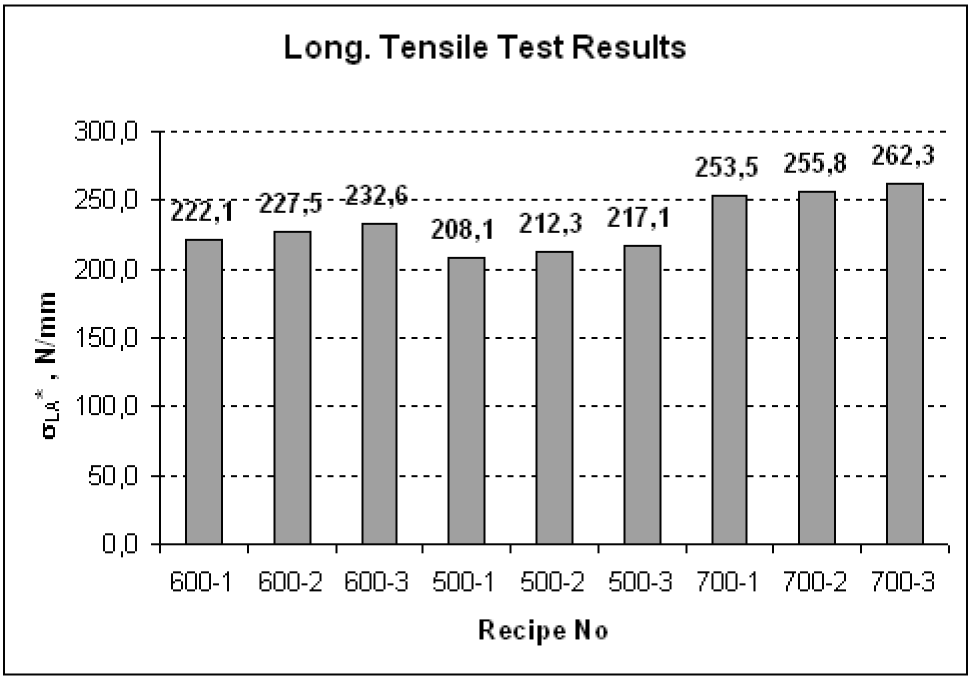


Figure 4.3 Average longitudinal tensile test results for the evaluation of type of resin

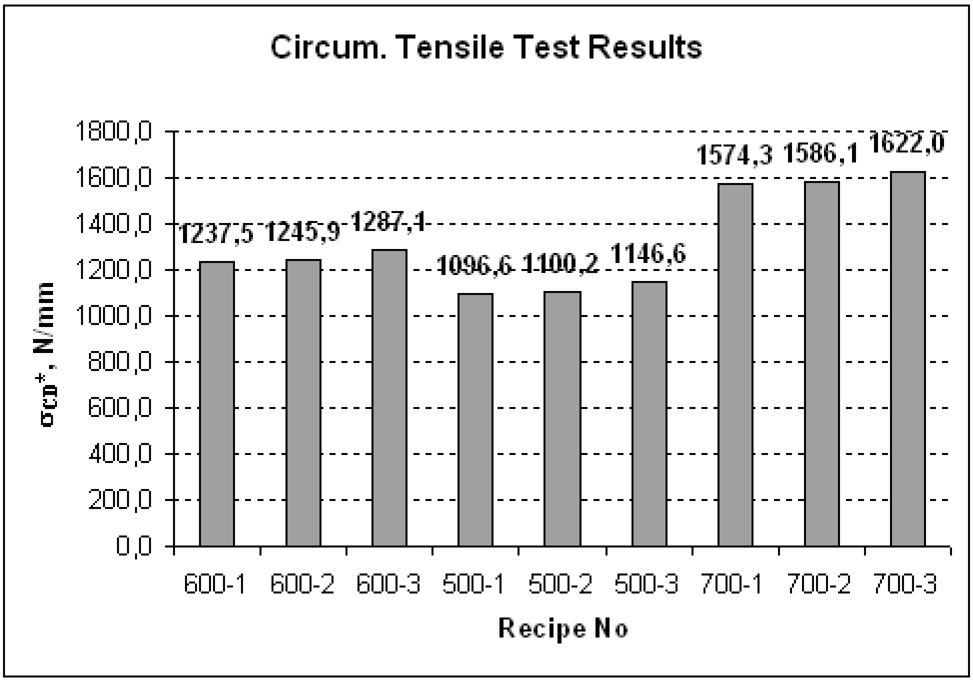


Figure 4.4 Average circumferential tensile test results for the evaluation of type of resin

4.2.1.1 Discussion on the Effect of Resin Matrix on Pipe Properties

As stated in the preceding sections, recipes 600-1, 600-2 and 600-3 had the same raw material amounts, but the only difference was resin types. The same thing is valid for 500-1, 500-2, 500-3 and 700-1, 700-2 and 700-3 recipes.

Theoretical values of modulus of elasticity and stiffness were calculated from equations 4.2 and 3.7 respectively. The experimental results and calculated modulus of elasticity and stiffness of the pipes for each recipe are compared in Figure 4.5.

Properties of composites can be determined through experimental measurements directly. However, when any change in the system variables occurs, experiments may become time consuming and cost prohibitive. Then, theoretical methods of determining composite properties can be used to predict the effects of a large number of system variables. Here, it can be seen from Figure 4.5 that calculated stiffness and elastic modulus values are conforming with the test results for all the recipes of 600-1, 600-2, 600-3, 500-1, 500-2, 500-3, 700-1, 700-2 and 700-3 (See Tables 4.4 and 4.5). Thus, it can be said that this might be a better way to make GRP pipe design calculations, i.e. it is easier to predict modulus of elasticity of pipe first from theoretical calculations. This may become more time and cost effective way.

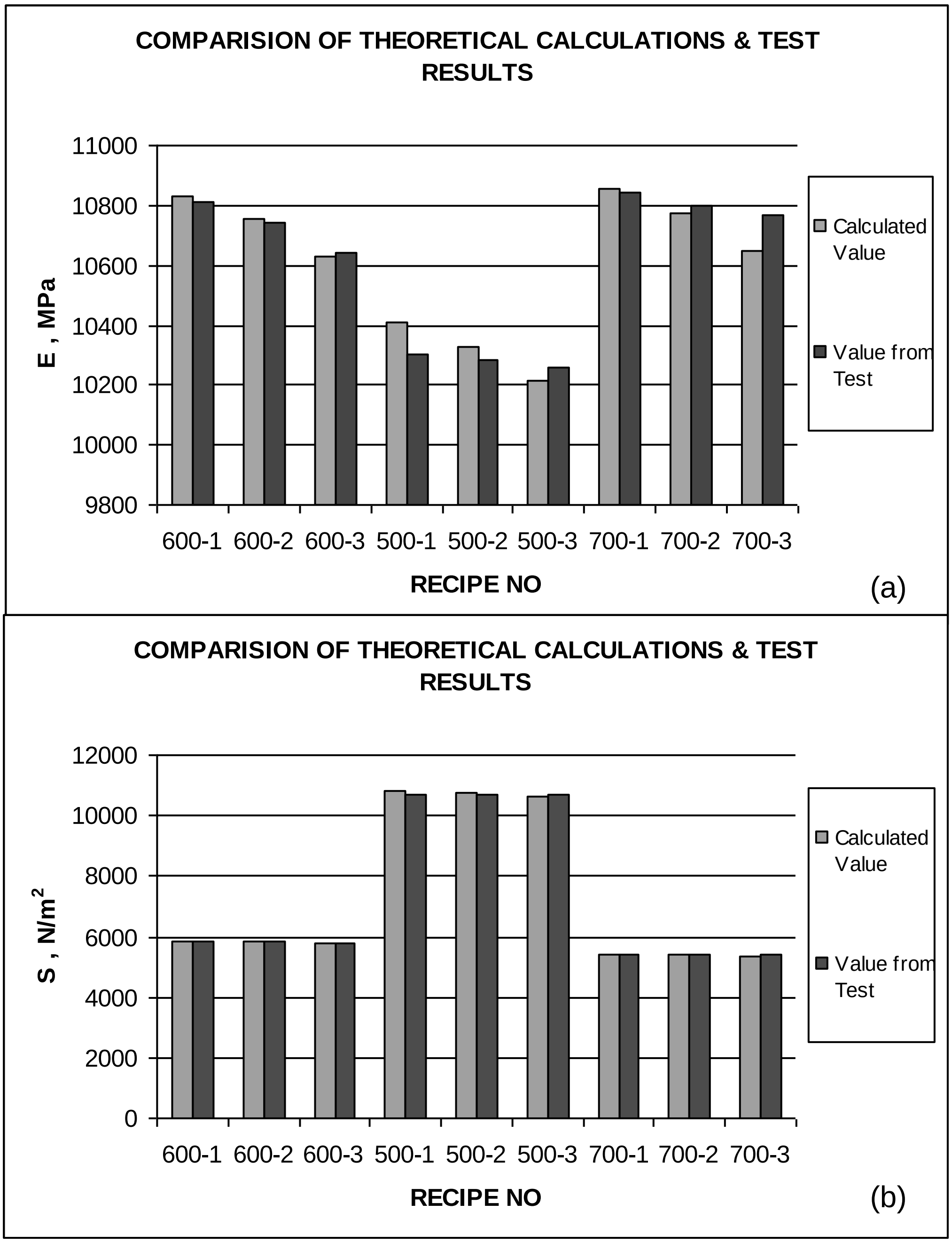


Figure 4.5 Comparison of theoretical calculations and test results for evaluation of the effect of resin type on pipe properties. (a) Comparison of theoretical modulus of elasticity and experimental results. (b) Comparison of theoretical stiffness and experimental results.

The pipes having recipes of 600-1, 500-1 and 700-1; which has orthophthalic resin in them, had the highest stiffness test results and modulus of elasticity values. These results were expected, because orthophthalic resin (BRE 310) has a higher modulus of elasticity than isophthalic resin (BRE 311), and isophthalic resin has higher modulus than vinyl ester resin (ATLAC E NOVA 1045). However this difference was very little and it can be said from these test results that, resin types used in this study did not have a significant effect on stiffness test (See Figure 4.1 and 4.2).

The effect of resin type may not be seen clearly from these test results, but when their effect on chemical resistance of the end thermoset product is considered the degree of cross linking is very important. The “side-by-side” nature of this cross linking of the molecular chains tends to means that polyester laminates suffer from brittleness when shock loadings are applied. The vinyl ester molecules of vinyl ester resin feature fewer ester groups than orthophthalic resins. The ester groups are susceptible to water degradation by hydrolysis which means that vinyl esters exhibit better resistance to water and many other chemicals than their polyester counterparts.

If the longitudinal and circumferential tensile strengths of these testing groups are compared (see Figure 4.3 and 4.4.), it can be said that there is not a significant difference was observed in the longitudinal tensile test results of pipes having recipes with orthophthalic resin and isophthalic resin. Pipes with vinyl ester resin had 3% to 4% higher longitudinal tensile strength results than pipes having recipes with orthophthalic resin. This observation is also valid for circumferential tensile strength results. It can also be said that pipes having recipes with vinyl ester resin had 3% to 4% higher circumferential tensile strength results than pipes with orthophthalic resin matrix.

Normally, isophthalic resins tend to show higher tensile and flexural properties than orthophthalic resins, since isophthalic resins usually form more linear, higher molecular weight polymers than orthophthalic resins. The vinyl ester resins exhibit excellent tensile and flexural properties as well as high elongation at break. The corrosion resistance and mechanical properties of vinyl ester composites are much improved over standard polyester resin composites. Circumferential and longitudinal tensile strength of vinyl ester resin pipe show this effect. However, this improvement of 3 to 4% in tensile tests of the product is not found satisfactory by the manufacturer to change the resin type of the GRP pipe from orthophthalic to vinyl ester due to higher cost of the vinyl ester resin. Because the unit price of vinyl ester resin used in this study was much higher than the unit price of orthophthalic resin (Vinyl ester resin cost was 6.13 $/kg, orthophthalic resin was 1.90 $/kg).

4.2.2 Test Group Used To Evaluate The Effect of Fiber Reinforcement On Pipe Properties

To evaluate the effect of fiber type on stiffness and tensile performance of GRP pipes, three different GRP pipe recipes by changing only the type of fiber reinforcement. The first test group of 600-1, 500-1 and 700-1 were produced by using E glass fiber. Test results of these groups are given in Section 4.2.1. The other test groups called 600-4, 500-4, 700-4 were produced by using ECR glass fiber. The only difference was the type of fiber.

