Pearson BTEC Level _ Higher Nationals in Engineering (RQF)

Unit 73: Material Engineering with Polymers

Unit Workbook 1

in a series of 2 for this unit

Learning Outcome 1 & 2

Molecular Structure and Performance Properties of Polymers

Contents

INTRODUCTION

Explore the capabilities and limitations of computer-based models in meeting design fundamentals and their use in solving problems in engineering.

- *Polymer Introduction:*
    - Polymer concept.
    - Definition of the main terms & polymer classification.
- *Molecular Structure:*
    - Chain structure and molar mass.
    - Chain molecule bonds, cohesion, adhesion, solubility and compatibility.
- *Polymer Morphology:*
    - Amorphous solid state & amorphous polymers.
    - Glass transition temperature.
- *The Main Types of Polymer Materials:*
    - Commodity and Engineering Thermoplastics.
    - Thermosets.
    - Rubber & Elastomers.
- *Simple Polymer Identification.*

GUIDANCE

This document is prepared to break the unit material down into bite size chunks. You will see the learning outcomes above treated in their own sections. Therein you will encounter the following structures;

Purpose	Explains *why* you need to study the current section of material. Quite often learners are put off by material which does not initially seem to be relevant to a topic or profession. Once you understand the importance of new learning or theory you will embrace the concepts more readily.
Theory	Conveys new material to you in a straightforward fashion. To support the treatments in this section you are strongly advised to follow the given hyperlinks, which may be useful documents or applications on the web.
Example	The examples/worked examples are presented in a knowledge-building order. Make sure you follow them all through. If you are feeling confident then you might like to treat an example as a question, in which case cover it up and have a go yourself. Many of the examples given resemble assignment questions which will come your way, so follow them through diligently.
Question	Questions should not be avoided if you are determined to learn. Please do take the time to tackle each of the given questions, in the order in which they are presented. The order is important, as further knowledge and confidence is built upon previous knowledge and confidence. As an Online Learner it is important that the answers to questions are immediately available to you. Contact your Unit Tutor if you need help.
Challenge	You can really cement your new knowledge by undertaking the challenges. A challenge could be to download software and perform an exercise. An alternative challenge might involve a practical activity or other form of research.
Video	Videos on the web can be very useful supplements to your distance learning efforts. Wherever an online video(s) will help you then it will be hyperlinked at the appropriate point.

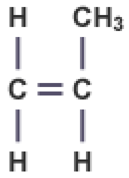

Figure 1.3: *Simple Representation of Propene*

This can then be represented as a repeat unit far more easily.
Consider how the monomer ***ethylene*** is turned into the polymer ***polyethylene*** (polythene). The hydrocarbon molecule ethylene (C_2H_4) has a double bond between the two carbon atoms. This can be changed into single bonds that join it to a carbon on both sides to form a chain.

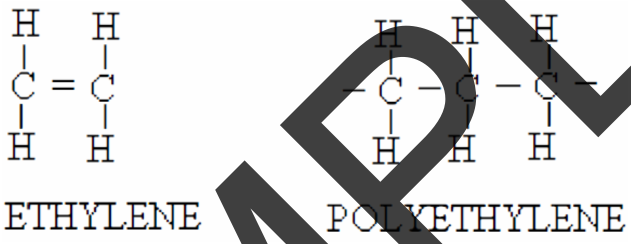

Figure 1.4: *Polyethylene Chain*

The atoms are joined with strong covalent bonds. The molecules are attracted to each other by Van der Waal forces and if the chains lay parallel, these can be quite strong.

