

Synthetic polymers and their applications

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Synthetic polymers and their applications

Introduction

This lesson deals with synthetic polymers and their properties and applications. Use of man-made synthetic polymeric materials plays a huge effect on our everyday life. A large number of industries (*e.g.* packaging, textile, automobile, paper *etc*) are based on **synthetic polymers** (poly = many; mer = parts) such as **polyethylene** (PE), **poly(vinyl chloride)** (PVC), polyesters, nylon, *etc.* and **natural polymers** such as rubber, cellulose, *etc.* These natural polymers have been used for a long time, for example natural rubber was discovered in 1492 by Columbus when he was in South America.

Synthetic polymers can be classified according to their response to heat. A **thermoplastic polymer** can be softened by heating and then transformed into desired shapes/products by moulding. In contrast, **thermosetting polymers** are permanently hard at elevated temperatures and pressures. They cannot be softened and remoulded. Polymers can be divided mainly into four types depending on their properties – plastics (*e.g.* PVC), fibres (*e.g.* polyamides), elastomers (*e.g.* rubber) and adhesives (*e.g.* resins). One of the most interesting uses of polymers (*e.g.* biomedical polymers) has been as replacements for diseased, worn out or missing parts of the human body such as leg, arm, lung, heart, liver, kidney, arteries, teeth, knee joints and hip joints. Synthetic polymers could pose a serious threat to environment unless we make them biodegradable.

All polymers are **macromolecules** with the same **repeating unit** but all macromolecules are not polymers. For example, **proteins** and **nucleic acids** (DNA and RNA) are macromolecules but they do not have the same repeating unit. Natural polymers and macromolecules such as polysaccharides (*e.g.* cellulose, starch, *etc*) and nucleic acids (responsible for heredity) based on sugars and phosphates.

When naming **homopolymers** (*i.e.* polymers with one monomer unit), the name of the monomer is written after the prefix poly, *e.g.* polyethylene. If the name of the monomer is **not a one word** the name of the monomer is written within brackets, *e.g.* poly(vinyl chloride).

Q: What are the important properties of synthetic polymers?

A: They are light weight, flexible, have moderate to high strength, resistant to chemicals, *etc*

Q: Name some *industrial applications* of polymeric materials.

A: Polymeric materials are used as elastomers (rubber), fibres (polyesters, nylon), adhesives (epoxy resins, acrylic resins), packaging/films (polyethylene, polypropylene), paints (polyacrylate), plastics (PVC), electrical insulators, *etc.*

1. Polyethylene (PE)

Let us first study the chemistry of well-known polymer **polyethylene** or **polyethene** or **polythene**, in which a large number of **ethylene** or **ethene** ($\text{CH}_2=\text{CH}_2$) molecules are linked to form a long *hydrocarbon chain* or the *hydrocarbon backbone*. Ethylene or ethene is called the **monomer** (mono = one; mer = parts) and $-\text{CH}_2\text{CH}_2-$ is the **repeating unit**. In the polymer formula, the repeating monomer unit is placed within *brackets* with *bonds extending to both sides*. The subscript **n** indicates the number of repeating units. Thus, $-\text{[CH}_2\text{-CH}_2\text{]}_n-$ is the formula used to represent polyethylene, with **n** repeating units. Note that **n** is a large integer.

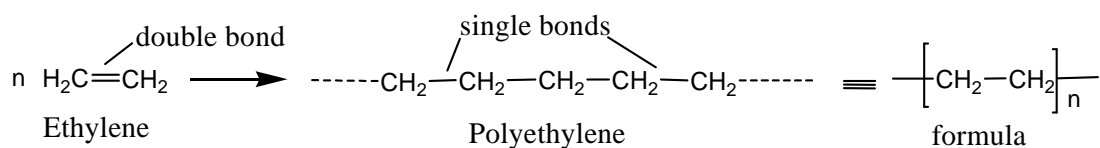


Figure 1 Formation of polyethylene

We know that ethylene is a gas produced in petroleum industry. Both carbon atoms are sp^2 -hybridized and it has a **planar** geometry. During polymerisation ethylene **gas** containing two sp^2 -carbon atoms (with a carbon-carbon double bond, $\text{C}=\text{C}$) is converted into a **white solid** with a long hydrocarbon chain in which each **tetrahedral** carbon atom ($-\text{CH}_2-$) is sp^3 -hybridized and forms two carbon-carbon single bonds to adjacent carbon atoms. Since each carbon atom is sp^3 -hybridized the 3D view of polyethylene is as follows.

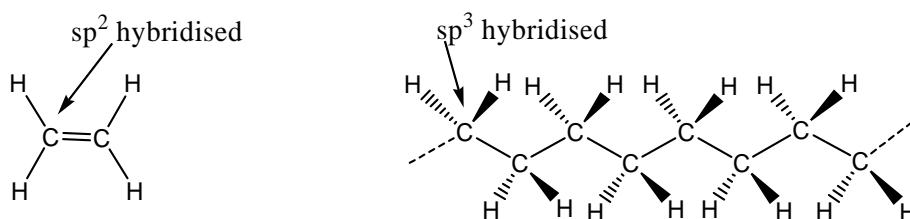
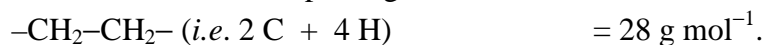


Figure 2 Geometry of ethylene and polyethylene (\blacktriangleright and \cdots indicates the stereochemistry at carbon centres)

Q: What is the molar mass of a polyethylene chain containing 100 repeating units?

A: The molar mass of a repeating unit



The molar mass of the polymer chain = mass of a repeating unit \times 100

$$= 28 \times 100 \text{ g mol}^{-1} = 2800 \text{ g mol}^{-1}$$

Q: Draw the structure of the **trimer** formed by linking three ethylene molecules.

A:

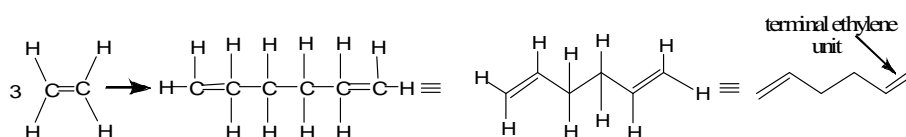


Figure 3 Trimer formed by linking of three ethylene molecules

Note that the two terminal carbon atoms are sp^2 -hybridized. But when there is a large number of repeating units, we write the **chemical formula of polyethylene** as $-\text{[CH}_2\text{CH}_2\text{]}_n-$ and we ignore the two terminal ethylene units.

There are two types of polyethylene depending on the density of the resulting polymer.

