



1 INTRODUCTION

Since their inception, plastics have undergone numerous modifications and improvements to the extent that they can now compare favourably with other applied engineering materials. Plastic materials can be modified with ease by the addition of a variety of additives and fillers to give desired end-use properties. However, their use has been limited by their non-biodegradable nature. In this context they have been considered environmentally unfriendly. Most countries are working on reducing the amount of plastic waste by means of recycling, but this has proved to be unsuitable and uneconomical for certain end-use applications. This global environmental awareness has caused an interest in the development of polymers that will fragment or degrade into benign by-products under composting environments. The use of renewable resources such as starch is considered a cheap way of developing biodegradable materials [Averous *et al.*, 2000]. The main challenge is to make the properties of such a material comparable to those of conventional polymers.

Synthetic biodegradable polymers have already been developed. They are mainly synthetic aliphatic polyesters, such as polycaprolactone, polyhydroxyvalerate, polyhydroxybutyrate and polylactic acid. These polymers degrade due to enzymatic hydrolysis of the ester linkage caused by microbial attack. There are various production methods. Polycaprolactone is polymerised from monomers derived from fossil fuels. Polylactic acid is polymerised from monomers produced from renewable resources via fermentation. Polyhydroxyvalerate and polyhydroxybutyrate are synthesised in bioreactors; microbes feed on the carbohydrates and form polymers inside their cells which are used as an energy-storage medium.

The main disadvantage with synthetic biodegradable polymers is their high cost [Averous *et al.*, 2000]. These polymers are sold at prices that are four to ten times the price of polyethylene. This is due to the complexity of the technology involved in the production of these materials. Cargill-Dow has emerged as one of the front-runners with their NatureWorks polylactic acid. Polylactic acid has the advantage that it is based on natural resources and, because the polymer is made under controlled conditions, it has good properties. However, although the polymer is made from renewable resources, the energy required for manufacturing means that only 20–50% less fossil fuel is required to produce the polymer [Bastioli *et al.*, 1994].

Control over the composition and structure of polymers from renewables is not possible. The main disadvantages with these polymers are their dominant hydrophilic character, critical ageing and their poor mechanical properties.

Thermoplastic starch (TPS) is a translucent amorphous material that looks and feels much like conventional plastics. It is obtained by ‘gelatinising’ native starch in the presence of suitable plasticisers, such as water or glycerol [Shogren *et al.*, 1992]. A controlled extrusion-compounding process can achieve this: applying gentle heating and high shear causes the starch granules to absorb the plasticisers, allowing them to melt at a reduced temperature without decomposing [Van Soest & Vliegenthart, 1997]. The TPS exiting the extruder is a viscous melt; it can be shaped into pellets that can be injection moulded into a variety of articles, just like conventional plastics.

Plain thermoplastic starch is inexpensive and biodegrades quickly. However, there are some drawbacks: it has limited water resistance; its properties and dimensional stability are influenced by moisture (humidity); it does not process as easily as conventional plastics; and the freshly moulded material ages, i.e. its properties change over time [Shogren & Jusberg, 1992]. The latter changes are caused by retrogradation. [Kim *et al.*, 1997], (Retrogradation is the change in properties of thermoplastic starch-based materials with time, caused by recrystallisation during ageing.) The structural changes include helix formation and crystallisation, which occur above the glass transition temperature.

The unacceptable physical and processing properties of thermoplastic starch can be improved by blending with other polymers. To retain biodegradability, it is conventional to use other biodegradable polyesters, such as poly- ϵ -caprolactone, polyhydroxy butyrate and polylactic acid [Bastioli., 1998]. In this study we considered the use of polyamides and recycled polyvinyl butyral as TPS modifying agents.

In South Africa large quantities of polyvinyl butyral (PVB) are recovered from scrap windscreens through a mechanical delamination process. There is, however, very little interest in recycling this post-consumer waste stream owing to a lack of suitable markets for it and the contamination with residual glass fragments. Consequently, it is disposed of in landfill or incinerated. Nevertheless, some PVB is recycled but this is, in the main, limited to recovered factory off-cuts.

The compatibility of PVB with other polymers is important as it is likely that the end-use for the recovered PVB will be in a PVB-polymer mixture, especially where the PVB has a useful effect on the blend properties.

The objective of this work was to determine the effects of water and glycerol content and of the starch source or type on the mechanical properties of maize-based thermoplastic starch (TPS). In addition, the effects of gypsum filler and polyamides or polyvinyl butyral as modifying agent were investigated. The polyvinyl butyral was based on material recycled from automotive windscreens.

1.1 Scope of the work

The aim of this project was to develop a low-cost, locally sourced and biodegradable starch-polymer blend for injection-moulding applications. To this end, the properties and processing of blends of thermoplastic starch (TPS), obtained from locally produced maize starches, with polyvinyl butyral (PVB) and/or polyamide were investigated. Varying the composition of the formulation should make it possible improve the processing behaviour and to modulate the properties of TPS from a very flexible material to a brittle one. The effects of the amylose:amylopectin ratio and of the plasticiser content on the mechanical properties and processability were analysed. In addition, the effect of blending on the mechanical properties, processability and rheology of the resulting blends was investigated. Finally, the effect of processing, by both single- and twin-screw extruders, on the final blend and blend properties was investigated.



