AN INVESTIGATION OF THE TENSILE AND FLEXURAL PROPERTIES OF POLYETHYLENE, HIGH DENSITY POLYETHYLENE AND ULTRA HIGH MOLECULAR WEIGHT POLYETHYLENE

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

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Date:

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ABSTRACT

The mechanical properties of the different types of polyethylene materials change significantly when the density or molecular weight changes. In general, strength increases with an increase in density and molecular weight, while ductility decreases. Therefore, characterization of mechanical properties of polyethylene materials according to their densities and molecular weights is an important aspect. For this reason, the relationships between density and molecular weight as regards to the mechanical behavior of the three types of polyethylene were studied in the present work. The tensile strength and flexural strength of PE, HDPE and UHMWPE were also investigated. The densities of PE (0.956 g/cm^3), HDPE (0.947 g/cm^3) and UHMWPE (0.943 g/cm^3) were found. The tensile strengths at yield of PE, HDPE and UHMWPE were determined as 28.268 MPa, 22.571 MPa and 20.500 MPa, respectively, while elongations at break were found as 685.368%, 690.280% and 526.587%. Flexural strengths were determined as 17.67 MPa, 25 MPa and 18.43 MPa for PE, HDPE and UHMWPE, respectively. The flexural modulus of PE was determined to be 1021 MPa, while those of HDPE and UHMWPE were 1136 MPa and 921 MPa, respectively. For the three types of polyethylene, flexural strength and modulus, and also tensile elongation at break were decreased with increase in density. The tensile strength, nevertheless, appeared to increase. It was noted also that elongation and flexural strength were influenced by molecular weight.

The stress-strain curve of UHMWPE revealed a different nature, and higher tensile strength in the fracture region. The stress-strain curves of PE and HDPE displayed ductile failure. The stress-strain curve of UHMWPE showed less failure occurred.

Keywords: polyethylene (PE), high density polyethylene (HDPE), ultra-high molecular weight polyethylene (UHMWPE), density, molecular weight, tensile test, flexural test

ÖZET

Polietilen malzemelerin mekanik özellikler, bu malzemelerin yoğunluk ve moleküler ağırlıklarına göre belirgin bir şekilde değişiklik gösterir. Yoğunluk ve moleküler ağırlığın artışı genellikle malzemenin mukavemetini artırırken sünekliğini azaltır. Bu nedenle, polietilen malzemelerin mekanik özelliklerini yoğunluklarına ve moleküler ağırlıklarına göre belirlemek önemlidir. Bu çalışmada polyetilen (PE), yüksek yoğunluklu polietilen (HDPE) ve ultra yüksek moleküler ağırlıklı polietilen (UHMWPE) olamak üzere üç farklı malzeme incelenmiştir. Malzemelerin yoğunlukları, sırası ile, 0.956 g/cm^3, 0.947 g/cm^3 ve 0.943 g/cm^3 olarak belirlenmiştir. Söz konusu malzemelerin akma mukavemetleri, 28.268 MPa, 22.571 MPa ve 20.500 MPa, kopma uzamaları, 685.368%, 690.280% ve 526.587%, bükülme dayanımları 17.67 MPa, 25 MPa ve 18.43 MPa ve bükülme karsayıları 1021 MPa, 1136 MPa ve 921 MPa olarak tesbit edilmiştir. Yoğunluğun artışı ile bükülme dayanımının, bükülme katsayısının ve kopma uzamasının arttığı gözlenirken akma mukavemetinin azaldığı gözlenmektedir. Uzama ve mukavemet değerlerinin moleküler ağırlıktan etkilendiği görülmüştür.

Sonuçlar, diğer plastiklere göre, UHMWPE malzemenin gerilme – genleme diyagramının farklı bir yapıda olduğunu göstermektedir. UHMWPE malzemenin kopma bölgesindeki mukavemeti tipik termoplastik polimerlere oranla daha yüksektir. PE ve HDPE malzemelerin gerilme – genleme eğrileri viskoelastik ve sünek malzeme özelliklerini yansıtırken UHMWPE malzemenin doğrusal ve kırılgan olduğu göze çarpmaktadır.

Anahtar Kelimeler: polietilen (PE) , yüksek yoğunluklu polietilen (HDPE) , ultra yüksek moleküler ağırlıklı polietilen (UHMWPE) ,yoğunluk, moleküler ağırlık, gerilme testi, esneklik testi.

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LIST OF SYMBOLS USED

A:	Area
b:	Width
E:	Young’s modulus
ε:	Strain
E_f:	Flexural Modulus
F:	Force
h:	Thickness
l:	Length
m:	Mass
s:	Deflection
T:	Temperature
Tg:	Glass transition temperature
V:	Volume
ε_f:	Flexural strain
ε_R:	Elongation at break
ρ:	Density
ρa:	Amorphous density
ρc:	Crystalline density
ρs:	Part density
σ:	Stress
σ_f:	Flexural strength
σ_S:	Tensile strength at yield

LIST OF ABBREVIATIONS USED

3D:	Three dimension
DMA:	Dynamic mechanical analysis
DSC:	Differential scanning calorimetry
ESC:	Environmental stress cracking
HDPE:	High density polyethylene
ISO:	International organization for standardization
MWD:	Molecular weight distribution
PA:	Polyamide
PC:	Polycarbonate
PDI:	Polydispersity index
PE:	Polyethylene
PMMA:	Poly (methyl methacrylate)
PP:	Polypropylene
PS:	Polystyrene
PTFE:	Polytetrafluoroethylene
PVA:	Poly vinyl alcohol
PVC:	Poly Vinyl chloride
SAXS:	Small-angle X-ray scattering
UHMWPE:	Ultra-high molecular weight polyethylene
UV:	Ultraviolet

CHAPTER 1

INTRODUCTION

The term ‘polymer’ comes from Greek (polys means ‘many’ and meros means ‘part’) and was first used in 1833 by the Swedish chemist Jons J. Berzelius (Jensen, 2008). Polymers are widely used in industry and trade because of their mechanical properties (Zaharudin et al., 2012). Polymer science focuses on areas such as the development, analysis and chemical reaction of polymers. It also deals with the relationships between the properties and structures of the polymers or between their properties and applications (Teyssedre & Laurent, 2013).

Due to the strength and flexural mechanical properties of polymers, their mechanical applications are continuously being developed. Polymer concerns are related to the increasing need for lightweight, environmental materials and the characterization of recycled polymers (Meijer & Govaert, 2005). The mechanical properties of polymers depend on a number of factors, including temperature, strength and strain rate. In addition, factors that are irrelevant in other types of materials, such as molecular weight, have an important role in strength and flexural properties. The focus here will be on the most important factors that can affect selection of polymers (Abood et al., 2011; Kailas, 2010).

In terms of polymer structure, it is suitable to classify polymers into different types. The original structure of the polymers groups them according to their chain chemistry. Carbon chain polymers have a backbone composed entirely of carbon atoms. They can also be classified according to their macroscopic molecular structure, which is independent of the chemistry of the molecular chain or practical groups. There are four groups of polymers according to this scheme: linear, branched, networked and cross-linked. Finally, polymers can be classified according to their formability (Tadmor & Gogos, 2006).

Modern polymers are developed by a polymer process; thus, manufactured polymers like suitable high density polyethylene and ultra-high molecular weight polyethylene materials are available. The properties of these polymers are related to their constituent molecular components and the arrangement of their chemical bonds. Ultra-high molecular weight polyethylene is an important engineering material used for many purposes. It also has a widespread range of properties, some of which are unique to polyethylene and do not occur in other materials (Mitchell, 2004).

Polymer production plays a very significant part in human life since many of the products we use every day are made from polymers. They not only influence our lifestyle, work and production but they surround us everywhere: in the rooms of our houses and in the products we use. Products made from polymers contribute to satisfying our basic human needs, including housing, health, clothing and transportation. Ultra-high molecular weight polyethylene (UHMWPE) has a very important use in implant materials. The list of fields for application of polymer products is virtually never-ending (Nicholson et al., 1999).

1.1 Objectives

These types of polyethylene materials, especially high density polyethylene (HDPE), are commonly used in the construction projects including projects of Kurdistan Regional Government-Minister of Municipalities & Tourism and also in Cyprus for the water pipeline from Turkey.

The purpose of this project is to investigate experimentally the tensile and flexural properties of polyethylene (PE), high density polyethylene (HDPE) and ultra-high molecular weight polyethylene (UHMWPE) and compare the results with those of previous studies, such as Sangir and Direct plastic companies.

1.2 Contents

The remaining chapters of this thesis are organized as follows**.** Chapter two is a literature review that gives general information about the structure and architecture of polymers and the mechanical behaviour of polyethylene when a load is applied. Chapter three describes the methodology used in the tensile and flexural tests. Chapter four presents the results of the tests carried out in the study. Finally, chapter five concludes the thesis and outlines probable future development of polymers based on this work.

CHAPTER 2

LITERATURE REVIEW

2.1 The Hydrocarbon Structure in Architecture of Polymers

Polymers are organic in origin. Most organic materials are hydrocarbons composed of hydrogen and carbon, so their intramolecular bonds are covalent. A carbon atom has four electrons and a hydrogen atom has one for covalent bonding. A covalent bond exists when each of the two bonding atoms contributes one electron, such as for the molecule of methane (CH_4). Double and triple bonds between two carbon atoms include the sharing of two and three couples of electrons, respectively. As an example, ethylene has the chemical formula (C_2H_4), which means it has two carbon atoms that are doubly bonded together, and each one is also single bonded to two hydrogen atoms, as shown in Figure 2.1.

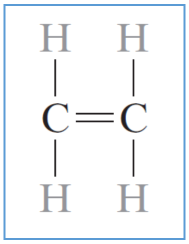
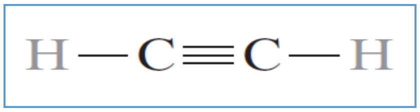


Figure 2.1: Double covalent bonds of ethylene (Callister & Rethwisch, 2007)

On the other hand, a triple bond occurs in acetylene (C_2H_2) as shown in Figure 2.2.



$H-C\equiv C-H$

Figure 2.2: Triple bond of acetylene (Callister & Rethwisch, 2007)

The term unsaturated is used for molecules that have double covalent bonds and triple covalent bonds. The paraffin family shows some of the simple hydrocarbons. The paraffin chain-like molecules consist of methane (CH_4), ethane (C_2H_6) propane (C_3H_8) and butane (C_4H_{10}). The covalent bonds in each molecule are strong, while only van der Waals and weak hydrogen bonds exist between the molecules, and these hydrocarbons have relatively low melting and boiling points. The term isomerism refers to a composition which may have different atomic arrangements of the same compound hydrocarbons. For example, there are two isomers for butane, the structure for normal butane is presented in Figure 2.3 (Callister & Rethwisch, 2007; Nelson, 2011).

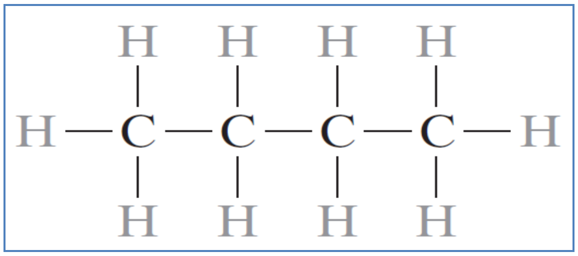


Figure 2.3: The structure of normal butane (Callister & Rethwisch, 2007)

2.2 General Molecule or Structure of Polymer

The molecules in polymers are huge in comparison to the hydrocarbon molecules and are often referred to as macromolecules due to their size**.** The atoms within each molecule are bound together via covalent interatomic bonds. In place of a carbon chain of polymers, the backbone of each chain is a thread of carbon atoms. Moreover, each carbon atom individually bonds to its two adjacent carbon atoms, which is shown schematically in Figure 2.4.

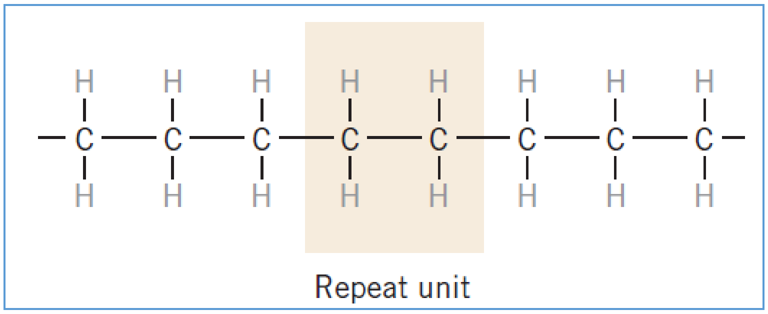


Figure 2.4: Repeat unit of hydrocarbon molecules of polyethylene (Callister & Rethwisch, 2007)

The term repeat unit refers to how these long molecules are composed of structural entities which are successively repeated along the chain. The smallest molecule from the polymer can be manufactured and is called a monomer. Hence, repeat unit and monomer mean different things, but occasionally the term monomer unit or monomer is used instead of the proper term repeat unit (Jones & Ashby, 2005; Callister & Rethwisch, 2007).

2.2.1 The Chemistry molecular structure of polymers

Polyethylene (PE) has a simple molecular structure which is presented in Figure 2.5. This molecular structure corresponds to a chemical formula in the form of $—(CH_2—CH_2)_n—$. The monomer element being presented within parentheses reveals that PE is manufactured from ethylene gas ($CH_2{=}CH_2$) by breaking the double covalent bonds and joining the gas molecules repeatedly at high pressure. For example, in the chemical formula of PE, values can be as small as a hundred on up to hundreds of thousands (Madi, 2013).

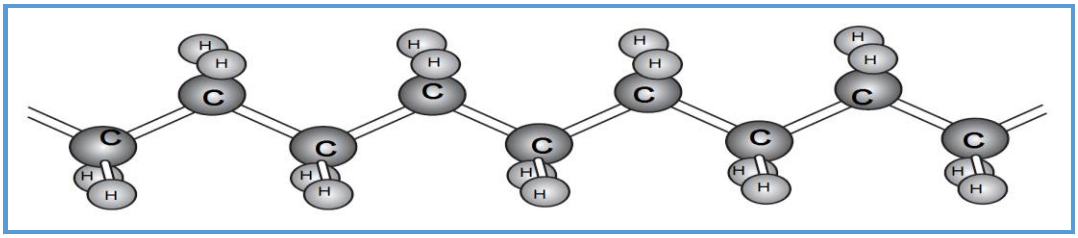
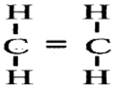
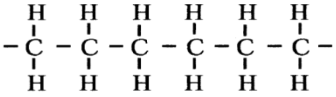
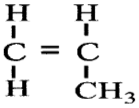
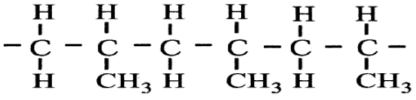
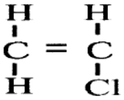
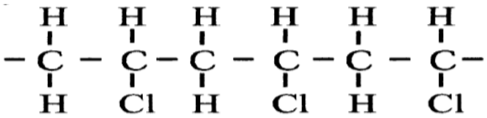
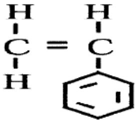
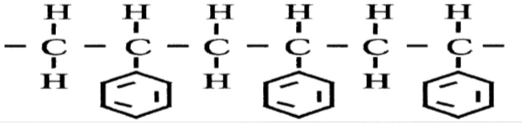
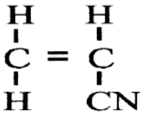
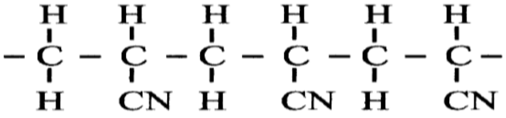
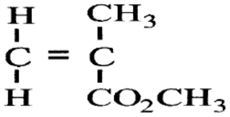
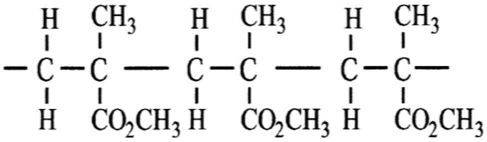
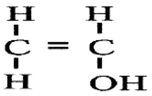


Figure 2.5: Molecular structure of linear polyethylene, where each carbon atom is also covalently linked to two hydrogen atoms (Madi, 2013)

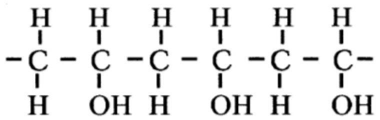
The chain molecular structures of several commercial polymers are shown in Table 2.1 Polypropylene (PP) and Poly(vinyl chloride) (PVC) have molecular structures similar to that of polyethylene (PE), both having basic –C–C– chains but with the significant difference that one hydrogen atom in the monomer is replaced by the methyl group, CH_3, in PP and by chlorine, Cl, in PVC (Teraoka, 2002).

Table 2.1: Polymers from monomers (Teraoka, 2002)

Monomer	**Polymers**
Ethylene 	Polyethylene 
Propylene 	Polypropylene 
Vinyl chloride 	Poly Vinyl chloride (PVC) 
Styrene 	Polystyrene 
Acrylonitrile 	Polyacrylonitrile 
Methyl Methacrylate 	Plexiglas or Lucite 
Vinyl alcohol	Polyvinyl alcohol (PVA)

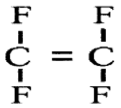


$\overset{H}{\underset{H}{C}} = \overset{H}{\underset{OH}{C}}$



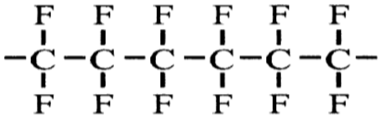
$-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{OH}{C}}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{OH}{C}}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{OH}{C}}-$

Tetrafluoroethylene



$\overset{F}{\underset{F}{C}} = \overset{F}{\underset{F}{C}}$

Polytetrafluoroethylene(Teflon)



$-\overset{F}{\underset{F}{C}}-\overset{F}{\underset{F}{C}}-\overset{F}{\underset{F}{C}}-\overset{F}{\underset{F}{C}}-\overset{F}{\underset{F}{C}}-\overset{F}{\underset{F}{C}}-$

Polystyrene (PS) has a similar basic backbone –C–C– but one hydrogen atom is replaced by a large aromatic ring (C_6H_6) (or benzene); it is a brittle polymer with low toughness. Some polymers have different chemical structures such as in polytetrafluoroethylene (PTFE,Teflon), where all hydrogen atoms are replaced by the element fluorine (F). Some polymers have different backbones such as poly (methyl methacrylate) (PMMA), which has a simple backbone containing its monomer of methyl CH_3 and the methacrylate group COO–CH3. Polyamide (PA) (nylon), another polymer, has an amide link (–NH–CO–) in the backbone (Dasgupta et al., 1996).

2.2.2 Molecular weights and molecular weight averages

Molecular weight and molecular weight averages affect the properties of polymers. The molecular weight provides information on the changes of the mechanical properties. Almost every manufactured polymer material contains molecules in various degrees of polymerization, and this determines the Average Molecular Weight. (Hamerton et al., 2014; Tai, 2000).

2.2.2.1 Molecular numbers and weights

There are several ways of defining average molecular weight. The average molecular number (Mn) can be acquired by dividing the chain lengths into a series of size ranges (*i*) and determining the number fraction of chain lengths within each size range (*i*). Average molecular weight (Mw) is also built on the weight fraction of molecules within the various size ranges (*i*).

Figure 2.6 shows the difference between the weight fraction and the number fraction. The total height of the blocks in each size range (*i*) gives the weight factor in calculating the average molecular weight. For the number average, each polymer chain is calculated equally irrespective of its length. For the weight average, the longer chain is calculated by a greater percentage. Changes in polymer molecular weight distribution are due to the adsorption of polymers (Lipatov et al., 2008; Callister & Rethwisch, 2007).

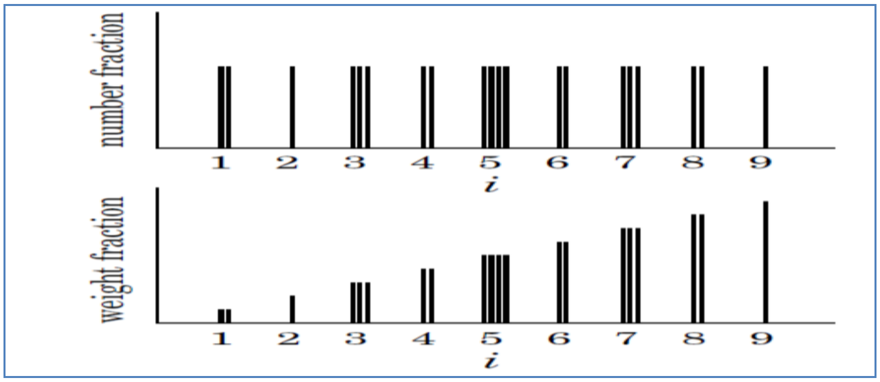


Figure 2.6: Distribution of the chain length of the polymer sample: according to number and weight fractions (Astle, 1988)

2.2.2.2 Polydispersity index (Degree of polymerization)

While the Mw or Mn values show the molecular weights suitable for polymer materials, individually, they do not offer information about the breadth of the distribution. On the other hand, the ratio of the two outcomes is very useful in this regard, and this is called the polydispersity index (PDI):

$$\mathrm{PDI}=\frac{\mathrm{Mw}}{\mathrm{Mn}} \tag{2.1}$$

The PDI is always greater than 1, except for the sample which consists of the same value for M, in which case the PDI = 1 (Roding et al., 2012).

2.2.3 Molecular shape and secondary bonds

The atoms are held together in compounds by forces which are called chemical bonds. The bonds between the carbon atoms within the chain and between the carbon and the hydrogen are the covalent bonds and are based on the hybrid valence electrons of the carbon. This outcome in the form of the molecule chain is shown in Figure 2.5. These hybrid valence electrons totally fill the valence bond; thus, these polymers are often transparent and used as insulators (Zumdahl, 2005).

When two polyethylene molecules have no distribution of valence electrons between them and instead have a weak van der Waals bond, this is responsible for the softness of the polyethylene. The Van der Waals, permanent hydrogen and dipole bonds, are secondary bonds. They are about 10 to 50 times weaker than the primary bonds of the metals and ceramics, with the same mechanical properties and have lower melting temperatures of 120 to 300^{O}C. The hybrid rigidly carries out the angle of (109.5^{o}) between the bonds, so the bond can rotate around its axis as shown in Figure 2.7 (Carraher, 2013).

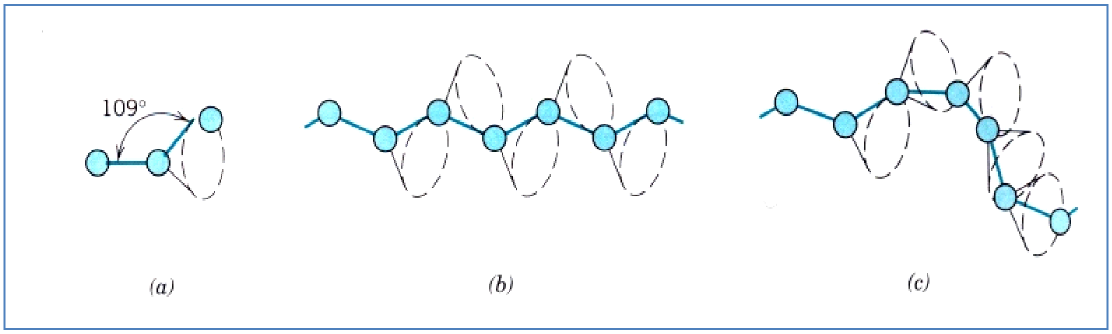


Figure 2.7: Rotation of the bonds around its axis with the angle of 109.5^{o} (Callister & Rethwisch, 2007)

The actual form of the polyethylene molecule chain is not a straight bar. Thus, the polymer chains have the irregular form sketched in the Figure 2.8. In the solid polymer, the individual chains are intertwined. This intertwining of molecule chains has considerable influence on the mechanical properties of polymers (Smith et al., 2006).

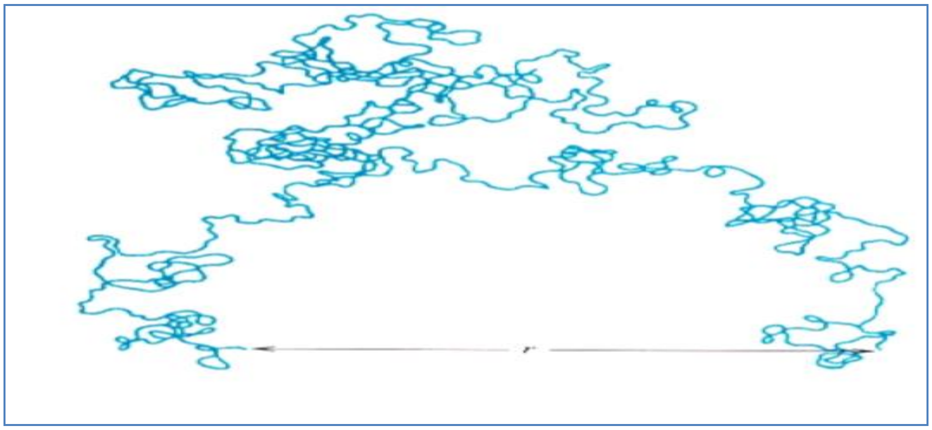


Figure 2.8: Irregular shape of a polymer molecule (Smith et al., 2006)

2.2.4 Geometry of the molecular chain structure

The shape of the molecule chains is very important in determining some of the mechanical and thermal characteristics of polymers. The main geometric shapes are: linear, branched, cross-linked and 3-D network as shown in Figure 2.9 (Kalpakjian & Schmid, 2010).

Linear

The linear polymer is the molecular chain of atoms arranged more or less in a straight line. This base of the chain is called the backbone. As a whole, the bonds within the molecular chain (intramolecular) are covalent. The common polymers with linear molecular structures are polyethylene, nylon, polystyrene, poly (methyl methacrylate), poly (vinyl chloride) and fluorocarbons.

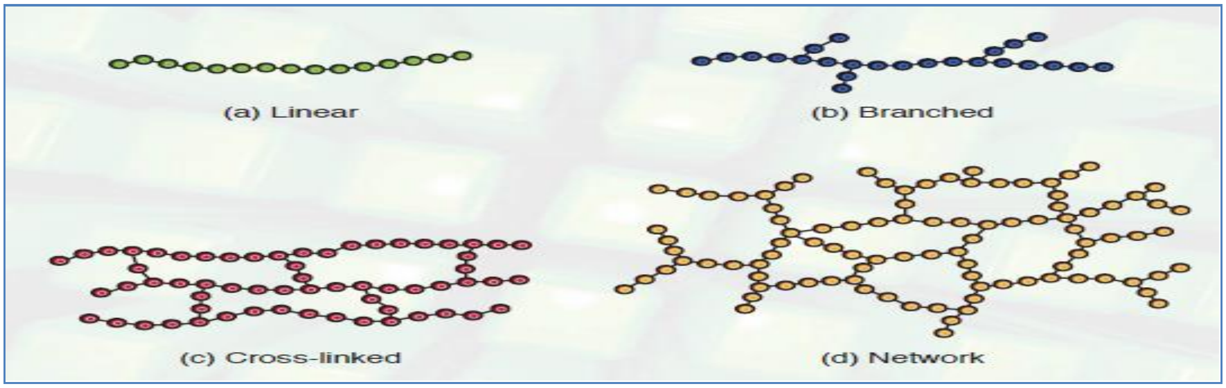


Figure 2.9: Main geometry shapes: Linear, Branched, Cross-Linked and 3-D Network (Kalpakjian & Schmid, 2010)

Branched

Sometimes side-branch chains which are comparable in length to the main backbone chain are attached to the main backbone chain, and such polymers are called branched polymers. Some polymers, such as polyethylene, can be produced in linear or branched forms. The branching affects the physical properties of polyethylene. The degree of the branching such as chain length can also be controlled. The branching forces of the molecular chains are packed rather loosely, making a lower density material. This has the result of decreasing the mechanical properties and formation becomes more flexible. Low density polyethylene can be considered an example (Dahotre & Harimkar, 2008).

Cross-Linked

In this type, the adjacent linear chains are connected one to another at different locations via covalent bonds. The inter-molecular bonds inside the chains and between the chains are both primary covalent bonds. The strong cross-linking bonds of the molecule chains are not affected by temperature. The cross-linking types in plastics and elastomers are relatively stronger. They do not melt, and thus are very difficult to recycle. The most common of the cross linked polymers are rubbers and elastomeric materials (Lewis, 2001).

Network

When a repeat unit (monomer) has 3 or more double bonds the polymers will form a 3-dimensional network instead of linear cross-linked chains. A polymer with a high degree of cross-linking may be classified as a network polymer. The materials with 3-dimensional networks (such as epoxies, phenol-formaldehyde and polyurethanes) have distinctive mechanical and thermal properties (Hiemenz, 1984).

2.2.5 The configuration of the molecular chain

The term ‘Configuration’ refers to the organization of the atoms or group of atoms along a molecular chain. Sometimes the term ‘microstructure’ is preferred instead. Configurational isomerism includes various arrangements of the atoms and substituents in a molecular chain which can be interconverted only by fracture or by the improvement of the primary chemical bonds. Configuration designates different spatial arrangement groups of elements or side chemical elements around the backbone of a molecular chain. Head-to-head and head-to-tail configurations refer to the arrangement of the same atoms or groups of atoms all over thedouble bond in the repeat unit. The head-to-tail and head-to-head configurations of a polymer chain cannot be interchanged without breaking the primary chemical bonds. The head-to-tail structure of polystyrene is shown in Figure 2.10, whereas the head-to-head structure of polystyrene can be seen in Figure 2.11 (Akay, 2012; Callister & Rethwisch, 2007).

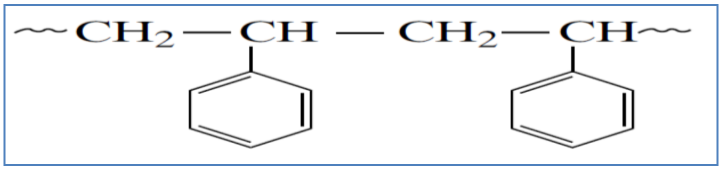


Figure 2.10: Head-to-tail structure of polystyrene (Akay, 2012)

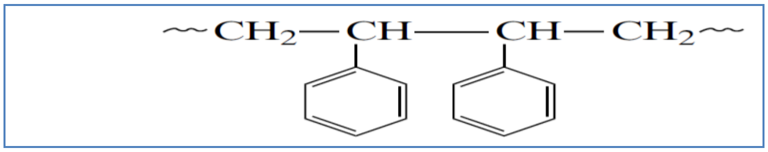


Figure 2.11: Head-to-head structure of polystyrene (Akay, 2012)

2.3 Polymer Types and Processing

Polymers can also be classified according to their mechanical and thermal behavior. Technologically, polymers are classified in two main classes, namely plastics and elastomers. Plastics are important engineering materials for many reasons. They have a widespread range of properties, some of which are unachievable in other materials, and in many cases are relatively low in cost. Plastics are again classified into two groups as thermoplastics (thermoplastic polymers) and thermosets (thermosetting polymers) depending on their mechanical and thermal behavior. A comparison of major polymer categories is given in Table 2.2 (Sinha, 2006).

Table 2.2: A comparison of polymer categories (Sinha, 2006)

Types	General structure	Example
Thermoplastics	Flexible linear molecular chains (branched or straight)	Polyethylene
Thermosets	Rigid three dimensional network (chains may be branched or linear)	Polyurethane
Elastomers	Lightly cross linked thermosets or thermoplastics, involving spring-like molecule chains	Natural rubber

Thermoplastics: The properties of thermoplastics increase or decrease when they are cooled or heated. Thermoplastics become soft when heating is used and have a hard finish when cooled. Thermoplastic materials are created by the application of heat and pressure. Some examples of thermoplastics are polyethylene, polypropylene, PVC, polystyrene nylons, polypropylene, acrylics and polymethyl methacrylate (plastic lenses or Perspex) (Clarke, 2011).

Thermosets: These plastics need heat and pressure to mold them into the required form. They are shaped into a permanent form and treated via chemical reactions such as widespread cross-linking. They cannot be melted or reformed into a new shape, but decay upon being heated to high temperatures. Hence, unlike thermoplastics, thermosets cannot be recycled. Thermosets are commonly stronger, but harder, than thermoplastics. Some advantages of thermosets in engineering applications include high rigidity, high thermal stability, light weight, high dimensional stability, high electrical resistance, thermal insulation properties and resistance to creep. Thermoset polymers cannot be joined and melted by thermal methods like laser or ultrasonic welding. Thermoset polymers are plastics with narrow cross-linked molecular structures, examples of which are epoxy resin (EP), polyester resin (UP) and phenolic resin (PF) (Klein, 2013).

Elastomers (rubbers): These polymers will stretch when a load is applied, even at room temperature, and return to their original shape when the load is released. They are composed of coil-like molecular chains; therefore, elongation can be reversed. The shape of the molecule chains of elastomers are cross-linking and branched (Rinnbauer, 2014).

2.4 Polymer Crystallinity and Crystals

An important structural characteristic of polymers is that they are easily transformed from the amorphous into the crystalline state. In fact, the transition of many polymers from amorphous to crystalline state occurs at approximately room temperature. This is because polymer crystallinity is not an automatic process.

