MECHANICAL PROPERTIES OF GLASS FIBRE REINFORCED POLYPROPYLENE THERMOPLASTIC PIPES

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A dissertation submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering.

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DECLARATION

I declare that this dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted for any degree or examination in any other university.

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(Yusuf Abiola Kareem)

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ABSTRACT

Glass fiber reinforced polypropylene pipes were fabricated from 6-10 layers of "Plytron" GN638T 25mm wide glass fiber pre-impregnated polypropylene tapes using filament winding/tape laying process, in-situ consolidation on a 1000mm long mandrel. Infrared heater and heat gun were used in heating the incoming tapes and the substrate at the nip point. The effects of process pressure and temperature on the mechanical properties were investigated by testing samples of test laminates and fabricated pipes for their mechanical properties. Results indicated that the mechanical properties of the test samples and pipes were affected by changes in process temperature and pressure, with an optimum process pressure and temperature being 16.8KPa and 280^0C respectively. The cost analysis of the fabricated pipes indicated that the materials and method of production employed in this research could be utilized to an economic advantage when compared with the prices of the same type of pipes in SA market.

In loving memories of my father and mother
Alhaji & Alhaja Abdulkareem Bello.
Innaa Lillahi Wa inna Ilayhi Raaji'un

Ya Rabbanaa Ya Gafaaru Igfrilanaa, Wa-Abee Wa Ummee,
Wakullil Muslimeen Walmuslimaat

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1 INTRODUCTION

1.1 Definition

A structural composite is a material system consisting of two or more phases on a macroscopic scale, whose mechanical performance and properties are designed to be superior to those of the constituent material acting independently. One of the phases is usually continuous and is called reinforcement (fibre), while the less stiff and weaker phase is continuous and is called matrix. Sometimes, due to chemical interactions or other processing effects, an additional phase, called interphase, exists between the reinforcement and the matrix. The properties of a composite material depend on the properties of constituents, geometry, and distribution of the phases [1].

1.1.2 Historical Development.

Historically, the concept of fibrous reinforcement is very old. There are biblical references to straw-reinforced clay bricks in ancient Egypt. Iron rods were used to reinforce masonry in the nineteenth century, leading to the development of steel-reinforced concrete. Glass fibre reinforced resins have been in use since about the first quarter of the twentieth century. Fibre reinforced composites have been more prominent than other types of composite for the simple reason that most materials are stronger and stiffer in the fibrous form than in any other form [2]. Commercial production of reinforced plastics began around 1940. Since then glass fibre has remained the highest volume fibre reinforcement for plastics [3].

The first fibreglass boat was made in 1942; reinforced plastics were also used in aircraft and electrical components at this time. Filament winding was invented in 1946 and incorporated into missile applications in the 1950s. The first boron and high strength carbon fibres were introduced in the early 1960s, with applications of advanced composites to aircraft components by 1968. Metal matrix composites such as boron/aluminium were introduced in 1970. Dupont developed Kevlar (or aramid) fibres in 1973. Starting in the late 1970s, applications of composites expanded widely to the aircraft, automotive, sporting goods, and biomedical industries. The 1980s marked a significant increase in high modulus fibre utilization [1]. According to a 1973 estimate, approximately 80% of all research and development effort in composite materials has been done since 1965. This percentage must have only increased since then [2].

At the present time, the most important composites are combinations of high-strength, but crack sensitive ceramic-type materials and polymers. The most common example of such a system is fibreglass (fibre-reinforced plastic). Glass fibres are very strong, but if notched they fracture readily. By encapsulating these fibres in a polyester (or polymer) resin matrix, they are protected from damage and the polyester (or polymer) transfers applied loads to the glass fibres so that their stiffness and strength can be utilized [4].

1.2 Fibres

The desirable functional requirements of the fibres in a fibre-reinforced composite are:

1. the fibre should have a high modulus of elasticity for an efficient utilization of reinforcement.
2. the fibre should have a high ultimate strength.
3. the variation of strength between individual fibres should be low.
4. the fibres should be stable and retain their strength during handling and fabrication.
5. the diameter and surface of the fibre should be uniform.

1.3 Matrix

The matrix is required to fulfil the following functions:

1. to bind together the fibres and protect their surfaces from damage during handling, fabrication and during the service life of the composite;
2. to disperse the fibres and separate them in order to avoid any catastrophic propagation of crack and subsequent failure of the composite;

3. to transfer stresses to the fibres efficiently by adhesion and/or friction (when composite is under load);
4. to be chemically compatible with fibre over a long period;
5. to be thermally compatible with fibres.

1.4 Glass Fibres

Glass is the most common fibre used in polymer matrix composites. A variety of different chemical compositions are commercially available. Common glass fibres are silica based (~50-60% SiO_2) and contain a host of other oxides of calcium, boron, sodium, aluminium, and iron.

The structure of glasses in their solid state, consist of rigid network of silica. The network structure is responsible for their superior strength. The variation of glass properties can be achieved by modifying the structure of silica with various additives. Among all the glass fibres used in composites, E-glass is the type most widely used. E-glass, which is essentially a borosilicate glass named for electrical applications, and S-glass (high strength), which is a magnesia/alumina/silica material with higher tensile strength than E-glass used for the same types of applications, but the E-glass is lower in cost and also it can be fabricated at lower temperatures.

Glass fibres used in composite materials are manufactured as continuous filaments. In this process, glass is fed into a furnace and melted. Then fibres are drawn from the molten glass at high speed. Commercially produced filaments have diameters ranging from 2.4 to 19 µm. These fibres after receiving a protective coating are gathered in the form of bundles, called strands.

The treatment of the glass fibres provides a suitable surface condition compatible with that of resin matrix, so that good adhesion can be achieved. Unsatisfactory bonding between the fibre and matrix can cause interfacial failure, and stress will not be transferred effectively at the weakened spot.

1.5 Polypropylene

Polypropylene is similar chemically to high-density polyethylene. It is made from polypropylene gas and consists of carbon and hydrogen atom only.

Polypropylene is an extremely versatile resin and is available in many grades and also as a copolymer (ethylene / propylene). It has the lowest density of all thermoplastics (in the order of 900 Kg/m^3) and this combined with strength, stiffness and excellent fatigue and chemical resistance makes it attractive in many situations. [5]

Polypropylene is low in cost, which is due to a relatively simple synthesis from the low cost petrochemical: propylene. To be useful in a wider range of applications, polypropylene is often copolymerised with polyethylene, yielding a material with the temperature resistance, stiffness and strength of polypropylene, but better impact resistance contributed by the flexible polyethylene linkages. When polypropylene is listed in technical literature, “homopolymer” or “copolymer’ is usually specified [6].

Polypropylene is used widely in film, fibre, sheet, and moulded applications. Most of the film is used in packaging. The fibre is used in carpeting, upholstery and apparel due to its wear and chemical resistance. Common moulded applications include bottle, pipes, containers, and tanks. Due to its low cost, polypropylene is used in toys, and disposable houseware [6].

Polypropylene was first introduced into the market in the 1950s. It has registered continued world-wide market share growth in recent years and it is predicted that consumption will still grow as polypropylene is increasingly used as a substitute for other materials such as glass, metal, and some engineering plastics [7].

In South Africa, Sasol Polymers is the leading producer of monomers, polymers, chlor-alkali chemicals and mining reagents. Sasol Polymers originated as a joint venture by South African chemical industry giants Sasol and AECI, then named Polifin [6].

AECI had access to the polyethylene and PVC polymer markets and Sasol, to the polypropylene market. In addition, Sasol bought competitive ethylene and propylene feedstock to the mix. In September 2000, the business changed its name to Sasol Polymers* and now operates as a division of Sasol Chemical Industries (SCI) [6].

1.6 Glass fibre reinforced polypropylene pipe

The use of extruded plastic pipes for both warm and cold water transport in housing construction has been developed over a number of years. And an important share of the materials employed in such applications is covered by polypropylene [8].

Most of the industries involved in the production of thermoplastics pipes in South Africa employ the extrusion method, which produce plain thermoplastics pipes such as polypropylene and high-density polyethylene without any glass fibre reinforcement. This is understandably due to the relative difficulties in bonding glass fibre reinforcement with these thermoplastic matrices especially polypropylene.

Henninger *et.al.* [9] made an effort aimed at addressing this setback, where the glass fibre bundles reinforcement were impregnated online with either polypropylene (PP) or Polyamide 12 (PA12), and then wound onto a mandrel using a filament winder. But apart from the complex set-up, many parameters such as, the impregnation temperature, roving pretension (brake force), process speed, nip-point temperature, and fibre volume content will determine to a large extent the impregnation and product quality.

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2 LITERATURE REVIEW

2.1 GLASS FIBRE REINFORCED THERMOPLASTICS FILAMENT WINDING

2.1.1 Introduction

In the middle 1980's, reinforced thermoplastics were publicized as the next family of composite materials due to several advantageous resin properties and the assertion of straightforward processibily [3]. Most frequently, carbon, glass, or aramid fibres are impregnated with thermosetting resins, such as epoxies and vinyl-esters. Lengthy cure times in an autoclave are required to complete the cross-linking process. Hence thermoplastic filament winding process has witnessed appreciable modifications/evolutions in recent times.

2.2 Material and Production Processes

A designer should be familiar with a few plastics, a few steel tools and so on; it was found that these would satisfy approximately 90% of design needs. The four major thermoplastics – polyethylene, polypropylene, PVC, and polystyrene – together represent over 85% by volume of world plastics consumption. Because of their lower prices, these commodity materials dominate the market, and in any materials selection procedure there are good economic reasons for considering them first before turning to the more expensive engineering plastics [4, 10]

Polyethylene is tough, ductile, and easily moulded, but their moduli, yield stresses, and melting points are relatively low. Polypropylene is stiffer, has higher yield stresses and melting point, but in comparison with polyethylene is more prone to fracture, especially at low temperatures. This is a consequence of the rise of yield stress of polypropylene below its T_g (glass transition temperature) [4,10]

2.3 Thermoset Filament Winding, Thermoplastic Filament Winding, and Thermoplastic Fibre Placement

Filament winding is a standard process for manufacturing parts of fibre-reinforced plastics. The process is well established for thermoset composites, yet its capabilities for processing fibre-reinforced thermoplastics have opened a wide array of potential applications previously impossible.

The additional capability to start and stop the fibre at any location on the mandrel enables further evolution of the process to fibre placement. This procedure can best be described as a combination of filament winding and automated tape laying on flat or curved surfaces. The process is no longer limited to a rotating mandrel, but a rotating mandrel may be added to increase the degrees of freedom [4].

In thermoset filament winding, the fibre passes through a thermoset resin bath where it is impregnated and the impregnated fibre is wound onto a mandrel. The process continues until the required layers on the mandrel are achieved. The product is later consolidated in the autoclave. While thermoplastic filament winding and thermoplastic filament placement do not need any resin bath, the incoming tape (or mat) is wound directly onto the mandrel where it is heated at the nip-point and consolidation is in-situ. Here no autoclave consolidation is required. The differences between the three manufacturing processes are outlined in Appendix A, Table A1.

Thermoplastic fibre deployment processes offer the major advantage, that curing no longer take place in the autoclave, but within the process (In-Situ-Consolidation). This is obtained by melting the matrix material under the influence of heat and welding it under pressure onto the preceding layer. They also offer an increased manufacturability of complex-shaped parts, as well as recyclability [4]

2.4 Heating Devices

There are various heat sources that can be used in heating the incoming tapes and subsequent laminates during the thermoplastics composites production process. Three general concepts using different types of heating elements are discussed below.

In all the three concepts, the incoming tapes may be preheated or the heat may be applied only at the nip-point. It is assumed that preheating the incoming tapes may reduce the void content and also has the advantage of reducing the energy needed in the small nip-point area, so that the tape is less likely subjected to overheating [11, 12]. Table A2 illustrates the comparison of the various heating sources applicable to thermoplastic glass fibre reinforced thermoplastic winding.

2.4.1 Laser Beam

Investigations by Beyeler and Guceri [11, 13, 14] showed the applicability of a laser beam for filament winding. The two major advantages of laser power are: excellent energy efficiency and fast response. These make it ideal to integrate a laser into a feedback control loop. The size and weight of a middle-category powered laser, however, make it impossible to carry the unit within the fibre placement head.

2.4.2 Hot Gas Torches (HGT)

Since hot gas torches are relatively small, they comply very well with demand for a lightweight and compact design. Although simple units are not very expensive, more sophisticated, well-insulated torches with little thermal mass may be costly. HGT's have other shortfall, too.

Their energy efficiency is low compared to other sources, since an electric coil has to be heated first, and then this energy has to be transmitted to a floating gas stream via convection. A lot of energy is wasted to heat the coil and housing.

Although they are of light weight, the metal part act as heat sinks. Therefore it takes the torch a long time to reach the process temperature. Switching off the system also causes problems: the gas flow cannot be shut down before the torches have cooled down to moderate temperatures.

2.4.3 Infrared Light (IR)

This heating method is also a very energy-efficient process with good response behaviour. Its applicability for filament winding of thermoplastics composites tapes has earlier been investigated by other researchers [6, 7, 15]. Although it does not reach the performance of a laser, it clearly outranks hot gas torches.

Small and lightweight line heaters are available in the market. However, for heating at the nip-point, the use of IR lamps is not a viable solution, since it would be necessary to concentrate the light in this small area via optical lenses [11].

2.4.4 Selected Heating Source

Comparing the pros and cons of the various heaters, a combination of infrared (IR) preheaters and hot gas torches have been chosen for this project. Series of infrared preheaters would be used to heat the incoming tapes close to their melting temperature while hot gas torches would be directed to the nip-point area for efficient and effective laminates consolidation.

2.5 Pre-impregnated Tapes

Fibres and reinforcements come in the form of tows, rovings, dry woven fabrics or non-woven fabrics or pre-impregnated tapes. Although fabrics and dry strands or tows currently account for most of reinforcement consumption, the use of pre-impregnated material is growing. Pre-impregnated fabrics (or tapes) also known as ‘prepregs’ are used to produce top-quality, high-performance laminates [1].

Pre-impregnated tapes (or prepregs) are a ready-made tape (thin sheets ~ 1mm thickness) made of fibres in a polymer matrix. They are available in standard width from 3 to 5 in. (76 to 127mm) (although tapes of larger and smaller width are also available). Depending on whether the polymer is thermoset or thermoplastics, the tape is stored in a refrigerator or at room temperature, respectively. One can lay these tapes manually or mechanically at various orientations to make a composite structure. Vacuum bagging and curing under pressures and temperature may follow [16].

Generally, pre-impregnated tapes come with a backing paper that must be removed before laminating. More than one type of fibre may be used to produce so-called hybrid composites. A pre-impregnated tape with fibres parallel to the long dimension (length) is called 0^o lamina or ply. A pre-impregnated tape that is cut with fibre perpendicular to the long dimension is designated as a 90^o lamina, while a pre-impregnated tape at an intermediate angle θ is designated as a θ ply [2].

2.5.1 Glass Fibre Polypropylene Pre-impregnated Tapes

There are various manufacturers of glass fibre polypropylene pre-impregnated tapes. This research employs Plytron GN 638 T glass fibre polypropylene pre-impregnated tapes: Plytron is the registered trademark for continuous unidirectional fibre reinforced thermoplastics of Plytron GmbH, Germany.

2.5.2 Applications

Plytron is already used in automobile industry as well as for sports and leisure goods. Due to the excellent mechanical properties, Plytron is used for applications for which engineering thermoplastics have been recommended. Plytron may be used for car floor panels, pipes reinforcements, frame structures, bumper beam, ballistic shields, truck panels, containers, appliance housings, boat or offshore structures [15].

2.6 Thermoplastic Production Concepts

Filament winding is a widely used processing routine for continuous fibre reinforced polymer for axially symmetric components. Initially developed for thermoset resins, it was successfully adopted for thermoplastics as well.

However, an intermediate product form, (e.g. commingled yarn; powder impregnated bundles; pre-impregnated tapes), in which the thermoplastics matrix is already in close contact to the reinforcing fibres must usually be used [17].

2.6.1 Polypropylene Thermoplastics

Composites made from continuous glass fibre and polypropylene are promising low cost materials, and their limited use is surprising in view of the very high strength/raw material cost ratio. One important cause of this is the difficulty of impregnation due to the high viscosity of polypropylene leading to bad quality materials because of poor fibre/matrix bonding. To overcome this difficulty, both pre-impregnated and in situ impregnated material concepts have been developed during the last couple of decades.

The pre-impregnated materials are fully impregnated before they are employed in structure, while in the in-situ impregnated materials the final consolidation procedure has to take place during the production of the actual products. The consolidation procedure will then delay the fabrication and accordingly increases the cost of the final products [18]. Therefore, this research project employs the pre-impregnated material concept.

However, if the pre-impregnated composite materials are to be competitive for application in low cost products, they also need to be produced by simple fast-running processes.

Three steps are usually involved in the fabrication process as far as thermoplastics matrix is concerned. First, under certain temperature, the solid matrix material becomes softened, then the matrix in the liquid form soaks and infiltrates the reinforcement fibres, and at last when the composite is cooling down, it turns into the solid form to fix the fibres in definite position. The second step is considered the most important, because it decides the distribution of the matrix among and wicking to the reinforcement fibres [19].

The direct melt impregnation is the simplest one-step route ideally resulting in a fully impregnated unidirectional pre-impregnated tape. The degree of impregnation is the most critical point in production and has substantial influence on the resulting mechanical properties of the composite material [17, 18, 19].

Furthermore, researchers have shown that in glass fibre polypropylene thermoplastics filament winding/tape laying, processing parameters, such as consolidation pressure, impregnation temperature, winding speed, and nip-point temperature to a large extent determine the mechanical properties and the integrity of the final products [18, 20, 21].

2.6.2 Thermoplastic In Situ Consolidation Process Concept

In Situ Process Fundamentals [20]

The thermoplastic in situ consolidation process first applies energy to heat the incoming tapes or tow and the already- deposited substrate to its resin melt temperature.

A normal compaction force is applied to the molten heat-affected zone and the layers are fused together. The laminate then re-freezes. An in-process quality sensing system, if achieved, could view the re-frozen area to measure some parameters related to the defects in the layer just deposited as shown in Figure 2.1.

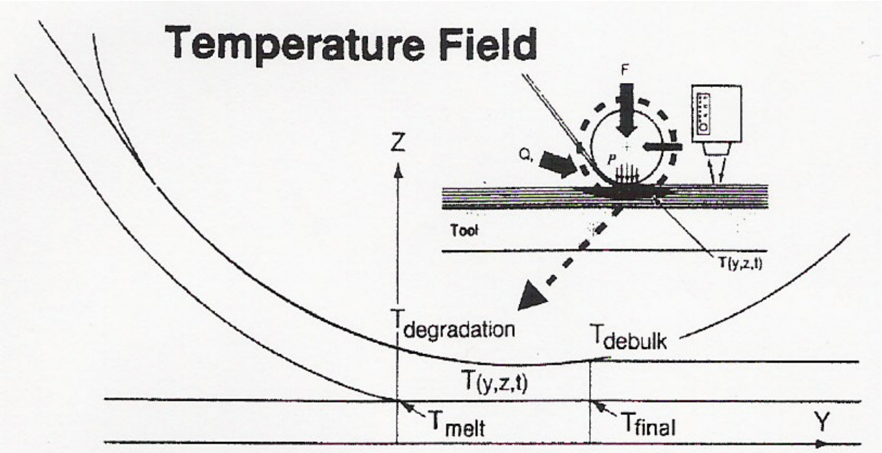

Figure 2.1: The in situ consolidation process applies heat and pressure to weld the layers. A conceptual in-process sensing system monitors layer quality

2.6.3 Heat Transfer Induced Temperature Field [20]

The coupling of the energy input determines the temperature field in the process spot. At the maximum process speed, a Z-direction temperature gradient exists where the highest temperature is at the top surface of the incoming material feedstock at the nip inlet. For best laminate quality, this temperature must not exceed the resin degradation temperature, T_{deg}. Because of the Z- direction temperature gradient, the lower surface just reaches T_{melt}. The compactor transfers enough heat to the composite so that at full process speed, the upper surface of the deposited layer just cooled to T_{debulk}, the temperature where the laminate spontaneously debulks or unconsolidates. T_{final} in between the welded layers depends on process dynamics as illustrated in Figure 2.2.

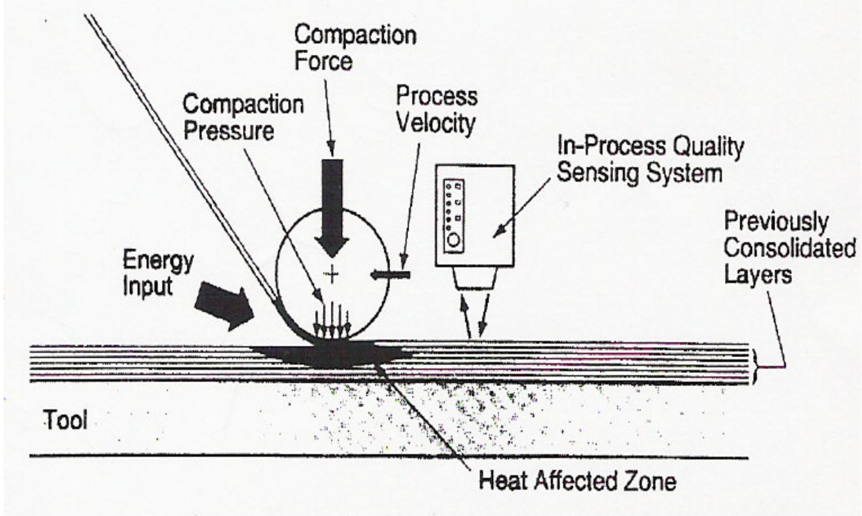

Figure 2.2: At maximum placement speed, the incoming layer lower interface reaches T_{melt} , without overheating the resin at the upper surface

2.6.4 Evolution of Intimate Contact and Healing [20]

The tow or tapes mating surfaces are initially rough, but their surfaces asperities disappear as they heat, melt, and deform during contact. As intimate contact evolves, surface healing can originate and progress.

Healing occurs by migration of polymer chains at any location of intimate contact. Elevated temperature, not pressure, drives healing, which is predicted to occur where $T>T_g$, even after the compaction roller. High temperature, up to the degradation temperature, drives quicker healing.