Only two recipes were applied to produce pipes with basalt fiber. The first one called 600-5 which had exactly the same amount of raw materials with 600-1 and 600-4, but the only difference was the type of fiber as mentioned before. Finally, a new recipe; 600-5-rev was applied to produce pipes to see the gain in the amount of fiber and resin when compared to 600-5.

The stiffness test measurements and results for samples of 600-4, 600-5, 600-5-rev, 500-4 and 700-4 are given in Appendix E, Tables E.1 to E.5. The longitudinal and circumferential tensile strength test measurements and results are given in Appendix F, Tables F.1 to F.5. Average test results are given in Appendix G, Table G.1 and summarized in Table 4.6 and finally the average test results are shown in Figure 4.6 to 4.9.

Table 4.6 Summarized average test results for the evaluation of type of fiber

Recipe No	**Average Stiffness Test Results**			**Average Longitudinal Tensile Test**	**Average Circumferential Tensile Test**
	$e_{average}$ mm	**S_0 N/m^2**	**E MPa**	**σ_{LA}* N/mm**	**σ_{CD}* N/mm**
600-1	11.61	5875	10814	222.1	1237.5
600-4	11.61	5986	11024	267	1310.2
600-5	11.6	6499	11981	287.7	1470.3
600-5r	11.33	5870	11636	231	1247.1
500-1	12.02	10724	10304	208.1	1096.6
500-4	12.02	11081	10653	231	1193.5
700-1	12.82	5425	10843	253.5	1574.3
700-4	12.82	5568	11135	282.7	1712.4

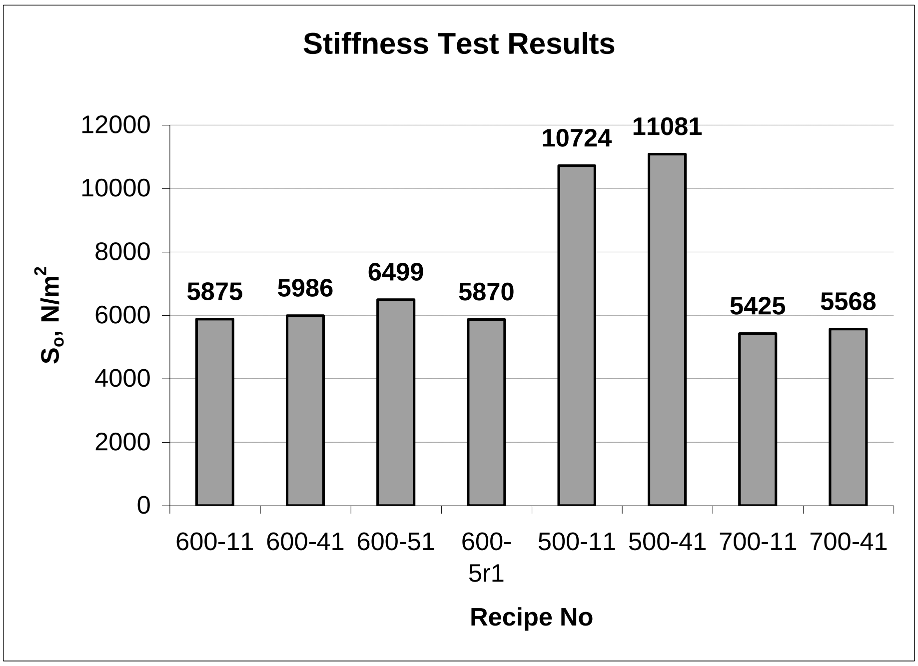


Figure 4.6 Average stiffness test results for the evaluation of type of fiber

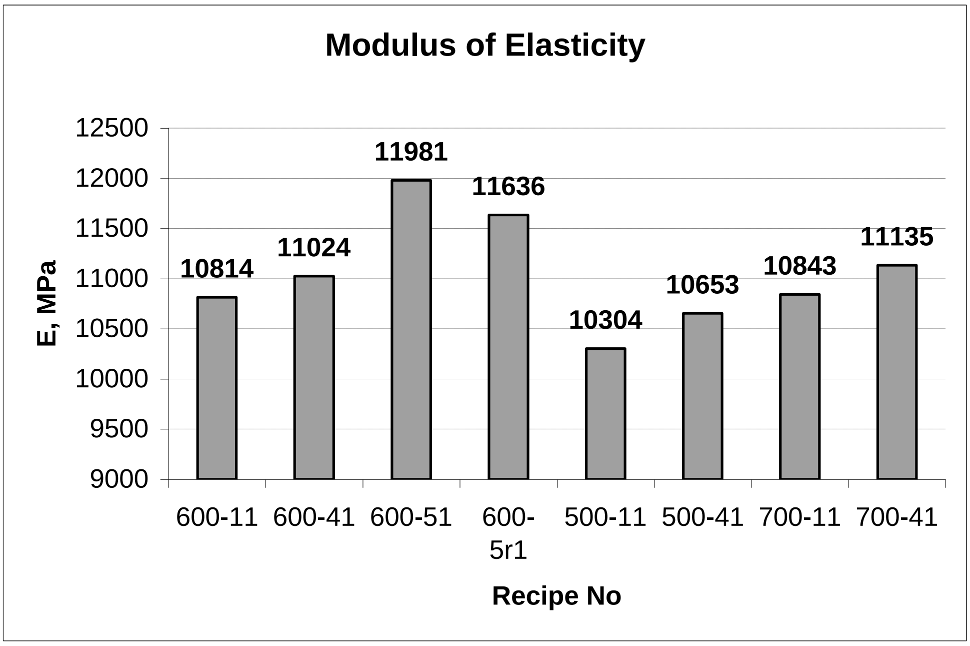


Figure 4.7 Average value of modulus of elasticity obtained from stiffness tests for the evaluation of type of fiber

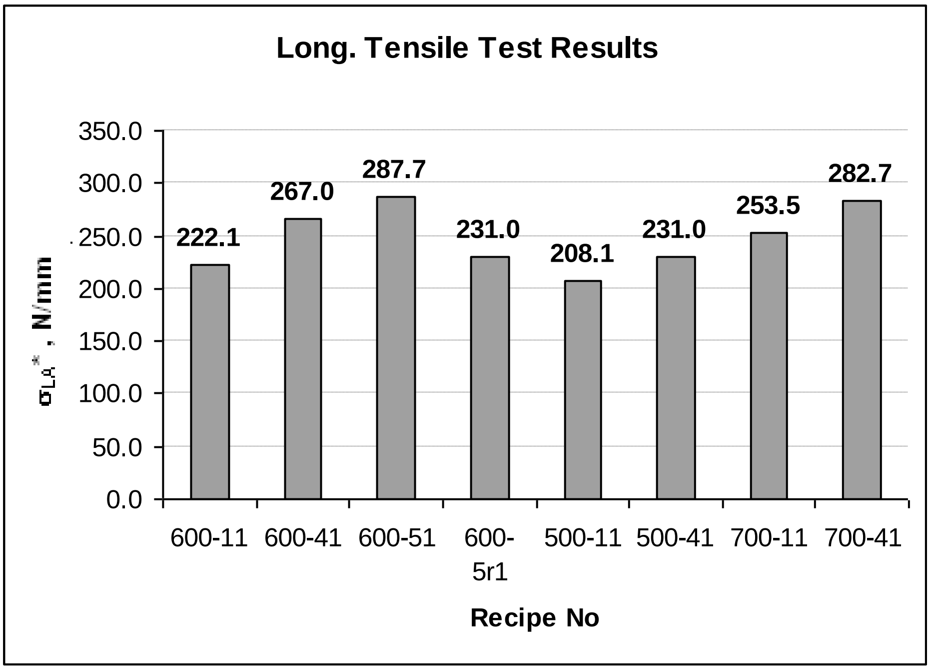


Figure 4.8 Average longitudinal tensile test results for the evaluation of type of fiber

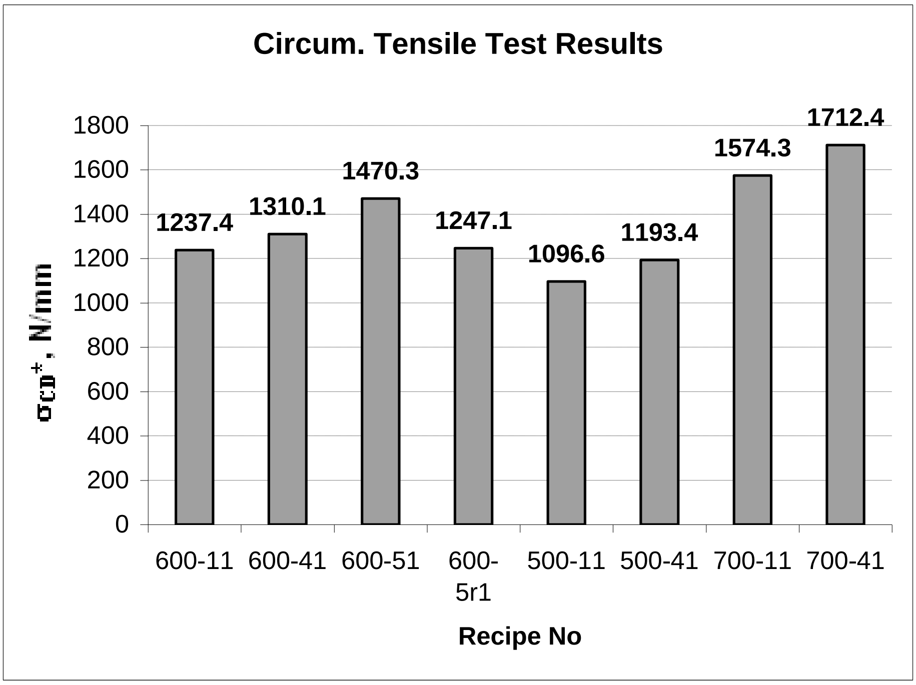


Figure 4.9 Average circumferential tensile test results for the evaluation of type of fiber

4.2.2.1 Discussion on The Effect of Fiber Reinforcement On Pipe Properties

As stated earlier recipes 600-1, 600-4 and 600-5 had the same raw material amounts but the only difference was the type of fiber. The same thing is valid for recipes 500-1, 500-4 and 700-1, 700-4. The experimental results and calculated theoretical values of stiffness and modulus of elasticity of the pipes for each recipe are compared in Figure 4.10.

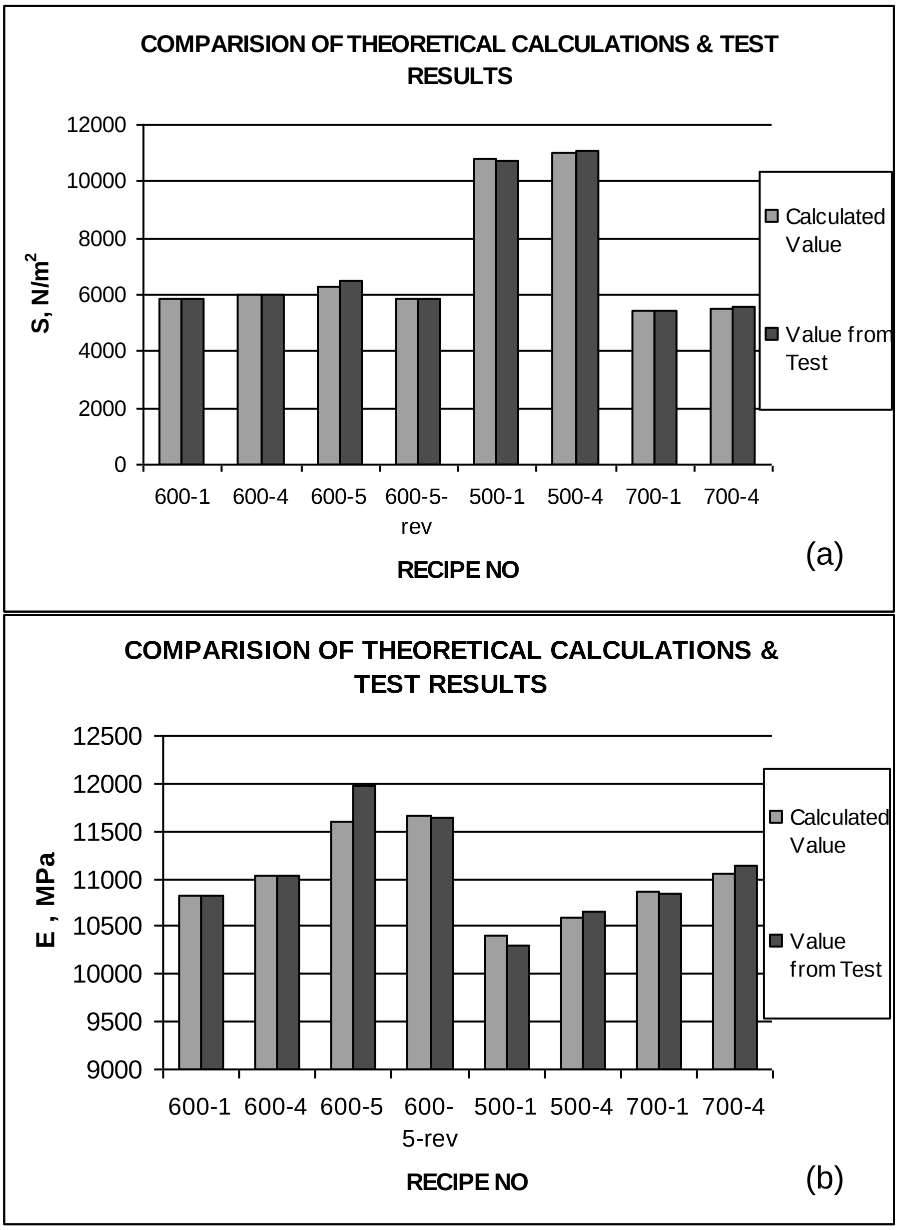


Figure 4.10 Comparison of theoretical calculations and test results for the evaluation of effect of fiber type on pipe properties. (a) Comparison of theoretical modulus of elasticity and experimental results. (b) Comparison of theoretical stiffness and experimental results.