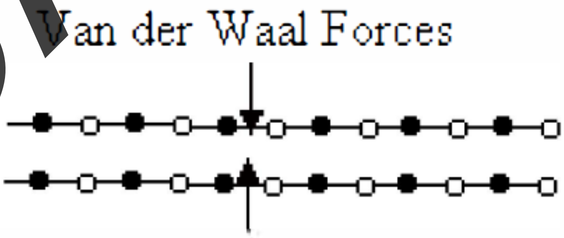

Figure 1.5: *Van der Waal Forces Between Molecules*

1.2 Molecular Structure

Overall polymer properties, including melting point, density, stiffness, hardness and strength, can all be affected by modifying the polymer properties on a molecular level. The molecular properties that can be modified are: chain length, adding plasticizers, cross linking and crystallinity.

1.2.1 Chain Structure & Molar Mass

The chain length of a polymer is literally the number of the molecules that are chained together. Polymer chains are usually depicted only in two dimensions, as this is a more useful way to display them on a page, but they are actually a three-dimensional structure.

The molar mass of an element is the mass (in grams) of 1 mole of substance. Due to the fact that atoms are too small to allow for meaningful measurement, science has grouped elements together into more useful units known as moles. A mole is in fact the number of carbon atoms in 12 grams of 'carbon-12' which works out as approximately 6.022×10^{23}, this constant is then used as the number of atoms given by one mole, and the mass of 1 mole of any substance is given as its molar mass.

In order to calculate the molar mass of an element you multiply the relative atomic mass by the molar mass constant (1 gram per mole). The relative atomic mass of an element is the average mass, in atomic units, of a sample of all its isotopes. This is found on the periodic table of elements, underneath the element symbol and is not usually a whole number. Some elements only occur in molecules containing 2 atoms or sometimes more, in order to work out the molar mass of one of these elements the relative atomic mass must be multiplied by the molar mass constant as well as the number of atoms in the molecule. For example, Oxygen is found in the form O_2, the relative atomic mass of Oxygen is 15.9994, this is multiplied by 1 g/mol and then multiplied by 2 to give a value of molar mass of 31.9988g/mol.

This same method can be applied to more complicated compounds, if we take for example Cellulose which has a chemical formula of $C_6H_{10}O_5$, if this is broken down into its separate elements it is easier to deal with. So, to take the C_6, we look up the relative atomic mass on the periodic table which is 12.011, multiply by the molar mass constant of 1g/mol and then multiply by 6 to give 72.066g/mol. The same is done for the other elements as shown below:

Element	**Relative Atomic Mass**	**Molar Mass**
C_6	12.011	72.066
H_{10}	1.008	10.08
O_5	15.999	79.995
Total:		162.141g/mol

162.141g/mol is the molar mass of one 'repeat unit' but a polymer is not only one unit, it is made up of chains of these units, additionally, in polymers, the chains do not often have the same molar mass. So, in order to find the molecular weight of a polymer sample, it is necessary to do a little more maths! The molecular weight is determined by the average molecular weight, defined by:

$$\bar{M} = \frac{W}{N}$$

The functionality of polymers is defined by the molecular size & structure, its degree of cross-linking or chain branching, its molecular weight and molecular weight distribution.

The influence of molecular weight of mechanical properties is represented below:

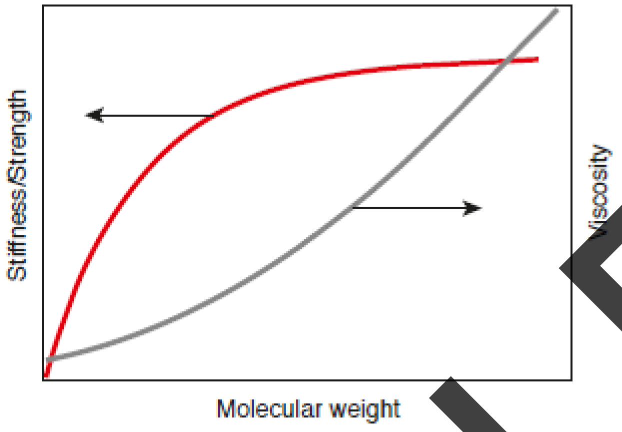

Figure 1.8: *Influence of Molecular Weight on Mechanical Properties*

Other factors are also affected by a change in molecular weight in a typical polymer material, as the molecular weight is increased the stiffness properties reach an asymptotic maximum whilst viscosity and flow temperature increase. Whilst by increasing the molecular weight, the degradation temperature actually decreases so it is therefore very important to identify the molecular weight that produces the desired material properties for the finished product, whilst maintaining ease of manufacture.