1. Low density polyethylene (LDPE) which is produced at high temperatures over (200°C) and high pressure (1000 atm).
2. High density polyethylene (HDPE) which is produced at ambient temperatures and low pressure (100 atm) in the presence of a catalyst.

Physical properties and uses of polyethylene

HDPE has a *higher density, greater rigidity and greater strength* as well as a *higher melting point*. It is used for the preparation of threaded bottle caps, radio and television cabinets, toys and large-diameter pipes. LDPE is a flexible, waxy, translucent material which has a relatively low melting point. LDPE is used in insulation for electric wiring, plastic/shopping bags, refrigerator dishes, squeeze bottles, and many other common household articles.

HDPE consists primarily of *linear molecules*, that is, long *un-branched* chains (*with molar mass ca. 3,000,000*). The chains can run alongside one another *in close contact* over relatively great distances. This permits strong *intermolecular forces of attraction* between the chains. The overall effect is to produce an *ordered (crystalline) structure* that imparts *rigidity, strength, and a higher melting temperature* to the polymeric material.

LDPE has *branched chains* that prevent the macromolecules from assuming a *crystalline structure*. This weakens the attraction between chains and produces a more flexible material and *lower melting temperature* than HDPE. Density, tensile strength and relative elongation

values at fraction for HDPE and LDPE are given below. *HDPE is stronger but less elastic than LDPE.*

	Density / g cm ⁻³	Tensile strength / MPa	Elongation at fraction (%)
HDPE	0.96	29	350
LDPE	0.92	15	600

Plasticizers

Some plastics are difficult to process and they can be made more flexible and easier to handle by incorporating **plasticizers** (e.g. *ortho*-phthalic acids or benzene-1,2-dicarboxylic acid, and phthalate esters). Plasticizers are not a part of the polymer structure but they are physically mixed with polymer molecules. Polychlorinated biphenyls (PCBs) are a set of banned plasticizers.

Glass transition temperature (T_g)

An important parameter of polymers is the **glass transition temperature**. Above this temperature, the polymer is rubbery and tough; below it, the polymer is hard, stiff and brittle like a glass.



Activity

- (i) Draw the structure of the **tetramer** formed by linking four ethylene molecules.
(ii) How many sp³-carbon atoms are found in the tetramer of ethylene?

2. Polypropylene (PP)

Polypropylene is made by polymerising propylene CH₃CH=CH₂. We know that replacement of one **hydrogen atom** in ethylene by a **methyl group** gives propylene or prop-1-ene. In industry, propylene is produced by thermally cracking higher hydrocarbons (e.g.. C₈H₁₈ → C₃H₆ + C₅H₁₂). The structure of the polypropylene can be represented as follows.

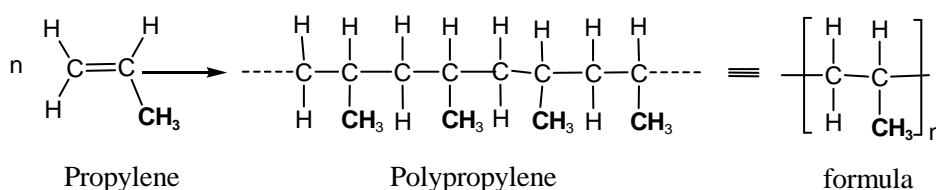


Figure 4 Formation of polypropylene

3. Addition Polymers

Polyethylene can be produced by **addition polymerisation**. During this process one ethylene molecule adds to another ethylene molecule to give the **dimer**. Then the resulting dimer reacts with another ethylene molecule to give a **trimer, tetramer, pentamer,**, **polymer**.

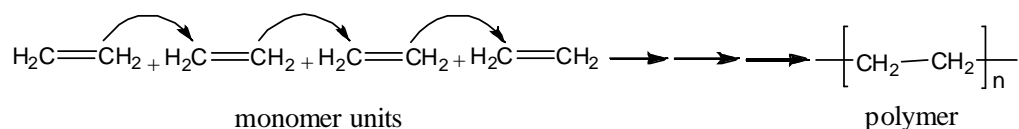


Figure 5 Addition polymerisation of ethane

The resulting polymer has the **same elemental composition** (or the C and H ratio) as the **monomer**. Ethylene can be polymerised as it can generate **two reactive sites** as shown below.

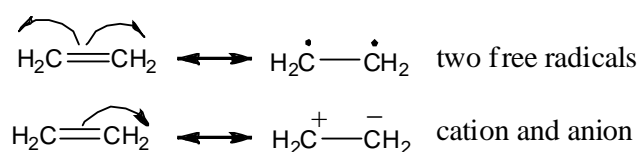


Figure 6 Possible electron movements in an ethylene molecule

The synthesis of PE does occur as shown below; **(a)** radicals are joined to produce a polymer. In a similar manner, **(b)** anions and cations are combined giving the same polymer.

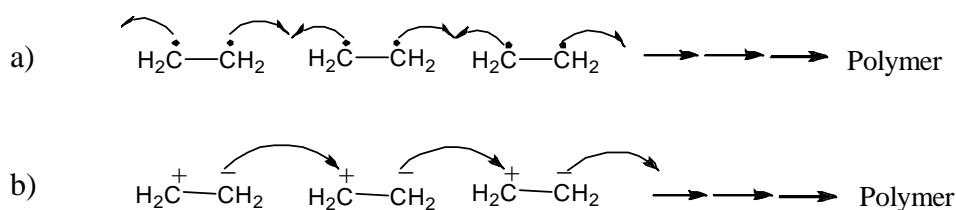


Figure 7 Synthesis of polyethylene

Unsaturated molecules such as alkenes, in particular **vinyl compounds**, serve as monomers in addition polymerisation. Note that there is **no loss of atoms** during addition polymerisation.

4. Ethylene and its derivatives

More ethylene is produced in USA than any other organic chemical and its impact on the US economy is very significant. Ethylene is produced by thermally cracking hydrocarbons containing two or more carbon atoms (*e.g.* $C_2H_6 \rightarrow C_2H_4 + H_2$ or $C_8H_{18} \rightarrow C_2H_4 + C_6H_{14}$). Ethylene is the starting material for the synthesis of many other chemicals and polymeric materials. Some derivatives of ethylene and their uses are given in Table 1.

Common Name	Applications
Ethylene chloride (CH_2ClCH_2Cl)	Solvent
Ethylene glycol (CH_2OHCH_2OH)	Antifreeze, polyester fibre
Vinyl chloride ($CH_2=CHCl$)	PVC, plastics
Styrene ($PhCH=CH_2$)	Polystyrene, plastics
Acetic acid (CH_3CO_2H)	Vinegar
Ethyl alcohol (CH_3CH_2OH)	Beverages, solvent

Table 1 Some derivatives of ethylene and their uses



Activity

2. What are the systematic (IUPAC) names of the following derivatives of ethylene?
(i) CH_2ClCH_2Cl , (ii) CH_2OHCH_2OH , (iii) $CH_2=CHCl$ and (iv) $PhCH=CH_2$.