Thus, if at t_1 only short chains begin repetition across, longer chains have extended by t_2 at the initial area of intimate contact and short chains start across at the fresh area. After t_2, the normal pressure is removed but more chains move across the interface until the temperature reaches T_g. The “degree-of-bonding” integrates intimate contact and healing together, coupling the incremental additional area coming into intimate contact and the degree of healing as shown in Figure 2.3

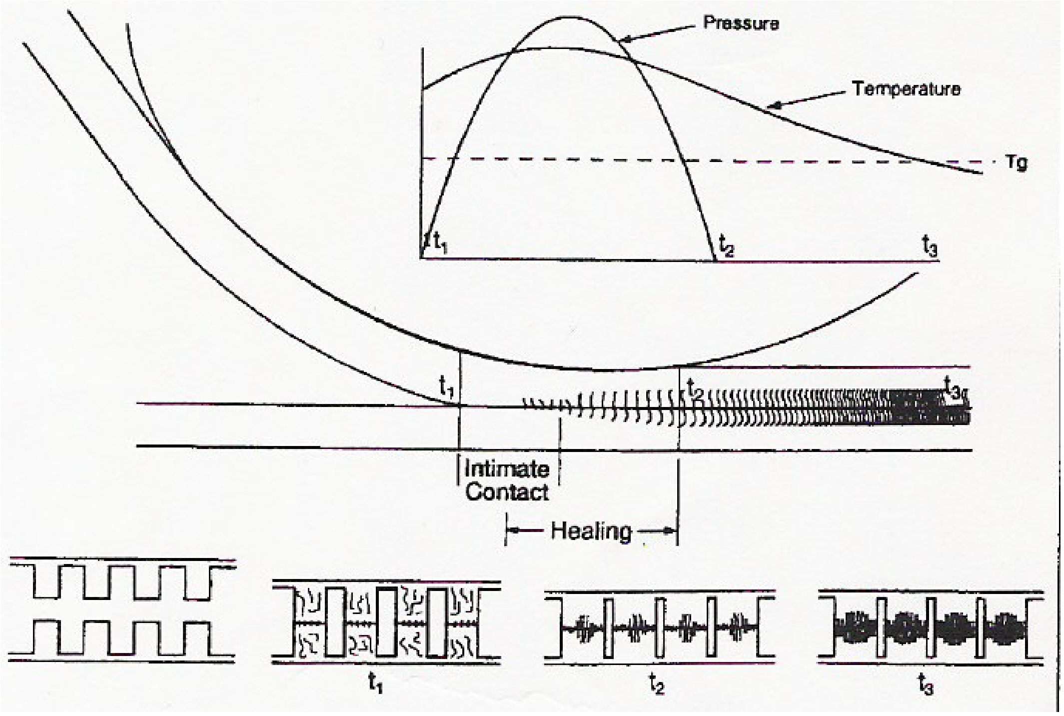

Figure 2.3: Layer- by-layer polymer healing occurs whenever surface intimate contact is established and the temperature maintained

2.6.5 Consolidation Squeeze Flow/Void Reduction [20]

Squeeze flow describes flow of the fibre/resin/void mixture as a function of the pressure distribution across the tow to yield the reduction in height and the increase in width. This is accompanied by a reduction in void content.

While the major mechanism of interply void reduction is increased intimate contact, the major mechanism of intraply void reduction is gas compression under the pressure roller, although coalescing, migration, and bubbling may occur as shown in Figure 2.4.

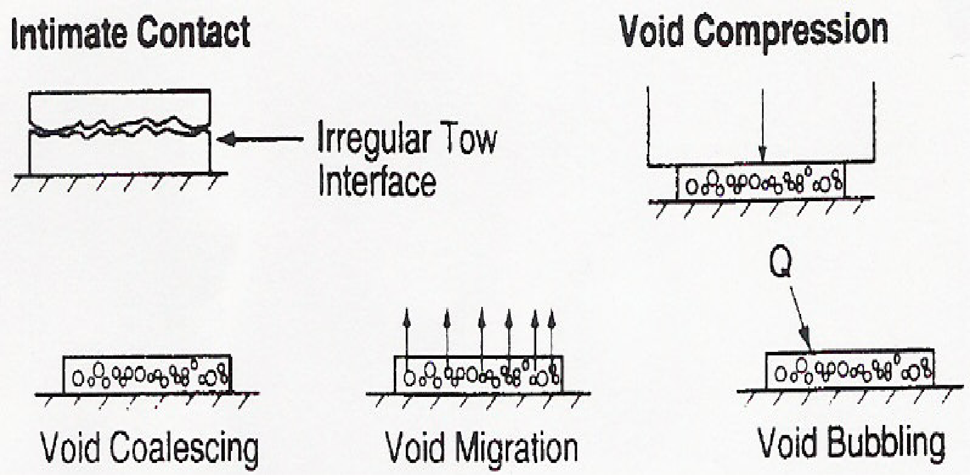

Figure 2.4: Mechanism of void elimination in thermoplastic placement process

2.7 Creep

When a constant stress is applied to a plastic it will change in size due to creep effect. Clearly the material cannot continue to get larger and eventually fracture will occur (Appendix H). This behaviour is referred to as creep rupture although the less acceptable (to engineers) term of static fatigue is used. The time taken for the material to fracture will depend on the stress level, the ambient temperature, the component geometry, the molecular structure, the fabrication method, etc. at some stresses the creep rate may be sufficiently low, that for most practical purposes the endurance of the material may be regarded as infinite. On the other hand, at high stresses the material is likely to fail shortly after the stress is applied [22].

The stiffening effect of the fibres (60% by weight) enable most engineering plastics to be used at temperatures approaching the melting point - a principle that applies equally well to other semi-crystalline plastics: without the reinforcement, creep is a major problem in the temperature range between T_g (glass transition temperature) and T_m (melting temperature). As both polyethylene and polypropylene have glass transitions that are below room temperature, they tend not only to creep under applied stresses, but also to warp in response to moulded –in stresses and physical ageing processes, including recrystallisation [22].

In reality, all materials lie somewhere in the spectrum of behaviour which ranges from at one extreme, that of a pure elastic solid (stress dependent only upon strain) to the other of a pure fluid (stress dependent only on the rate of strain). In other words, all materials are to some extent viscoelastic, exhibiting both viscous and elastic properties [23].

2.8 Project Analysis

The following factors were put into consideration before setting out the objectives of this research:

1. Continuous fibre-reinforced thermoset plastic materials have been in commercial use for a long time. They are widely used in high volume industrial applications such as pipes, tanks, boats, etc. [18]. In low cost products it is necessary to apply materials that are able to keep the product price at an acceptable level and at the same time give a quality that can compete with other materials. In this area of application (that is, in medium to low cost products) the thermoplastic matrix composites have not so far gained any wide spread commercial use [18].

   Polypropylene is similar to high-density polyethylene, but it is stiffer, harder, and offers higher strength than many grades of polyethylene. It also has higher usage temperature than HD polyethylene, and more importantly, offers lower cost as shown in Appendix I. Likewise, glass fibre is still the most suitable means of reinforcement for typical thermoplastic matrices (such as polypropylene polyethylene, etc.) in low to medium products. Therefore, composites made from continuous glass fibre and polypropylene will result in good quality and promising low cost materials [4, 7, 18].

2. In South Africa polypropylene is mostly used as liners for thermoset filament winding. At the time of this research, there is no industry in South Africa producing a wholly glass fibre reinforced polypropylene thermoplastic pipes. Also there is no company in South Africa involved in the production of glass fibre pre-impregnated polypropylene tapes.

3. Recent research in the application of polypropylene matrix and glass fibre reinforcement originates from the United States and some European countries, especially Germany. South Africa being the front-runner in the thermoset and the thermoplastic production and research in Africa (as evident in the 'Africa Materials conference' 2004) holds a vantage position in exploring this seemingly economically viable area.

4. According to Lamonta *et.al.* [20], thermoplastic filament winding/tape laying has achieved autoclave level properties in thin and thick right circular cylinders. Polypropylene can be tailored to many fabrication methods and applications. Excellent chemical resistance, the lowest density, highest melting point (in the family of olefin fibres/or matrix), and moderate cost makes it an important fibre (or matrix) in industrial applications [7]. Therefore, this method can be applied to glass fibre reinforced polypropylene pre-impregnated tapes.

2.9 Objectives

From the project analysis above, the objectives of this research are:

1. Production of fibre reinforced polypropylene pipes using the most suitable method of production
2. Investigating the mechanical properties of these pipes
3. Making comparison with existing costs of production.

3 PRODUCTION

3.1 Tape Winding

3.1.1 Introduction

Filament winding has been the dominant method of composites pipes production, but tape winding and tape laying processes have since evolved, and are relatively very efficient, particularly in thermoplastics pipes production using glass fibre pre-impregnated thermoplastic tapes. The use of the thermoset matrices is the cause of various process drawbacks, such as the slipping of rovings and tows which limits the selection of the fibre orientations in the final part, the exothermic reaction of the thermoset matrix creates problems in case of thick laminates, the curing of the thermoset increases manufacturing time and necessitates further tooling and ancillary materials.

These limitations do not occur when a pre-impregnated fibre-reinforced thermoplastic tape is bonded on-line to the substrate. The bonding process of the incoming tape to the substrate begins to develop in the region close to the nip line. It consists of two steps. First compaction forces are applied to the nip to create an intimate contact between the joining surfaces. Second, the polymer chains diffuse through the contact areas. On-line bonding can be applied to the automated tape winding and the automated tape placement. Both manufacturing processes have the potential to spread the use of composite materials and are very promising in terms of cost-effectiveness and implementation of tailored design solutions [24].

3.1.2 Filament Winder Modification

Filament winding is a widely used processing routine for continuous fibre reinforced polymer for axially symmetric components. Initially developed for thermoset resins, it was successfully adopted for thermoplastics as well. However, an intermediate product form, in which the thermoplastic matrix is already in close contact to the reinforcing fibres (e.g. commingled yarn; powder impregnated bundles; pre-impregnated tapes), must usually be used [17]. Glass fibre reinforced polypropylene tape, which satisfies the above condition will be used in this research.

The filament winder in the Composites laboratory at Wits University is a tri-axial winder with a permanent metal tube mandrel. It is a wet-winding unit making use of a resin bath, which was situated above a bookshelf creel and both are moved linearly along the mandrel as one unit by an axial screw [5].

Since pre-impregnated tapes was used in this research, accessories applicable to a thermoplastic tape laying process, such as infrared heaters, tow guides, and a compaction roller replaced the resin bath and the bookshelf creel.

Therefore, several modifications were carried out on the winder. These modifications include: compaction roller, tow guide, and infrared heat.

Compaction Roller

A compaction roller of one meter long, 80mm radius, 43kg total weight with two bearing grooves as guides for the roller's end bearing were incorporated into the winder unit.

Tow Guide

Tow guide accessories were used to guide and align the incoming tape over the infrared heat source onto the mandrel at $35^0/-35^0$, $55^0/-55^0$ and 90^0 along the mandrel plane.

Infrared Heat

The resin bath was removed from the carriage shelve, and in its place, a 1500W infrared short wave heater was fixed lying below the feed strip of the pre-impregnated tape before the nip-point.

3.2 Preliminary Tests

One of the few major drawbacks of polypropylene is its poor bonding characteristics and poor wettability. But possessing the highest melting point and the lowest density in the olefin family, excellent chemical resistance and moderate cost makes polypropylene an important material in industrial applications [16].

Preliminary tests were carried out on the bonding characteristics of polypropylene using Wikitex* sample woven fabrics (50mm width) of polypropylene and glass fibre.

The fabrics were clamped together using two plates of mild steel to achieve adequate contact/compaction.

3.2.1 Test 1

Sample 1

This consists of equal composition (by volume) of interwoven polypropylene and glass fibre.

The sample was cut into 50mm x 100mm strips of five layers, clamped together to a pressure of about 0.71 MPa and heated to 180°C (approximate melting temperature of polypropylene) in an oven for 2 hours. The heat was shut off. It was then cooled in the oven to room temperature.

The test sample layers were pulled in opposite directions to determine the degree of mechanical bonding between the layers. The layers were easily separated with the application of a peel stress less than 3 MPa; hence no further analysis was carried out on the sample.

Sample 2

The same procedure (as above) was used for samples of varying compositions by volume (approximately 10-90%). But all showed similar poor mechanical bonding characteristics.

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3.2.2 Test 2

The sample was similar to that used in Sample1 of Test1 i.e. 50 percent (by volume) of interwoven polypropylene and glass fibre woven fabric.

The sample was cut into 50mm x 100mm strips of five layers, clamped together to a pressure of about 0.71 MPa and heated to 240^{o}C (enough to melt polypropylene appreciably) in an oven for 2 hours. The heat was shut off. It was then cooled in the oven to room temperature.

The test sample layers were also pulled in opposite directions to determine the degree of mechanical bonding between the layers. But in this sample, a peel stress of about 12 MPa was required to separate the layers. This showed an indication of bonding between the layers of the sample strips when compared with the manufacturer's transverse tensile strength of the Plytron pre-impregnated tape, which is 11 MPa.

The microscopic natures of the different surfaces of the separated layers were then investigated using a JSM840 Scanning Electron Microscope (SEM).
Figures 3.1 and 3.2 show the peeled layers surfaces under the microscope.

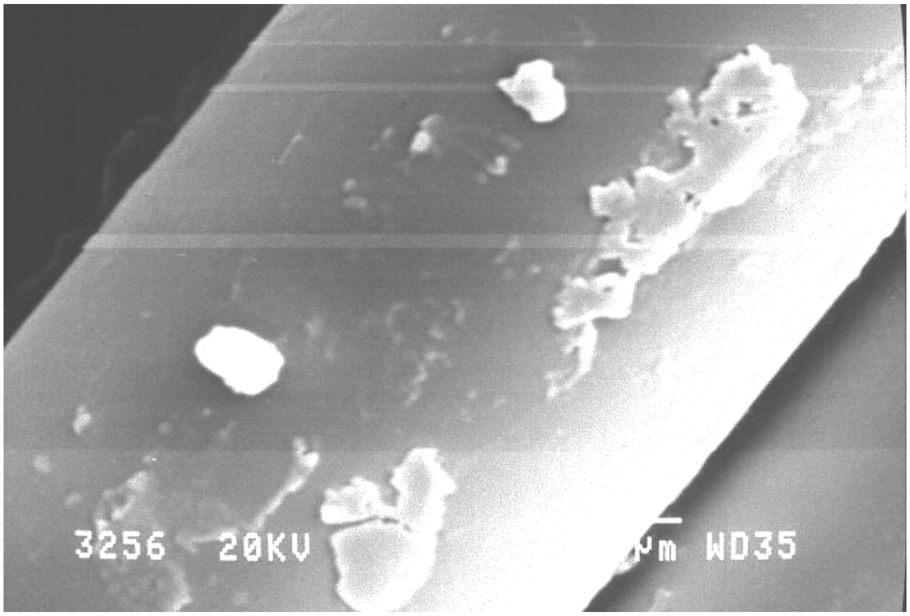


Figure 3.1: Fragments of polypropylene stuck to the glass fibre

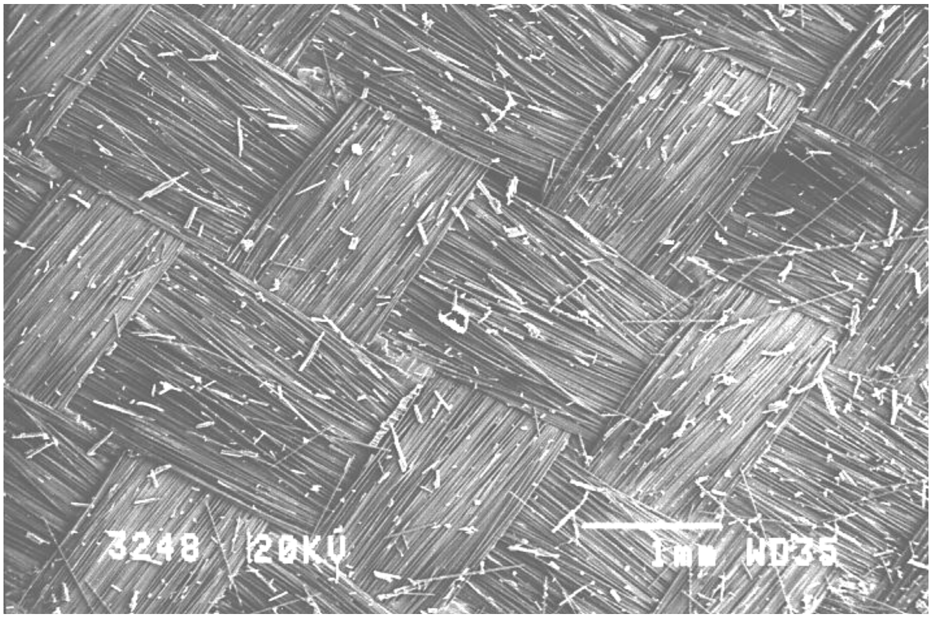


Figure 3.2: Wider view of polypropylene fragments on the glass fibre layer

The SEM analysis showed traces of polypropylene matrix on the glass fibres; this indicates that there was some physical bonding between the glass fibres and the polypropylene matrix.

Trevor I'ons, in his Masters Research work in 2002 [6], showed that oxyfluorination of polypropylene fibres in a plastic matrix resulted in an improvement in the mechanical properties. However this will require extra stages/processes (with their ensuing cost implications) and, of course, additional parameters to be considered in the fabrication process.

The above trial tests indicated that with appropriate application of heat and pressure, bonding between glass fibres and polypropylene matrix could be achieved in the fabrication of the proposed glass fibre reinforced polypropylene thermoplastic pipes.

3.3 Preliminary Process Design

Thermoplastic tape laying technique was chosen as the mode of the pipe fabrication after considering the merits and demerits of the various types of applicable pipe production processes discussed in section 2.3. The heat source of the process would be a combination of infrared heat source and a hand held heat gun.

Furthermore, optimum values of the process parameters viz. the process temperature and pressure have to be determined. These parameters should be able to give good mechanical properties in terms of the longitudinal and transverse strength of the material.

Hence, trial tests were carried out on the proposed material- 'Plytron' pre-impregnated tapes to investigate the tensile properties - longitudinal and transverse strength under different process temperatures and pressures.

3.4 Tensile Properties

Glass reinforced polypropylene thermoplastics test laminate were made using a 90mm x 150mm mould. The laminates were stacked along and across the fibre orientations in separate processes to determine the tensile properties along and transverse to the fibre direction of the material. The moulds were exposed to temperature range between 180-320^{0}C in an oven for two hours at a constant consolidation pressure (22.6 MPa). The moulds were then removed and allowed to cool at room temperature (23^{0}C).

Likewise a constant consolidation temperature of 280^{0}C was used and the consolidation pressure varied from ambient pressure – 34 KPa for low-pressure investigation, and 1.8 – 3 MPa for high-pressure tests. Tests were conducted in accordance with BS 2782 procedures on strips of these laminates to investigate the effects of consolidation temperature and pressure on the tensile strength.

The tensile tests were carried out using the Lloyd tensile testing machine as shown in Figures 3.3 - 3.5.

Figure 3.3: The Lloyd tensile testing machine

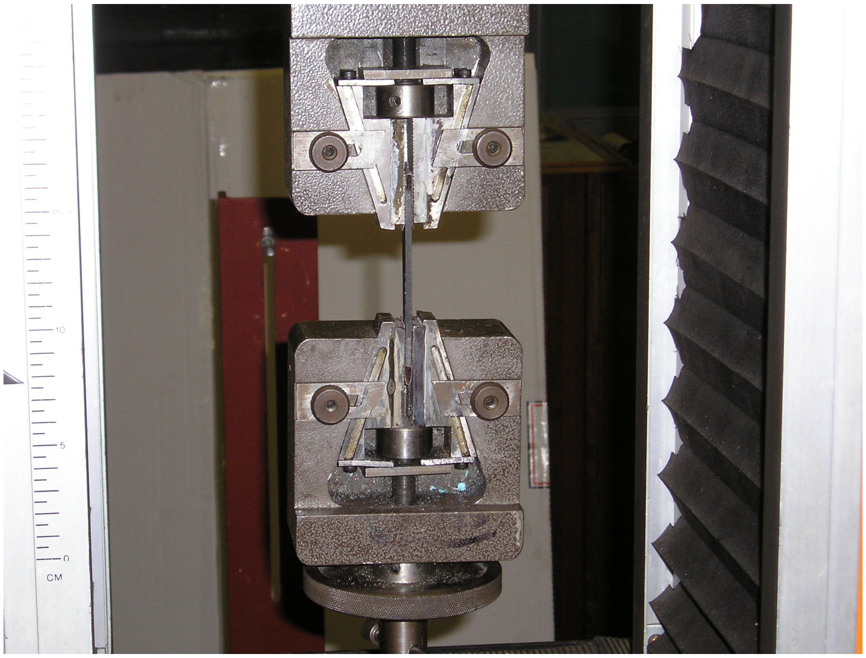


Figure 3.4: Laminate test strip in tension before failure

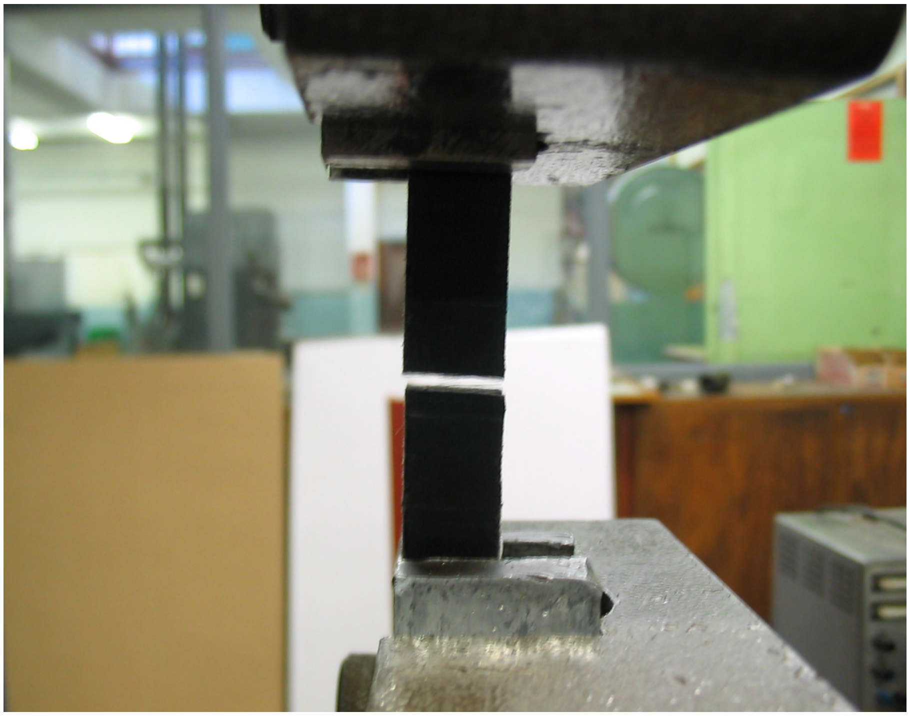


Figure 3.5: Typical failed test strip of laminates during tensile test

3.4.1 Tensile Properties at Different Consolidation Temperatures

Using a predetermined consolidation pressure (2.2 MPa), the effects of consolidation temperature on the tensile strength of the laminates was investigated by varying the consolidation temperature between 200^0C - 320^0C. The complete sets of results are presented in Table B1-Appendix B.

