Natural Degradation on Plastics and Corrosion of Plastics in Industrial Environment

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Introduction

Corrosion leads to the degradation of material as a result of exposure to natural environment (humidity and pollutants) and also due to exposure to toxic chemicals. The degradation due to corrosion can appear from a simple dis-coloration to a blister, crack or even loss of weight due to dissolution of material. Generally, corrosion is considered to be a problem of metallic materials, that too especially steels, and one of the methods to combat corrosion is to use alternative materials or carry out protection by any of the corrosion protective methods such as coatings, or cathodic protection. The use of plastics is one of the solutions to avoid corrosion. So it may appear a bit strange to talk about corrosion of plastics. Yes, though, it may appear strange but plastics do corrode. It may be possible that their corrosion appearance, surface damage due to corrosion or degradation, may look different than steel. It is, therefore, worth learning, how this change happens and also, because of large number of available plastic types, it is also important to understand which plastic type corrodes and which resists corrosion. Basically, this is the aim of this article that on what basis corrosion occurs on plastics and how to differentiate the corrosion on plastics based upon their chemical structure, composition or physical properties.

Like a standard term for oil and gas, plastics can also be called as life line of a country as tonnage of plastics used in a country decides how advanced it is. The amount of plastics used in hundreds of odd applications is huge. According to one estimate the total global tonnage of the seven most important plastics was estimated of 304 million tons in 2016 (Dominik *et al.*, 2019). Detailed information on the corrosion of plastics is even more important to understand, both its degradation mode and kinetics, as one of the biggest concern of the use of plastics is its disposal ability, which leads to a large amount of waste generation and entering landfills, animal chocking, sea pollution etc. Plastic break-down is usually a very slow process, and it depends upon the environmental factors and can take even 1000 years to completely biodegrade a plastic.

The word "plastic" originates from Greek word *plastikos*, which means it can easily be molded or shaped. The main focus on plastic has been due to its wide range of applications in many day to day usages, like food packages to several industrial storages of chemicals, domestic water piping system to industrial piping's, from toys to boat hulls, plastic wraps to industrial incubators etc. Another reason for large number of applications of plastics is that most of the plastics meet one of the basic requirements of light weight, chemically stability and cost effectiveness.

Plastics are made from polymers, broadly defined as thermoplastic, thermosetting and elastomers and based upon these, they are categorized as, thermoplast, thermosets and rubbers. Thermoplasts are long chain linear molecules, when heated under pressure above the Glass Transition Temperature (Tg) turn into plastics. Thermosets are specific class of polymers that form well-defined, irreversible, chemical networks that tend to grow in three dimensional network through the process of curing, which can either occur due to heating or through the addition of a curing agent, therefore causing a crosslinking formation between its chemical components, and giving the thermoset a strong and rigid structure that can be added to other materials to increase strength.

In 1860, the first plastic was developed from plant material and in1907, the first synthetic plastic, Bakelite, was developed. About 98% of the plastics are made of seven important plastics, namely, polyvinyl chloride, polyethylene, polypropylene, polyethylene terephthalate (PET, PETE), polystyrene, polycarbonate, and poly(methyl methacrylate) (Plexiglas) encountered in daily life (see "Relevant Websites section"). They can be differentiated in terms of their characteristic degradation mode and resistances to heat, light and chemicals. Polyethylene, polypropylene, and poly(methyl methacrylate) are sensitive to oxidation and UV radiation, while PVC may change color at high temperatures due to hydrogen chloride gas emission, PET is sensitive to hydrolysis and attack by strong acids, while polycarbonate depolymerizes rapidly when exposed to strong alkalies.

The most used plastic in consumer products, today, is polyethylene. More than 80 million metric tons are produced annually for several uses such as packaging, plastic bags and plastic film (see "Relevant Websites section").

Corrosion of Polymers

Corrosion of polymers is almost entirely different from that of metallic materials. While the initiation of corrosion in metals is the chemical (direct reaction) or electrochemical dissolution by flow of electrons, in plastics, which is an insulation material, flow of electron is fully prohibited. Further, in metals, there are eight forms of corrosion ranging from uniform, localized, galvanic, stress corrosion cracking, hydrogen attack, oxygen and chloride attack, leading to embrittlement, trans or inter-granular cracking, micro-biological corrosion. The plastics, usually, are degraded by UV light, oxygen, strong acids and microbiological attack. The attack is mostly in the form of embrittlement of plastics and cracking.

As per the title of the article, corrosion of plastics can be divided into two categories:

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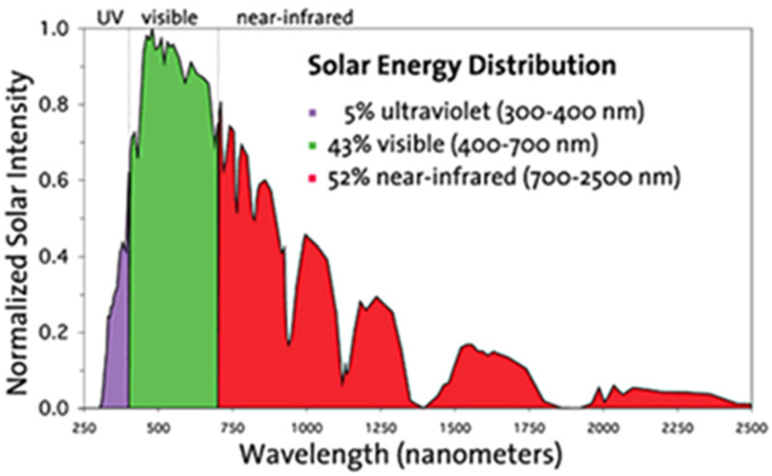


Fig. 1 Description of solar radiation.

(1) Natural degradation of plastics
(2) Degradation due to the external reaction by toxic gases or corrosive chemicals.

The natural degradation of plastics is mainly in the out door exposures. One of the main culprit of environment is sunlight. A solar radiation has a very long wavelength range, starting from ultraviolet (UV), less than 400 nm (shown by violet color in **Fig. 1**), visible 400–750 nm (shown by green color in **Fig. 1**), and infrared (IR), starting from 750 nm up to 1250 nm (called near IR) and beyond as far IR (shown by red color in **Fig. 1**). Each range has its own effect on materials, metals and plastics.

UV is considered to be rather dangerous, responsible for damaging material in terms of causing cracks and embrittlement, surface cracking and chalking, visible results in fading the color, while IR imparts strong heat on the surface.

The main damage of plastics is done by what is known as photochemical degradation caused by photons which result in the breaking of chemical bonds. There is critical threshold of wavelength of light with enough energy to cause the cracking of chemical bonds. Phenolic groups in epoxy based polymers, vinyl with double bonds are very much affected by UV light. Strongly bonded polymers with single bond or aliphatic linkage rings are a little affected by UV light. Very strongly bonded polymers with – C–F– bonds are not affected by UV light at all. That is why PVDF types of plastics are considered very stable in outdoor exposures. In the same way, polymers with higher molecular weight grades of resin generally exhibit better weatherability than the lower molecular weight resins (Schweitzer, 2006).

Other Mechanisms of Polymer Degradation

Plastics are basically made of polymers whose stability depends upon exposure to heat, chemicals and microorganism. Many polymers start degrading merely after 60–80°C, while others sustain stability based upon their glass transition temperature. In the same way, several polymers degrade because of chemical reaction with highly toxic chemicals such as acids or alkalies. Another important degradation mechanism of plastics is bio-degradation which is also a serious concern in polymer degradation. But it is possible to formulate polymers which can work at relatively higher temperatures, sustain strong acids and toxic chemicals and are not affected by bacterial degradation.

In this section we will first explain various categories of plastic degradation with their mechanism giving suitable examples. This will be followed by listing of various polymers which have been formulated to resist corrosion.

Thermal Degradation

Thermal degradation due to heat is perhaps the simplest mechanism of degradation of plastics. They undergo, both physical and chemical changes when exposed to heat, which usually result in undesirable changes in the plastic properties. The heat can lead to thermal decomposition or thermal degradation. Thermal decomposition leads to extensive chemical species while thermal degradation causes a loss of physical, mechanical, or electrical properties. The effect of heat is the molecular deterioration leading to breaking of the long chain backbone of the polymer and possible reaction with one another, causing change in the properties of the polymer. This can result in changes in the molecular weight of the polymer and typical property changes such as reduction in ductility, embrittlement, chalking or cracking of the plastic. The thermal decomposition may lead to a complex mixture of compounds including lower polymer monomers and gases such as carbon monoxide, ammonia, ketones etc.

The most general mechanism of thermal degradation of plastics under heat and light is schematically depicted in **Fig. 2**, (see "Relevant Websites section") which consists mainly of three steps: initiation, propagation and termination.

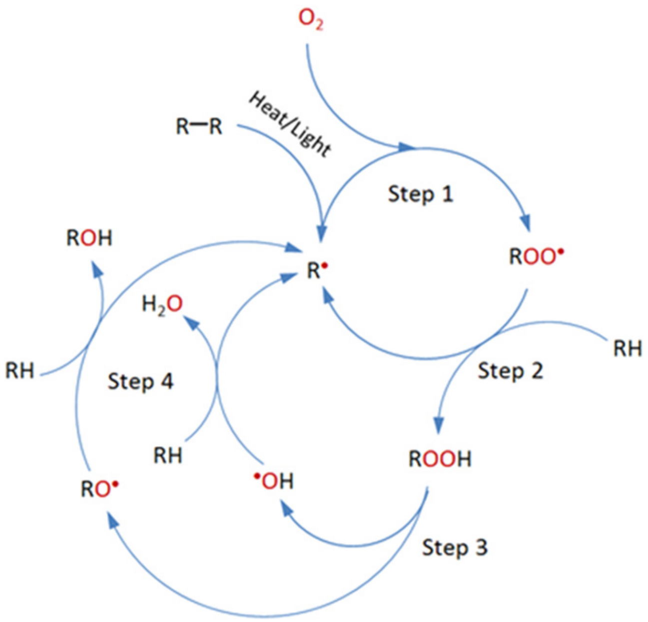


Fig. 2 General Mechanism of Thermal degradation (see "Relevant Websites section').

In **Step1** of oxidative degradation, radicals are formed due to either hydrogen atom is relieved from the polymer chains or by homolytic scission of a carbon-carbon bond. This can occur at any time, during manufacturing, processing or during service when exposed to heat or light.

$$R - H \rightarrow R \cdot + H\cdot \tag{1}$$

In **Step 2** the propagation of thermal degradation involves a number of reactions:

(1) the reaction of a free radical ($R\cdot$) with an oxygen molecule (O_2) to form a peroxy radical ($ROO\cdot *$), which then abstracts a hydrogen atom from another polymer chain to form a hydroperoxide (ROOH).
(2) The hydroperoxide splits then into two new free radicals, ($RO\cdot$) + ($\cdot OH$), which abstract labile hydrogens from other polymer chains.