Figure 4.10 shows that, the theoretical calculation of stiffness and modulus of elasticity of GRP pipes are in accordance with the test results. Pipe samples having recipe of 600-5 which were reinforced with basalt fiber had higher modulus of elasticity, since basalt fiber has relatively higher modulus of elasticity than E and ECR glass fibers.

The ratios of the test results of E glass reinforced pipes and ECR reinforced pipes are given in Table 4.7.

Table 4.7 The ratios of the test results of E glass reinforced pipes and ECR reinforced pipes

Recipe No		**600-4/600-1**	**500-4/500-1**	**700-4/700-1**
Tests		**difference %**		
Stiffness Test Results	**S_0 , N/m^2**	1.9	3.3	2.6
	E , MPa	1.9	3.4	2.7
Longitudinal Tensile Test Results	**σ_{LA}* ; N/mm**	20.2	11.0	11.5
Circumferential Tensile Test Results	**σ_{CD}*; N/mm**	5.9	8.8	8.8

From Table 4.7, it can be seen that ECR reinforced pipes show higher performance than E glass reinforced pipe. Stiffness of ECR reinforced samples were found approximately 2% to 3.3 % higher, longitudinal tensile strengths were found 11% to 20% higher and circumferential tensile strength test results were 6% to 9% higher than the corresponding property of E glass fiber reinforced pipe samples.

The pipes having recipes of 600-1, 500-1 and 700-1; which have E glass fibers in them, showed the lowest stiffness test results and modulus of elasticity values. These results were expected, because E glass fiber has the lowest modulus of elasticity. Basalt fiber has the highest modulus of elasticity. The most important difference was the modulus of elasticity of pipes having 600-5 recipe.

Basalt fiber reinforced pipes having recipe of 600-5 showed the highest performance over E glass and ECR glass reinforced pipes. The ratio of the test results of these pipes are given in Table 4.8.

Table 4.8 The ratio of the test results of basalt fiber reinforced pipes and E or ECR glass reinforced pipes

Recipe No		**600-5 / 600-1**	**600-5 / 600-4**
Tests		**difference %**	
Stiffness Test Results	**S_0 , N/m^2**	9.6	8.6
	E , MPa	10.8	8.7
Longitudinal Tensile Test Results	**σ_{LA}* ; N/mm**	29.5	7.8
Circumferential Tensile Test Results	**σ_{CD}*; N/mm**	18.8	12.2

From Table 4.8, it can be seen that basalt fiber reinforced pipes show higher performance than E glass and ECR glass reinforced pipes. Stiffness of basalt reinforced samples was found 8.6 % and 9.6 % higher, longitudinal tensile strength was found 7.8% and 29.5% higher and circumferential tensile strength was 12.2% and 18.8% higher than ECR glass fiber reinforced pipe and E glass fiber reinforced pipe samples respectively. These results are expected, because basalt fibers have higher mechanical properties in comparison to E and ECR glass fibers.

The samples having 600-5-rev recipe with basalt fibers have stiffness result which is close to the stiffness result of FRP pipes having 600-1 recipe. Also, its modulus of elasticity was higher than modulus of elasticity of FRP pipes having 600-1 recipe. The circumferential tensile strengths of basalt fiber reinforced pipes having recipe of 600-5-rev were also almost the same as glass fiber reinforced pipes having recipe of 600-1. The longitudinal tensile strength of basalt fiber reinforced pipes having recipe of 600-5-rev were about 3.9% higher than the longitudinal tensile strength as glass fiber reinforced pipes having 600-1 recipe. These experimental results of pipes having 600-5-rev recipe when compared to pipes having recipes of 600-5 and 600-1 is shown in Table 4.9.

Table 4.9 The ratio of the test results of pipes having recipe of 600-5-rev when compared to pipes having recipes of 600-5 and 600-1

Recipe No		**600-5 over 600-5-rev**	**600-1 over 600-5-rev**
Tests		**difference %**	
Stiffness Test Results	**S_0 , N/m^2**	10.7	0.1
	E , MPa	3.0	-7.1
Longitudinal Tensile Test Results	**σ_{LA}* ; N/mm**	24.5	-3.9
Circumferential Tensile Test Results	**σ_{CD}*; N/mm**	17.9	-0.8

All these comparison to evaluate the basalt fiber and E glass fiber reinforced pipe properties, raw material gain is summarized in Table 4.10.

Table 4.10 Comparison of recipes 600-5 and 600-5-rev

Recipe No		**600-1**	**600-5-rev**	**Difference**
Design Wall Thickness, e	**mm**	11.6	11.32	0.28
Total Body Resin	**kg**	66.07	64.33	1.74
Total Liner Resin	**kg**	22.58	22.58	-
Total Fiber	**kg**	42.92	40.84	2.08
Total Sand	**kg**	121.15	121.15	-
Total Weight of 6 m pipe	**kg**	252.72	248.9	3.82

Basalt reinforced pipes was 3.82 kg lighter and 0.28 mm thinner in wall than E glass fiber reinforced pipes. The gain in fiber amount was 2.08 kg and the gain in resin was 1.74 kg per 6 m of pipe. Basalt reinforced pipe has advantages over E glass reinforced pipe about weight and thickness properties.

The price gain in cost of 6m pipe is shown in Table 4.11. Basalt reinforced pipe was 22.06 $ more expensive than E glass reinforced pipe. This raw material gain was not seen as a good gain in cost by the manufacturer.

Table 4.11 Comparison of cost of basalt fiber reinforced pipe and E glass fiber reinforced pipe

Material Cost	**Unit price $/kg**	**600-1 cost $ / 6m pipe**	**600-5-rev cost $ / 6m pipe**
Body Resin	1.90	125.53	122.23
E Glass Fiber	1.55	66.53	-
Basalt Fiber	2.25	-	91.89
Total		192.06	214.12

Test results of basalt reinforced polyester pipe were not as good as the individual properties of basalt fiber. The test samples and their failure were not good as glass fiber reinforced ones when compared by visually.

CHAPTER 5

CONCLUSIONS

The properties of a FRP composite pipe mainly depend on the properties of its raw materials and their distribution. In this study, the effects of resin types which were orthophthalic, isophthalic, vinyl ester resins and the effects of fiber types which were E glass, ECR glass and basalt fiber on the stiffness and tensile properties of FRP pipes produced by centrifugal casting process were investigated.

Experimental methods used in this study were simple and direct. Theoretical calculations were also used to predict the experimental stiffness test results. Theoretical calculations of stiffness and modulus of elasticity values of FRP pipe samples were in accordance with experimental results.

There were no significant differences in the longitudinal tensile test results of pipes having orthophthalic resin and isophthalic resin. Pipes having recipes with vinyl ester resin had 3% to 4% higher longitudinal and circumferential tensile strengths than pipes having orthophthalic resin. In conclusion, the use of different resin types of orthophthalic, isophthalic and vinyl ester resin did not affect the stiffness and tensile strength of FRP pipes very much.

Secondly, the effects of fiber reinforcement type were on stiffness and tensile properties of FRP pipe were evaluated. The theoretical calculation of stiffness and modulus of elasticity of GRP pipes were in accordance with the test results. Basalt fiber reinforced pipes having recipe of 600-5 showed higher performance over ECR glass fiber reinforced pipes and ECR glass reinforced pipes, showed higher performance over E glass fiber reinforced pipes.

Third and main objective of this study was to evaluate the effect of basalt fiber reinforcement on FRP pipe performance. To achieve this aim, recipe 600-5 was designed to produce pipe having almost the same stiffness value with the 600-1 recipe. This was made to see the amount reduction in resin when basalt fiber is used. This aim was achieved. The samples having 600-5-rev recipe with basalt fibers had stiffness result close to pipes having 600-1 recipe. Also, its modulus of elasticity was higher than pipes having 600-1 recipe. This is an advantage of basalt fiber over E glass fiber. From these test results it can be seen that by using less amount of basalt fiber in recipe 600-5-rev, almost the same stiffness value and relatively higher modulus of elasticity value is obtained when compared to pipes having E glass fiber reinforced pipes with recipe of 600-1.

Basalt fiber reinforced pipes having recipe of 600-5-rev had very similar stiffness, circumferential tensile strength and 4% higher longitudinal tensile strength when compared to E glass fiber reinforced pipes having 600-1 recipe.

Owing to higher cost of basalt fiber, basalt fiber reinforced pipe was more expensive than E glass fiber reinforced pipe. When basalt fiber is used in place of E glass fiber in FRP, the raw material gain may not be evaluated as a desired decrease in cost by the manufacturers. But depending on the application areas which needs higher performance of FRP product, basalt fiber reinforcement can be more effectively used when compared to E glass fiber reinforcement.

In the future, selection of a proper matrix for basalt fiber for producing basalt fiber reinforced composites may be investigated. Also, long term performance of the basalt fiber reinforced composite pipe might be tested.

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APPENDIX A

PIPE RECIPES IN TERMS OF VOLUME FRACTIONS OF THE RAW MATERIALS

Table A.1 **600-1, 600-2, 600-3, 600-4** recipes of DN 600 PN 10 SN 5000 pipe (length: 6 meter) in terms of volume fractions of the raw materials

Pipe Layers	Volume of layers	Density of layers	Body Resin	Liner Resin	Fiber	Sand
	dm^3	kg/dm^3	$v_{body\ resin}$	$v_{liner\ resin}$	v_f	v_s
e1	14.32	2.01	0.45	-	-	0.55
e2	6.64	1.89	0.49	-	0.51	-
e3	3.35	1.77	0.57	-	0.43	-
e4	11.86	2.26	0.27	-	0.18	0.56
e5	21.48	2.08	0.40	-	0.02	0.58
e6	21.36	2.11	0.38	-	0.02	0.60
e7	10.36	2.06	0.41	-	0.05	0.54
e8	8.92	1.62	0.68	-	0.32	-
e9	11.62	1.57	0.72	-	0.28	-
e10	11.58	1.49	0.42	0.36	0.22	-
e11	14.66	1.20	-	1.00	-	-

Table A.2 **600-5** recipe of DN 600 PN 10 SN 5000 pipe (length: 6 meter) in terms of volume fractions of the raw materials

Pipe Layers	Volume of layers	Density of layers	Body Resin	Liner Resin	Fiber	Sand
	dm^3	kg/dm^3	$v_{body\ resin}$	$v_{liner\ resin}$	v_f	v_s
e1	14.32	2.01	0.45	-	-	0.55
e2	6.43	1.95	0.50	-	0.50	-
e3	3.27	1.82	0.59	-	0.41	-
e4	11.74	2.28	0.27	-	0.17	0.56
e5	21.46	2.08	0.40	-	0.02	0.58
e6	21.33	2.11	0.38	-	0.02	0.60
e7	10.32	2.07	0.41	-	0.05	0.54
e8	8.75	1.65	0.70	-	0.30	-
e9	11.43	1.60	0.73	-	0.27	-
e10	11.43	1.51	0.43	0.36	0.21	-
e11	14.66	1.20	-	1.00	-	-

Table A.3 **600-5-rev** recipe of DN 600 PN 10 SN 5000 pipe (length: 6 meter) in terms of volume fractions of the raw materials