It can also be noted that the tensile strength of the test laminates along the direction of fibre orientation marginally varied between an average minimum strength of 592 MPa at 200^0C and an average maximum of 595 MPa at 280^0C.

However, when the laminates were tested transverse to the direction of fibre orientation, Table B1- Appendix B showed that the tensile strength of the test laminates was 8.5 MPa at 200^0C consolidation temperature, which increased to 12.4 MPa optimum strength at 280^0C consolidation temperature, after which a further increase in the consolidation temperature resulted in a decrease to 10.3 MPa tensile strength at the highest test consolidation temperature of 320^0C.

Therefore, the above results showed that the consolidation temperatures has no appreciable effect on the tensile strength of the laminates along the direction of fibre orientation, but significantly influences the tensile strength of the laminates transverse to the fibre direction.

Also, 280^0C can be deduced as the optimum consolidation temperature.

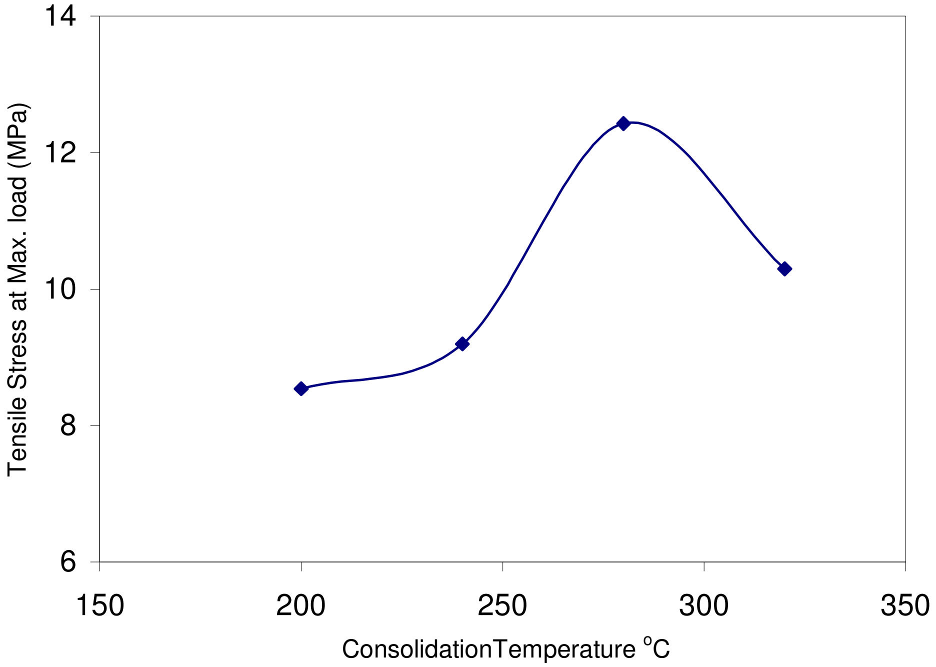


Figure 3.6: Transverse tensile strength vs. consolidation temperature at constant consolidation pressure

3.4.2 Tensile Properties at Different Consolidation Pressures

Using the deduced consolidation temperature (280^0C), the effects of consolidation pressure on the tensile strength of the laminates was investigated by varying the consolidation pressure between 0 -33.8 KPa and 1.85 – 3.0 MPa.

From Table B3 and B4, the transverse tensile strength of the laminates increased with an increase in consolidation pressures from an average of 1 MPa at atmospheric consolidation pressure (0 KPa) to an average of 11.14 MPa at 2.22 MPa consolidation pressure. After which the tensile strength decreased to an average of 10.69 MPa at 3 MPa consolidation pressure.

Also, Table B5 showed that the longitudinal tensile strength of the laminates has the lowest and highest averages of 592 MPa and 596 MPa at 3 MPa and 2.6 MPa consolidation pressures, respectively.

Hence, consolidation pressure has no appreciable effect on the longitudinal strength of the laminates. While the transverse tensile strength increased significantly with an increase in the consolidation pressures in the low pressure region, but the tensile strength of specimens consolidated at varying high pressures (1.85 – 3.0 MPa) are rarely affected by the process pressures.

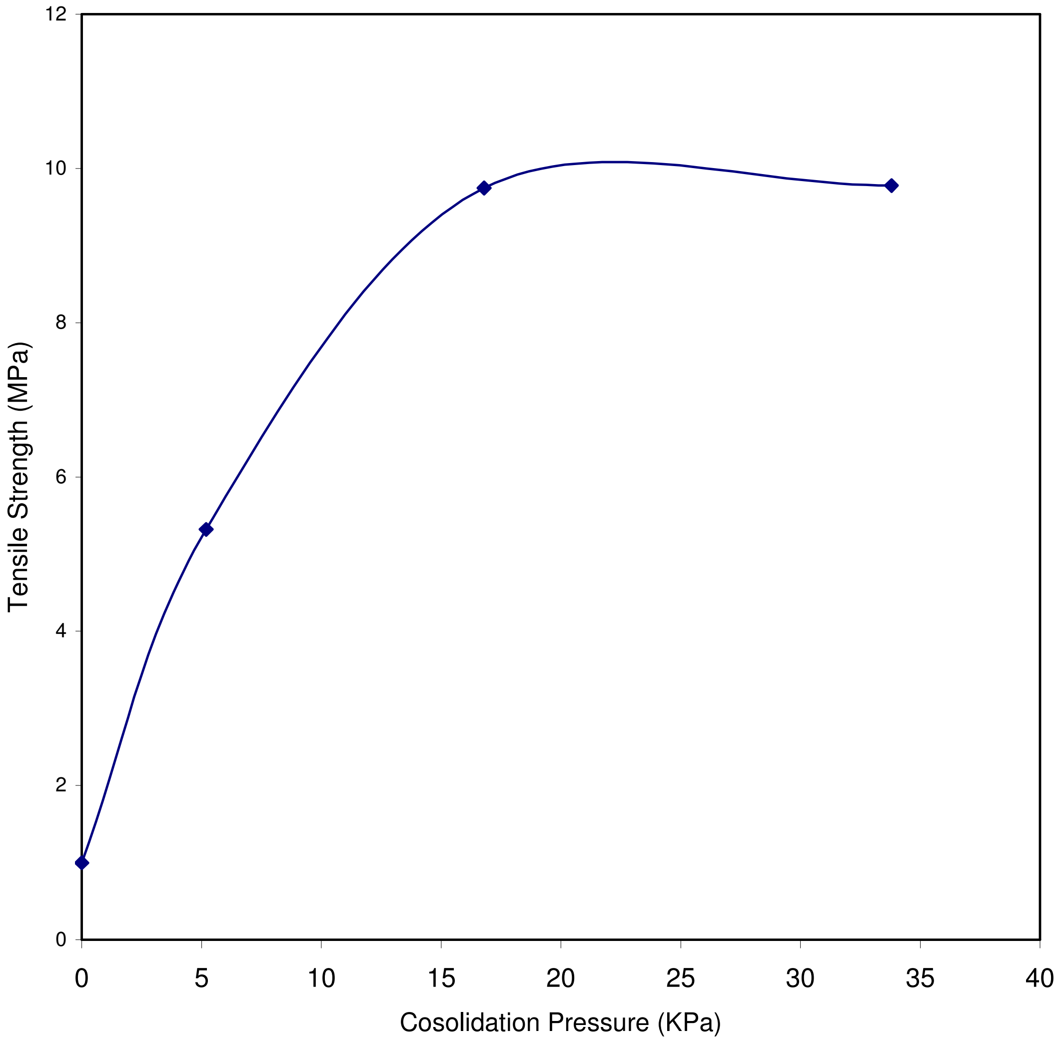


Figure 3.7: Transverse tensile strength vs. low consolidation pressure at constant consolidation temperature

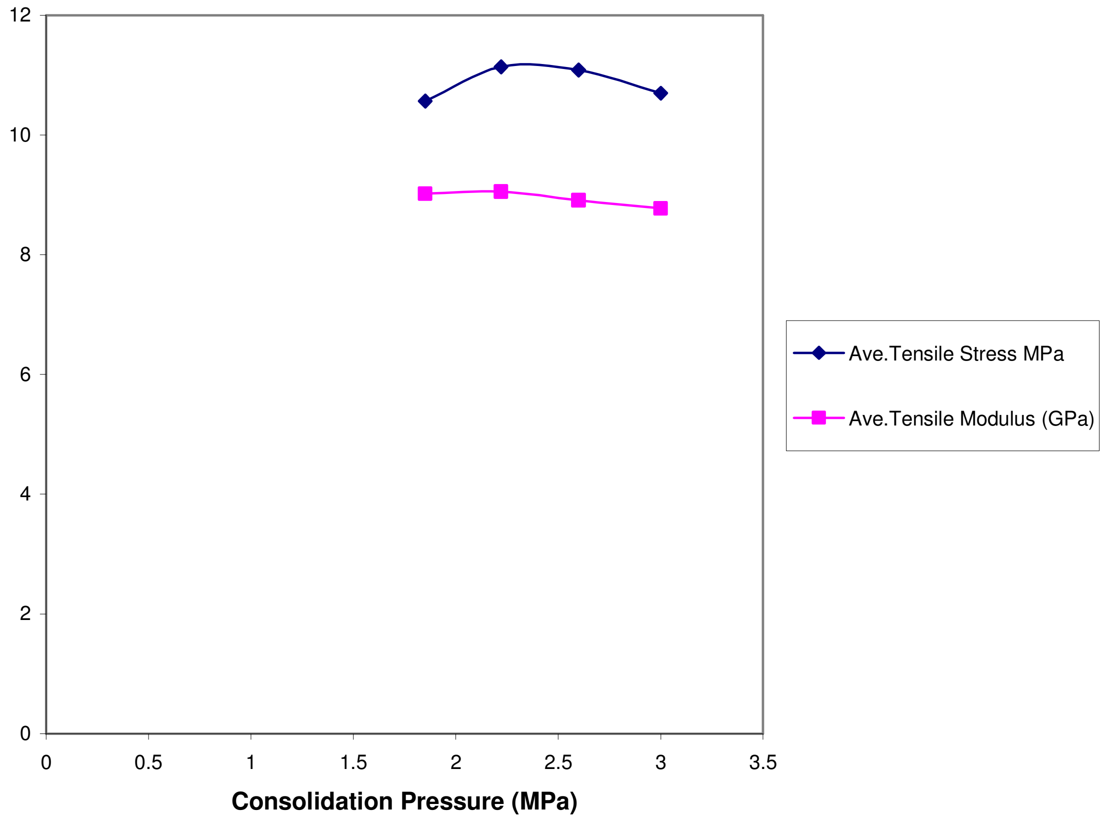


Figure 3.8: Transverse tensile strength and modulus vs. low consolidation pressure at constant consolidation temperature

3.5 Preliminary Design Conclusions

1. The longitudinal tensile strength was rarely affected by the changes in the process temperature. But the transverse tensile strength varied with an increase in the process temperature from 8.5 MPa at 200^0C to an optimum of 12.4 MPa at 280^0C and decreased to 10.3 MPa at 320^0C.

2. Similarly, the longitudinal tensile strength was marginally affected by the changes in the process pressures, but the transverse strength increased with the increase in process pressure from 1 MPa at atmospheric pressure to an optimum of 10 MPa at 34 KPa process pressure. Further increase in the process pressure did not yield any corresponding appreciable increase in strength.

3.6 Pipe Fabrication

The fabrications of the pipes were carried out using the modified filament winder in the composites facility, northwest engineering building, Wits University.

The results obtained from the tensile tests were used in the approximation of the process pressure and temperature. Unlike the inferred optimum process temperature, availability and design constraint limited the process pressure below the optimum.

The glass fibre reinforced polypropylene thermoplastics tape reel was mounted on an improvised shaft in front of the tow guide. The pre-impregnated tape passes through the tow guide and over the infrared heat lamp where it is heated up to 170^0C and aligned at $35^0/-35^0$, $55^0/-55^0$, or 90^0 to the plane of the mandrel as shown in Figures 3.3 - 3.5.

A hand held heat gun with a heat stream of about 260^0C was directed at the nip-point to further heat up the pre-impregnated tape well above its melting point before compaction. An infrared thermometer was used to monitor and maintain the nip-point temperature at 260^0C. The mandrel speed was set at 12rev/min; the carriage was manually driven such that successive tapes lie parallel to each other.

The process was repeated until the mandrel was fully covered and a pipe of one layer made. The tow guide was then adjusted such that the tape meets the mandrel perpendicular to the direction of the first layer to produce a second layer e.g. at (-55^0, 55^0, or as applicable) to the mandrel plane. The entire process was repeated three times to produce a metre long six layer glass fibre reinforced thermoplastics pipes.

Figure 3.9: Pipe production at 35^0 winding angle

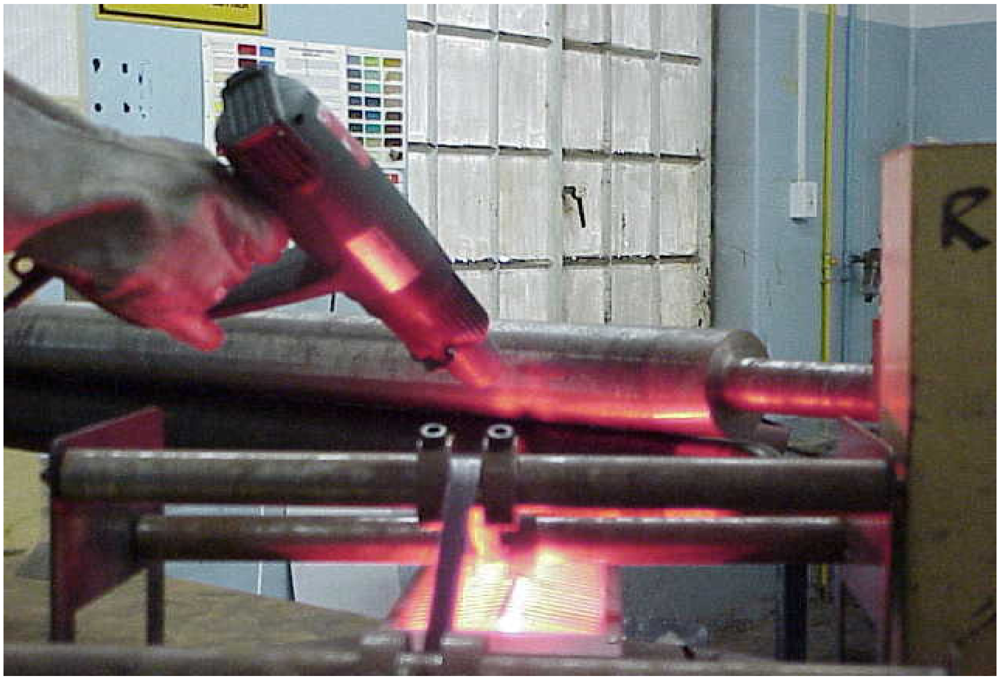


Figure 3.10: Pipe production at 55^0 winding angle

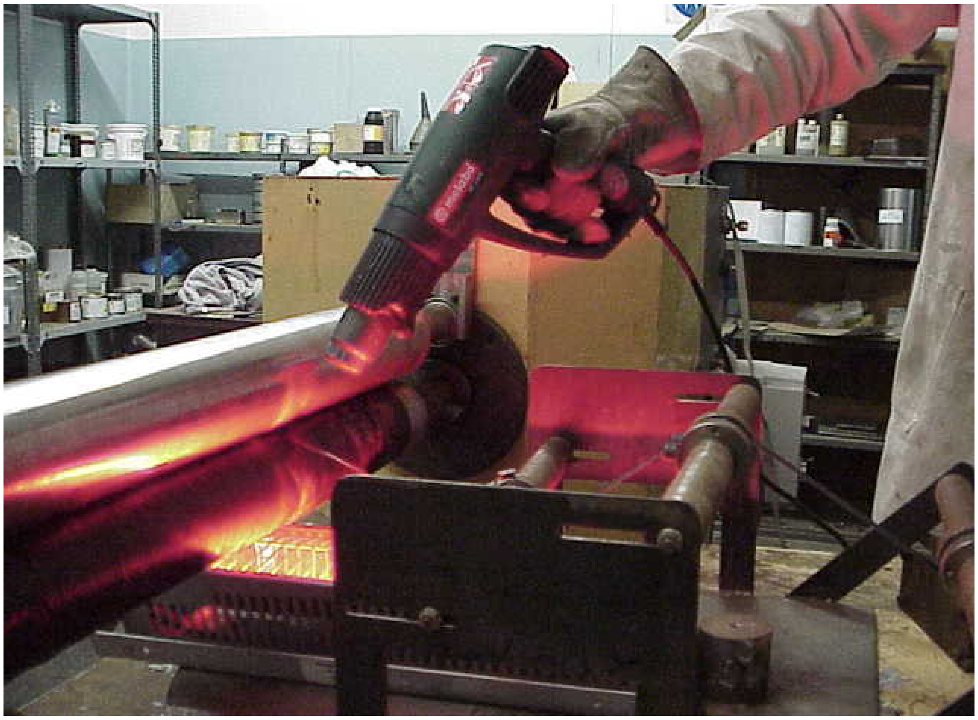


Figure 3.11: Pipe production at 90^0 winding angle

4 TESTING, RESULTS AND DISCUSSION

4.1 Introduction

In order to determine the mechanical properties of the produced pipes, the following tests were carried out on the pipes and test laminates according to the American Standard for Testing and Materials; ASTM D2990, D2292, and the British Standard; BS 5480.

1. Hydrostatic Pressure tests.
2. Apparent tensile Strength of ring or tubular reinforced plastics by split disc method

4.1.1 Failure of Test Pipes

During the burst test process, any pipe that developed a leak, wept, or ruptured was classified as a failed specimen except that the leakage or failure was within one diameter of the end closure in accordance with BS 5480 and ASTM D2290 procedures on pipe burst tests.

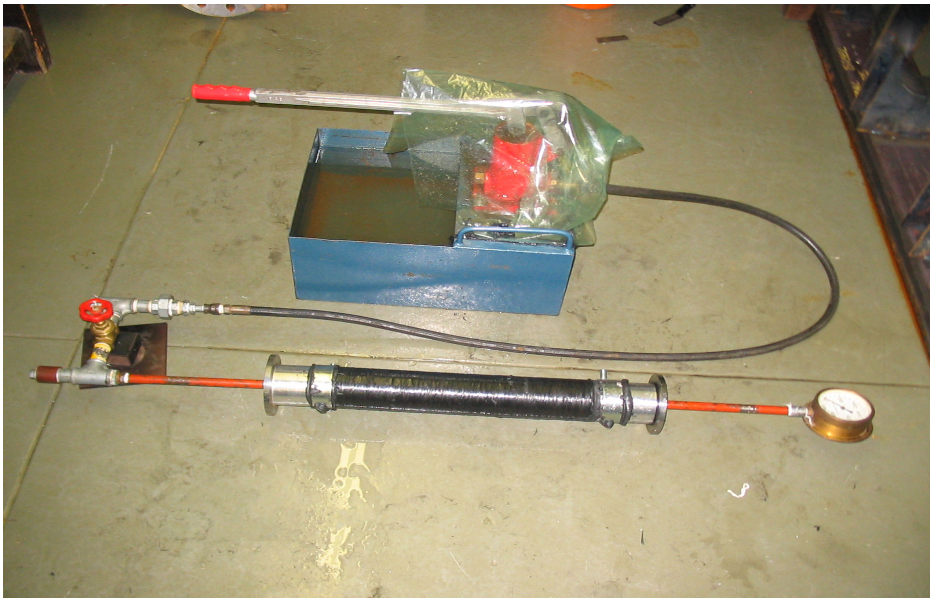


Figure 4.1: Typical set up for the burst test

4.2 Hydrostatic Pressure Test

This was carried out in accordance with ASTM D2292 and BS 5480: 1990, Appendix C. The pipe was sealed at both ends, but axial movement was not restrained. Water was pumped into the pipe using a hand pump increasing the pressure till failure, which must occur within 3 minutes of pumping. Figures 4.1 and 4.2 further illustrate the procedure.

Figure 4.2: Failure of the pipe during burst test

The axial tensile strength of the pipe can be calculated using the following formula [25]:

$\sigma_z = P (D - t) / (4 \times t)$.

where;

σ_z = average axial tensile strength, in Megapascals (MPa)

p = average internal test pressure, in bars,

D = the average outside diameter, in millimetres (mm),

t = the minimum wall thickness, in millimetres (mm),

Using pipe diameter d = 80 mm and pipe wall thickness t = 2.9 mm in the equation above, the average axial tensile strength and the corresponding average test pressure for each pipe specimen is shown in Table 4.1 below.

Therefore, the pipes failed at a pressure range of 2.5 – 3.1 bars in the test specimens used as illustrated in Table 4.1 below.

Table 4.1 Hydrostatic Pressure Test

Specimen no	Average Test Pressure	Average Axial Tensile Strength
	(Bar)	(MPa)
P35	2.83	2.01
P55	2.77	2.02
P90	2.70	2.00

All the pipes failed at about the same pressure within the hydrostatic pressure range 2.5 – 3.1 bar. Considering the type of failure in the pipes, which was a crack perpendicular to the axial direction of the pipes [23], it could be deduced that this resulted in an axial tensile strength of 1.896 MPa minimum and a maximum of 2.096 MPa, Table.4.1. The pipes were likely to have failed by fibre de-bonding, which led to the pipes weeping within the same test pressure range [25].

This mode of failure could be due to water flowing through the pores and voids in the pipe, and subsequently weeping and leaking at the surface as shown in

Figures 4.15 and 4.16. This could also be due to the absence of appreciable chemical bonding between the fibre and the matrix [26].