A large number of structural characteristics contribute to the ability of amorphous chain polymers to rearrange themselves in an ordered molecular structure. These factors (such as the chemical components, the bond angles of the backbone and the side groups) are related to the structural design of the chain. Crystalline polymers can be classified into two common categories: extended chain crystallinity and folded chain crystallinity. The first type of crystalline structure in polymers has a precise alignment and highly regular lamellae (platelets) in the chains, each of which consists of a number of molecules. Some typical examples of such extended chains are polyethylene, poly (vinyl alcohol) and poly (vinyl chloride).

The second type of crystalline structure in polymers is chain folding. Polymer chains can fold in a regular fashion to form plate-like crystallites called lamellae. The chains of a polymer not only fold, but can extend from one lamella to another to form amorphous regions. In polymers crystallized from the melt, these lamellae often radiate from a central nucleation site, forming three-dimensional spherical structures called spherulites, as illustrated in Figure 2.12.

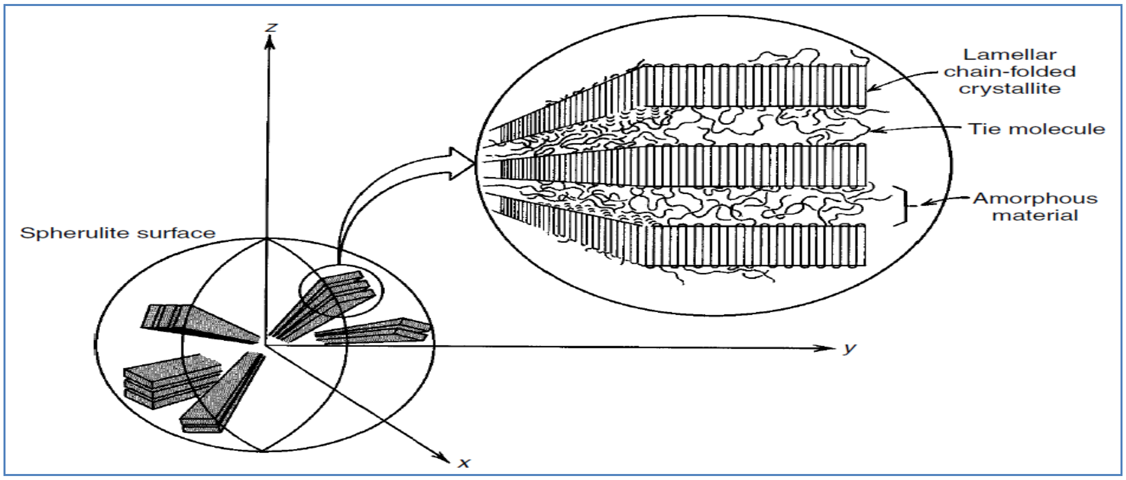


Figure 2.12: A schematic illustration of chain folding leading to lamellar stacking to form spherulites and lamellar crystallites (Mitchell, 2004)

As with the other classes of materials, polymers can be either polycrystalline or single crystals. Polycrystalline polymers are more appropriately termed semi-crystalline polymers, since the region between the crystalline domains in polymers can be quite large and result in a significant amorphous component of the polymer. The crystalline regions in semi-crystalline polymers are called crystallites. They have dimensions of several hundred angstroms, but the length of a polymer chain is generally much larger than this.

A polymer crystal structure related to chain folding is called the fringed micelle model. Such polymer chains do not fold in a regular fashion but extend from one crystalline region to another, again forming amorphous regions between the crystallites as shown in Figure 2.13 (Mitchell, 2004).

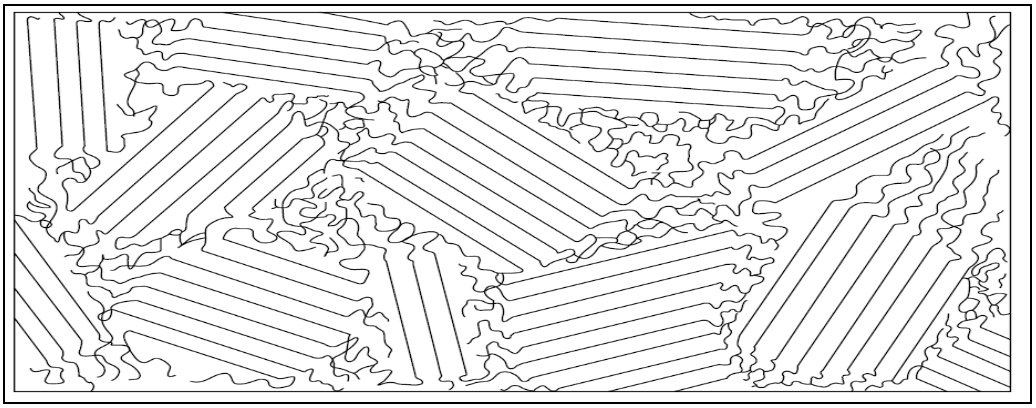


Figure 2.13: The fringed-micelle typical of polymer crystallinity (Mitchell, 2004)

The crystalline region and amorphous region have various densities. Crystalline density (ρ_c) is greater than amorphous density (ρ_a) because of its more compact structure. The percentage of crystallinity in a semicrystalline polymer with main part density (ρ_S) can then be calculated from the respective crystalline and amorphous densities:

$$\% \text{ crystallinity } = \frac{\rho_c(\rho_s - \rho_a)}{\rho_s(\rho_c - \rho_a)} \times 100 \tag{2.2}$$

Polymer single crystals possess the density of the crystal, ρc. Polymer single crystals do not usually form in the main part, but rather from more carefully controlled formation techniques such as vapor deposition (Mitchell, 2004). On the other hand, differential scanning calorimetry (DSC) is used to measure the degree of crystallinity in the polymers (Kong & Hay, 2002).

2.5 Effects of Temperature on Thermoplastic Polymers

The properties of thermoplastics change depending upon temperature. For better design of components and selection of processing techniques, investigation of the effects of temperature on material properties is necessary. The effects of temperature on the behaviour of thermoplastics and molecular structure is shown in Figure 2.14. Thermoplastics can be crystalline or amorphous when they are cooled below their melting temperature. The crystallinity in thermoplastics can be introduced by temperature (slow cooling) or by the application of stress that can untangle chains. When tensile stress is applied to thermoplastics, the weak bonding between the molecular chains can be overwhelmed, and the molecular chains can slide and rotate relative to one another. The ease with which the chains slide depends on both the polymer structure and the temperature.

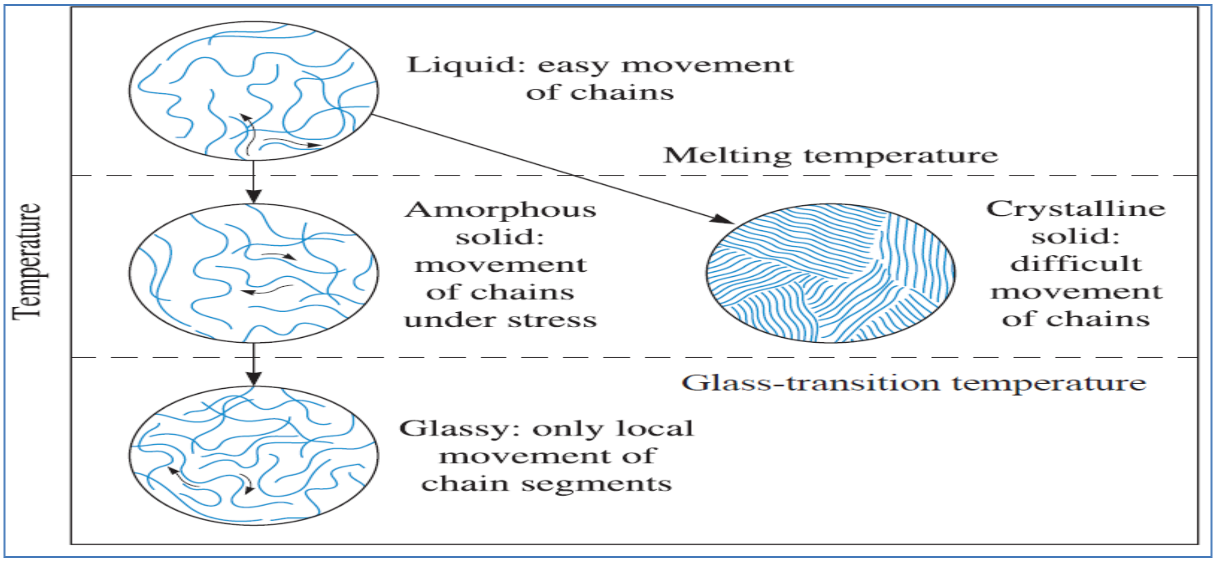


Figure 2.14: The effects of temperature on the behavior of thermoplastics and their molecular structure (Askeland et al., 2011)

Degradation temperature

As a result of very high temperatures, the covalent bonds between the atoms in the linear molecular chain may be destroyed, and the polymer material may char or burn. In thermoplastics, decomposition occurs in the liquid state; in thermosets, the decomposition takes place in the solid state. This is called the degradation (decomposition) temperature (Ambuken et al., 2014).

Liquid polymers

Thermoplastic materials usually do not melt at a specific temperature. Furthermore, there is a range of temperatures over which melting can happen. The approximate melting ranges of typical polymers are shown in Table 2.3. At or above the melting temperature Tm, bonding between the intertwined and twisted chains is weak. If a force is applied, the chains slide past one another, and the polymer flows with virtually no elastic strain. The modulus of elasticity and strength are nearly zero, and the polymer is suitable for casting and many forming processes (Hourston, 2010; Askeland, et al., 2011).

Table 2.3: Glass-transition, melting and processing temperature ranges for thermoplastics (Askeland et al., 2011)

Polymer	Melting temperature range	Glass transition temperature range (Tg)	Processing temperature range
Low density polyethylene	98-115	-90 to -25	149-232
high density polyethylene	130-137	-110	177-260
Polyvinyl chloride	175-212	87	___
Polypropylene	160-180	-25 to -20	190-288
Polystyrene	240	85-125	
Polytetrafluoroethylene (Teflon)	327		
6,6-nylon	243-260	49	260-327
Polycarbonate	230	149	271-300
Polyester	255	75	

Rubbery and leathery states

Below the melting temperature, the polymer molecular chains are still intertwined and twisted. All of the polymers have an amorphous structure. Just below the melting temperature, the polymer material behaves in a rubbery manner. At lower temperatures, bonding between the molecular chains is stronger, the polymer material becomes stronger and stiffer and a leathery behavior is observed. When stress is applied, both plastic and elastic deformation of the polymer occurs. When the stress is removed, the elastic deformation rapidly improves, but the polymer material is permanently deformed because of the movement in the molecular chains. Permanent deformations can be accomplished, allowing the polymer to be designed into suitable forms by extrusion and molding.

2.6 Mechanical Properties of Thermoplastic polymers

Most molten and solid thermoplastics can exhibit a non-Newtonian and viscoelastic behavior. The non-Newtonian behavior includes the strain and stress which are not linearly linked with the parts of the stress-strain curve. The viscoelastic behavior is caused when an external force is applied to a thermoplastic polymer so that both plastic and elastic deformation occurs. The deformation process of the polymer material depends on the amount and the length of time of the force that is applied (Askeland, et al., 2011). The mechanical properties of the thermoplastic polymers (as shown in Table 2.4) can be controlled by both morphological and molecular architecture. A tensile test is used to determine the mechanical properties of the polymer with a stress-strain curve. The curve for a typical thermoplastic polymer is illustrated in Figure 2.15 (Varela et al., 2014).

Table 2.4: Some properties of selected thermoplastic polymers (Askeland et al., 2011)

Thermoplastic polymers	**Tensile strength (MPa)**	**Elongation %**	**Elastic modulus (MPa)**	**Density (gm/cm^3)**
Polyethylene low density	20	800	275	0.92
Polyethylene high density	38	130	1241	0.96
Ultra-high molecular weight	48	350	689	0.934
Polyvinyl chloride (PVC)	62	100	4136	1.42
Polypropylene (PP)	41	700	1516	0.90
Polystyrene (PS)	55	60	3102	1.06
Polyacrylonitrile (PAN)	62	4	3998	1.15
(Teflon)	48	400	5515	2.17
Polyamide (PA)(Nylon)	82	300	3447	1.14
Polyester (PET)	72	300	4136	1.36
Polycarbonate (PC)	75	130	2757	1.20
Polyimide (PI)	117	10	2068	1.39

Elastic Behavior in thermoplastics can result in deformation. The covalent bonds in the molecular chain become distorted and stretched when a stress is applied extending the molecular chains too elastically. When the stress is released, the distortion rapidly returns to its orginal shape. This behavior is similar to that of ceramics and metals, which are also distorted elastically by the elongation of the covalent bonds. Furthermore, some parts of the polymer chain may be deformed when the stress is released and these parts return to their original length over a period of the time – often hours or months.

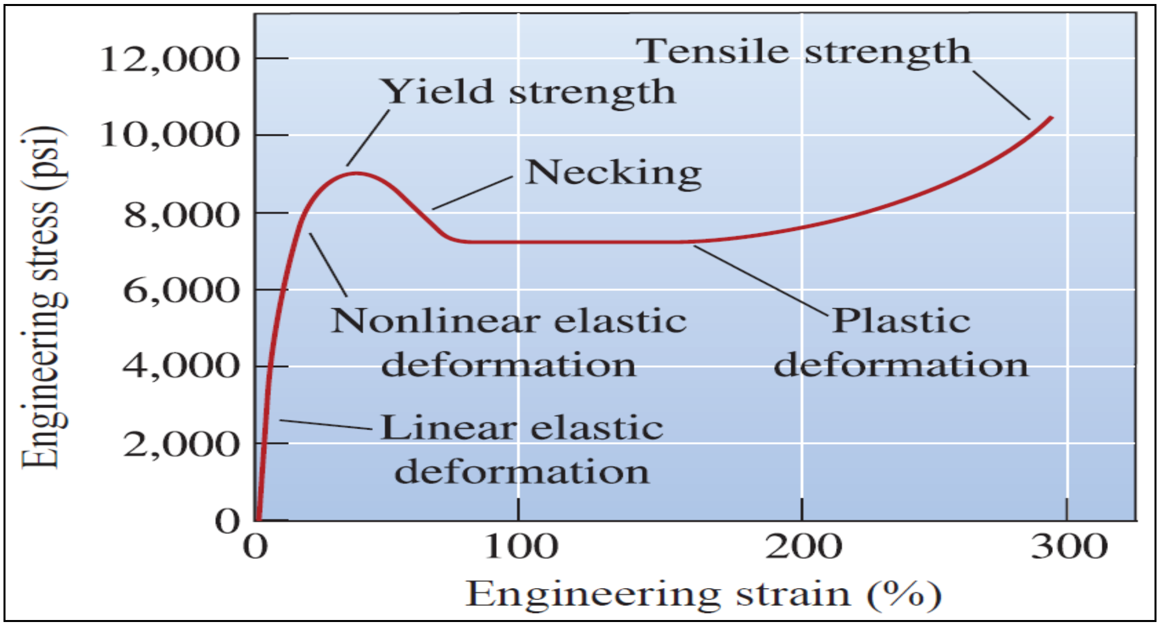


Figure 2.15: The engineering stress-strain curve for a typical thermoplastic polymer (Askeland, et al., 2011)

Plastic behavior in an amorphous thermoplastic material means it is distorted plastically when a stress forces it at maximum yield strength. Dissimilar deformation occurs in the case of the metals, but plastic distortion is not a sign of dislocation movement. Instead, chains stretch, slide, rotate and untangle under force to permanent distortion. The drop in stress below the yield point can be clarified via this phenomenon. Originally, the molecular chains may be highly intertwined and tangled. When the stress is adequately high, the chains begin to straighten and untangle. Necking also takes place, allowing continued slipping of chains at lower stress. Finally, the chains come closer together and parallel. Stronger van der Waals bonding between the closely aligned molecular chains needs higher levels of stress to complete the deformation and the fracture process as shown in Figure 2.16 (Askeland & Phule, 2003).

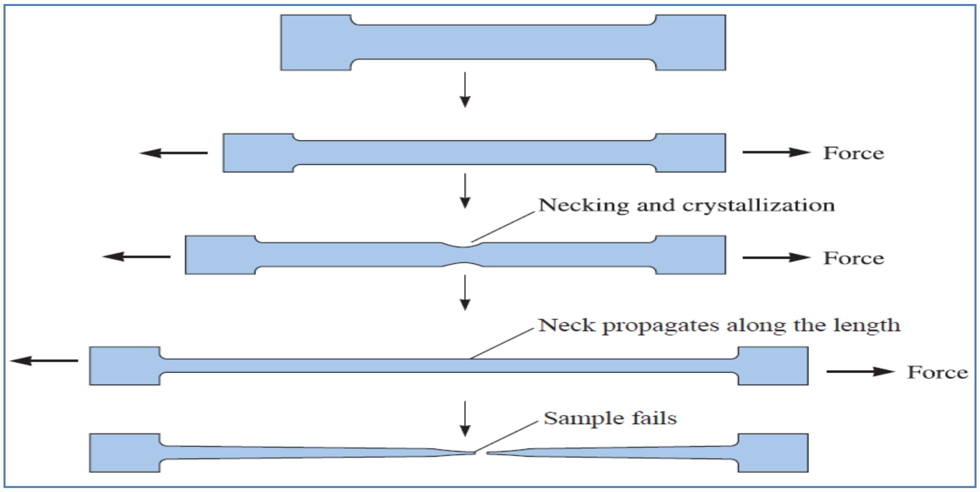


Figure 2.16: Neck behavior of amorphous thermoplastics (Askeland et al., 2011)

2.7 Mechanical Behavior of Polyethylene

2.7.1 Deformation of amorphous polymers and ductile failure

Ductile failure is a type of failure that usually happens over a short length of time at high levels of stress. From the macroscopic level, the ductile tensile failure results in the commencement of observable necking (deformation) in the sample polymer. For polyethylene materials, tensile ductile behavior is influenced by the nature of the semi-crystalline material. As shown in Figure 2.17, tensile ductile deformation is illustrated by a stress-strain curve in the polyethylene material on the micro scale. Before the yield point, no visible deformation is observed in the material and the load is mostly carried by the lamellae of the rigid crystalline. The strain developments of the stress also increase and a yield point occurs. During the period between the yield point and the beginning of strain hardening, the load on the sample being tested remains at a comparatively constant level. In this region, the deformation is the combination of the amorphous phase reorganizing itself and the lamellae of the crystal sliding past each other, but each separate crystal itself remains unbroken. As shown in Figure 2.17, the strain values between 0.5 and 1.0 indicate increasing alignment, orientation of crystalline phases and amorphous phases in the direction of the drawing as the the stress-strain values increase. At a strain value of 1.5, a severe increase in the stress value shows that increased strain causes strain hardening. For the duration of the strain hardening, the amorphous phase has stretched to full extension resulting in more deformation of polymer material in this stage due to the breaking and unfolding of the lamellae as presented in Figure 2.17. The breaking of the lamellae into smaller portions results in the typical coarse tough surface of ductile failure. When the deformation level of the molecular network reaches its limit, the lamellae start to break up into a variety of blocks (Alvarado et al., 2010).

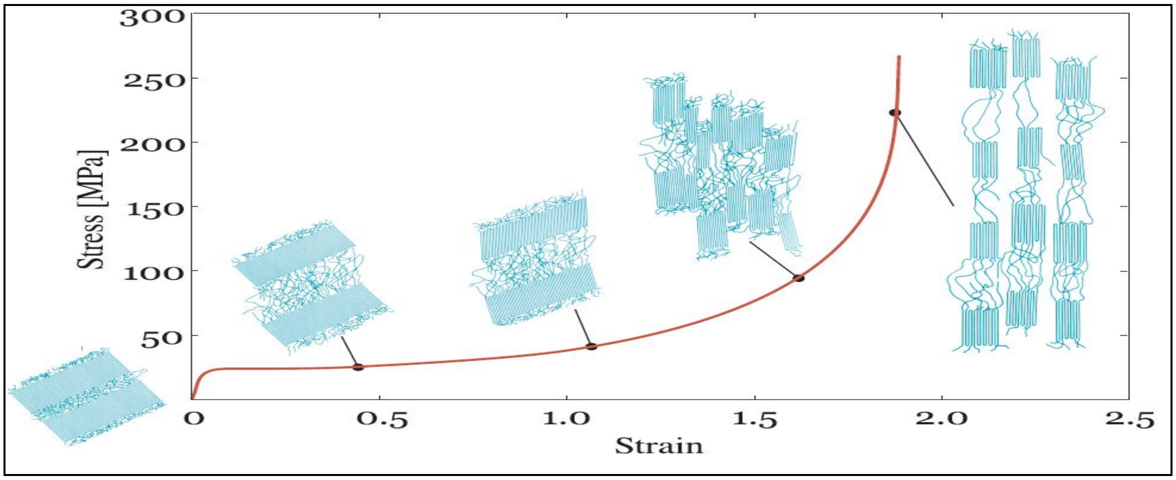


Figure 2.17: Tensile deformation of an amorphous polymer (Bartczak et al., 1992)

2.7.2 Deformation of crystalline polymers and brittle failure

Brittle failure is different from ductile failure since as the polymer material goes through brittle failure, brake cleaning with little deformation of the material occurs and a smooth fracture appears on the surface. Under the scanning electron microscope (SEM), it can be seen that the surface actually involves short random pull outs (Cheng, 2008). Brittle failure occurs when a low stress level is applied over a long period of time. As seen in Figure 2.18 (a-b), from the first steps of brittle fracture the amorphous polymer starts to elongate under tension. The reason for this is that over the longer time period the interlamellar associations under stress start to untangle and relax while the remaining relationships develop very slowly. Once the few remaining interlamellar associations extend to their boundaries, they are not capable of pulling lamellae separately and this results in the brittle fracture of the polymer, as demonstrated in Figure 2.18 (c). Microscopic analysis was employed to verify the deformation mechanisms of the tensile method before and after yielding in the polyethylene materials examined (Cheng, 2008).

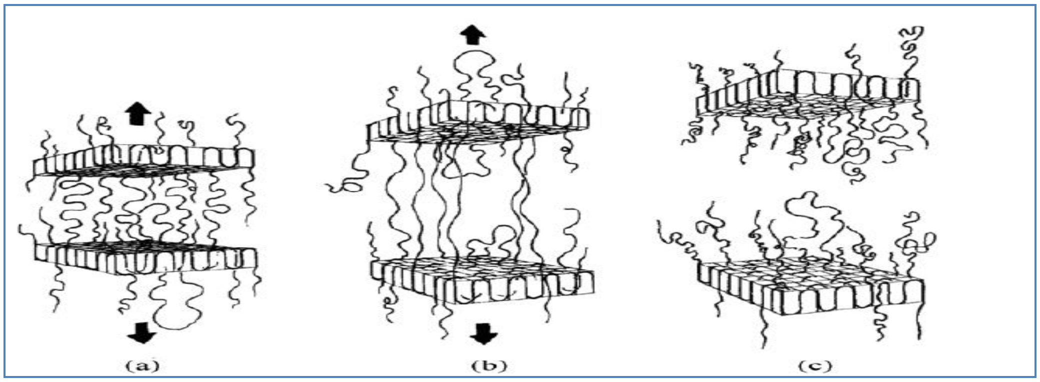


Figure 2.18: Stages of brittle fracture; (a) lamellae starting to pull away (b) tie-molecules stretching tight (c) complete break of lamellae (Cheng, 2008)

2.7.3 Strain hardening

Strain hardening is an event which is seen in completely drawn polymers. The reason for increasing stress during the period of strain hardening is that the molecular orientation of the polymer molecular chains increases the strength of the polymer material. Strain hardening starts to happen once the most amorphous part of the polyethylene is extended to its restrictive extensibility (Maria et al., 2008). The extensibility of the polymer network is affected by the number of the load-behavior connection points in the system. In semi-crystalline polymer materials [for example, high density polyethylene (HDPE)] the network connection points are shaped by crystalline structures and physical entanglements. The deformations at high levels of strain are similar to strain hardening, whereas extreme morphology reform takes place in semi-crystalline polymer materials and the crystalline structure is destroyed (Peterlin, 1965).

2.7.4 Environmental stress cracking

Another type of stress failure is environmental stress cracking (ESC) which occurs in polymers when they are subjected to a dangerous environment such as foamy water. It can be observed in pipe networks and certain polymer applications. The kind of break related to environmental stress cracking ESC is considered a clean crack, as a result of the brittle fracture mechanism. All cracking in polymers due to dangerous environmental conditions (such as the degradation of a polymer as a result of exposure to UV light) can be called environmental stress cracking (ESC). The most important result of such cracking is mechanical failure in the material. Environmental stress cracking (ESC) can cause the catastrophic failure of polyethylene (PE) structures without any kind of visible warning. Environmental stress cracking (ESC) happens at relatively low stress levels since such structures are usually used as service loads (Brostow and Corneliussen, 1986).

2.8 Defects in Crystalline Polymers

Crystalline polymers are solid materials in which defects are caused by chain folding, chain ends and limited molecular freedom of movement. The defects of the polymer result in global (twisting, bending) or local (grain boundaries, dislocations) distortions of the molecular symmetry with marked effects on the material properties. A diagram representation of the defects in the crystallites of the polymer is given in Figure 2.19 to show the localization of the distortion. A characteristic distortion is the twisting and curving of the organic crystals and the polymer molecule, the defects being immediate. The crystalline regions in the polymers are constructed on the long chain molecule structure and are accompanied by at least some amorphous regions. While considered less severe than defect structures in ceramics and metals, crystalline defects like vacancies, dislocations and interstitials have been detected in polymers.

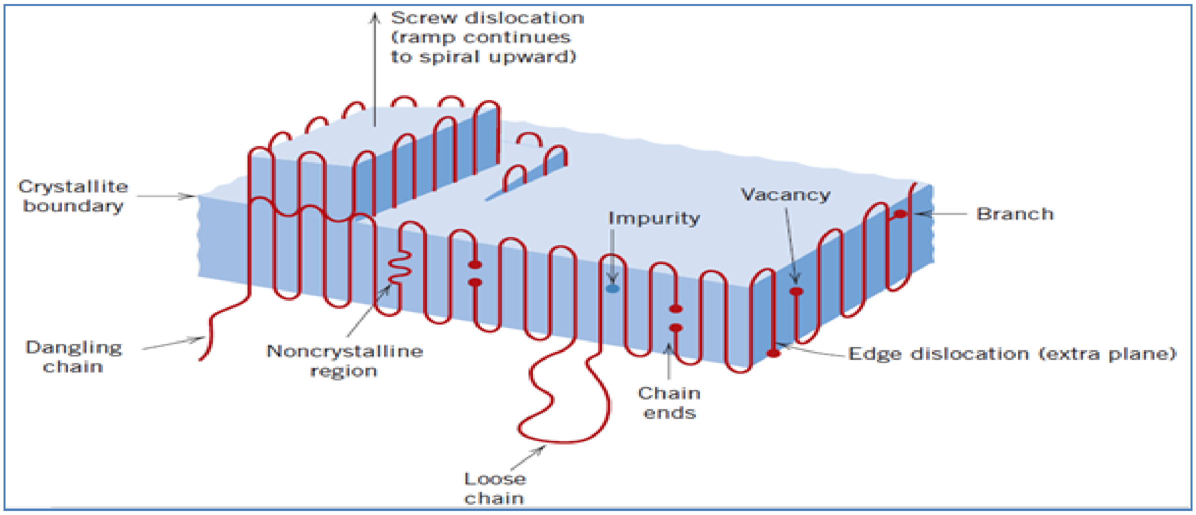


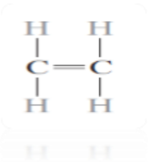
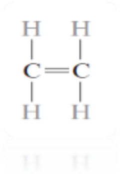
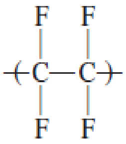
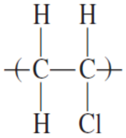
Figure 2.19: Diagram representation of defects in the crystallites of a polymer (Callister and Rethwisch, 2007)

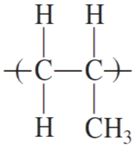
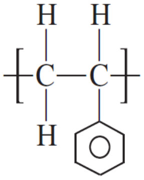
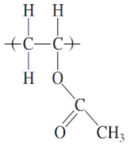
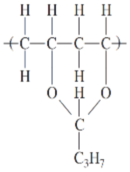
Due to their relationship with the linear macromolecules, molecule chain ends can be observed as point defects because they do not have the same chemical properties as the correct chain. Vacancies, which are typically related to molecular chain ends, and external atoms acting as interstitials are also presented. Screw dislocations and edge dislocations have been detected in the polymers. In the crystalline regions of the polymers, where spherulites compose the folded chain molecules structure, differences in folding may be observed as defects (Kubel et al., 2000; Callister and Rethwisch, 2007).

2.9 Applications of Some Polymers

As regards the chemistry of polymers, it is necessary to note whether the molecular structure has branching or side chains. Knowledge of the molecular structure of polymers can contribute significantly while determining the application process. Those polymers which are used in such applications are shown in Table 2.5. While some of the polymers can have a simple backbone containing its monomer, other polymers can have side branches such as methyl CH3 and the methacrylate group COO–CH3. Copolymers consist of two or more different arrangements of monomers in the interior of the same macromolecules or chains. This system can produce new materials with the desired mixture of properties.

Table 2.5: Properties and uses of some industrially important polymers (Askeland et al., 2011)

Name	**Repeating unit**	**Typical properties**	**Typical use**
High density Polyethylene		Greatest difference in linear and branched due to high crystallinity; high Tm, Tg, softening range; greater tensile strength and hardness.	pipes, sheets, conduits, films, housewares, extrusion coating, bottles, toys, cable insulation and wires
Low density Polyethylene		Dependent on molecular weight distribution, molecular weight, etc.; good toughness and outstanding electrical properties, low density, moisture resistance, resilience, high tear strength	sheeting; films for wrapping bags, poachers, frozen foods, textile materials, etc.; tablecloths, cable insulators and electrical wiring; coating for papers, foils, other films; squeeze bottles
Polytetrafluoroethylene (Teflon)		Chemical inertness, high dielectric strength, low dielectric loss, low friction properties, constant mechanical and electrical properties from 20°C to about 250°C, ductile, high impact strength	Coatings for frying pans; cable and wire insulation; insulation for oils, motors, generators, transformers; pumps; valve packings and gaskets; non-lubricated bearings
Poly (vinyl chloride) and poly (vinylidene		Relatively unstable to light and heat, resistance to chemicals, fire, fungi, insects, moisture	floor coverings and film sheets; food covers, handbags, rainwear, electrical cables, phonograph records

chloride)			
Polypropylene		High tensile strength and hardness, high resistance to marring, good gloss; high softening range permits polymer to be sterilized; chemical inertness, moisture resistance , good electrical properties	filaments, webbing, rope, carpeting, cordage, small housewares, injection molding in automotives, applications in appliance
Polystyrene		Easily colored; easily fabricated; transparent; clear; fair thermal and mechanical properties; good resistance to acids, oxidizing, bases and reducing agents	manufacture of heat- and impact-resistant copolymers, ABS resins, ion-exchange resins, lighting fixtures, toys, plastic optical components, foam, home furnishing packaging
Poly(vinyl acetate)		Water sensitive with respect to physical properties such as strength and adhesion; fair adhesion, generally good weather ability	latex paints, chewing gum,
Poly(vinyl butyral)		Good adhesion to rough/smoothe surfaces good stability & clarity; insensitivity to moisture	as interlayer in automotive safety glass

Some polymers with different backbones, such as poly (methyl methacrylate) PMMA, are used widely to replace glass in manufacturing. Polycarbonate (PC) is a very strong glassy polymer and has good mechanical properties with a range of temperatures, very good dimensional stability and good resistance to burning as well as environmental and chemical conditions. PC is used commonly in transparent roof panels (Koutsos, 2009). Advances in the science of polymers have led to an increase in novel transfer systems. The development of new polymers with unique properties can open the way for a variety of applications previously impossible. Water soluble polymers have widespread industrial applications such as paint, paper, food, textiles, water treatment, coatings, adhesives and constructions. (Kadajji & Betageri, 2011).

CHAPTER 3

METHODOLOGY

3.1 Materials

3.1.1 Polyethylene

Polyethylene (PE) is one of the most important thermoplastic polymers, but its use is limited to certain applications because of its low melting point, swelling or solubility in hydrocarbons, and its tendency to crack when stressed (Khonakdar et al., 2003). Polyethylene is derived from either the modification of natural gas (a methane, ethane, propane mix) or the catalytic cracking of crude oil into gasoline. Under the required temperature and pressure and with the aid of a catalyst, the double bond of the ethylene monomer is unlocked and many monomers connect to form long molecular chains. Today, the methods used for polyethylene manufacturing are typically categorized as "**low pressure**" and "**high pressure**" processes.

High pressure process

Polyethylene was primarily produced in Britain in the 1930's via the high-pressure process by ICI (Imperial Chemical Industries). They discovered that ethylene gas could be converted into a white solid by heating it under very high pressure in the presence of minute quantities of oxygen, as shown in Figure 3.1.