2 LITERATURE REVIEW

2.1 Biopolymers

Biodegradability is dependent on the chemical nature of the material and the constitution of the final product. Biodegradable plastics can be synthetic or natural polymers. Natural biodegradable polymers are based on renewable resources, whereas synthetic biodegradable polymers are petroleum-based. Biodegradation is degradation caused by biological activity, such as enzyme action, which leads to major changes in the chemical structure in a given time period into simple molecules, such as carbon dioxide and water [Billmeyer, 1966].

2.2 Starch structure and properties

Native starch is the term used to describe starch in the form in which it occurs in plants, such as potatoes, wheat, cassava, rice and maize. In plants, starch occurs in the form of granules. The granules vary in shape, size and relative proportions of amylose and amylopectin, depending on the source of the starch. Starch is therefore described by its plant source as cornstarch, potato starch, tapioca starch, etc. [Souza & Andrade, 2001].

Starch is composed of carbon, hydrogen and oxygen in the ratio of 6:10:5 [$C_6H_{10}O_5$], placing it in the class of carbohydrate organic compounds. Starch is considered to be a polymer of glucose, with the linkages between the glucose units being formed as if condensation has taken place. The glucose units are connected through an oxygen atom, connecting through carbon atom 1 of one glucose unit to carbon atom 4 of the next glucose unit, forming a long chain of interconnected glucose units. This linkage of one glucose unit to another one through the C-1 oxygen atom is called the *glycoside bond* [Souza & Andrade, 2001].

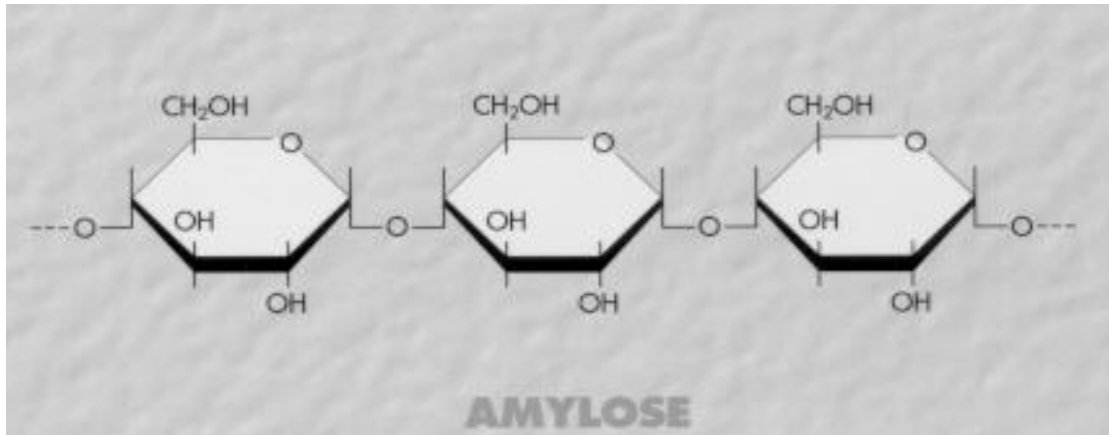


Figure 1: Structure of amylose [African Products, s.a.]

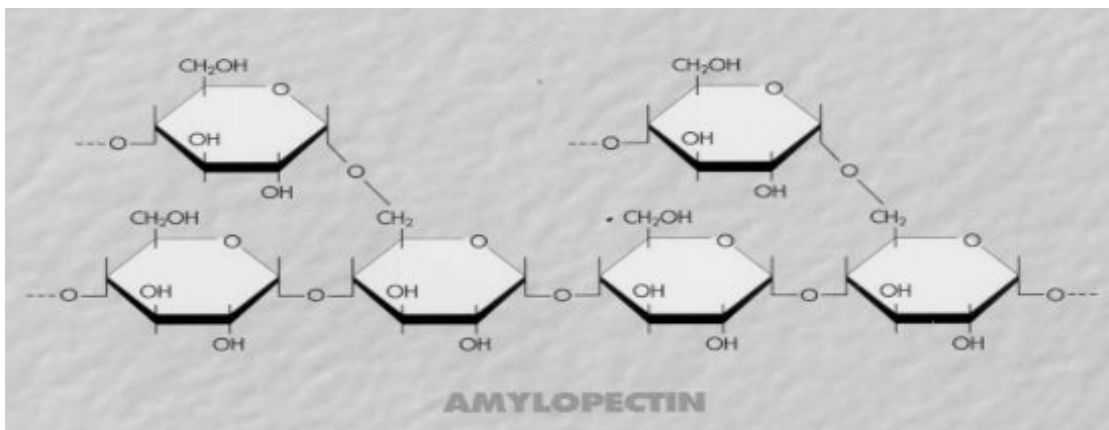


Figure 2: Structure of amylopectin [African Products, s.a.]

Starch in its native state consists of a mixture of two polysaccharides: amylose and amylopectin. Amylose is a linear polymer, while amylopectin is highly branched. The glucose units in amylose are connected to each other through 1-4 linkages [Hulleman *et al.*, 1998]. The relative amounts of these two polymers in a particular type of starch determine the properties of the starch. The molecular structures of amylose and amylopectin are given in Figures 1 and 2 respectively [Bello-Perez & Paredes-Lopez, 1995]. Typical starch compositions are given in Table 1.