Pipe Layers	**Volume of layers**	**Density of layers**	**Body Resin**	**Liner Resin**	**Fiber**	**Sand**
	dm^3	**kg/dm^3**	**$v_{body\ resin}$**	**$v_{liner\ resin}$**	**v_f**	**v_s**
e1	14.32	2.01	0.45	-	-	0.55
e2	6.81	1.79	0.56	-	0.44	-
e3	3.44	1.77	0.57	-	0.43	-
e4	11.98	2.33	0.21	-	0.19	0.60
e5	19.94	2.11	0.38	-	0.02	0.60
e6	19.79	2.14	0.35	-	0.02	0.62
e7	10.38	2.12	0.37	-	0.05	0.58
e8	9.07	1.56	0.73	-	0.27	-
e9	11.81	1.55	0.74	-	0.26	-
e10	11.68	1.49	0.43	0.36	0.22	-
e11	14.66	1.20	-	1.00	-	-

Table A.4 **500-1, 500-2, 500-3, 500-4** recipes of DN 500 PN 10 SN 10000 pipe (length: 6 meter) in terms of volume fractions of the raw materials

Pipe Layers	**Volume of layers**	**Density of layers**	**Body Resin**	**Liner Resin**	**Fiber**	**Sand**
	dm^3	**kg/dm^3**	$v_{body\ resin}$	$v_{liner\ resin}$	v_f	v_s
e1	11.99	1.95	0.49	-	-	0.51
e2	4.31	1.83	0.53	-	0.47	-
e3	2.60	1.75	0.59	-	0.41	-
e4	9.92	2.25	0.27	-	0.17	0.56
e5	22.84	2.03	0.43	-	0.02	0.55
e6	22.64	2.13	0.36	-	0.02	0.62
e7	7.20	2.15	0.35	-	0.06	0.59
e8	4.99	1.83	0.53	-	0.47	-
e9	9.66	1.63	0.68	-	0.32	-
e10	9.62	1.50	0.42	0.35	0.23	-
e11	11.98	1.20	-	1.00	-	-

Table A.5 Standard **700-1, 700-2, 700-3, 700-4** recipes of DN 700 PN 10 SN 5000 pipe (length:6 meter) in terms of volume fractions of the raw materials

Pipe Layers	Volume of layers	Density of layers	Body Resin	Liner Resin	Fiber	Sand
	dm^3	kg/dm^3	$v_{body\ resin}$	$v_{liner\ resin}$	v_f	v_s
e1	16.25	1.93	0.50	-	-	0.50
e2	9.27	1.83	0.53	-	0.47	-
e3	4.04	1.72	0.61	-	0.39	-
e4	13.46	2.24	0.28	-	0.16	0.56
e5	28.76	2.12	0.37	-	0.03	0.60
e6	28.59	2.16	0.34	-	0.03	0.63
e7	13.33	2.10	0.38	-	0.06	0.56
e8	13.72	1.60	0.70	-	0.30	-
e9	13.18	1.57	0.72	-	0.28	-
e10	13.14	1.50	0.42	0.36	0.22	-
e11	17.03	1.20	-	1.00	0.00	-

APPENDIX B

STIFFNESS TEST RESULTS FOR THE EVALUATION OF TYPE OF RESIN

Table B.1 Stiffness test results for recipe no 600-1

Sample No	$e_{average}$ mm	L mm	d_e mm	d_m mm	y mm	f	F N	S_0 N/m^2	Std. Dev.	I mm^3	E MPa
600-11-1	11.62	300	633.1	621.48	18.64	0.019	1702	5888	8,54	130.7	10810
600-11-2	11.62	300	633.1	621.48	18.64	0.019	1705	5898		130.7	10829
600-11-3	11.62	300	633.1	621.48	18.64	0.019	1700	5881		130.7	10797
600-12-1	11.59	300	633.1	621.51	18.65	0.019	1692	5853	9,07	129.7	10831
600-12-2	11.59	300	633.1	621.51	18.65	0.019	1690	5846		129.7	10818
600-12-3	11.59	300	633.1	621.51	18.65	0.019	1695	5864		129.7	10850
600-13-1	11.61	300	633.1	621.49	18.64	0.019	1697	5871	8,54	130.4	10806
600-13-2	11.61	300	633.1	621.49	18.64	0.019	1695	5864		130.4	10793
600-13-3	11.61	300	633.1	621.49	18.64	0.019	1700	5881		130.4	10825
600-14-1	11.63	300	633.1	621.47	18.64	0.019	1705	5899	17,50	131.0	10801
600-14-2	11.63	300	633.1	621.47	18.64	0.019	1700	5881		131.0	10769
600-14-3	11.63	300	633.1	621.47	18.64	0.019	1710	5916		131.0	10832
600-15-1	11.60	300	633.1	621.50	18.65	0.019	1692	5853	6,35	130.0	10803
600-15-2	11.60	300	633.1	621.50	18.65	0.019	1695	5864		130.0	10822
600-15-3	11.60	300	633.1	621.50	18.65	0.019	1695	5864		130.0	10822

Table B.2 Stiffness test results for recipe no 600-2

Sample No	$e_{average}$ mm	L mm	d_e mm	d_m mm	y mm	f	F N	S_0 N/m^2	Std. Dev.	I mm^3	E MPa
600-21-1	11.60	300	633.1	621.50	18.65	0.019	1682	5819		130.0	10739
600-21-2	11.60	300	633.1	621.50	18.65	0.019	1685	5829	8,54	130.0	10758
600-21-3	11.60	300	633.1	621.50	18.65	0.019	1680	5812		130.0	10726
600-22-1	11.62	300	633.1	621.48	18.64	0.019	1690	5847		130.7	10734
600-22-2	11.62	300	633.1	621.48	18.64	0.019	1693	5857	8,54	130.7	10753
600-22-3	11.62	300	633.1	621.48	18.64	0.019	1695	5864		130.7	10765
600-23-1	11.64	300	633.1	621.46	18.64	0.019	1695	5864		131.4	10709
600-23-2	11.64	300	633.1	621.46	18.64	0.019	1699	5878	9,07	131.4	10734
600-13-3	11.64	300	633.1	621.46	18.64	0.019	1700	5881		131.4	10741
600-24-1	11.63	300	633.1	621.47	18.64	0.019	1694	5860		131.0	10731
600-24-2	11.63	300	633.1	621.47	18.64	0.019	1697	5871	7,37	131.0	10750
600-24-3	11.63	300	633.1	621.47	18.64	0.019	1693	5857		131.0	10725
600-25-1	11.64	300	633.1	621.46	18.64	0.019	1698	5874		131.4	10728
600-25-2	11.64	300	633.1	621.46	18.64	0.019	1702	5888	12,53	131.4	10753
600-25-3	11.64	300	633.1	621.46	18.64	0.019	1705	5899		131.4	10772

Table B.3 Stiffness test results for recipe no 600-3

Sample No	$e_{average}$ mm	L mm	d_e mm	d_m mm	y mm	f	F N	S_0 N/m^2	Std. Dev.	I mm^3	E MPa
600-31-1	11.60	300	633.1	621.50	18.65	0.019	1665	5760		130.0	10630
600-31-2	11.60	300	633.1	621.50	18.65	0.019	1670	5777	8,54	130.0	10662
600-31-3	11.60	300	633.1	621.50	18.65	0.019	1668	5770		130.0	10649
600-32-1	11.61	300	633.1	621.49	18.64	0.019	1669	5774		130.4	10628
600-32-2	11.61	300	633.1	621.49	18.64	0.019	1673	5788	10,69	130.4	10653
600-32-3	11.61	300	633.1	621.49	18.64	0.019	1675	5795		130.4	10666
600-33-1	11.62	300	633.1	621.48	18.64	0.019	1672	5784		130.7	10619
600-33-2	11.62	300	633.1	621.48	18.64	0.019	1675	5795	9,07	130.7	10638
600-33-3	11.62	300	633.1	621.48	18.64	0.019	1677	5802		130.7	10651
600-34-1	11.63	300	633.1	621.47	18.64	0.019	1675	5795		131.0	10610
600-34-2	11.63	300	633.1	621.47	18.64	0.019	1679	5809	9,07	131.0	10636
600-34-3	11.63	300	633.1	621.47	18.64	0.019	1680	5812		131.0	10642
600-35-1	11.61	300	633.1	621.49	18.64	0.019	1667	5767		130.4	10615
600-35-2	11.61	300	633.1	621.49	18.64	0.019	1670	5777	14,19	130.4	10634
600-35-3	11.61	300	633.1	621.49	18.64	0.019	1675	5795		130.4	10666

Table B.4 Stiffness test results for recipe no 500-1

Sample No	$e_{average}$ mm	L mm	d_e mm	d_m mm	y mm	f	F N	S_0 N/m^2	Std. Dev.	I mm^3	E MPa
500-11-1	12.02	300	530.1	518.08	15.54	0.019	2580	10707		144.7	10288
500-11-2	12.02	300	530.1	518.08	15.54	0.019	2585	10728	14,98	144.7	10308
500-11-3	12.02	300	530.1	518.08	15.54	0.019	2587	10736		144.7	10316
500-12-1	12.01	300	530.1	518.09	15.54	0.019	2576	10690		144.3	10298
500-12-2	12.01	300	530.1	518.09	15.54	0.019	2573	10678	6,11	144.3	10286
500-12-3	12.01	300	530.1	518.09	15.54	0.019	2575	10686		144.3	10294
500-13-1	12.02	300	530.1	518.08	15.54	0.019	2580	10707		144.7	10288
500-13-2	12.02	300	530.1	518.08	15.54	0.019	2583	10719	10,54	144.7	10300
500-13-3	12.02	300	530.1	518.08	15.54	0.019	2585	10728		144.7	10308
500-14-1	12.03	300	530.1	518.07	15.54	0.019	2590	10749		145.0	10301
500-14-2	12.03	300	530.1	518.07	15.54	0.019	2593	10761	8,33	145.0	10313
500-14-3	12.03	300	530.1	518.07	15.54	0.019	2594	10765		145.0	10317
500-15-1	12.02	300	530.1	518.08	15.54	0.019	2590	10748		144.7	10328
500-15-2	12.02	300	530.1	518.08	15.54	0.019	2588	10740	14,98	144.7	10320
500-15-3	12.02	300	530.1	518.08	15.54	0.019	2583	10719		144.7	10300

Table B.5 Stiffness test results for recipe no 500-2

Sample No	$e_{average}$ mm	L mm	d_e mm	d_m mm	y mm	f	F N	S_0 N/m^2	Std. Dev.	I mm^3	E MPa
500-21-1	12.02	300	530.1	518.08	15.54	0.019	2583	10719		144.7	10300
500-21-2	12.02	300	530.1	518.08	15.54	0.019	2580	10707	6,11	144.7	10288
500-21-3	12.02	300	530.1	518.08	15.54	0.019	2581	10711		144.7	10292
500-22-1	12.01	300	530.1	518.09	15.54	0.019	2573	10678		144.3	10286
500-22-2	12.01	300	530.1	518.09	15.54	0.019	2571	10669	8,50	144.3	10278
500-22-3	12.01	300	530.1	518.09	15.54	0.019	2575	10686		144.3	10294
500-23-1	12.02	300	530.1	518.08	15.54	0.019	2575	10686		144.7	10268
500-23-2	12.02	300	530.1	518.08	15.54	0.019	2577	10694	8,00	144.7	10276
500-23-3	12.02	300	530.1	518.08	15.54	0.019	2573	10678		144.7	10260
500-24-1	12.01	300	530.1	518.09	15.54	0.019	2581	10711		144.3	10318
500-24-2	12.01	300	530.1	518.09	15.54	0.019	2585	10727	10,58	144.3	10334
500-24-3	12.01	300	530.1	518.09	15.54	0.019	2580	10707		144.3	10314
500-25-1	12.03	300	530.1	518.07	15.54	0.019	2575	10686		145.0	10242
500-25-2	12.03	300	530.1	518.07	15.54	0.019	2577	10695	8,50	145.0	10250
500-25-3	12.03	300	530.1	518.07	15.54	0.019	2579	10703		145.0	10258