5. Poly(vinyl chloride) (PVC)

Poly(vinyl chloride) $-[CH_2CHCl]_n-$ is an addition polymer of vinyl chloride ($CH_2=CHCl$). The presence of chlorine atoms along the polymer backbone increases the attractive forces among the chains. Thus, PVC is a stronger and harder polymer than polyethylene. PVC does not catch fire easily (fire resistant). PVC is used to manufacture films, water pipes, gutters and insulated wires, *etc.*

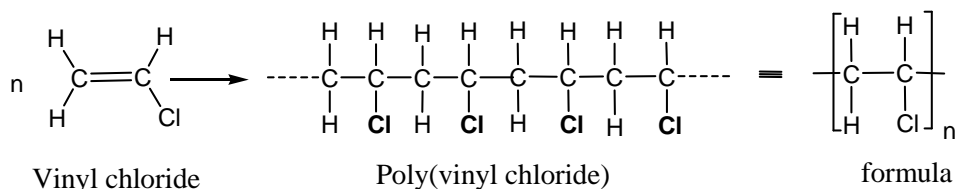


Figure 8 Formation of poly(vinyl chloride)

6. Polystyrene (PS)

Polystyrene $-\text{[CH}_2\text{CHPh]}_n-$ is produced by polymerizing the monomer, vinyl benzene or styrene ($\text{CH}_2=\text{CHPh}$). PS has the large phenyl group in alternative carbon atoms along the polymer backbone. PS is a transparent material and is used as packaging and insulation material.

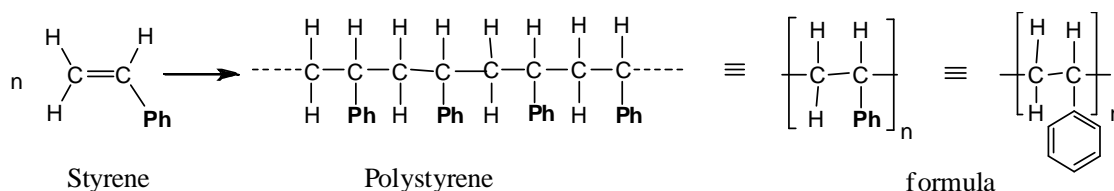


Figure 9 Formation of polystyrene

7. Teflon (PTFE)

Teflon or polytetrafluoroethane (PTFE) is obtained by polymerizing tetrafluoroethane ($\text{CF}_2=\text{CF}_2$). It is a chemically inert polymer and resists chemical attacks, thus, it is used to manufacture taps, seals, valves for laboratories, and plants in chemical industries. Teflon is also used as a surface coating in non-stick cook-ware and to manufacture fire-proof clothing.

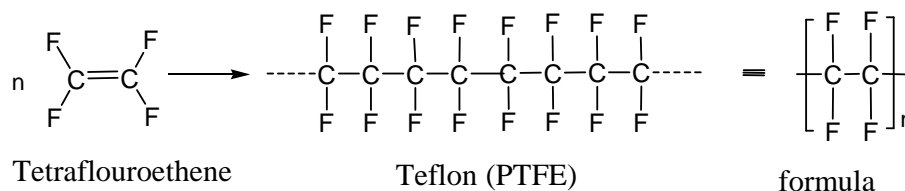
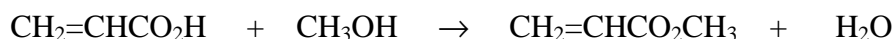


Figure 10 Formation of Teflon

8. Poly(methyl acrylate) (PMA)

The monomer methyl acrylate is produced by esterification of acrylic acid (2-propionic acid) with methanol.



The addition polymer PMA has the ester functionality in alternative carbons of the polymer chain as shown below.

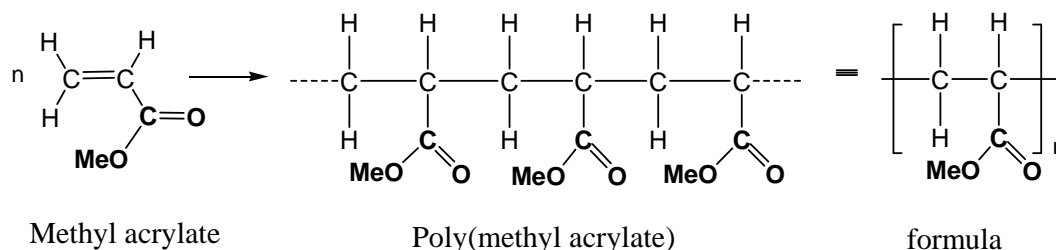


Figure 11 Formation of poly(methyl acrylate)



Activity

3. Give a list of vinyl monomers and the corresponding polymers.
4. Draw the structure of poly(methyl methacrylate) produced from the monomer, $\text{CH}_2=\text{C}(\text{CH}_3)\text{CO}_2\text{CH}_3$.

9. Condensation polymers

Condensation polymers are produced *via* **condensation polymerization** in which a *small portion of the monomer is not incorporated into the final polymer*. During this process, monomers having **two functional groups** react together eliminating small molecules such as H_2O and HCl . For example, preparation of **polyglycine** $-\text{[HNCH}_2\text{C(=O)]}_n-$ from the simplest amino acid **glycine** ($\text{H}_2\text{NCH}_2\text{CO}_2\text{H}$) by removing **water** molecules. Note that polyglycine is a homopolymer which can also be represented as $-\text{[HNC(=O)CH}_2\text{]}_n-$ or $-\text{[C(=O)NHCH}_2\text{]}_n-$. It is a poly(amino acid) containing amide $-\text{HNC(=O)-}$ or $-\text{C(=O)NH-}$ bonds. Polyamide, polyesters and polyurethanes are condensation polymers.