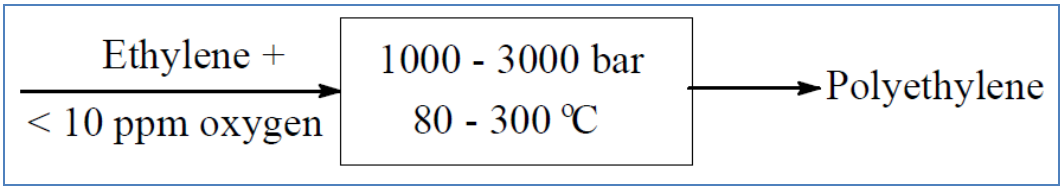


Figure 3.1: High-pressure process used by ICI (Priscilla, 2010)

The polymerisation reaction which occurs is a random one, producing a wide distribution of molecule sizes. By controlling the reaction conditions, it is possible to choose the average molecular weight and molecular weight distribution. Then via the high-pressure process used by ICI, the new plastic ‘polythene’ was produced, and the density of the product is in the range of about 0.915 to 0.930 g/cm^3. This is known as LDPE.

Low pressure process

The creation of the LDPE material was followed by the innovation of HDPE in Germany and Italy in 1952. Researchers succeeded in producing a new aluminum-based catalyst that allowed the polymerization of ethylene at a much lower pressure level than the ICI process, as shown in Figure 3.2

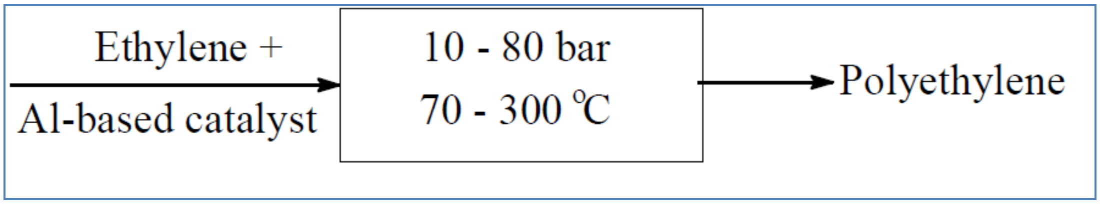


Figure 3.2: Lower-pressure process by ICI (Priscilla, 2010)

The polyethylene obtained using this process was found to be much stiffer than the one produced by the ICI process since it had a density range of around 0.940 - 0.970 g/cm^3. The increased density and stiffness resulted from the much lower chain branching (Priscilla, 2010). This polyethylene belongs to the same family of materials whether in the low density or the high density form. According to the American Society for Testing and Materials (ASTM), polyethylene materials can be separated into four different categories; however, polyethylene material manufacturers use different material designations based on density or molecular weight, as shown in the Table 3.1.

Tables 3.1: Classification of the density polyethylene according to the ASTM (Contreras, J. A. 2007)

Type	ASTM		Industrial Acronym
	Density (unit)	**Terminology**	
I	0.910-0.925	Low	ULLDPE,LLDPE,LDPE
II	0.926-0.940	Medium	MDPE
III	0.941-0.959	High	HDPE
IV	0.960 and above	High-homopolymer	HMWPE-UHMWPE

In this experimental work, the description and characteristic properties of the white polyethylene sheets used in this study are shown in Table 3.2. The most common characteristics of such plastics are their machinability, corrosion resistance, low weight and good electrical insulation and thermal properties. The white polyethylene **(**PE) sheets can be modified in size and colour (Anon, 2014).

Table 3.2: Mechanical properties of PE sheet (Anon, 2014)

Mechanical and physical properties		Value	Unit
Density	ISO 1183	0.950	g/cm^3
Tensile Strength at yield (σ_S)	ISO 527	27	MPa
Elongation at yield (ε_S)	ISO 527	9	%
Elongation at break (ε_R)	ISO 527	≥700	%
Modulus of elasticity (Et)	ISO 527	1150	MPa
Flexural strength	ISO 178	22	MPa

3.1.2 High density polyethylene (HDPE)

High-density polyethylene *(*HDPE*)* has a density range of around 0.941 - 0.965 g/cm^3 ($0.941 < \text{density} < 0.965$) and is the thermoplastic polymer material derived when carbon and hydrogen atoms join together in an organized form. The distribution of the molecular weight and the number of branching chains determine many of the mechanical and chemical properties of the final product. The property characteristics of the polyethylene material depend on the arrangement of the molecular chains. HDPE branches off the main molecular chains. The number, size and type of molecular chains of these side molecular chains determine such properties as density, tensile strength, stiffness, hardness, flexibility and elongation. Since these are the result of the manufacturing effort, they last for the duration of the service performance of the HDPE material.

HDPE is considered to be a semi-crystalline polymer material made up of both crystalline and amorphous regions. The crystalline regions are very well ordered, neatly folded, layered (in parallel) and closely packed molecular chains. Thus, a molecule chain has properties that are locally directionally dependent on the crystal within the crystalline region. The amorphous regions are tangled molecules branching off or preventing the closure and layered packing of the trunks, the random resultant arrangement is less dense.

There are two types of interlamellar links; the first are tie-molecules that are chains crystallized in two or more lamellae at the same time. The second type of inter-lamellar links consists of physical chain entanglements that can be made up by the entanglements of cilia, loose loops and even tie-molecules.

The distribution and size of the crystalline regions are a determining factor in the environmental stress crack resistance and the tensile strength of the end product. During processing, the energy and elevated temperatures associated with the shaping and forming of the polyethylene cause random orientations of molecule chains in the molten material to directionally align in the orifice of the extrude. When the bulk of a polyethylene chain is overcome by tension, the polyethylene movements modify its shape (Gabriel & Moran, 1998).

Different lengths of these molecular chains produce different types of polyethylene, each one taking unique mechanical properties. Longer molecular chain lengths typically produce an increase in the tensile strength of the polyethylene (Hughes et al., 2013). Figure 3.3 provides the arrangements of a crystal lamellae of polyethylene material at different density levels. When the density increases, hardness, strength, and stiffness also increase; however, increasing density also has some disadvantages. For example, increased density results in the polyethylene becoming less ductile and more likely to crack (Alvarado et al., 2010).

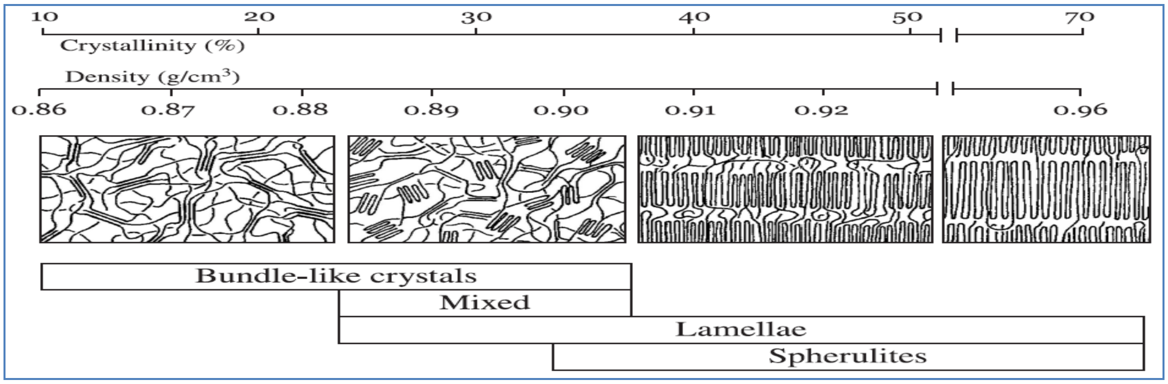


Figure 3.3: Crystal structure classification of polymers (Bensason et al., 1996)

For this experimental work, high-density polyethylene (HDPE) is a very multi-purpose engineering plastic. The description and properties of the HDPE sheet are given in Table 3.3 (Direct plastics, 2014).

Table 3.3: Mechanical properties of HDPE (Direct plastics, 2014)

Mechanical and physical properties		**Value**	**Unit**
Density	ISO 1183	0.955	g/cm^3
Tensile strength at yield (σ_S)	ISO 527	25	MPa
Elongation at yield (ε_S)	ISO 527	9	%
Modulus of elasticity in tension (Et)	ISO 527	1000	MPa
Modulus of elasticity in flexion (Et)	ISO 178	1000-1400	MPa

3.1.3 Ultra-high molecular weight polyethylene (UHMWPE)

Ultra-high molecular weight polyethylene (UHMWPE) is a type of polyethylene material which is categorized as the liner homopolymer, and its monomers are identical to those of other types of polyethylene – the fundamental polymer which is made from ethylene (C2H4). The molecular weight of UHMWPE is 6,000,000 g/mol, while the molecular weight of HDPE is 200,000 g/mol. Many processes are used to obtain UHMWPE in sheets and rods or any shape the manufacturer needs. The sheets produced can range in size, the dimensions depending on the size of the compression press used (Harris et al., 1996).

UHMWPE is a polymer with applications in several different areas. Ultra-high molecular weight polyethylene is very important in the production of implant materials. It has uses in the beverage and food industry because of its capacity to prevent the growth of bacteria and fungi. In addition, it can be used in truck and dumptruck bedliners and in the cores of golf balls, for snow and ski board surfaces and to decrease noise. UHMWPE also has applications in the medical field, where it is used in total joint replacement. It has the highest resistance to impacts in comparison with other plastic materials (Pal et al., 2005).

The several advantages discussed above contribute to the wide use of UHMWPE. In spite of the advantages of this material, there are some drawbacks. As stated above, one advantage of UHMWPE is its ability to resist wear. Unfortunately, there are some serious consequences when dealing with wear, which can cause both mechanical and biological failure (Brunner, 2006).

Polyethylene has different molecular weights that were analysed with the help of wide-angle X-ray diffraction, dynamic mechanical analysis (DMA) and small-angle X-ray scattering (SAXS) to reveal the molecular weight dependence of the mechanical, thermal and crystalline properties (Urena et al., 2014).

In this experimental work, the UHMWPE sheet has a very low friction coefficient and is an excellent material for abrasion resistance and wear. This sheet is tough, smooth, lightweight and easy to weld. The description and properties of the UHMWPE sheet are given in Table 3.4 (Direct plastics, 2014).

Table 3.4: Mechanical properties of UHMWPE (Direct plastics, 2014)

Mechanical and physical properties		Value	Unit
Density	ISO 1183	0.930	g/cm^3
Tensile strength at yield (σ_S)	ISO 527	17	MPa
Elongation at yield (ε_S)	ISO 527	11	%
Modulus of elasticity in tension (Et)	ISO 527	700	MPa
Modulus of elasticity in flexion (Et)	ISO 178	800	MPa

3.2 Density Testing

3.2.1 Sample preparation

The specimens consist of pieces of different polyethylene materials cut to any suitable shape to facilitate proof identity. ISO 1183 was used and the dimensions of each piece must be selected to document the precise measurement of the location center. Specimens that are less than 5 mm in diameter are usually suitable, as shown in Figure 3.4. When cutting test specimens from larger samples of different polyethylene materials, one must be careful to ensure that the physical characteristics of the polyethylene materials are not changed due to extreme high temperatures. The surface of the test specimen must be smooth and free from hollows to minimize the set up of the air bubbles upon immersion in the liquid; otherwise, there will be errors in testing (EN ISO 1183, 2004).

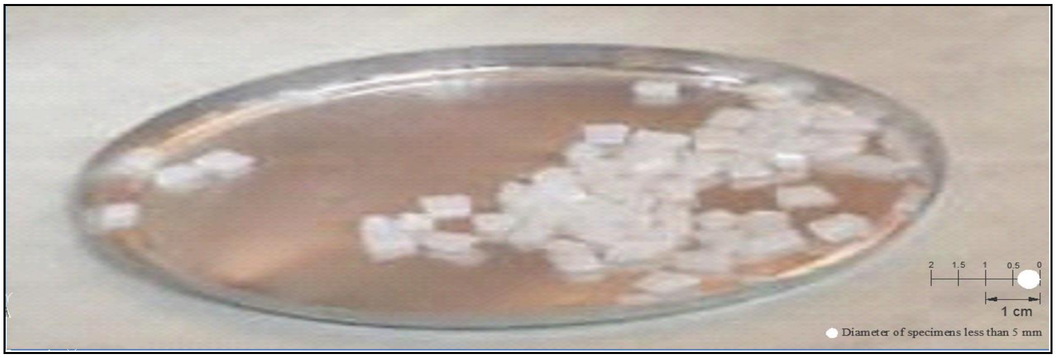


Figure 3.4: Test specimens for the density test

3.2.2 Density tests

Density is the ratio of the mass (m) of the sample to its unit volume V (at temperature T) expressed in kg/m^3, (g/cm^3). Specific gravity is the measure of the ratio of the mass (m) of the sample material at room temperature (23°C) to the same volume of water. Density determination by Sartorius MSU224S-000-DU is a very precise method. The theoretical density can be computed using the following equation (Wolfhart, 2014) :

$$\rho = W1/\ [(W1+W2)\ -W3] \times \text{Density of ethanol}\ (0.79\ \text{g/cm}^3) \qquad (3.1)$$

Where W1 is the mass (m) of the test specimen in air, W3 is the mass (m) of the Sartorius MSU224S-000-DU containing ethanol, and W2 is the mass (m) of the Sartorius MSU224S-000-DU containing the test specimen and ethanol. Using the above formula, the density was measured (EN ISO 1183, 2004), (Wolfhart, 2014). Density is often used to see differences in the physical structure or composition of plastic materials. The density of plastic materials often depends on the test specimen preparation method chosen. For this study, ISO 1183 was used to determine the density of different polyethylene materials. The test was carried out on a Sartorius MSU224S-000-DU materials testing machine, as shown in Figure 3.5, using the test liquid (ethanol-C_2H_5OH) at room temperature (23°C). The test procedure for the density test is as follows: the test specimen is weighted in air, then weighted immersed in liquid (ethanol-C_2H_5OH) at room temperature (23°C) and the density is calculated.

The accuracy of the method for measuring the density depends on many factors, such as apparatus (Repeatability ≤ ± 0.07 mg, Linearity ≤ ± 0.2 mg, Weighing capacity 220 g, Readability 0.1 mg.), liquid bath (capable of being thermostatically controlled to within ±0,1°C or ±0,5°C, depending on the sensitivity required) and calibrated glass floats (covering the density range in which measurements are to be made and approximately evenly distributed throughout this range. Determine the exact density of each glass float calibrated as above by placing it in a mixture of two suitable liquids in the bath maintained at T ± 0,1°C, where T is 23°C or 27°C (EN ISO 1183, 2004).

Figure 3.5: Sartorius MSU224S-000-DU materials testing machine

3.3 Tensile Testing

3.3.1 Sample preparation

The preparation of the test specimens for the tensile test includes cutting die from a sheet of the raw material and then using the milling machine MOD 1643 (Figure 3.6) according to the operation instructions.

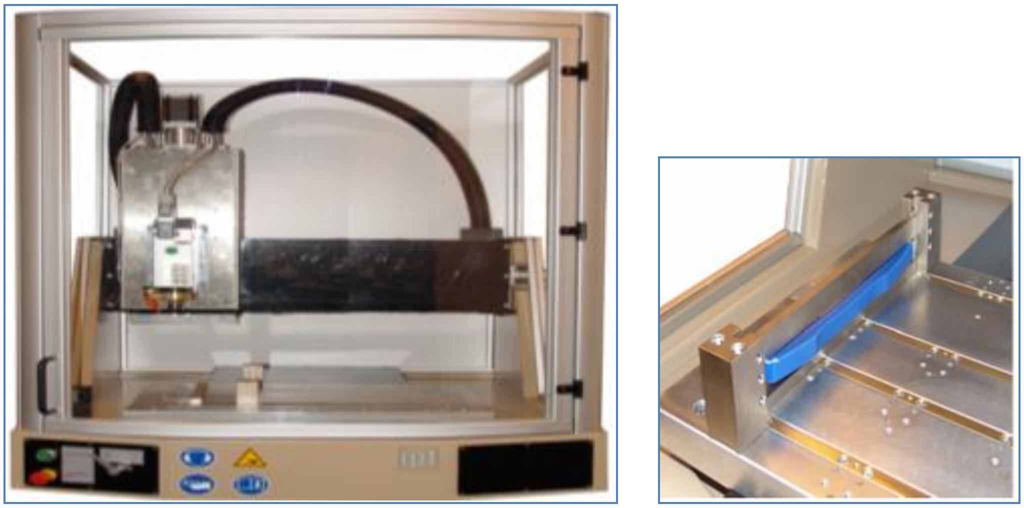


Figure 3.6: Operation of the milling machine MOD 164

The thicknesses of the polyethylene materials used for test specimens are 8mm and 12.7 mm according to ISO 527. The specimen and the dimensions are illustrated in Figure 3.7. The dimensions and tolerance standards are shown in Table 3.5. The usual specimen shape used for tensile tests is the dog-bone. For the duration of the test, a uniaxial load is applied at both ends of the specimen. The ratio of the nominal strain to the crosshead speed is used for the original gauge length of the specimens (EN ISO 527-2, 1996), (Standard ASTM D638 2008) and (Shan et al., 2007).

Table 3.5: Specimen dimensions for the tensile test (EN ISO 527-2, 1996)

Symbol	Description	Dimensions (mm)
l_3	Overall length	200±5
l_1	Length of narrow parallel-sided portion	60±0.5
r	Radius	≥60
l_2	Distance between broad parallel-sided portions	106 to120
b_2	Width at ends	20,0±0.2
b_1	Width of narrow portion	10,0 ± 0,2
h	Preferred thickness	That of the sheet
L_0	Gauge length	50,0 ± 0,5
L	Initial distance between grips	115 ± 1

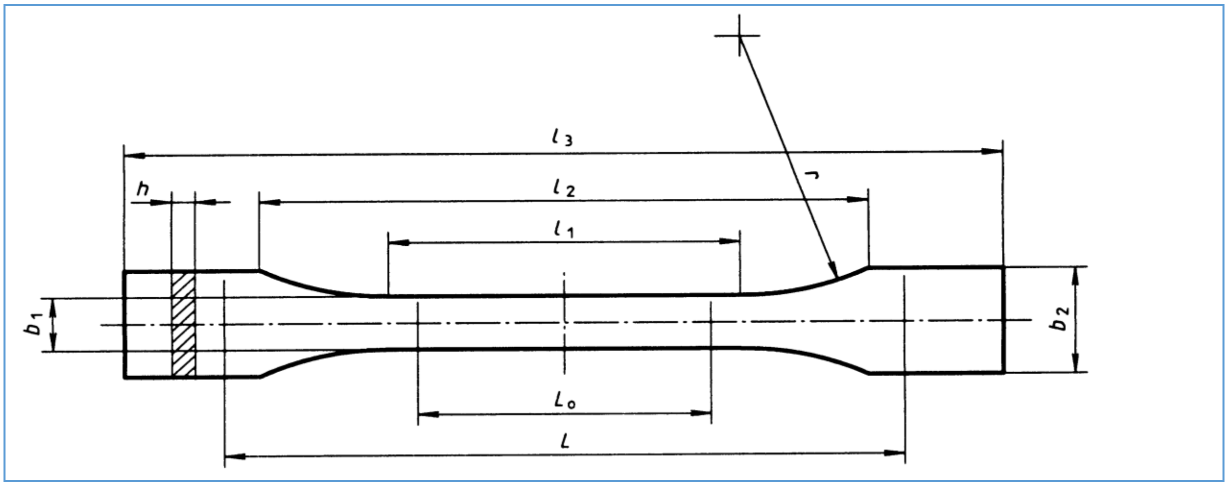


Figure 3.7: Sample prepared for the tensile test (EN ISO 527-2, 1996)

3.3.2 Tensile test

Tensile tests measure the force required for a break and the extent of elongation or stretching of the specimen. The stress-strain curves are produced based on the tensile tests and are used to determine tensile modulus. The data acquired from the results of the tensile tests can help identify the best materials and design equipment to survive the application of forces and make an important contribution to the quality control of materials (EN ISO 527-2, 1996), (Wolfhart, 2014). In this study, the ISO 527-2 tensile test standard is used. The specimen is positioned in the grips of the test machine, and then the grip is pulled and stretched to the failure point. The speed is determined in ISO 527-2 for the material requirement, and the tensile modulus and elongation are determined by an extensometer. The test was carried out on the Testometric M500-100 AT Universal testing machine, an advanced materials testing machine that uses a wide range of testing applications up to (100) kN. The Testometric materials testing machine has a twin column with a maximum crosshead movement of 1050 mm and is connected to a computer as shown in Figure 3.8. Tensile tests for plastics enable the measurement of:

- Tensile strength at yield point
- Tensile modulus
- Tensile strain

- Elongation and percent of elongation at break
- Elongation and percent of elongation at yield

The calculation and expression of the results of the stress at yield on the basis of the initial cross-section area of the test specimen polyethylene materials were done using the following equation:

$$\sigma = \frac{F}{A_o} \tag{3.2}$$

The calculation of the elongation and percent elongation from yield was done using the following equation:

$$\varepsilon = \frac{l - l_o}{l_o} \times 100 \tag{3.3}$$

All the data produced is beneficial for research and development and for qualitative characterization. Thus, all the factors must be carefully controlled to obtain accurate relative results (EN ISO 527-2, 1996), (Standard ASTM D638, 2008). The tensile behaviour of semi-crystalline materials is analysed at dissimilar strain rates at a wide range of temperatures from 23 to 120°C (Gomez et al., 2012).

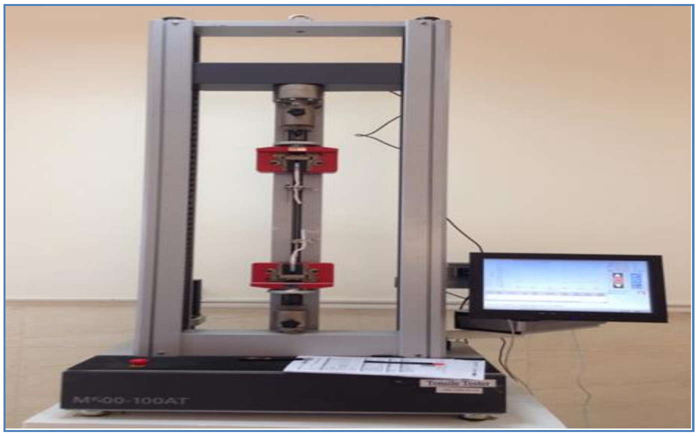


Figure 3.8: Testometric M500-100 AT universal testing machine

3.4 Flexural Testing

3.4.1 Sample preparation

The test specimens were cut from sheets and the actual dimensions used in calculations were measured in accordance with test methods ISO 178. The dimensions of the specimens of the solid polyethylene must be measured accurately; all dimensions are important in determining the actual results for the different properties of the tests as shown in Figure 3.9. A variety of specimen shapes can be used for tests, but for ISO 178 a specific type of specimen is described. The dimensions of the preferred test specimen are:

Length, *l*: 80 ±2 mm
Width, *b*: 10.0 ±0.2 mm
Thickness, *h:* 4.0±0.2 mm

When it is undesirable or impossible to use the preferred test specimen, other test specimens can be used. The following limits will apply. The length and thickness of the test specimen must have the same measurements as the preferred test specimen, i.e.

$$\frac{l}{h} = 20 \pm 2 \tag{3.4}$$

The width of the specimen is given in Table 3.6.

Table 3.6: Values of the test specimen width *b* in relation to thickness *h* (ISO 178, 2001)

Nominal thickness h	Width b
$1 < h \leq 3$	25±0.5
$3 < h \leq 5$	10.0±0.5
$5 < h \leq 10$	15.0±0.5
$10 < h \leq 20$	20.0±0.5
$20 < h \leq 35$	35±0.5
$35 < h \leq 50$	50.0±0.5

The size (in mm) of the polyethylene specimens used for this study is:
Length, *l*: 200 ±2 mm
Width, *b*: 20 ±0.2 mm
Thickness, *h:* 12.7±0.2 mm

The sizes of the high-density polyethylene and the ultra-high molecular weight polyethylene specimens used in the study are:
Length, *l*: 100 ±2 mm
Width, *b*: 15 ±0.2 mm
Thickness, *h:* 8±0.2 mm

The polishing of the test specimens must be done in only one direction because the values achieved on the specimens with machined surfaces may differ from those achieved on the specimens with the original surfaces of the sheets (ISO 178, 2001), (ASTM D790 1997).

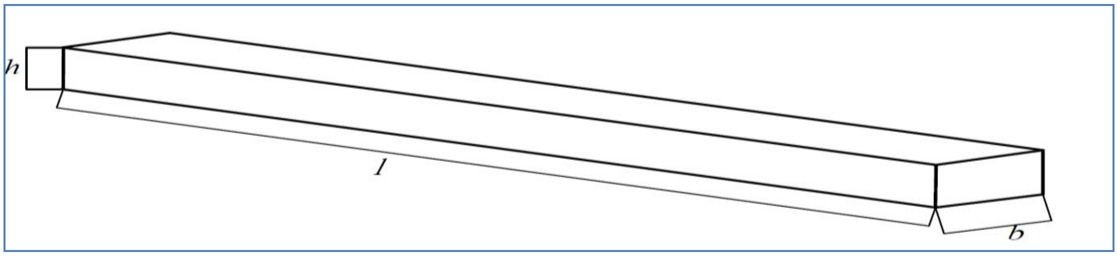


Figure 3.9: A 3D view of the flexural test sample

3.4.2 Flexural test

Flexural test methods were employed for the determination of the flexural properties of the type of polyethylene materials used in this study. Flexural test techniques are usually applicable to both semi-rigid and rigid polyethylene materials (ASTM D790, 1997). These flexural test methods are applied using the three point loading organization appropriate for a simple supported test beam. In this study, the ISO 178 flexural test standard was followed for testing specimens of rigid polyethylene materials. The specimens were tested on the WP 300.04 bending device, a materials testing machine that has a maximum load range for testing applications up to (20) kN. The specimen was positioned on the two supports and the central loading edge must be arranged as shown in Figure 3.10.

Figure 3.10: WP 300.04 bending device (Tangkasanugerah, C., 2014)

The test speed is the rate of relative movement between the two supports and the loading edge. The two supports and the midway loading edge must be arranged as illustrated in Figure 3.11. The two supports and the midway loading edge must be parallel to within ±0.2 mm in excess of the width of the test specimen.

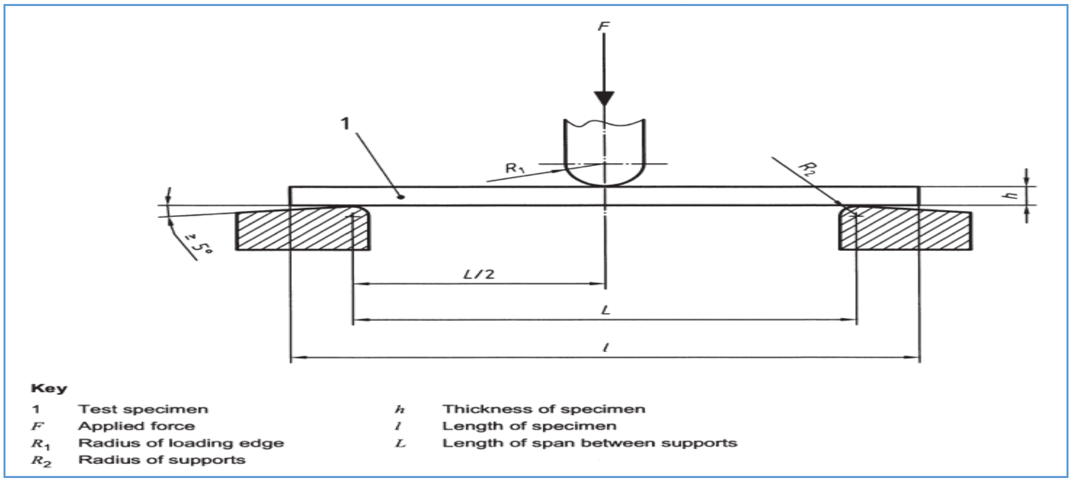


Figure 3.11: Position of test specimen at the start of the test (ISO 178, 2001)

The calculation and expression of the results of the flexural test on polyethylene materials regarding such parameters as flexural stress (σ_f) are done using the following equation:

$$\sigma_f = \frac{3FL}{2bh^2} \tag{3.5}$$

For the parameter of flexural strain (ε_f), the following equation is used:

$$\varepsilon_f = \frac{6\mathrm{sh}}{\mathrm{L}^2} \tag{3.6}$$

The calculation of the flexural modulus (E_f) is done using the following equation:

$$E_f = \frac{\sigma_f}{\varepsilon_f} \tag{3.7}$$

The bending specimen was investigated and the relationship between the load and the elastic deformation was evaluated (ISO 178, 2001).

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Density Test

Density tests were performed in the construction and housing laboratory of Slemani according to the procedure outlined in ISO 1183. The machine used in the study was a Sartorius MSU224S-000-DU. The dry weight of each sample was measured on an electronic balance of the Sartorius MSU224S-000-DU. The samples were then weighed and submerged in Ethanol, C_2H_5OH with a density of Ethanol is 0.79 g/cm^3.

Three specimens with diameters of less than 5 mm were tested at each step and the average values were considered. The density values of the polyethylene (PE), high density polyethylene (HDPE) and ultra-high molecular weight polyethylene (UHMWPE) for each test in this study are provided in Tables 4.1, 4.2 and 4.3 respectively. In addition, the densities of polyethylene (PE), high density polyethylene (HDPE) and ultra-high molecular weight polyethylene (UHMWP) were in the range of 0.940-0.960 g/m^3.

Table 4.1: Results of the density measurements for PE

Test No. (PE)	Mass in air W1 (g)	Mass in liquid W3 (g)	Liquid density (g/cm^3)	Density (g/cm^3)
1	0.1078	0.0186	0.79	0.955
2	0.1096	0.0192	0.79	0.958
3	0.1070	0.0185	0.79	0.955
Average	0,1081	0.0187	0.79	0.956

The average of the three densities measured for PE (0.956 g/cm^3) here appeared to be greater than is given by the ISO 1183 standard (0.950 g/cm^3) seen in Table 3.2.

Table 4.2: Results of the density measurements for HDPE

Test No. **(HDPE)**	**Mass in air** **W1 (g)**	**Mass in liquid** **W3 (g)**	**Liquid density** **(g/cm^3)**	**Density** **(g/cm^3)**
1	0.1015	0.0180	0.79	0.960
2	0.1052	0.0160	0.79	0.932
3	0.1071	0.0180	0.79	0.950
Average	0,1046	0.0173	0.79	0.947

The average of the three densities measured for HDPE (0.947 g/cm^3) here was found to be below the value (0.955 g/cm^3) given by the ISO 1183 standard seen in Table 3.3, but still within the range of values (0.941 - 0.959 g/cm^3) stated in the ATEM and industrial polyethylene density standard seen in Table 3.1.

Table 4.3: Results of the density measurements for UHMWPE

Test No. **(UHMWPE)**	**Mass in air** **W1 (g)**	**Mass in liquid** **W3 (g)**	**Liquid density** **(g/cm^3)**	**Density** **(g/cm^3)**
1	0.1018	0.0159	0.79	0.936
2	0.1053	0.0175	0.79	0.947
3	0.1009	0.0167	0.79	0.947
Average	0.1026	0.0167	0.79	0.943

The average of the three densities measured for UHMWPE (0.943 g/cm^3) here was greater than the value given in the ISO 1183 standard (0.930 g/cm^3) in Table 3.4 but less than the range of values (0.960 g/cm^3 and above) of the ATEM and industrial polyethylene density standard seen in Table 3.1.

4.2 Tensile Test

Tensile tests were performed in the central construction and housing laboratories of the Slemani Polyethylene Lab unit according to the procedure outlined in ISO 527-2. A universal testing machine 0500-10084 – Testometric was used. A50.0 kN head load with 10.0 N pretension and 50 mm gauge length was used for the test. The crosshead speed was fixed at 25.0 mm/min in all the experiments with PE, and 50.0 mm/min in all the experiments with HDPE and UHMWPE. The dimensions of the specimens for PE were 10 mm in width, 200 mm in length and 12.7 mm in thickness. While the HDPE and UHMWPE samples had the same width and length as PE, they had a thickness of 8 mm.

Young's modulus (E), tensile strength at yield (σ_S), strain (ε), elongation at yield (ε_S) and elongation at break (ε_R) were measured. Five specimens were tested at each step and the average values were considered. The mechanical properties of the PE, HDPE and UHMWPE samples are listed in Tables 4.4, 4.5 and 4.6 respectively.

The stress-strain curves of the PE, HDPE and UHMWPE samples are shown in Figures 4.1, 4.2 and 4.3, respectively. The stress-strain curves of PE and HDPE displayed ductile failure. The stress-strain curve of UHMWPE differed dramatically from those of PE and HDPE since it showed less failure behaviour.

As shown in Figures 4.1 and 4.2, an elastic deformation occurred in the PE and HDPE materials. The covalent bonds in the molecular chain were distorted and stretched. In the PE and HDPE materials, plastic deformation occurred when a stress forced maximum yield strength. Chains undergoing plastic deformation stretch, slide, rotate, and untangle under force to the point of permanent deformation. The stress-strain curve of UHMWPE shows that the relationship between stress and strain is proportional to the strain increase when the stress increases until it reaches the yield point. However, elastic deformation occurred and plastic deformation did not, as shown in Figure 4.3.