Table B.6 Stiffness test results for recipe no 500-3

Sample No	$e_{average}$ mm	L mm	d_e mm	d_m mm	y mm	f	F N	S_0 N/m^2	Std. Dev.	I mm^3	E MPa
500-31-1	12.01	300	530.1	518.09	15.54	0.019	2567	10653		144.3	10262
500-31-2	12.01	300	530.1	518.09	15.54	0.019	2565	10644	6,66	144.3	10254
500-31-3	12.01	300	530.1	518.09	15.54	0.019	2568	10657		144.3	10266
500-32-1	12.02	300	530.1	518.08	15.54	0.019	2573	10678		144.7	10260
500-32-2	12.02	300	530.1	518.08	15.54	0.019	2575	10686	8,50	144.7	10268
500-32-3	12.02	300	530.1	518.08	15.54	0.019	2571	10669		144.7	10252
500-33-1	12.03	300	530.1	518.07	15.54	0.019	2570	10666		145.0	10222
500-33-2	12.03	300	530.1	518.07	15.54	0.019	2572	10674	8,50	145.0	10230
500-33-3	12.03	300	530.1	518.07	15.54	0.019	2568	10657		145.0	10214
500-34-1	12.02	300	530.1	518.08	15.54	0.019	2560	10624		144.7	10208
500-34-2	12.02	300	530.1	518.08	15.54	0.019	2563	10636	10,54	144.7	10220
500-34-3	12.02	300	530.1	518.08	15.54	0.019	2565	10645		144.7	10228
500-35-1	12.00	300	530.1	518.10	15.54	0.019	2573	10677		144.0	10312
500-35-2	12.00	300	530.1	518.10	15.54	0.019	2577	10694	12,77	144.0	10328
500-35-3	12.00	300	530.1	518.10	15.54	0.019	2579	10702		144.0	10336

Table B.7 Stiffness test results for recipe no 700-1

Sample No	$e_{average}$ mm	L mm	d_e mm	d_m mm	y mm	f	F N	S_0 N/m^2	Std. Dev.	I mm^3	E MPa
700-11-1	12.83	300	718.3	705.47	21.16	0.019	1785	5440	7,55	175.9	10853
700-11-2	12.83	300	718.3	705.47	21.16	0.019	1783	5434		175.9	10840
700-11-3	12.83	300	718.3	705.47	21.16	0.019	1780	5425		175.9	10822
700-12-1	12.81	300	718.3	705.49	21.16	0.019	1775	5409	7,55	175.1	10843
700-12-2	12.81	300	718.3	705.49	21.16	0.019	1772	5400		175.1	10825
700-12-3	12.81	300	718.3	705.49	21.16	0.019	1770	5394		175.1	10813
700-13-1	12.84	300	718.3	705.46	21.16	0.019	1784	5437	6,24	176.4	10821
700-13-2	12.84	300	718.3	705.46	21.16	0.019	1788	5449		176.4	10845
700-13-3	12.84	300	718.3	705.46	21.16	0.019	1785	5440		176.4	10827
700-14-1	12.81	300	718.3	705.49	21.16	0.019	1777	5415	3,00	175.1	10855
700-14-2	12.81	300	718.3	705.49	21.16	0.019	1775	5409		175.1	10843
700-14-3	12.81	300	718.3	705.49	21.16	0.019	1776	5412		175.1	10849
700-15-1	12.82	300	718.3	705.48	21.16	0.019	1785	5440	8,66	175.5	10878
700-15-2	12.82	300	718.3	705.48	21.16	0.019	1785	5440		175.5	10878
700-15-3	12.82	300	718.3	705.48	21.16	0.019	1780	5425		175.5	10848

Table B.8 Stiffness test results for recipe no 700-2

Sample No	**$e_{average}$ mm**	**L mm**	**d_e mm**	**d_m mm**	**y mm**	**f**	**F N**	**S_0 N/m^2**	**Std. Dev.**	**I mm^3**	**E MPa**
700-21-1	12.82	300	718.3	705.48	21.16	0.019	1770	5394	8,66	175.5	10787
700-21-2	12.82	300	718.3	705.48	21.16	0.019	1775	5409		175.5	10817
700-21-3	12.82	300	718.3	705.48	21.16	0.019	1775	5409		175.5	10817
700-22-1	12.81	300	718.3	705.49	21.16	0.019	1770	5394	7,55	175.1	10813
700-22-2	12.81	300	718.3	705.49	21.16	0.019	1765	5379		175.1	10782
700-22-3	12.81	300	718.3	705.49	21.16	0.019	1768	5388		175.1	10800
700-23-1	12.83	300	718.3	705.47	21.16	0.019	1780	5425	4,58	175.9	10822
700-23-2	12.83	300	718.3	705.47	21.16	0.019	1778	5419		175.9	10810
700-23-3	12.83	300	718.3	705.47	21.16	0.019	1777	5416		175.9	10804
700-24-1	12.82	300	718.3	705.48	21.16	0.019	1773	5403	5,20	175.5	10805
700-24-2	12.82	300	718.3	705.48	21.16	0.019	1770	5394		175.5	10787
700-24-3	12.82	300	718.3	705.48	21.16	0.019	1770	5394		175.5	10787
700-25-1	12.82	300	718.3	705.48	21.16	0.019	1769	5391	9,00	175.5	10781
700-25-2	12.82	300	718.3	705.48	21.16	0.019	1772	5400		175.5	10799
700-25-3	12.82	300	718.3	705.48	21.16	0.019	1775	5409		175.5	10817

Table B.9 Stiffness test results for recipe no 700-3

Sample No	$e_{average}$ mm	L mm	d_e mm	d_m mm	y mm	f	F N	S_0 N/m^2	Std. Dev.	I mm^3	E MPa
700-31-1	12.82	300	718.3	705.48	21.16	0.019	1760	5364	8,66	175.5	10726
700-31-2	12.82	300	718.3	705.48	21.16	0.019	1765	5379		175.5	10756
700-31-3	12.82	300	718.3	705.48	21.16	0.019	1760	5364		175.5	10726
700-32-1	12.82	300	718.3	705.48	21.16	0.019	1763	5373	4,58	175.5	10744
700-32-2	12.82	300	718.3	705.48	21.16	0.019	1766	5382		175.5	10763
700-32-3	12.82	300	718.3	705.48	21.16	0.019	1765	5379		175.5	10756
700-33-1	12.82	300	718.3	705.48	21.16	0.019	1770	5394	0,00	175.5	10787
700-33-2	12.82	300	718.3	705.48	21.16	0.019	1770	5394		175.5	10787
700-33-3	12.82	300	718.3	705.48	21.16	0.019	1770	5394		175.5	10787
700-34-1	12.81	300	718.3	705.49	21.16	0.019	1765	5379	7,55	175.1	10782
700-34-2	12.81	300	718.3	705.49	21.16	0.019	1768	5388		175.1	10800
700-34-3	12.81	300	718.3	705.49	21.16	0.019	1763	5373		175.1	10770
700-35-1	12.81	300	718.3	705.49	21.16	0.019	1764	5376	3,00	175.1	10776
700-35-2	12.81	300	718.3	705.49	21.16	0.019	1766	5382		175.1	10788
700-35-3	12.81	300	718.3	705.49	21.16	0.019	1765	5379		175.1	10782

APPENDIX C

LONGITUDINAL AND CIRCUMFERENTIAL TENSILE TEST RESULTS FOR THE EVALUATION OF TYPE OF RESIN

Table C.1 Longitudinal and circumferential tensile test results for recipe no 600-1

Sample No	Longitudinal Tensile Test Results						Circumferential Tensile Test Results					
	$e_{average}$ mm	L mm	b_G mm	F N	σ_{LA}* N/mm	Std. Dev.	$e_{average}$ mm	L mm	b mm	F_{ult} N	σ_{CD}* N/mm	Std. Dev.
600-11-1	11.62	300	25.11	5690	226.6	0.40	11.62	300	30.02	37100	1235.8	0.98
600-11-2	11.61	300	25.13	5675	225.8		11.62	300	30.05	37150	1236.3	
600-11-3	11.63	300	25.14	5683	226.1		11.61	300	30.08	37130	1234.4	
600-12-1	11.59	300	25.21	5480	217.4	0.25	11.59	300	30.12	37308	1238.6	0.57
600-12-2	11.58	300	25.23	5490	217.6		11.60	300	30.14	37356	1239.4	
600-12-3	11,59	300	25.22	5475	217.1		11,59	300	30.16	37348	1238.3	
600-13-1	11,61	300	25.14	5510	219.2	0.30	11,61	300	30.20	37380	1237.7	1.07
600-13-2	11,60	300	25.16	5500	218.6		11,62	300	30.18	37395	1239.1	
600-13-3	11,60	300	25.11	5496	218.9		11.61	300	30.21	37370	1237.0	
600-14-1	11.63	300	25.33	5776	228.0	0.26	11.62	300	30.17	37424	1240.4	1.33
600-14-2	11.62	300	25.36	5785	228.1		11.63	300	30.15	37470	1242.8	
600-14-3	11.63	300	25.34	5790	228.5		11.63	300	30.15	37465	1242.6	
600-15-1	11.60	300	25.24	5540	219.5	0.44	11.59	300	30.20	37270	1234.1	0.85
600-15-2	11.61	300	25.21	5535	219.6		11.61	300	30.20	37250	1233.4	
600-15-3	11.59	300	25.23	5557	220.3		11.61	300	30.22	37244	1232.4	

Table C.2 Longitudinal and circumferential tensile test results for recipe no 600-2

Sample No	Longitudinal Tensile Test Results						Circumferential Tensile Test Results					
	$e_{average}$ mm	L mm	b_G mm	F N	σ_{LA}* N/mm	Std. Dev.	$e_{average}$ mm	L mm	b mm	F_{ult} N	σ_{CD}* N/mm	Std. Dev.
600-21-1	11.60	300	25.02	5675	226.8	0.29	11.61	300	30.10	37400	1242.5	1.38
600-21-2	11.61	300	25.04	5680	226.8		11.60	300	30.13	37500	1244.6	
600-21-3	11.60	300	25.06	5670	226.3		11.60	300	30.12	37410	1242.0	
600-22-1	11.62	300	25.10	5755	229.3	0.67	11.61	300	30.15	37350	1238.8	1.32
600-22-2	11.62	300	25.14	5762	229.2		11.63	300	30.17	37450	1241.3	
600-22-3	11.61	300	25.17	5742	228.1		11.62	300	30.19	37460	1240.8	
600-23-1	11.64	300	25.37	5710	225.1	0.49	11.65	300	30.07	37480	1246.4	1.55
600-23-2	11.63	300	25.34	5725	225.9		11.64	300	30.08	37400	1243.4	
600-23-3	11.65	300	25.35	5730	226.0		11.63	300	30.05	37430	1245.6	
600-24-1	11.63	300	25.21	5733	227.4	0.35	11.63	300	30.09	37600	1249.6	0.83
600-24-2	11.63	300	25.22	5746	227.8		11.62	300	31.00	38700	1248.4	
600-24-3	11.64	300	25.23	5754	228.1		11.63	300	31.03	38725	1248.0	
600-25-1	11.64	300	25.14	5736	228.2	0.44	11.64	300	30.05	37500	1247.9	4.17
600-25-2	11.63	300	25.12	5749	228.9		11.63	300	30.08	37680	1252.7	
600-25-3	11.65	300	25.13	5755	229.0		11.64	300	30.07	37775	1256.2	

Table C.3 Longitudinal and circumferential tensile test results for recipe no 600-3

Sample No	Longitudinal Tensile Test Results						Circumferential Tensile Test Results					
	$e_{average}$ mm	L mm	b_G mm	F N	σ_{LA}* N/mm	Std. Dev.	$e_{average}$ mm	L mm	b mm	F_{ult} N	σ_{CD}* N/mm	Std. Dev.
600-31-1	11.60	300	25.00	5800	232.0	0.51	11.59	300	30.30	38850	1282.2	1.11
600-31-2	11.61	300	25.02	5830	233.0		11.61	300	30.35	38874	1280.9	
600-31-3	11.59	300	25.03	5825	232.7		11.61	300	30.36	38861	1280.0	
600-32-1	11.61	300	25.04	5840	233.2	0.26	11.60	300	30.41	39040	1283.8	0.85
600-32-2	11.60	300	25.06	5846	233.3		11.61	300	30.44	39100	1284.5	
600-32-3	11.61	300	25.05	5855	233.7		11.62	300	30.46	39074	1282.8	
600-33-1	11.62	300	25.03	5765	230.3	0.38	11.63	300	30.25	38660	1278.0	0.15
600-33-2	11.62	300	25.04	5770	230.4		11.62	300	30.27	38675	1277.7	
600-33-3	11.63	300	25.06	5789	231.0		11.62	300	30.26	38670	1277.9	
600-34-1	11.63	300	25.11	5890	234.6	0.61	11.62	300	30.11	38650	1283.6	1.88
600-34-2	11.64	300	25.13	5905	235.0		11.64	300	30.15	38600	1280.3	
600-24-3	11.63	300	25.17	5885	233.8		11.63	300	30.17	38630	1280.4	
600-35-1	11.61	300	25.21	5840	231.7	0.26	11.60	300	30.22	38945	1288.7	19.76
600-35-2	11.62	300	25.19	5835	231.6		11.60	300	30.26	39990	1321.5	
600-35-3	11.61	300	25.18	5845	232.1		11.62	300	30.24	40045	1324.2	