Since, each initiating radical can produce two new free radicals, the process can accelerate depending on the ease with which the hydrogen is removed from other polymer chains and free radicals very quickly further react.

$$R \cdot + O_2 \rightarrow ROO\cdot \tag{2}$$

$$ROO \cdot + RH \rightarrow R \cdot + ROOH \tag{3}$$

$$ROOH \rightarrow RO \cdot + \cdot OH \tag{4}$$

$$RO \cdot + RH \rightarrow R \cdot + ROH \tag{5}$$

$$\cdot OH + RH \rightarrow R \cdot + H_2O \tag{6}$$

In Step 3, recombination of two radicals or by disproportionation/hydrogen removal. Recombination of two chain radicals results in an increase of the molecular weight and crosslinking density:

$$R \cdot + R \cdot \rightarrow R - R \tag{7}$$

$$2\,ROO \cdot \rightarrow ROOR + O_2 \tag{8}$$

$$R \cdot + ROO \cdot \rightarrow ROOR \tag{9}$$

$$R \cdot + RO \cdot \rightarrow ROR \tag{10}$$

$$HO \cdot + ROO \cdot \rightarrow ROH + O_2 \tag{11}$$

This results in the enbrittlement and cracking of the polymer. On the other hand termination by chain scission, results in the decrease of the molecular weight leading to softening of the polymer and reduction of the mechanical properties

$$R_n\cdot + R_m \cdot \rightarrow R_{n-2} - -2Rc_2 + R_m \tag{12}$$

$$2\,RCOO \cdot \rightarrow RC = O + ROH + O_2 \tag{13}$$

Table 1 Compares corrosion resistance of various plastics in acids and alkalies (see "Relevant Websites section")

Commercial name of plastic	*Structural formula (Group)*	*Low pH compatibility*	*High pH compatibility*
TECAFINE PE, PP	Polyethylene & Polypropylene	0.5	13.5
TECAFORM AH[a]	Acetal co-polymer	4	13
TECAFORM AD	Homopolymer with PTFE fiber	4	9
TECAMID, TECAST[a]	Crystalline Polyamide, Nylon 6	4	12
TECAPET	PET	1	9
TECAFLON PVDF[b]	PVDF	0.5	13.5
TECAFLON PTFE[a]	PTFE	0.5	13.5
TECATRON	PPS	0.5	13.5
TECAPEEK[a]	PEEK	0.5	13.5

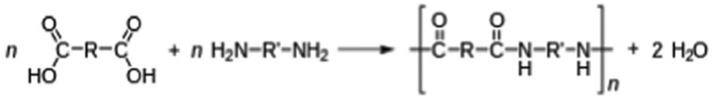
[a]Resistant.
[b]Limited Resistant.
Note: #Glass fiber reinforced grades show a slightly lower resistance to strong alkalies compared to unfilled grades.
**PVDF reacts sensitively to contact with hot alkalies by causing stress cracks when exposed to mechanical stress. The exposure limits are pH 12 and 40°C, neither one of which may be exceeded.

The reactions in the termination will depend on the type of polymer and on the conditions. For example, polyolefins with short alkyl side groups like polypropylene and polybutylene, and unsaturated polymers like natural rubber (polyisoprene) undergo predominantly chain scission, whereas polyethylene, and rubbers with somewhat less active double bonds like polybutadiene and polychloropene suffer from embrittlement due to crosslinking during ageing. PVC is also susceptible to thermal degradation, particularly during processing, and can suffer from extensive property loss if not adequately protected against thermal degradation during processing. Heat stabilizers are usually used during blending to control thermal degradation. In general, the fluoropolymers, (such as PTFE, FEP, PFA, PVDF, ETFE and ECTFE) have excellent thermal degradation resistance because of the strength of the carbon - fluorine (C-F) bonds in the long chain backbone (see "Relevant Websites section").

Corrosion of Plastics by Chemicals

Corrosion of plastics is quite different in comparison to metal corrosion. Comparing steel to a simple plastic, corrosion in steel can be minimized by application of a coating, or using cathodic protection or by the use of some inhibitor chemicals in the solution in the container. In plastics, it is not possible to protect by any of the given methods used in steel but still it is possible to create high performance plastics which can resist strong acids, alkalies or several toxic organic solvents and chemicals. By choosing the right polymer family, it is possible to choose a plastic which can withstand even the harshest environmental conditions without the need for additional protection such as surface treatment, painting or cathodic protection. Table 1 gives a list of various plastics which show resistant to a strong and weak acids, alkalies, solvents and polar organic solvents.

Hydrolysis of plastics takes place in acidic or basic water to give lower molecular weight molecules. For example polymers like polyesters, polyamides and polycarbonates can be degraded by hydrolysis. Polyamide is sensitive to degradation by acids and will crack when attacked by strong acids. For example, the fracture surface of a fuel connector showed the progressive growth of the crack from acid attack, known as stress corrosion cracking, and in this case was caused by hydrolysis of the polymer. It was the reverse reaction of the synthesis of the polymer:



(14)

Chemical resistance is highly dependent on the molecule structure of a polymer as for thermoplastics, whether they are amorphous (e.g., PC, PVC, PS, PMMA) or partially crystalline (e.g., PE, PA, PP, POM). Partially crystalline are more resistant to organic substances and solvents than amorphous polymers. Thermosetting resins (e.g., PUR, EP, UP) can, due to their cross-linked structure not be dissolved, but can be subjected to swelling or chemical reaction (e.g., hydrolysis).

Physical effects on polymers are caused by interaction with the environment. This may lead to swelling, dissolving or leakage of additives. The interaction is dependent on diffusion of substances into the polymer, and the process is in some cases reversible.

Organic substances usually affect polymers through physical interaction, while substances like strong acids or bases normally result in an irreversible breakdown of polymers.

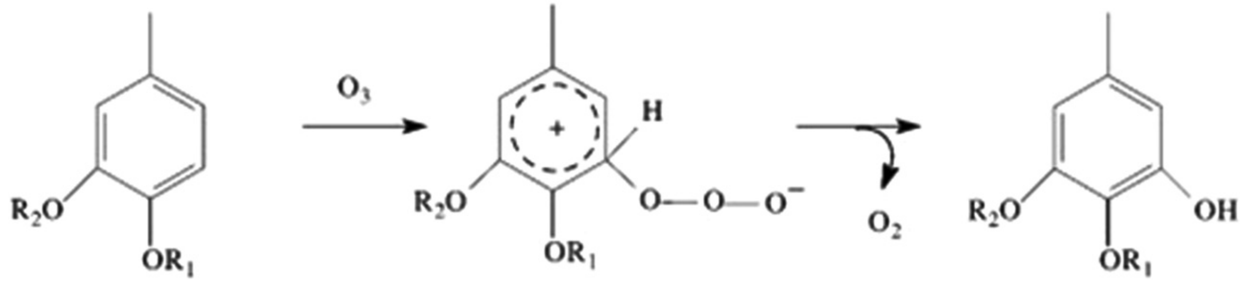


Fig. 3 Showing the attack of ozone on aromatic ring resulting in the formation of hydroxyl group.

Table 2 A list of some very common plastics with their rating, excellent, good, fair and poor (see "Relevant Websites section")

Name of the Plastic	*Grading*	*Remarks with additional properties*
Polyetheretherketone (PEEK)	A	High Tensile Strength, resistance to chemicals, low creep and temperature resistance up to 240°C
Polycarbonate	A	Lower Heat tolerant, but possess excellent insulating properties
CPVC	A	Little water absorption, an ideal choice for diffusion venture system which entrain ozone gases directly into water
PTFE (Teflon)	A	Ideal for a design exposed to extreme temperature of 260°C.
PVDF (Kynar)	A	does not possess the tensile strength or the temperature range
Polyvinylchloride (PVC)	B	minor effects may occur such as slight corrosion and discoloration
Acrylonitrile Butadiene Styrene (ABS)	B	In low concentration, when used in mechanical assemblies in ozone generating systems ABS is an excellent choice
Polyethylene (PE)	B (in water)C (in air)	In a water based ozone generating system, its excellent lubrication qualities makes it an excellent choice for bearing surfaces.
Acetal (Delrin), Neoprene, and Polypropylene	C	These materials are not recommended for constant exposure to ozone and can suffer softening, loss of strength, and swelling if used in a continuous ozone environment
All NylonsAll Rubbers	D	are severely affected by ozone exposure, causing severe cracking, splitting, and corrosion

Note: A – Excellent, B-Good, C- fair and D-Poor.

Effect of Ozone on Plastics

Ozone can be referred as oxygen with three atoms O_3. Ozone is highly reactive and has a strong bactericidal action on various substances. Ozone is present everywhere. Usually the concentration of ozone in the atmospheric air varies from 0 to 7 per hundred million.

Ozone has high reactivity for many plastics and polymers. Every ozone molecules react with a chain of polymer molecules and break the chain. Rubber under stress is an easy target for ozone reaction.

Ozone preferentially reacts with olefinic compounds. The reactions of ozone with aromatic compounds involve an initial electrophilic attack by the oxidant, followed by the loss of oxygen that results in hydroxylation of the aromatic ring (**Fig. 3**). Formation of the hydroxyl group increases the reactivity toward electrophilic substitution reactions. Therefore, it is probable that in a subsequent step, ozone may react with the aromatic ring with a 1,3-cycloaddition (Ozonolysis).

Ozone safe plastics are used extensively in the food processing industry, water purification, and medical industries. Ozone is also used to kill bacteria and mold spores. Ozone can be applied in a dissolved state and introduced into water or as a gas (Disinfection with Gaseous Ozonation).

Although, many different types of plastics have properties which make them suitable for use in an ozone environment, many other plastics are highly vulnerable to degradation when exposed to ozone. The plastics that are ozone-safe are used in ozone generating equipment in several industries and have replaced many more expensive materials such as metal components and fasteners.

Following **Table 2** compares various plastics with their rating towards Ozone corrosion, when exposed.

Chlorine-Induced Cracking

Chlorine gas is considered very reactive to many polymers, especially acetal and polybutylene. It has been found that the plastic pipelines made from these resins, fail extensively in the presence of chlorine gas and the attack has been identified as chlorine induced cracking. The gas attacks the sensitive parts of the chain molecules, especially secondary or tertiary carbon atoms, oxidizing the chain, resulting in cleavage. Residual chlorine in water systems combined with elevated temperatures, can produce an oxidizing environment. Since, many metals and plastics are susceptible to oxidation and oxidizing agents, this condition can dramatically shorten the service life of components made from these materials. Thus, the traces of chlorine (ppm level), which is added in water to overcome the anti-microbial attack on the tubes, is responsible for this chlorine-induced attack on plastic pipelines.

Another chlorine based compounds used for disinfectant purpose of drinking water are chloramines, or chlorine dioxide (Vertova *et al.*, 2019). It is observed that chlorine dioxide is more aggressive than other disinfectants against polyolefins (polyethylene, polypropylene, and polybutylene). The most general mechanism for all these to attack polymers, appears to be similar, i.e. depletion of the stabilizer at the inner pipe surface, oxidation of the inner layer due to breaking of the carbon–hydrogen or carbon–carbon bonds, microcracking of the inner layer, crack propagation through the wall with oxidation in advance of the crack front, reduction of molecular weight, which decreases the tensile strength of the polymer, and final rupture of the remaining pipe, ultimately resulting in pipe failure (Chung *et al.*, 2007). From the practical experience, it has been found that out of the most commonly used plastic materials, for the production of plastic pipes are the polyethylene (PE) and polypropylene (PP) in the drinking water distribution network in households. A significant number of pipes fail prematurely when exposed to drinking water containing ClO_2 (Ifwarson and Aoyama, 1998; Bradley and Bradley, 1997). One explanation for this could be that the chlorine dioxide is diffuses into the polymer more readily than other disinfectants. In addition, it heavily reacts with phenols.

Micro-Biological Induced Corrosion of Plastics

Biofouling and microbial populations on plastics

Biofouling or biological fouling is the accumulation of microorganisms, plants, algae, or small creatures such as fish, barnacles on wetted surfaces that have a mechanical function, causing structural or other functional deficiencies. It can occur on any material, metallic or non-metallic. Plastics are also affected by Biofouling. Heavy biofouling was noticed within a span of few months of a polypropylene plastic, indicating the growth of algae, bacteria and other microorganisms on the surfaces, PP cups as shown in (**Fig. 4**). After 378–427 days in the microcosm, consisted of natural seawater, the wet and dry weights of the biofilms grew steadily. The wet weight measurements indicated the presence of thick slimy biofilm layers on all the added components. The dry weight of the biofilms removed from the plastics ranged from 0.068 to 0.459 mg/cm^2 of plastic surface, exposed to the seawater, which corresponded to the biofilm growth rates of 0.063–0.441 mg/cm^2 per year (Gerritse, 2020).

Plastics are very much affected by bacteria, microbes and in combination with UV light, stress and other factors they disintegrate, lose small micro particles. This is called fragmentation of plastics and is thought to be initiated by polymer chain backbone weathering through exposure to sunlight (UV), oxidants, hydrolysis and physical shearing, for example through currents, waves, or friction with sand (Barnes *et al.*, 2009; Andrady *et al.*, 1993). The oxidation and shortening of polymer chains and leaching of plasticizers makes plastic materials brittle and stimulates the formation of surface cracks and fragmentation (Ter Halle *et al.*, 2016). As a result, micro- and nanometer sized plastic particles may be released from the surface of larger fragments (Andrady, 2011). This can result in the generation of numerous micro- and nanoplastic particles from a single plastic object. In theory, one bag composed of two plastic sheets 50 cm $\times$ 40 cm $\times$ 50 μm thick could generate 20 particles with a volume of 1 mm^3, 20 million particles with a volume of 1 μm^3 or 20 trillion particles with a volume of 1 nm^3.