Table 1: Composition of potato and maize starches

Type of starch	Potato	Maize	Waxy maize	High-amylose maize
% Amylopectin	79	74	100	30
DP of amylopectin	60 000	60 000	60 000	60 000
% Amylose	21	26	0	70
DP of amylose	6 000	1 300	-	1 300

DP = Degree of polymerisation, i.e. the number of glucose atoms in the molecule

2.3 Starch gelatinisation

In its native form, granular starch is partially crystalline. When dry starch granules are heated, thermal degradation occurs before the granular crystalline melting point is reached. As a result, starch cannot be melt-processed in its native form. In order to melt-process native starch, the hydrogen bonds holding the starch molecules together have to be reduced. The reduction of starch hydrogen bonding can be achieved in the presence of a solvent, such as water. When starch is heated in an aqueous medium, the phase transition forms an ordered to disordered state called *gelatinisation* [Kim *et al.*, 1997].

The properties of starch in water are the bases on which starch can be melt-processed. When starch is heated with the solvent at a critical temperature, the solvent interacts with the starch hydroxyl groups, thus reducing the hydrogen bonding among the starch molecules. This allows individual chains to move freely relative to each other, thus allowing starch to be melt-processed. The critical temperature at which this phenomenon occurs is called the *gelatinisation temperature* [Willett & Doane, 2002].

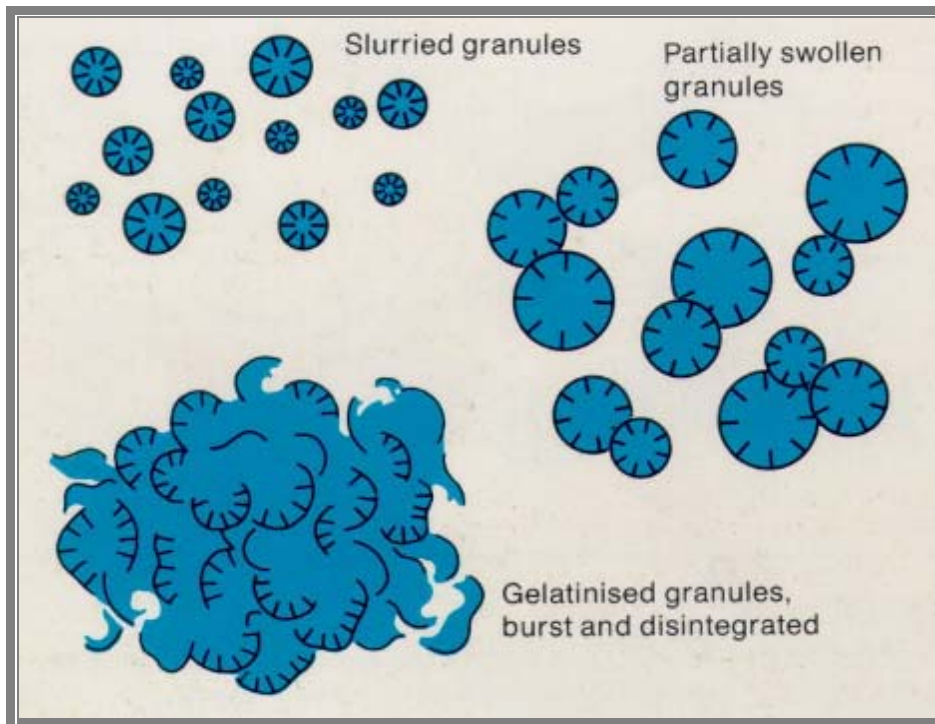


Figure 3: Illustration of the gelatinisation process [African Products, s.a.]

2.4 Starch modification

Starch modifications are carried out in order to provide products with the required end-use properties. These modifications are aimed at changing the gelatinisation characteristics, solids–viscosity relationship, gelling tendency of starch dispersions and hydrophilic character, and at introducing ionic character [Souza & Andrade, 2001].

2.4.1 Modifications aimed at changing the amylose/amylopectin content

Hybrid breeding has been the most successful way of developing starches containing mainly amylopectin. These waxy starches have been available since 1942.

2.4.2 Modification by controlled degradation

This process involves the scission of the starch molecules to fragments of lower molecular weight. Commercially, the conversion is carried out by the action of oxidising agents, acids and/or heat.



2.4.2.1 *Oxidation*

Native starch can be treated with a variety of oxidising agents. The agent most commonly used is sodium hypochlorate. In the first stage of oxidation, the starch chain is hydrolysed into shorter fragments, thus reducing the molecular mass. This results in a reduction in the viscosity of the system. The starch hydroxyl groups are oxidised to aldehyde and ketones. The introduction of the carbonyl group into the amylose molecules reduces retrogradation [African Products, s.a.].

2.4.2.2 *Acid-converted starches*

In this process starch is treated with a mineral acid at low temperature, below the starch gelatinisation temperature, to keep the granules intact. Under these conditions, the acid hydrolyses the starch, breaking the linkages between glucose monomers to yield shorter chains. Hydrolysis initially takes place at the branching points of amylopectin, producing a starch that has a higher proportion of linear molecules. Since the polymer chains have been shortened, the starches have a lower molecular mass than unmodified starches, as well as low viscosities [African Products, s.a.].

2.4.3 Pregellatinisation

Pregellatinised starches are prepared by cooking and drying starch slurries in heated drums or by means of extrusion. Since the granular structure has been disrupted, this process produces starches that swell in cold water [Souza & Andrade, 2001].

2.4.4 Cross-linking

The gellatinisation and swelling properties of the starch granule can be modified by the addition of a cross-linking agent. This is done by reacting a starch with chemicals containing more than one functional group, which are able to react with at least two hydroxyl groups. The most common cross-linking agents used in starch are linear dicarboxylic acid anhydrides (e.g. adipic acid) or phosphates (e.g. phosphorous oxychloride trimetaphosphates) [Souza & Andrade, 2001].