Table C.4 Longitudinal and circumferential tensile test results for recipe no 500-1

Sample No	Longitudinal Tensile Test Results						Circumferential Tensile Test Results					
	$e_{average}$ mm	L mm	b_G mm	F N	σ_{LA}* N/mm	Std. Dev.	$e_{average}$ mm	L mm	b mm	F_{ult} N	σ_{CD}* N/mm	Std. Dev.
500-11-1	12.02	300	25.01	5250	210	0.58	12.02	300	30.12	33000	1096	2.08
500-11-2	12.02	300	25.02	5270	211		12.01	300	30.14	33050	1097	
500-11-3	12.02	300	25.00	5280	211		12.02	300	30.15	33150	1100	
500-12-1	12.01	300	25.03	5225	209	0.58	12.02	300	30.21	33095	1095	1.00
500-12-2	12.02	300	25.02	5230	209		12.02	300	30.25	33080	1094	
500-12-3	12.02	300	25.01	5249	210		12.02	300	30.26	33075	1093	
500-13-1	12.01	300	25.00	5140	206	0.58	12.02	300	30.33	33060	1090	0.58
500-13-2	12.02	300	25.04	5162	206		12.02	300	30.31	33059	1091	
500-13-3	12.01	300	25.03	5170	207		12.01	300	30.29	33048	1091	
500-14-1	12.02	300	25.02	5104	204	0.58	12.02	300	30.04	33063	1101	1.15
500-14-2	12.02	300	25.04	5090	203		12.01	300	30.08	33057	1099	
500-14-3	12.02	300	25.00	5110	204		12.02	300	30.09	33075	1099	
500-15-1	12.02	300	24.99	5265	211	0.58	12.02	300	30.11	33149	1101	1.00
500-15-2	12.01	300	25.00	5283	211		12.02	300	30.14	33151	1100	
500-15-3	12.02	300	25.01	5240	210		12.02	300	30.10	33164	1102	

Table C.5 Longitudinal and circumferential tensile test results for recipe no 500-2

Sample No	Longitudinal Tensile Test Results						Circumferential Tensile Test Results					
	$e_{average}$ mm	L mm	b_G mm	F N	σ_{LA}* N/mm	Std. Dev.	$e_{average}$ mm	L mm	b mm	F_{ult} N	σ_{CD}* N/mm	Std. Dev.
500-21-1	12.03	300	25.00	5318	213	0.58	12.02	300	30.23	33360	1104	1.15
500-21-2	12.02	300	25.00	5327	213		12.02	300	30.26	33345	1102	
500-21-3	12.02	300	25.00	5338	214		12.03	300	30.22	33295	1102	
500-22-1	12.02	300	25.07	5310	212	0.00	12.02	300	30.35	33225	1095	1.00
500-22-2	12.02	300	25.09	5317	212		12.01	300	30.37	33233	1094	
500-22-3	12.02	300	25.08	5305	212		12.02	300	30.41	33237	1093	
500-23-1	12.02	300	25.04	5375	215	1.00	12.02	300	30.16	33294	1104	0.58
500-23-2	12.02	300	25.03	5360	214		12.01	300	30.18	33307	1104	
500-23-3	12.02	300	25.05	5346	213		12.02	300	30.21	33315	1103	
500-24-1	12.01	300	25.00	5231	209	0.58	12.02	300	30.05	33011	1099	1.00
500-24-2	12.01	300	25.02	5250	210		12.01	300	30.06	32985	1097	
500-24-3	12.00	300	25.01	5225	209		12.02	300	30.08	33037	1098	
500-25-1	12.02	300	25.15	5340	212	1.15	12.01	300	30.10	33192	1103	0.58
500-25-2	12.02	300	25.10	5365	214		12.02	300	30.09	33185	1103	
500-25-3	12.03	300	25.20	5350	212		12.02	300	30.12	33187	1102	

Table C.6 Longitudinal and circumferential tensile test results for recipe no 500-3

Sample No	Longitudinal Tensile Test Results						Circumferential Tensile Test Results					
	$e_{average}$ mm	L mm	b_G mm	F N	σ_{LA}* N/mm	Std. Dev.	$e_{average}$ mm	L mm	b mm	F_{ult} N	σ_{CD}* N/mm	Std. Dev.
500-31-1	12.01	300	25.04	5425	217	0.58	12.01	300	30.22	35000	1158	1.15
500-31-2	12.02	300	25.07	5405	216		12.02	300	30.26	34980	1156	
500-31-3	12.01	300	25.06	5415	216		12.02	300	30.24	34950	1156	
500-32-1	12.02	300	25.00	5535	221	0.58	12.02	300	30.34	34975	1153	0.58
500-32-2	12.02	300	25.02	5540	221		12.01	300	30.36	34968	1152	
500-32-3	12.01	300	25.00	5556	222		12.01	300	30.33	34972	1153	
500-33-1	12.02	300	25.00	5390	216	0.58	12.02	300	30.52	34950	1145	1.00
500-33-2	12.03	300	25.04	5408	216		12.02	300	30.50	34945	1146	
500-33-3	12.02	300	25.02	5378	215		12.02	300	30.49	34962	1147	
500-34-1	12.02	300	25.00	5513	221	1.00	12.02	300	30.17	34942	1158	0.58
500-34-2	12.01	300	25.03	5508	220		12.02	300	30.15	34958	1159	
500-34-3	12.02	300	25.05	5490	219		12.01	300	30.20	34961	1158	
500-35-1	12.01	300	25.17	5325	212	0.58	12.01	300	30.35	33972	1119	0.58
500-35-2	12.01	300	25.11	5338	213		12.02	300	30.35	33947	1119	
500-35-3	12.01	300	25.14	5320	212		12.01	300	30.35	33990	1120	

Table C.7 Longitudinal and circumferential tensile test results for recipe no 700-1

Sample No	Longitudinal Tensile Test Results						Circumferential Tensile Test Results					
	$e_{average}$ mm	L mm	b_G mm	F N	σ_{LA}* N/mm	Std. Dev.	$e_{average}$ mm	L mm	b mm	F_{ult} N	σ_{CD}* N/mm	Std. Dev.
700-11-1	12.83	300	25.32	6500	257	1.53	12.83	300	30.21	47580	1575	0.00
700-11-2	12.82	300	25.36	6450	254		12.82	300	30.23	47600	1575	
700-11-3	12.83	300	25.34	6450	255		12.83	300	30.25	47630	1575	
700-12-1	12.81	300	25.15	6250	249	0.58	12.81	300	30.33	47495	1566	1.00
700-12-2	12.80	300	25.14	6230	248		12.81	300	30.31	47536	1568	
700-12-3	12.81	300	25.12	6240	248		12.81	300	30.35	47549	1567	
700-13-1	12.84	300	25.62	6600	258	0.58	12.83	300	30.42	47760	1570	1.73
700-13-2	12.83	300	25.64	6640	259		12.83	300	30.39	47791	1573	
700-13-3	12.84	300	25.67	6629	258		12.84	300	30.37	47690	1570	
700-14-1	12.81	300	25.33	6326	250	0.00	12.81	300	30.08	47400	1576	0.00
700-14-2	12.82	300	25.34	6334	250		12.82	300	30.10	47450	1576	
700-14-3	12.81	300	25.31	6320	250		12.82	300	30.10	47430	1576	
700-15-1	12.81	300	24.97	6400	256	0.58	12.82	300	30.24	47930	1585	3.21
700-15-2	12.82	300	25.04	6390	255		12.82	300	30.22	47856	1584	
700-15-3	12.82	300	25.03	6387	255		12.82	300	30.25	47775	1579	

Table C.8 Longitudinal and circumferential tensile test results for recipe no 700-2

Sample No	Longitudinal Tensile Test Results						Circumferential Tensile Test Results					
	$e_{average}$ mm	L mm	b_G mm	F N	σ_{LA}* N/mm	Std. Dev.	$e_{average}$ mm	L mm	b mm	F_{ult} N	σ_{CD}* N/mm	Std. Dev.
700-21-1	12.81	300	25.06	6380	255	0.58	12.81	300	30.31	48100	1587	1.00
700-21-2	12.82	300	25.07	6398	255		12.82	300	30.29	48125	1589	
700-21-3	12.82	300	25.10	6385	254		12.81	300	30.30	48130	1588	
700-22-1	12.81	300	25.10	6207	247	0.00	12.81	300	30.30	47148	1556	1.53
700-22-2	12.81	300	25.13	6215	247		12.82	300	30.30	47190	1557	
700-22-3	12.81	300	25.14	6210	247		12.81	300	30.29	47230	1559	
700-23-1	12.83	300	25.07	6685	267	0.58	12.83	300	30.17	48200	1598	1.53
700-23-2	12.82	300	25.05	6673	266		12.83	300	30.21	48190	1595	
700-23-3	12.83	300	25.05	6669	266		12.83	300	30.19	48185	1596	
700-24-1	12.81	300	25.42	6440	253	0.58	12.82	300	30.08	48167	1601	0.58
700-24-2	12.82	300	25.41	6449	254		12.82	300	30.09	48155	1600	
700-24-3	12.82	300	25.44	6453	254		12.82	300	30.10	48167	1600	
700-25-1	12.82	300	25.52	6556	257	0.58	12.82	300	30.25	48000	1587	1.53
700-25-2	12.82	300	25.48	6559	257		12.82	300	30.22	48039	1590	
700-25-3	12.82	300	25.46	6563	258		12.81	300	30.26	48074	1589	

Table C.9 Longitudinal and circumferential tensile test results for recipe no 700-3

Sample No	Longitudinal Tensile Test Results						Circumferential Tensile Test Results					
	$e_{average}$ mm	L mm	b_G mm	F N	σ_{LA}* N/mm	Std. Dev.	$e_{average}$ mm	L mm	b mm	F_{ult} N	σ_{CD}* N/mm	Std. Dev.
700-31-1	12.82	300	25.04	6600	264	0.58	12.82	300	30.50	48850	1602	1.53
700-31-2	12.83	300	25.06	6610	264		12.82	300	30.49	48820	1601	
700-31-3	12.82	300	25.05	6642	265		12.83	300	30.47	48880	1604	
700-32-1	12.82	300	25.00	6490	260	2.08	12.82	300	30.05	48850	1626	1.53
700-32-2	12.81	300	25.02	6423	257		12.81	300	30.03	48730	1623	
700-32-3	12.82	300	25.03	6418	256		12.82	300	30.04	48770	1624	
700-33-1	12.81	300	25.00	6685	267	1.15	12.81	300	30.47	49582	1627	0.58
700-33-2	12.82	300	25.04	6679	267		12.81	300	30.45	49575	1628	
700-33-3	12.82	300	25.03	6640	265		12.82	300	30.45	49566	1628	
700-34-1	12.81	300	25.01	6505	260	0.00	12.81	300	30.22	49003	1622	0.58
700-34-2	12.80	300	25.02	6505	260		12.81	300	30.26	49050	1621	
700-34-3	12.81	300	25.04	6510	260		12.81	300	30.25	49030	1621	
700-35-1	12.81	300	25.21	6623	263	0.00	12.81	300	30.25	49475	1636	2.08
700-35-2	12.82	300	25.19	6615	263		12.81	300	30.27	49405	1632	
700-35-3	12.81	300	25.16	6625	263		12.81	300	30.25	49447	1635	

APPENDIX D

AVERAGE STIFFNESS, LONGITUDINAL AND CIRCUMFERENTIAL TENSILE TEST RESULTS FOR THE EVALUATION OF TYPE OF RESIN

Table D.1 Average stiffness, longitudinal and circumferential tensile test results for the evaluation of type of resin