Fig. 4 Biofouling of polypropylene cup, after From left to right) 0, 57, 183 and 390 days in the microcosm, respectively. Reproduced from Gerritse, J., 2020. Fragmentation of plastic objects in a laboratory seawater microcosm. Sci. Rep. 10, 10945.

Corrosion of Plastics Based Upon Their Composition, Structure and Physical Properties

There are lots of polymers which can be formulated in different plastics with varying Corrosion properties, mechanical properties, high temperature stability and weathering resistance. What could be the simplest way to understand plastics? The answer is - based upon their composition. Thus, the simplest way to classify various plastics, based upon their composition is:

(1) Pure hydrocarbon polymers: polyethylene, polypropylene, etc.
(2) Those modified with oxygen in the polymer chain such as acrylic, acronitriles.
(3) Those with nitrogen addition in polymer chain such as PAN and nylon.
(4) Those modified with sulfur addition in polymer chain, such as PES and PSF.
(5) Those modified with chloride reaction, such as PVDC and CPVC.
(6) Those with fluorine addition in Polymer chain, PTFE and PVDF.
(7) Those with Chlorine and Fluorine addition in Polymeric chain.

Thus classification of plastics in terms of their chemical composition, gives a very important indication of their stability and reactivity to natural parameters such as UV light and weathering as well as to exposure in various chemicals.

The main carbonaceous plastics with no heteroatoms are polyolefins, polydienes, and aromatic hydro-carbon polymers, polyethylene and polypropylene. Polydienes are generally elastomeric and contain one double bond per repeating unit.

The most important oxygen-containing polymers are cellulosics, polyacrylics, and polyesters. Polyacrylics are the only major oxygen-containing polymers with carbon–carbon chains. The most widely used polyacrylicis poly(methyl methacrylate) (PMMA) which has high light transmittance, dyeability, and transparency. The most important polyesters are manufactured from glycols, for example, polyethylene terephthalate (PET) or poly-butylene terephthalate (PBT), or from biphenol A (poly-carbonate). They are used as engineering thermoplastics, as fibers, for injection-molded articles, and unbreakable replacements for glass.

Nitrogen-containing materials include nylons, poly-urethanes, polyamides, and polyacrylonitrile. Nylons, having repeating units containing the characteristic group $>CO>NH>$, are made into fibers and also into a number of injection-molded articles. Nylons are synthetic aliphatic polyamides. There are also natural polyamides (e.g., wool, silk, and leather) and synthetic aromatic polyamides (of exceptionally high thermal stability and used for protective clothing). Polyurethanes (PU) are extensively used for foams (flexible and rigid), or as thermal insulation.

Chlorine-containing polymers are exemplified by poly(vinyl chloride), the most widely used synthetic polymer, together with polyethylene and polypropylene. It is unique in that it is used both as a rigid material (unplasticized) and as a flexible material (plasticized). Flexibility is achieved by adding plasticizers or flexibilizers. Through, the additional chlorination of PVC, leads to chlorinated poly(vinyl chloride) (CPVC) with very different physical and fire properties from PVC. Two other chlorinated materials are of commercial interest, polychloroprene (a polydiene, used for oil-resistant wire and cable materials and resilient foams) and poly(vinylidene chloride) [PVDC] used for making films and fibers. All these polymers have carbon–carbon chains.

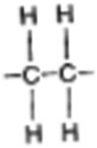
Fluorine-containing polymers are characterized by high thermal and chemical inertness and low coefficient of friction. The most important material in the family is polytetrafluoroethylene (PTFE); others are poly(vinyli-dene fluoride) (PVDF), poly(vinyl fluoride) (PVF), and fluorinated ethylene polymers (FEP) (Beyler and Hirschler).

We will now discuss about their composition and properties.

Plastics With Pure Hydrocarbon Composition

Polyethylene (PE)

Polyethylene or polythene is the most commonly used plastic today. It is a linear, homo-polymer, primarily used for packaging. As of 2017, over 100 million tonnes of polyethylene resins are being produced annually, accounting for 34% of the total plastics market (see "Relevant Websites section"). It is perhaps the best known thermoplast. Polymerization of ethylene gas leads to the formation of PE. It can be produced in various grades, differing in molecular structures, crystallinity, molecular weight and molecular distribution. The basic structure of polyethylene monomer is:



Physical and mechanical properties differ in density and molecular weight with classification of PE with three densities, LDPE – low density PE (0.91–0.925 gm/cm^3) with polymer structure with both long and short branches (Schweitzer, 2006). It is a very flexible material with principal uses in packaging film, trash and grocery bags, agricultural mulch, wire and cable insulation, squeeze bottles, toys, and housewares. HDPE – High Density PE (0.925–0.940) with M.P. more than 20°C higher than LDPE, it can withstand repeated exposure to 120°C so that it can be sterilized. Applications include blow-molded bottles for milk and household cleaners; blow-extruded grocery bags, construction film, and agricultural mulch; and injection-molded pails, caps, household appliance, and toys. All PE's are relatively soft and hardness increases as density increases. Higher density also ensures better dimensional stability. Thermal stability of PE's ranges from 88°C to 121°C for the highest density material .

There is another classification based upon molecular weight according to which PE's have four categories (Schweitzer, 2006):

(1) Medium Molecular Weight: less than 100,000,
(2) High Molecular Weight: 110,000–250,000,
(3) Extra High Molecular Weight (**EHMW**): 250,000 to 1500,000 and
(4) Ultra high Molecular Weight (**UHMW**) of more than 1500,000.

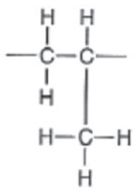
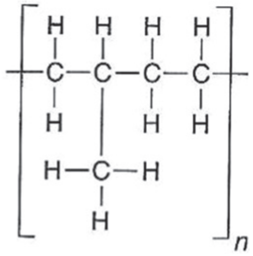
Usually ultra high Molecular Weight PE has a value of 3.1million. Every PE resin consists of a mixture of large Mol. Wt and small Mol. Wt and this mixture varies in various PE types. If Mol. Wt. is close to average, it is called narrow, however, when distribution is large, it is called broad.

The two varieties of PE generally used for corrosive applications are **EHMW** and **UHMW**. PE exhibits wide variety of corrosion resistance ranging from potable water to exposure to waste. It is resistant to most mineral acids, including sulfuric acid up to 70% concentration, inorganic salts, alkalies and chlorinated hydrocarbons.

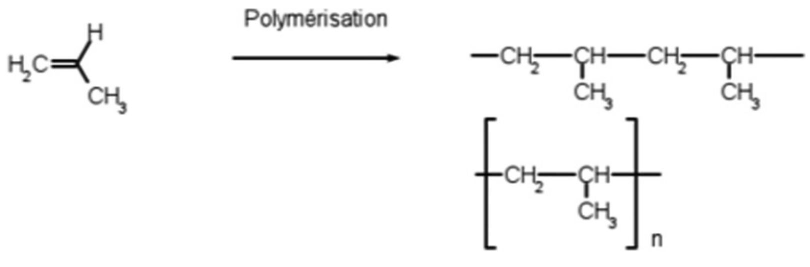
PE is subject to UV degradation and has poor weatherability.

Polypropylene (PP)

PP is one of the most common and versatile thermoplastics. It is closely related to polyethylene – both of them as member of polyolefin group, composed of only carbon and hydrogen. Based upon its chemical structure, it can be called as isotactic PP or atactic PP, as shown below (Schweitzer, 2006):

	
Isotactic PP	Atactic PP

The isotactic PP accounts for 97% of production. It has a highly ordered structure. Atactic PP is a viscous liquid having a propylene matrix. PP can be produced either as homopolymer or as a copolymer with polyethylene. Homopolymer is a long chain high MW molecule with minimum random orientation and have optimum chemical, thermal and physical properties and is therefore a preferred plastic for difficult and strong chemical or heat environment. It is prepared by polymerization of propene monomer (see "Relevant Websites section"):



(15)

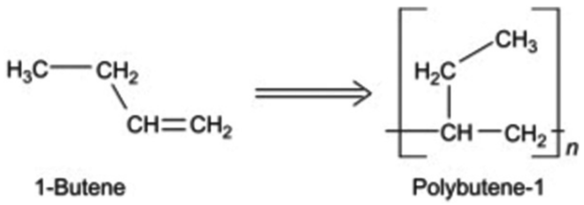
Polypropylene is liable to chain degradation from exposure to temperatures above 100°C. Oxidation usually occurs at the tertiary carbon centers leading to chain breaking via reaction with oxygen. In external applications, degradation is evidenced by cracks and crazing. PP is not affected by organic solvents and most inorganic chemicals and non-oxidizing acids except halogens and severe oxidizing conditions. It can be used with sulfur bearing compounds caustic solvents, acids and other organic chemicals. If exposed to sunlight, PP can be affected by UV light unless a proper UV protection shield is used.

Fig. 5 Some of the applications of Polypropylene.

The fact that polypropylene can well withstand injection molding process, it can be used to make thin layers of plastic. It is very suited to applications such as, hinges on medication pot, lids on shampoo bottles and other containers that will be bent and manipulated a lot and mustn't break with some applications shown in Fig. 5. Polypropylene is waterproof and extremely resistant to moisture absorption, which adds to its packaging benefits and flexibility as a packaging material. Its semi-crystalline nature offers high flexural strength too, making it resilient to general wear and tear and ideal for items that must undergo higher levels of physical stress. It is also resilient against mildew, mold, rot and bacteria.

Polybutylene (PB)

Polybutylene is a semi-crystalline polyolefin thermoplastic, based on poly-1-butene and includes homopolymer and a series of copolymers (butane/ethylene). Polybutylene-1 (PB-1) is made from 1-butene, as shown in below. Schweitzer (2006)



(16)

It is a high molecular weight (725,000 g/mol), linear, isotactic, polymer (Crystallinity 48%–55%). It is also used synergistically as a blend element to modify the characteristics of other polyolefins like polypropylene and polyethylene. Because of its specific properties, PB-1, when applied as a pure or reinforced resin, can replace materials like metal, rubber and engineering polymers.

Polybutylene is stable till 93°C. It has high flexibility and creep resistance over a wide temperature range. It has low water absorption ($< 0.03\%$) and resists chemicals such as detergents, oils, fats, acids, bases, alcohol, ketones, aliphatic hydrocarbons and hot polar solutions and is considered to be stress corrosion cracking resistant. It also has good abrasion resistance. It is partially soluble in chlorinated hydrocarbons. It undergoes pitting attack in chlorinated water. It is also subjected to the UV degradation.

It can be used for flexible pressure piping, chemical process equipment and can also be used for molded appliances parts. Other applications include domestic water heaters, electrical insulation, compression packaging, wire and cable, shoe soles, and polyolefin modification. It is also used for and Peelable easy-to-open packaging.

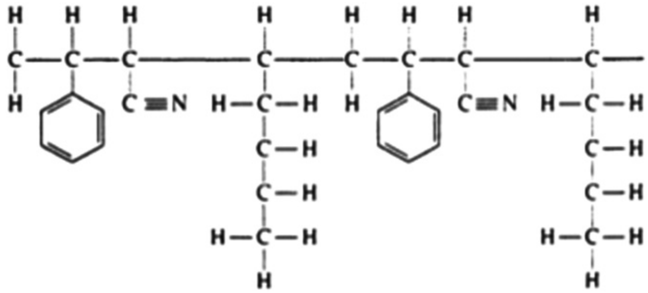
Acrylonitrile-Butadiene-Styrene (ABS)

Acrylonitrile Butadiene Styrene (ABS) is an *engineering thermoplastic*, amorphous polymer. ABS is made up of three monomers: acrylonitrile, butadiene and styrene (see "Relevant Websites section"):

- *Acrylonitrile*: It is a synthetic monomer produced from propylene and ammonia. This component contributes to ABS chemical resistance & heat stability
- *Butadiene*: It is produced as a by-product of ethylene production from steam crackers. This component delivers toughness & impact strength to ABS polymer
- *Styrene*: It is manufactured by dehydrogenation of ethyl benzene. It provides rigidity & processability to ABS plastic

Fig. 6 Some of the applications of acronitrile.