2.4.5 Cationisation

Starch cationisation is performed by chemical means in changing the electrical charge from slightly negative to positive. The cationisation process is done by substituting the hydrogen atoms on the starch molecules with quaternary ammonium chemical groups. The cationic



activity in the starch derivative results from the positive charge on the ammonium ion. The number of cationic groups per glucose molecule determines the degree of substitution. The degree of substitution varies from 0.01 to 0.10 [Valle *et al.*, 1991]. Cationic starches are of large-scale importance in industry due to their affinity for negatively charged substrates (cellulose and other fibres) [Souza & Andrade, 2001].

2.4.6 Acetylating

Starch esterification proceeds either by direct reaction with carboxylic acids or by indirect reaction with carboxylic acid derivatives. Common reagents used in the esterification of starch are acetic anhydride, acetic anhydride-pyridine, ketene, vinyl acetate, acetic acid and acetic anhydride–acid. Direct acid esterification is proton-catalysed, with the formation of a starch ester and water. Indirect esterification uses nucleophilic substitution at the unsaturated carbon atom. Acetylated starches of commercial importance are the derivatives of low substitution, since the process preserves the granular structure of starch molecules [Souza & Andrade, 2001].

2.4.7 Dextrinisation

The action of heat on dry native starch in the presence or absence of a catalyst causes *dextrinisation*. The starch is initially dried to obtain a low moisture content; this is followed by acidification using gaseous hydrochloric acid. The mixture is then heated in an agitated vessel under vacuum. The chemical reaction that takes place during dextrinisation is not clear: it seems that hydrolysis takes place mostly on the 1,4 sites, together with a certain amount of rearrangement to the 1,6 sites [Souza & Andrade, 2001].

2.4.8 Grafting

Starch graft polymers are prepared by initially generating free radicals on the starch which will later serve as micro-initiators for the synthetic monomer. Several free-radical-initiating systems, such as chemical initiation, irradiation initiation and mastication, have been suggested for the preparation of starch grafts. The method chosen is governed by the type of polymer used for grafting and the required end-use properties of the grafted polymer [Chinnaswamy & Hanna, 1990].

2.5 Starch as a thermoplastic material

The use of starch as a plastic material has been recorded in literature since the 1950s. Since then a lot of research has been done on starch, but starch has gained limited applications as a packaging material. The main advantages of starch as a material are its low cost, abundance and availability from agricultural crops. When compared with synthetic polymeric material, starch has two main disadvantages:

1. Starch contains hydroxyl groups, which impart hydrophilic properties to starch. Amylose dissolves in water and amylopectin swells in the presence of water. This means that starch disintegrates in water and loses its properties when exposed to moisture [De Carvalho *et al.*, 2001].
2. Starch in its native form it is not thermoplastic. When it is heated, pyrolysis occurs before the crystalline melting point of starch is reached. Therefore it cannot be melt-processed using conventional plastics equipment [Andersen & Hodson, 2001].

In the literature, various techniques are given for rendering starch suitable for use as a material, such as deconstructing starch (thermoplastic), filling synthetic polymers with starch, blending starch with other thermoplastic polymers and making starch-based nano-composites. [Bastioli *et al.*, 1995].

Thermoplastic starch is formed through the destructuring of the native starch granules by heating at relatively high temperatures, under high shear conditions and with limited amounts of water [Hulleman *et al.*, 1998]. The liquid swells the starch granule and reduces hydrogen bonding and crystallinity in the granule. This results in an increase in molecular mobility and makes it possible to melt-process native starch below its degradation temperature [Van Soest *et al.*, 1996a]. By altering the moisture content and extrusion parameters, thermoplastic products with different properties can be made [Bikiaris *et al.*, 1998].

The amount of water used, in combination with the temperature chosen, has a significant effect on the conversion of starch. Starch conversion can be achieved in two ways. Under excess water, all the crystallites in the starch could be pulled apart by swelling, leaving none to be melted at higher temperatures. Conversion can also be achieved in a limited-water environment, which is the usual condition during extrusion. In the latter process, the swelling

forces are less significant and the crystallites melt at temperatures much higher than the gelatinisation temperature in excess water [Yu and Christie, 2001].

During extrusion, starch is subjected to relatively high pressure (up to 10^3 psi), heat and mechanical shear forces, resulting in gelatinisation, melting and fragmentation. Starch extrusion is carried out at lower moisture contents, from 12% to 16%, which is below the amount of water necessary for gelatinisation. The starch granules are physically torn apart by mechanical shear forces, thus allowing faster transfer of water into the starch molecules. This results in the disruption of molecular bonds and loss of crystallinity, which in turn leads to high molecular mobility, thereby enabling the starch to be processed below its degradation temperature [Avérous *et al.*, 2001]. This means that a mixture of small amounts of gelatinised and melted states of starch, as well as fragments, exists simultaneously during extrusion. Gelatinisation is influenced by variables such as moisture content, screw speed, temperature, feed composition (amylose:amylopectin ratio) and residence time [Yu and Christie, 2001].

2.5.1 Effect of relative humidity

When thermoplastic starch is wetted or exposed to high humidities, absorption of water occurs. Thermoplastic starch is not water resistant and is therefore susceptible to starch ageing, leading to poor mechanical properties. In potato starch, water uptake decreases with an increase in plasticiser content at lower relative humidities, while the opposite has been observed at higher humidities. The effect of plasticiser content on the water uptake of potato starch at varying relative humidities is illustrated in Figure 4 [Van Soest & Vliegenhart, 1997].