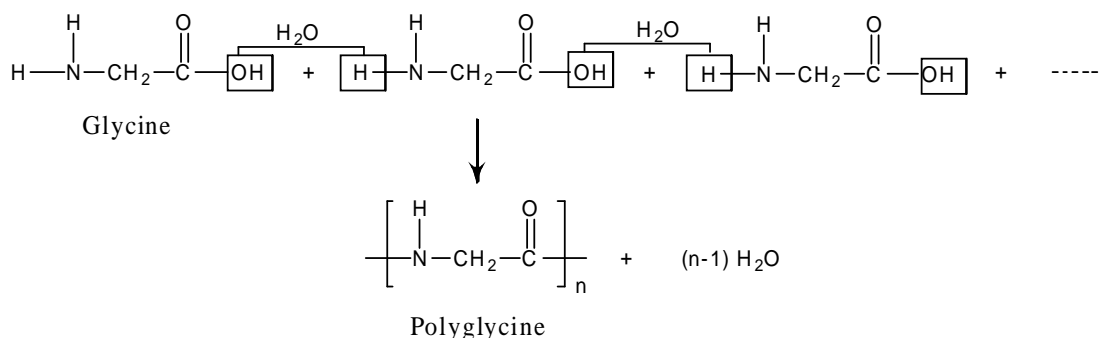


Figure 12 Formation of polyglycine, a condensation polymer

10. Polyamides

Silk and wool (natural protein based fibres) are polyamides. Let us consider the synthesis of nylon 6,6 by condensation polymerization of 1,6-diaminohexane $\text{H}_2\text{N}(\text{CH}_2)_6\text{NH}_2$ and adipic acid $\text{HO}_2\text{C}(\text{CH}_2)_4\text{CO}_2\text{H}$. The numbers 6,6 refers to the number of carbons in the amine and the acid, respectively. It was invented in 1938 by Wallace H Carothers at Du-Pont. Adipoyl chloride, $\text{Cl}(\text{O}=\text{C})(\text{CH}_2)_4\text{C}(=\text{O})\text{Cl}$, can be used instead of adipic acid.

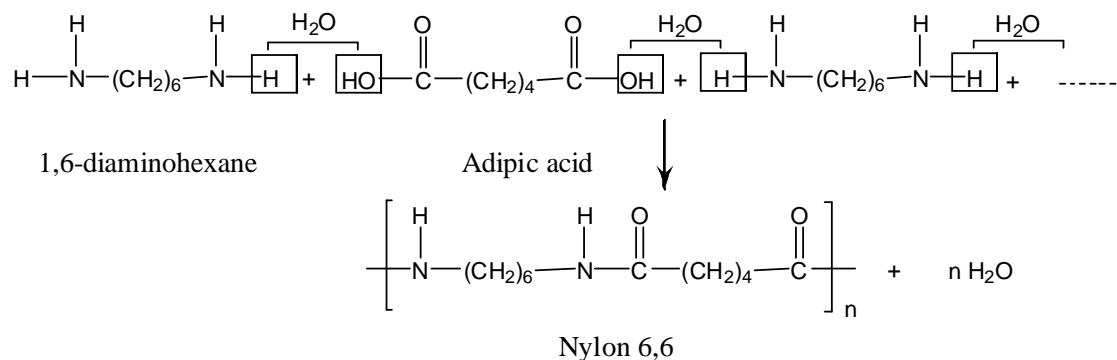


Figure 13 Synthesis of nylon 6,6 from an amine and an acid with 6 carbons each

Uses of polyamides include manufacture of clothing (shirts and stockings), carpets, ropes, tire cords, parachutes, paint brushes, electrical parts, surgical sutures, etc.



Activity

5. Draw the structure of the homopolymer that could be obtained by condensation polymerisation of 6-aminohexanoic acid.

11. Polyesters

Polyesters are condensation polymers prepared by using diols and dicarboxylic acids or monomers containing both functional groups. They have ester bonds $-\text{C}(=\text{O})\text{O}-$ or $-\text{OC}(=\text{O})-$ along the backbone. For example, Terylene is formed using ethylene glycol and terephthalic acid (benzene-1,4-dicarboxylic acid).

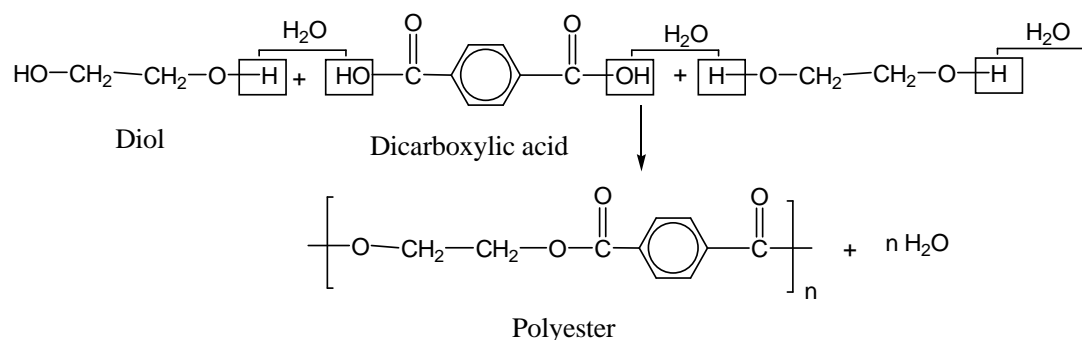
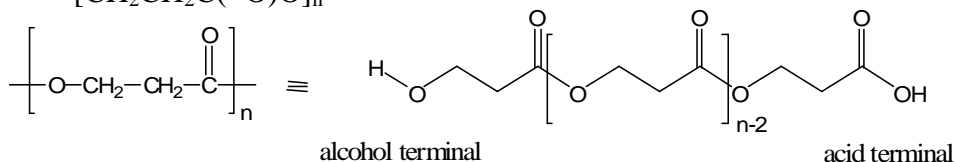


Figure 14 Synthesis of polyester

Terylene is used to prepare fibre glass, textile, photographic films and audio tapes. It is a substitute for natural fibres such as cotton and wool.

Q: What is the polymer that could be obtained by the condensation polymerisation of HOCH₂CH₂CO₂H?

A: $-\text{[OCH}_2\text{CH}_2\text{C(=O)]}_n-$ or $-\text{[CH}_2\text{CH}_2\text{OC(=O)]}_n-$ or $-\text{[CH}_2\text{CH}_2\text{C(=O)O]}_n-$



12. Rubber and vulcanization of rubber

Natural rubber obtained from the milk of rubber tree (latex) is a polymer of *cis*-isoprene or *cis*-2-methyl-1,3-butadiene and it is called **polyisoprene** which is now produced in industry. Natural rubber is soft and tacky when hot.