ABS is produced by emulsion or continuous mass technique. The chemical formula of Acrylonitrile Butadiene Styrene is $(C_8H_8 \cdot C_4H_6 \cdot C_3H_3N)_n$. The natural material is an opaque ivory color and is readily colored with pigments or dyes. Its molecular formula is:



ABS is an ideal material of choice for various structural applications, because of its high rigidity, good impact resistance, even at low temperatures, good insulating properties, good abrasion and strain resistance and high dimensional stability - mechanically strong and stable over time.

Acrylonitrile Butadiene Styrene offers a high degree of surface quality and also exhibits good electrical insulating properties. Pure ABS polymers are prone to attack by oxidizing agents and strong acids and they can undergo stress corrosion cracking in the presence of certain organic compounds. It is resistant to aliphatic hydrocarbons but can react with aromatic or chlorinated hydrocarbons (Schweitzer, 2006).

ABS is also degraded by UV light unless incorporated by certain additives.

ABS plastics are used in appliance control panels, housings (shavers, vacuum cleaners, food processors), refrigerator liners, etc. Household and consumer goods are the major applications of ABS. Keyboard keycaps are commonly made out of ABS. Business machines and camera housings blowers, bearings, gears, pump impellers, chemical tanks, fume hoods, ducts, piping and electrical conduit. ABS is one of the most versatile materials available for 3D printing today. ABS comes in the form of a long filament wound around a spool. ABS is the FDM (Fusion Deposition modeling) process where material is heated and squeezed through a fine nozzle to build your design in 250 μm layers. Some of the applications of acronitrile are shown in **Fig. 6**.

Summary of Hydrocarbon Based Plastics

Table 3 summarizes the physical, chemical, mechanical and corrosion properties hydrocarbon polymers with some idea of practical applications and its market in 2016 and growth for the next 5 years.

Those Modified with Oxygen in the Polymer Chain Such as Acrylic, Acronitriles

Acrylics

Acrylic Plastic, known by several names such as plexiglass, PMMA and Lucite is a useful, clear material that resembles glass, but offers better transparency and weighs 50% less than glass of equal thickness. Acrylic is known as one of the clearest materials, offering a transparency rate of 93% and can be used in a wide variety of applications. Acrylics are based on poly-methylmethylacrylate with chemical structure as (Schweitzer, 2006):

Table 3 Physical, Chemical, mechanical, UV weathering properties of various carbonaceous plastics

S. No.	*Name of plastic*	*Chemical formula*	*Density (g/cm^3)*	*Melting point oC*	*Mechanical Properties*	*Corrosion Properties*	*Temperature Limit°C*	*UV weathering*	*Market share[a] (2016/CAGR 2022*	*Few important applications*
1	Polyethylene (PE)	$(C_2H_4)n$	0.88–0.96	115–135	Depend on density and Mol. Wt.	Good with water, mineral acids, salts	88–121	Poor	111b/5.5%	Packages, wrappers
2	Polypropylene (PP)	$(C_3H_6)_n$	0.855 amorphous 0.946 crystalline	171	tough and flexible Young's Modulus 1300–1800 N/mm^2	Resistant to organic solvents and no oxidizing acids	−15 and +120	Poor	71b/5.6%	Several household applications, plastic sheets
3	Polybutylene (PB)	$(C_4H_8)_n$	0.95	135	highly flexibility and creep resistance Elastic modulus 290–295 MPa	Low water absorption, resistant to chemicals, fats bases	93	Poor	1.8b/4.6%	Flexible pressure Piping system
4	Acrylonitrile-Butadiene-Styrene (ABS)	$(C_8H_8 \cdot C_4H_6 \cdot C_3H_3N)_n$	1.060–1.080	~ 110	Highly Rigid, High Impact Strength, good dimensional stability	Poor solvent resistance, particularly aromatic, ketones and esters, undergoes SCC	85	Poor	23.9b/7.1%	Appliances control panels, keyboards, 3D printing wires

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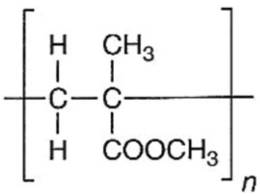
Fig. 7 Acrylic, cast sheets, clear rod, tube and colored sheet.

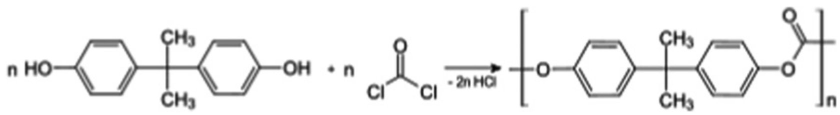


Acrylics have a number of characteristics, which make them ideal plastic: highly transparent, high impact resistant, easy to clean and polish, high durability, light and easy to transport, scratch resistant and shatter resistant. Chemically they are attacked by strong organic solvents such as acetone, gasoline. However, they exhibit excellent weathering resistance and are not affected by sunlight. The extent of light transmission in acrylics is 92%.

Acrylics are used for lenses, aircraft and lighting fixtures, coatings, textile fibers, outdoor signs and boat windshields. Acrylic comes in a wide variety of forms, *cast and extruded Sheets* with large range of thicknesses, rods which do not bend easily and nor shrink, making them a great alternative to other materials and acrylic tubes which are durable and strong (see **Fig. 7**).

Polycarbonate (PC)

Polycarbonates are classified as engineering thermoplasts because of their high engineering design capability as they are strong, tough materials, and some grades are optically transparent. They contain carbonate groups in their chemical structures. They are easily worked, molded, and thermoformed. Because of these properties, polycarbonates find many applications. The main polycarbonate material is produced by the reaction of bisphenol A (BPA) and phosgene COCl (see "Relevant Websites section")



(17)

PC is resistant to aliphatic hydrocarbons and weak acids but limited resistance to weak alkalies but attacked by strong alkalies and acids and is soluble in keton, esters and chlorinated hydrocarbons. Resistant to most oils and greases, it is not affected by UV light and has excellent weatherability.

Polycarbonate is a durable material. Although it has high impact-resistance, it has low scratch-resistance. Unlike most thermoplastics, polycarbonate can undergo large plastic deformations without cracking or breaking. As a result, it can be processed and formed at room temperature using sheet metal techniques, such as bending on a brake.

PC's are one of the most stable polymers in wet environments. Operating temperatures are from – 120–135°C. In high humidity the temperature limit drops to 100°C (Schweitzer, 2006).

Polycarbonates have extensive applications, right from extruded water bottles to medical devices especially as safety glasses which protects the eye from UV light. One of the very important application of polycarbonate is to make green houses (see **Fig. 8**) using its sheet, this provides sunlight free from UV light which is stopped by it. It is used for windows in chemical equipment and glazing in chemical plants. Also used in outdoor energy management devices, lighting diffusers and globes.

Natural Degradation of Polycarbonates

In the presence of UV light, oxidation of this polymer yields compounds such as ketones, phenols, o-phenoxybenzoic acid, benzyl alcohol and other unsaturated compounds.

Fig. 8 Polycarbonate recording disks, safety goggles and Greenhouse.

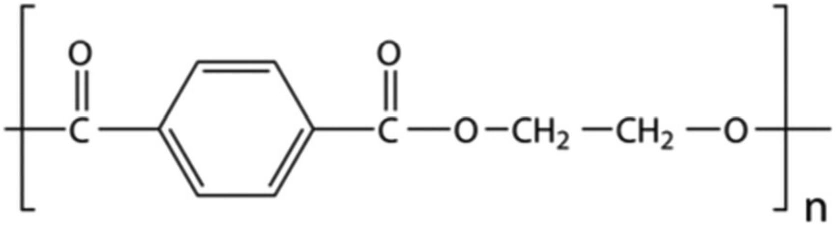
$$(OC_6H_4)_2C(CH_3)_2CO)_n + O_2, R* \rightarrow (OC_6H_4)_2C(CH_3CH_2)CO)_n \quad (18)$$

Another degradation route of Polycarbonates is Photo-aging. Absorption of UV radiation causes cleavage of covalent bonds which initiates the photo-aging process, leading to the formation of phenyl salicylate, dihydroxybenzophenone groups, and hydroxydiphenyl ether groups (Carroccio *et al.*, 2002).

Thermal degradation of polycarbonates (as waste) gives a mixture of liquids and gaseous pollutants, about 40–50 wt% liquid, 14–16 wt% gases, while 34–43 wt% remained as solid residue. Liquid products contained mainly phenol derivatives (~75 wt%) and bisphenol (~10 wt%) also present (Carroccio *et al.*, 2002).

Polyethylene Terephthalate (PET)

Polyethylene terephthalate (PET or PETE) is a general-purpose thermoplastic polymer which belongs to the *polyester family* of polymers. Polyester resins are known for their excellent combination of properties such as mechanical, thermal, chemical resistance as well as dimensional stability. PET is a semicrystalline thermoplastic with chemical structure (Schweitzer, 2006):

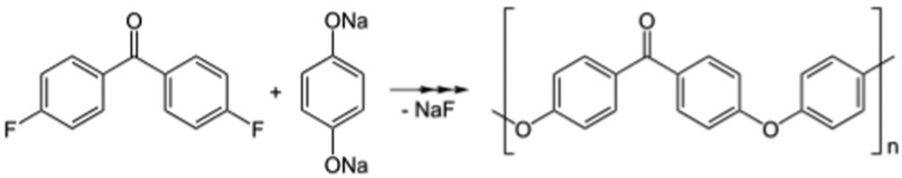


PET is resistant to dilute mineral acids, aliphatic hydrocarbons, aromatic hydrocarbons, ketones and esters with limited resistance to hot water and washing soda. It is not resistant to alkaline and chlorinated hydrocarbons. It has good resistance to UV and has stable weatherability.

PET is among those plastics which are an important part of your everyday life. It is an important commercial polymer having application ranging from packaging, fabrics, films, molded parts for automotive, electronics. PET is used in automotive industry for housing, racks, minor parts and latch mechanism. It is also used in water purification, food handling equipment and pump and valve components. PET water bottles are well known (**Fig. 9**).

Poly Ether Ether Keton (PEEK)

PEEK polymers are made by the reaction of 4,4′-difluorobenzophenone with the disodium salt of hydroquinone, which is generated in situ by deprotonation with sodium carbonate. The reaction is conducted around 300°C in polar aprotic solvent - such as diphenyl sulfone.



(19)

PEEK is a linear thermoplast which can be used in applications where high mechanical strength is coupled with difficult chemical and thermal environment. It has a long thermal range of application, from −85–250°C. Its Young's modulus is 3.6 GPa and its tensile strength is 90–100 MPa. PEEK has a glass transition temperature of around 143°C and melts around

Fig. 9 Water PET water bottles.

343°C. It is highly resistant to thermal degradation, as well as to attack by both organic and aqueous environments. It is attacked by halogens and strong acids, as well as some halogenated compounds and aliphatic hydrocarbons at high temperatures (Schweitzer, 2006).

PEEK is resistant to water at room and higher temperatures and also has inherent tendency to be abrasion resistance. It is resistant to all inorganic and organic solvents. Being aromatic, PEEK is not resistant to UV light and outdoor weathering but is resistant to hard gamma radiations.

PEEK is used to make bearing piston parts, pumps, compressor plate valves, and electrical cable insulation. It is also used to make parts compatible with high vacuum applications, especially for aerospace, automotive, electronic, and chemical industries. PEEK Polyether Ether Ketone (2020) PEEK is considered an advanced biomaterial used in medical implants, e.g., use with a high-resolution magnetic resonance imaging (MRI), for creating a partial replacement skull in neurosurgical applications. It is also used as raw material for 3D printing.

Summary of Plastics With Oxygen in the Polymeric Chain

Table 4 summarizes the physical, chemical, mechanical, UV properties of various hydrocarbon polymers having oxygen in their polymer chain along with their main applications and market size.