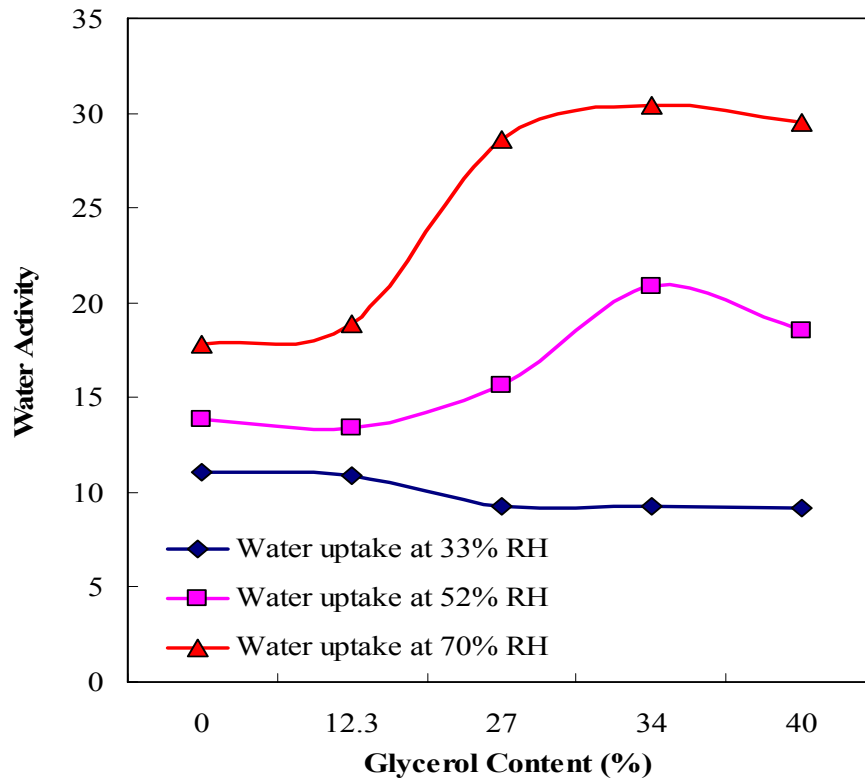


Figure 4: Water uptake as a function of glycerol content and equilibrium relative humidity [Van Soest & Knooren, 1997]

2.5.2 Effect of plasticisers

A plasticiser is a material that is incorporated into a plastic material to increase flexibility, workability or distensibility. Plasticiser molecules penetrate the starch granules, destroying the inner hydrogen bonds of the starch under high temperature, high pressure and shearing. This eliminates starch-starch interactions owing to their replacement by starch-plasticiser interactions. In the literature, other hydrophilic liquids that are used as plasticisers for thermoplastic starch are given; these include glycerol, sorbitol, glycols, maltodextrin and urea. Water is the most common solvent or plasticiser used with starch. Because the plasticiser molecules are smaller and more mobile than the starch molecules, the starch network can be easily deformed without rupture [Yu *et al.*, 1998].

The melting and decomposition temperatures of starch decrease with an increase in plasticiser content. The presence of 2% glycerol monostearate (GMS) in glycerol-plasticised wheat starch reduces the melt viscosity and improves the water sensitivity. The decrease in melting and decomposition temperatures for cornstarch plasticised by glycerol is illustrated in Figure 5 [Liu *et al.*, 2001].

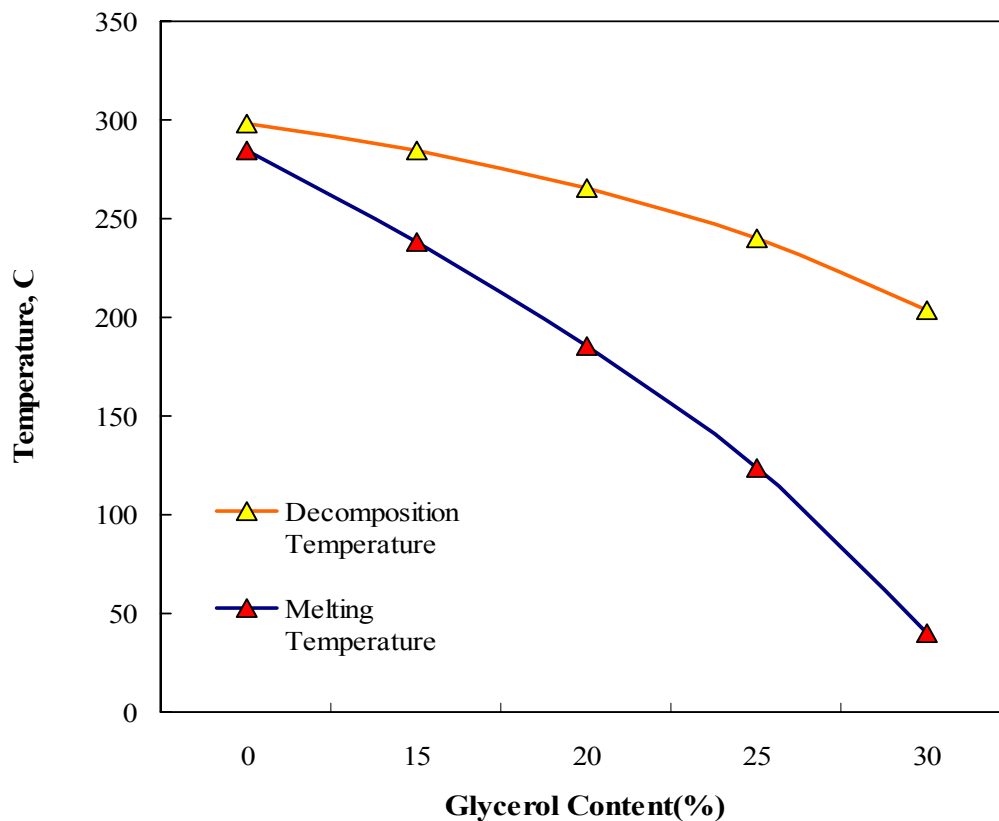


Figure 5: Effect of glycerol on the processing window of cornstarch [Liu *et al.*, 2001]