As seen in Figures 4.4 and 4.5, ductile tensile failure can be observed as necking (deformation) in the samples of PE and HDPE materials, where the behavior is influenced by the nature of the covalent bonds in the molecular chain of those materials. The strain of

UHMWPE increased proportionally when the stress increased and necking did not occur, but the thickness of the gauge length of the sample continued to thin down until it broke. The brittle failure of the UHMWPE was different from the ductile failure of the PE and HDPE. The UHMWPE material had a clean break with little deformation and a smooth fracture which appeared on the surface as shown in Figure 4.6.

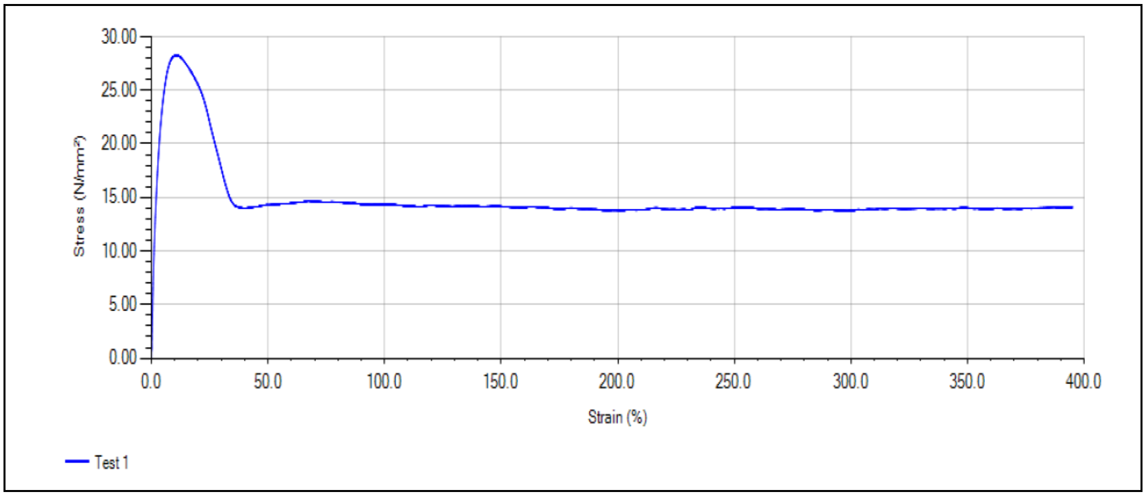


Figure 4.1: Stress-strain curve of PE obtained from sample 1 in Table 4.4

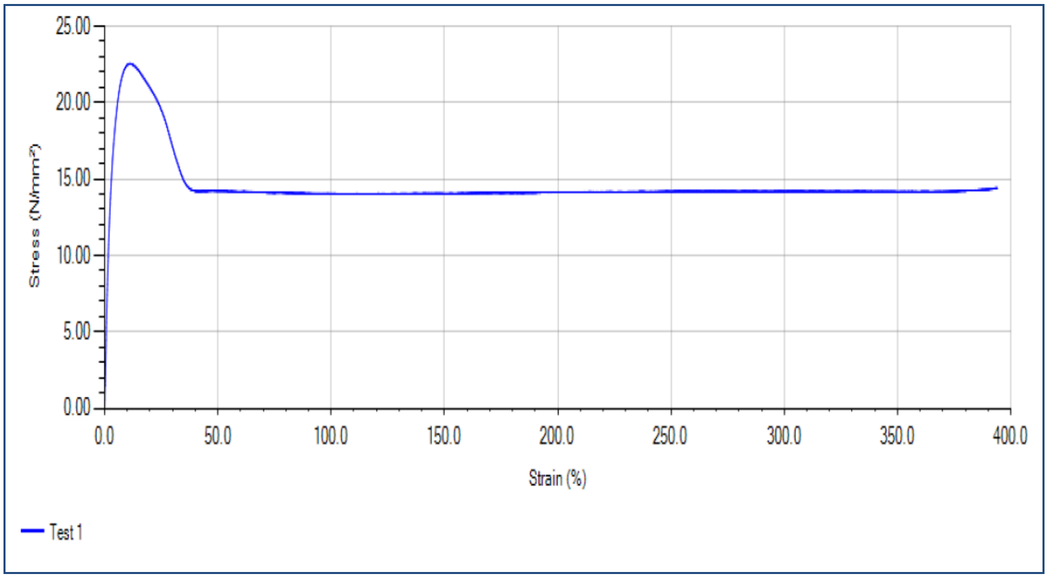


Figure 4.2: Stress-strain curve of HDPE sample 1 in Table 4.5

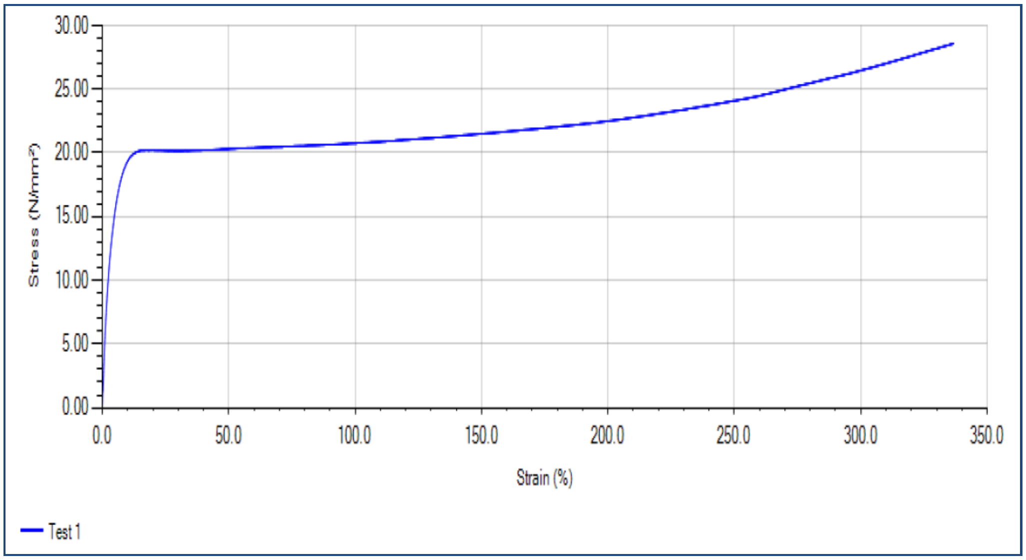


Figure 4.3: Stress-strain curve of UHMWPE sample 1 of Table 4.6

Table 4.4: Results of tensile test for PE

Test No. (PE)	**Tensile strength at yield (σ_y) (MPa)**	**Tensile strength(σ_S) (MPa)**	**Strain (ε)**	**Elongation at yield (ε_S)**	**Elongation at break (ε_R)**	**Young's Modulus (E) (MPa)**
1	28.261	28.261	395.131	6.902	690.262	937.762
2	28.365	28.365	386.700	6.734	673.4	733.514
3	28.191	28.191	394.022	6.880	688.044	951.369
4	28.371	28.371	394.735	6.894	689.47	805.621
5	28.159	28.159	392.833	6.856	685.666	718.938
Average	28.268	28.268	392.684	6.853	685.368	829.440

The average of the five tensile strength values for PE (28.268 MPa) here appeared to be greater than is given by the ISO 527 standard (27 MPa), as seen in Table 3.2. The average of the five elongation at yield values for PE (6.853 %) here appeared to be lower than is given by the ISO 527 standard (9%), as can be seen in Table 3.2. The average of the five elongation at break values for PE (685.368) here appeared to be lower than is given by the ISO 527 standard (>700), as seen in Table 3.2.

Table 4.5: Results of tensile test for HDPE

Test No. (HDPE)	**Tensile strength at yield (σ_y) (MPa)**	**Tensile strength(σ_S) (MPa)**	**Strain (ε)**	**Elongation at yield (ε_S)**	**Elongation at break (ε_R)**	**Young's Modulus(E) (N/mm^2)**
1	22.544	22.544	394.391	6.887	688.782	655.462
2	22.456	22.456	395.393	6.907	690.786	674.823
3	22.531	22.531	396.706	6.934	693.412	681.591
4	22.606	22.606	393.480	6.869	686.968	667.635
5	22.718	22.718	395.727	6.914	691.454	674.678
Average	22.571	22.571	395.139	6.902	690.280	670.849

The average of the five tensile strength values for HDPE (22.571 MPa) here was found to be above the value (25 MPa) given by the ISO 527 standard, as seen in Table 3.3. The average of the five elongation at yield values for HDPE (6.902 %) here appeared to be lower than is given by the ISO 527 standard (9%), as shown in Table 3.3. The average of the five Young's Modulus values for HDPE (670.849 MPa) here appeared to be lower than is given by the ISO 527 standard (1241 MPa), as can be seen in Table 2.4.

Table 4.6: Results of tensile test for UHMWPE

Test No. (UHMWPE)	Tensile strength at yield (σ_y) (MPa)	Tensile strength (σ_S),(MPa)	Strain (ε)	Elongation at yield (ε_S)	Elongation at break (ε_R)	Young's Modulus(E) (MPa)
1	20.287	28.591	336.978	5.739	573.956	422.595
2	20.600	28.038	319.163	5.383	538.326	492.038
3	20.500	27.307	297.411	4.948	494.822	464.078
4	20.530	28.845	305.958	5.119	511.916	493.391
5	20.560	27.731	306.633	5.132	513.916	501.837
Average	20.500	28.102	313.228	5.264	526.587	474.787

The average of the five tensile strength at yield values for UHMWPE (20.500 MPa) was greater than the value given in the ISO 527 standard (17 MPa) seen in Table 3.4. Nevertheless, the average of the five elongation at yield values for UHMWPE (5.264%) appeared to be lower than is given by the ISO 527 standard (11%), as can be seen in Table 3.4. The average of the five Young's Modulus values for UHMWPE (474.787 MPa) appeared to be lower than is given by the ISO 527 standard (689 MPa), as shown in Table 2.4.

4.3 Flexural Test

The flexural tests were performed in the laboratories of Slemani Polytechnic University according to the procedure outlined in ISO 178. The flexural tests were performed on a universal testing WP 300.04 Bending Device (25.0 kN head load) machine with a 3 point bend fixture. The specimen dimensions for PE were 20 mm in width, 200 mm in length and 12.7 mm in thickness, while the HDPE and UHMWPE were 15 mm in width, 100 mm in length and 8 mm in thickness. Five specimens were tested at each step and the average values were considered.

The force-deflection curves for PE, HDPE and UHMWPE are presented in Figures 4.7, 4.8 and 4.9 respectively. Force-deflection curves showed that the deflection in the beam in the PE, HDPE, and UHMWPE increases with an increase in the force until the point where deformation occurs and becomes permanent – (0.21, 9.77), (0.16, 5.01) and (0.13, 5.12) respectively.

The flexural properties of strength, strain and modulus for PE, HDPE, and UHMWPE are demonstrated in Tables 4.7, 4.8 and 4.9. The flexural strength of the PE, HDPE, and UHMWPE samples was measured to find each material's stiffness. Flexural strength was determined by the maximum force that a PE, HDPE, and UHMWPE material could withstand before it broke or yielded. Yield means that a material is past its recoverable deformation, so it will no longer go back to the original shape.

Figures 4.10, 4.11, and 4.12 show the flexural test specimens of PE, HDPE, and UHMWPE respectively. From the start before the yield point of the material, no visible flexion is observed and a load is mostly carried by the lamellae of the amorphous and crystalline regions. The flexural developments of the load also increase and a yield point occurs. The yield is the deformation, it is the combination of the amorphous phase reorganizing itself and the lamellae of the crystal sliding past each other, but each separate crystal itself remains unbroken.

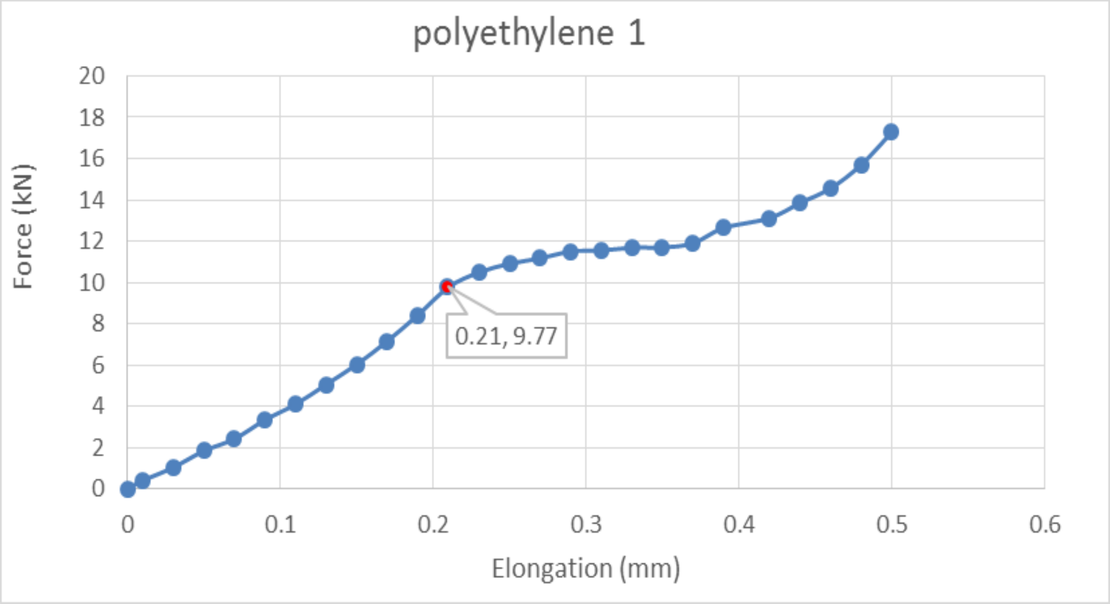


Figure 4.7: Force-deflection curve of PE for sample 1 of Table 4.7

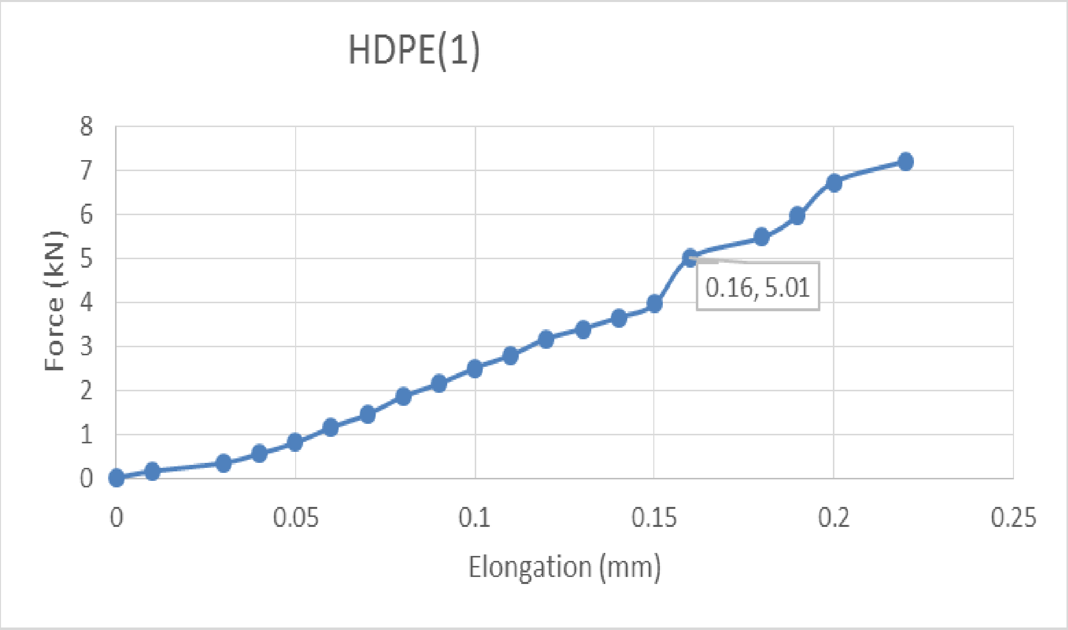


Figure 4.8: Force-deflection curve of HDPE for sample 1 of Table 4.8

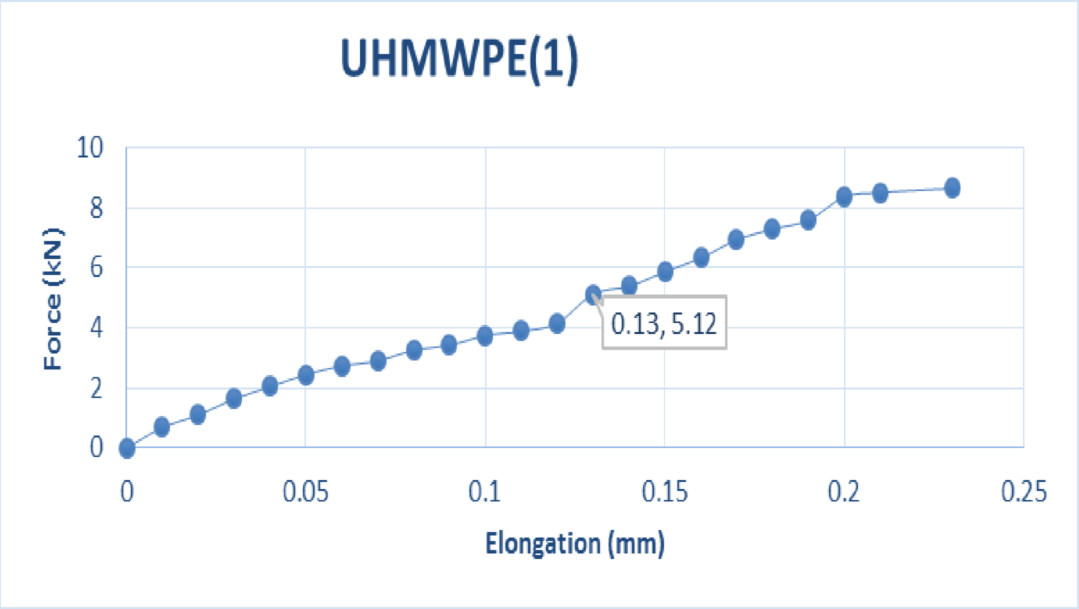


Figure 4.9: Force-deflection curve of UHMWPE for sample 1 of Table 4.9

Table 4.7: Results of flexural test for PE

Test No. (PE)	Force (kN)	Deflection (S) (mm)	Flexural strength (σ_f) (MPa)	Flexural strain (ε_f)	Flexural Modulus (E_f) (MPa)
1	0.21	9.77	19.53	0.0186	1050
2	0.22	10.12	20.46	0.0192	1065
3	0.18	9.2	16.74	0.0175	956
4	0.17	6.9	15.81	0.0131	1206
5	0.2	9.53	18.60	0.0181	1027
Average	0.19	9.10	17.67	0.0173	1021

The average of the five flexural strength values for PE (17.67 MPa) appeared to be less than is given by the ISO 178 standard (22 MPa) seen in Table 3.2.

Table 4.8: Results of flexural test for HDPE

Test No. (HDPE)	Force (kN)	Deflection (S) (mm)	Flexural strength (σ_f) (MPa)	Flexural strain (ε_f)	Flexural Modulus (MPa)
1	0.16	5.01	25	0.024	1041
2	0.17	4.31	26.56	0.020	1328
3	0.16	4.09	25	0.019	1315
4	0.15	5.2	23.43	0.024	976
5	0.16	4.75	25	0.022	1136
Average	0.16	4.67	25	0.022	1136

The average of the five flexural modulus values for HDPE (1136 MPa) was found to be within the range of values (1000 -1400 MPa) given by the ISO 178 standard (Table 3.3).

Table 4.9: Results of flexural test for UHMWPE

Test No. **(UHMWPE)**	**Force (kN)**	**Deflection (s) (mm)**	**Flexural strength (σ_f) (MPa)**	**Flexural strain (ε_f)**	**Flexural Modulus (MPa)**
1	0.13	5.12	20.31	0.024	846
2	0.12	3.61	18.75	0.017	1102
3	0.12	4.35	18.75	0.020	937
4	0.11	4.61	17.18	0.022	780
5	0.11	3.82	17.18	0.018	954
Average	0.118	4.30	18.43	0.020	921

The average of the five flexural modulus values for UHMWPE (921 MPa) appeared to be greater than the 800 MPa given by the ISO 178 standard (Table 3.4).

Figure 4.10: A test sample of PE before and after the flexural test

Figure 4.11: A test sample of HDPE before and after the flexural test

Figure 4.12: A test sample of UHMWPE before and after the flexural test

The mechanical, tensile and flexural properties of PE, HDPE and UHMWPE are shown in Table 4.10, which also gives a comparison of the results of the density, tensile and flexural tests of the Sangir and Direct plastics companies with the findings of the present study.

Table 4.10: Comparison of tensile and flexural properties of PE and HDPE and UHMWPE with the supplier's data

Material Property	Standard	Units	PE	HDPE	UHMWPE
Density (ρ)[1]	ISO 1183	g/cm^3	0. 956	0. 947	0.943
Density (ρ)[2]	ISO 1183	g/cm^3	0. 950	0.955	0.930
Tensile strength at yield (σ_S) [1]	ISO 527	MPa	28.268	22.571	20.500
Tensile strength at yield (σ_S)[2]	ISO 527	MPa	27	25	17
Elongation at yield (ε_S)[1]	ISO 527	%	9	9	11
Elongation at yield (ε_S)[2]	ISO 527	%	6.853	6.902	5.264
Elongation at break (ε_R)[1]	ISO 527	-	685.368	690.280	526.587
Elongation at break (ε_R)[2]	ISO 527	-	≥ 600	≥ 600	≥ 500
Young's Modulus (E)[1]	ISO 527	MPa	829.440	670.849	474.787
Young's Modulus (E)[2]	ISO 527	MPa	1150	1000	700
Flexural strength (σ_f)[1]	ISO 178	MPa	17.67	25	18.43
Flexural strength (σ_f)[2]	ISO 178	MPa	22	-	-
Flexural modulus (E_f)[1]	ISO 178	MPa	1021	1136	921
Flexural modulus (E_f)[2]	ISO 178	MPa	-	1000-1400	800

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[1] present work

[2] Direct Plastic& Anon, 2014

The polyethylene materials at higher density and molecular weight became more rigid and reduced the elongation at break (Rosa et al., 2005). The basic molecular weight in different solid polyethylene materials has a major influence on certain mechanical properties (Imbeni et al., 2001).

A comparison of the results for different polyethylene samples shows that the mechanical, tensile and flexural properties of PE were generally higher than those of HDPE and UHMWPE. As shown in Table 4.10, there is some discrepancy between the results of the present study and the Sangir and Direct plastics companies' data, as well as that of ISO 527 and 178. This discrepancy may have arisen due to the choice of parameters for the tensile, density and flexural tests, such as ambient temperature, humidity, dimensional compliance and size of specimen (Gabauer, 2000).

The results of flexural testing are influenced by such factors as contact stress, wedging stress, beam twisting and friction at beam contact points and load dislocation. The roles of corner chamfers and load readout errors cannot be neglected either. Another error can result from increasing the load manually (Baratta et al., 1987). The sensor of the machine test shows a high sensitivity to flexion, so manually increasing the load in this test is also undesirable (Kuang et al., 2002).

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this work, the density, tensile and flexural properties of three polyethylene types, namely, PE, HDPE and UHMWPE were investigated. The physical and mechanical properties of polyethylene were measured using three different tests (density, tensile and flexural test) and compared with the results of previous studies.

The densities of PE (0.956 g/cm^3), HDPE (0.947 g/cm^3) and UHMWPE (0.943 g/cm^3) were found. The tensile strengths at yield of PE, HDPE and UHMWPE were 20.500 MPa, 22.571 MPa and 28.102 MPa, respectively, while elongations at break were 685.368%, 690.280% and 526.587%. Flexural strengths were 17.67 MPa, 25 MPa and 18.43 MPa for PE, HDPE and UHMWPE, respectively. The flexural modulus of PE was 1021 MPa, while those of HDPE and UHMWPE were 1136 MPa and 921 MPa, respectively, were also found.

While the densities of PE (0.950 g/cm^3), HDPE (0.955 g/cm^3) and UHMWPE (0.930 g/cm^3), were given by the supplier’s data of these materials. The tensile strengths at yield of PE (27 MPa), HDPE (25 MPa) and UHMWPE (17 MPa) and the elongations at break of PE (≥ 600), HDPE (≥ 600) and UHMWPE (≥ 500). The flexural strength of PE (22 MPa), then the flexural modulus HDPE (1000-1400 MPa) and UHMWPE (800 MPa), were given by the supplier’s data of these materials.

It was found that density has an effect on the tensile strength at yield, elongation at break, Young’s modulus and flexural strength of PE, HDPE and UHMWPE. Tensile strength at yield and Young’s modulus increased, but flexural strength decreased as the density of polyethylene increased. Elongation at yield and elongation at break decreased with the increase in the molecular weight of the polyethylene materials.

The results showed that when compared to the other types of plastics, the stress-strain curve of UHMWPE revealed a different nature. Unlike a typical thermoplastic polymer, it has a higher tensile strength in the fracture region. The stress-strain curves of PE and HDPE displayed ductile failure. The stress-strain curve of UHMWPE showed less failure occurred.

5.2 Recommendations

Based on the results of the study, the following recommendations for future research can be made:

- A full range of mechanical properties should be presented, for example, hardness and impact tests can be conducted for PE, HDPE, and UHMWPE.
- Efforts should be made to improve the determination of tensile strength at break for polyethylene and high density polyethylene test specimens. As for the shorter test specimen, an investigation should be carried out to determine tensile strength at break because the shorter test specimen would reach full extension and fracture more readily.
- Identifying the differences between the mode of stress-strain curves of UHMWPE and other types of polyethylene would also be a useful direction for future studies to take.

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APPENDICES

APPENDIX 1

ISO Standards

BRITISH STANDARD

BS EN ISO
1183-2:2004

Plastics — Methods for determining the density of non-cellular plastics —

Part 2: Density gradient column method

The European Standard EN ISO 1183-2:2004 has the status of a British Standard

ICS 83.080.01

National foreword

This British Standard is the official English language version of EN ISO 1183-2:2004. It is identical with ISO 1183-2:2004. It partially supersedes BS 2782-6:Methods 620A to 620D:1991.

The UK participation in its preparation was entrusted to Technical Committee PRI/21, Testing of plastics, which has the responsibility to:

- aid enquirers to understand the text;
- present to the responsible international/European committee any enquiries on the interpretation, or proposals for change, and keep the UK interests informed;
- monitor related international and European developments and promulgate them in the UK.

A list of organizations represented on this committee can be obtained on request to its secretary.

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Summary of pages

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EUROPEAN STANDARD

NORME EUROPÉENNE

EUROPÄISCHE NORM

EN ISO 1183-2

July 2004

ICS 83.080.01

English version

Plastics - Methods for determining the density of non-cellular plastics - Part 2: Density gradient column method (ISO 1183-2:2004)

Plastiques - Méthodes de détermination de la masse volumique des plastiques non alvéolaires - Partie 2: Méthode de la colonne à gradient de masse volumique (ISO 1183-2:2004)

Kunststoffe - Verfahren zur Bestimmung der Dichte von nicht verschäumten Kunststoffen - Teil 2: Verfahren mit Dichtegradientensäule (ISO 1183-2:2004)

This European Standard was approved by CEN on 22 June 2004.

CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CEN member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the Central Secretariat has the same status as the official versions.

CEN members are the national standards bodies of Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

EUROPEAN COMMITTEE FOR STANDARDIZATION
COMITÉ EUROPÉEN DE NORMALISATION
EUROPÄISCHES KOMITEE FÜR NORMUNG

Management Centre: rue de Stassart, 36 B-1050 Brussels

Ref. No. EN ISO 1183-2:2004: E

Foreword

This document (EN ISO 1183-2:2004) has been prepared by Technical Committee ISO/TC 61 "Plastics" in collaborationwith Technical Committee CEN/TC 249 "Plastics", the secretariat of which is held by IBN.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by January 2005, and conflicting national standards shall be withdrawn at the latest by January 2005.

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

Endorsement notice

The text of ISO 1183-2:2004 has been approved by CEN as EN ISO 1183-2 2004 without any modifications.

INTERNATIONAL STANDARD

ISO 1183-2

First edition
2004-07-15

Plastics — Methods for determining the density of non-cellular plastics —

Part 2:

Density gradient column method

Plastiques — Méthodes de détermination de la masse volumique des plastiques non alvéolaires —

Partie 2: Méthode de la colonne à gradient de masse volumique

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Contents

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies) . The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 1183-2 was prepared by Technical Committee ISO/TC 61, *Plastics*, Subcommittee SC 5, *Physical-chemical properties*.

Together with the other parts (see below), this part of ISO 1183 cancels and replaces ISO 1183:1987, which has been technically revised.

ISO 1183 consists of the following parts, under the general title *Plastics — Methods for determining the density of non-cellular plastics*:

Part 1: Immersion method, liquid pyknometer method and titration

method Part 2: Density gradient column method

Part 3: Gas pyknometer method

EN ISO 1183-2:2004

INTENRATIONAL TSANDADR **IS-3811 O2:(4002E)**

Plastics — Methods for determining the density of non-cellular plastics —

Part 2:
Density gradient column method

WARNING — The use of this part of ISO 1183 may involve hazardous materials, operations or equipment. This part of ISO 1183 does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this part of ISO 1183 to establish appropriate health and safety practices and to determine the applicability of any regulatory limitations prior to use.

1 Scope

This part of ISO 1183 specifies a gradient column method for the determination of the density of non-cellular moulded or extruded plastics in void-free form. Density gradient columns are columns containing a mixture of two liquids, the density in the column increasing uniformly from top to bottom.

NOTE This part of ISO 1183 is applicable to pellets as long as they are void-free. Density is frequently used to follow variations in physical structure or composition of plastic materials. Density may also be useful in assessing the uniformity of samples or specimens. Often the density of plastic materials will depend upon the choice of specimen preparation method. When this is the case, precise details of the specimen preparation method will have to be included in the appropriate material specification.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 31-3, *Quantities and units — Part 3: Mechanics*

ISO 291, *Plastics — Standard atmospheres for conditioning and testing*

ISO 1183-1:2004, *Plastics — Methods for determining the density of non-cellular plastics — Part 1: Immersion method, liquid pyknometer method and titration method*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
density
ρ

ratio of the mass m of a sample to its volume V (at the temperature t) expressed in kg/m3, kg/dm3 (g/cm3), or

Table 1 — Density terms

Term	Symbol	Formulation	Units
Density	ρ	m/V	kg/m^3 kg/dm^3 (g/cm^3) kg/l (g/ml)
Specific volume	v	V/m (= $1/\rho$)	m^3/kg dm^3/kg (cm^3/g) l/kg (ml/g)

4 Conditioning

Conditioning and testing shall be in accordance with ISO 291 or the appropriate material standard. In general, conditioning specimens to constant temperature is not required, because the determination itself brings the specimen to the constant temperature of the test.

Specimens which change in density during the test to such an extent that the change is greater than the required accuracy of the density determination shall be conditioned prior to measurement in accordance with the applicable material specification. When changes in density with time or atmospheric conditions are the primary purpose of the measurements, the specimens shall be conditioned as described in the material specification and, if no material specification exists, then as agreed upon by the interested parties.

5 Method

5.1 Apparatus

5.1.1 Density gradient column, consisting of a suitable graduated column, not less than 40 mm in diameter, with a cover. The height of the column shall be compatible with the accuracy required. A graduation interval of 1 mm for the scale on the column is normal.

5.1.2 Liquid bath, capable of being thermostatically controlled to within ± 0,1 °C or ± 0,5 °C, depending on the sensitivity required (see Annex B).

5.1.3 Calibrated glass floats, covering the density range in which measurements are to be made and approximately evenly distributed throughout this range.

NOTE These may be purchased from an accredited source or prepared as described in 5.4.1.

5.1.4 Balance, accurate to 0,1 mg.

5.1.5 Siphon or pipette assembly, for filling the gradient column (5.1.1), as shown in Figure B.1 or B.2, or any other suitable device.

5.2 Immersion liquids

Required are two miscible liquids of different densities, freshly distilled in the case of pure liquids. The densities of various liquids are given in Annex A as a guide.

The liquid with which the specimen comes into contact during the measurement shall have no effect on the specimen.

5.3 Specimens

Specimens shall consist of pieces of the material cut to any convenient shape for ease of identification. The dimensions of each piece shall be chosen to permit accurate measurement of the position of the centre of the piece.

When cutting specimens from larger samples, care shall be taken to ensure that the characteristics of the material are not changed due to excessive heat generation. The surface of the specimen shall be smooth and free from cavities to minimize the entrapment of air bubbles upon immersion in the liquid, otherwise errors will be introduced.

NOTE Specimens of less than 5 mm in diameter are normally suitable.

5.4 Procedure

5.4.1 Preparation and calibration of glass floats

5.4.1.1 The glass floats (5.1.3) may be produced by any convenient method. They shall be approximately spherical, of diameter not greater than 5 mm and fully annealed.