Those With Nitrogen in the Polymeric Chain

Polyamides PA

Polyamides or Nylon is the major engineering and high performance thermoplastics class because of its good balance of properties. Polyamides contain *repeating amide linkages* i.e., –CO-NH–. They are available in several grades, aliphatic, aromatic or semi aromatic see in Fig. (see "Relevant Websites section"). Nylons are identified by the number of carbon atoms in the diamine and dibasic acid used to produce the particular grade. Nylon 6/6 is formed using hexamethylenediamine and adipic acid, both of which contain six carbon atoms **Fig. 10**.

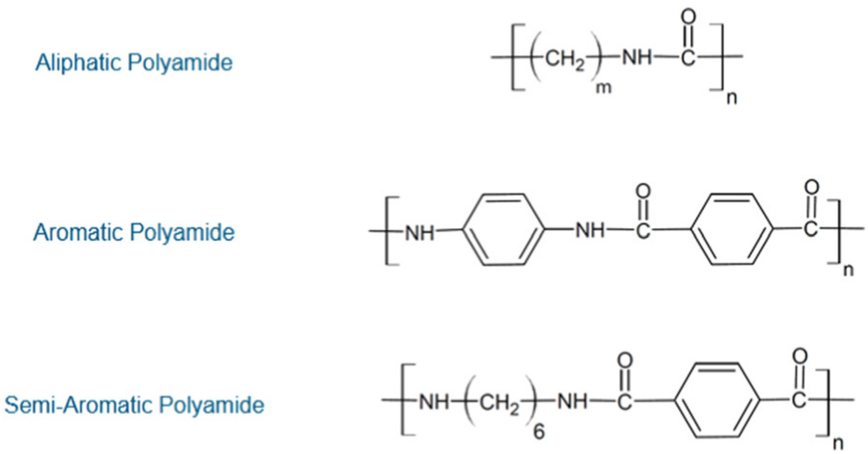


Table 4 Physical, Chemical, mechanical, UV weathering properties of various hydrocarbon polymers with oxygen atoms in the polymer chain

S. No.	*Name of plastic*	*Chemical formula*	*Density (g/cm^3)*	*Melting point °C*	*Mechanical properties*	*Corrosion properties*	*Temperature limit °C*	*UV weathering*	*Market share[a] (2016/CAGR 2022*	*Few important applications*
1	Acrylic	$(C_5O_2H_8)n$	1.18	160	Tough, good impact, scratch & shatter resistant	are attacked by strong organic solvents such as acetone, gasoline	80	V good	1.3b/6%(only sheet)	Sheets, rods, tubes and frames
2	Polycarbonate (PC)	$[OC(OC_6H_4)_2CMe_2]_n$	1.20–1.22	155	High impact resistance but low scratch resistance	Dilute acids, alkalies alcohol, good, water absorption 0.1%	115–130	Fair	15.24b/6%	Safety eye wares, extruded water bottles, greenhouse
3	Polyethylene Terephthalate (PET)	$(C_{10}H_8O_4)_n$	1.38	260	higher strength and stiffness, doesn't not break or fracture and shatters resistant	Dilute min. acids, aliphatic & aromatic solvents, ketones and esters	-60–130	Good	55.12 b/ 5.21%	Water bottles food packages
4	Polyetheretherketon (PEEK)	$[C_{18}H_{18}O_3]$	1.3	343	Superior strength-to-weight ratio Creep-resistant, abrasion resistant	Attacked by halogens & strong acids	-85–250	Poor	0.5b/6.3%	Bearings, valves, medical implants, 3D raw material

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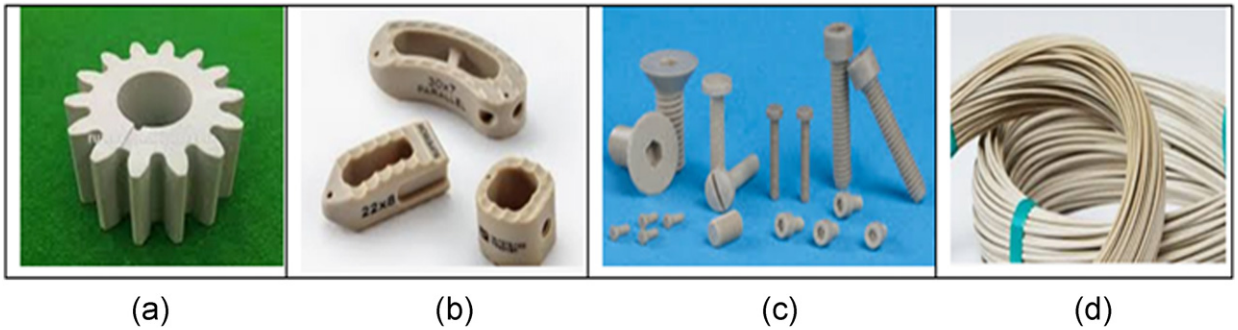
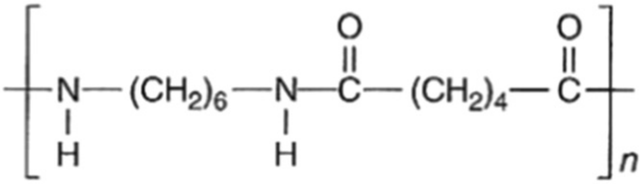


Fig. 10 PEEK plastics: (a) bearings, (b) medical implants (c) screws, bolts (d) 3D raw material. Reproduced from PEEK (Polyether Ether Ketone), 2020. Available at: www.scientificspine.com. Retrieved 2020-05-06.



Nylon 6/6

Polyamides occur both naturally and artificially. Wool and silk are naturally occurring polyamides and artificially made polyamides can be made through step-growth polymerization or solid-phase synthesis yielding materials such as nylons, aramids, and sodium poly(aspartate).

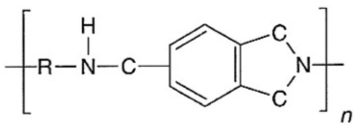
The polyamides exhibit excellent resistance to several chemicals, such as strong inorganic alkalies, particularly ammonium hydroxide and ammonia even at elevated temperatures. Strong alkalies such as sodium and potassium hydroxide are resistant at room temperature. Nylons have good weatherability and are also resistant to UV degradation and ozone. Polyamides retain useful mechanical properties over a temperature range of -51 to 200°C (Schweitzer, 2006).

Synthetic polyamides are commonly used in textiles, automotive industry, carpets, kitchen utensils and sportswear due to their high durability and strength. The transportation manufacturing industry is the major consumer, accounting for 35% of polyamide (PA) consumption.

PA's are also used to produce gears, cans, bearings, wire insulation, pie fittings and hose fittings. Blend of PA/ABS are used for appliances, lawn and garden equipment, power tools and sport goods. It is also used to in automotive industry to produce interior functional components, fasteners, housings and shrouds.

Polyamide –Imide (PAI)

PAI is a thermally processable plastic. The amide link in the polymer chain makes this material melt processable. PAIs have excellent strength and stiffness, wear resistance, and friction properties. They can be used in applications like surgical instruments and instrument components and parts that require tight tolerances and dimensional stability. Polyamide –imide is a hetrocycle polymer having one atom of nitrogen in one of the rings of the molecular chain with a formula given below (Schweitzer, 2006):

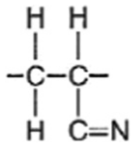


PAIs are produced by the reaction of trimellitic anhydride with an aromatic diamine in a high-boiling solvent like NMP or dimethyl acetamide or using heat and vacuum to remove the water formed. PAIs have the highest strength of any un-reinforced polymer with excellent creep resistance. They have good stiffness and strength and excellent wear and friction properties. These polymers are also inherently flame retardant and have good chemical resistance (see "Relevant Websites section"). PAI is resistant to acetic acid and phosphoric acid and sulfuric acid (up to 30–35%). It is not resistant to NaOH. PAI has also resistance to UV light. It is used to make bearings and pistons in compressors Glass-reinforced grades provide even additional strength, stiffness, and durability for high-performing parts with tight tolerances and dimensional stability.

Applications of polyamide–imides include pumps, valves, gear wheels, accessories for refrigeration plant and electronic components. Interesting materials may be made by blending the polymer with graphite and PTFE. This reduces the coefficient of friction by about 10%.

Polyacrylonitrile (PAN)

PAN is a member of the olefin family, somewhat similar to polyethylene and polypropylene in terms of appearance, general chemical characteristics and electrical properties. PAN are usually copolymers of acrylonitrile and methyl acrylate, or acrylonitrile and methyl methacrylate: The structure of PAN is given below (Schweitzer, 2006):



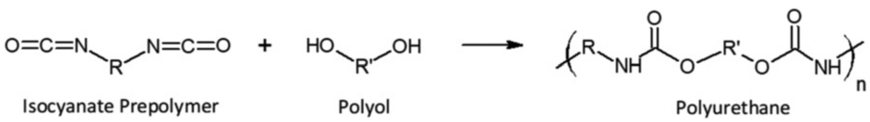
PAN has properties involving low density, thermal stability, high strength and modulus of elasticity. These unique properties have made PAN an essential polymer in high tech.

Its high tensile strength and tensile modulus are established by fiber sizing, coatings, production processes, and PAN's fiber chemistry. Its mechanical properties derived are important in composite structures for military and commercial aircraft (see "Relevant Websites section"). PAN has corrosion resistance properties very similar to polypropylene and polyethylene.

Polyacrylonitrile has been used as fibers in hot gas filtration systems, outdoor awnings, sails for yachts, and fiber-reinforced concrete. Copolymers containing polyacrylonitrile are often used as fibers to make knitted clothing like socks and sweaters, as well as outdoor products like tents and similar items. It is used to produce molded appliances parts, automotive parts, garden hose, vending machine tubing, chemical apparatus, typewriter cases and luggage shells.

Polyurethane (PUR)

Polyurethanes (PUR) are one of the largest classes of polymers with properties that can be tailored over a wide range of applications. They can be thermosetting or thermoplastic, rigid and hard or flexible and soft. They are formed from the reaction of an organic diisocyanate with a diol compound, which leads to urethane linkages in the backbone (-NH-C(=O)-O-).



(20)

The properties of PURs greatly depend on the structure of the polymer backbone (see "Relevant Websites section"). They can be tailored to have high strength, high rigidity or high flexibility and toughness. Most of these urethanes have good resistance to oil, (aromatic) hydrocarbons, oxygen, and ozone. Two major drawbacks of PURs are their susceptibility to microbial attack and the tendency of aromatic urethanes to discolor (yellow) when exposed to UV light. Polyurethanes are produced from either polyethers or polyesters. Those produced from polyether are more resistant to hydrolysis and have higher resilience, good energy absorbing characteristics and good chemical resistance.

The polyester based urethanes are stiffer and have higher compression and tensile moduli, higher tear strength and cut resistance, higher operating temperature, optimum abrasion resistance and fuel and oil. The detailed chemical formula of a polyester based polyurethane is are given below:

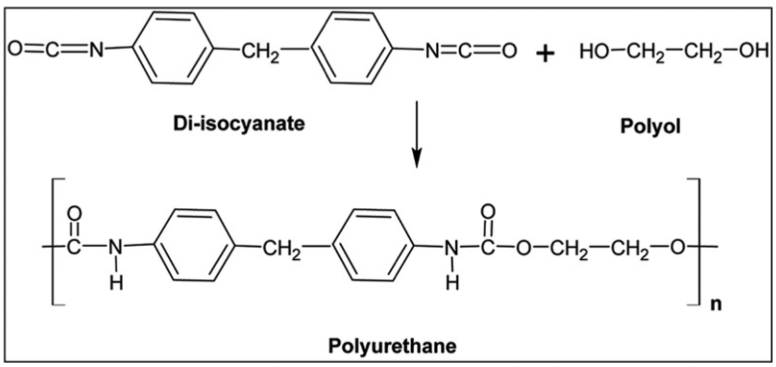
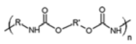


Table 5 Physical, Chemical, mechanical, UV weathering properties of various hydrocarbon polymers with nitrogen atoms in the polymer chain

S.No.	*Name of plastic*	*Chemical formula*	*Density (g/cm^3)*	*Melting point °C*	*Mechanical properties*	*Corrosion properties*	*Temperature Limit °C*	*UV weathering*	*Market share*[a] *(2016/CAGR 2022 (US$)*	*Few important applications*
1	Polyamide (PA)	$(C_6H_{11}NO)n$ (PA)	1.12–1.14 (PA6)	180–230	retain useful mechanical properties till 200°C	Resistant to strong acids and alkalies at RT but affected at high temperatures	*80–150*	Good weather ability, resistance to UV	2.36b/5.9%	textiles, automotive industry, carpets, kitchen utensils and sportswear
2	Polyamide –Imide (PI)	$[\text{-R-}C_9H_7N\text{ -}]n$	1.43	310–375 (processing temperature)	superior wear properties and high impact strength	High Chemical resistance	400–500	Good	501.7 m/6.5%	Plates and rods and bearings and pistons in compressors.
3	Polyacrylonitrile (PAN)	$(C_3H_3N)_n$	1.184	300	high strength and modulus of elasticity	soluble in polar solvents, such as dimethylformamide, ethylene and propylene carbonates. sodium thiocyanate, zinc chloride & nitric acid.	65–85	Good	7940 m/-0.04%	Fibers,
4	Polyurethane (PUR)		0.43–0.65	87–90				Aliphatic – Very good-Aromatic - poor	55.20 b/6.0%	flexible and rigid foams, solid elastomers, extrusion and injection-molded parts, coatings, sealants

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PUR exhibit excellent resistance to oxygen ageing, but have limited life in high humidity and high temperature applications. Water affects PUR in two ways: temporary plastization and permanent degradation (Schweitzer, 2006).