The span between melting temperature (T_m) and decomposition temperature (T_d) represents the processing window. The processing window extends with an increase in the amount of glycerol [Liu *et al.*, 2001]. Figures 6 and 7 illustrate the effect of glycerol on the tensile strength and elongation-to-break of thermoplastic starch. Tensile strength decreases with an increase in the amount of glycerol, while elongation-at-break increases with an increase in glycerol content within a certain range. Beyond this range, elongation-at-break decreases with an increase in glycerol content. At high glycerol concentrations, the interactions among molecules are very weak because they have replaced the interactions among starch-starch macromolecules. The addition of a small amount of boric acid leads to an increase in mechanical properties, especially elongation-at-break. Boric acid reacts with both glycerol and starch to form an interconnected network [Yu *et al.*, 1998].

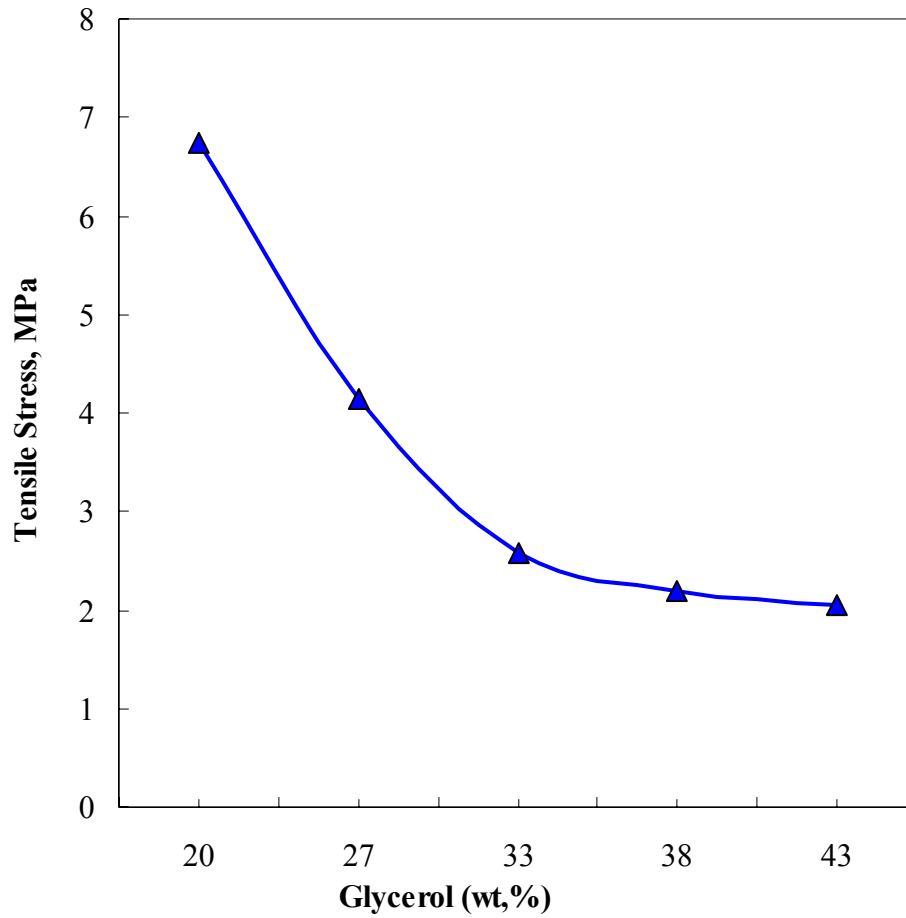


Figure 6: Schematic illustration of the effect of glycerol content on the tensile strength of potato starch [Yu *et al.*, 1998]