5.4.1.2 To prepare the glass floats for use, prepare a series of mixtures of about 500 ml of the two immersion liquids (5.2) covering the density range to be used in the density gradient column (5.1.1). With the floats and column at ambient temperature, place the floats carefully into these mixtures.

Adjust selected floats to match approximately the densities of the mixtures:

a) either by rubbing the float on a glass plate covered with a thin slurry of silicon carbide of particle size less than 38 µm (400 mesh) or another suitable abrasive;

b) or by etching the float with hydrofluoric acid.

5.4.1.3 Determine the exact density of each glass float calibrated as above by placing it in a mixture of two suitable liquids (5.2) in the bath (5.1.2) maintained at (t ± 0,1) °C, where t is 23 °C or 27 °C (whichever will be used for the density gradient column). If the float sinks, add the denser of the two liquids (if the float rises, add the less dense) and stir gently to homogenize. Allow the mixture to stabilize. If the float still moves, adjust the density of the mixture again. Repeat this procedure until the float remains stationary for at least 30 min.

5.4.1.4 For each float, determine, to the nearest 0,000 1 g/ml, the density of the solution in which the float remained in equilibrium, using the pyknometer method (method B) described in ISO 1183-1:2004 or any other suitable method. Apply the buoyancy correction described in ISO 1183-1:2004, Clause 6, if necessary. Record this density as the density of the float.

NOTE Calibrated glass floats may also be purchased from accredited manufacturers.

5.4.2 Preparation of density gradient column

Methods for preparing the density gradient column are not specified in this part of ISO 1183, but examples of two methods are given in Annex B.

5.4.3 Measurement of density

Wet three test specimens with the less dense of the two liquids used in the column and gently place them in the column. Allow the column and specimens to reach equilibrium, which will require 10 min or more. Films less than 0,05 mm thick require at least 1,5 h to settle. Rechecking thin-film specimens after several hours is advisable.

for removing air bubbles from the specimens are a fine wire carefully manipulated or applying a vacuum to the column.

. Find the height of each specimen on the chart and read off the correspondi ng density.

b) Calculation method

Calculate the density $\rho_{S,x}$ of each specimen by interpolation, using the equation:

$$\rho_{s,x} = \rho_{F1} + \frac{(x - y) \cdot (\rho_{F2} - \rho_{F1})}{z - y} \qquad (1)$$

where

ρ_{F1} and ρ_{F2}	are the densities of the two floats at the lower and higher ends, respectively, of the density range;
x	is the distance of the specimen above an arbitrary level;
y and z	are the distances above the same arbitrary level of the two floats of density ρ_{F1} and ρ_{F2}, respectively.

NOTE Method b) does not reveal calibration errors. These can only be detected by using method a), the graphical method. Method b) can be used when the calibration is known to be linear within the range being used.

If the relationship between float position and density is not linear, a second order polynomial may be used for interpolation of density.

Corrections for buoyancy, if required, can be calculated as described in ISO 1183-1:2004, Clause 6.

6 Test report

The test report shall include the following information:

a) a reference to this part of ISO 1183;

b) all details necessary for complete identification of the material tested, including the specimen preparation method and pretreatment, if applicable;

c) the immersion liquids used;

d) the value of the density determined for each of the three specimens and the arithmetic mean of these values;

e) the temperature of the determination;

f) details of any buoyancy corrections made;

g) the date of the determination.

Annex A

(informative)

Liquid systems suitable for density determinations

WARNING — Some of the following chemicals may be hazardous.

Table A.1 — Examples of suitable liquid systems

System	**Density range** g/cm^3
Methanol/benzyl alcohol	0,79 to 1,05
Isopropanol/water	0,79 to 1,00
Isopropanol/diethylene glycol	0,79 to 1,11
Ethanol/water	0,79 to 1,00
Toluene/carbon tetrachloride	0,87 to 1,60
Water/aqueous solution of sodium bromide[a]	1,00 to 1,41
Water/aqueous solution of calcium nitrate	1,00 to 1,60
Ethanol/aqueous solution of zinc chloride[b]	0,79 to 1,70
Carbon tetrachloride/1,3-dibromopropane	1,60 to 1,99
1,3-Dibromopropane/ethylene bromide	1,99 to 2,18
Ethylene bromide/bromoform	2,18 to 2,89
Carbon tetrachloride/bromoform	1,60 to 2,89
Isopropanol/methylglycol acetate	0,79 to 1,00

[a] A density of 1,41 is equivalent to a mass fraction of about 40 % sodium bromide.

[b] A density of 1,70 is equivalent to a mass fraction of about 67 % zinc chloride.

The following may also be used in various mixtures:

	Density (g/cm^3)
n-Octane	0,70
Dimethylformamide	0,94
Tetrachloroethane	1,60
Ethyl iodide	1,93
Methylene iodide	3,33

Annex B
(informative)

Preparation of density gradient column

B.1 Place the graduated column in the thermostatically controlled bath (5.1.2). Select a suitable combination of liquids (5.2) from the table in Annex A. When a sensitivity of 0,001 g/cm^3 is required, the temperature of the bath should be maintained to within ± 0,5 °C and the density range covered by the column limited to less than 0,2 g/cm^3 (preferably 0,1 g/cm^3). When a sensitivity of 0,000 1 g/cm^3 is required, the temperature of the bath should be maintained to within ± 0,1 °C, and the density range limited to less than 0,02 g/cm^3 (preferably 0,01 g/cm^3). The extreme upper and lower parts of the column should not be used, and readings should not be taken outside the calibrated zone.

Any of several methods for preparing the gradient column may be used, including the two methods given in B.2 and B.3.

B.2 Method 1: Assemble the apparatus as shown in Figure B.1, using two vessels of the same size and volume. Then select appropriate amounts of two suitable liquids, which have previously been carefully de-aerated by gentle heating or application of a vacuum. An effective method is with an ultrasonic cleaner.

Place a suitable amount of the less dense liquid into vessel 2 (the amount should be at least half of the total volume of liquid required in the gradient column — see Note 1) and turn on the magnetic stirrer. Adjust the stirrer speed so that the surface of the liquid does not move significantly. Place an equal amount of the denser liquid into vessel 1. Take care that no air is drawn into the liquid. Use the less dense liquid (starting liquid in vessel 2) to prime the siphon (5.1.5), which should be equipped with a capillary tip at the delivery end for flow control, then start delivery of the liquid to the gradient column. Fill the column to the uppermost graduation required (see Note 2).

Allow the density gradient column thus prepared to settle for at least 24 h.

NOTE 1 Calculate the density $\rho 2$ of the liquid in vessel 2 using the equation:

$$\rho_2 = \rho_{max} - \frac{2 \cdot (\rho_{max} - \rho_{min}) \cdot V_1}{V} \qquad (2)$$

where

ρ_{min} is the lower limit of the required density range, taken to be 0,01 g/cm^3 lower than the density of the least dense glass float calibrated for the gradient column being used;

ρ_{max} is the upper limit of the required density range, i.e. the density of the liquid in vessel 1, taken to be 0,005 g/cm^3 higher than the density of the densest glass float calibrated for the gradient column being used;

V is the total volume required in the gradient column;

V_1 is the initial volume of the liquid in vessel 1.

NOTE 2 Preparation of a suitable gradient column may require 1 h to 1,5 h or longer, depending upon the volume required in the column.

B.3 Method 2: Assemble the apparatus as shown in Figure B.2. This method is basically the same as method 1 except for the following points:

a) the denser liquid is placed in vessel 2 and the less dense liquid in vessel 1;

b) a siphon is used for delivery of the liquid from vessel 1 to vessel 2, and from vessel 2 to the column;

c) the liquid is gently introduced at the top of the column, allowing it to flow down the inside surface of the column wall;

d) the equation for calculating the density ρ_2 is Equation (3):

$$\rho_2 = \rho_{\min} - \frac{2 \cdot (\rho_{\min} - \rho_{\max}) \cdot V_1}{V} \qquad (3)$$

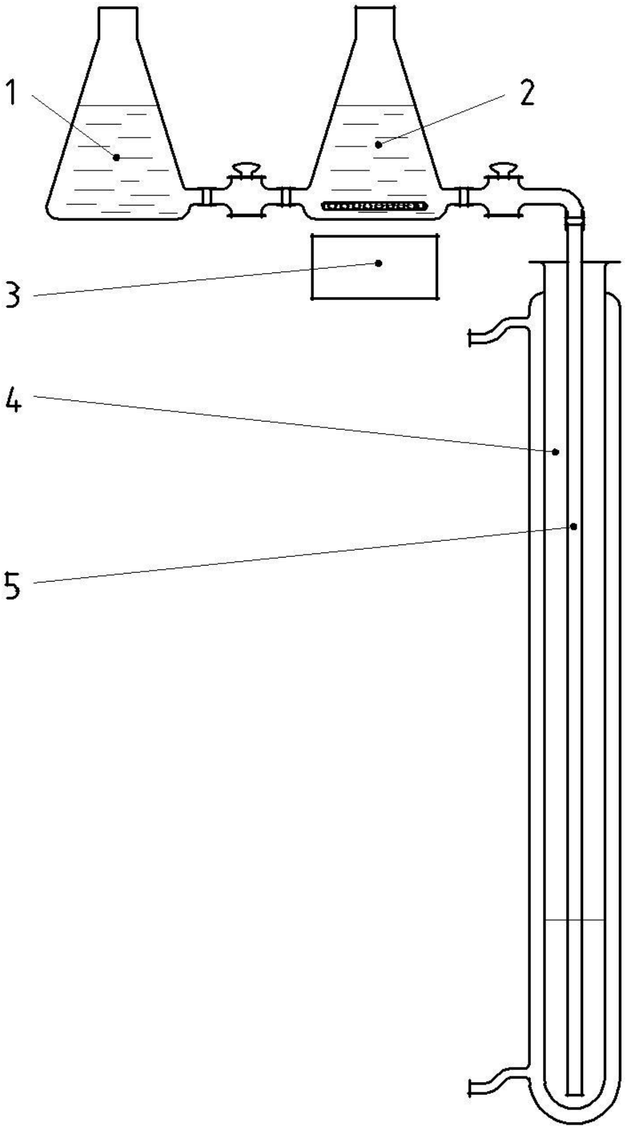
B.4 Dip the clean floats in the lower density liquid and place them gently in the column. If it is observed that the floats stay grouped together and do not spread out evenly in the column, discard the mixture and repeat the filling procedure.

Alternatively, the floats may be placed in the column during filling of the column. If the floats stay grouped together and do not spread out evenly in the column, discard the mixture and repeat the filling procedure.

Use at least one float per 0,01 g/cm^3 of the density gradient when the density is required to be accurate to within 0,001 g/cm^3. Use at least one float per 0,001 g/cm^3 when the density is required to be accurate to within 0,000 1 g/cm^3. In any case, at least five floats should be used in order to give a reasonable calibration curve.

B.5 Cap the column and keep it in a constant-temperature bath for 24 h to 48 h. At the end of this time, measure, to the nearest millimetre, the distance of the centre of each float from the bottom of the column and plot a curve of the densities of the floats as a function of their height.

A straight line is preferable. However, a plot with a slight curvature is acceptable. If the line shows any discontinuity or more than one point of inflection, the mixture shall be discarded and the filling procedure repeated.



Key

1 vessel 1 (more dense liquid)

2 vessel 2 (less dense liquid)

3 magnetic stirrer

4 column

5 capillary filling tube

Figure B.1 — Density gradient column filling apparatus for method 1

BRITISH STANDARD

BS EN ISO
527-2:1996
BS2782-3:
Method322:
1994

Incorporating
Amendment No.1
BS2782-3:
Method322:1994
renumbered

Plastics — Determination of tensile properties —

Part2: Test conditions for moulding and extrusion plastics

The European Standard ENISO 527-2:1996 has the status of a British Standard

IMPORTANT NOTE. Before reading this method it is essential to read BS2782-0, Introduction, issued separately.

Committees responsible for this British Standard

The preparation of this British Standard was entrusted by the Plastics and Rubber Standards Policy Committee (PRM/-) to Technical Committee PRM/21, upon which the following bodies were represented:

British Plastics Federation
British Textile Confederation
Department of the Environment (Building Research Establishment)
Department of Trade and Industry (National Physical Laboratory)
Electrical and Electronic Insulation Association (BEAMA Ltd.)
GAMBICA (BEAMA Ltd.)
Institute of Materials
Ministry of Defence
Packaging and Industrial Films Association
Pira International
RAPRA Technology Ltd.

This British Standard, having been prepared under the directionof the Plastics and Rubber Standards Policy Committee, was published underthe authority of the Standards Board and comes intoeffect on
15 January1994

The following BSI references relate to the work on this standard:
Committee reference PRM/21
Draft for comment91/39044DC

ISBN 0 580 22701 4

Amendments issued since publication

Amd. No.	Date	Comments
8639	November 1996	Indicated by a sideline in the margin

Contents

National foreword

This British Standard has been prepared by Technical Committee PRI/21 and is the English language version of EN ISO527-2:1996 *Plastics— Determination of tensile properties—* Part2: *Test conditions for moulding and extrusion plastics*. Itis identical with ISO527-2:1993, published by the International Organization for Standardization (ISO). Together with BS2782:Method321:1993 it supersedes Method320A and 320B given in BS2782:Methods320A to320F:1976, which are deleted by amendment.

Cross-references

International standard	Corresponding British Standard
ISO293:1986	BS2782 *Methods of testing plastics* Method901A:1988 *Compression moulding test specimens of thermoplastic material* (Identical)
ISO294:1975	Method910A:1977 *Injection moulding test specimens of thermoplastic materials* (Identical)
ISO295:1991	Method902A:1992 *Plastics— Compression moulding of test specimens of thermosetting materials* (Identical)
ISO527-1:1993	Method321:1993 *Determination of tensile properties General principles* (Identical)
ISO2818:1980	Method930A:1977 *Preparation of test specimens by machining* (Technically equivalent)

The Technical Committee has reviewed the provisions of ISO37:1977 and ISO1926:1979, to which normative reference is made in the text, and has decided that they are acceptable for use in conjunction with this standard.

WARNING NOTE. This British Standard, which is identical with ISO527-2, does not necessarily detail all the precautions necessary to meet the requirements of the Health and Safety at Work etc.Act1974. Attention should be paid to any appropriate safety precautions and the method should be operated only by trained personnel.

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

Summary of pages

This document comprises a front cover, an inside front cover, pagesi andii, theEN ISO title page, pages2 to8, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

EUROPEAN STANDARD

NORME EUROPEENNE

EUROPÄISCHE NORM

EN ISO527-2

May1996

ICS 83.080

Descriptors: See ISO document

English version

Plastics— Determination of tensile properties— Part2:Test conditions for moulding and extrusion plastics

(ISO527-2:1993 including Corr1:1994)

Plastiques— Détermination des propriétés en traction— Partie2: Conditions d’essai des plastiques pour moulage et extrusion

(ISO527-2:1993inclus Corr1:1994)

Kunstoffe— Bestimmung der Zugeigenschaften— Teil2: Prüfbedingungen für Form- und Extrusionsmassen

(ISO527-2:1993 einschließlich Corr1:1994)

This European Standard was approved by CEN on1994-12-14. CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

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CEN

European Committee for Standardization
Comité Européen de Normalisation
Europäisches Komitee für Normung

Central Secretariat: rue de Stassart 36, B-1050 Brussels

Foreword

The text of the International Standard from Technical Committee ISO/TC61, Plastics, of the International Organization for Standardization (ISO) has been taken over as a European Standard by Technical Committee CEN/TC249, Plastics, the secretariat of which is held by IBN.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by November1996, and conflicting national standards shall be withdrawn at the latest by November1996.

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

1 Scope

1.1 This part of ISO527 specifies the test conditions for determining the tensile properties of moulding and extrusion plastics, based upon the general principles given in ISO527-1.

1.2 The methods are selectively suitable for use with the following range of materials:

— rigid and semirigid thermoplastics moulding, extrusion and cast materials, including compounds filled and reinforced by e.g.short fibres, small rods, plates or granules but excluding textile fibres (seeISO527-4 and ISO527-5) in addition to unfilled types;

— rigid and semirigid thermosetting moulding and cast materials, including filled and reinforced compounds but excluding textile fibres as reinforcement (seeISO527-4 and ISO527-5);

— thermotropic liquid crystal polymers.

The methods are not suitable for use with materials reinforced by textile fibres (seeISO527-4 and ISO527-5), with rigid cellular materials or sandwich structures containing cellular material.

1.3 The methods are applied using specimens which may be either moulded to the chosen dimensions or machined, cut or punched from injection- or compression-moulded plates. The multipurpose test specimen is preferred (seeISO3167:1993, *Plastics— Multipurpose test specimens*).

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this part of ISO527. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this part of ISO527 are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO37:1977, *Rubber, vulcanized — Determination of tensile stress-strain properties.*

ISO293:1986, *Plastics — Compression moulding test specimens of thermoplastic materials.*

ISO294:—, *Plastics — Injection moulding of test specimens of thermoplastic materials*[1].

ISO295:1991, *Plastics — Compression moulding of test specimens of thermosetting materials.*

ISO527-1:1993, *Plastics — Determination of tensile properties — Part1: General principles.*

ISO1926:1979, *Cellular plastics — Determination of tensile properties of rigid materials.*

ISO2818:—, *Plastics — Preparation of test specimens by machining*[2].

3 Principle

See ISO527-1:1993, clause **3**.

4 Definitions

For the purposes of this part of ISO527, the definitions given in ISO527-1 apply.

5 Apparatus

See ISO527-1:1993, clause **5**.

6 Test specimens

6.1 Shape and dimensions

Wherever possible, the test specimens shall be dumb-bell-shaped types1A and1B as shown in Figure 1. Type1A is preferred for directly-moulded multipurpose test specimens, type1B for machined specimens.

NOTE 1Types1A and1B test specimens having4mm thickness are identical to the multipurpose test specimens according to ISO3167, typesA andB, respectively.

For the use of small specimens, seeAnnex A.

6.2 Preparation of test specimens

Test specimens shall be prepared in accordance with the relevant material specification. When none exists, or unless otherwise specified, specimens shall be either directly compression- or injection moulded from the material in accordance with ISO293, ISO294 or ISO295, as appropriate, or machined in accordance with ISO2818 from plates that have been compression- or injection-moulded from the compound.

All surfaces of the test specimens shall be free from visible flaws, scratches or other imperfections. From moulded specimens all flash, if present, shall be removed, taking care not to damage the moulded surface.

Test specimens from finished goods shall be taken from flat areas or zones having minimum curvature. For reinforced plastics, test specimens should not be machined to reduce their thickness unless absolutely necessary. Test specimens with machined surfaces will not give results comparable to specimens having non-machined surfaces.

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[1] To be published. (Revision of ISO294:1975)

[2] To be published. (Revision of ISO2818:1980)

6.3 Gauge marks

See ISO527-1:1993, subclause **6.3** .

6.4 Checking the test specimens

See ISO527-1:1993, subclause **6.4** .

7 Number of test specimens

See ISO527-1:1993, clause **7** .

8 Conditioning

See ISO527-1:1993, clause **8** .

9 Procedure

See ISO527-1:1993, clause **9** .

For the measurement of the modulus of elasticity, the speed of testing shall be1mm/min for specimen types1A and1B (seeFigure 1). For small specimens see Annex A.

10 Calculation and expression of results

See ISO527-1:1993, clause **10** .

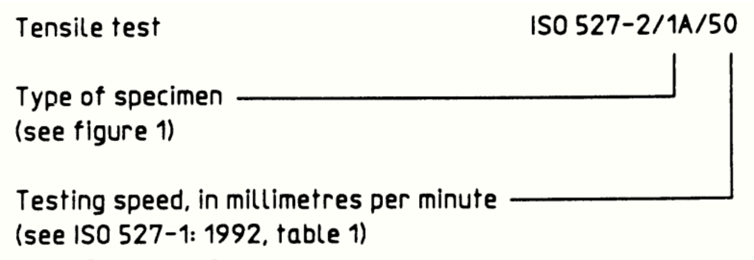
11 Precision

The precision of this test method is not known, because interlaboratory data are not available. When interlaboratory data are obtained, a precision statement will be added with the next revision.

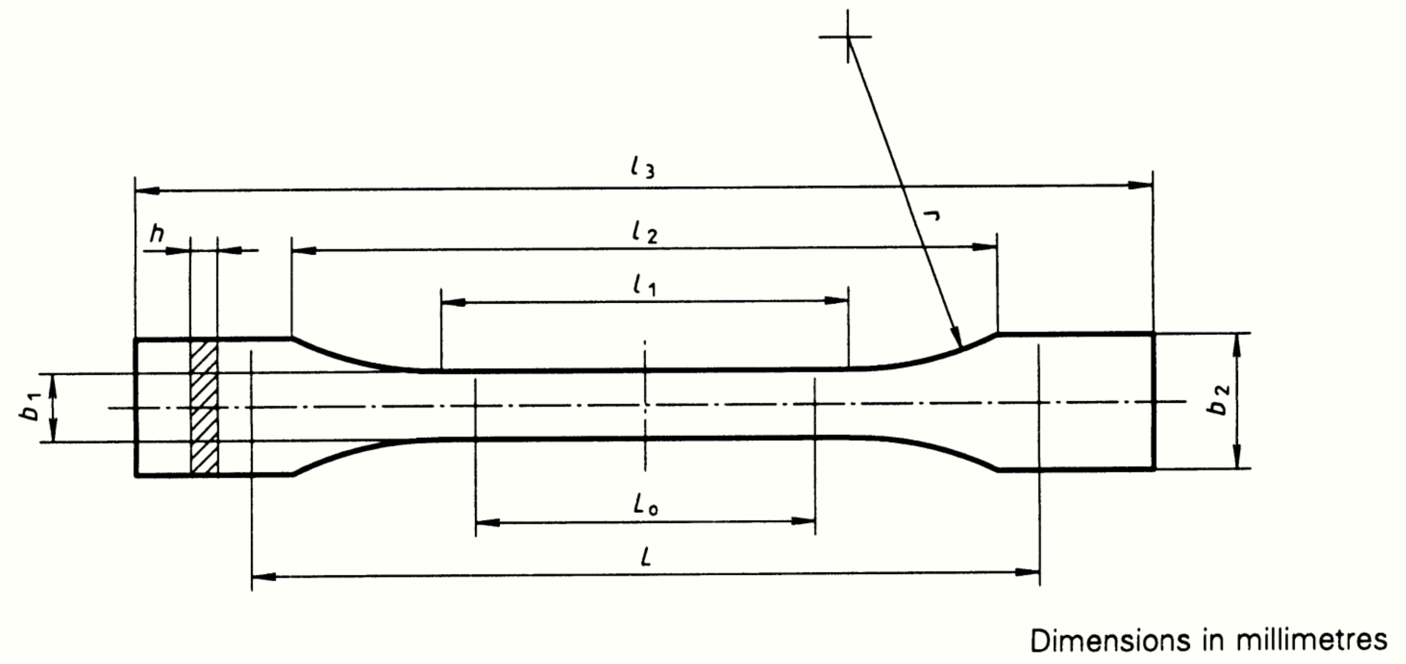
12 Test report

The test report shall include the following information:

a) a reference to this part of ISO527, including the type of specimen and the testing speed according to:



For itemsb) toq) in the test report, see ISO527-1:1993,12b) to q).



	Specimen type	1A 1B		
l_3	Overall length		W 150 [a]	
l_1	Length of narrow parallel-sided portion 80± 2 60,0± 0,5			
r	Radius	20 to25 W 60		[b]
l_2	Distance between broad parallel-sided portions 104to113	[c]		106 to120 [c]
b_2	Width at ends		20,0± 0,2	
b_1	Width of narrow portion		10,0± 0,2	
h	Preferred thickness		4,0± 0,2	
L_0	Gauge length		50,0± 0,5	
L	Initial distance between grips 115± 1			$l_2{}^{+5}_{0}$

NOTESpecimen type1A is preferred for directly-moulded multipurpose test specimens, type1B for machined specimens.

[a] For some materials, the length of the tabs may need to be extended (e.g. l_3 =200mm) to prevent breakage or slippage in the testing jaws.

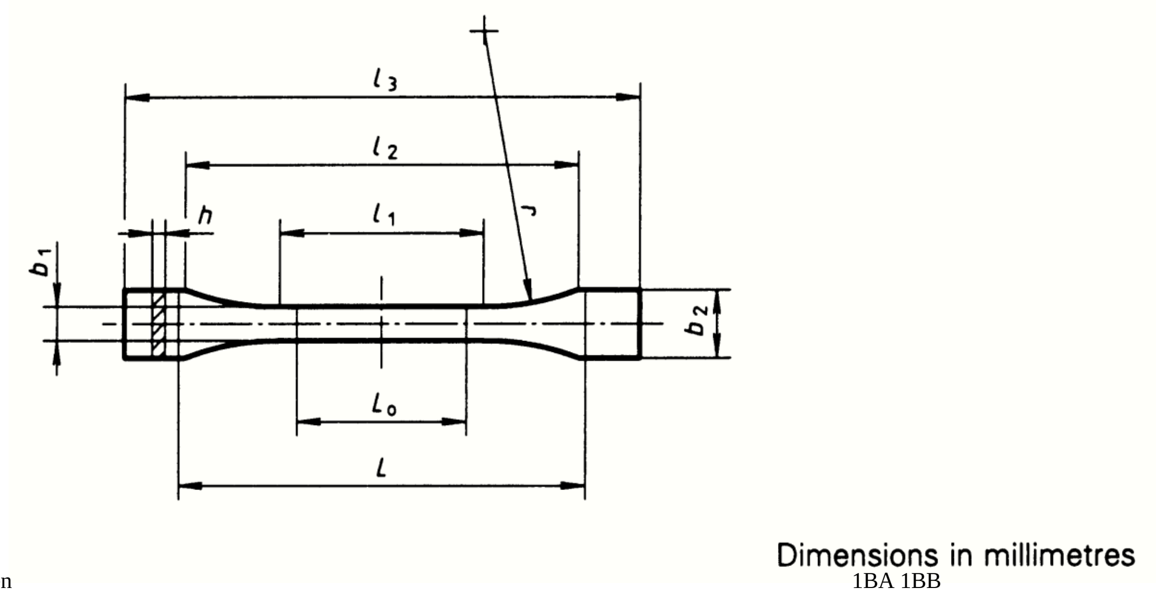
[b] $r = [(l_2 - l_1)^2 + (b_2 - b_1)^2]/4(b_2 - b_1)$

[c] Resulting from l_1, r, b_1 and b_2, but within the indicated tolerance.

Figure 1 — Test specimen types1A and1B

Annex A (normative)
Small specimens

If for any reason it is not possible to use a standard type1 test specimen, specimens of the types1BA,1BB (seeFigure A.1),5A or5B (seeFigure A.2) may be used, provided that the speed of testing is adjusted to the value given in **5.1.2**, Table1 of ISO527-1:1993, which gives the nominal strain rate for the small test specimen closest to that used for the standard-sized specimen. The rate of nominal strain is the quotient of the speed of testing (see **4.2** in ISO527-1:1993) and the initial distance between grips. Where modulus measurements are required, the test speed shall be1mm/min. It may be technically difficult to measure modulus on small specimens because of small gauge lengths and short testing times. Results obtained from small specimens are not comparable with those obtained from type1 specimens.

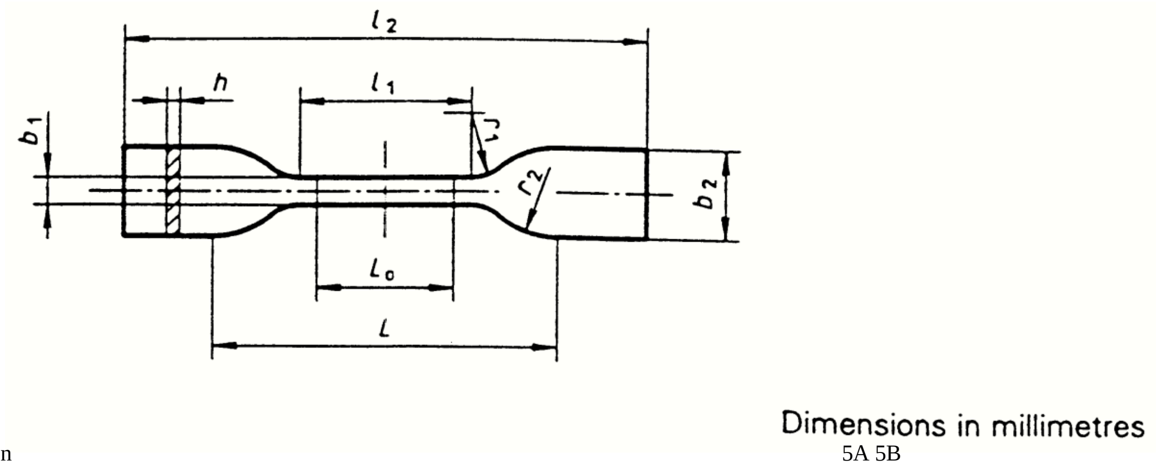


Dimensions in millimetres

	Type of specimen	1BA	1BB
l_3	Overall length	W 75	W 30
l_1	Length of narrow parallel-sided portion	30 ± 0,5	12 ± 0,5
r	Radius	W 30	W 12
l_2	Distance between broad parallel-sided portions	58 ± 2	23 ± 2
b_2	Width at ends	10 ± 0,5	4 ± 0,2
b_1	Width of narrow portion	5 ± 0,5	2 ± 0,2
h	Thickness	W 2	W 2
L_0	Gauge length	25 ± 0,5	10 ± 0,2
L	Initial distance between grips	$l_2{}^{+2}_{0}$	$l_2{}^{+1}_{0}$

NOTEThe specimen types 1BA and 1BB are proportionally scaled to type 1B with a reduction factor of 1 : 2 and 1 : 5 respectively with the exception of thickness.

Figure A.1 — Test specimen types1BA and1BB



	Type of specimen	5A	5B
l_2	Overall length, minimum	W 75	W 35
b_2	Width at ends	12,5 ± 1	6 ± 0,5
l_1	Length of narrow parallel-sided portion	25 ± 1	12 ± 0,5
b_1	Width of narrow parallel-sided portion	4 ± 0,1	2 ± 0,1
r_1	Small radius	8 ± 0,5	3 ± 0,1
r_2	Large radius	12,5 ± 1	3 ± 0,1
L	Initial distance between grips	50 ± 2	20 ± 2
L_0	Gauge Length	20 ± 0,5	10 ± 0,2
h	Thickness	W 2	W 1

NOTETest specimen types 5A and 5B are approximately proportional to type 5 of ISO 527-3 and represent respectively types 2 and3 of ISO 37.

Figure A.2 — Test specimen types5A and5B

Annex ZA (normative)
Normative references to international publications with their relevant European publications

This European Standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies.

Publication	**Year**	**Title**	**EN**	**Year**
ISO527-1	1993	*Plastics— Determination of tensile properties —* Part1: *General principles*	EN ISO527-1	1996

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DEUTSCHE NORM **June 2003**

Plastics Determination of flexural properties (ISO 178 : 2001)
English version of DIN EN ISO 178

EN ISO 178

ICS 83.080.01

Supersedes
February 1997 edition.

Kunststoffe – Bestimmung der Biegeeigenschaften (ISO 178 : 2001)

European Standard EN ISO 178 : 2003 has the status of a DIN Standard.

A comma is used as the decimal marker.

National foreword

This standard has been published in accordance with a decision taken by CEN/TC 249 to adopt, without alteration, International Standard ISO 178 as a European Standard.

The responsible German body involved in its preparation was the *Normenausschuss Kunststoffe* (Plastics Standards Committee), Technical Committee *Mechanische Eigenschaften und Probekörperherstellung.*

The DIN Standards corresponding to the International Standards referred to in clause 2 of the EN are as follows:

ISO Standard	DIN Standard(s)
ISO 291	DIN EN ISO 291
ISO 293	DIN 16770-1 and DIN EN ISO 293 *)
ISO 294-1	DIN EN ISO 294-1
ISO 295	DIN EN ISO 295
ISO 2818	DIN EN ISO 2818
ISO 3167	DIN EN ISO 3167
ISO 10724-1	DIN EN ISO 10724-1

Amendments

This standard differs from the February 1997 edition in that it has been revised in form and substance.

Previous editions

DIN 53452: 1941-05, 1944-11, 1952-02, 1977-04; DIN 53453: 1943-11, 1952-02, 1954-07, 1958-05, 1965-10, 1975-05; DIN 53457: 1968-05, 1987-06, 1987-10; DIN EN ISO 178: 1997-02.

~~*) Currently~~ at draft stage.

Continued overleaf.

EN comprises 17 pages.