The versatile urethane chemistry allows for the production of a wide range of products including flexible and rigid foams, solid elastomers, extrusion and injection-molded parts, coatings, sealants, and adhesives. Flexible, high-resilience foamed products include mattresses, upholstered furniture, carpet underlays and auto parts like cushions, backs, and armrests. Rigid foamed products with a closed cell morphology are used as insulations for commercial and residential buildings. Other applications of rigid foam include insulations for tanks, pipes, water heaters, refrigerators, and freezers. Examples of solid elastomeric products are durable elastomeric wheels and tires for forklifts, skateboards, roller coasters and escalators. Polyurethanes are also used as electrical potting compounds, adhesives, coatings, sealants, and for the fabrication of synthetic fibers. PUR are used where the properties of good abrasion resistance and low coefficient of friction are required (see "Relevant Websites section").

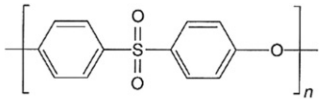
Summary of Plastics With Nitrogen in the Polymeric Chain

Table 5 summarizes the physical, chemical, mechanical and corrosion properties for hydrocarbon polymers with nitrogen atoms in the polymer chain with some idea of practical applications and its market in 2016 and growth for the next 5 years.

By the Addition of Sulfur in the Polymeric Chain

Polyethersulfone (PES)

Polyethersulfone (PES) is an amorphous, transparent, and pale amber high-performance thermoplastic. It is the most temperature resistant, transparent commercially available thermoplastic resin. It is a high temperature engineering thermoplastic with high stability and mechanical strength. Its chemical structure is as follows (Schweitzer, 2006):

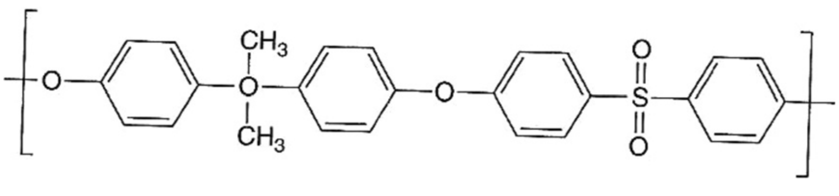


It has relatively high water absorption. It is sensitive to small moisture in atmosphere leading to dimensional changes. It has excellent resistance to aliphatic hydrocarbons, some chlorinated hydrocarbons and aromatics. It is attacked by strong acids and is soluble in polar solvents and can undergo SCC in ketones and esters. It is susceptible to UV degradation.

It is used for medical appliances, sterilization of electrical equipment, chemical plants. Aircraft and aerospace appliances, office equipment, photocopier parts see **Fig. 11**.

Polysulfones (PSF)

Polysulfones are high performance thermoplastics, known for their toughness and stability at high temperatures. Because of high cost of raw materials and processing, polysulfones are used in specialty applications and often a superior replacement for polycarbonates. Its chemical structure is (Schweitzer, 2006):



It has a temperature range from −100 to 150°C. It has Benzene linkages, but still it is not degraded by UV light like other benzene or phenolic based polymers and thus have good weatherability.

PSF is resistant to sterilization by several methods such as steam autoclaving, dry heat, certain chemicals and radiations. It will stand exposure to soap, detergent, and hydrocarbon oils even at elevated temperatures and under moderate stress levels. It has strong resistance to mineral acids, alkali, and salt solutions and also to polar organic solvents such as esters, ketones and chlorinated and aromatic hydrocarbons.

PSF is used for hot water piping systems, lenses, iron handles, switches and circuit breakers. Its rigidity and high temperature performance make it ideal for medical, microwave and electronic applications.

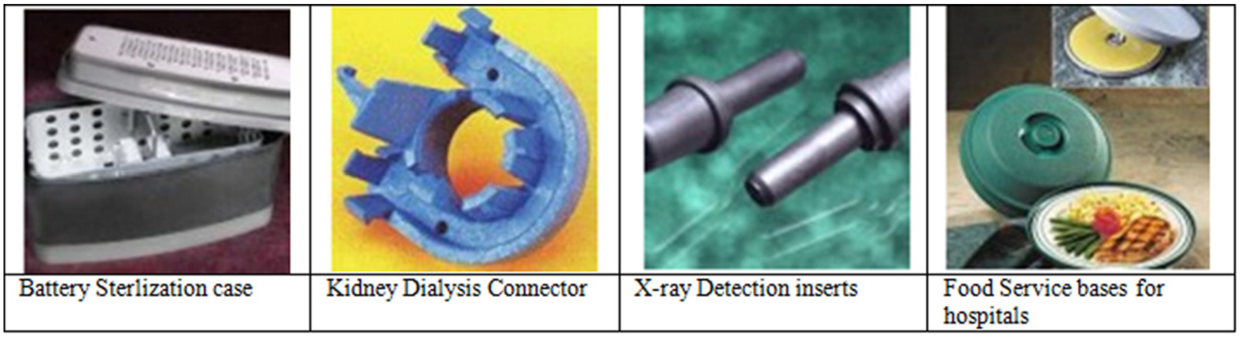


Fig. 11 Shows some important applications of PES (see "Relevant Websites section").

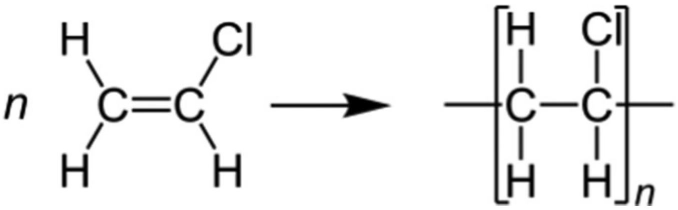
Summary of Plastics With Sulfur in the Polymeric Chain

Table 6 summarizes the physical, chemical, mechanical and corrosion properties of some of the hydrocarbon polymers with sulfur atoms in the polymer chain with some idea of practical applications and its market in 2016 and growth for the next 5 years.

Those Modified With Chloride in the Polymer Chain

Polyvinyl Chlorides (PVC)

Polyvinyl Chloride (PVC) is one of the most commonly used *thermoplastic* in the world. It is made by the polymerization of vinyl Chloride as given below:



(21)

PVC is formed in two forms, a rigid or unplasticized polymer (RPVC), and second as a flexible plastic. Flexible, plasticized or regular PVC is softer due to the addition of plasticizers. Flexible PVC is commonly used as insulation on electrical wires or in flooring for homes, hospitals, schools, and other areas where a sterile environment is a priority. Rigid PVC is also used in construction as pipe for plumbing. PVC pipe is often referred to by its "schedule" (e.g., Schedule 40 or Schedule 80). Major differences between the schedules include things like wall thickness, pressure rating, and color (see "Relevant Websites section").

The two types of plastics, rigid with normal Impact (type1) and high impact (type 2). Type 1 is also has high chemical resistance, while type 2 has high impact with reduced chemical resistance. Type1 resist attack by most acids and strong alkalies, gasoline, kerosin, aliphatic alcohols and hydrocarbons, particularly useful for handling hydrochloric acids. Type 2 PVC has much lower resistance to these chemicals (Schweitzer, 2006).

PVC may be attacked by aromatic and chlorinated organic compounds and lacquer solution. PVC is resistant to normal atmospheric pollutants and does not degraded by UV light.

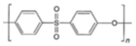
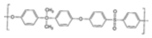
PVC has several applications – transport of water, gas, and corrosive chemical thru piping, electrical conduit and wire insulation, automotive use for exterior applications as body side molding.

Finally it is important to mention, Polyvinyl Chloride has very poor heat stability and it emits toxic fumes when melted and/or subject to a fire. For this reason additives which stabilize the material at higher temperatures are typically added to the material during production.

Chlorinated Polyvinyl Chloride (CPVC)

CPVC (chlorinated polyvinyl chloride) is a strong, durable material is formed by addition of chlorine to PVC using free radical chlorination reaction to the level of 67%. It can also be formed by direct reaction of acetylene and hydrochloric acid with chlorination up to 57%. Its structure is as follows (Schweitzer, 2006):

Table 6 Physical, Chemical, mechanical, UV weathering properties of various hydrocarbon polymers with sulfur atoms in the polymer chain

S.No.	*Name of plastic*	*Chemical formula*	*Density (g/cm^3)*	*Melting point °C*	*Mechanical properties*	*Corrosion properties*	*Temperature Limit °C*	*UV weathering*	*Market share[a] (2016/ CAGR 2022 (US$)*	*Few important applications*
1	Polyether Sulfone (PES)		1.37–1.47	227–238	good mechanical behavior between − 50 and 180	resistance to aliphatic hydrocarbons and attacked by strong mineral acids	150–180	Poor	Not available	Electrical/electronics, sterilization, medical equipment's, connectors
2	Polysulfones (PSF)		1.25	185	high strength and stiffness, and good dimensional stability	strong resistance to mineral acids, alkali, and salt solutions and also to polar organic solvents	-100 to 200	Good	Polyaryl sulfone Market Worth $2.9 Billion By 2025 I CAGR: 7.7%	water piping systems, lenses, iron handles, switches and circuit breakers

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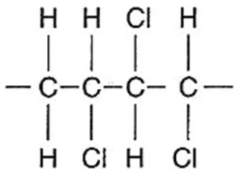


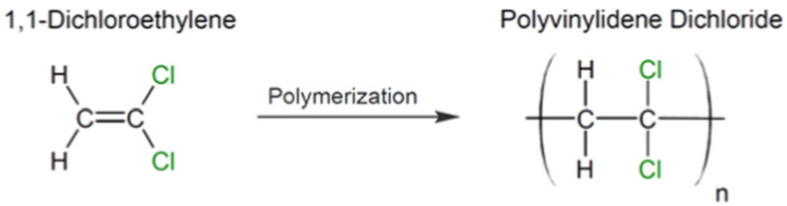
CPVC is a high-temperature plastic pressure piping system for potable plumbing. in 1959 Compared to PVC, its temperature resistance increases from 60° to 82°C with special formulations extending to 93°C. CPVC assures safety of potable water and long-term reliability, resistance to corrosion, tuberculation, deposits, resistance to Chlorine and chloramine, lightweight, easy to transport, durable and tough to survive jobsite installations.

There are several similarities of PVC and CPVC, however, the corrosion resistance of CPVC is somewhat inferior to PVC. In general PVC is inert to most mineral acids, bases, salts and paraffinic hydrocarbons, CPVC is not recommended for most polar organic solvents such as chlorinated or aromatic hydrocarbons, esters, and ketones. When exposed to direct sunlight, *CPVC* shows "*UV* degradation", but only between 0.001 and 0.003 in. Long-term sunlight exposure can decrease the *CPVC* impact strength and *resistance*.

It has several applications: hot- and cold-water plumbing distribution, residential and commercial lines, fire protection, chilled water piping, hydronic piping and distribution (radiators, fan coils, etc.) and various kinds of fittings (see **Fig. 12**).