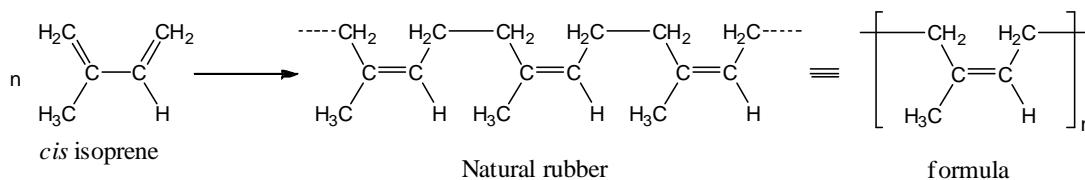


Figure 15 Formation of polyisoprene with unconjugated double bonds

Because of the *cis*-arrangement of the double bonds in the polymer backbone, the polymer chains are coiled, twisted and inter-twined with one another. The stretching of rubber involves straightening out the coiled macromolecules. Elastic property of rubber (*i.e.* the ability of a material to regain its former shape after a distorting force is removed) can be improved by cross linking the polymer chains with disulphide and polysulphide bonds ($-\text{S}_n-$).

Vulcanization of rubber

Natural rubber can be made harder by a reaction with sulphur or disulphur dichloride (S_2Cl_2); this process is called **vulcanization** and the extent of vulcanization (formation of cross-links) depends on the amount of sulphur used. Here sulphur atoms link hydrocarbon chains which are now prevented from being pulled apart (slipped) when the rubber is stretched. Ebonite is the first synthetic plastic made by vulcanizing natural rubber.

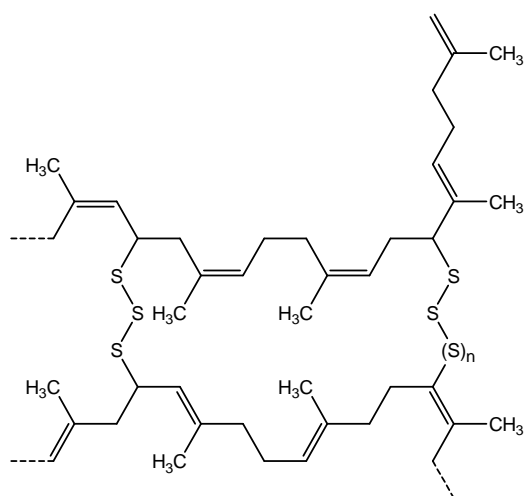


Figure 16 Vulcanized rubber with sulphide bonds

Vulcanized rubber obtained using (1-5% sulphur) is much harder and more elastic than untreated rubber and is suitable for making excellent automobile tires (by vulcanizing rubber for 10 min at 170 °C), whereas natural rubber is totally unsuited for this purpose. Vulcanization was discovered accidentally by Charles Goodyear in 1839. He was the founder of the Goodyear tyre company.

13. Copolymers

When we use a mixture of two monomers together in different ratios we can prepare a **copolymer** with both monomer units. Thereby we can change the properties of the resulting polymer.

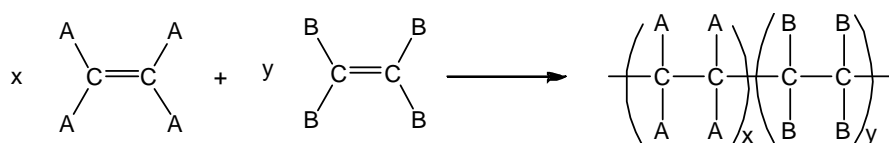


Figure 17 Formation of copolymers

Copolymers contain at least two repeating units. **Styrene-butadiene rubber (SBR)** is a copolymer prepared by the polymerization of a mixture of styrene (25%) and butadiene (75%).

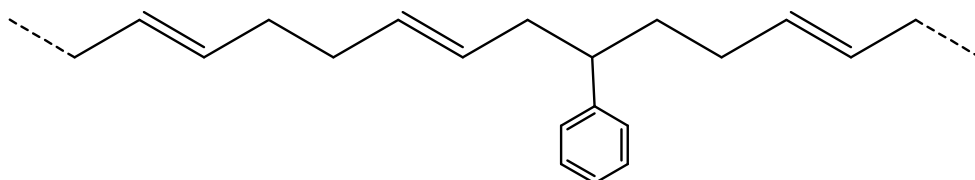


Figure 18 Structure of SBR

SBR is used to prepare non-bounce tyres. This synthetic rubber is more resistant to *oxidation* and *abrasion* than natural rubber, but it has less satisfactory mechanical properties.

14. Bakelite

The oldest synthetic *thermosetting polymer* prepared in 1905 by Baekeland is “bakelite”, which is rigid, very strong and would not melt at all on heating. Bakelite is a *condensation polymer* prepared by combining two different monomers, *phenol* and *formaldehyde*. The final product (**phenol-formaldehyde resin**) has a complex, three-dimensional network. The extensive *cross linking* between polymer chains results in its rigidity. It has great strength, without having great weight, a most useful combination of properties. It is used as a binder in plywood, varnishes for electric coils, moulding compounds for the manufacture of plug and switches, and automobile parts such as steering wheels.

15. Conducting polymers

We know metals conduct electricity (*e.g.* copper wire) as they have mobile electrons in the rigid metal lattice. *Can we prepare polymeric materials with delocalised electrons?* Some organic polymers are soft, flexible and are commonly used as wire insulators. It is important to manufacture materials with considerable flexibility and electrical conductivity.

Polyethylene has sp^3 -hybridised carbon atoms in the polymer backbone and has no delocalised electrons available to exhibit electrical conductivity. Thus, polyethylene is an insulator. We know that graphite having a delocalised π -electron cloud can act as a conductor but diamond with a sp^3 -hybridised carbon network is a non-conducting material.

Now it is very clear what we need is a polymer with an array of conjugated double bonds in order to make it conduct electricity. When we polymerise acetylene ($HC \equiv CH$) or its derivatives with a carbon-carbon triple bond ($-C \equiv C-$), we should get a polymer with conjugated double bonds.

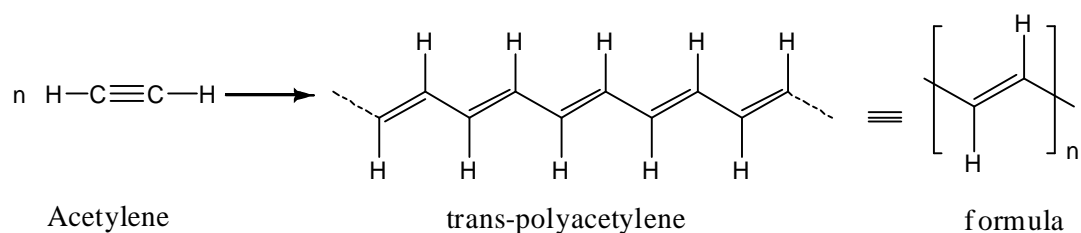


Figure 19 Synthesis of *trans-polyacetylene*, a conducting polymer

Here each carbon centre is sp^2 -hybridised and contains an unpaired electron. The repeating unit is $-\text{CH}=\text{CH}-$ or $-\text{C}_2\text{H}_2-$. Some common examples of conducting polymers with extended conjugation are shown below.