DIN EN ISO 178 : 2003-06
English price group 12 *Sales No. 1112*
10.03

National Annex NA

Standards referred to

(and not included in **Normative references**, **Bibliography** and **Annex ZA**)

DIN 16770-1	Preparation of specimens of thermoplastic moulding materials by compression moulding
DIN EN ISO 291	Plastics – Standard atmospheres for conditioning and testing (ISO 291 : 1997)
DIN EN ISO 294-1	Plastics – Injection moulding of test specimens of thermoplastic materials – Part 1: General principles, and moulding of multipurpose and bar test specimens (ISO 294-1 : 1996)
DIN EN ISO 295	Plastics – Compression moulding of test specimens of thermosetting materials (ISO 295 : 1991)
DIN EN ISO 2818	Plastics – Preparation of test specimens by machining (ISO 2818 : 1994)
DIN EN ISO 3167	Plastics – Multi-purpose test specimens (ISO 3167 : 1993)
DIN EN ISO 10724-1	Injection moulding of test specimens of thermosetting powder moulding compounds (PMCs) – Part 1: General principles and moulding of multipurpose test specimens (ISO 10724-1 : 1998)

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN ISO 178

February 2003

ICS 83.080.01

Supersedes EN ISO 178 : 1996.

English version

Plastics

Determination of flexural properties
(ISO 178 : 2001)

Plastiques – Détermination des propriétés en flexion (ISO 178 : 2001)

Kunststoffe – Bestimmung der Biegeeigenschaften (ISO 178 : 2001)

This European Standard was approved by CEN on 2002-12-12.

CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Management Centre or to any CEN member.

The European Standards exist in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the Management Centre has the same status as the official versions.

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ÈÉË

European Committee for Standardization
Comité Européen de Normalisation
Europäisches Komitee für Normung

Management Centre: rue de Stassart 36, B-1050 Brussels

Ref. No. EN ISO 178 : 2003 E

Foreword

International Standard
ISO 178 : 2001 Plastics – Determination of flexural properties,

which was prepared by ISO/TC 61 ‘Plastics’ of the International Organization for Standardization, has been adopted by Technical Committee CEN/TC 249 ‘Plastics’, the Secretariat of which is held by IBN, as a European Standard.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, and conflicting national standards withdrawn, by August 2003 at the latest.

In accordance with the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard:

Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Malta, the Netherlands, Norway, Portugal, Slovakia, Spain, Sweden, Switzerland, and the United Kingdom.

Endorsement notice

The text of the International Standard ISO 178 : 2001 was approved by CEN as a European Standard without any modification.

NOTE: Normative references to international publications are listed in Annex ZA (normative).

Contents

Page

1 Scope

1.1 This International Standard specifies a method for determining the flexural properties of rigid (see 3.12) and semi-rigid plastics under defined conditions. A standard test specimen is defined, but parameters are included for alternative specimen sizes for use where appropriate. A range of test speeds is included.

1.2 The method is used to investigate the flexural behaviour [1] of the test specimens and for determining the flexural strength, flexural modulus and other aspects of the flexural stress/strain relationship under the conditions defined. It applies to a freely supported beam, loaded at midspan (three-point loading test).

1.3 The method is suitable for use with the following range of materials:

- thermoplastics moulding and extrusion materials, including filled and reinforced compounds in addition to unfilled types; rigid thermoplastics sheets;
- thermosetting moulding materials, including filled and reinforced compounds; thermosetting sheets.

In agreement with ISO 10350-1 and ISO 10350-2, this International Standard applies to fibre-reinforced compounds with fibre lengths $\leqslant 7{,}5$ mm prior to processing. For long-fibre-reinforced materials (laminates) with fibre lengths $> 7{,}5$ mm, see reference [2] in the bibliography.

The method is not normally suitable for use with rigid cellular materials and sandwich structures containing cellular material [3, 4].

NOTE For certain types of textile-fibre-reinforced plastics, a four-point bending test is preferred. It is described in reference [2].

1.4 The method is performed using specimens which may be moulded to the specified dimensions, machined from the central portion of a standard multipurpose test specimen (see ISO 3167) or machined from finished or semi-finished products such as mouldings, or extruded or cast sheet.

1.5 The method specifies preferred dimensions for the test specimen. Tests which are carried out on specimens of different dimensions, or on specimens which are prepared under different conditions, may produce results which are not comparable. Other factors, such as the test speed and the conditioning of the specimens, can also influence the results. Especially for semi-crystalline polymers, the thickness of the oriented skin layer, which is dependent on moulding conditions and thickness, affects the flexural properties. Consequently, when comparable data are required, these factors must be carefully controlled and recorded.

1.6 Flexural properties can only be used for engineering design purposes for materials with linear stress/strain behaviour. For non-linear behaviour, the flexural properties are only nominal. The bending test should preferentially be used with brittle materials, for which tensile tests are difficult.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 291:1997, *Plastics — Standard atmospheres for conditioning and testing*

ISO 293:1986, *Plastics — Compression moulding test specimens of thermoplastic materials*

ISO 294-1:1996, *Plastics — Injection moulding of test specimens of thermoplastic materials — Part 1: General principles, and moulding of multipurpose and bar specimens*

ISO 295:—[1], *Plastics — Compression moulding of test specimens of thermosetting materials*

ISO 2602:1980, *Statistical interpretation of test results — Estimation of the mean — Confidence interval*

ISO 2818:1994, *Plastics — Preparation of test specimens by machining*

ISO 3167:2001, *Plastics — Multipurpose test specimens*

ISO 5893:1993, *Rubber and plastics test equipment — Tensile, flexural and compression types (constant rate of traverse) — Description*

ISO 10724-1:1998, *Plastics — Injection moulding of test specimens of thermosetting powder moulding compounds (PMCs) — Part 1: General principles and moulding of multipurpose test specimens*

3 Terms and definitions

For the purposes of this International Standard, the following terms and definitions apply.

3.1

test speed

v

rate of relative movement between the supports and the loading edge

NOTE It is expressed in millimetres per minute (mm/min).

3.2

flexural stress

σ_f

nominal stress of the outer surface of the test specimen at midspan

NOTE It is calculated from the relationship given in 9.1, equation (5), and is expressed in megapascals (MPa).

3.3

flexural stress at break

σ_{fB}

flexural stress at break of the test specimen (see Figure 1, curves a and b)

NOTE It is expressed in megapascals (MPa).

3.4

flexural strength

σ_{fM}

maximum flexural stress sustained by the test specimen during a bending test (see Figure 1, curves a and b)

NOTE It is expressed in megapascals (MPa).

---

[1] To be published. (Revision of ISO 295:1991)

3.5

flexural stress at conventional deflection

σ_{fc}

flexural stress at the conventional deflection s_C defined in 3.7 (see Figure 1, curve c)

NOTE It is expressed in megapascals (MPa).

3.6

deflection

s

distance over which the top or bottom surface of the test specimen at midspan deviates from its original position during flexure

NOTE It is expressed in millimetres (mm).

3.7

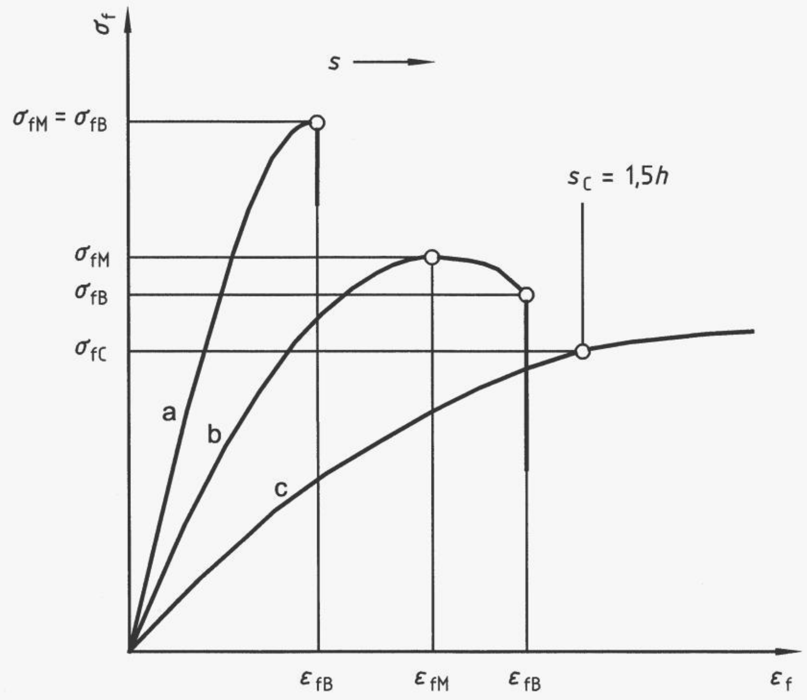
conventional deflection

s_C

deflection equal to 1,5 times the thickness h of the test specimen

NOTE 1 It is expressed in millimetres (mm).

NOTE 2 Using a span L of $16h$, the conventional deflection corresponds to a flexural strain (see 3.8) of 3,5 %.



Curve a Specimen that breaks before yielding.

Curve b Specimen that gives a maximum and then breaks before the conventional deflection s_C.

Curve c Specimen that neither gives a maximum nor breaks before the conventional deflection s_C.

Figure 1 — Typical curves of flexural stress σ_f versus flexural strain ε_f and deflection s

3.8
flexural strain
ε_{f}
nominal fractional change in length of an element of the outer surface of the test specimen at midspan

NOTE 1 It is expressed as a dimensionless ratio or as a percentage (%).

NOTE 2 It is calculated in accordance with the relationships given in 9.2, equations (6) and (7).

3.9
flexural strain at break
$\varepsilon_{\mathrm{fB}}$
flexural strain at break of the test specimen (see Figure 1, curves a and b)

NOTE It is expressed as a dimensionless ratio or as a percentage (%).

3.10
flexural strain at flexural strength
$\varepsilon_{\mathrm{fM}}$
flexural strain at maximum flexural stress (see Figure 1, curves a and b)

NOTE It is expressed as a dimensionless ratio or as a percentage (%).

3.11
modulus of elasticity in flexure
flexural modulus
E_{f}
ratio of the stress difference $\sigma_{\mathrm{f2}} - \sigma_{\mathrm{f1}}$ to the corresponding strain difference $\varepsilon_{\mathrm{f2}}$ (= 0,002 5) − $\varepsilon_{\mathrm{f1}}$ (= 0,000 5) [see 9.2, equation (9)]

NOTE 1 It is expressed in megapascals (MPa).

NOTE 2 The flexural modulus is only an approximate value of Young's modulus of elasticity.

NOTE 3 With computer-aided equipment, the determination of the modulus E_{f} using two distinct stress/strain points can be replaced by a linear regression procedure applied to the part of the curve between these two points.

3.12
rigid plastic
a plastic that has a modulus of elasticity in flexure or, if that is not applicable, then in tension, greater than 700 MPa under stated conditions [ISO 472]

4 Principle

The test specimen, supported as a beam, is deflected at a constant rate at the midspan until the specimen fractures or until the deformation reaches some predetermined value. During this procedure, the force applied to the test specimen is measured.

5 Test machine

5.1 General

The machine shall comply with ISO 5893 and the requirements given in 5.2 to 5.4.

5.2 Test speed

The machine shall be capable of maintaining the test speed (see 3.1), as specified in Table 1.

Table 1 — Recommended values of the test speed, v

Test speed, v mm/min	Tolerance %
1[a]	± 20[b]
2	± 20[b]
5	± 20
10	± 20
20	± 10
50	± 10
100	± 10
200	± 10
500	± 10

[a] The lowest speed is used for specimens with thicknesses between 1 mm and 3,5 mm (see 8.5).

[b] The tolerances on the 1 mm/min and 2 mm/min speeds are lower than indicated in ISO 5893.

Acceleration, seating and machine compliance may contribute to a curved region at the start of the stress/strain curve. This can be avoided as explained in 8.4 and 9.2.

5.3 Supports and loading edge

Two supports and a central loading edge shall be arranged as shown in Figure 2. The supports and the loading edge shall be parallel to within ± 0,2 mm over the width of the test specimen.

The radius R_1 of the loading edge and the radius R_2 of the supports shall be as follows:

$R_1 = 5{,}0\ \text{mm} \pm 0{,}1\ \text{mm}$;

$R_2 = 2{,}0\ \text{mm} \pm 0{,}2\ \text{mm}$ for test specimen thicknesses $\leqslant 3$ mm;

$R_2 = 5{,}0\ \text{mm} \pm 0{,}2\ \text{mm}$ for test specimen thicknesses > 3 mm.

The span L shall be adjustable.

NOTE It may be necessary to prestress the specimen to obtain correct alignment and specimen seating and to avoid a curved region at the start of the stress/strain curve (see 8.4).

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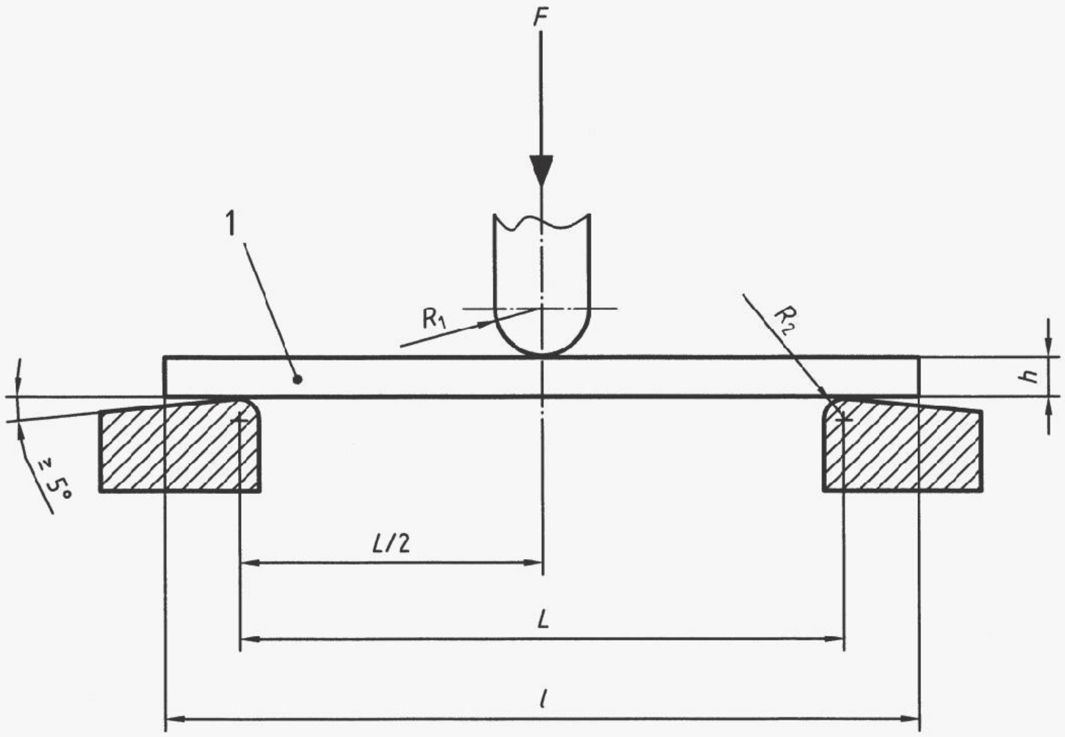

Key

1	Test specimen	h	Thickness of specimen
F	Applied force	l	Length of specimen
R_1	Radius of loading edge	L	Length of span between supports
R_2	Radius of supports		

Figure 2 — Position of test specimen at start of test

5.4 Load- and deflection-indicating equipment

The error in the indicated force shall not exceed 1 % of the actual value and the error in the indicated deflection shall not exceed 1 % of the actual value (see ISO 5893).

NOTE 1 When determining the flexural modulus, the actual values used are those corresponding to the upper limit of the strain difference, i.e. $\varepsilon_2 = 0{,}002\,5$. Thus when using the preferred specimen type (see 6.1.2), a specimen thickness h of 4 mm and a span L of $16h$ (see 8.3), for instance, equation (6) gives a deflection s_2 of 0,43 mm. In this case, the tolerance on the deflection-measuring system has to be ± 4,3 µm.

NOTE 2 Systems have become commercially available that use ring-shaped strain gauges, and thus any lateral forces which may be generated by misalignment of the test set-up are compensated for.

6 Test specimens

6.1 Shape and dimensions

6.1.1 General

The dimensions of the test specimens shall comply with the relevant material standard and, as applicable, with 6.1.2 or 6.1.3. Otherwise, the type of specimen shall be agreed between the interested parties.

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6.1.2 Preferred specimen type

The dimensions, in millimetres, of the preferred test specimen are

length, l: 80 ± 2

width, b: 10,0 ± 0,2

thickness, h: 4,0 ± 0,2

In any one test specimen, the thickness within the central third of the length shall not deviate by more than 2 % from its mean value. The width shall not deviate from its mean value within this part of the specimen by more than 3 %. The specimen cross-section shall be rectangular, with no rounded edges.

NOTE The preferred specimen may be machined from the central part of a multipurpose test specimen complying with ISO 3167.

6.1.3 Other test specimens

When it is not possible or desirable to use the preferred test specimen, the following limits shall apply.

The length and thickness of the test specimen shall be in the same ratio as for the preferred test specimen, i.e.

$$\frac{l}{h} = 20 \pm 1 \tag{1}$$

unless affected by the provisions of 8.3 a), 8.3 b) or 8.3 c).

NOTE Certain specifications require that test specimens from sheets of thickness greater than a specified upper limit shall be reduced to a standard thickness by machining one face only. In such cases, it is conventional practice to place the test specimen such that the original surface of the specimen is in contact with the two supports and the force is applied by the central loading edge to the machined surface of the specimen.

The width of the specimen shall be as given in Table 2.

Table 2 — Values of specimen width b in relation to thickness h

Dimensions in millimetres

Nominal thickness h	Width b[a]
$1 < h \leqslant 3$	25,0 ± 0,5
$3 < h \leqslant 5$	10,0 ± 0,5
$5 < h \leqslant 10$	15,0 ± 0,5
$10 < h \leqslant 20$	20,0 ± 0,5
$20 < h \leqslant 35$	35,0 ± 0,5
$35 < h \leqslant 50$	50,0 ± 0,5

[a] For materials with very coarse fillers, the minimum width shall be 30 mm.

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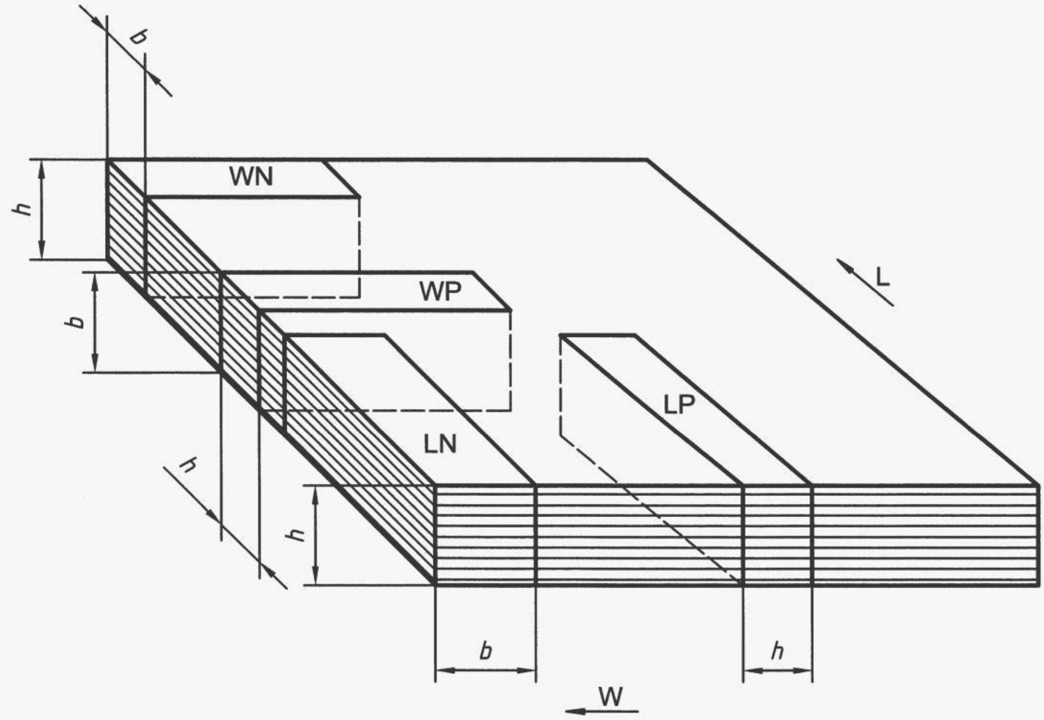
6.2 Anisotropic materials

6.2.1 In the case of materials having physical properties that depend on direction, e.g. elasticity, the test specimens shall be chosen so that the flexural stress will be applied in the same, or in a similar, direction as that to which products (moulded articles, sheets, tubes, etc.) will be subjected in service, if this direction is known. The relationship between the test specimen and the end-product envisaged will determine the feasibility of using standard test specimens.

NOTE The position or orientation and the dimensions of the test specimens sometimes have a very significant influence on the test results.

6.2.2 When the material shows a significant difference in flexural properties in two principal directions, it shall be tested in these two directions. The orientation of the test specimen relative to the principal directions shall be recorded (see Figure 3).



Key

L Product length direction

W Product width direction

Position of specimen	Product direction	Direction of force
LN	Length	Normal
WN	Width	
LP	Length	Parallel
WP	Width	

Figure 3 — Position of test specimen in relation to product direction and direction of force

6.3 Preparation of test specimens

6.3.1 Moulding and extrusion compounds

Specimens shall be prepared in accordance with the relevant material specification. When none exists, and unless otherwise specified, specimens shall be directly compression moulded or injection moulded from the material in accordance with ISO 293, ISO 294-1, ISO 295 or ISO 10724-1, as appropriate.

6.3.2 Sheets

Specimens shall be machined from sheets in accordance with ISO 2818.

6.4 Specimen inspection

The specimens shall be free of twist, and their opposite surfaces shall be parallel and adjacent surfaces perpendicular. All surfaces and edges shall be free from scratches, pits, sink marks and flash.

The specimens shall be checked for conformity with these requirements by visual observation against straight edges, squares and flat plates, and by measuring with micrometer calipers.

Specimens showing measurable or observable departures from one or more of these requirements shall be rejected or machined to proper size and shape before testing.

NOTE Injection-moulded test specimens usually have draft angles of between 1° and 2° to facilitate demoulding. Therefore, the side faces of moulded test specimens will generally not be quite parallel.

6.5 Number of test specimens

6.5.1 At least five test specimens shall be tested in each direction of test (see Figure 3). The number of specimens may be more than five if greater precision of the mean value is required. It is possible to evaluate this by means of the confidence interval (95 % probability, see ISO 2602).

6.5.2 In the case of directly injection-moulded test specimens, at least five shall be tested.

NOTE It is recommended that specimens always be tested oriented in the same way, i.e. with the surface which was in contact with the cavity plate or that which was in contact with the fixed plate (see ISO 294-1 or ISO 10724-1, as appropriate) always in contact with the supports, in order to exclude the effects of any asymmetry generated by the moulding process.

6.5.3 The results from test specimens that rupture outside the central third of their span length shall be discarded and new test specimens tested in their place.

7 Conditioning

The test specimens shall be conditioned as specified in the standard for the material being tested. In the absence of this information, select the most appropriate conditions from ISO 291, unless otherwise agreed upon by the interested parties, e.g. for testing at high or low temperatures. The preferred set of conditions in ISO 291 is atmosphere 23/50, except when the flexural properties of the material are known to be insensitive to moisture, in which case humidity control is unnecessary.

8 Procedure

8.1 Conduct the test in the atmosphere specified in the standard for the material being tested. In the absence of this information, select the most appropriate conditions from ISO 291, unless otherwise agreed upon by the interested parties, e.g. for testing at high or low temperatures.

8.2 Measure the width b of the test specimens to the nearest 0,1 mm and the thickness h to the nearest 0,01 mm in the centre of the test specimens. Calculate the mean thickness $\bar{h}$ for the set of specimens.

Discard any specimens with a thickness exceeding the tolerance of ±2 % of the mean value and replace them by other specimens chosen at random.

NOTE For the purposes of this International Standard, the test specimen dimensions used to calculate flexural properties are measured at room temperature only. For the measurement of properties at other temperatures, therefore, the effects of thermal expansion are not taken into account.

8.3 Adjust the span L to comply with the following equation:

$$L = (16 \pm 1)\,\bar{h} \tag{2}$$

and measure the resulting span to the nearest 0,5 %.

Equation (2) shall be used except in the following cases:

a) For very thick and unidirectional fibre-reinforced test specimens, if necessary to avoid delamination in shear, use a span length based on a higher value of the ratio $L/\bar{h}$.

b) For very thin test specimens, if necessary to enable measurements to be made within the working range of the test machine, use a span length based on a lower value of the ratio $L/\bar{h}$.

c) For soft thermoplastics, if necessary to prevent indentation of the supports into the test specimen, use a higher value of the ratio $L/\bar{h}$.

8.4 Do not load the specimen substantially prior to testing. Such loads may be necessary, however, to avoid a curved region at the start of the stress/strain diagram. For modulus measurement, the flexural stress in the specimen at the start of a test σ_{f0} (see Figure 4) shall be positive and shall lie within the range

$$0 \leqslant \sigma_{f0} \leqslant 5 \times 10^{-4} E_f \tag{3}$$

which corresponds to a prestrain of $\varepsilon_{f0} \leqslant 0{,}05\ \%$, and when measuring characteristics such as σ_{fM}, σ_{fC} or σ_{fB} it shall lie within the range

$$0 \leqslant \sigma_{f0} \leqslant 10^{-2} \sigma_f \tag{4}$$

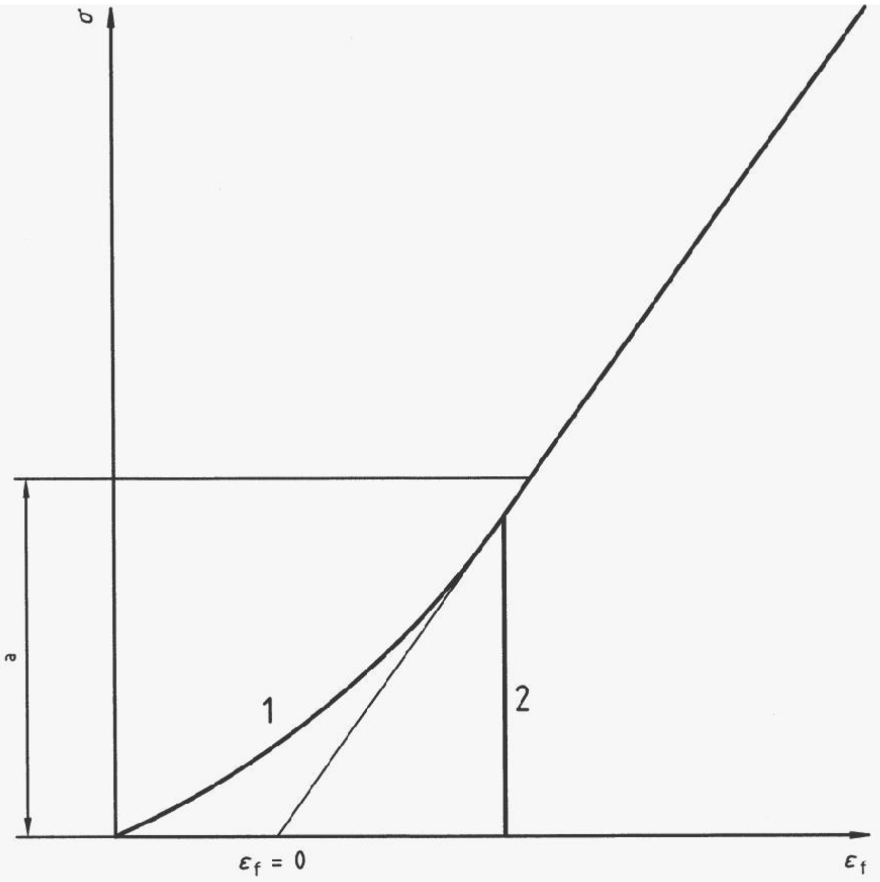
NOTE The flexural modulus of strongly viscoelastic, ductile materials like polyethylene, polypropylene or moist polyamides is influenced markedly by prestressing.

8.5 Set the test speed in accordance with the standard for the material being tested. In the absence of this information, select a value from Table 1 that gives a flexural strain rate as near as possible to 1 % per minute. This gives a test speed of 2 mm/min for the preferred test specimen specified in 6.1.2.

8.6 Place the test specimen symmetrically on the two supports and apply the force at midspan (see Figure 2).

8.7 Record the force and the corresponding deflection of the specimen during the test, using, if practicable, an automatic recording system that yields a complete flexural-stress/deflection curve for this operation [see 9.1, equation (5)].

Determine all relevant stresses, deflections and strains defined in clause 3 from a force/deflection or stress/deflection curve or from equivalent data. See annex A for a method of compliance correction.



Key

1 Initial part of stress/strain plot showing a curved region.

2 Initial part of stress/strain plot showing a step due to forces being measured only above a trigger threshold.

[a] $\leqslant 5 \times 10^{-4} E_f$ or $\leqslant 10^{-2} \sigma_f$

Figure 4 — Example of stress/strain plots with an initial curved region and with a step, and determination of zero-strain point

9 Calculation and expression of results

9.1 Flexural stress

Calculate the flexural-stress parameters defined in clause 3 using the following equation:

$$\sigma_f = \frac{3FL}{2bh^2} \qquad (5)$$

where

σ_f is the flexural-stress parameter in question;

F is the applied force, in newtons;

L is the span, in millimetres;

b is the width, in millimetres, of the specimen;

h is the thickness, in millimetres, of the specimen.

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9.2 Flexural strain

Calculate the flexural-strain parameters defined in clause 3 using one of the following equations:

$$\varepsilon_\mathrm{f} = \frac{6sh}{L^2} \tag{6}$$

$$\varepsilon_\mathrm{f} = \frac{600sh}{L^2}\ \% \tag{7}$$

where

ε_f is the flexural-strain parameter in question, expressed as a dimensionless ratio or as a percentage;

s is the deflection, in millimetres;

h is the thickness, in millimetres, of the test specimen;

L is the span, in millimetres.

If a curved region is found in the initial part of the stress/strain diagram, extrapolate to zero strain from stresses slightly above the initial flexural stress described in 8.4 (see also Figure 4).

9.3 Flexural modulus

To determine the flexural modulus, calculate the deflections s_1 and s_2 corresponding to the given values of the flexural strain $\varepsilon_{\mathrm{f}1} = 0{,}000\,5$ and $\varepsilon_{\mathrm{f}2} = 0{,}002\,5$ using the following equation:

$$s_i = \frac{\varepsilon_{\mathrm{f}i} L^2}{6h} \qquad (i = 1;\ 2) \tag{8}$$

where

s_i is one of the deflections, in millimetres;

$\varepsilon_{\mathrm{f}i}$ is the corresponding flexural strain, whose values $\varepsilon_{\mathrm{f}1}$ and $\varepsilon_{\mathrm{f}2}$ are given above;

L is the span, in millimetres;

h is the thickness, in millimetres, of the specimen.

Calculate the flexural modulus E_f, expressed in megapascals, using the following equation:

$$E_\mathrm{f} = \frac{\sigma_{\mathrm{f}2} - \sigma_{\mathrm{f}1}}{\varepsilon_{\mathrm{f}2} - \varepsilon_{\mathrm{f}1}} \tag{9}$$

where

$\sigma_{\mathrm{f}1}$ is the flexural stress, in megapascals, measured at deflection s_1;

$\sigma_{\mathrm{f}2}$ is the flexural stress, in megapascals, measured at deflection s_2.

For computer-aided equipment, see note 3 to 3.11.

NOTE All equations concerning flexural properties hold exactly for linear stress/strain behaviour only (see 1.6); thus for most plastics they are accurate at small deflections only. The equations given may, however, be used for comparison purposes.

9.4 Statistical parameters

Calculate the arithmetic mean of the test results and, if required, the standard deviation and the 95 % confidence interval of the mean value using the procedure given in ISO 2602.

9.5 Significant figures

Calculate the stresses and the modulus to three significant figures. Calculate the deflections to two significant figures.

10 Precision

The precision of this test method is not known because interlaboratory data are not available. When interlaboratory data are obtained, a precision statement will be added at the following revision.

11 Test report

The test report shall include the following information:

a) a reference to this International Standard;

b) all the information necessary for identification of the material tested, including type, source, manufacturer's code-number, form and previous history where these are known;

c) for sheets, the thickness of the sheet and, if applicable, the directions of the major axes of the specimens in relation to some feature of the sheet;

d) the shape and dimensions of the test specimens;

e) the method of preparing the specimens;

f) the test conditions and conditioning procedures, if applicable;

g) the number of specimens tested;

h) the nominal span used;

i) the test speed;

j) the accuracy grading of the test machine (see ISO 5893);

k) the surface on which the force was applied;

l) the individual test results, if required;

m) the mean values of the individual results;

n) the standard deviations and the 95 % confidence intervals of these mean values, if required;

o) the date of the test.

Annex A
(normative)

Compliance correction

If the deflection s cannot be measured directly and must be replaced by precisely recording the change s_C in the distance between the crossheads of the test machine, this change in distance shall be corrected for the compliance C_M of the machine. C_M is determined using a reference bar of highly rigid reference material of known tensile modulus, e.g. steel sheeting. The deflection s is calculated using the equations

$$s = s_C - C_M F \tag{A.1}$$

and

$$C_M = \frac{s_R}{F} - \frac{L_R^3}{4 E_R b_R h_R^3} \tag{A.2}$$

where

s is the deflection, in millimetres;

s_C is the change, in millimetres, in the distance between two selected points on the test machine;

C_M is the compliance, in millimetres per newton, of the test machine between the selected points;

s_R is the change, in millimetres, in the distance between the selected points when using the reference specimen;

F is the force, in newtons;

E_R is the tensile modulus, in megapascals, of the reference material;

L_R is the span, in millimetres, during compliance determination;

b_R is the width, in millimetres, of the reference specimen;

d_R is the thickness, in millimetres, of the reference specimen.