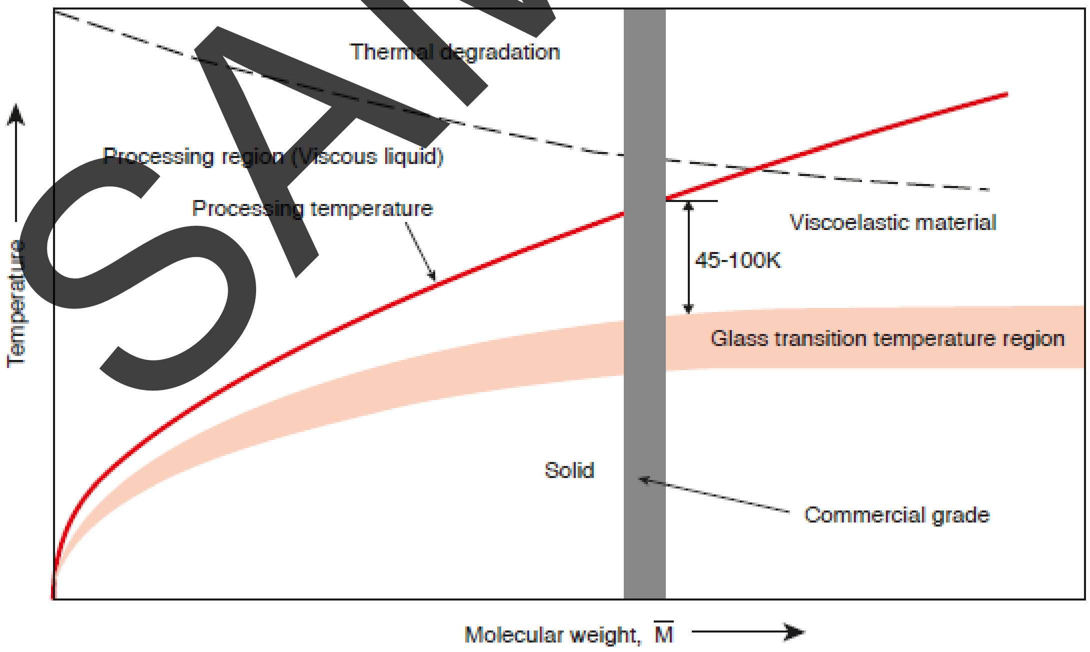

Figure 1.9: *Relationships Between Molecular Weight, Temperature and Properties*

1.3.2 Glass Transition Temperature

Glass Transition Temperature is a key feature of Thermosetting polymers, which is essentially the temperature range in which the polymer transitions from a rigid or hard 'glassy' state to a 'rubberier' state that is compliant and pliable. It is important to note that Glass Transition Temperature (T_g) is not the same as the Melting Point (T_m). The T_g is not exactly a distinct transition that occurs but rather a range over which the polymer chains have massively increased manoeuvrability and only happens to polymers in an amorphous state. However, the common practice is to define the Glass Transition Temperature as the midpoint of the range, bounded by two flat tangents above and below the midpoint. An example of the representation of T_g is shown below:

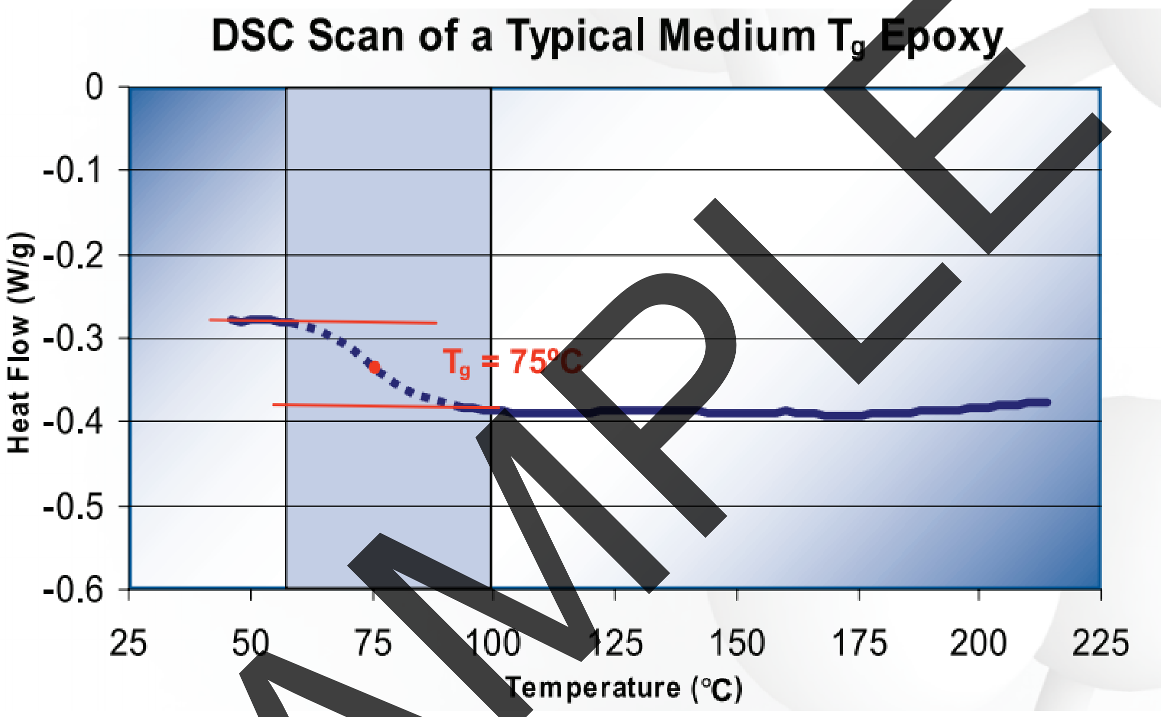

Figure 2.2: *T_g Graph of a Typical Polymer*

The Glass Transition Temperature is found using Differential Scanning Calorimetry (DSC) and is performed on a sample of the polymer that has been cured fully.

The T_g can be reduced by moisture absorption, so during production it is important to consider the environment, specifically the humidity. It can also be influenced by additives which are often included in polymers to give different properties to the finished product. Usually polymers with a higher T_g have a better heat resistance and so consequently, when at high temperature these polymers exhibit the best tensile properties.

A practical example where the Glass Transition Temperature can be seen to have an effect is within a car, many dashboards are made of polymer materials with additional plasticizers. Over time, these plasticizers may evaporate which increases the T_g of the material and results in the dashboard becoming more brittle, causing cracks.

1.4 The Main Types of Polymer Materials

There are several main types of polymer used in engineering applications, they include: Commodity & Engineering Thermoplastics, Thermosets and Rubber & Elastomers. Each have distinctly different properties and characteristics that can be made use of and tailored to different practical ends.

1.4.1 Commodity & Engineering Thermoplastics

Commodity and Engineering plastic are similar in that their basic form is essentially the same but also differ in several ways. Engineering plastics are generally utilised in applications that require better thermal and/or mechanical properties than the commodity plastics. Engineering plastics are ordinarily produced in far smaller quantities than commodity plastics because they are rather more expensive and so they are therefore more likely to be used to make smaller products or for applications of low volume. Commodity plastics are usually used in high volume operations and across a very large range of applications due to their versatility and relatively low cost.