Sample No	Average Stiffness Test Results						Average Long. Tensile Test		Average Circum. Tensile Test	
	$e_{average}$, mm		S_0 , N/m^2		E , MPa		σ_{LA}* , N/mm		σ_{CD}* , N/mm	
600-11	11.62	11.61	5889	5875	10812	10814	226.2	222.1	1235.5	1237.5
600-12	11.59		5854		10833		217.4		1238.8	
600-13	11.61		5872		10808		218.9		1237.9	
600-14	11.63		5899		10801		228.2		1241.9	
600-15	11.60		5860		10816		219.8		1233.3	
600-21	11.60	11.63	5820	5860	10741	10741	226.6	227.5	1243.0	1245.9
600-22	11.62		5856		10751		228.9		1240.3	
600-23	11.64		5874		10728		225.7		1245.1	
600-24	11.63		5863		10735		227.8		1248.7	
600-25	11.64		5887		10751		228.7		1252.3	
600-31	11.60	11.61	5769	5787	10647	10640	232.6	232.6	1281.0	1287.1
600-32	11.61		5786		10649		233.4		1283.7	
600-33	11.62		5794		10636		230.6		1277.9	
600-34	11.63		5805		10629		234.5		1281.4	
600-35	11.61		5780		10638		231.8		1311.5	
500-11	12.02	12.02	10724	10724	10304	10304	210.7	208.1	1097.7	1096.6
500-12	12.01		10685		10293		209.3		1094.0	
500-13	12.02		10718		10299		206.3		1090.7	
500-14	12.03		10758		10310		203.7		1099.7	
500-15	12.02		10736		10316		210.7		1101.0	
500-21	12.02	12.02	10712	10697	10293	10284	213.3	212.3	1102.7	1100.2
500-22	12.01		10678		10286		212.0		1094.0	
500-23	12.02		10686		10268		214.0		1103.7	
500-24	12.01		10715		10322		209.3		1098.0	
500-25	12.03		10695		10250		212.7		1102.7	

Table D.1 continued

500-31	12.01	12.02	10651	10664	10261	10257	216.3	217.1	1156.7	1146.6
500-32	12.02		10678		10260		221.3		1152.7	
500-33	12.03		10666		10222		215.7		1146.0	
500-34	12.02		10635		10219		220.0		1158.3	
500-35	12.00		10691		10325		212.3		1119.3	
700-11	12.83	12.82	5433	5425	10838	10843	255.3	253.5	1575.0	1574.3
700-12	12.81		5401		10827		248.3		1567.0	
700-13	12.84		5442		10831		258.3		1571.0	
700-14	12.81		5412		10849		250.0		1576.0	
700-15	12.82		5435		10868		255.3		1582.7	
700-21	12.82	12.82	5404	5402	10807	10802	254.7	255.8	1588.0	1586.1
700-22	12.81		5387		10798		247.0		1557.3	
700-23	12.83		5420		10812		266.3		1596.3	
700-24	12.82		5397		10793		253.7		1600.3	
700-25	12.82		5400		10799		257.3		1588.7	
700-31	12.82	12.82	5369	5380	10736	10769	264.3	262.3	1602.3	1622.0
700-32	12.82		5378		10754		257.7		1624.3	
700-33	12.82		5394		10787		266.3		1627.7	
700-34	12.81		5380		10784		260.0		1621.3	
700-35	12.81		5379		10782		263.0		1634.3	

APPENDIX E

STIFFNESS TEST RESULTS FOR THE EVALUATION OF TYPE OF FIBER

Table E.1 Stiffness test results for recipe 600-4

Sample No	$e_{average}$ mm	L mm	d_e mm	d_m mm	y mm	f	F N	S_0 N/m^2	Std. Dev.	I mm^3	E MPa
600-41-1	11.60	300	633.1	621.50	18.65	0.019	1728	5978		130.0	11032
600-41-2	11.60	300	633.1	621.50	18.65	0.019	1730	5985	9.07	130.0	11045
600-41-3	11.60	300	633.1	621.50	18.65	0.019	1725	5967		130.0	11013
600-42-1	11.61	300	633.1	621.49	18.64	0.019	1730	5985		130.4	11016
600-42-2	11.61	300	633.1	621.49	18.64	0.019	1735	6002	9.81	130.4	11048
600-42-3	11.61	300	633.1	621.49	18.64	0.019	1735	6002		130.4	11048
600-43-1	11.62	300	633.1	621.48	18.64	0.019	1733	5995		130.7	11007
600-43-2	11.62	300	633.1	621.48	18.64	0.019	1735	6002	7.00	130.7	11019
600-43-3	11.62	300	633.1	621.48	18.64	0.019	1737	6009		130.7	11032
600-44-1	11.61	300	633.1	621.49	18.64	0.019	1728	5978		130.4	11004
600-44-2	11.61	300	633.1	621.49	18.64	0.019	1730	5985	8.54	130.4	11016
600-44-3	11.61	300	633.1	621.49	18.64	0.019	1733	5995		130.4	11035
600-45-1	11.60	300	633.1	621.50	18.65	0.019	1725	5967		130.07	11013
600-45-2	11.60	300	633.1	621.50	18.65	0.019	1728	5978	9.07	130.07	11032
600-45-3	11.60	300	633.1	621.50	18.65	0.019	1723	5960		130.07	11001

Table E.2 Stiffness test results for recipe 600-5

Sample No	$e_{average}$ mm	L mm	d_e mm	d_m mm	y mm	f	F N	S_0 N/m^2	Std. Dev.	I mm^3	E MPa
600-51-1	11.59	300	633.1	621.51	18.65	0.019	1870	6469	12.34	129.7	11970
600-51-2	11.59	300	633.1	621.51	18.65	0.019	1872	6476		129.7	11983
600-51-3	11.59	300	633.1	621.51	18.65	0.019	1877	6493		129.7	12015
600-52-1	11.60	300	633.1	621.50	18.65	0.019	1873	6479	3.51	130.0	11958
600-52-2	11.60	300	633.1	621.50	18.65	0.019	1875	6486		130.0	11971
600-52-3	11.60	300	633.1	621.50	18.65	0.019	1874	6483		130.0	11965
600-53-1	11.60	300	633.1	621.50	18.65	0.019	1875	6486	3.51	130.0	11971
600-53-2	11.60	300	633.1	621.50	18.65	0.019	1876	6490		130.0	11977
600-53-3	11.60	300	633.1	621.50	18.65	0.019	1877	6493		130.0	11984
600-54-1	11.61	300	633.1	621.49	18.64	0.019	1880	6504	8.54	130.4	11972
600-54-2	11.61	300	633.1	621.49	18.64	0.019	1885	6521		130.4	12003
600-54-3	11.61	300	633.1	621.49	18.64	0.019	1883	6514		130.4	11991
600-55-1	11.62	300	633.1	621.48	18.64	0.019	1885	6521	7.00	130.7	11972
600-55-2	11.62	300	633.1	621.48	18.64	0.019	1887	6528		130.7	11985
600-55-3	11.62	300	633.1	621.48	18.64	0.019	1889	6535		130.7	11997

Table E.3 Stiffness test results for recipe 600-5-rev

Sample No	$e_{average}$ mm	L mm	d_e mm	d_m mm	y mm	f	F N	S_0 N/m^2	Std. Dev.	I mm^3	E MPa
600-5r1-1	11.33	300	633.1	621.77	18.65	0.019	1699	5875	10.50	121.2	11652
600-5r1-2	11.33	300	633.1	621.77	18.65	0.019	1702	5885		121.2	11672
600-5r1-3	11.33	300	633.1	621.77	18.65	0.019	1705	5896		121.2	11693
600-5r2-1	11.34	300	633.1	621.76	18.65	0.019	1702	5885	9.07	121.5	11641
600-5r2-2	11.34	300	633.1	621.76	18.65	0.019	1705	5896		121.5	11661
600-5r2-3	11.34	300	633.1	621.76	18.65	0.019	1707	5903		121.5	11675
600-5r3-1	11.35	300	633.1	621.75	18.65	0.019	1690	5844	5.77	121.8	11528
600-5r3-2	11.35	300	633.1	621.75	18.65	0.019	1693	5854		121.8	11548
600-5r3-3	11.35	300	633.1	621.75	18.65	0.019	1690	5844		121.8	11528
600-5r4-1	11.31	300	633.1	621.79	18.65	0.019	1691	5847	6.81	120.5	11659
600-5r4-2	11.31	300	633.1	621.79	18.65	0.019	1694	5857		120.5	11680
600-5r4-3	11.31	300	633.1	621.79	18.65	0.019	1690	5844		120.5	11652
600-5r5-1	11.33	300	633.1	621.77	18.65	0.019	1697	5868	5.13	121.2	11638
600-5r5-2	11.33	300	633.1	621.77	18.65	0.019	1699	5875		121.2	11652
600-5r5-3	11.33	300	633.1	621.77	18.65	0.019	1700	5878		121.2	11658

Table E.4 Stiffness test results for recipe 500-4

Sample No	$e_{average}$ mm	L mm	d_e mm	d_m mm	y mm	f	F N	S_0 N/m^2	Std. Dev.	I mm^3	E MPa
500-41-1	12.02	300	530.1	518.08	15.54	0.019	2660	11039		144.7	10607
500-41-2	12.02	300	530.1	518.08	15.54	0.019	2665	11060	10.54	144.7	10627
500-41-3	12.02	300	530.1	518.08	15.54	0.019	2663	11051		144.7	10619
500-42-1	12.02	300	530.1	518.08	15.54	0.019	2670	11080		144.7	10647
500-42-2	12.02	300	530.1	518.08	15.54	0.019	2673	11093	8.89	144.7	10659
500-42-3	12.02	300	530.1	518.08	15.54	0.019	2674	11097		144.7	10663
500-43-1	12.01	300	530.1	518.09	15.54	0.019	2669	11076		144.3	10670
500-43-2	12.01	300	530.1	518.09	15.54	0.019	2665	11059	8.50	144.3	10654
500-43-3	12.01	300	530.1	518.09	15.54	0.019	2667	11068		144.3	10662
500-44-1	12.02	300	530.1	518.08	15.54	0.019	2677	11109		144.7	10675
500-44-2	12.02	300	530.1	518.08	15.54	0.019	2675	11101	10.07	144.7	10667
500-44-3	12.02	300	530.1	518.08	15.54	0.019	2672	11089		144.7	10655
500-45-1	12.02	300	530.1	518.08	15.54	0.019	2673	11093		144.7	10659
500-45-2	12.02	300	530.1	518.08	15.54	0.019	2675	11101	4.62	144.7	10667
500-45-3	12.02	300	530.1	518.08	15.54	0.019	2675	11101		144.7	10667

Table E.5 Stiffness test results for recipe 700-4

Sample No	$e_{average}$ mm	L mm	d_e mm	d_m mm	y mm	f	F N	S_0 N/m^2	Std. Dev.	I mm^3	E MPa
700-41-1	12.82	300	718.3	705.48	21.16	0.019	1825	5562	4.58	175.5	11122
700-41-2	12.82	300	718.3	705.48	21.16	0.019	1823	5556		175.5	11110
700-41-3	12.82	300	718.3	705.48	21.16	0.019	1826	5565		175.5	11128
700-42-1	12.81	300	718.3	705.49	21.16	0.019	1815	5531	8.66	175.1	11087
700-42-2	12.81	300	718.3	705.49	21.16	0.019	1815	5531		175.1	11087
700-42-3	12.81	300	718.3	705.49	21.16	0.019	1810	5516		175.1	11057
700-43-1	12.83	300	718.3	705.47	21.16	0.019	1840	5608	0.00	175.9	11187
700-43-2	12.83	300	718.3	705.47	21.16	0.019	1840	5608		175.9	11187
700-43-3	12.83	300	718.3	705.47	21.16	0.019	1840	5608		175.9	11187
700-44-1	12.82	300	718.3	705.48	21.16	0.019	1836	5595	9.17	175.5	11189
700-44-2	12.82	300	718.3	705.48	21.16	0.019	1834	5589		175.5	11177
700-44-3	12.82	300	718.3	705.48	21.16	0.019	1830	5577		175.5	11153
700-45-1	12.82	300	718.3	705.48	21.16	0.019	1827	5568	10.82	175.5	11134
700-45-2	12.82	300	718.3	705.48	21.16	0.019	1820	5547		175.5	11092
700-45-3	12.82	300	718.3	705.48	21.16	0.019	1825	5562		175.5	11122