4.2.1 Circumferential Tensile Strength Using the Split Disc Method

This was similarly carried out according to ASTM D2290: 71, Procedure A. Test rings were cut from different fabricated pipes and tested in the Lloyd tensile testing machine as shown in Figures 4.3- 4.4

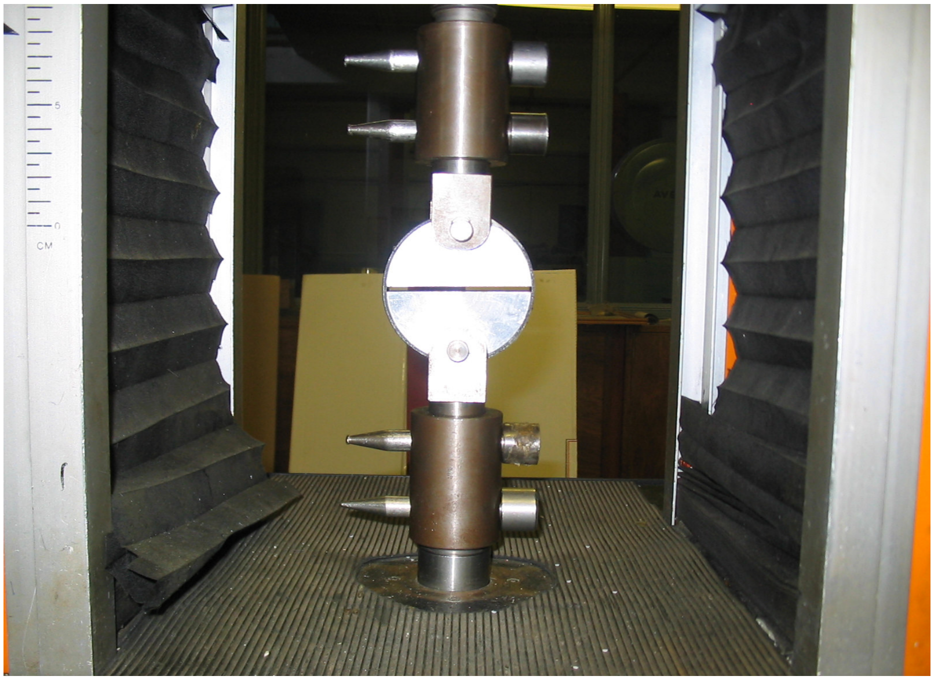


Figure 4.3: Initial circumferential tensile strength using the split disc method

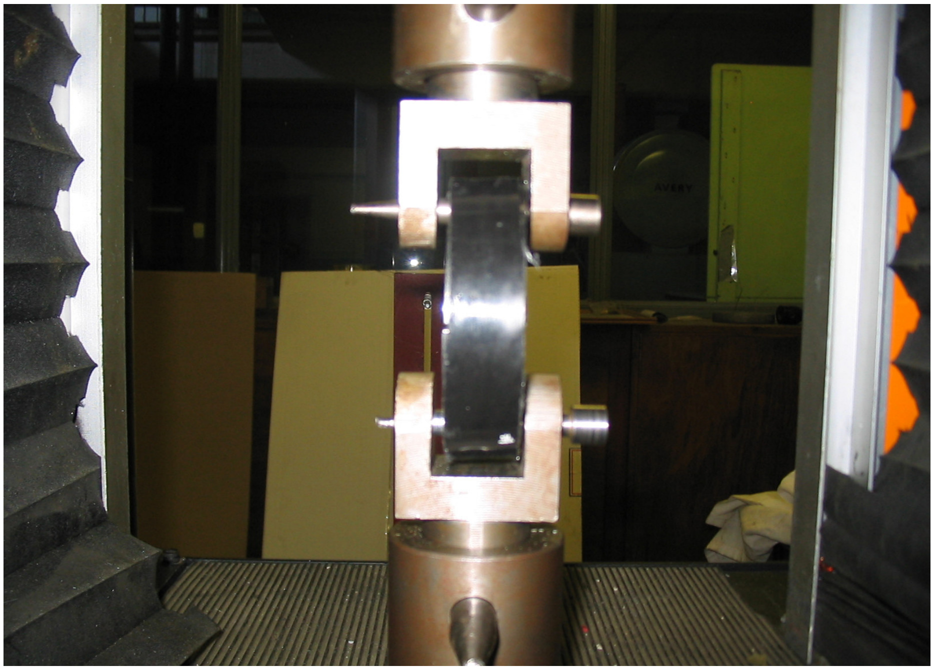


Figure 4.4: Side view of the test ring before failure

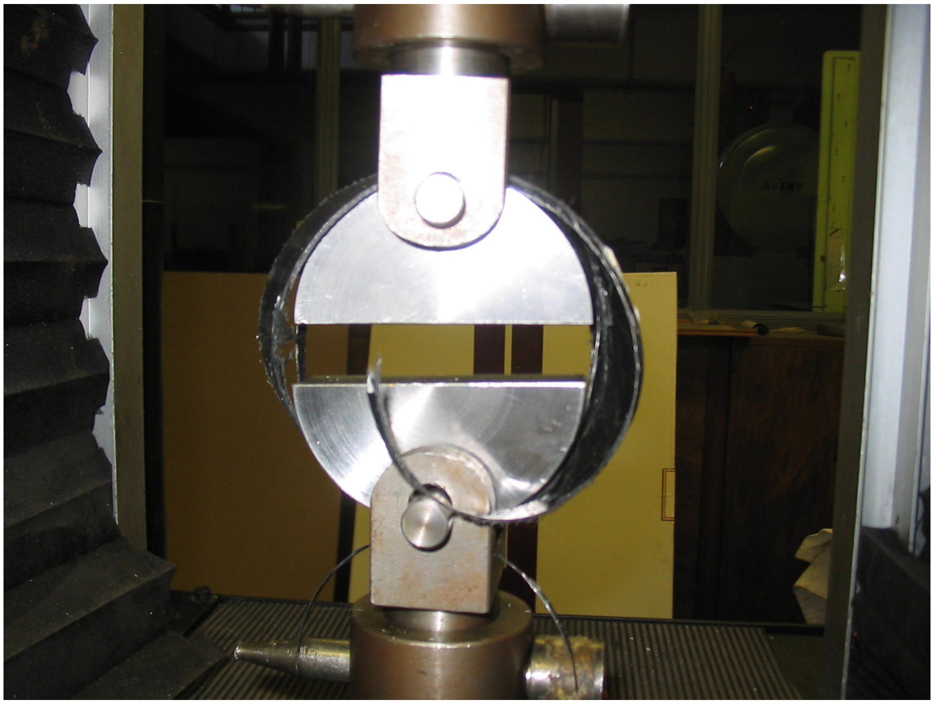


Figure 4.5: Failed test ring during the split disc test

The results followed a slightly different trend from the hydrostatic test. The test specimen pipes fabricated at 90^0 winding angle failed at the highest circumferential strength of 548 MPa, and a lowest circumferential strength of 536 MPa, as shown in Table 4.2.

Table 4.2 Circumferential Tensile Strength by Split Disc Test

Specimen No.	Max. Load	Mean Width	Wall thickness	Winding angle	Circum. Tensile Strength
	(KN)	(mm)	(mm)	(Degree)	(MPa)
S90B1	52.96	16.83	2.92	90	538.83
S90B2	51.92	16.36	2.96	90	536.08
S90B3	54.53	17.01	2.98	90	537.88
S90B4	52.87	16.34	2.95	90	548.41
				Average	540.30
				Std Deviation	4.79

Unlike hydrostatic pressure test, the pipes failed within an apparent circumferential tensile strength range of 536 MPa – 548 MPa, as shown in Table 4.2 above, this can be attributed to the fact that at 90^0, the test is being carried out directly parallel to the direction of fibre orientation.

The discrepancy in the hydrostatic tensile strength and the circumferential tensile strength using split disc methods could be attributed to the fact that in the circumferential tensile strength tests using the split disc method, the reinforcement which is the glass fibre played a major role against the applied load, while in the hydrostatic pressure test, the nature of the failure revealed a transverse crack to the direction of fibre orientation.

The nature of crack initiation at the boundaries of fibres indicates that the fibre to matrix bond strength is very important in trying to achieve a good transverse tensile strength, with the bond strength being determined by the matrix adhesion properties, the fibre sizing and defects (in the form of voids or inclusions) [27].

These cracks would normally be formed in a region of relative high local fibre concentration, where the stress concentrations are accentuated [9], as shown in Figures 4.13 and 4.15.

Hence, the pipes might have failed mainly due to fibre de-bonding of the matrix as shown in Figures 4.6 – 4.8. This is also an indication of the bond strength of the pre-impregnated polypropylene pipes.

4.3. Effect of Consolidation Temperature

From Figure 3.6 the effect of consolidation temperature on the bonding characteristics and the tensile strength of the final product are clearly illustrated. At a constant consolidation pressure, the tensile strength of the laminates increased with an increase in consolidation temperature up to about 280^0C after which the tensile strength decreased with further increase in consolidation temperature.

Increasing the impregnation (or process temperature) comes along with a rise in the mechanical properties and a corresponding reduction in void content. This is due to the fact that higher temperatures result in a lower melt viscosity [9]; this could have resulted in more fibres being encapsulated by the now less viscous matrix, and also the reduction in void content as illustrated in Figures 4.9 - 4.11.

These microstuctural characteristics indicate that a moulding temperature of 200^0C (significantly above the melting temperature of the matrix) under maintained pressure leads to good fibre dispersion, due to the reduced matrix viscosity at a higher temperature, which results in a high level of matrix flow and glass fibre wetting under Darcy’s law [26].

But at temperature higher than 280^0C, the effect of material degradation could have offset the effects of increased fibre encapsulation and reduction in void content, resulting in reduced tensile strength of the laminate.

Thermal degradation of specimen produced at such high temperature ~315 ^{0}C produce lower molecular weight polypropylene chains, which are known to crystallize faster [27]. This is quite in accordance with the tensile strength of the specimens produced at 320^{0}C consolidation temperature.

4.4 Effect of Consolidation Pressure

To be able to effectively investigate the effects of process pressure on the mechanical properties of the produced pipes, two pressure regions were used. These were the lower pressure range (0 – 33KPa) and the upper pressure range (1.85 – 3.0 MPa).

At a constant consolidation temperature, an increase in consolidation pressure resulted in a corresponding increase in the tensile strength of the test laminates in the low pressure experimental range (0 – 33.8 KPa) as shown in Figure 3.7. This again could be due to increased viscous matrix flow, and subsequent encapsulation of the fibres by the matrix, and also, reduction in material void content due to increasing compaction force.

This was evident in the laminates at the datum (or 0 KPa) consolidation pressure; the bottom layers were better bonded and provided better fibre-matrix mixture than the top layers of the same laminate. The slightly higher pressure being applied to the lower layers due to the overlaying weight of upper layers were enough to cause a significant difference in their respective physical bonding characteristics.

This is because at the lower pressure, insufficient consolidation, poor fibre dispersion and poor matrix crystallinity due to incomplete melting of the matrix, resulting from high viscosity and poor impregnation or wetting of the fibres [22]. But at a consolidation pressure higher than 16.8 KPa, an increase in consolidation pressure did not produce any significant increase in the tensile strength of the laminate.

From Tables B4 and B5, in the high pressure (1.85 – 3.0 MPa) consolidated specimens at constant consolidation temperature (280^0C), increase in the consolidation pressures did not result in any appreciable increase in the longitudinal and transverse tensile strength.

At higher pressure, the consolidation quality, fibre dispersion and impregnation or wetting of the fibres was significantly improved, which will yield a material with low void content as shown in Figure 4.14.

But the inherent weak interfacial strength of the glass fibre and the polypropylene matrix will result in wider distribution of fibre matrix bonding, which promotes fibre breaking (as shown in Figure 4.7), thus leading to more rapid degradation of properties [10, 27].

This indicates the dependence of the transverse and longitudinal tensile strength more on the process temperature than process pressure with regards to the fibre/matrix combination and fabrication method employed.

4.5 Tensile Properties

The tensile test results showed that the tensile strength and tensile modulus of the test laminates were greater when tested along the fibre direction than when tested transverse to the direction of the fibre.

From Tables B4 and B5, the maximum tensile strength and modulus of the test laminates along and transverse to the fibre directions regardless of the process pressure and temperature were 595 MPa, 20 GPa and 11MPa, 9 GPa respectively.

This was because, in composites with unidirectional reinforcement, the static strength and modulus in fibre direction are strongly dominated by the properties and content of the fibres. Transversely, matrix properties, details in composite's mesostructure (e.g. voids, fibre misalignments, bundling phenomena, etc.), and the quality of the fibre-matrix-interface are more decisive [9].

4.5.1 Scanning Electron Microscopic (SEM) Investigation

There are various modes of failure of glass fibre reinforced thermoplastic materials. They can fail by matrix rupture, fibre debonding, fibre breakage, or a combination of these. In order to correctly identify the failure modes a JSM840 Scanning Electron Microscope was used to investigate the visual characteristics of the failed samples.

The scanning electron microscopic investigation of the failed glass fibre reinforced polypropylene thermoplastics sample revealed that the modes of failure were both fibre breakage and fibre de-bonding when tested along the fibre direction, but predominantly fibre de-bonding of the glass fibre from the polypropylene matrix regardless of consolidation temperature and pressure when tested transverse to the direction of fibre orientation as shown in Figures 4.6 - 4.8.

The microscopic cross-section view of the laminates also indicated that there were better encapsulation of the fibre by the matrix and less void in laminates compacted at higher temperatures and pressures.

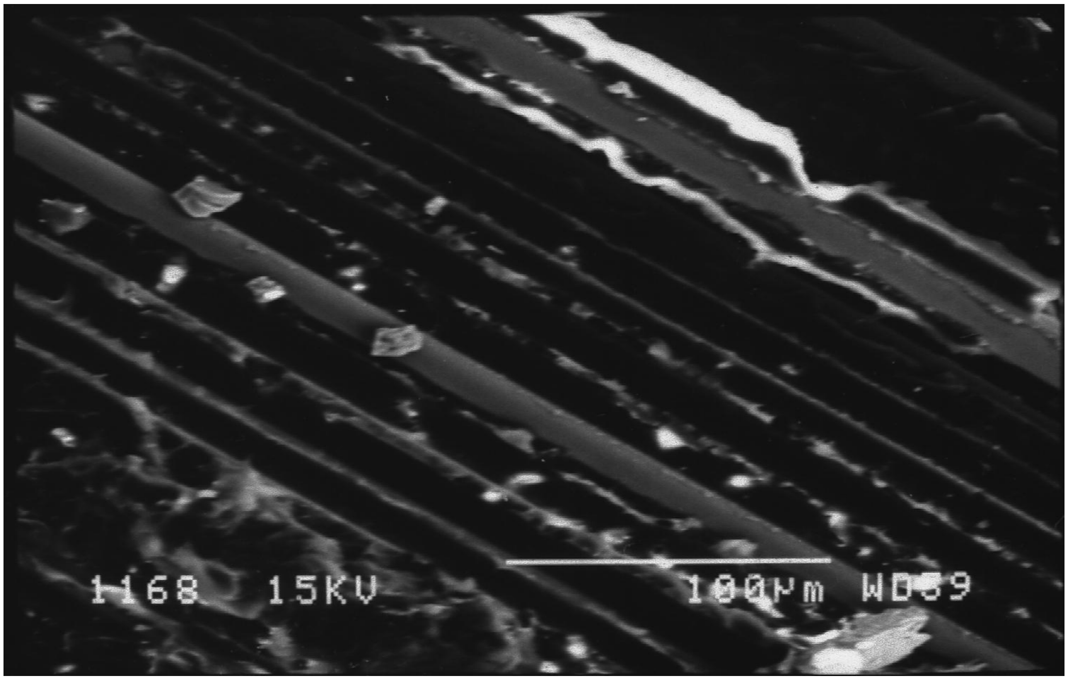


Figure 4.6: SEM image of failed samples tested transverse to fibre direction

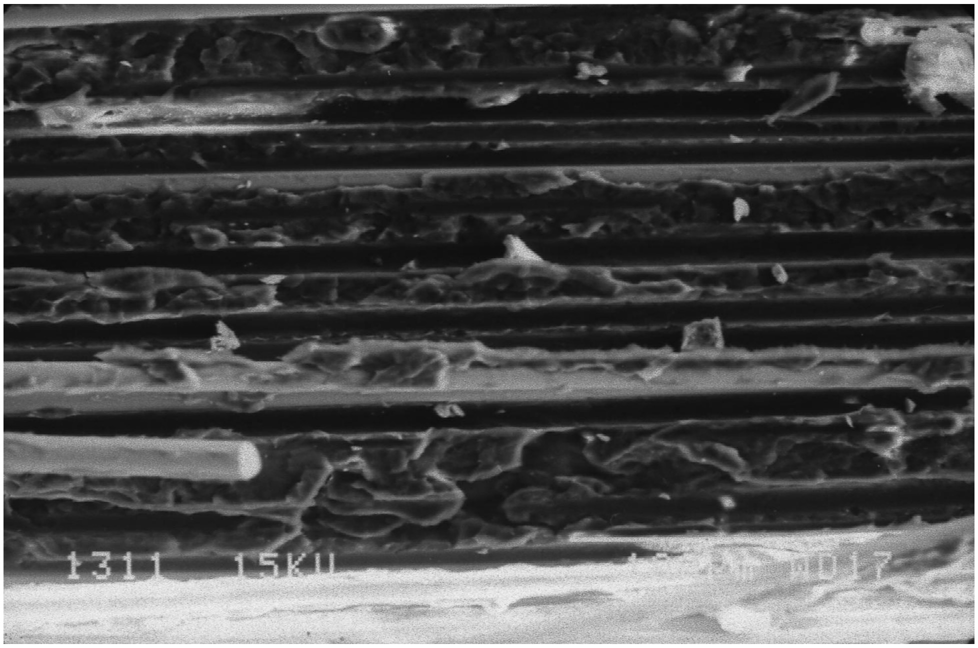


Figure 4.7: SEM image of failed test sample

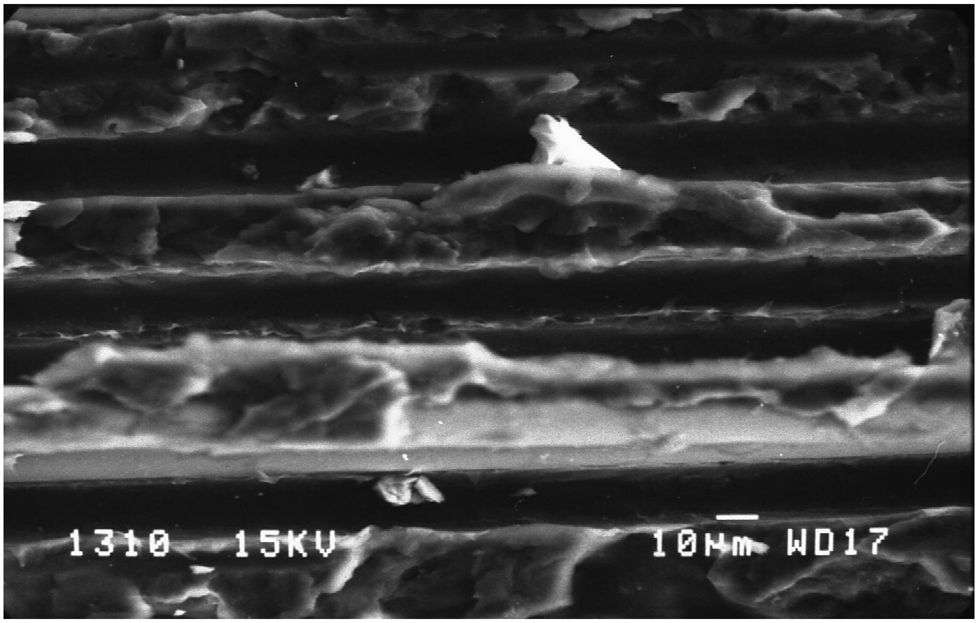


Figure 4.8: SEM image of failed sample at higher resolution

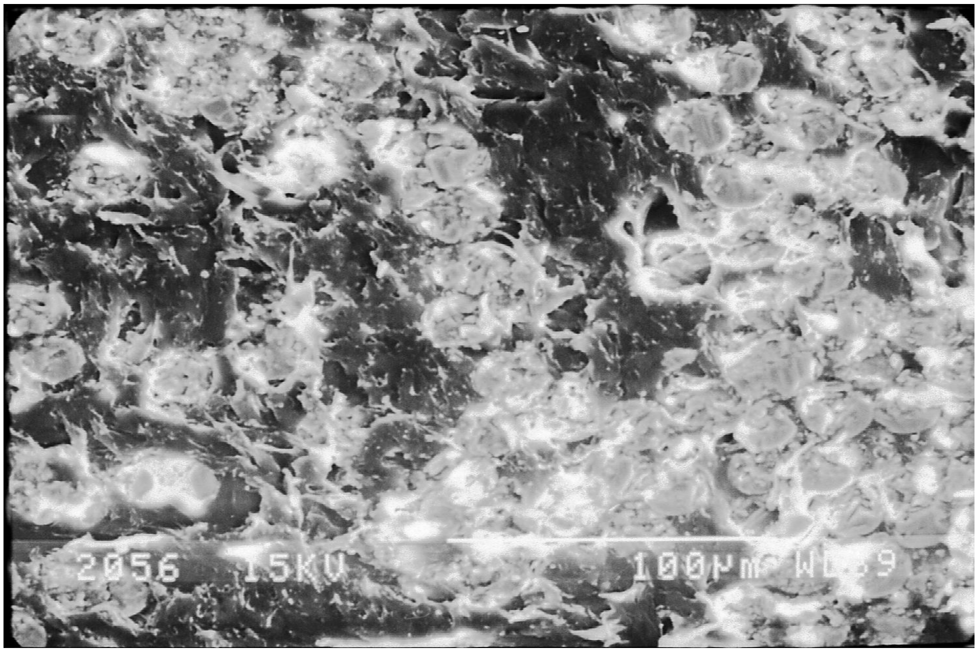


Figure 4.9: X-section SEM image of 200^{0}C consolidation temperature test sample