Polyvinylidene Chloride (PVDC)

Polyvinylidene dichloride (PVDC), also called polyvinylidene chloride, is a clear, semi-crystalline thermoplastic produced by addition polymerization of 1,1-dichloroethylene as shown below:



(22)

It has improved strength, hardness and better chemical resistance than PVC. It is resistant to oxidants, mineral acids, and solvents. Its operating temperature range is from −18 to 80°C. PVDC is also superior to polypropylene in many chloride based plating baths, handling of municipal water and waste water. It is also resistant to UV light and good weathering resistance **Fig. 13**.

Some of its wide ranging applications in plating industry, handling deionized water, pharmaceutical and food processing industry. It is also used for pipelining.

PVDC is mainly used in packaging of food, drugs, cosmetics, and other perishable or delicate products to extend shelf life. In comparison with many common films, PVDC coated films have superior gas and moisture barrier properties as shown in **Fig. 1** for water, carbon dioxide, oxygen and nitrogen and excellent heat sealability. These films often compete with acrylic, and PVOH coated films. PVC-PVDC copolymers or blends are sometimes used in gasoline filters, valves, and pipe fittings **Fig. 14**.

Summary of Plastics With Chlorine in the Polymeric Chain

Table 7 summarizes the physical, chemical, mechanical and corrosion properties of some of hydrocarbon polymers with chlorine atom in the polymer chain with some idea of practical applications and its market in 2016 and growth for the next 5 years.

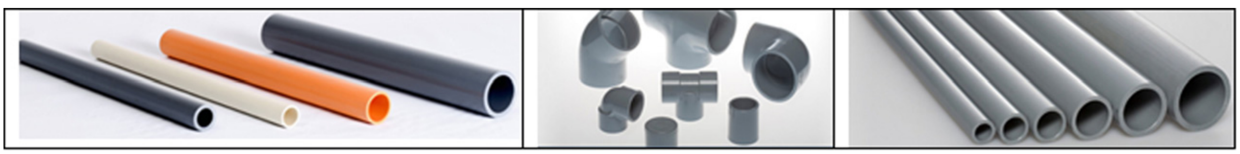
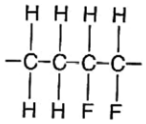


Fig. 12 Use of CPVC as fittings and pipes.

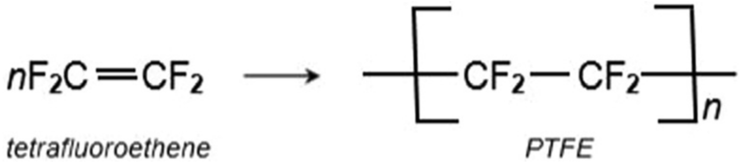
Those With Fluorine in the Polymeric Chain

Ethylene Tetrafluoroethylene ETFE

Ethylene Tetrafluoroethylene (ETFE) is a fluorine-based plastic designed to have high corrosion resistance and strength over a wide range of temperature. ETFE has a trademark name of Tefzel with following formula (Schweitzer, 2006):



The PTFE is made by the polymerization of monomer - $CF_2 = CF_2$ - by radical polymerization. TFE gas is passed into water containing a radical initiator, e.g. ammonium persulfate, $(NH_4)_2S_2O_8$, at 310–350K and a pressure of 10–20 atm.



(23)

TFE monomer is made from the pyrolysis of TFE at 940–1500K (see "Relevant Websites section").

It is high temperature plastic polymer with maximum service temperature of 149°C. It is a rugged thermoplastic material with excellent reinforcing properties with carbon or glass fibers because of very good bonding with resin. ETFE film is self-cleaning (due

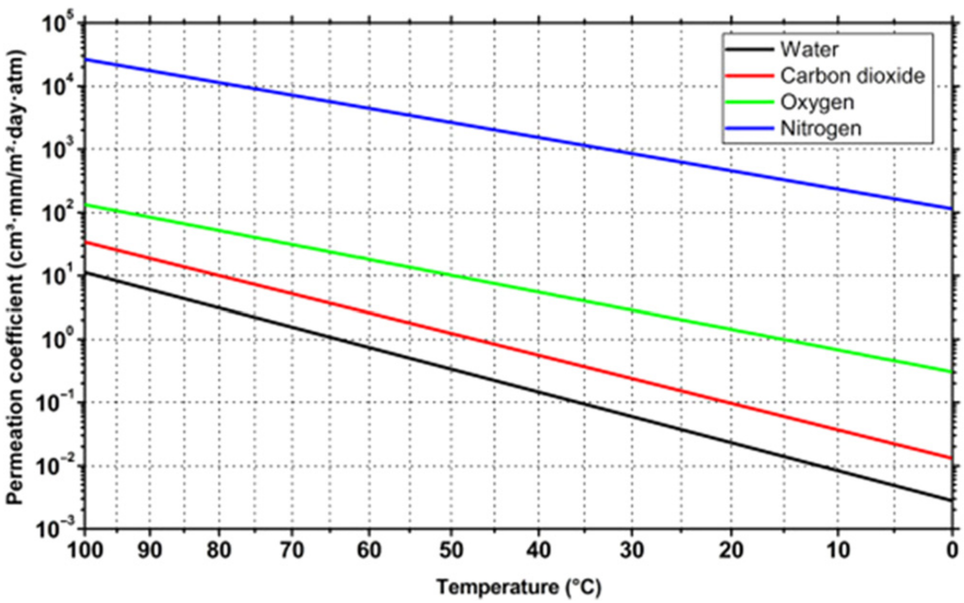


Fig. 13 Penetration coefficient of PVDC for water, carbon dioxide, oxygen or nitrogen. Reproduced from McKeen, L.W., 2017. Permeability Properties of Plastics and Elastomers, fourth ed. William Andrew.

to its nonstick surface) and recyclable.

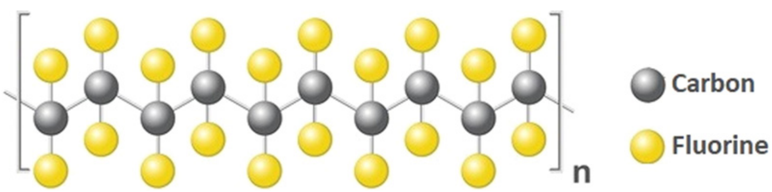


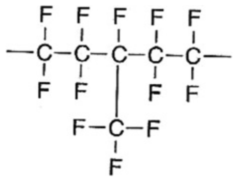
Fig. 14 Structure of PTFE.

It is inert to strong mineral acids, halogens, inorganic bases and metal salt solutions. Only very strong oxidizing acids such as nitric, sulfuric acid at high concentration near boiling point and organic bases such as amines have little effect on ETFE. It is also not affected by alcohols, ketones or esters and normal polymer solvents. It is also not affected by UV light.

ETFE has excellent electrical and chemical properties and is especially suited for applications requiring, high Mechanical Strength, chemical resistance and good thermal and electrical properties. The *mechanical properties of ETFE* are superior to those of *PTFE* and *FEP (*perfluoroalkoxy resins).

Fluorinated Ethylene- Propylene FEP

A fully fluorinatedethylene-propylene, thermoplastic with some branching with formula:



FEP (fluorinated ethylene propylene) is chemically a copolymer of hexafluoropropylene and tetrafluoroethylene. It was developed as a melt processable version of PTFE. As such, it inherits all the chemical resistance and non-stick properties of PTFE whilst offering the ability to be extruded and thermoformed. FEP exhibits almost same corrosion resistance as PTFE, but at lower operating temperatures. It has maximum operating temperature of 200°C. Above 204°C for prolong heating, it loses its strength. The strength can however be enhanced using glass fiber reinforcement. It is resistant to most of the chemicals except some extremely oxidizers such as chlorine trifluoride. FEP is not degraded by UV light and has excellent weathering resistance (Schweitzer, 2006).

FEP is used as a lining material for process vessels and piping, laboratory wares and other process equipment's.

Polytetrafluoroethylene (PTFE)

Polytetrafluoroethylene or PTFE is the highest performing fluoropolymer, known by a trade name *Teflon*. It is made up for carbon and fluorine atoms, *a fully fluorinated thermoplastic with formula*:

The *fine PTFE powder* is prepared by controlled emulsion polymerization, in the form of tiny particles. Fine PTFE powders can be processed into thin sections by paste extrusion or used as additives to increase wear resistance or frictional property of other materials. It operates at temperature from – 25 to 210°C. PTFE is unique in corrosion resistance and is virtually inert in most materials. A very few very strong oxidizers and reducing agents can react with PTFE. Elemental sodium or potassium attack PTFE. High fluid compounds such as chlorine trifluoride is absorbed by PTFE and the mixture becomes a source of ignition. 80% NaOH, aluminum chloride, ammonia and certain amines at high temperatures have same effect as elemental sodium. PTFE has excellent weathering properties and can sustain sunlight for more than 10 years.

One of the common applications of this polymer is non-stick coating in kitchen cookware, pans, baking trays etc. Apart from used in the kitchen, PTFE is used as a cost-effective solution for industries ranging from oil & gas, chemical processing, industrial to electrical/electronic and construction sector: wire and cable insulation, corrosion protection linings including tanks and piping's. Its low surface friction makes its use in automotive industry (see **Fig. 15**).

Polyvinylidene Fluoride (PVDF)

PVDF is a crystalline, high molecular weight polymer containing 50% fluorine. Its structure is similar to that of PTFE, except that it is not fully fluorinated (Schweitzer, 2006) :

PVDF exhibits excellent mechanical strength and toughness, stiffness, high dielectric strength, abrasion resistance, creep resistance, high purity, chemical inertness, low flammability, and low moisture absorption. It is chemically resistant to most acids, bases and organic solvents. It is resistant to wet and dry chlorine. It can operate between -40 and 160°C without loosing any strength and chemical stability. The only precaution is with strong alkalies, fuming acids, polar solvents, amines, ketones and esters. In strong alkalies it undergoes SCC **Fig. 16**.

PVDF may be synthesized from the gaseous vinylidene fluoride (VDF) monomer by a free-radical (or controlled-radical) polymerization process. This may be followed by processes such as melt casting, or processing from a solution (e.g. solution casting, spin coating, and film casting). Compared to other fluoropolymers, it has an easier melt process because of its relatively low melting point of around 177°C.

PVDF has several applications similar to other fluoropolymers. PVDF resin is heated and handled for use in extrusion and injection molding to produce PVDF pipes, sheets, coatings, films, and molded PVDF products, such as bulk containers. Some industry applications are: chemical processing, construction and architecture, healthcare and pharmaceutics, biomedical, petrochemical, oil and gas research (PVDF Performance & Characteristics Data).

Table 7 Physical, Chemical, mechanical, UV weathering properties of various hydrocarbon polymers with chlorine atom in the polymer chain

S. No.	*Name of plastic*	*Chemical formula*	*Density (g/cm^3)*	*Melting point °C*	*Mechanical properties*	*Corrosion properties*	*Temperature Limit °C*	*UV weathering*	*Market share[a] (2016/ CAGR 2022 (US$)*	*Few important applications*
1	Polyvinyl Chlorides (PVC)	$(C_2H_3Cl)n$	1.4	100–260	Type 1- rigid low impact And Type 2 –flexible with high impact	attacked by aromatic and chlorinated organic compounds and lacquer	60	Good	44 m/ 4.25%	Flexible for insulation, rigid for piping
2	Chlorinated Polyvinyl Chloride (CPVC)	$(C_9H_{11}Cl_7)n$	1.56	150	Higher Tensile strength and Modulus than PVC, that is why can replace metal pipelines	Somewhat lower than PVC	80	Fair	2.8 b/ 9.1%	Pipings and fittings
3	Polyvinylidene Chloride (PVDC)	$(C_2H_2Cl_2)n$	1.63	160–170	Tensile strength 25–110 MPa and modulus 0.3–0.55 GPa	superior chemical resistance to alkalies and acids, is insoluble in oil and organic solvents	70–90	Excellent UV & weathering resistance	2.5b/2.5%	Food packaging, coatings over PVC

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One of the most common applications of PVDF is a coating on aluminum composite panels used to clad house walls. PVDF coated steel fasteners are very well known in chemical industry (see Fig. 17).