Some prime examples of engineering plastics include Nylon (which is, in fact, a generic name for a family of synthetic polyamides) and ABS (Acrylonitrile Butadiene Styrene). ABS is used to make products such as Lego, drain pipes, musical instruments and cases for electrical components and Nylon is used to produce such products as tights, food packaging, ropes, combs, gaskets and toothbrushes. Nylon is an immensely useful material as it can be produced in various different forms, including fibres, filaments, extruded profiles, strings and powders.

Commodity plastics include Polyethylene, Polypropylene and Polystyrene. Polyethylene can be used to make a variety of common products from plastic bags, milk bottles to cling film, tubing and packaging material. Polypropylene and Polystyrene are also used in a large variety of applications, ranging from low friction gears, caps for ketchup bottles, children’s toys as well as appliances, plant pots and single-use beverage containers (respectively).

Another distinct type of polymer is Aramids/ Para-Aramids, which are characterised by being heat resistant as well as very strong, they are also exclusively synthetic fibres. This group of polymers includes products such as ‘Kevlar’ which are commonly used in military body armour, marine hull reinforcement and in bicycle tyres. Materials in this group are distinct molecularly because, within the fibre, the chain molecules are highly orientated along the axis of the fibre. Para-Aramids and Aramids exhibit certain notable traits which can be used to identify them specifically. They have a very high young’s modulus, have good resistance to abrasion and cutting, are non-conductive and are resistive to organic solvents. They are however, sensitive to degradation from UV radiation and shock load.

1.4.3 Rubber & Elastomers

Natural Rubber is a highly elastic substance garnered from latex sap, usually of the Hevea and Ficus trees, this sap is then refined so that it can be used as a practical material. Natural rubber is 'vulcanised' in order to imbue it with favourable properties, when stressed, the material will deform and then revert to its original shape when the stress is relieved. Natural rubber acts as a highly effective water barrier, has high tensile strength and resistance to fatigue, maintains low heat generation and is very able to stick to both itself as well as other materials (this factor makes it very easy to fabricate into different products). It is used across a variety of applications from medical gloves and condoms to vehicle tyres, balloons, and even in some adhesives.

There are several synthetic rubbers that are used as alternatives to natural rubber, over the years there have been advancements in synthetic rubber (SR) production and different materials have been produced which have varying properties. SR products are processed and 'vulcanised' in the same way as natural rubber, but the raw material is obtained via polycondensation or polymerisation of unsaturated monomers. This group of rubbers has better abrasion resistance than natural rubber as well as better heat and aging resistance. The mechanical properties are otherwise fairly similar to natural rubber, along with added properties such as being resistant to grease and oil and flame retardant. SR is used in similar applications to natural rubber such as in tyres but is more often used in products such as hoses, seals and conveyor belts. Some common types include acrylonitrile butadiene (known as Nitrile) which is often used to make O Rings, styrene butadiene which is used extensively in vehicle tyres, butyl rubber (often called butyl) used to make chemical resistant gloves and ethylene propylene rubber (EPR) closely related to EPDM which are both used to produce self-amalgamating tape, garden hoses and high voltage cable insulation.

Vulcanisation is the chemical process used to harden rubber, usually it involves treating the raw rubber material with sulphur although there are some less frequently used methods. With synthetic rubbers, they can be vulcanised using metal oxides or using 'room-temperature vulcanising'.

In general, there are three basic processing techniques for rubbers: Extrusion, Compression moulding and Injection moulding.

Extrusion: The rubber polymers are heated and mixed in a long container, they are then forced through an orifice at pressure and vulcanised.

Compression moulding: Raw rubber is mixed with other ingredients and rolled into sheets. The sheets are then compressed at pressure around a mould and vulcanised, before being released from the mould in the required form.

Injection Moulding: From the raw rubber, sheets are produced as in compression moulding. These sheets are heated and mixed in a container and then forced at pressure into a mould, steam vulcanised and then cooled, finally being released from the mould in the desired shape.