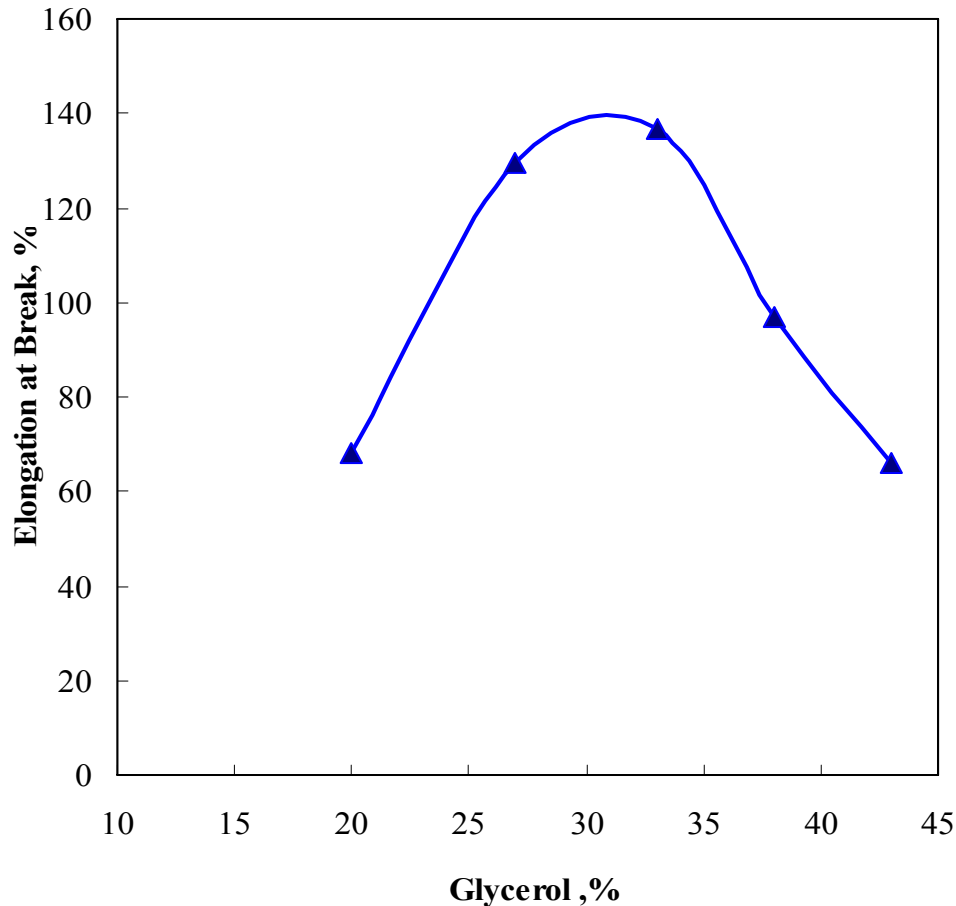


Figure 7: Schematic diagram illustrating the effect of glycerol content on elongation-to-break [Yu *et al.*, 1998]

Water and glycerol are the most common plasticisers used in the processing of thermoplastic starch. The type of plasticiser used influences the glass transition temperature (T_g) of TPS [Van Soest *et al.*, 1996b]. However, urea and various glycols (triethylene glycol, polyethylene glycol and glycerol), and mixtures of these, have also been used as plasticisers for the gelatinisation of cornstarch. At lower urea:glycol ratios (0.2:1), the starch extrudates are brittle and shatter like glass, despite the fact that the T_g was lowered to 50 °C. An increase in the urea:glycol ratio in the starch ribbon from 0.2:1 to 0.6:1 decreased the tensile strength from 19 MPa to 7 MPa and caused a slight decrease in elongation. The mechanical properties of the ribbons remained stable with time at 50% relative humidity, showing that the glass transition is below room temperature where the system is in thermodynamic equilibrium. Urea also disrupts starch hydrogen bonding, so no retrogradation occurs. Starch ribbons containing high levels of urea were stiff due to the low mobility of urea as compared with

ribbons containing high levels of glycols. This is due to the higher mobility or fluidity of glycols [Khalil *et al.*, 2002].

2.5.3 Effect of ageing

One of the disadvantages of thermoplastic starch is its brittleness which is caused by its relatively high glass transition temperature (T_g) and the lack of a sub- T_g main chain relaxation area. During storage this brittleness increases due to retrogradation. *Retrogradation* is the change in mechanical properties of thermoplastic starch caused by a recrystallisation process. The recrystallisation process is caused by the tendency of macromolecules to form hydrogen bonds during the expulsion of water and/or other solvents. This process can be divided into the recrystallisation of amylose and the irreversible crystallisation of amylopectin. Since the reversible recrystallisation of amylose is slower, retrogradation is referred to as the long-term recrystallisation of amylopectin [De Graaf *et al.*, 2003].

Glycerol-containing starch plastics have been shown to recrystallise into various crystalline structures during storage, resulting in changes in mechanical properties. The amylose content of TPS forms the E_h -type of crystallites which are not stable and which rearrange after several days into the V_h -type of crystallites. Like amylopectin, amylose also forms the B-type of crystallites during storage [Van Soest *et al.*, 1996c]. The amount of single helical structures (E_h and V_h) is dependent on the amount water used during processing rather than on the amount of total plasticiser (glycerol and water). During ageing the amount of single helical structures does not increase and therefore retrogradation is caused by the recrystallisation into double helical structures (B-type crystallinity). The formation of B-type crystallinity is dependent on the plasticiser content. The higher glycerol-containing extruded material takes up more water during storage and therefore increases the rate of retrogradation [Van Soest & Vliegenhart, 1997].

2.6 Starch-filled plastics

Granular starch can be mixed with molten thermoplastics without gelatinising the starch. In this case the starch acts as filler for the polymer, reducing the total material cost. Because the starch granules are not gelatinised or plasticised, the processing has to be done below the thermal degradation temperature of the starch. Since the starch retains its granular form, it does not contribute to the mechanical properties of the mixture, and these properties decrease

with increasing starch content. Many examples can be found in the literature, for both biodegradable and non-biodegradable synthetic polymers [Shogren *et al.*, 1993]. This technique is only commercially viable if the saving in materials cost is greater than the added processing cost. Unfortunately, there is an inverse relationship between starch content and material properties. Often, material properties reach an unacceptably low level before a significant cost saving can be made.