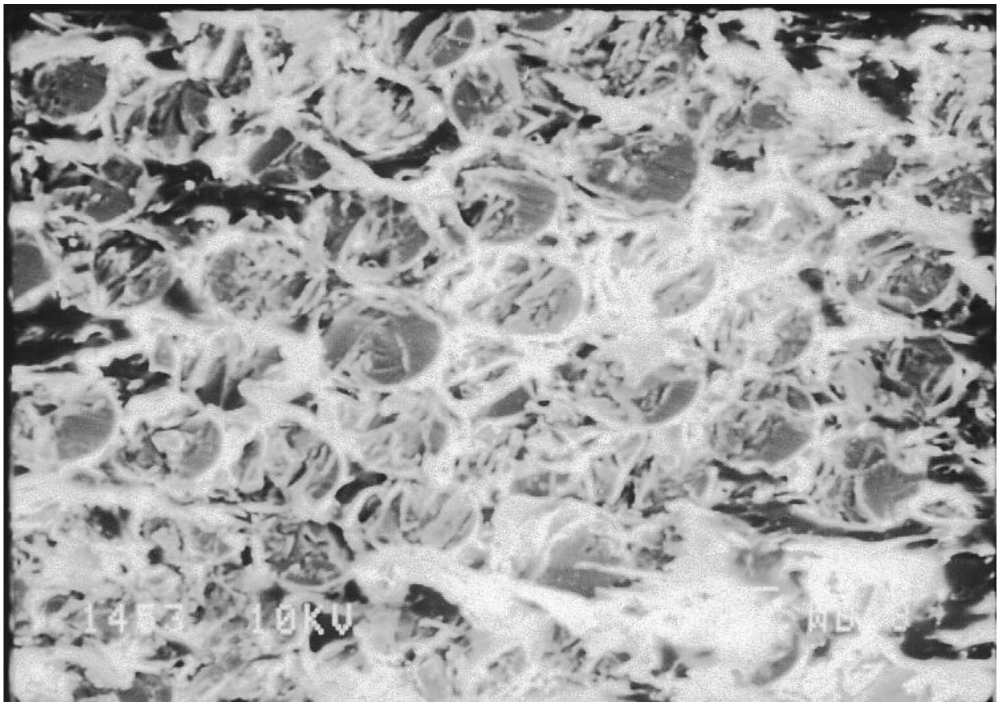


Figure 4.10: X-section SEM image of 280^{0}C consolidation temperature test sample

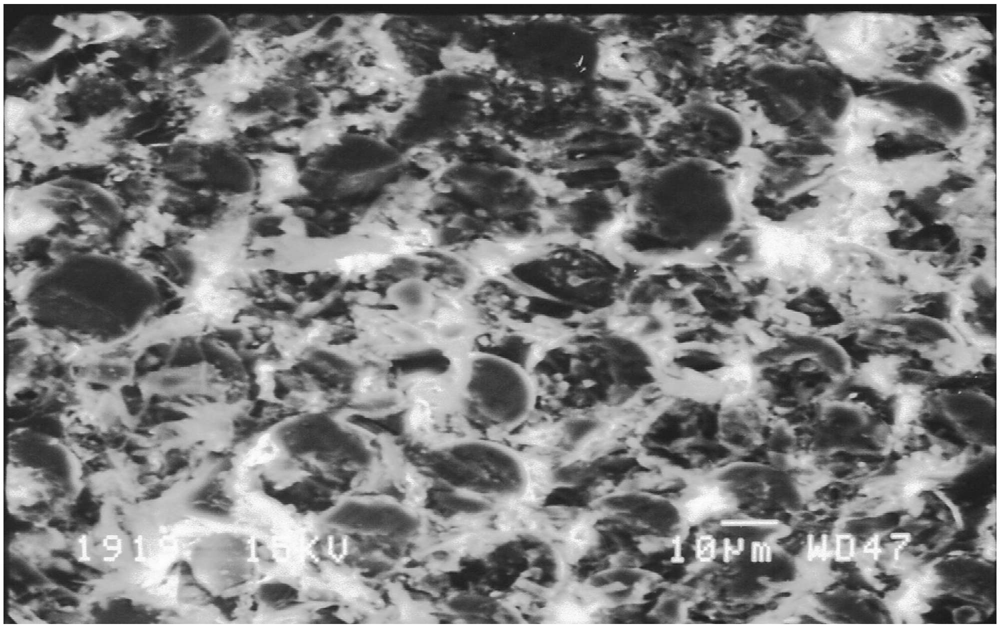


Figure 4.11: X-section SEM image of 320^{0}C consolidation temperature test sample

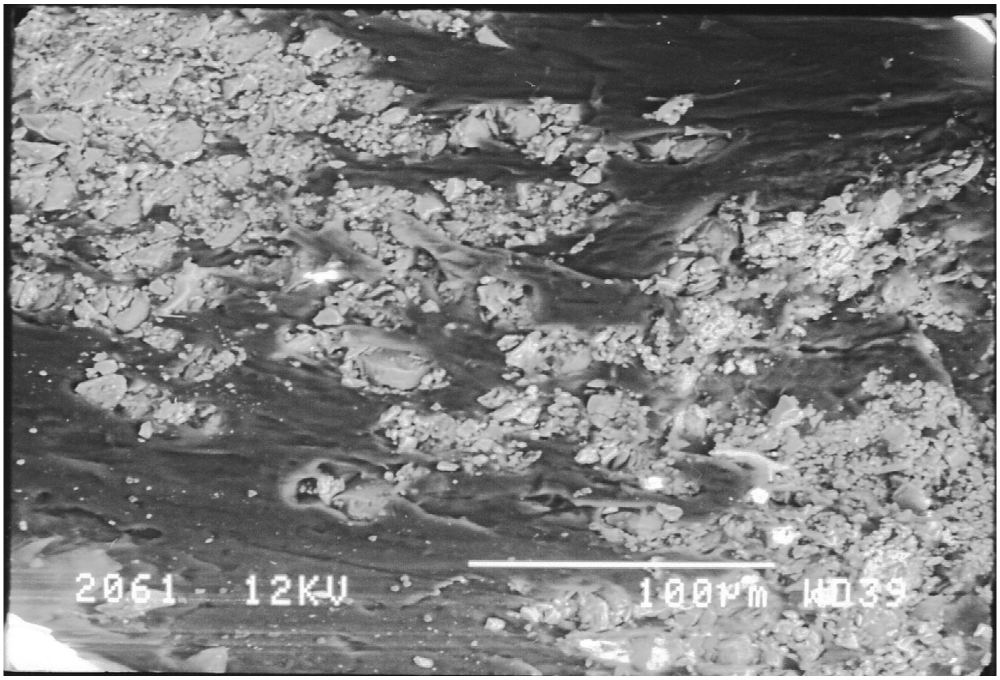


Figure 4.12: X-section SEM image of the virgin pre-impregnated tape

4.5.2 Visual Microscopic Investigation

To further investigate the micro mechanical characteristics of the test laminates and the fabricated pipes, the x-sectional areas of these specimens were also viewed using a visual microscope.

From Figure 4.13, further investigation using the visual microscope also revealed consistent fibre and matrix arrangements in the test laminates compacted at low temperatures and pressures with distinct fibre concentrated and resin rich areas.

The cross-sectional view of some pipes showed good and compact visible fibre/matrix arrangements as shown in Figure 4.14, while some showed production defects such as voids and pores as revealed in Figures 4.15 and 4.16.

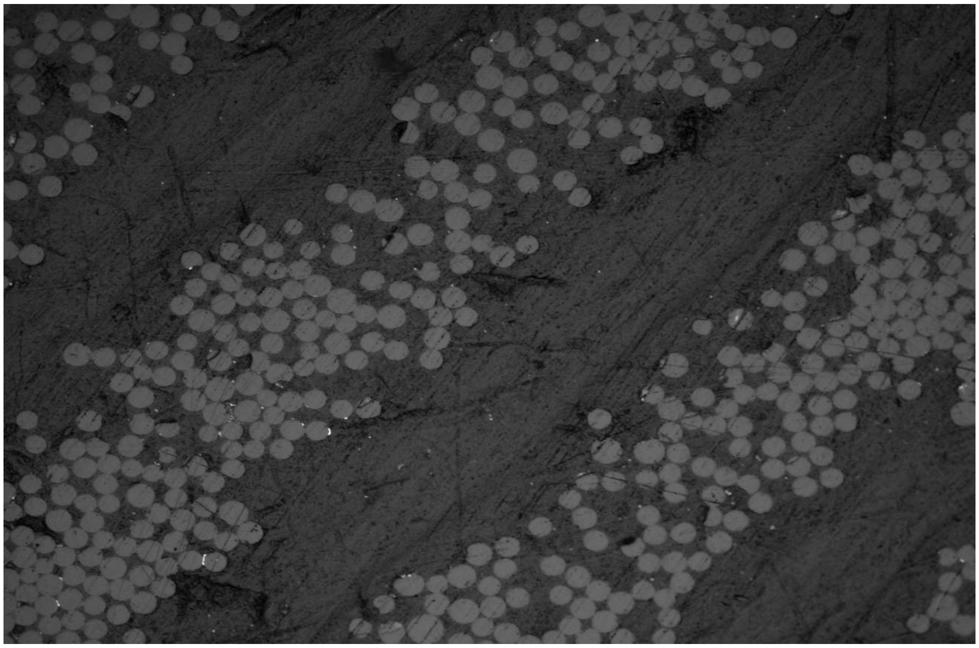


Figure 4.13: Visual Microscopic X- section view of a typical low temperature and pressure test laminate

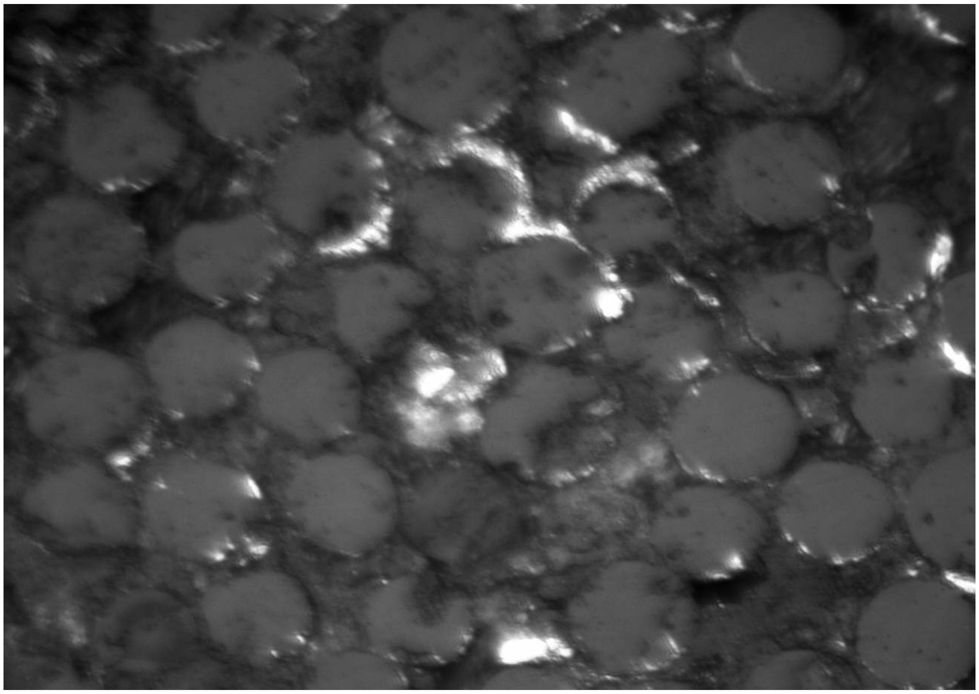


Figure 4.14: Closer X-section view of the fibre/matrix distribution in the high pressure test laminate

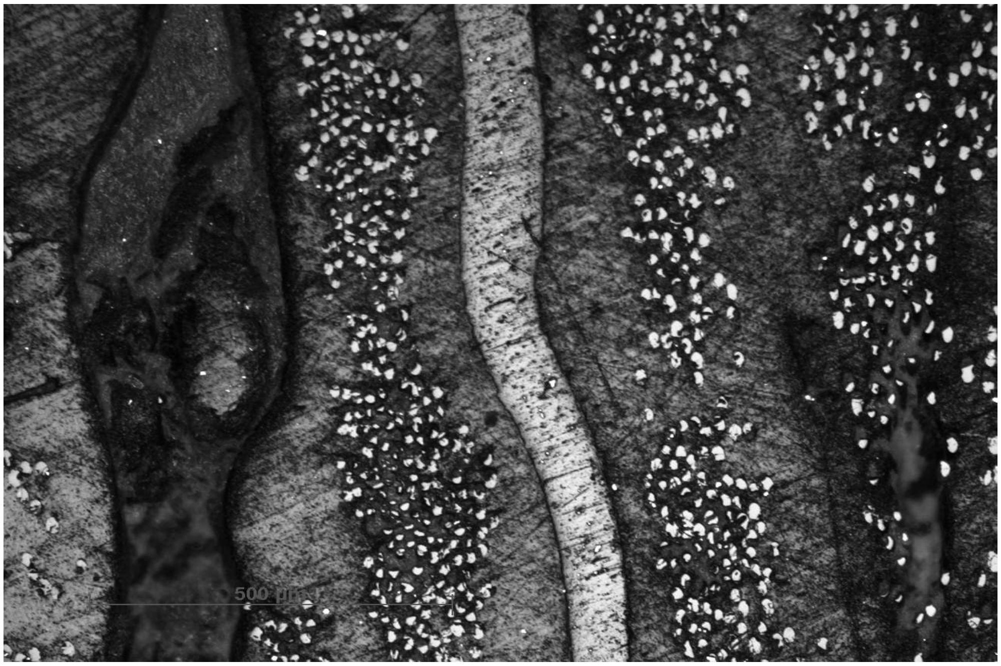


Figure 4.15: Visual microscopic X- section of a sample of the produced pipes

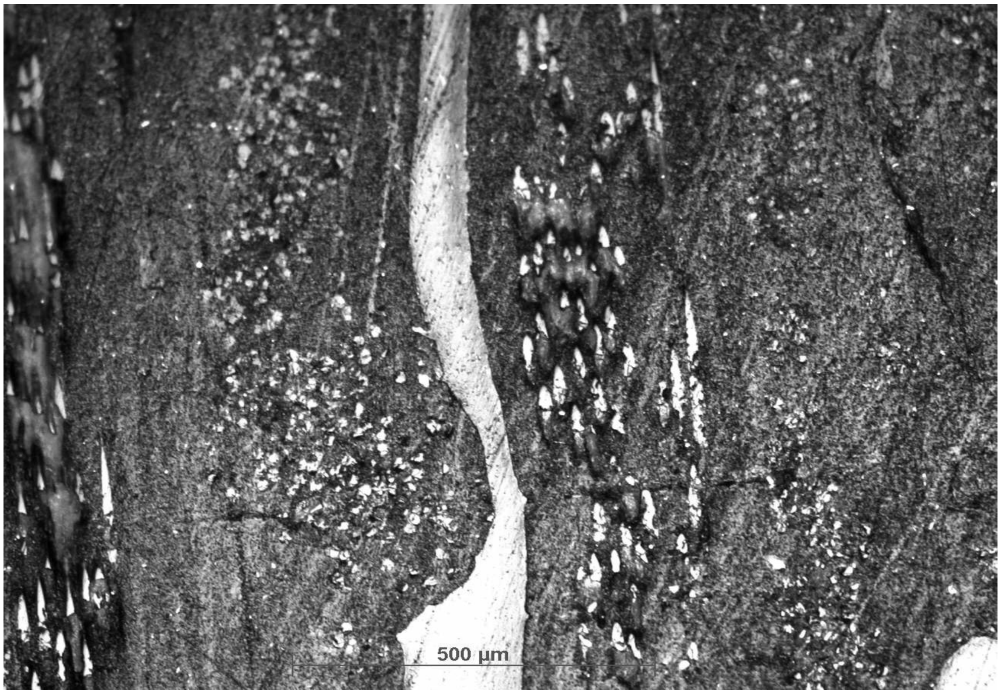


Figure 4.16: Pores in the pipes revealed by the visual microscope

4.5.3 Scanning / Visual Microscopic Investigations

The scanning electron microscopic investigation was used to determine the microscopic bonding characteristics of the pre-impregnated glass fibre polypropylene laminates. From Figures 4.6 - 4.9, the failed materials of the test laminates showed very little bonding between the fibre and the matrix.

Analysis of these failed samples indicated that failure occurred mainly by fibre de-bonding as shown in Figures 4.6 - 4.8, though there were few cases of fibre breakage and laminate debonding as shown in Figure 4.7.

Also, many of the fibres though largely encapsulated by the matrix at the optimum consolidation temperature with regards to the chosen consolidation pressure were found to be almost clean and have very few matrix materials adhered to them after failure suggesting that the fibre were "ripped off" the matrix at failure. This could largely be as a result of poor matrix - fibre adhesion due to the absence of a strong mechanical bond between the fibre and matrix.

From Figures 4.12, 4.15, and 4.16, the scanning electron and visual microscopic investigations of the virgin pre-impregnated glass fibre polypropylene tape and the subsequent fabricated pipes revealed voids and non-uniform fibre-matrix distribution, in practice; voids contain trapped air and can be sources of weakness and defects in the final products.

Any material, which contains a geometrical discontinuity, will experience an increase in stress in the vicinity of the discontinuity. This stress concentration effect is caused by the re- distribution of the lines of force transmission through the material when they encounter the discontinuity. Causes of stress concentration include holes (including void, pores, and inclusions), notches, keyways, corners, etc. [26].

The effect of voids on strength is much greater, particularly for the matrix-dominated strengths. Apart from the directly detrimental effect of voids in leaving parts of the fibres unsupported and in allowing for crack initiation adjacent to the fibres, they also act as stress raisers in the matrix. The actual void content will depend on a number of factors including the manufacturing process used for the pre-impregnated tapes and the pipes, and also the matrix types [27].

4.6 Hydrostatic Design Strength

Estimation 1

The design pressure P was evaluated as follows:

$P = (Q_c \times 2 \times t) / (d \times k)$ ……………………………………… (1)

Where;

Q_c = Circumferential tensile strength,

t = mean thickness of pipe,

d = average outside pipe diameter,

k = design factor.

Therefore,

$P = (540 \times 2 \times 3) / (80 \times 6)$

P = 6.75 MPa

P = 67.5 Bar

67.5 Bar is the hydrostatic design pressure at 23^0C.

The hydrostatic design pressure at other operating temperatures can be computed using the pressure derating factors in a similar manner.

Table 4.3: First Hydrostatic Design Pressure Using Pressure Derating Factor

Water temperature (^{0}C)	Factor applied to maximum working pressure at 20^0C (i.e. pressure rating)	Design Pressure rating (MPa)
0 – 20	1	6.75
20 – 25	0.8	5.4
25 – 30	0.63	4.25
30 – 35	0.5	3.375
35 – 40	0.4	2.7
40 – 45	0.32	2.16
45 - 60	0.25	1.688

Estimation 2

Since polypropylene has glass transition temperature that is lower than room temperature, it tends to creep under applied pressure [22]. Therefore, a hydrostatic design basis is required to incorporate the effect of creep and other essential engineering factors in the design factor k above.

These design factors are categorised into five groups as follows [28]:

k_1 = factors relating to method of manufacture

k_2 = factors relating to long term behaviour (creep)

k_3 = factors relating to heat distortion temperature

k_4 = factors relating to cyclic loading

k_5 = factors relating to curing procedure [28].

For fibre-reinforced polypropylene as used in this research, these factors were deduced as follows:

$k_1 = 1.5$, $k_2 = 1.2$ with a liner or $k_2 = 2.0$ if no liner is used, $k_3 = 1.25$, $k_4 = 12.0$, and $k_5 = 1.4$ [28]

Therefore,

$k = 1.5 \times 2.0 \times 1.25 \times 2.0 \times 1.4 = 10.5$

Using this in equation I above,

$P = (540 \times 2 \times 3) / (80 \times 10.5)$

$P = 4.05$ MPa

$P = 40.5$ Bar

The hydrostatic design pressure at other operating temperatures can also be computed using the pressure derating factors in a similar manner.

Table 4.4: Second Hydrostatic Design Pressure Using Pressure Derating Factor

Water temperature (^{0}C)	Factor applied to maximum working pressure at 20^{0}C (i.e. pressure rating)	Design Pressure rating (MPa)
0 – 20	1	4.05
20 – 25	0.8	3.24
25 – 30	0.63	2.55
30 – 35	0.5	2.025
35 – 40	0.4	1.62
40 – 45	0.32	1.296
45 - 60	0.25	1.013

Estimation 3

Designing with a thermoplastic liner gives:

k = 1.5 x 1.2 x 1.25 x 2 x 1.4 = 6.3

Hence, deign pressure P:

P = (540 x 2 x 3) / (80 x 6.3)

P = 6.429 MPa

P = 64.29 Bar.

Similarly, the hydrostatic design pressure at other operating temperatures can be computed using the pressure derating factors.

Table 4.5: Third Hydrostatic Design Pressure Using Pressure Derating Factor

Water temperature (^{0}C)	Factor applied to maximum working pressure at 20^{0}C (i.e. pressure rating)	Design Pressure rating (MPa)
0 – 20	1	6.429
20 – 25	0.8	5.143
25 – 30	0.63	4.05
30 – 35	0.5	3.215
35 – 40	0.4	2.572
40 – 45	0.32	2.057
45 - 60	0.25	1.607

4.7 Economic Analyses

The four major thermoplastics – polyethylene, polypropylene, PVC, and polystyrene – together represent over 85% by volume of world plastics consumption. Because of their lower prices, these commodity materials dominate the market, and in any material selection procedure there are good economic reasons for considering them first before turning to the more expensive engineering plastics [10]. Polypropylene apart from its high stiffness is the lightest and cheapest in the olefin family.

The cost of a composite material has two parts: the cost of its constituent materials; and the cost of compounding them (that is, incorporating one of the constituents (fibres) into the other (polymer matrix)).

Suppose the cost per unit mass of fibre is C_f and that of the matrix is C_m and the cost of incorporating per unit mass of composite is C_i. The total cost per unit mass of the composite is C and the cost for mass m is then given by [10],

$$mC = C_f M_f + C_m M_m + C_i M.$$

Using the above method on the cost per meter length of fibre reinforced polypropylene pipes with respect to general South African market price [7, 29], and that produced in the research work.

4.7.1 South African market

Cost per meter length of glass/polypropylene + polypropylene liner = **R450.00**

Refer to Appendix E.

4.7.2 Analysis 1

Pipes produced at Wits Laboratory:

A meter of the fabricated pipe weighed 0.73kg.

Hence the followings can be deduced.

Fibre and matrix;

Cost of 20 Kg pre-impregnated tape = R5400.00

Transport cost (Germany to RSA) = R2820.00

Total cost = R8220.00

Total cost of pre-impregnated tape per Kg = R 411.00

Cost of pre-impregnated tape/meter length (Cf + Cm) i.e. (411x 0.73) = R 300.3

Cost of pre-impregnated tape/meter length CL16 (300.3 x 0.24) = R 72.07

Production;

The production time of a meter length pipe was 4 hours.