APPENDIX F

LONGITUDINAL AND CIRCUMFERENTIAL TENSILE TEST RESULTS FOR THE EVALUATION OF TYPE OF FIBER

Table F.1 Longitudinal and circumferential tensile test results for recipe 600-4

Sample No	Longitudinal Tensile Test Results						Circumferential Tensile Test Results					
	$e_{average}$ mm	L mm	b_G mm	F N	σ_{LA}* N/mm	Std. Dev.	$e_{average}$ mm	L mm	b mm	F_{ult} N	σ_{CD}* N/mm	Std. Dev.
600-41-1	11.60	300	25.04	6625	264.6	0.64	11.59	300	30.30	39375	1299.5	2.60
600-41-2	11.60	300	25.06	6630	264.6		11.61	300	30.28	39425	1302.0	
600-41-3	11.59	300	25.01	6645	265.7		11.60	300	30.25	39467	1304.7	
600-42-1	11.61	300	24.99	6640	265.7	0.75	11.60	300	30.17	39568	1311.5	2.30
600-42-2	11.62	300	24.97	6650	266.3		11.59	300	30.16	39487	1309.3	
600-42-3	11.62	300	24.98	6675	267.2		11.62	300	30.18	39652	1313.9	
600-43-1	11.62	300	25.50	6840	268.2	0.80	11.63	300	30.22	39614	1310.9	1.65
600-43-2	11.62	300	25.55	6894	269.8		11.61	300	30.24	39587	1309.1	
600-43-3	11.63	300	25.53	6867	269.0		11.62	300	30.25	39554	1307.6	
600-44-1	11.61	300	25.31	6905	272.8	0.35	11.60	300	30.33	39830	1313.2	0.60
600-44-2	11.60	300	25.29	6910	273.2		11.60	300	30.35	39874	1313.8	
600-44-3	11.61	300	25.27	6885	272.5		11.62	300	30.37	39864	1312.6	
600-45-1	11.60	300	25.16	6585	261.7	0.40	11.59	300	30.41	39974	1314.5	1.87
600-45-2	11.62	300	25.18	6590	261.7		11.61	300	30.38	40004	1316.8	
600-45-3	11.61	300	25.15	6600	262.4		11.62	300	30.43	39957	1313.1	

Table F.2 Longitudinal and circumferential tensile test results for recipe 600-5

Sample No	Longitudinal Tensile Test Results						Circumferential Tensile Test Results					
	$e_{average}$ mm	L mm	b_G mm	F N	σ_{LA}* N/mm	Std. Dev.	$e_{average}$ mm	L mm	b mm	F_{ult} N	σ_{CD}* N/mm	Std. Dev.
600-51-1	11.59	300	25.04	7200	287.5	0.70	11.58	300	30.17	44300	1468.3	1.19
600-51-2	11.60	300	25.06	7225	288.3		11.59	300	30.15	44250	1467.7	
600-51-3	11.59	300	25.03	7230	288.9		11.61	300	30.15	44200	1466.0	
600-52-1	11.60	300	25.16	7280	289.3	0.46	11.59	300	30.21	44550	1474.7	0.70
600-52-2	11.61	300	25.18	7299	289.9		11.58	300	30.23	44597	1475.3	
600-52-3	11.59	300	25.17	7304	290.2		11.59	300	30.22	44607	1476.1	
600-53-1	11.60	300	25.13	7130	283.7	0.61	11.59	300	30.25	44400	1467.8	1.41
600-53-2	11.61	300	25.11	7144	284.5		11.61	300	30.27	44397	1466.7	
600-53-3	11.61	300	25.10	7150	284.9		11.60	300	30.29	44375	1465.0	
600-54-1	11.61	300	25.26	7220	285.8	0.40	11.60	300	30.42	44700	1469.4	0.78
600-54-2	11.60	300	25.27	7210	285.3		11.62	300	30.44	44725	1469.3	
600-54-3	11.61	300	25.25	7195	285.0		11.61	300	30.47	44730	1468.0	
600-55-1	11.62	300	25.31	7360	290.8	0.15	11.63	300	30.52	44900	1471.2	2.20
600-55-2	11.63	300	25.33	7374	291.1		11.62	300	30.50	44945	1473.6	
600-55-3	11.63	300	25.29	7359	291.0		11.62	300	30.48	44976	1475.6	

Table F.3 Longitudinal and circumferential tensile test results for recipe 600-5-rev.

Sample No	Longitudinal Tensile Test Results						Circumferential Tensile Test Results					
	$e_{average}$ mm	L mm	b_G mm	F N	σ_{LA}* N/mm	Std. Dev.	$e_{average}$ mm	L mm	b mm	F_{ult} N	σ_{CD}* N/mm	Std. Dev.
600-5r1-1	11.33	300	25.05	5780	230.7	0.47	11.32	300	30.28	37670	1244.1	1.80
600-5r1-2	11.34	300	25.06	5776	230.5		11.33	300	30.33	37630	1240.7	
600-5r1-3	11.32	300	25.03	5792	231.4		11.34	300	30.35	37675	1241.4	
600-5r2-1	11.34	300	25.00	5750	230.0	0.49	11.35	300	30.41	37790	1242.7	1.15
600-5r2-2	11.33	300	25.01	5775	230.9		11.34	300	30.39	37749	1242.2	
600-5r2-3	11.34	300	25.03	5760	230.1		11.35	300	30.37	37674	1240.5	
600-5r3-1	11.35	300	25.10	5803	231.2	0.50	11.36	300	30.21	37500	1241.3	2.31
600-5r3-2	11.36	300	25.13	5795	230.6		11.35	300	30.18	37594	1245.7	
600-5r3-3	11.35	300	25.11	5816	231.6		11.35	300	30.17	37480	1242.3	
600-5r4-1	11.31	300	25.21	5810	230.5	0.20	11.32	300	30.22	37830	1251.8	1.69
600-5r4-2	11.30	300	25.22	5807	230.3		11.31	300	30.19	37890	1255.1	
600-5r4-3	11.31	300	25.25	5826	230.7		11.31	300	30.21	37848	1252.8	
600-5r5-1	11.33	300	25.06	5820	232.2	0.25	11.33	300	30.25	37580	1242.3	21.97
600-5r5-2	11.32	300	25.08	5816	231.9		11.33	300	30.23	37577	1243.0	
600-5r5-3	11.33	300	25.05	5805	231.7		11.32	300	30.27	38768	1280.7	

Table F.4 Longitudinal and circumferential tensile test results for recipe 500-4

Sample No	Longitudinal Tensile Test Results						Circumferential Tensile Test Results					
	$e_{average}$ mm	L mm	b_G mm	F N	σ_{LA}* N/mm	Std. Dev.	$e_{average}$ mm	L mm	b mm	F_{ult} N	σ_{CD}* N/mm	Std. Dev.
500-41-1	12.02	300	25.10	5830	232	0.58	12.02	300	30.25	36015	1191	1.15
500-41-2	12.02	300	25.12	5842	233		12.01	300	30.20	36025	1193	
500-41-3	12.02	300	25.09	5823	232		12.02	300	30.25	36033	1191	
500-42-1	12.01	300	25.16	5810	231	0.00	12.02	300	30.09	36041	1198	1.73
500-42-2	12.01	300	25.20	5815	231		12.01	300	30.10	36052	1198	
500-42-3	12.02	300	25.18	5814	231		12.01	300	30.15	36039	1195	
500-43-1	12.02	300	25.27	5790	229	0.58	12.02	300	30.31	35995	1188	1.00
500-43-2	12.01	300	25.25	5810	230		12.02	300	30.29	36017	1189	
500-43-3	12.02	300	25.26	5807	230		12.02	300	30.27	36007	1190	
500-44-1	12.03	300	25.30	5840	231	0.58	12.02	300	30.33	36073	1189	1.00
500-44-2	12.02	300	25.32	5855	231		12.02	300	30.29	36082	1191	
500-44-3	12.03	300	25.34	5833	230		12.03	300	30.31	36066	1190	
500-45-1	12.02	300	25.13	5830	232	0.58	12.01	300	30.05	36082	1201	1.15
500-45-2	12.01	300	25.17	5824	231		12.00	300	30.09	36075	1199	
500-45-3	12.00	300	25.14	5816	231		12.00	300	30.10	36095	1199	

Table F.5 Longitudinal and circumferential tensile test results for recipe 700-4

Sample No	Longitudinal Tensile Test Results						Circumferential Tensile Test Results					
	$e_{average}$ mm	L mm	b_G mm	F N	σ_{LA}* N/mm	Std. Dev.	$e_{average}$ mm	L mm	b mm	F_{ult} N	σ_{CD}* N/mm	Std. Dev.
700-41-1	12.82	300	25.10	7200	287	0.00	12.82	300	30.15	51250	1700	1.53
700-41-2	12.81	300	25.11	7210	287		12.81	300	30.10	51230	1702	
700-41-3	12.82	300	25.13	7205	287		12.81	300	30.16	51247	1699	
700-42-1	12.81	300	25.20	7025	279	0.00	12.81	300	30.07	51300	1706	1.15
700-42-2	12.81	300	25.23	7033	279		12.82	300	30.05	51280	1706	
700-42-3	12.81	300	25.22	7025	279		12.81	300	30.04	51295	1708	
700-43-1	12.83	300	25.27	7155	283	0.00	12.82	300	30.10	51330	1705	2.52
700-43-2	12.82	300	25.26	7140	283		12.82	300	30.18	51310	1700	
700-43-3	12.82	300	25.25	7140	283		12.82	300	30.15	51345	1703	
700-44-1	12.82	300	25.19	7139	283	0.58	12.82	300	30.25	52015	1720	2.08
700-44-2	12.83	300	25.21	7145	283		12.83	300	30.26	52020	1719	
700-44-3	12.82	300	25.18	7140	284		12.82	300	30.21	52046	1723	
700-45-1	12.82	300	25.13	7042	280	1.73	12.82	300	30.07	52125	1733	1.15
700-45-2	12.81	300	25.15	7039	280		12.82	300	30.09	52100	1731	
700-45-3	12.82	300	25.15	7105	283		12.82	300	30.10	52108	1731	

APPENDIX G

AVERAGE STIFFNESS, LONGITUDINAL AND CIRCUMFERENTIAL TENSILE TEST RESULTS FOR THE EVALUATION OF TYPE OF FIBER

Table G.1 Average stiffness, longitudinal and circumferential tensile test results for the evaluation of type of fiber

Sample No	Average Stiffness Test Results						Average Long. Tensile Test		Average Circum. Tensile Test	
	$e_{average}$, mm		S_0 , N/m^2		E , MPa		σ_{LA}* , N/mm		σ_{CD}*, N/mm	
600-11	11.62	11.61	5889	5875	10812	10814	226.2	222.1	1235.5	1237.5
600-12	11.59		5854		10833		217.4		1238.8	
600-13	11.61		5872		10808		218.9		1237.9	
600-14	11.63		5899		10801		228.2		1241.9	
600-15	11.60		5860		10816		219.8		1233.3	
600-41	11.60	11.61	5977	5986	11030	11024	265.0	267.0	1302.1	1310.2
600-42	11.61		5996		11037		266.4		1311.6	
600-43	11.62		6002		11019		269.0		1309.2	
600-44	11.61		5986		11018		272.8		1313.2	
600-45	11.60		5968		11015		261.9		1314.8	
600-51	11.59	11.60	6479	6499	11989	11981	288.2	287.7	1467.3	1470.3
600-52	11.60		6483		11965		289.8		1475.4	
600-53	11.60		6490		11977		284.4		1466.5	
600-54	11.61		6513		11989		285.4		1468.9	
600-55	11.62		6528		11985		291.0		1473.5	
600-5r1	11.33	11.33	5885	5870	11672	11636	230.9	231.0	1242.1	1247.1
600-5r2	11.34		5895		11659		230.3		1241.8	
600-5r3	11.35		5847		11535		231.1		1243.1	
600-5r4	11.31		5849		11664		230.5		1253.2	
600-5r5	11.33		5874		11649		231.9		1255.3	

Table G.1 continued

500-11	12.02	12.02	10724	10724	10304	10304	210.7	208.1	1097.7	1096.6
500-12	12.01		10685		10293		209.3		1094.0	
500-13	12.02		10718		10299		206.3		1090.7	
500-14	12.03		10758		10310		203.7		1099.7	
500-15	12.02		10736		10316		210.7		1101.0	
500-41	12.02	12.02	11050	11081	10618	10653	232.3	231.0	1191.7	1193.5
500-42	12.02		11090		10656		231.0		1197.0	
500-43	12.01		11068		10662		229.7		1189.0	
500-44	12.02		11100		10666		230.7		1190.0	
500-45	12.02		11098		10664		231.3		1199.7	
700-11	12.83	12.82	5433	5425	10838	10843	255.3	253.5	1575.0	1574.3
700-12	12.81		5401		10827		248.3		1567.0	
700-13	12.84		5442		10831		258.3		1571.0	
700-14	12.81		5412		10849		250.0		1576.0	
700-15	12.82		5435		10868		255.3		1582.7	
700-41	12.82	12.82	5561	5568	11120	11135	287.0	282.7	1700.3	1712.4
700-42	12.81		5526		11077		279.0		1706.7	
700-43	12.83		5608		11187		283.0		1702.7	
700-44	12.82		5587		11173		283.3		1720.7	
700-45	12.82		5559		11116		281.0		1731.7	