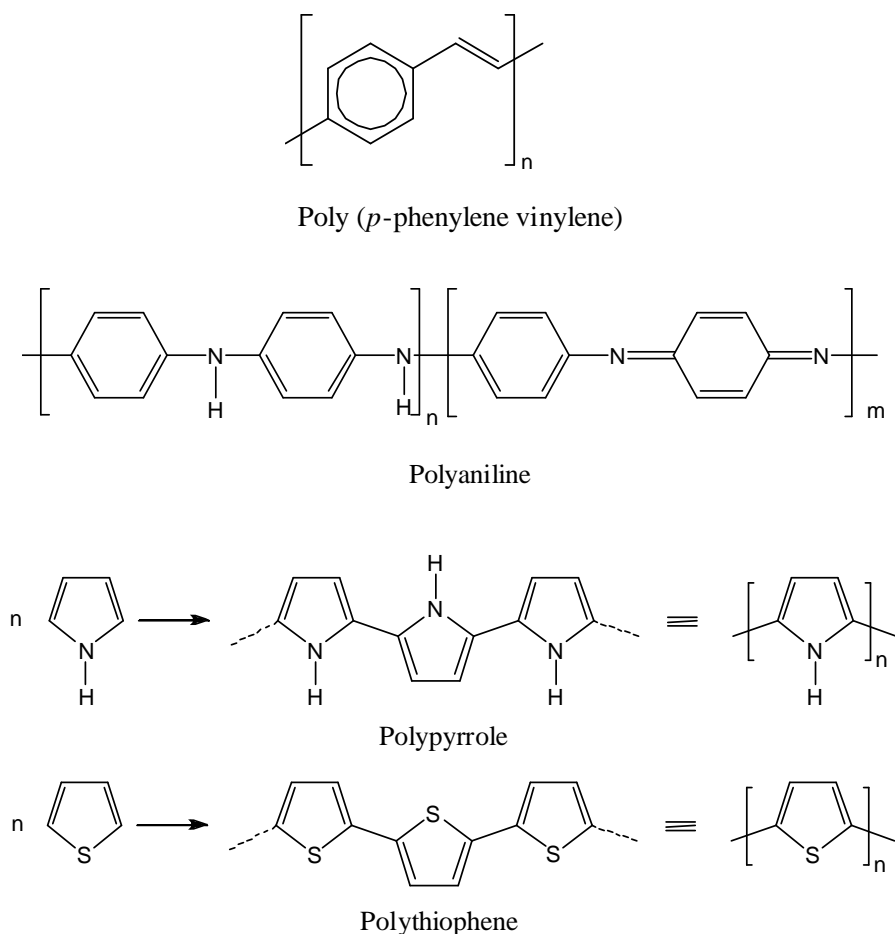


Figure 20 Poly(*p*-phenylene vinylene), polyaniline, polypyrrole and polythiophene.

Conducting polymers are used in printed circuits, electrical displays and as electrolytes.

Summary

- All polymers are macromolecules with the same repeating unit but all macromolecules are not polymers.
- Synthetic polymers are of two types – (i) thermoplastic polymers which can be softened by heating and then formed into desired shapes, (ii) thermosetting polymers which cannot be softened and remoulded.
- PE, PP, PVC, PS, PMA, PTFE and polyisoprene can be produced by addition polymerisation of the corresponding monomer. The resulting polymer has the same elemental composition as the monomer.
- LDPE is produced at high temperature and high pressure; HDPE is produced at ambient temperatures and low pressure in the presence of a catalyst.
- Polyamide and polyesters (condensation polymers) are produced *via* condensation polymerization and during this process small molecules such as H₂O and HCl are eliminated.

- Because of the *cis*-arrangement of the double bonds in the backbone of natural rubber (polyisoprene), the polymer chains are coiled, twisted and intertwined with one another. Natural rubber can be made harder by vulcanization with sulphur or disulphur dichloride (S_2Cl_2).
- Copolymers can be prepared by polymerizing a mixture of two monomers together, the properties of the resulting polymer depends on the monomer ratios used for the polymerization.
- Bakelite (phenol-formaldehyde resin) is a three-dimensional condensation-polymer prepared by combining phenol and formaldehyde.
- Conducting polymers should have an array of conjugated double bonds or a delocalised electron cloud in order to make them conduct electricity.



Learning Outcomes

Once you have finished studying this lesson you should be able to

- describe/define the terms such as monomer, polymer, repeating unit, addition and condensation polymerization, thermoplastics, thermosetting polymers, copolymers, HDPE, LDPE, Bakelite *etc*
- discuss the preparation, properties and applications of various polymers given in this lesson.
- list physical properties and uses of HDPE and LDPE
- describe vulcanization of rubber and the importance of vulcanized rubber
- describe the importance of copolymerization
- explain why conducting polymers are important and how they conduct electricity

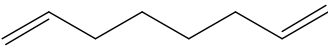


Activities

6. Polysiloxane or silicone oil used as a lubricant is produced from condensation polymerization of the monomer dimethyl silanol, $(CH_3)_2Si(OH)_2$. Draw the structure of polysiloxane.
7. Poly(lactic acid) (PLA) is a biodegradable polyester made from lactic acid, $CH_3CH(OH)CO_2H$. Draw the structure of PLA.
8. Poly(vinyl acetate) is an adhesive (Elmer's glue) and found in chewing gum. Vinyl acetate is prepared by acetylating vinyl alcohol. Draw the structure of poly(vinyl acetate).
9. Nylon-4,6 is made from 1,4-diaminobutane ($H_2NCH_2CH_2CH_2CH_2NH_2$) and adipic acid ($HO_2C(CH_2)_4CO_2H$). Draw the structure of nylon-4,6.
10. Kevlar, a polyamide used to make bulletproof vests, is made from 1,4-phenylenediamine and terephthalic acid (benzene-1,4-dicarboxylic acid). Write the chemical formula of Kevlar. Why Kevlar is a stronger polymer than other polyamides and polyesters?
11. Write reaction conditions for conversion of ethylene into the following compounds.