PVDF is also commonly used as insulation on electrical wires, because of its combination of flexibility, low weight, low thermal conductivity, high chemical corrosion resistance, and heat resistance.

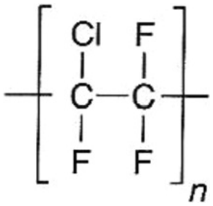
Summary of Plastics With Fluorine in the Polymeric Chain

Table 8 summarizes the physical, chemical, mechanical and corrosion properties of some of hydrocarbon polymers with fluorine atom in the polymer chain the with some idea of practical applications and its market in 2016 and growth for the next 5 years.

Those With Chlorine and Fluorine in the Polymeric Chain

PolyChlotrifluroethylene (PCTFE)

PCTFE is a thermoplastic chlorofluoropolymer. It is similar to polytetrafluoroethene (PTFE), except that it is a homopolymer of the monomer chlorotrifluoroethylene (CTFE) instead of tetrafluoroethene. It has the lowest water vapor transmission rate of any plastic (Kurita, 1988) CTFE is sold under a trade name of Kel-F. It is a fluorocarbon with following structure:



It is prepared by the free-radical polymerization of chlorotrifluoroethylene (CTFE) and can be carried out by solution, bulk, suspension and emulsion polymerization (Ebnesajjad, 2015) Melt Processible Fluoropolymers. It has high tensile strength and

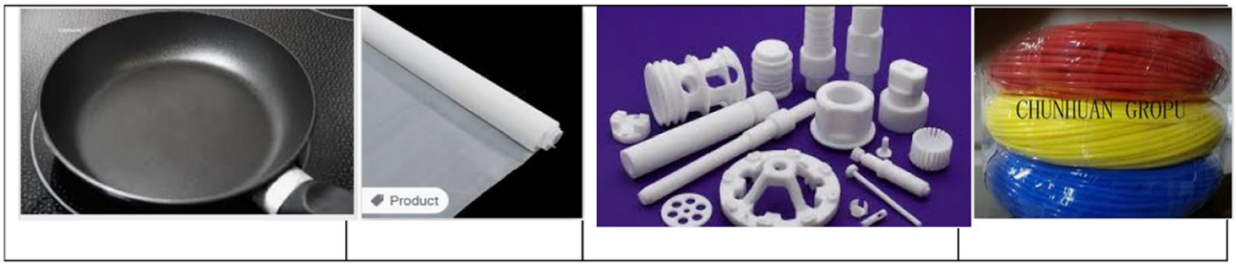


Fig. 15 Examples of PTFE products.

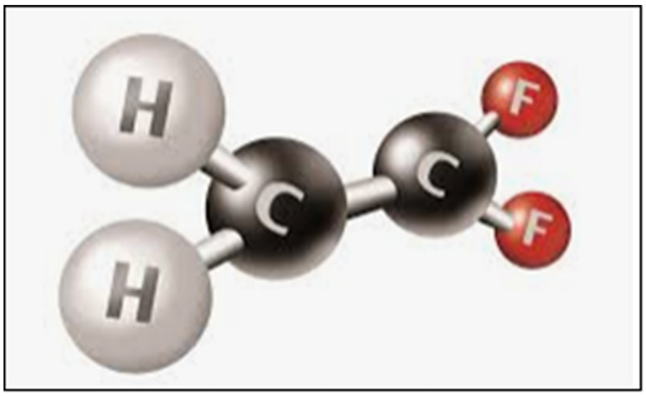


Fig. 16 Structure of PVDF showing two strong – C- F - bonds.

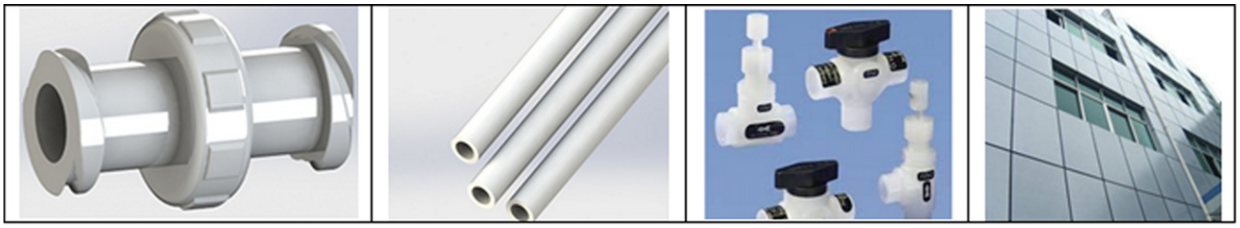


Fig. 17 PVDF fittings, tubes, needle valves and coated aluminum composite panels.

good thermal characteristics. It is nonflammable and the heat resistance is up to 175°C. It has a low coefficient of thermal expansion. The presence of a chlorine atom, having greater atomic radius than that of fluorine, hinders the close packing possible in PTFE. This results in having a relatively lower melting point among fluoropolymers, around 210–215°C.

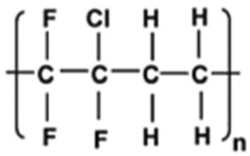
It has wide range of corrosion resistance but lower than PTFE, FEP and PFA. PCTFE is resistant to the attack by most chemicals and oxidizing agents, a property exhibited due to the presence of high fluorine content. However, it swells slightly in halocarbon compounds, ethers, esters and aromatic compounds. PCTFE is resistant to oxidation because it does not have any hydrogen atom.

PCTFE finds majority of its application due to two main properties: water repulsion and chemical stability. PCTFE films are used as a protective layer against moisture. These include: moisture barrier in pharmaceutical blister packaging, protection of liquid-crystal display (LCD) panels, which are sensitive to moisture, and cryogenic seals and components.

Due to its chemical stability, it acts as a protective barrier against chemicals. It is used as a coating and prefabricated liner for chemical applications. PCTFE is also used for laminating other polymers like PVC, polypropylene, PETG, APET etc. PCTFE is used to protect sensitive electronic components because of its excellent electrical resistance and water repulsion. Other uses include flexible printed circuits and insulation of wires and cables.

Ethylenechlorotrifluroethylene ECTFE

ECTFE is 1:1 alternating copolymer of ethylene and cholrotrifluroethylene with chemical formula:



It has excellent corrosion resistance from low temperatures of −20 to 117°C. It is resistant to several chemicals such as strong mineral and oxidizing acids, alkalies and almost all organic solvents except amines like aniline or dimethylamine. It also has excellent abrasion resistance. It is sold in a trade name of Halar. It also has good permeation resistance to oxygen, carbon dioxide and chlorine gas and about 100 times better than PTFE OR FEP and low water absorption of less than 0.01%. Schweitzer (2006).

ECTFE also exhibits excellent resistance to weathering and UV radiations and also found resistance to gamma rays from Cobalt-60 radiations.

Its applications are as pipe and vessel liners and in piping systems, chemical process equipment and high temperature wire and cable insulation.

Summary of Plastics With Chlorine and Fluorine in the Polymeric Chain

Table 9 summarizes the physical, chemical, mechanical and corrosion properties of some of hydrocarbon polymers with chlorine and fluorine atoms in the polymer chain the with some idea of practical applications and its market in 2016 and growth for the next 5 years.

Summary and Final Conclusions

In order to summarize the article, it is worth mentioning eleven most common plastics, viz., *PET*, the most widely produced plastic in the world, used predominantly as a fiber (known by the trade name "polyester") and for bottling or packaging. *Polyethylene*, including LDPE and HDPE and UHMW, an extremely strong plastic, used for medical devices; *PP*, a semi-transparent, has a low-friction surface, doesn't react well with liquids, is easily repaired from damage and has good electrical resistance; *PVC & CPVC*, perhaps the most important plastics for plumbing, piping and for insulation of electrical wires; *Polycarbonate*, a transparent material known for its particularly high impact strength and is used in greenhouses where high transmittance and high strength are

Table 8 Physical, Chemical, mechanical, UV weathering properties of various hydrocarbon polymers with fluorin atom in the polymer chain

S. No.	*Name of Plastic*	*Chemical formula*	*Density (g/cm^3)*	*Melting point °C*	*Mechanical properties*	*Corrosion properties*	*Temperature limit °C*	*Annual production (tons)***	*UV Weathering*	*Market share*[a] *(2016/CAGR 2022 (US$)*	*Few important applications*
1	Ethylene Tetra-fluroethylene (ETFE)	$(C_4H_6F_2)n$	1.68	225–270	tough - high strength version of PTFE.	Excellent, no effect of any acid, alkaline solvent	149	19.1K	Excellent	327 m/8.0%	Building Cladding
2	Fluorinated Ethy-lene- Propylene (FEP)	$(C_6F_{12})n$	2.12–2.17	253–282	No break on Impact,	Excellent resistant to all acids	-250–200	28.4K	Excellent	695 m/8.3%	Lining material for process vessel and piping
3	Polytetrafluoro ethylene (PTFE)	$(C_2F_4)n$	2.2	327	Tough	Excellent, resistant to all acids and alkalies and organic solvents	210	2 00K	Excellent	1.87b/6.1%	Cookware corrosion resistant coatings
4	Polyvinylidene Fluoride (PVDF)	$(C_2H_2F_2)n$	1.78	169	toughness, stiffness, , abrasion resistance, creep resistance	Chemically inert and low water absorption	150	46K	Excellent	960 m/7.6%	PVDF tubing, film/foil, sheet, couplings, rod, pipe Coatings

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Table 9 Physical, Chemical, mechanical, UV weathering properties of various hydrocarbon polymers with chlorin and fluorin atoms in the polymer chain

S. No.	*Name of plastic*	*Chemical formula*	*Density (g/cm^3)*	*Melting point °C*	*Mechanical properties*	*Corrosion properties*	*Temperature limit °C*	*UV weathering*	*Market share[a] (2016/CAGR 2022 (US$)*	*Few important applications*
1	PolyChlotrifluroethylene (PCTFE)	$(C_2ClF_3)n$	1.54	210–215	tensile strength and low thermal expansion	resistant to the attack by most chemicals and oxidizing agents	175	Excellent	537.3 m/2.2%	Moisture resistance films, linings, electronic components, LCD
2	Ethylenechlorotrifluroethylene (ECTFE)	$(C_4H_4F_3Cl)$ n	1.68	240	good impact resistance and a Young's modulus	resistant to most chemicals except hot polar and chlorinated solvent	150	Excellent	376 m/6.2%	Because of high resistance to Chemicals, it is used as an insulation film, lining in electrical industry

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Fig. 18 Important applications of 11 important plastics.

both required; *Acrylic (PMMA)*, best known for its use in optical devices, an extremely transparent, scratch resistant, and much less susceptible to damaging human skin or eye tissue; *Nylon (PA)*, used in variety of applications, in clothing, reinforcement in rubber material like car tires, for use as a rope or thread, and for a number of injection molded parts for automotives; *ABS* having strong resistance to corrosive chemicals and physical impacts, is easy to machine, and has a low melting temperature making it particularly simple to use in injection molding manufacturing processes or 3D printing; *Acetal (POM)*, a high tensile strength plastic with significant creep resistant properties that bridge the material properties gap between most plastics and metals, known for high resistance to heat, abrasion, water, and chemical compounds, makes it very useful for applications that utilize gears; *Peek*, highly resistant to water at room and higher temperatures and also has inherent tendency to be abrasion resistance, used for gears; and *PVDF*, the highly corrosion resistance with several applications for making devices and special applications as most corrosion resistance coating.

Plastics have become a very important global material of modern age. Though, as mentioned above, there are different applications of several individual plastics as shown in Fig. 18, however, it is possible to categorise many of these applications in four categories, *housing and construction, electrical and insulation devices, packaging, transport, covering automobiles, aerospace, ships and marine and railways*. Importance of plastics over other materials can be estimated from the fact that more patents are filed today in many countries, each year in plastics than for glass, metal and paper combined. There are constant innovations occurring with polymers that can help revolutionize industries. These include shape-memory polymers, light-responsive polymers and self-healing polymers.

The final word about corrosion and natural deterioration of plastics shows that there are several plastics which are totally free from corrosion and natural degradation. *Hence, it is only the selection criteria of plastics which can help you choose a safe and corrosion resistance plastic*.

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