Alternatively, if it is possible to measure precisely the deflection Δs_R of the reference specimen relative to the supports, the machine compliance can be determined from the equation

$$C_M = \frac{1}{F}\left(s^* - \Delta s_R\right) \tag{A.3}$$

where

s^* is the displacement indicated by the equipment during the test, e.g. crosshead displacement;

Δs_R is the deflection of the reference specimen as determined by a calibrated reference instrument.

In this case, the modulus of the reference material does not have to be known.

Ensure that the compliance C_M is constant for the relevant range of forces. The simple linear relation assumed here ($s_C = C_M \times F$) for machine deformation due to compliance may be not valid if e.g. seating effects in one or more components of the machine occur.

Bibliography

[1] ISO 527-1:1993, *Plastics — Determination of tensile properties — Part 1: General principles*

[2] ISO 14125:1998, *Fibre-reinforced plastic composites — Determination of flexural properties*

[3] ISO 1209-1:1990, *Cellular plastics, rigid — Flexural tests — Part 1: Bending test*

[4] ISO 1209-2:1990, *Cellular plastics, rigid — Flexural tests — Part 2: Determination of flexural properties*

[5] ISO 472:1999, *Plastics — Vocabulary*

Annex ZA
(normative)

Normative references to international publications with their relevant European publications

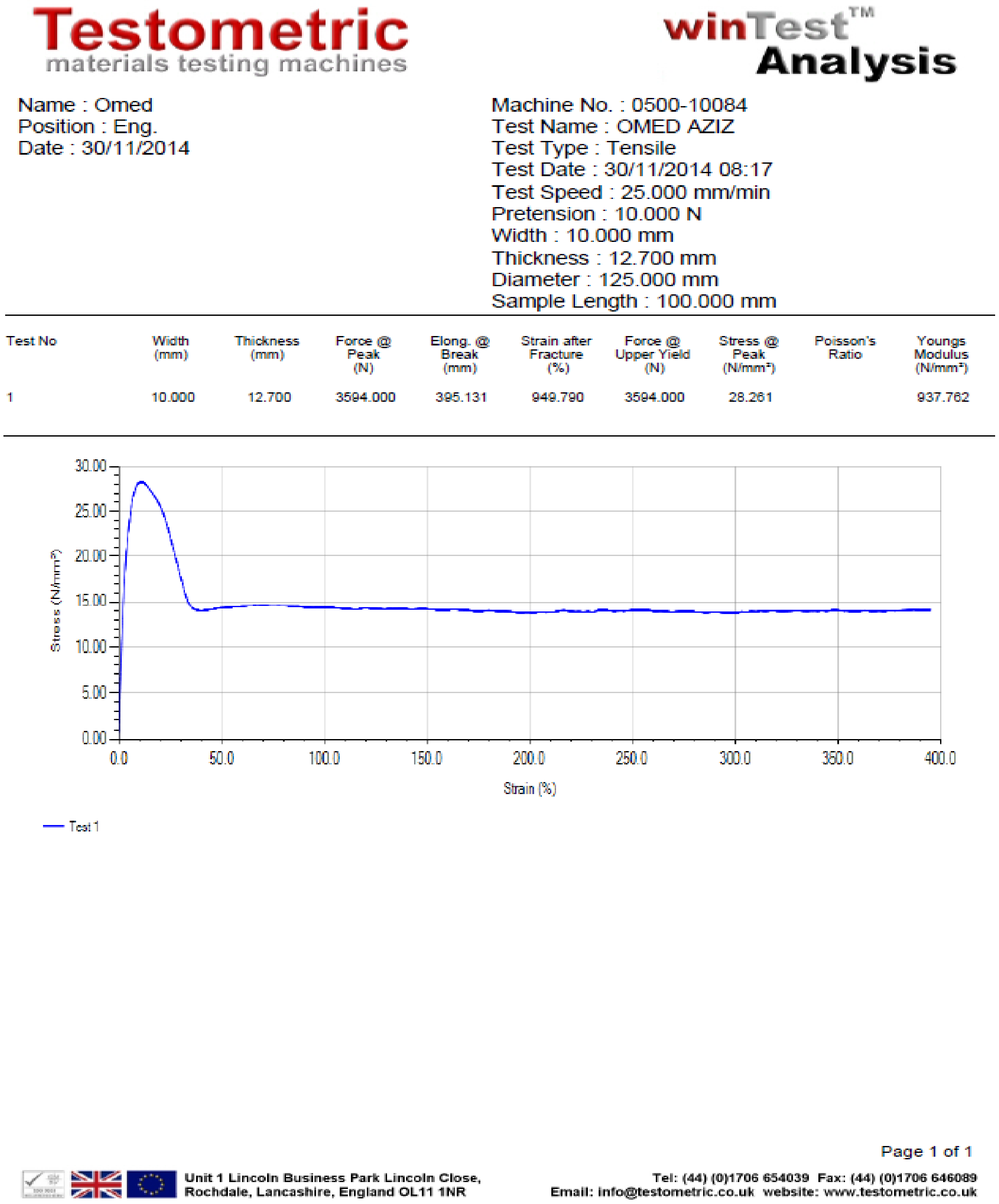
This European Standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies (including amendments).

NOTE Where an International Publication has been modified by common modifications, indicated by (mod.), the relevant EN/HD applies.

Publication	Year	Title	EN	Year
ISO 291	1997	Plastics - Standard atmospheres for conditioning and testing	EN ISO 291	1997
ISO 294-1	1996	Plastics - Injection moulding of test specimens of thermoplastic materials - Part 1: General principles, and moulding of multipurpose and bar test specimens	EN ISO 294-1	1998
ISO 2 818	1994	Plastics - Preparation of test specimens by machining	EN ISO 2818	1996
ISO 3167	1993	Plastics - Multipurpose-test specimens	EN ISO 3167	1996
ISO 10724-1	1998	Plastics - Injection moulding of test specimens o f thermosetting powder moulding compounds (PMCs) - Part 1: General principles and moulding of multi purpose test specimens	EN ISO 10724-1	2001

APPENDIX 2

Tensile Test Data



Testometric
materials testing machines

winTest™ Analysis

Name : Omed
Position : Eng.
Date : 30/11/2014

Machine No. : 0500-10084
Test Name : OMED AZIZ
Test Type : Tensile
Test Date : 30/11/2014 08:17
Test Speed : 25.000 mm/min
Pretension : 10.000 N
Width : 10.000 mm
Thickness : 12.700 mm
Diameter : 125.000 mm
Sample Length : 100.000 mm

Test No	Width (mm)	Thickness (mm)	Force @ Peak (N)	Elong. @ Break (mm)	Strain after Fracture (%)	Force @ Upper Yield (N)	Stress @ Peak (N/mm²)	Poisson's Ratio	Youngs Modulus (N/mm²)
1	10.000	12.700	3594.000	395.131	949.790	3594.000	28.261		937.762

Page 1 of 1

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Rochdale, Lancashire, England OL11 1NR

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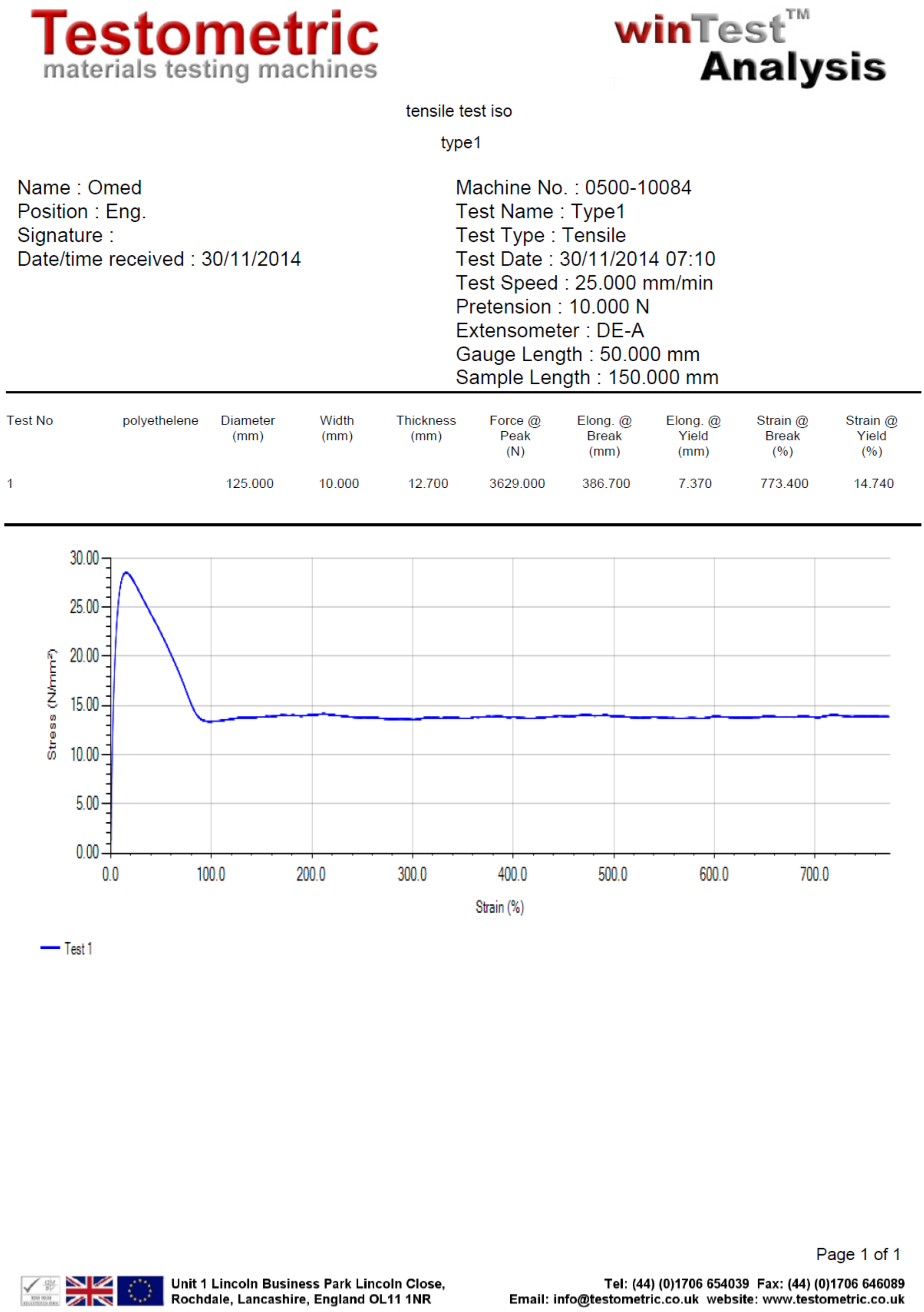
Email: info@testometric.co.uk website: www.testometric.co.uk



tensile test iso

type1

Name : Omed
Position : Eng.
Signature :
Date/time received : 30/11/2014

Machine No. : 0500-10084
Test Name : Type1
Test Type : Tensile
Test Date : 30/11/2014 07:10
Test Speed : 25.000 mm/min
Pretension : 10.000 N
Extensometer : DE-A
Gauge Length : 50.000 mm
Sample Length : 150.000 mm

Test No	polyethelene	Diameter (mm)	Width (mm)	Thickness (mm)	Force @ Peak (N)	Elong. @ Break (mm)	Elong. @ Yield (mm)	Strain @ Break (%)	Strain @ Yield (%)
1		125.000	10.000	12.700	3629.000	386.700	7.370	773.400	14.740

Page 1 of 1

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PE3

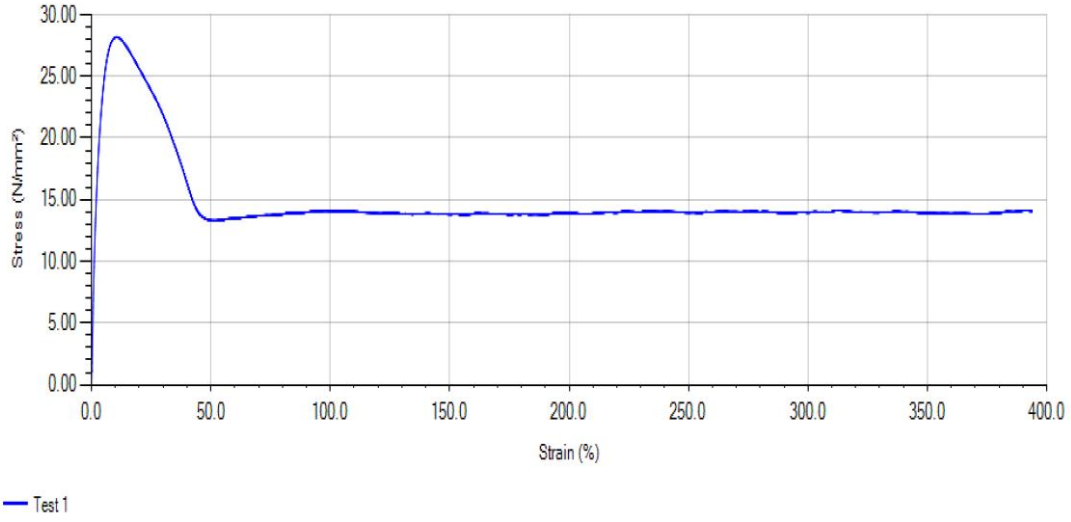
Sample3

Name : Omed
Position : Eng.
Date : 30/11/2014

Machine No. : 0500-10084
Test Name : OMED AZIZ
Test Type : Tensile
Test Date : 30/11/2014 07:47
Test Speed : 25.000 mm/min
Pretension : 10.000 N
Width : 10.000 mm
Thickness : 12.700 mm
Diameter : 125.000 mm
Sample Length : 100.000 mm

Test No	Width (mm)	Thickness (mm)	Elong. @ Break (mm)	Elong. @ 0.000 N (mm)	Force @ Peak (N)	Strain @ 0.000 N/mm^2 (%)	Strain after Fracture (%)	Force @ Upper Yield (N)	Elong. @ 0.000 N/mm^2 (mm)
1	10.000	12.700	394.022		3585.000		949.675	3585.000	

Test No	Stress @ Peak (N/mm^2)	Time to Failure (Secs)	Youngs Modulus (N/mm^2)
1	28.191	945.120	951.369



Testometric
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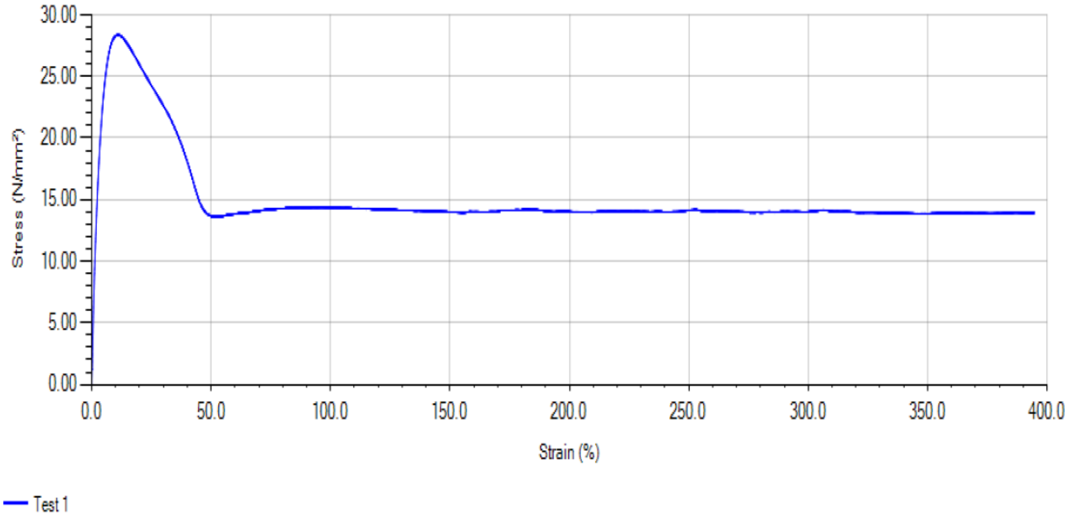
Polyethylene

Sample 4

Name : Omed
Position : Eng.
Date : 30/11/2014
PE : 4
Sample : 4

Machine No. : 0500-10084
Test Name : OMED AZIZ
Test Type : Tensile
Test Date : 30/11/2014 08:38
Test Speed : 25.000 mm/min
Pretension : 10.000 N
Width : 10.000 mm
Thickness : 12.700 mm
Diameter : 125.000 mm
Sample Length : 100.000 mm

Test No	Width (mm)	Thickness (mm)	Force @ Peak (N)	Elong. @ Break (mm)	Strain after Fracture (%)	Force @ Upper Yield (N)	Stress @ Peak (N/mm²)	Secant Stiffness 0.000 to 0.000 % (N/mm)	Youngs Modulus (N/mm²)
1	10.000	12.700	3608.000	394.735	949.837	3608.000	28.371		805.621



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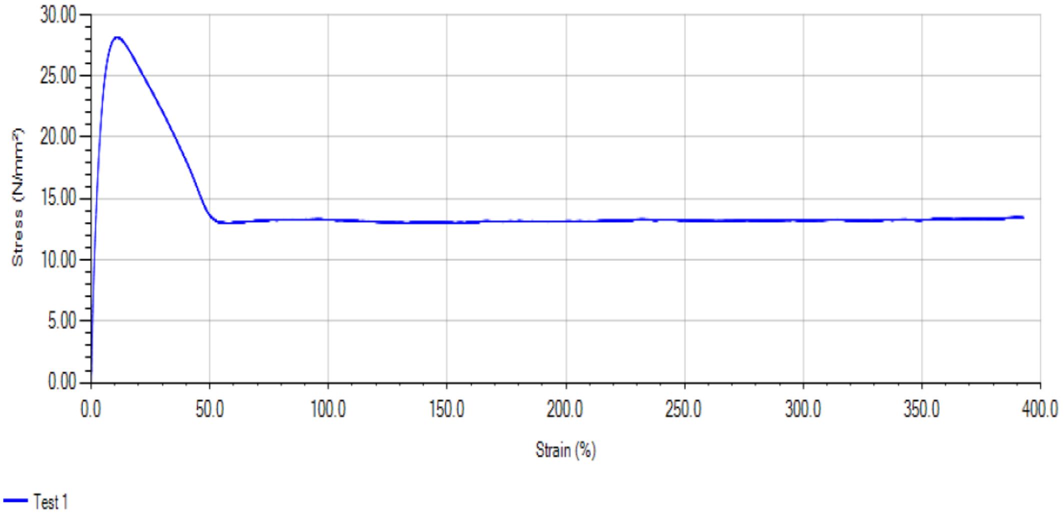
Polyethylene

Sample 5

Name : Omed
Position : Eng.
Date : 30/11/2014
PE : 5
Sample : 5

Machine No. : 0500-10084
Test Name : OMED AZIZ
Test Type : Tensile
Test Date : 30/11/2014 09:04
Test Speed : 25.000 mm/min
Pretension : 10.000 N
Width : 10.000 mm
Thickness : 12.700 mm
Diameter : 125.000 mm
Sample Length : 100.000 mm

Test No	Width (mm)	Thickness (mm)	Force @ Peak (N)	Elong. @ Break (mm)	Strain after Fracture (%)	Force @ Upper Yield (N)	Elong. @ Lower Yield (mm)	Stress @ Peak (N/mm²)	Youngs Modulus (N/mm²)
1	10.000	12.700	3581.000	392.833	949.826	3579.000	15.014	28.159	718.938



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HDPE

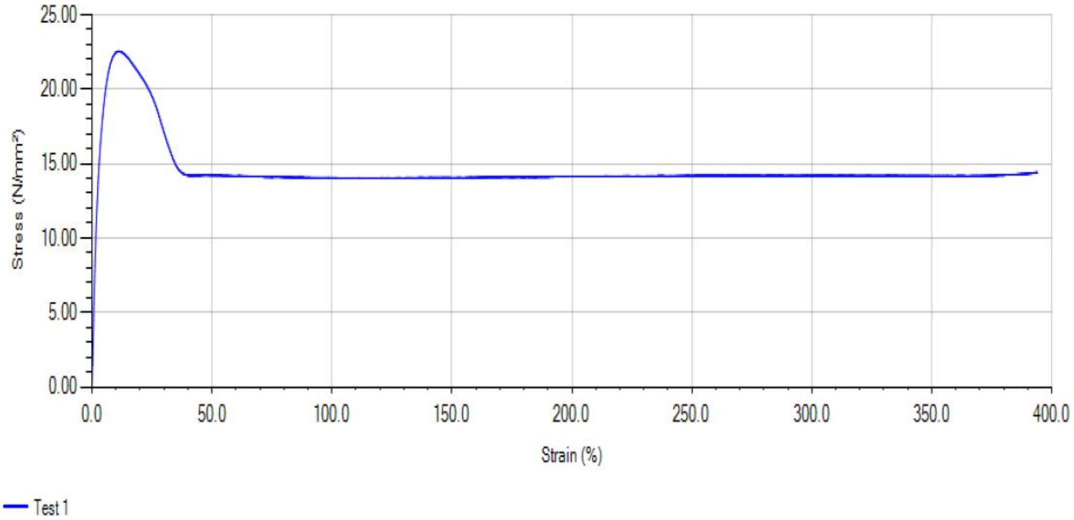
Sample1

Name : Omed
Position : Eng.
Date : 30/11/2014
HDPE : 1

Machine No. : 0500-10084
Test Name : OMED AZIZ
Test Type : Tensile
Test Date : 30/11/2014 10:27
Test Speed : 50.000 mm/min
Pretension : 10.000 N
Width : 10.000 mm
Thickness : 8.000 mm
Diameter : 90.000 mm
Sample Length : 100.000 mm

Test No	Width (mm)	Thickness (mm)	Force @ Peak (N)	Elong. @ Break (mm)	Strain after Fracture (%)	Force @ Upper Yield (N)	Elong. @ Lower Yield (mm)	Stress @ Peak (N/mm²)	Youngs Modulus (N/mm²)
1	10.000	8.000	1808.000	394.391	949.276	1808.000	11.258	22.544	665.462

Test No	Elongation after Fracture (mm)	Plastic Strain @ Break (%)
1	949.931	391.953



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HDPE

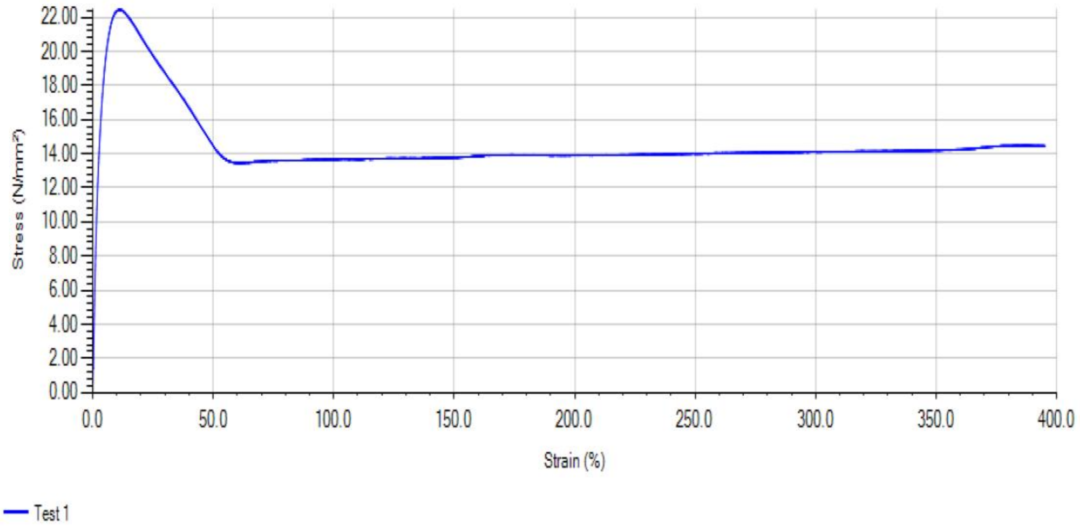
Sample2

Name : Omed
Position : Eng.
Date : 30/11/2014
HDPE : 2

Machine No. : 0500-10084
Test Name : OMED AZIZ
Test Type : Tensile
Test Date : 30/11/2014 10:41
Test Speed : 50.000 mm/min
Pretension : 10.000 N
Width : 10.000 mm
Thickness : 8.000 mm
Diameter : 90.000 mm
Sample Length : 100.000 mm

Test No	Width (mm)	Thickness (mm)	Force @ Peak (N)	Elong. @ Break (mm)	Strain after Fracture (%)	Force @ Upper Yield (N)	Elong. @ Lower Yield (mm)	Stress @ Peak (N/mm²)	Youngs Modulus (N/mm²)
1	10.000	8.000	1801.000	395.393	949.444	1801.000	15.833	22.456	674.823

Test No	Elongation after Fracture (mm)	Plastic Strain @ Break (%)
1	949.947	393.038



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HDPE

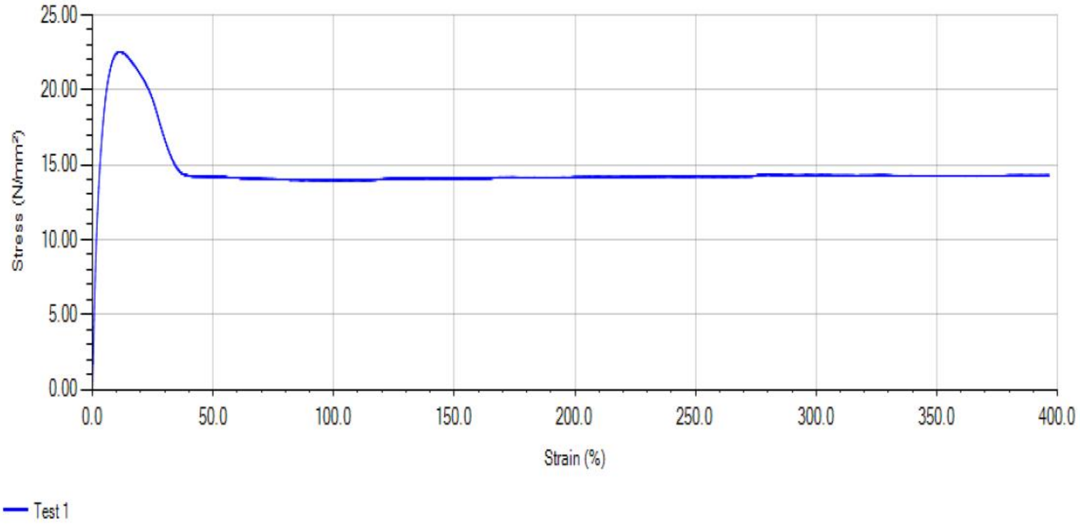
Sample3

Name : Omed
Position : Eng.
Date : 30/11/2014
HDPE : 3

Machine No. : 0500-10084
Test Name : OMED AZIZ
Test Type : Tensile
Test Date : 30/11/2014 10:55
Test Speed : 50.000 mm/min
Pretension : 10.000 N
Width : 10.000 mm
Thickness : 8.000 mm
Diameter : 90.000 mm
Sample Length : 100.000 mm

Test No	Width (mm)	Thickness (mm)	Force @ Peak (N)	Elong. @ Break (mm)	Strain after Fracture (%)	Force @ Upper Yield (N)	Elong. @ Lower Yield (mm)	Stress @ Peak (N/mm²)	Youngs Modulus (N/mm²)
1	10.000	8.000	1807.000	396.706	949.565	1807.000	14.303	22.531	681.591

Test No	Elongation after Fracture (mm)	Plastic Strain @ Break (%)
1	949.959	394.445



HDPE

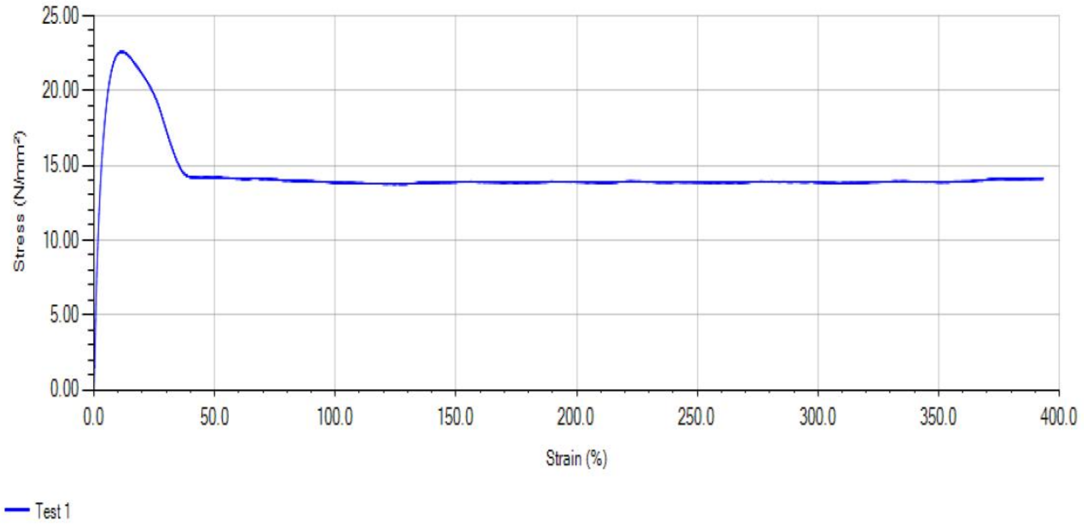
Sample4

Name : Omed
Position : Eng.
Date : 30/11/2014
HDPE : 4

Machine No. : 0500-10084
Test Name : OMED AZIZ
Test Type : Tensile
Test Date : 30/11/2014 11:18
Test Speed : 50.000 mm/min
Pretension : 10.000 N
Width : 10.000 mm
Thickness : 8.000 mm
Diameter : 90.000 mm
Sample Length : 100.000 mm

Test No	Width (mm)	Thickness (mm)	Force @ Peak (N)	Elong. @ Break (mm)	Strain after Fracture (%)	Force @ Upper Yield (N)	Elong. @ Lower Yield (mm)	Stress @ Peak (N/mm²)	Youngs Modulus (N/mm²)
1	10.000	8.000	1813.000	393.480	949.484	1813.000	16.258	22.606	667.635

Test No	Elongation after Fracture (mm)	Plastic Strain @ Break (%)
1	949.951	391.174



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HDPE

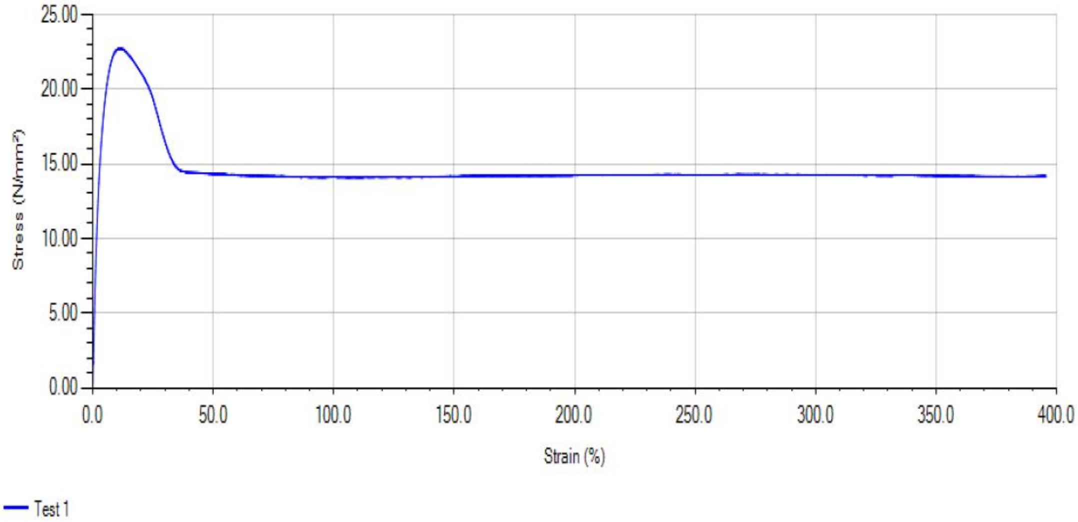
Sample 5

Name : Omed
Position : Eng.
Date : 30/11/2014
HDPE : 5

Machine No. : 0500-10084
Test Name : OMED AZIZ
Test Type : Tensile
Test Date : 30/11/2014 11:06
Test Speed : 50.000 mm/min
Pretension : 10.000 N
Width : 10.000 mm
Thickness : 8.000 mm
Diameter : 90.000 mm
Sample Length : 100.000 mm

Test No	Width (mm)	Thickness (mm)	Force @ Peak (N)	Elong. @ Break (mm)	Strain after Fracture (%)	Force @ Upper Yield (N)	Elong. @ Lower Yield (mm)	Stress @ Peak (N/mm²)	Youngs Modulus (N/mm²)
1	10.000	8.000	1822.000	395.727	949.591	1822.000	14.261	22.718	674.678