(i) CH_2ClCH_2Cl	(ii) CH_2OHCH_2OH	(iii) CH_3CH_2OH
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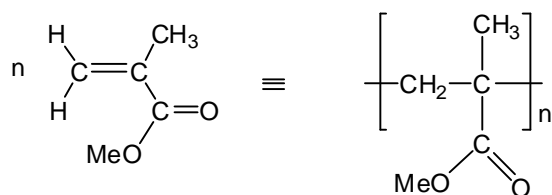
Answer guide to activities

1. (i) $\text{CH}_2=\text{CHCH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}=\text{CH}_2$ or  (ii) Four sp^3 -carbons and four sp^2 -carbons

2. (i) 1,2-Dichloroethane (ii) 1,2-Dihydroxyethane
(iii) Chloroethene (iv) Phenylethene

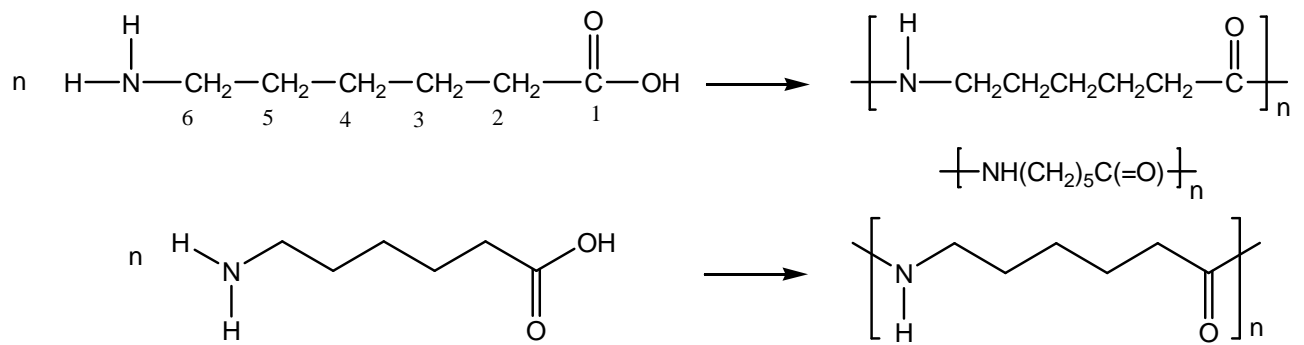
3. Monomer	Polymer
(i) $\text{CH}_2=\text{CHCl}$ (vinyl chloride)	$\left[\text{CH}_2-\underset{\text{Cl}}{\text{CH}} \right]_n$ poly(vinyl chloride)
(ii) $\text{CH}_2=\text{CHOH}$ (vinyl alcohol)	$\left[\text{CH}_2-\underset{\text{OH}}{\text{CH}} \right]_n$ poly(vinyl alcohol)
(iii) $\text{CH}_2=\text{CHCN}$ (acrylonitrile)	$\left[\text{CH}_2-\underset{\text{CN}}{\text{CH}} \right]_n$ poly(acrylonitrile)
(iv) $\text{CH}_2=\text{CHCO}_2\text{H}$ (acrylic acid)	$\left[\text{CH}_2-\underset{\text{CO}_2\text{H}}{\text{CH}} \right]_n$ poly(acrylic acid)
(v) $\text{CH}_2=\text{CHCO}_2\text{Me}$ (methyl acrylate)	$\left[\text{CH}_2-\underset{\text{CO}_2\text{Me}}{\text{CH}} \right]_n$ poly(methyl acrylate)
(vi) $\text{CH}_2=\text{CHPh}$ (styrene)	$\left[\text{CH}_2-\underset{\text{Ph}}{\text{CH}} \right]_n$ polystyrene

4.

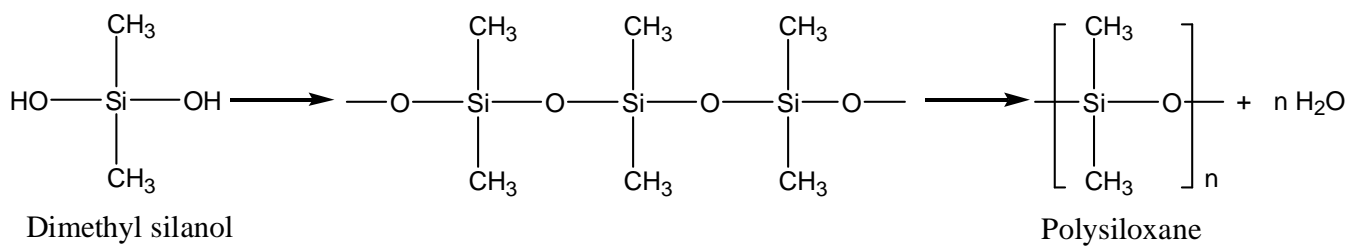


poly(methyl methacrylate)