Therefore,

Filament winder

2.2 KW at R0.3508 x 4 hrs = R3.087

Infra red lamp,

1.5 KW at R0.3508 x 4 hrs = R2.105

Heat gun,

1.6 KW at R0.3508 x 4 hrs = R2.245

Fixed cost = R 25.00

Labour cost = R 72.00

Total cost of production per meter length (Ci) = R 104.44

Total cost of pipe per meter length (Cf + Cm + Ci) = R 176.51

If a liner is used then;

Cost of liner per meter length = R174.00

Total cost of pipe per meter length (Cf + Cm + Ci) = R 350.51

4.7.3 Analysis 2

Assuming the research production of the pipes was carried out in the country of origin of the raw material (Germany), or carried out in South Africa without transportation cost. Then;

Cost of 20 Kg pre-impregnated tape = R5400.00

Total cost of pre-impregnated tape per Kg = R 270.00
Cost of pre-impregnated tape/meter length (Cf + Cm) i.e. (270x 0.73) = R 197.1
Cost of pre-impregnated tape/meter length CL16 i.e. (197.1 x 0.24) = R 47.3

Production;
The production time of a meter length pipe was 4 hours.
Therefore,
Filament winder
2.2 KW at R0.3508 x 4 hrs = R 3.087
Infra red lamp,
1.5 KW at R0.3508 x 4 hrs = R 2.105

Heat gun,
1.6 KW at R0.3508 x 4 hrs = R 2.245
Fixed cost = R 25.00
Labour cost = R 72.00
Total cost of production per meter length (Ci) = R 104.44
Total cost of pipe per meter length (Cf + Cm + Ci) = R 151.70

If a liner is used then;
Cost of liner per meter length = R174.00
Total cost of pipe per meter length (Cf + Cm + Ci) = R325.70

The costs of a meter length of the pipe produced in Wits University Laboratory were R175.51 and R350.51 without and with a liner respectively with the cost of airfreight from the place of origin of the Glass fibre pre-impregnated polypropylene tape (Germany) included. But the costs were R 151.7 and
R 325.7 per meter length without and with a liner respectively if the cost of transport (air freight) was not considered.

If these probable price indicators are compared with the average price in the South African market [7, 29], there is a seemingly possible economic advantage in the mass production of these pipes in South Africa as illustrated in Figure 4.17.

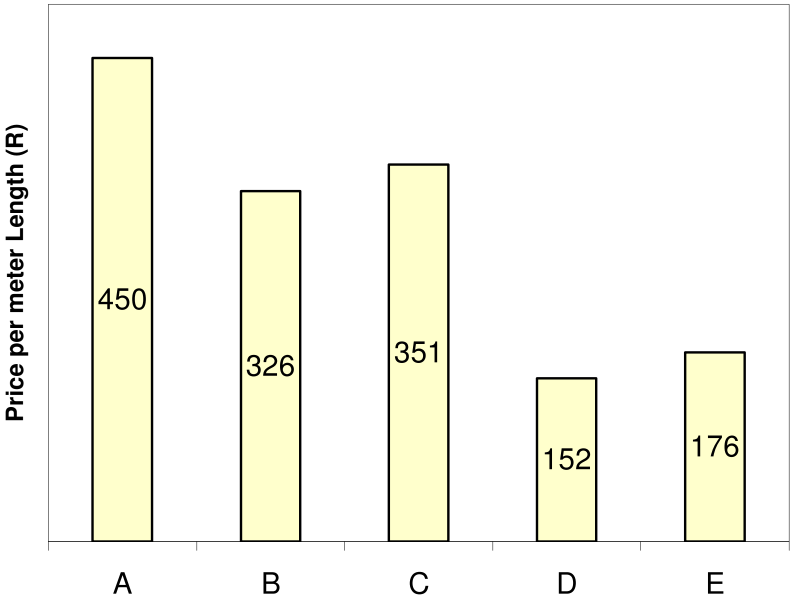


Figure 4.17: Comparison of the cost of the fabricated pipe with the South African market

Where:

A = SA Market

B = Wits Lab (Liner without Transport)

C = Wits Lab (Liner with Transport)

D = Wits Lab (No liner, without Transport)

E = Wits Lab (No liner with Transport)

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions were made in the investigation of the effects of process pressure and temperature on the mechanical properties of glass fibre reinforced polypropylene test laminates and fabricated pipes. Conclusion was also made on the economic practicability of the chosen raw materials, and method of production.

5.1.1 Effect of Temperature

Increase in process temperature resulted in increase in the strength of the produced pipe up to an optimum of 280^0C after which further increase led to lower strength in the pipes.

5.1.2 Effect of Pressure

Process pressure also had a significant effect on the test laminates and fabricated pipe.

The tensile strength of the test laminates increased with the increase in the compaction pressure to an optimum pressure of 20 KPa. An increase in the compaction pressure even up to 3 MPa did not give any appreciable corresponding increase in the tensile strength.

Hence, within the experimental limits, a minimal compaction pressure of
20 KPa is sufficient for the process if the compaction temperature could be maintained at 280^0C.

5.1.3 Tensile Properties

The tensile strength and modulus of the test laminates were greater when tested along the direction of fibre reinforcement than in the transverse direction.

5.1.4 Hydrostatic Pressure and Pressure Class

The fabricated pipes in this research could be categorized as class 49
depending on the temperature of the fluid it will convey [29].
The mode of failure of the pipe i.e. by weeping during the hydrostatic pressure test indicated that perhaps the porosity of the virgin tape and the produced pipe might be too high to allow for compact conveyance of the intended fluids (domestic and industrial applications).

5.1.5 Optimum Production Parameters

Considering the experimental set up and procedure, the optimum production parameters could be conveniently assumed as:

Process Pressure, 20 KPa
Process Temperature, 280^0C
Ambient Temperature, 23^0C

5.1.6 Economic Analysis

Considering the analysed South African markets prices and the corresponding Wits laboratory fabrication cost prices as shown in Figure 4.17. The choice of raw materials and production process could be harnessed to a level of economic advantage.

5.2 Recommendation

1. Using a very high process pressure did not yield a justifiable enhancement in mechanical properties of the test laminates. Therefore, 20 KPa and 280^0C compacting pressure and temperature, respectively are recommended for similar production processes.

2. It is recommended that protective liner/s be used before winding the Pre-impregnated glass fibre reinforced polypropylene tapes on the mandrel. This is an effective way to prevent premature weeping/leaking, thereby increasing the hydrostatic pressure capacity of the pipe.

3. Further research is recommended to explore other economic methods of producing glass fibre reinforced polypropylene plastic pipes.
   However, the use of appropriate liners should be able to prevent weeping (and leakage) and other forms of premature failures as shown in Figure 4.2. And this could further increase the hydrostatic design pressure of the pipe from class 49 to 55 [30].
   Therefore, the possible use of a combination of polypropylene liner and vinyl ester (or polyester) fibre glass reinforcement should also be investigated.

4. Likewise, it is also recommended that further studies/research be carried out on the technical and economic possibilities of locally produced glass fibre reinforced polypropylene pre- impregnated glass tapes in South Africa.

APPENDIX A

MATERIAL PROPERTIES, FABRICATION HEAT SOURCES AND METHODS

Table A1: Fibre Deployment Methods [4]

Thermoset Filament Winding	**Thermoplastic Filament Winding**	**Thermoplastic Filament placement**
Geodesic path only	Geodesic or non-geodesic path	Geodesic or non-geodesic path
Convex surfaces	Convex or concave surfaces	
Autoclave curing	In-Situ consolidation	In-Situ consolidation
Endless fibre	Endless fibre	Start and stop fibres
Winding angle 15 to 90^{O}	Winding angle 0 to 90^{O}	Ply angle 0 to 90^{O}. Angle –ply laminates without fibre crossing

Table A2: Comparison of Possible Heat Sources [4]

	Hot Gas Torch	**Laser Beam**	**Infrared Light**
Energy Efficiency	--	+	+/-
Response Time	--	+	+/-
Size	++	-	+/-
Weight	++	-	+
Price	+/_	-	+

Where + and – indicate pros and cons respectively.

Table A3: Properties of Plytron GN638T Glass Fibre Polypropylene Pre-Impregnated tape

Property		0°	[-45,0,45,90]s	[(0.90)]s
Density	g/cm^3	1,48	1,5	1,5
Tensile strength	MPa	720(1) 11(2)	178	360
Tensile modulus	GPa	28	11	16
Strain to break	%	1,9	2,4	2,5
Flexural strength	MPa	436(1)	229(3) 110(4)	300(1) 254(2)
Flexural modulus	GPa	21(1)	8,4(3) 3(4)	16,8(1) 8,4(2)
Isopescu shear strength	MPa	19(1)		
Shear modulus (G12)	GPa	1,39		
Boeing compression strength	MPa	366		
Fracture toughness (G10)	kJ/m^2	0,94		
Falling weight impact (3mm)	J		50	
Izod impact (notched)				
at 23°C		383		
at –30°C		425		
HDT at 1.8 MPa	°C	156		
HDT at 0.45 MPa	°C	164		
Vicat B (50°C)		134		
UL 94 Rating		HB		
Oxygen index			19,5	
Thermal expansion coefficient	10^{-6}/K	7(1) 90(2)	20(3) 20(4)	20(1) 20(3)

[1] Surface Fibres in 0° direction

[2] Surface Fibres in 90° direction

[3] Fibres are 2nd ply in from surface

[4] Fibres are 4th ply in from surface

Glass content	%w/w	60
Glass content	cc	38
Ply thickness	mm	0,25
Width	mm	14

APPENDIX B

DETERMINATION OF TENSILE PROPERTIES

BS 2782: Part 10: Method 1003: 1977

TEST TEMPERATURE: 23^0C

The tensile strength at maximum force σ,

$\sigma = F/ (b \times h)$

Where,

σ = is the stress at maximum force, in MegaPascals (MPa);

F = maximum tensile force, in Newton (N);

b = the mean initial width of the test specimen, in millimetres (mm);

h = the mean initial thickness of the test specimen, in millimetres (mm).

The Tensile Modulus $E_{T,}$

$E_T = (L_0R/A_0) \times \Delta F_1/ \Delta Z_1$

Where

E_T = the initial tangent modulus of elasticity, in MegaPascals (MPa);

ΔF_1 = the change in force in Newton (N);

L_0 = the gauge length of the extensometer, in millimetres (mm);

R = the magnification ratio of the extensometer;

A_0 = the initial cross-sectional area of the test specimen (mm^2);

ΔZ_1= is the change in apparent extension, in millimetres (mm).

Table B1: Longitudinal Properties at 2.2 MPa Consolidation Pressure

Consolidation Temperature = 200^{0}C				
Sample No	Min width	Mean Thickness	Load	Tensile Strength
	(mm)	(mm)	(KN)	(MPa)
LA1	10.78	2.79	18.02	599.15
LA2	10.52	2.77	17.45	598.83
LA3	10.75	2.81	17.91	592.90
LA4	10.81	2.84	17.92	583.71
LA5	10.62	2.82	17.58	587.01
			Average	592.32
			Std. Dev.	6.92
Consolidation Temperature = 240^{0}C				
Sample No	Min width	Mean Thickness	Load	Tensile Strength
	(mm)	(mm)	(KN)	(MPa)
LB1	10.77	2.83	18.07	592.87
LB2	10.76	2.88	18.41	594.09
LB3	10.76	2.84	17.86	584.46
LB4	10.79	2.82	18.33	602.41
LB5	10.75	2.81	18.08	598.53
			Average	594.47
			Std. Dev.	6.76
Consolidation Temperature = 280^{0}C				
Sample No	Min width	Mean Thickness	Load	Tensile Strength
	(mm)	(mm)	(KN)	(MPa)
LC1	10.66	2.74	17.49	598.80
LC2	10.71	2.78	17.73	595.49
LC3	10.72	2.76	17.59	594.51
LC4	10.74	2.78	17.64	590.81
LC5	10.68	2.84	18.04	594.77
			Average	594.88
			Std. Dev.	2.85
Consolidation Temperature = 320^{0}C				
Sample No	Min width	Mean Thickness	Load	Tensile Strength
	(mm)	(mm)	(KN)	(MPa)
LD1	10.71	2.74	17.43	593.96
LD2	10.74	2.76	17.64	595.09
LD3	10.72	2.75	17.39	589.89
LD4	10.73	2.74	17.45	593.53
LD5	10.75	2.75	17.56	593.10
			Average	593.30
			Std. Dev.	1.99

Table B2: Transverse Properties at 2.2 MPa Consolidation Pressure

Consolidation Temperature = 200^{0}C					
Sample No	Width	Thickness	Consolidation Temp.	Load	Tensile Stress
	(mm)	(mm)	(^{0}C)	(N)	(MPa)
TA1	11.24	2.81	200	237.24	7.51
TA2	10.53	2.76	200	291.1	10.02
TA3	10.37	2.74	200	263.2	9.26
TA4	10.49	2.78	200	223.5	7.66
TA5	11.02	2.83	200	256.6	8.23
				Average	8.54
				Std. Dev.	1.08
Consolidation Temperature = 240^{0}C					
Sample No	Width	Thickness	Consolidation Temp.	Load	Tensile Stress
	(mm)	(mm)	(^{0}C)	(N)	(MPa)
TB1	10.86	2.56	240	301.4	10.84
TB2	10.76	2.65	240	244.8	8.59
TB3	10.59	2.62	240	291.2	10.50
TB4	10.88	2.59	240	228.5	8.11
TB5	10.67	2.61	240	221.6	7.96
				Average	9.20
				Std. Dev.	1.37
Consolidation Temperature = 280^{0}C					
Sample No	Width	Thickness	Consolidation Temp.	Load	Tensile Stress
	(mm)	(mm)	(^{0}C)	(N)	(MPa)
TC1	10.8	2.71	280	324.1	11.07
TC2	9.91	2.66	280	364.4	13.82
TC3	10.05	2.65	280	352.5	13.24
TC4	10.76	2.71	280	329.7	11.31
TC5	10.54	2.68	280	358.3	12.68
				Average	12.42
				Std. Dev.	1.20
Consolidation Temperature = 320^{0}C					
Sample No	Width	Thickness	Consolidation Temp.	Load	Tensile Stress
	(mm)	(mm)	(^{0}C)	(N)	(MPa)
TD1	10.03	2.68	320	265.5	9.88
TD2	10.08	2.54	320	237.4	9.27
TD3	10.58	2.55	320	275.2	10.20
TD4	10.17	2.58	320	286.8	10.93
TD5	10.35	2.61	320	302.7	11.21
				Average	10.30
				Std. Dev.	0.78

Table B3: Transverse Properties at Varying Low Pressures and 280^0C Consolidation Temperature

Consolidation Pressure = 0 KPa				
Sample No	Width	Thickness	Load	Tensile Stress
	(mm)	(mm)	(N)	(MPa)
A1	11.24	2.81	26.1	0.83
A2	10.53	2.76	31.1	1.07
A3	10.37	2.74	28.2	0.99
A4	10.49	2.78	33.5	1.15
A5	11.02	2.83	29.6	0.95
			Average	0.99
			Std. Dev.	0.122
Consolidation Pressure = 5.2 KPa				
Sample No	Width	Thickness	Load	Tensile Stress
	(mm)	(mm)	(N)	(MPa)
B1	10.86	2.56	186.4	6.71
B2	10.76	2.65	117.8	4.13
B3	10.59	2.62	155.7	5.61
B4	10.88	2.59	124.2	4.41
B5	10.67	2.61	159.8	5.74
			Average	5.32
			Std. Dev.	1.05
Consolidation Pressure = 16.8 KPa				
Sample No	Width	Thickness	Load	Tensile Stress
	(mm)	(mm)	(N)	(MPa)
C1	10.8	2.71	294.3	10.06
C2	9.91	2.66	264.2	10.02
C3	10.05	2.65	282.6	10.61
C4	10.76	2.71	279.9	9.60
C5	10.54	2.68	238.3	8.44
			Average	9.75
			Std. Dev.	0.82
Consolidation Pressure = 33.8 KPa				
Sample No	Width	Thickness	Load	Tensile Stress
	(mm)	(mm)	(N)	(MPa)
D1	10.03	2.68	268.5	9.99
D2	10.08	2.54	237.9	9.29
D3	10.58	2.55	279.4	10.36
D4	10.17	2.58	286.9	10.93
D5	10.35	2.61	224.7	8.32
			Average	9.78
			Std. Dev.	1.01

Table B4: Transverse Properties at Varying High Pressures and 280^0C Consolidation Temperature

Consolidation Pressure = 1.85MPa

Sample No	Min width	Min.Thickness	Load	Tensile Stress	Tensile Modulus
	(mm)	(mm)	(N)	(MPa)	(GPa)
THPA1	10.83	2.83	324.33	10.58	8.97
THPA2	10.92	2.81	328.56	10.71	8.99
THPA3	10.65	2.85	356.95	11.76	9.53
THPA4	11.12	2.79	301.75	9.73	8.72
THPA5	10.96	2.82	311.39	10.08	8.89
			Average	10.57	9.02
			Std. Dev.	0.77	0.30

Consolidation Pressure = 2.22MPa

Sample No	Min width	Min.Thickness	Load	Tensile Stress	Tensile Modulus
	(mm)	(mm)	(N)	(MPa)	(GPa)
THPB1	10.88	2.81	337.88	11.05	8.94
THPB2	10.69	2.78	369.54	12.44	9.33
THPB3	10.76	2.75	334.79	11.31	9.18
THPB4	10.93	2.79	326.31	10.70	8.92
THPB5	10.97	2.76	308.55	10.19	8.90
			Average	11.14	9.05
			Std. Dev.	0.84	0.19

Consolidation Pressure = 2.6MPa

Sample No	Min width	Min.Thickness	Load	Tensile Stress	Tensile Modulus
	(mm)	(mm)	(N)	(MPa)	(GPa)
THPC1	10.98	2.75	331.86	10.99	8.87
THPC2	10.75	2.79	337.27	11.25	9.01
THPC3	10.8	2.79	338.84	11.25	9.00
THPC4	10.74	2.78	330.91	11.08	8.99
THPC5	10.81	2.77	325.48	10.87	8.69
			Average	11.08	8.91
			Std. Dev.	0.16	0.14

Consolidation Pressure = 3.0MPa

Sample No	Min width	Min.Thickness	Load	Tensile Stress	Tensile Modulus
	(mm)	(mm)	(N)	(MPa)	(GPa)
THPD1	10.89	2.69	328.92	11.23	8.84
THPD2	10.89	2.72	323.77	10.93	8.81
THPD3	10.78	2.75	309.83	10.45	8.80
THPD4	10.81	2.73	311.54	10.56	8.82
THPD5	10.85	2.71	303.28	10.31	8.59
			Average	10.70	8.77
			Std. Dev.	0.38	0.10

Table B5: Longitudinal Properties at 280^{0}C Consolidation Temperature

Consolidation Pressure = 1.85MPa					
Sample No	Min width	Mean Thickness	Load	Tensile Strength	Tensile Modulus
	(mm)	(mm)	(KN)	(MPa)	(GPa)
LHPA1	10.89	2.82	18.18	591.99	19.64
LHPA2	10.59	2.81	17.86	600.18	20.05
LHPA3	10.78	2.85	17.95	584.25	19.59
LHPA4	10.84	2.79	18.19	601.45	20.18
LHPA5	10.58	2.81	17.64	593.34	19.74
			Average	594.24	19.84
			Std. Dev.	6.94	0.26
Consolidation Pressure = 2.22MPa					
Sample No	Min width	Mean Thickness	Load	Tensile Strength	Tensile Modulus
	(mm)	(mm)	(KN)	(MPa)	(GPa)
LHPB1	10.98	2.81	17.97	582.42	20.00
LHPB2	10.96	2.78	18.24	598.65	20.06
LHPB3	10.78	2.75	17.79	600.10	20.18
LHPB4	10.91	2.79	18.13	595.62	20.01
LHPB5	10.99	2.76	17.88	589.47	19.57
			Average	593.25	19.97
			Std. Dev.	7.30	0.23
Consolidation Pressure = 2.6MPa					
Sample No	Min width	Mean Thickness	Load	Tensile Strength	Tensile Modulus
	(mm)	(mm)	(KN)	(MPa)	(GPa)
LHPC1	10.68	2.78	17.48	588.74	19.78
LHPC2	10.73	2.79	17.72	591.92	20.02
LHPC3	10.78	2.73	17.48	593.96	20.03
LHPC4	10.74	2.78	18.02	603.54	20.12
LHPC5	10.81	2.76	17.94	601.30	20.12
			Average	595.89	20.01
			Std. Dev.	6.29	0.14
Consolidation Pressure = 3.0MPa					
Sample No	Min width	Mean Thickness	Load	Tensile Strength	Tensile Modulus
	(mm)	(mm)	(KN)	(MPa)	(GPa)
LHPD1	10.69	2.69	17.33	602.66	20.00
LHPD2	10.77	2.75	17.47	589.85	19.68
LHPD3	10.68	2.74	17.39	594.26	19.98
LHPD4	10.71	2.72	17.15	588.72	19.73
LHPD5	10.73	2.7	16.98	586.10	19.72
			Average	592.32	19.82
			Std. Dev.	6.49	0.16

APPENDIX C

DETERMINATION OF HYDROSTATIC PRESSURE

ASTM Designation: D 2992 – 71

TEST TEMPERATURE: 23^0C

Hydrostatic Pressure

During the hydrostatic pressure test, the pipe failed by weeping/burst perpendicular to the 90^0 wound fibre orientation or lateral to the pipe axis. Therefore, relationship between stress and pressure shall be determined by using the ISO formula for axial stress as follows.