2.7 Starch blends

In polymer science, blending is done in order to improve unsatisfactory physical properties of the existing polymer. In starch plastics, moisture sensitivity and critical ageing have made it necessary to associate thermoplastic starch with other polymers. In order to preserve the biodegradability of the final blend, only biopolymers are used. When thermoplastic starch is melt-mixed with any other thermoplastic, the mixture can be considered a polymer blend. Because starch is hydrophobic, it forms compatible blends with polar polymers like polyesters. To retain biodegradability, only biodegradable polyesters such as poly- ϵ -caprolactone, polybutylene succinate adipate (PBSA), polyhydroxy butyrate (PHB) and polylactic acid are often used [Ratto *et al.*, 1999].

Blending starch with degradable synthetic aliphatic polyesters has become a major focus in the development of biodegradable polymers. Wheat thermoplastic starch was found to be not fully compatible with poly- ϵ -caprolactone (PCL) at different ratios of TPS:PCL, with TPS as the major phase of the blend (< 50%). The addition of at least 10% of PCL significantly reduced water sensitivity and dimensional stability. The mechanical properties of the blend are dependent on the plasticiser level in the TPS. For low-plasticised TPS, the addition of PCL resulted in a decrease in the material's elastic modulus, while impact strength improved. For rubbery TPS, the addition of PCL increased the modulus, while the impact strength decreased [Averous *et al.*, 2001]. Application of starch-PCL blends is limited because this material has a melting point of 60 °C and therefore softens at temperatures above 40 °C [Lorcks *et al.*, 2001a, 2001b].

Other polyesters, such as polybutylene succinate (PBS) or polybutylene succinate adipate (PBSA), have been blended with starch to improve the mechanical properties. The rheology of PBSA-TPS blends is better than that of starch on its own. The tensile strength of the blends

was lower than that of the polyester on its own, but was independent of the amount of starch added. The addition of 5% starch reduces the half-life significantly as compared with that of the polyester on its own. The half-life declined with an increase in the starch content. A minimum of 20% starch content was recommended for blending with PBSA [Ratto *et al.*, 1999].

Polyhydroxy butyrate (PHB) is fully compatible with potato TPS. Film formation started with a PHB:starch ratio of 0.3:0.7. The physical properties were found to be maximal at a ratio of 0.7:0 [Godbole *et al.*, 2003].

2.8 Starch-based nano-composites

A recent innovation at TNO (Netherlands Organisation for Applied Scientific Research) is the incorporation of nano-particles into thermoplastic potato starch. Naturally occurring clays are milled, treated with organic cations to separate the particles (intercalation) and incorporated into thermoplastic starch. The starch-based nano-composites can be blended with polyesters to improve their properties. The concept is illustrated in Figure 8:

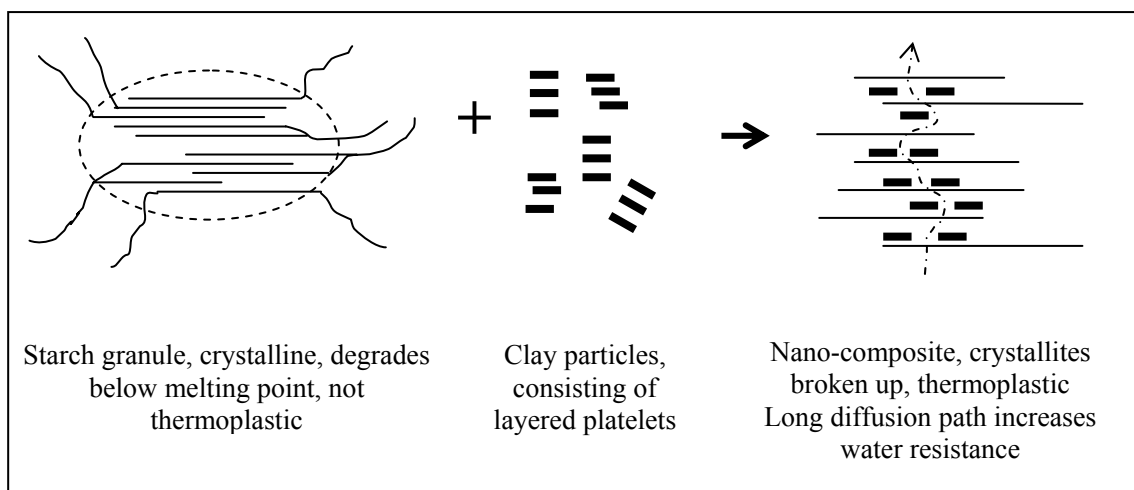


Figure 8: Preparation of a starch-based nano-composite

The presence of the clay improves the starch/plasticiser/polyester blend in the following ways:

- The clay platelets disrupt hydrogen bonding between the starch chains, thereby reducing the crystallinity and making the starch more thermoplastic.

- The platelets increase the length of the diffusion path that the water has to follow to penetrate the material. Therefore the water resistance is improved.
- Some material properties, e.g. stiffness and permeability, are improved by the presence of the clay particles.

This technology has improved one of the main problems associated with starch-based plastics, namely water resistance. It is a major step forward in the development of starch-based plastics. However, all the work has been done on potato starch, and is therefore not relevant to South Africa where only maize starch is produced. Overall, therefore, this project investigated the properties and processing of blends of thermoplastic starch, obtained from locally manufactured maize starches, with polyvinyl butyral (PVB) and/or polyamide for injection-moulded products. The ultimate aim of this work was to develop a cheap, fully biodegradable starch-polymer blend for injection moulding using local resources.