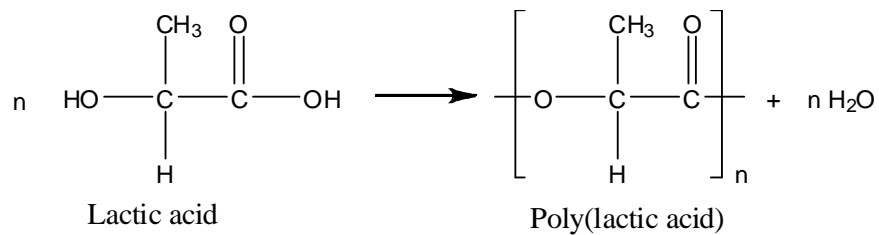
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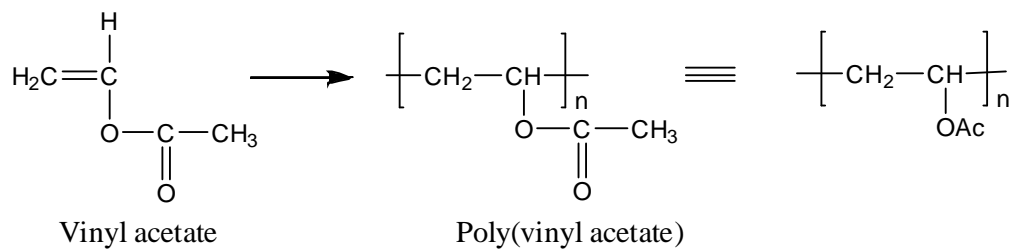
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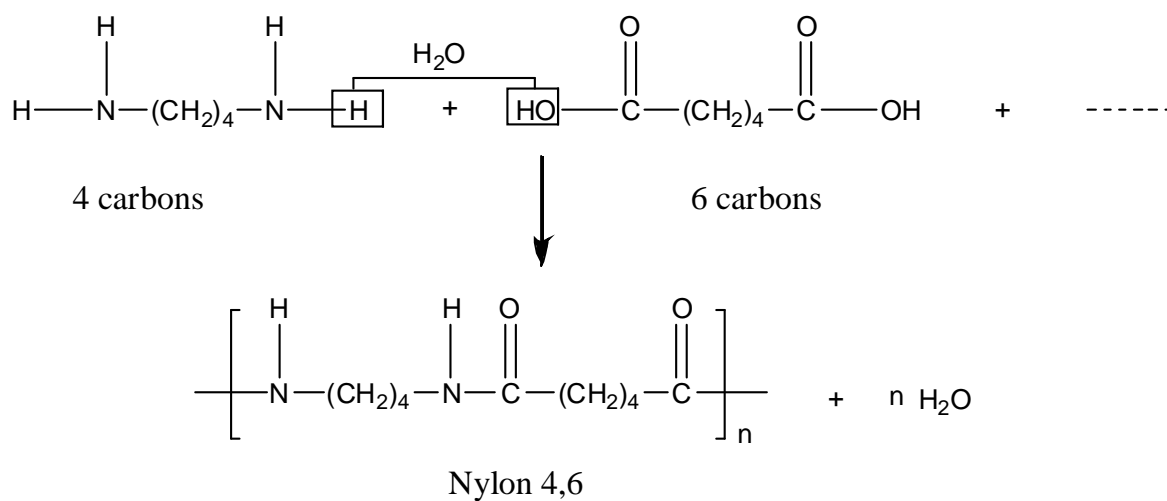
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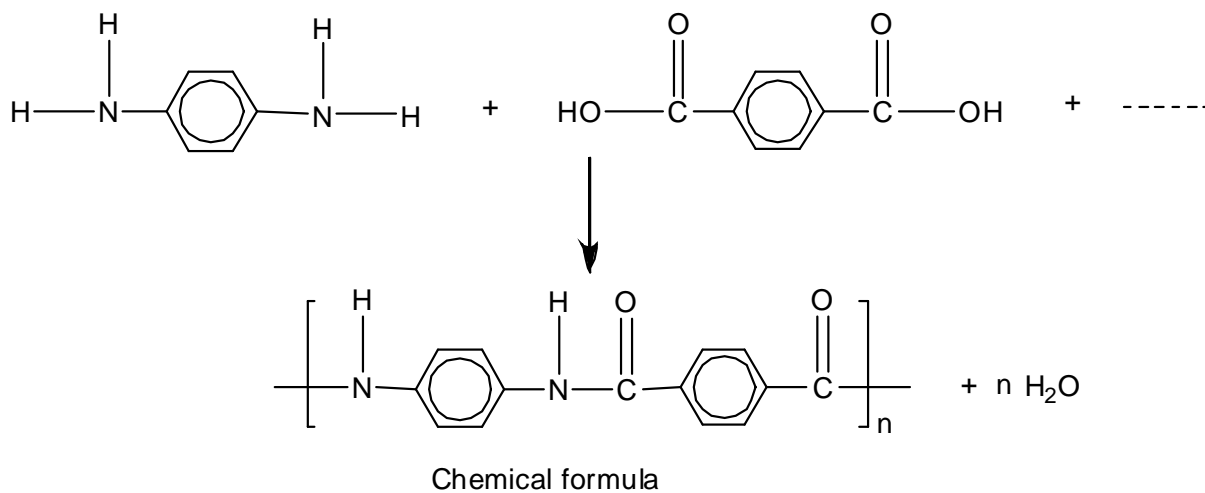
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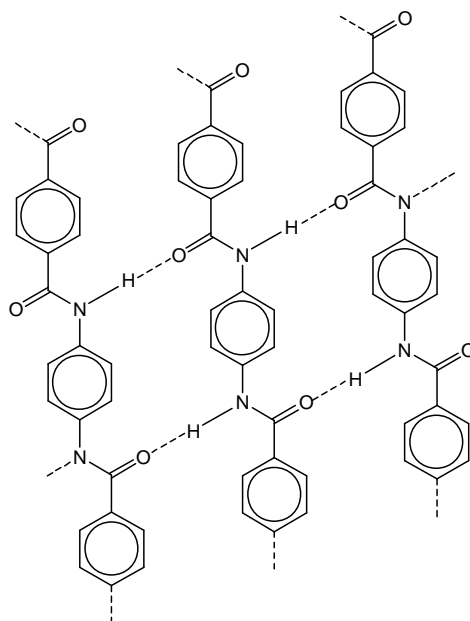
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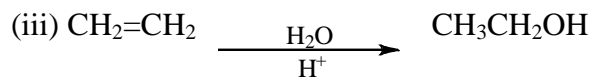
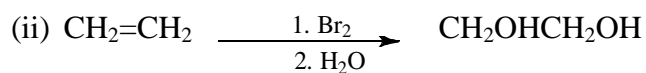
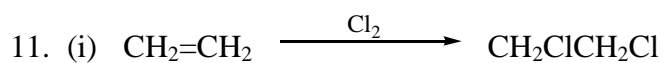


This polymer shows very high tensile strength and elasticity compared to other polyamides (e.g. nylon 6,6) and polyesters, due to strong hydrogen bonding between planar polymer chains. They are packed like sheets as shown below.



Elasticity and tensile strength of some polymers are given below.

Polymer	Natural silk	Nylon 6,6	Polyester	Kevlar
Elasticity (GPa)	7-10	6	15	150
Tensile strength (MPa)	350-600	800	900	2800





Study Questions

1. Describe the meanings of the following terms, monomer, polymer, and macromolecule.
2. Giving examples, describe
 - (i) addition polymerization and
 - (ii) condensation polymerization.
3.
 - (i) Why is rubber elastic?
 - (ii) What occurs in the vulcanization of rubber?
 - (iii) How does vulcanization improve the properties of rubber?
4. How do LDPE and HDPE differ in their structures?
5. What is meant by thermosetting and thermoplastic polymers? How do they differ in their properties?
6. How would you prepare vinyl acetate ($\text{CH}_2=\text{CHO}_2\text{CCH}_3$) from ethylene?
7. Isobutylene, $(\text{CH}_3)_2\text{C}=\text{CH}_2$, polymerises to form polyisobutylene, a sticky polymer used as an adhesive. Write the 2D representation of polyisobutylene. Copolymerization of isobutylene with 1,3-butadiene ($\text{CH}_2=\text{CHCH}=\text{CH}_2$) in the monomer ratio of (3:1) forms butyl rubber. Write 2D representation of butyl rubber.
8. Write the general formulae for the polymers formed due to polymerization of the following monomers.
 - (i) $\text{CH}_2=\text{CHOH}$
 - (ii) acrylonitrile
 - (iii) 1,3-butadiene.
9. Draw the structures of adipic acid, terephthalic acid, *ortho*-phthalic acids, *meta*-phthalic acids, diethyl orthophthalate and polychlorinated biphenyls (PCBs) with the composition $\text{C}_{12}\text{H}_8\text{Cl}_2$.

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