The hydrostatic pressure in the axial direction $\sigma_{z,}$
$\sigma_z = P (D – t)/4t$
Where:
σ_z = the hydrostatic pressure in MPa,
P = the internal pressure, in bars,
D = the average outside diameter, in millimetres (mm),
t = the minimum wall thickness, in millimetres (mm),

Table C1: Hydrostatic Pressure Test

Sample No	Test Pressure	Mean Internal Diameter	Wall Thickness	Winding Angle	Axial Tensile Strength
	(Bar)	(mm)	(mm)	(Degree)	(MPa)
P35A	2.6	80	2.84	35	1.90
P35B	2.8	80	2.85	35	2.04
P35C	3.1	80	2.93	35	2.09
				Average	2.01
				Std Deviation	0.15
Sample No	Test Pressure	Mean Internal Diameter	Wall Thickness	Winding Angle	Axial Tensile Strength
	(Bar)	(mm)	(mm)	(Degree)	(MPa)
P55A	2.8	80	2.81	55	2.06
P55B	2.6	80	2.78	55	1.94
P55C	2.9	80	2.91	55	2.10
				Average	2.02
				Std Deviation	0.07
Sample No	Test Pressure	Mean Internal Diameter	Wall Thickness	Winding Angle	Axial Tensile Strength
	(Bar)	(mm)	(mm)	(Degree)	(MPa)
P90A	2.5	80	2.62	90	1.97
P90B	2.7	80	2.86	90	1.96
P90C	2.9	80	2.89	90	2.08
				Average	2.00
				Std Deviation	0.07

APPENDIX D

APPARENT TENSILE STRENGTH OF RING OR TUBULAR PLASTICS AND REINFORCED PLASTICS BY SPLIT DISK METHOD

ASTM Designation D 2290 - 71

TEST TEMPERATURE: 23^0C

The apparent tensile strength (at yield or rupture, or both) of the pipe $\sigma_{\theta,}$

$\sigma_\theta = P_\theta / 2A_{min}$

Where:
σ_θ = apparent yield or ultimate tensile stress of the specimen, in MegaPascals (MPa),

P_θ = the maximum load/ or breaking load, in Newton (N),

A_{min} = the minimum cross-sectional area of the two measurements, d x b, in $mm^{2,}$

d = thickness at minimum area, millimetres, (mm),

b = width at minimum area, millimetres (mm),

APPENDIX E

BUDGET QUOTATION – PP/GRP & HDPE/GRPM PIPE

SOURCE: FIBER-WOUND SA (PTY) LTD.

DATE: DECEMBER 2005

1. Scope of Work

Manufacture, supply, and delivery of 90 OD PP/GRP & HDPE/GRP piping, generally in accordance with Fibre-Wound standard manufacturing procedures.

2. Budget Price

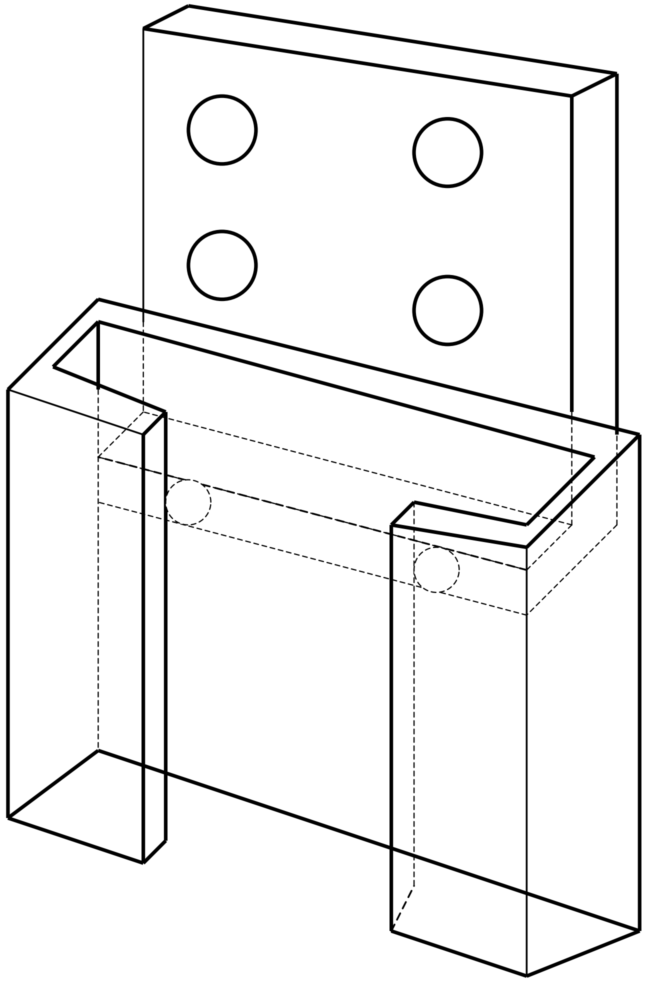
2.1.	90 OD PP/GRP Reinforced CL 16 pipe 5m length	-	R2150.00
2.2.	90 OD Straight Polypropylene CL 16 pipe 5m length	-	R 870.00
2.3.	90 OD HDPE/GRP Reinforced CL 16 pipe 5m length	-	R2150.00
2.2.	90 OD Straight HDPE CL 16 pipe 5m length	-	R 870.00

Therefore,

Price per meter length:

2.1.	90 OD PP/GRP Reinforced CL 16 pipe 1m length	-	R 430.00
2.2.	90 OD Straight Polypropylene CL 16 pipe 1m length	-	R 174.00
2.3.	90 OD HDPE/GRP Reinforced CL 16 pipe 1m length	-	R 430.00
2.2.	90 OD Straight HDPE CL 16 pipe 1m length	-	R 174.00

APPENDIX F: FILAMENT WINDER MODIFCATION DRAWINGS

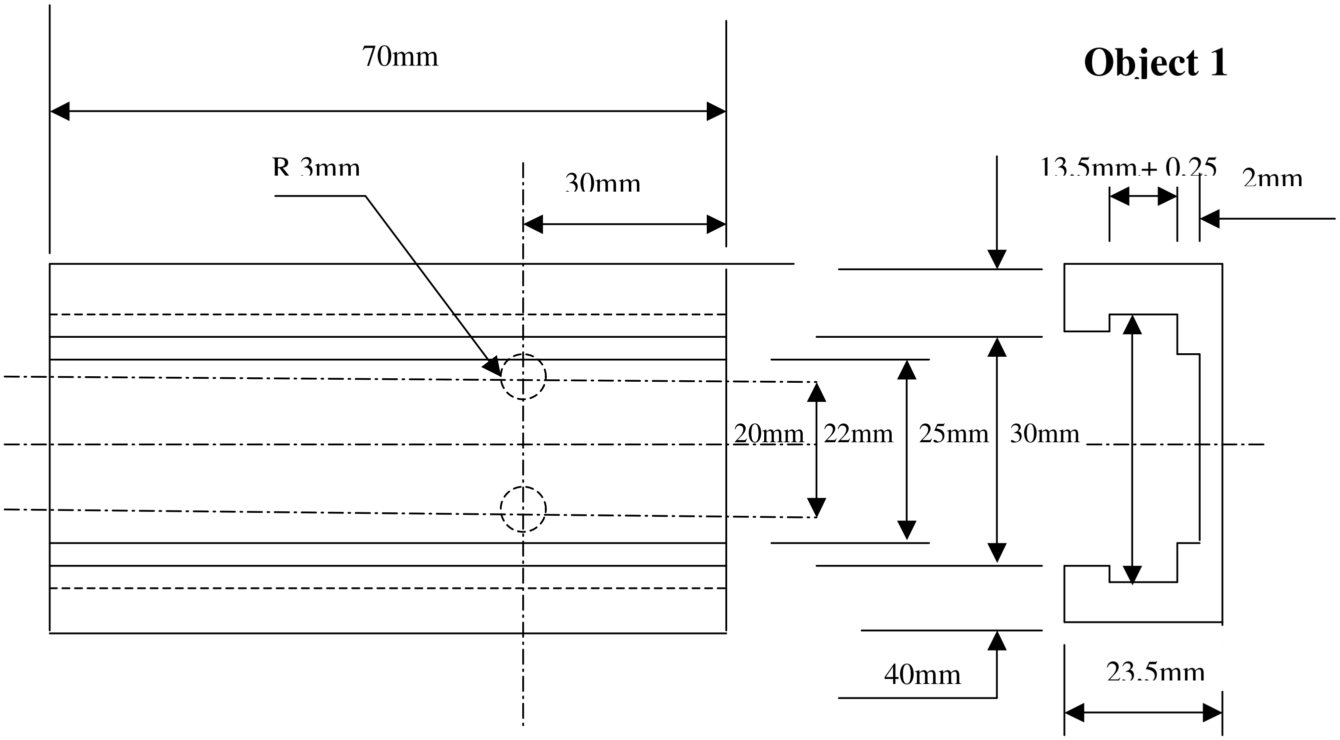


OBJECT : Assembled Roller Groove

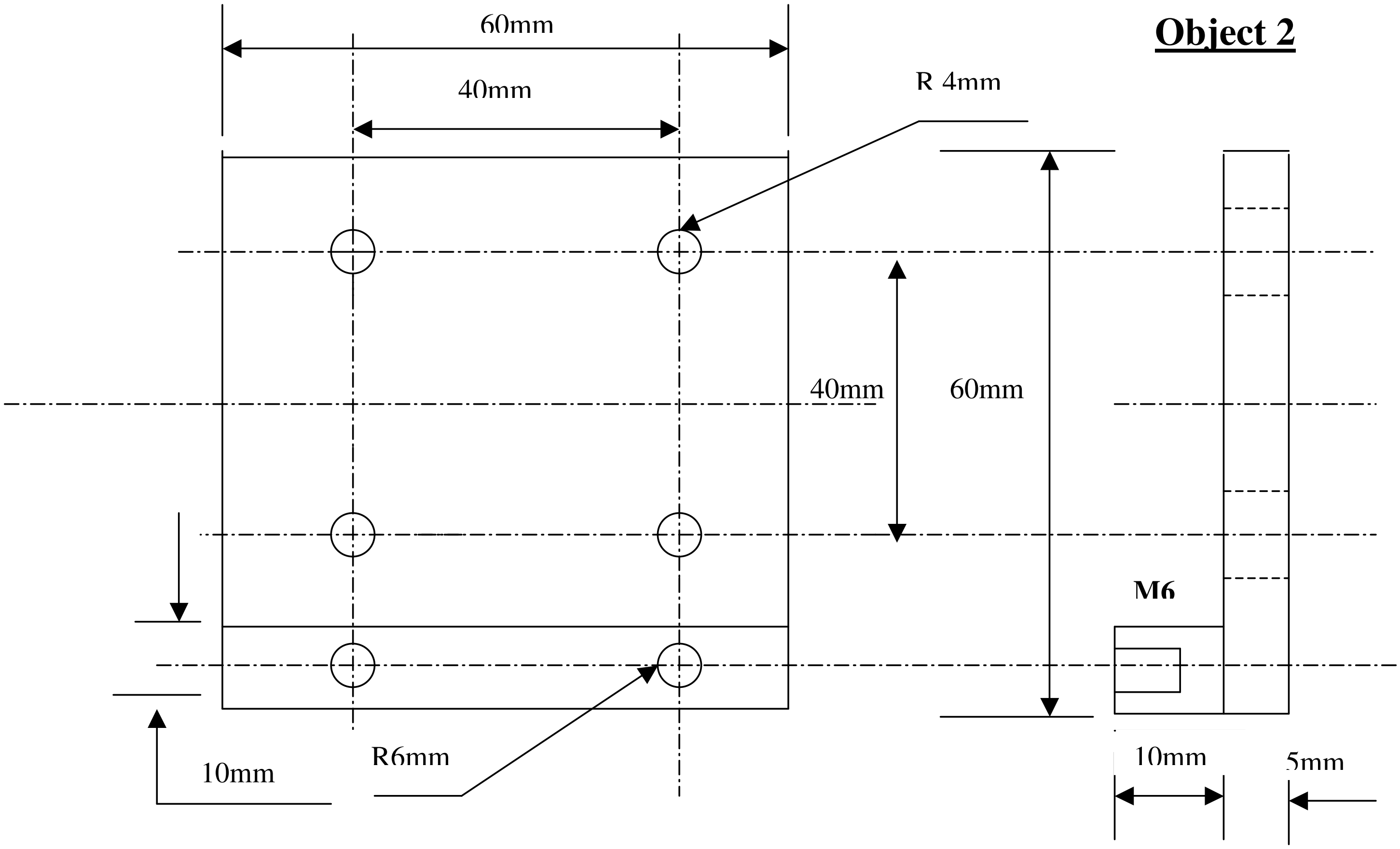
DRAWN BY: Yusuf Kareem (Mech. Engrg.)

DATE : 5 February 2004

Object 1

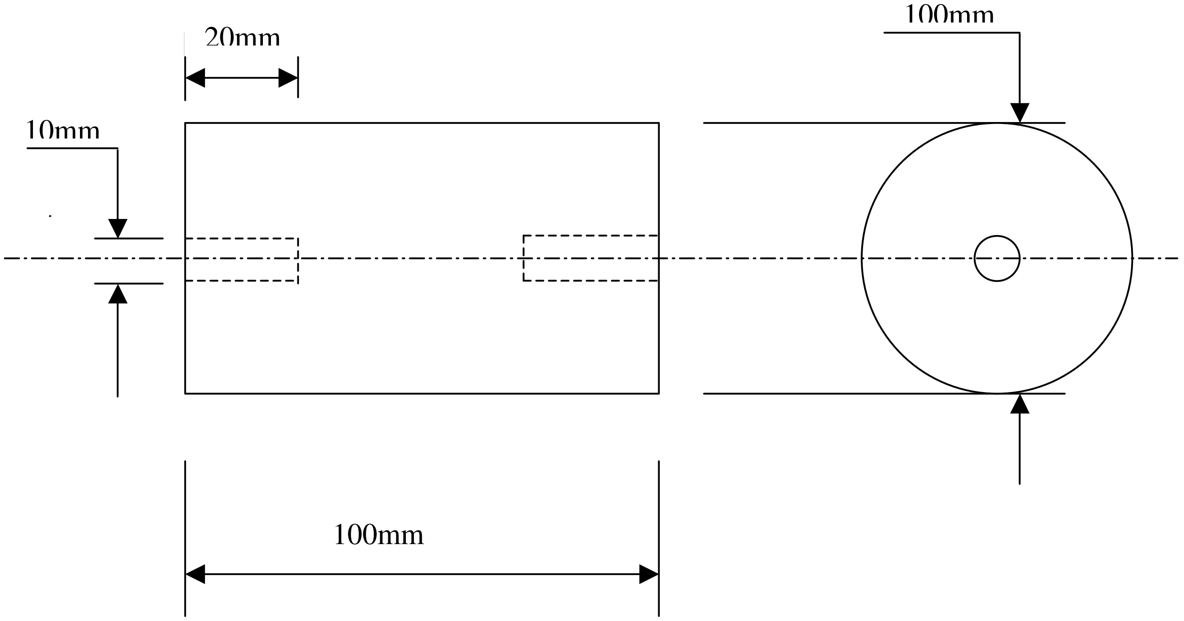


Object 2



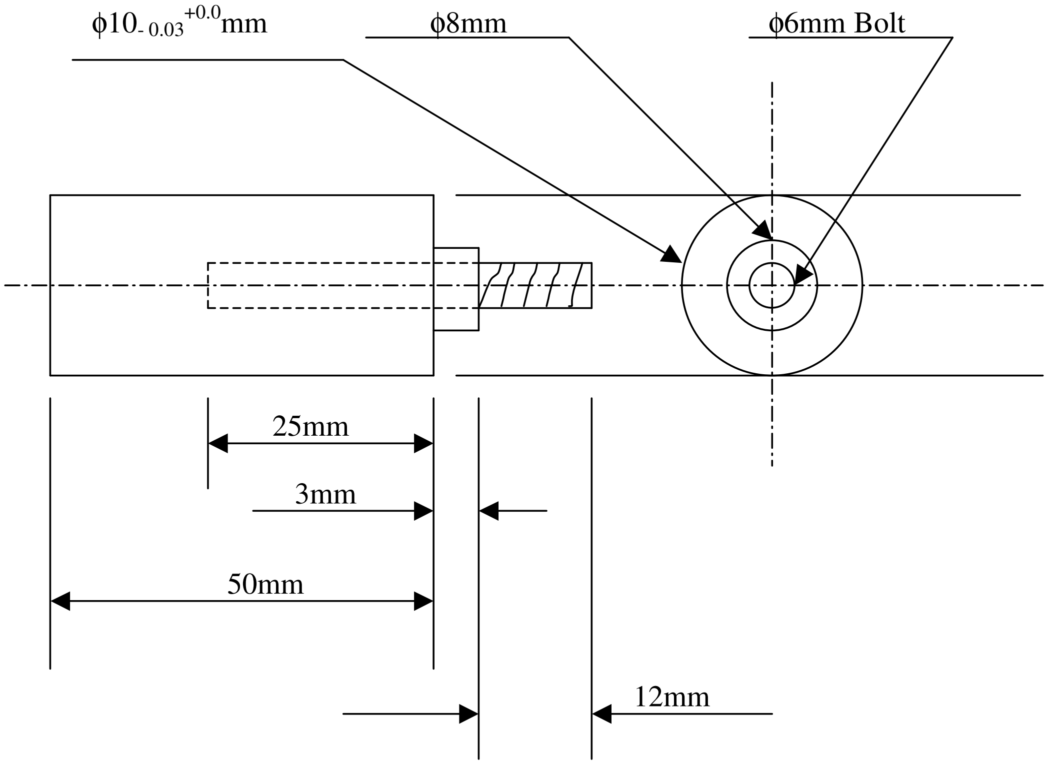
Not to scale

OBJECT 1 : Roller groove
OBJECT 2 : Groove Clamp
DRAWN BY: Yusuf Kareem (Mech. Engrg)
DATE : 5 February 2004.
MATERIAL: Mild Steel 5mm plate
QUANTITY: 2 Each



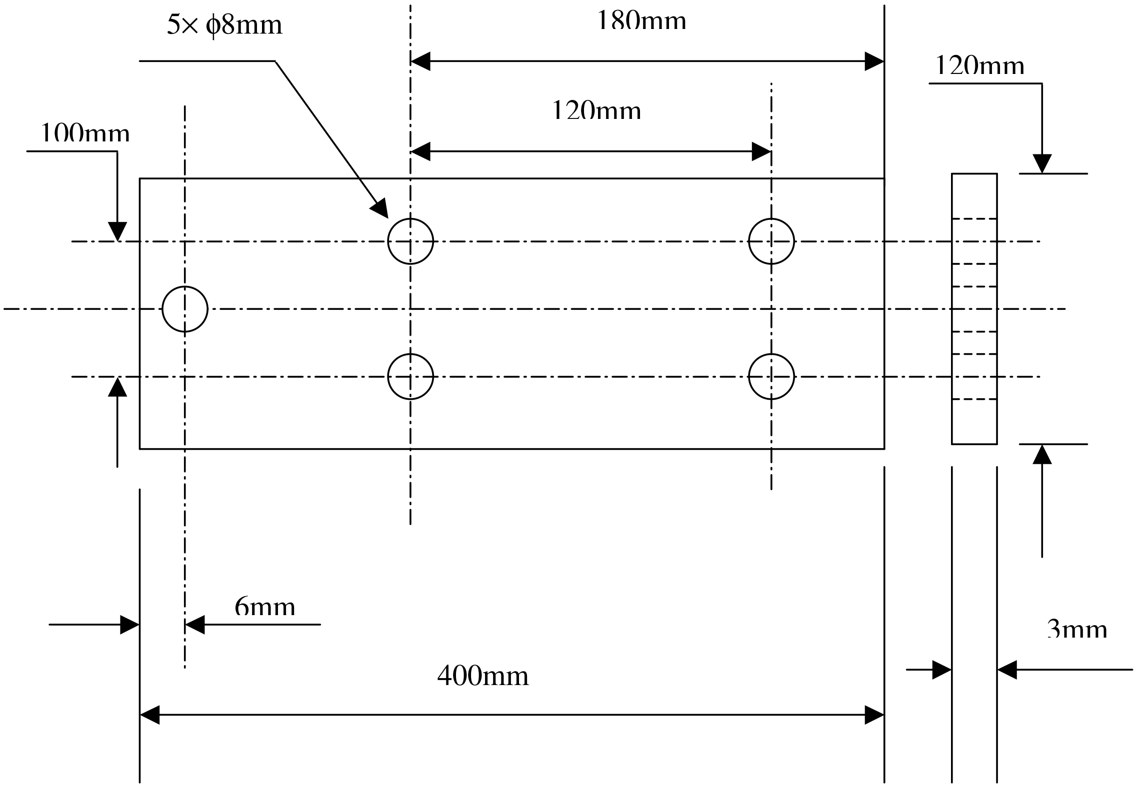
Not to scale

**OBJECT : **Tape Roller
DRAWN BY: Yusuf Kareem (Mech. Engrg)
**DATE : **13 May 2004.
MATERIAL: Mild Steel
QUANTITY: 3



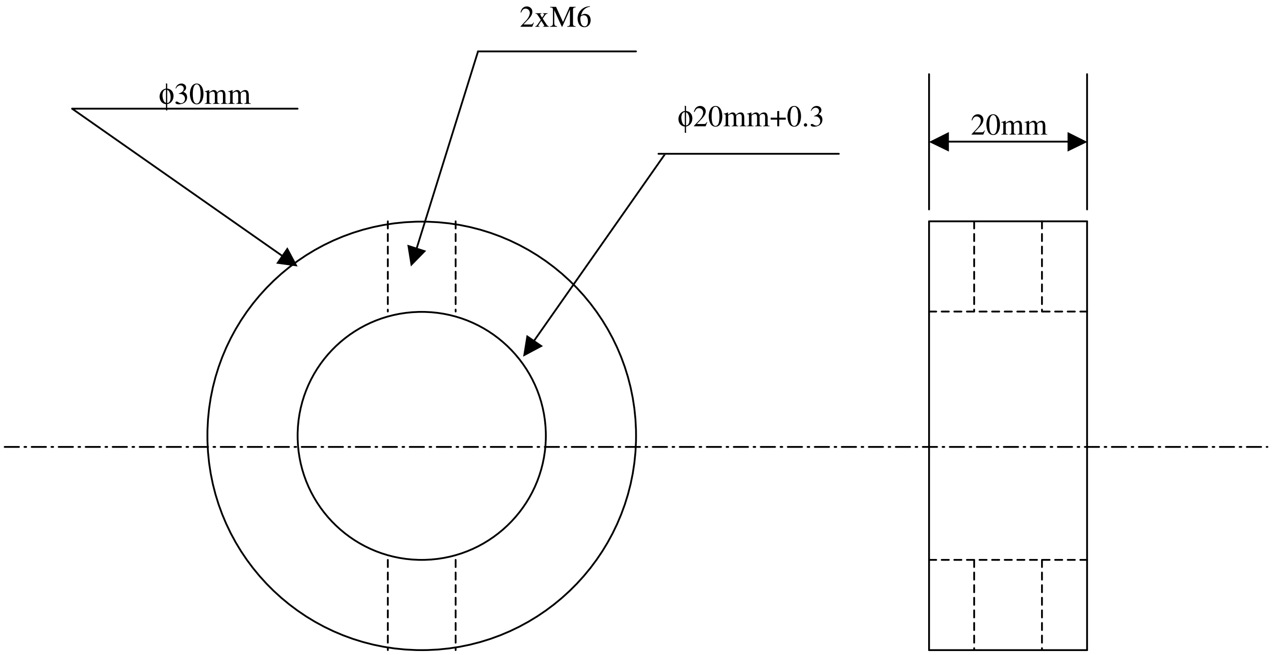
<u>Not to scale</u>

OBJECT : Plastic shaft with bolt
DRAWN BY: Yusuf Kareem (Mech. Engrg)
DATE : 14 May 2004.
MATERIAL: Plastic
QUANTITY: 1