Test No	Elongation after Fracture (mm)	Plastic Strain @ Break (%)
1	949.961	393.470



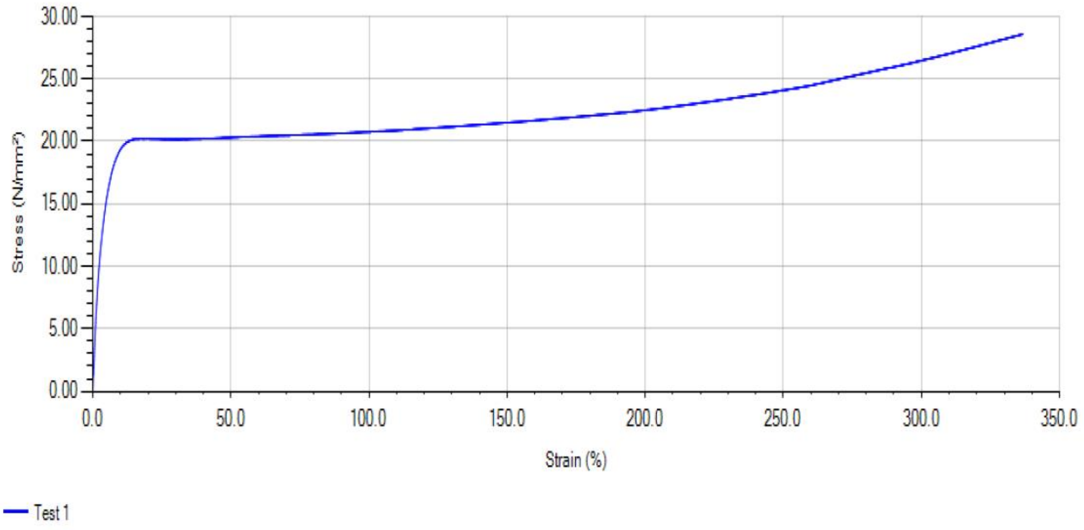
UHMWPE

Sample 1

Name : Omed
Position : Eng.
Date : 30/11/2014
UHMWPE : 1

Machine No. : 0500-10084
Test Name : OMED AZIZ
Test Type : Tensile
Test Date : 30/11/2014 09:28
Test Speed : 50.000 mm/min
Pretension : 10.000 N
Width : 10.000 mm
Thickness : 8.000 mm
Diameter : 90.000 mm
Sample Length : 100.000 mm

Test No	Width (mm)	Thickness (mm)	Force @ Peak (N)	Elong. @ Break (mm)	Strain after Fracture (%)	Force @ Upper Yield (N)	Elong. @ Lower Yield (mm)	Stress @ Peak (N/mm²)	Youngs Modulus (N/mm²)
1	10.000	8.000	2293.000	336.978	892.460	1623.000	21.579	28.591	422.495



Testometric
materials testing machines

winTest™
Analysis

UHMWPE

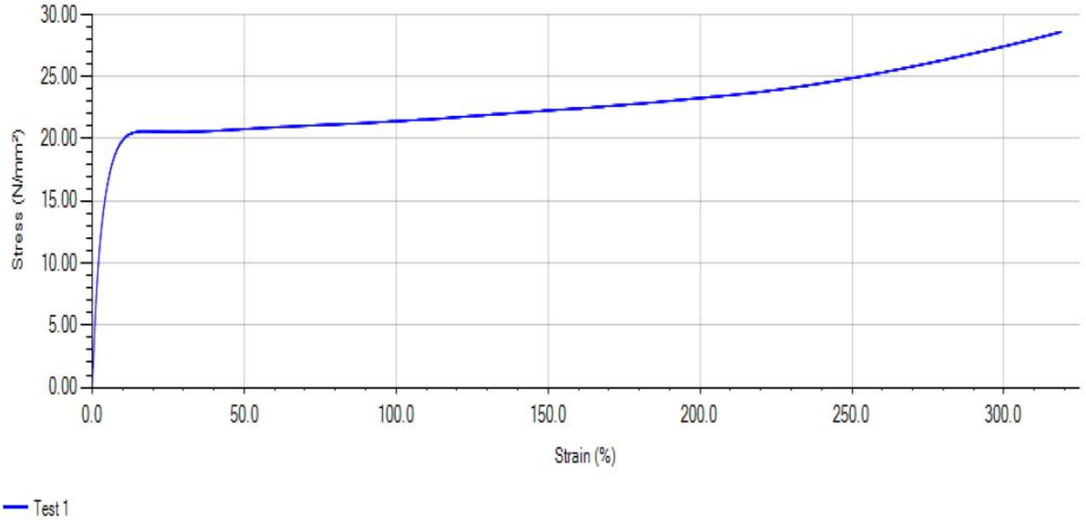
Sample 2

Name : Omed
Position : Eng.
Date : 30/11/2014
UHMWPE : 2

Machine No. : 0500-10084
Test Name : OMED AZIZ
Test Type : Tensile
Test Date : 30/11/2014 09:42
Test Speed : 50.000 mm/min
Pretension : 10.000 N
Width : 10.000 mm
Thickness : 8.000 mm
Diameter : 90.000 mm
Sample Length : 100.000 mm

Test No	Width (mm)	Thickness (mm)	Force @ Peak (N)	Elong. @ Break (mm)	Strain after Fracture (%)	Force @ Upper Yield (N)	Elong. @ Lower Yield (mm)	Stress @ Peak (N/mm²)	Youngs Modulus (N/mm²)
1	10.000	8.000	2294.000	319.163	873.441	1645.000	13.865	28.603	492.038

Test No	Elongation after Fracture (mm)	Plastic Strain @ Break (%)
1	873.943	313.166



Testometric
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UHMWPE

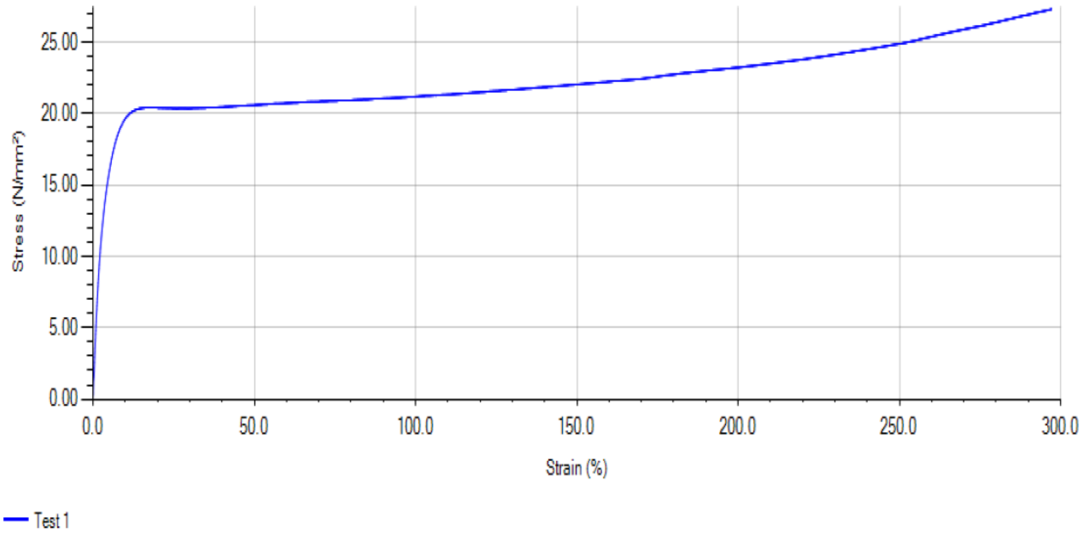
Sample3

Name : Omed
Position : Eng.
Date : 30/11/2014
UHMWPE : 3

Machine No. : 0500-10084
Test Name : OMED AZIZ
Test Type : Tensile
Test Date : 30/11/2014 09:54
Test Speed : 50.000 mm/min
Pretension : 10.000 N
Width : 10.000 mm
Thickness : 8.000 mm
Diameter : 90.000 mm
Sample Length : 100.000 mm

Test No	Width (mm)	Thickness (mm)	Force @ Peak (N)	Elong. @ Break (mm)	Strain after Fracture (%)	Force @ Upper Yield (N)	Elong. @ Lower Yield (mm)	Stress @ Peak (N/mm²)	Youngs Modulus (N/mm²)
1	10.000	8.000	2190.000	297.411	852.335	2190.000		27.307	464.076

Test No	Elongation after Fracture (mm)	Plastic Strain @ Break (%)	Elong. @ Lower Yield (mm)	Energy to Peak (N.m)	Secant Stiffness 0.000 to 0.000 % (N/mm)
1	852.930	291.320		532.728	



Testometric
materials testing machines

winTest™ Analysis

UHMWPE

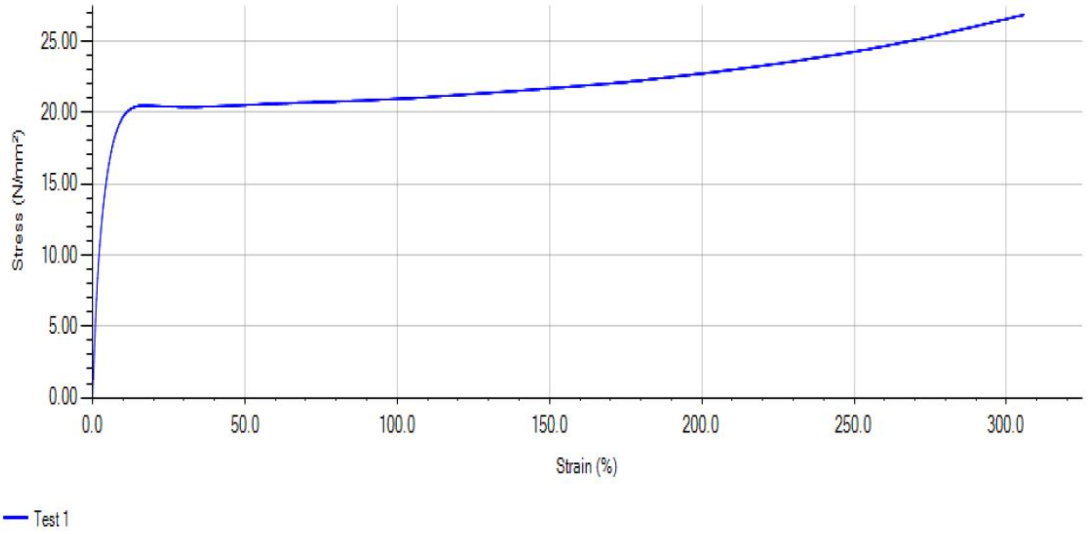
Sample4

Name : Omed
Position : Eng.
Date : 30/11/2014
UHMWPE : 4

Machine No. : 0500-10084
Test Name : OMED AZIZ
Test Type : Tensile
Test Date : 30/11/2014 10:04
Test Speed : 50.000 mm/min
Pretension : 10.000 N
Width : 10.000 mm
Thickness : 8.000 mm
Diameter : 90.000 mm
Sample Length : 100.000 mm

Test No	Width (mm)	Thickness (mm)	Force @ Peak (N)	Elong. @ Break (mm)	Strain after Fracture (%)	Force @ Upper Yield (N)	Elong. @ Lower Yield (mm)	Stress @ Peak (N/mm²)	Youngs Modulus (N/mm²)
1	10.000	8.000	2153.000	305.958	861.365	1643.000	20.120	26.845	493.391

Test No	Elongation after Fracture (mm)	Plastic Strain @ Break (%)
1	861.934	300.315



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Testometric
materials testing machines

winTest™
Analysis

UHMWPE

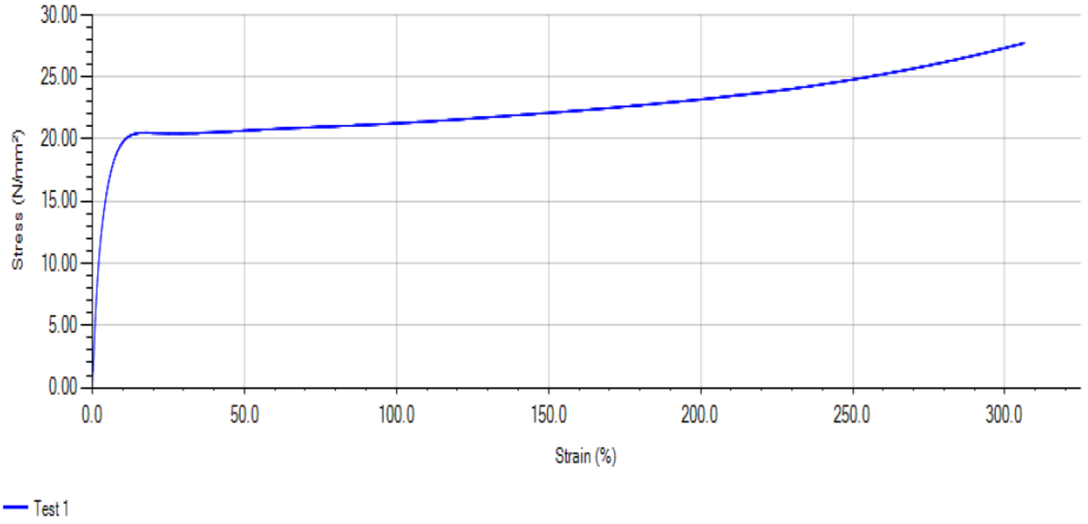
Sample5

Name : Omed
Position : Eng.
Date : 30/11/2014
UHMWPE : 5

Machine No. : 0500-10084
Test Name : OMED AZIZ
Test Type : Tensile
Test Date : 30/11/2014 10:17
Test Speed : 50.000 mm/min
Pretension : 10.000 N
Width : 10.000 mm
Thickness : 8.000 mm
Diameter : 90.000 mm
Sample Length : 100.000 mm

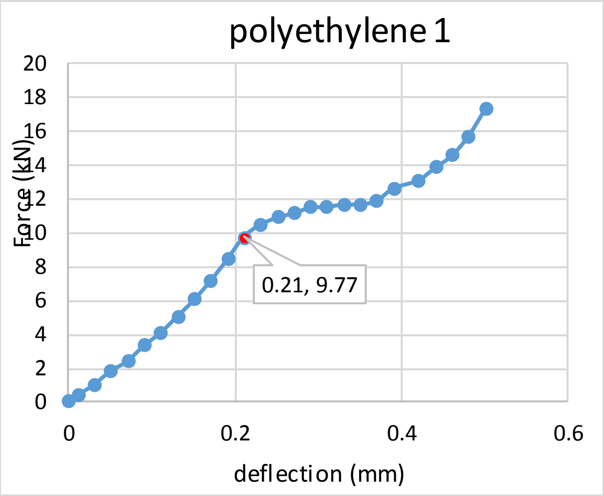
Test No	Width (mm)	Thickness (mm)	Force @ Peak (N)	Elong. @ Break (mm)	Strain after Fracture (%)	Force @ Upper Yield (N)	Elong. @ Lower Yield (mm)	Stress @ Peak (N/mm²)	Youngs Modulus (N/mm²)
1	10.000	8.000	2224.000	306.633	862.280	1645.000	22.875	27.731	501.837

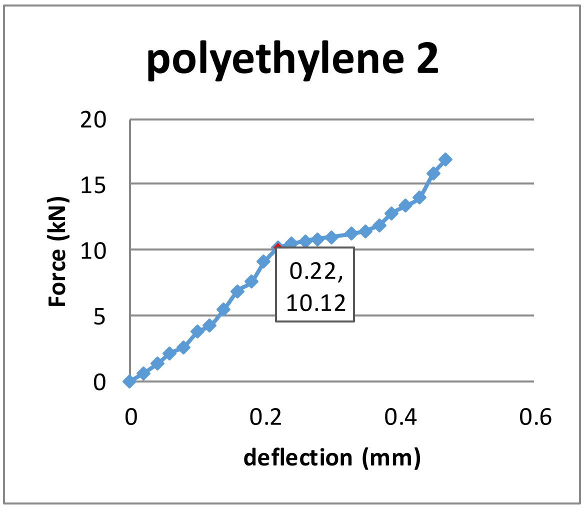
Test No	Elongation after Fracture (mm)	Plastic Strain @ Break (%)
1	862.925	300.878

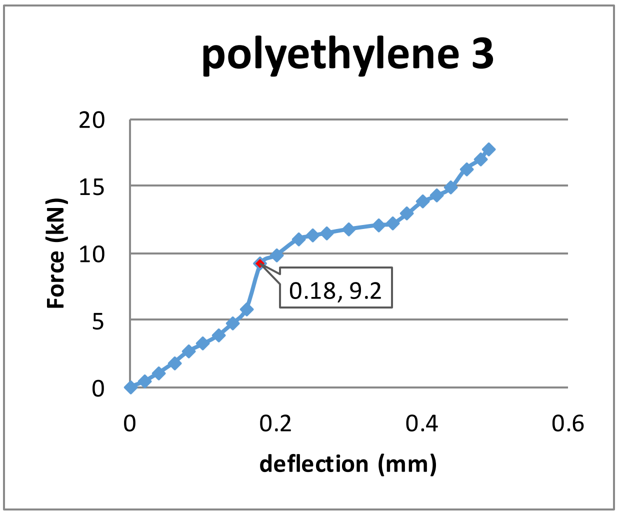


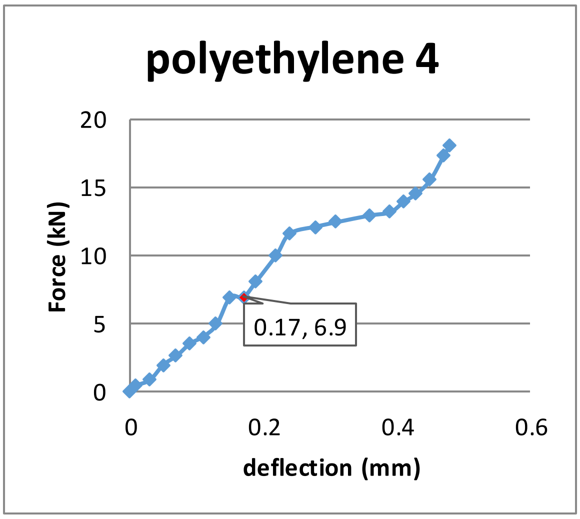
APPENDIX 3

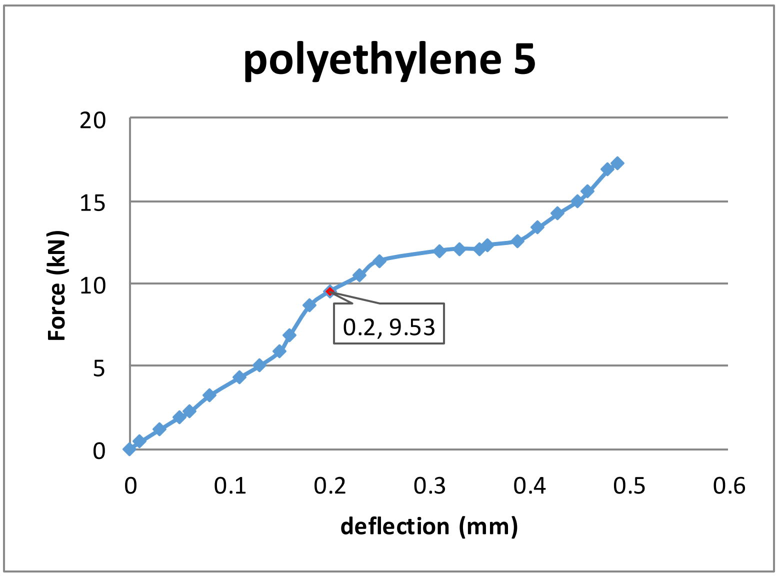
Flexural Test Data

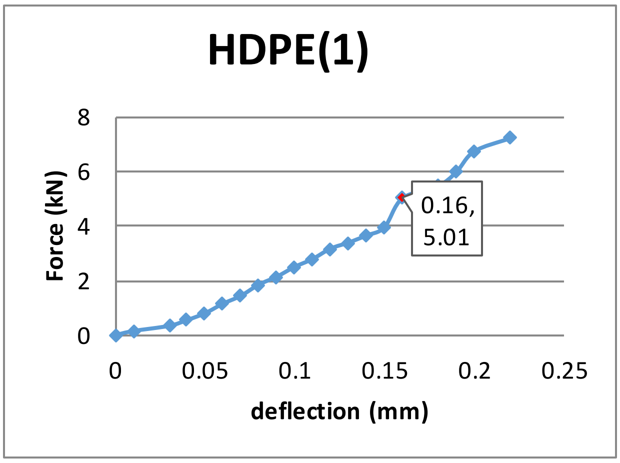


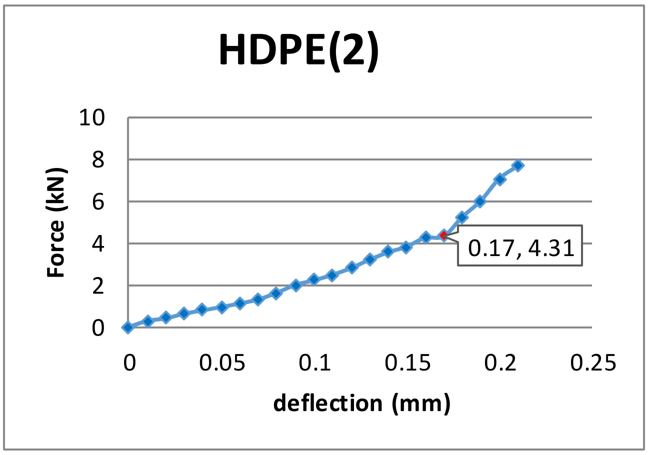


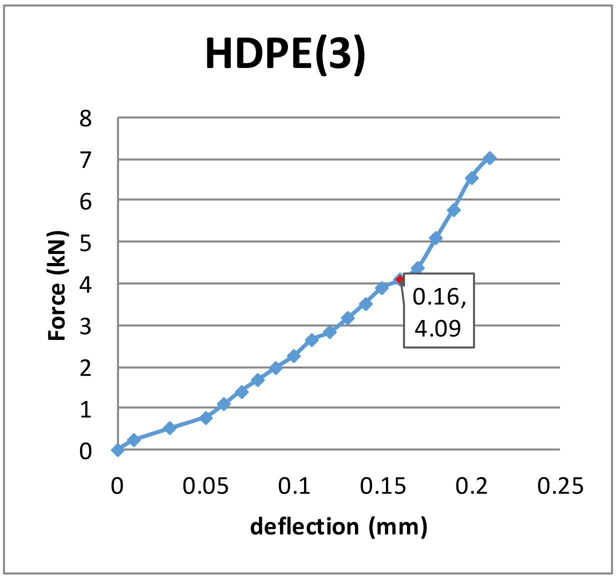


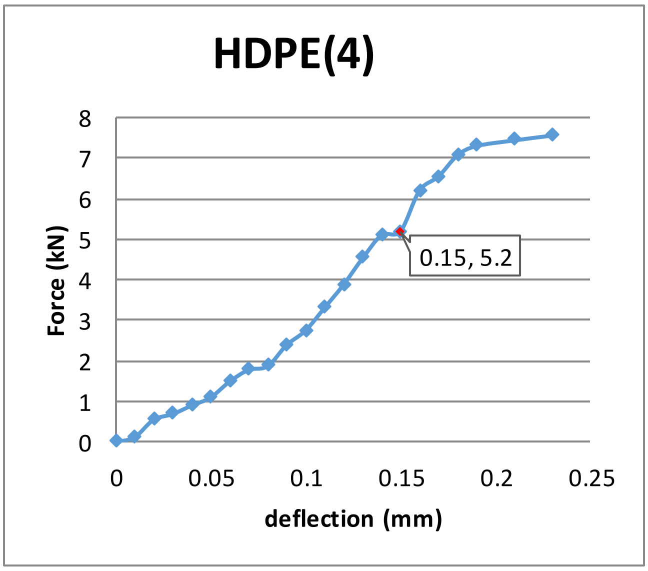


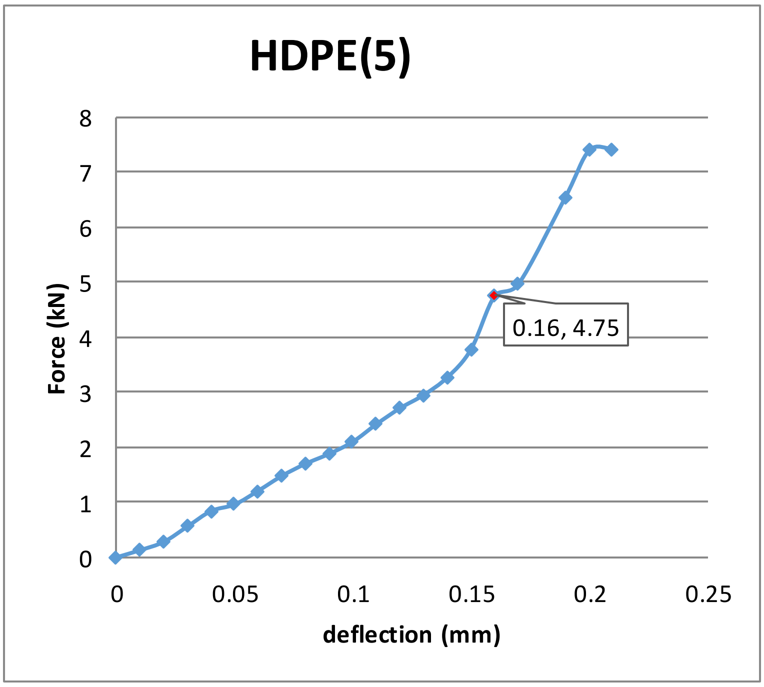


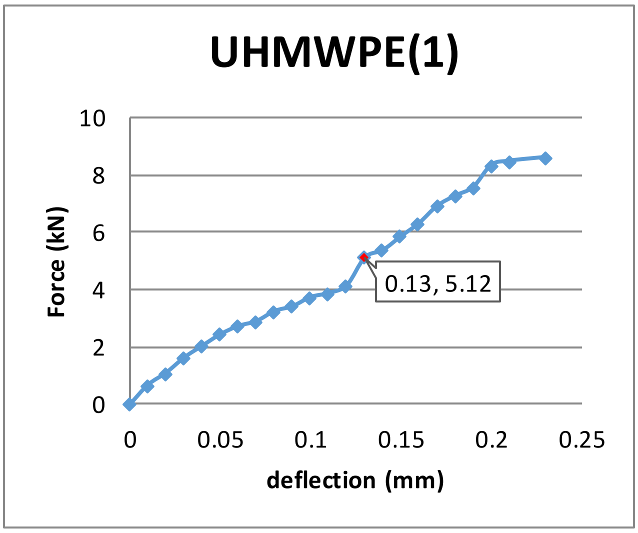

HDPE(1)
Force (kN)
0
2
4
6
8
0
0.05
0.1
0.15
0.2
0.25
deflection (mm)
0.16, 5.01

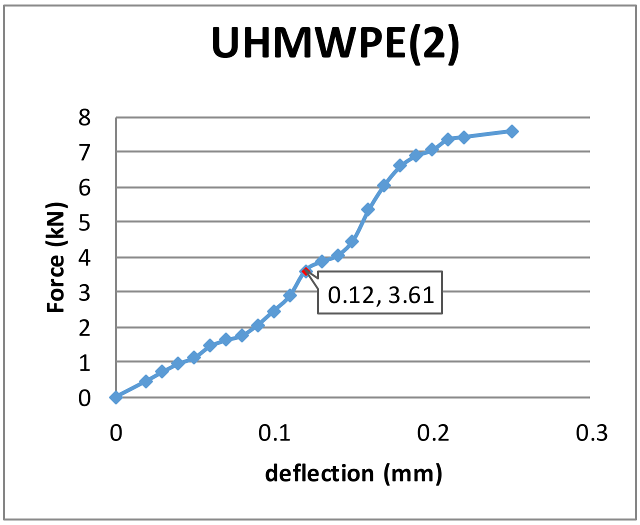

HDPE(2)
Force (kN)
0
2
4
6
8
10
0
0.05
0.1
0.15
0.2
0.25
deflection (mm)
0.17, 4.31

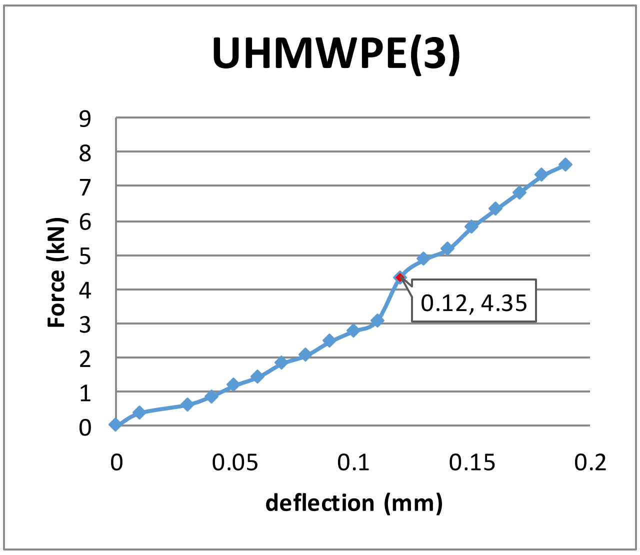

HDPE(3)
Force (kN)
0
1
2
3
4
5
6
7
8
0
0.05
0.1
0.15
0.2
0.25
deflection (mm)
0.16, 4.09

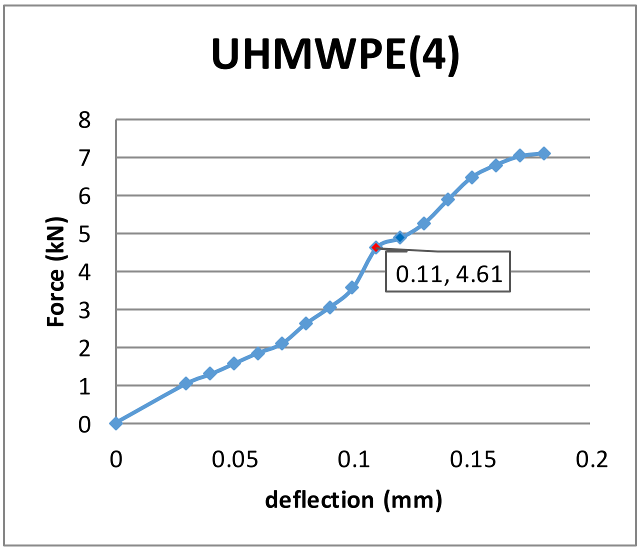

HDPE(4)
Force (kN)
0
1
2
3
4
5
6
7
8
0
0.05
0.1
0.15
0.2
0.25
deflection (mm)
0.15, 5.2

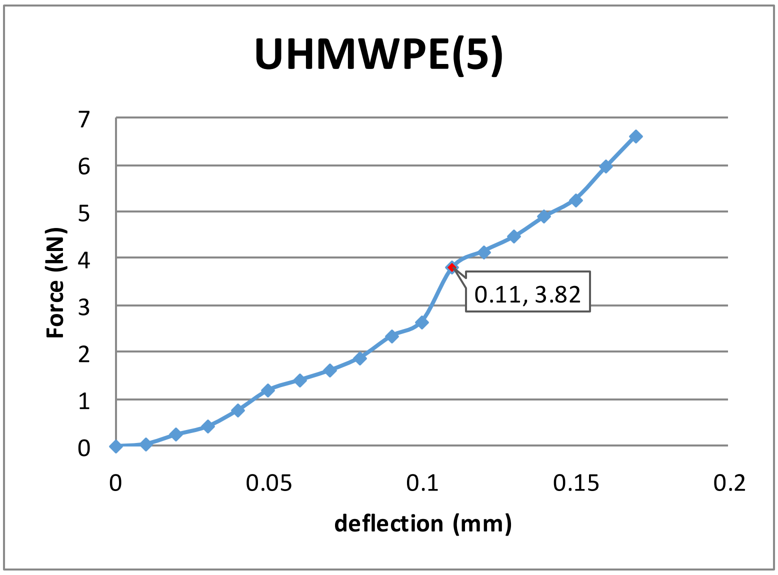

HDPE(5)
Force (kN)
0
1
2
3
4
5
6
7
8
0
0.05
0.1
0.15
0.2
0.25
deflection (mm)
0.16, 4.75


UHMWPE(1)
Force (kN)
10
8
6
4
2
0
0
0.05
0.1
0.15
0.2
0.25
deflection (mm)
0.13, 5.12


UHMWPE(2)
Force (kN)
8
7
6
5
4
3
2
1
0
0
0.1
0.2
0.3
deflection (mm)
0.12, 3.61


UHMWPE(3)
Force (kN)
9
8
7
6
5
4
3
2
1
0
0
0.05
0.1
0.15
0.2
deflection (mm)
0.12, 4.35


UHMWPE(4)
Force (kN)
8
7
6
5
4
3
2
1
0
0
0.05
0.1
0.15
0.2
deflection (mm)
0.11, 4.61


UHMWPE(5)
Force (kN)
7
6
5
4
3
2
1
0
0
0.05
0.1
0.15
0.2
deflection (mm)
0.11, 3.82