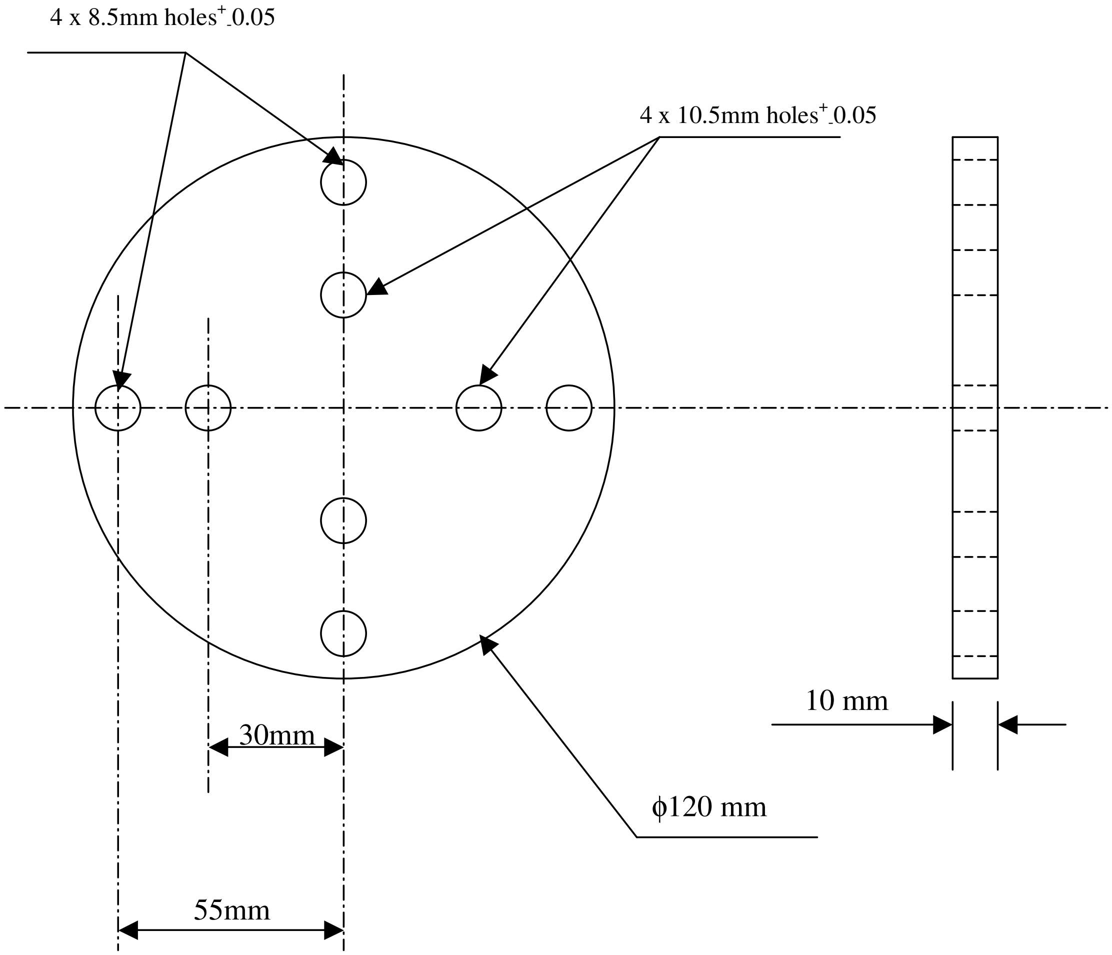
Not to scale

OBJECT : Tape Roller Support Plate
DRAWN BY: Yusuf Kareem (Mech. Engrg)
DATE : 21 May 2004.
MATERIAL: Mild Steel 3mm plate
QUANTITY: 2



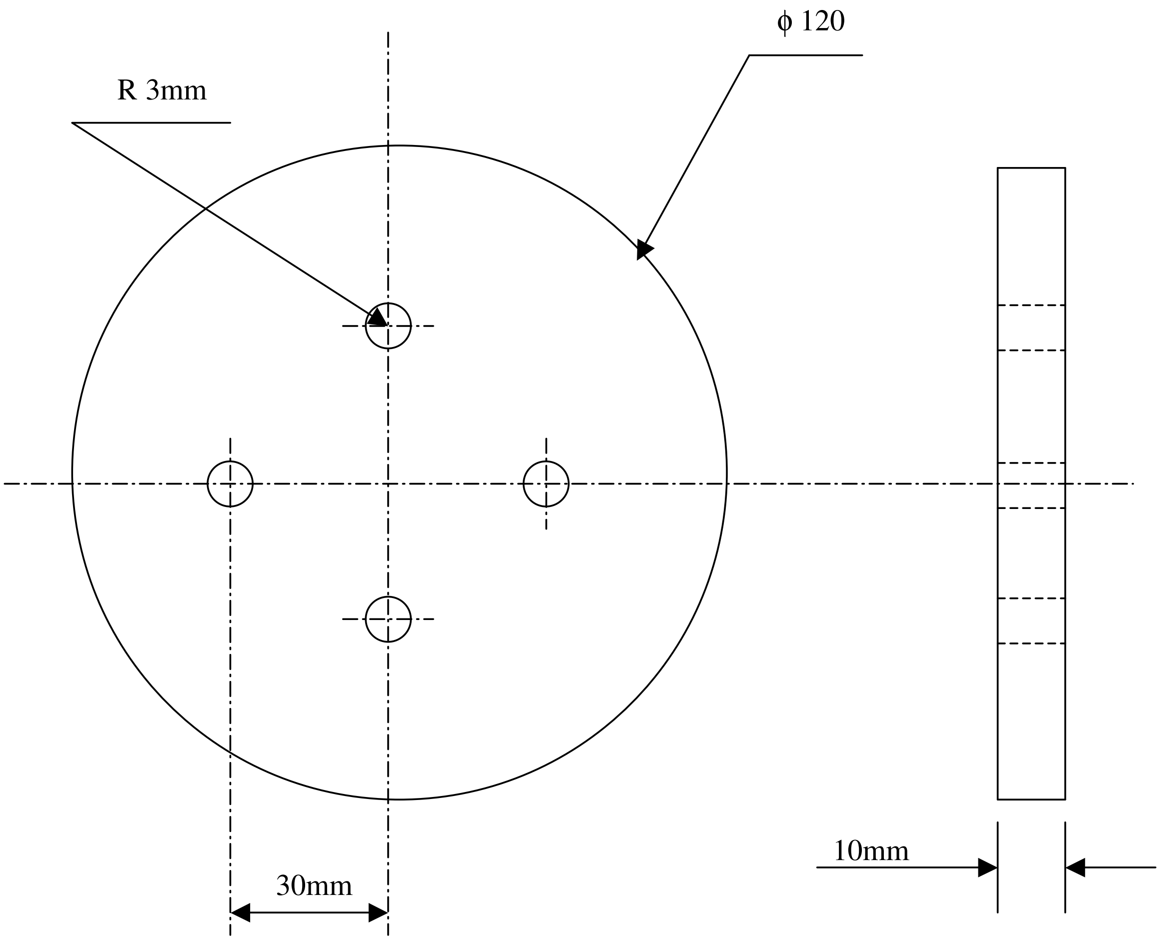
Not to scale

OBJECT : Roller Clamp
DRAWN BY: Yusuf Kareem (Mech. Engrg)
DATE : 7 June 2004.
MATERIAL: Mild Steel
QUANTITY: 1



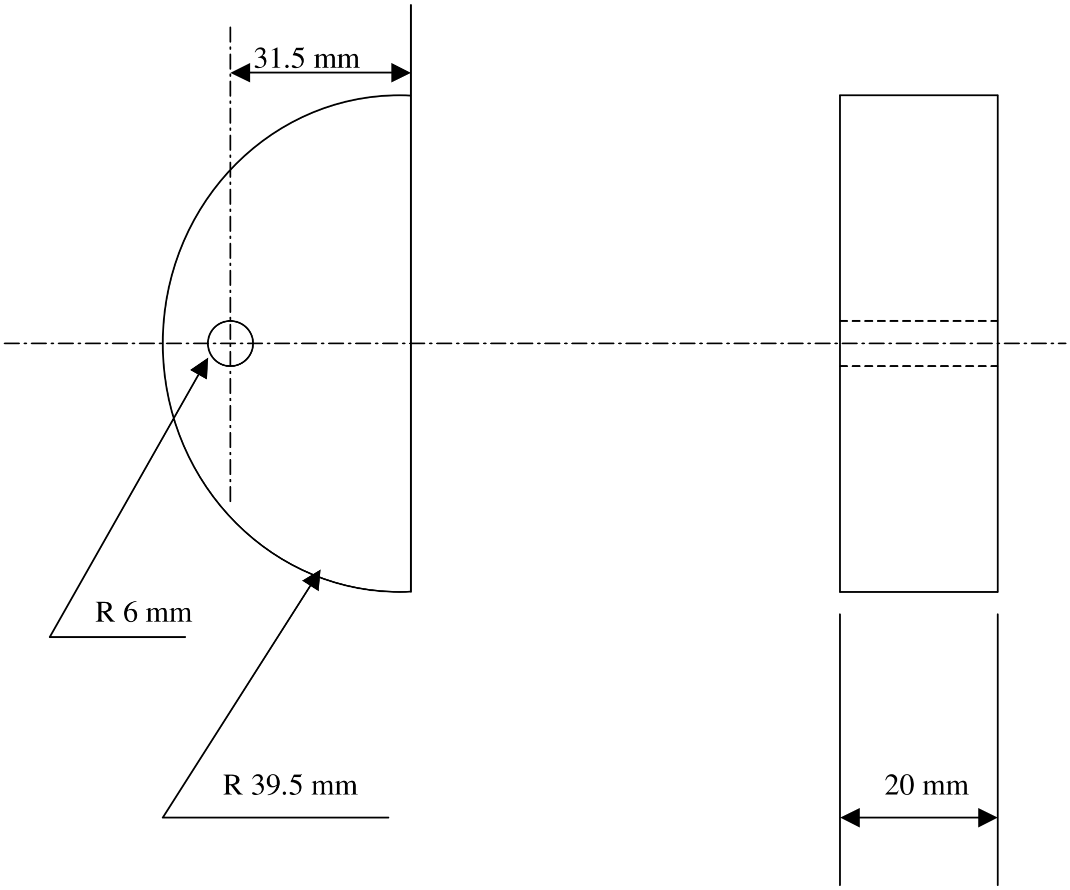
Not to scale

OBJECT : Cover Plate
DRAWN BY: Yusuf Kareem (Mech. Engrg)
DATE : 21 January 2005.
MATERIAL: Mild Steel
QUANTITY: 2



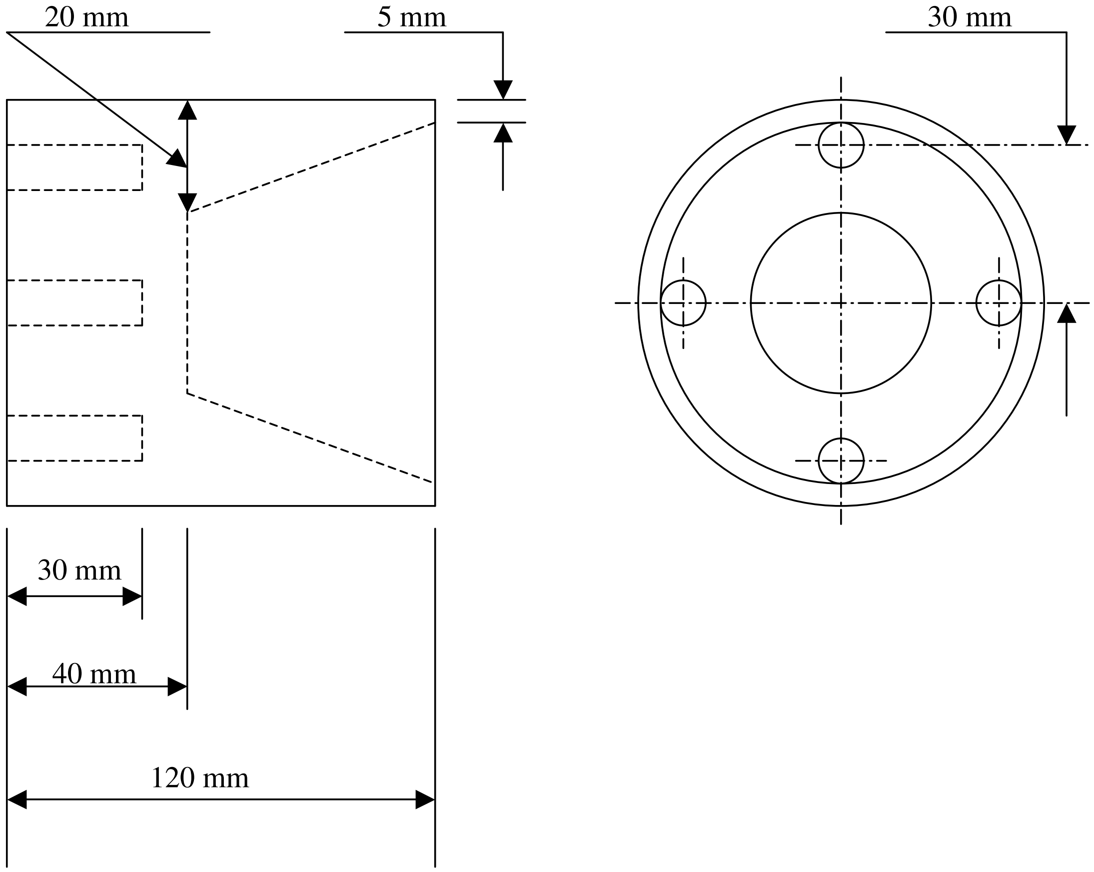
Not to scale

OBJECT **:** Pressure Face Plate
DRAWN BY: Yusuf Kareem (Mech. Engrg)
DATE **:** 27 January 2006.
MATERIAL: Mild Steel
QUANTITY: 2



Not to scale

OBJECT : Split Disc
DRAWN BY: Yusuf Kareem (Mech. Engrg)
DATE : 27 January 2006.
MATERIAL: Mild Steel
QUANTITY: 4



Not to scale

OBJECT : Stopper
DRAWN BY: Yusuf Kareem (Mech. Engrg)
DATE : 27 January 2006.
MATERIAL: Mild Steel
QUANTITY: 2

APPENDIX G

Table G1: GLASS CONTENT TEST ON PLYTRON GN638T GLASS FIBRE RE-INFORCED POLYRPOPYLNE TAPE

Sample No.	Dry boat (g)	Boat + Sample (g)	Boat + Calcinated Sample (g)	Wt. of Glass	% mass of Glass
PL1	31.2714	34.145	32.982	1.1622	59.548
PL2	28.162	31.218	30.001	1.2173	60.169
PL3	29.028	32.003	30.852	1.1509	61.301
			Average	**1.1768**	**60.339**

APPENDIX H

CREEP BEHAVIOUR IN PLASTICS [22]

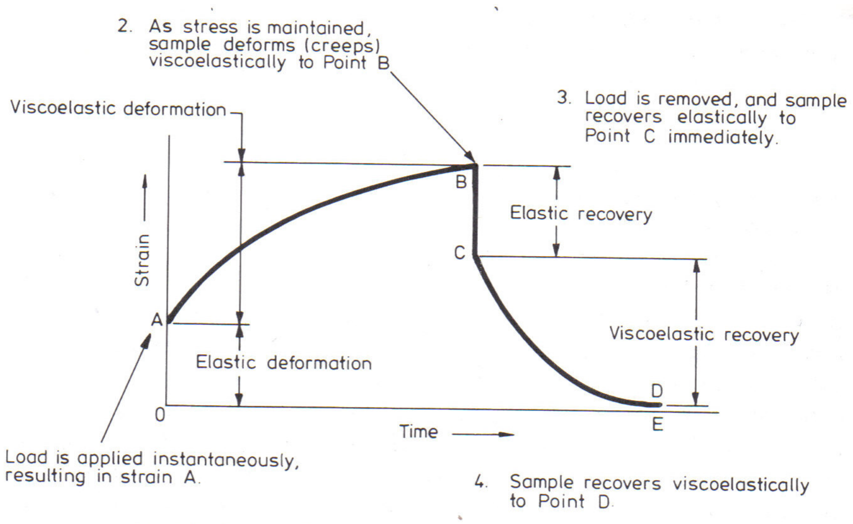


Fig 1.9 Typical Creep and recovery behaviour of a plastic

Figure G1: Typical Creep and recovery behaviour of a plastic

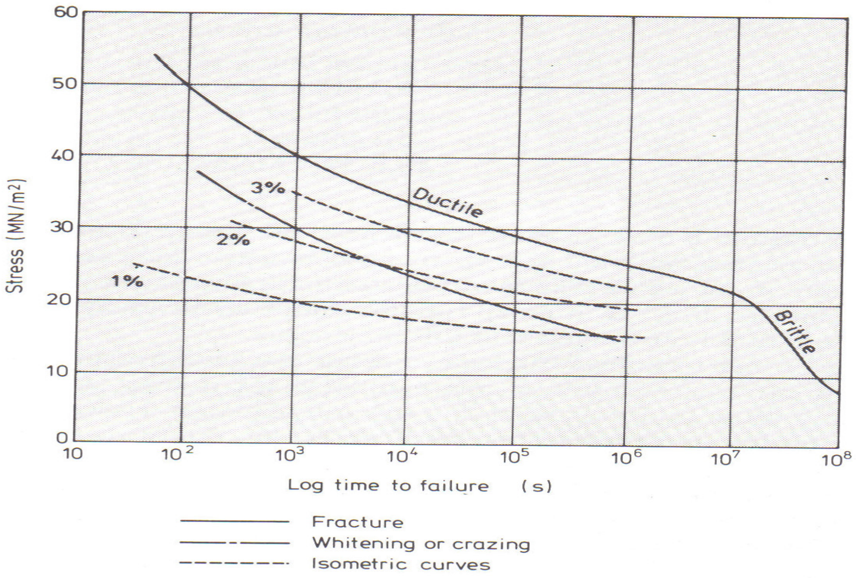
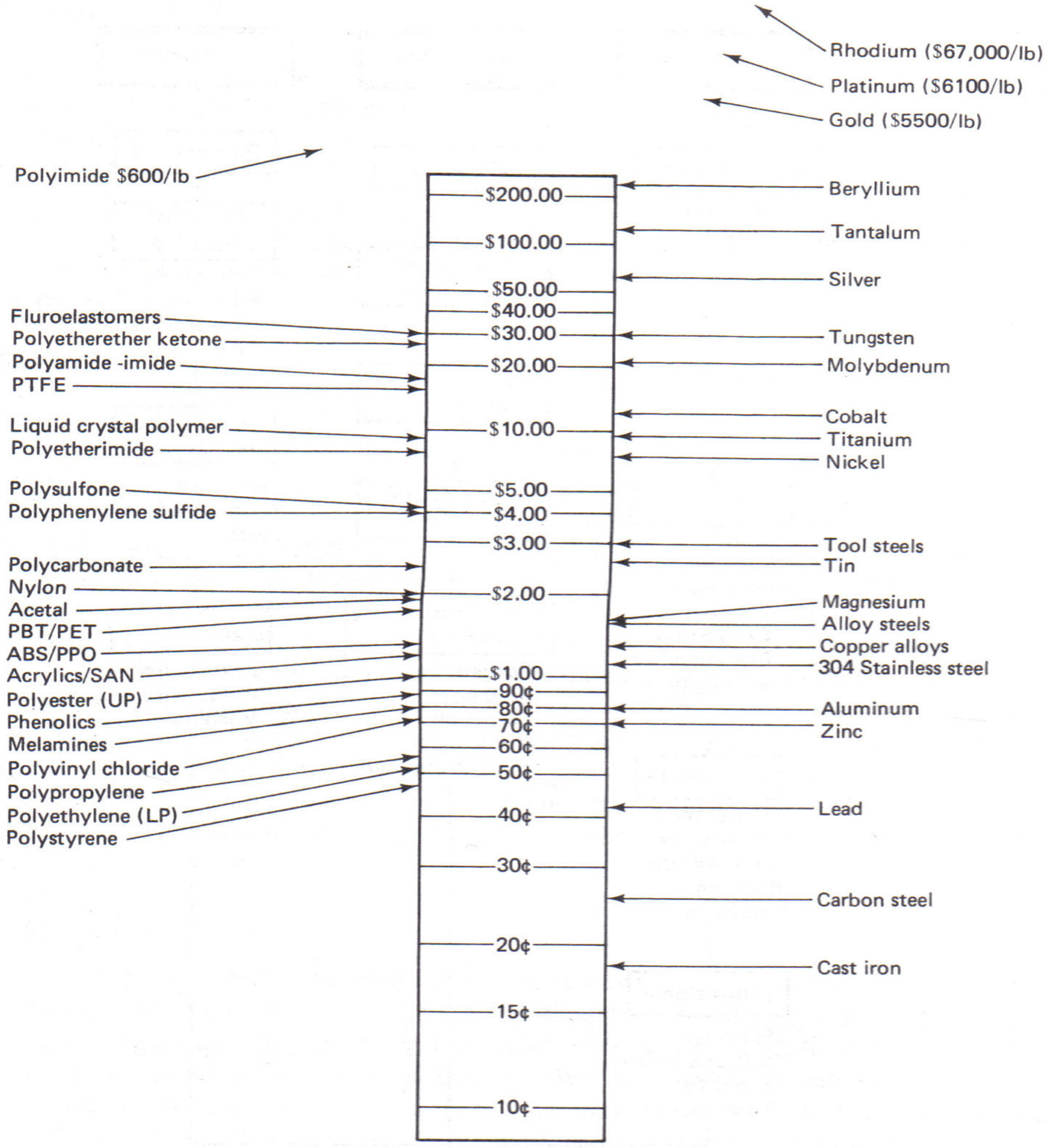


Figure G2: Typical Creep rupture behaviour of plastics

APPENDIX I

COMPARATIVE COSTS OF ENGINEERING MATERIALS [4]



Multiply by 2.2 to
get #/kg.

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