Biodegradation of Polymeric Insulators Used in Electrical power

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الملخص

المواد البوليميرية لها مجموعة متنوعة من الاستخدامات بسبب التنوع الهيكلي. يعد تحللها البيولوجي مصدر قلق شائع لأنه عند استخدامها كعوازل كهربائية فإن انهيار سلامتها الهيكلية يعرض الناس لمخاطر كهربائية. تبدأ عملية تحلل العوازل بواسطة الأغشية الحيوية بتكوين غشاء حيوي على سطحه. يجب أن يكون تكوين الأغشية الحيوية في ظل ظروف بيئية مناسبة مثل الرطوبة أو البيئة الرطبة. تعرض هذه الورقة عملية التحلل البيولوجي للعوازل البوليميرية. يتناول العمل إلى العمليات التي تشارك في نفس العوامل ، والعوامل التي تزيد من عملية التحلل البيولوجي. بمجرد تكوين الأغشية الحيوية على سطحها ، ستفرز الكائنات الحية الدقيقة إنزيمات تستطيع مهاجمة وتحلل سطح البوليمر.
يخلص البحث إلى أن العوامل الأكثر شيوعًا التي تساعد في التحلل الحيوي هي تركيب البوليمرات، وطبيعتها البلورية، والعوامل البيئية.

Abstract

Polymeric materials have a variety of uses due to structural versatility. Their biodegradation is a common concern since when used as electrical insulators the breach of their structural integrity exposes people to electrical dangers. The process of degradation of the insulators by biofilms begins by the formation of a biofilm on its surface. Formation of the biofilm has to be under appropriate environmental conditions like in a damp or moist environment. This paper presents the process of biodegradation of polymeric insulators. It looks at the processes that are involved in the same and the factors that amplify the biodegradation process. Once the biofilms have been formed on their surface, the microbes will secrete enzymes that can attack and hydrolyze the surface of the polymer.

The paper concludes that the most common factors that aid the biodegradation are the composition of the polymers, the crystalline nature, and the environmental factors.

Keywords: *Polymeric, Biodegradation, Environment, Carbon, Biofilms, Enzymes microorganisms.*

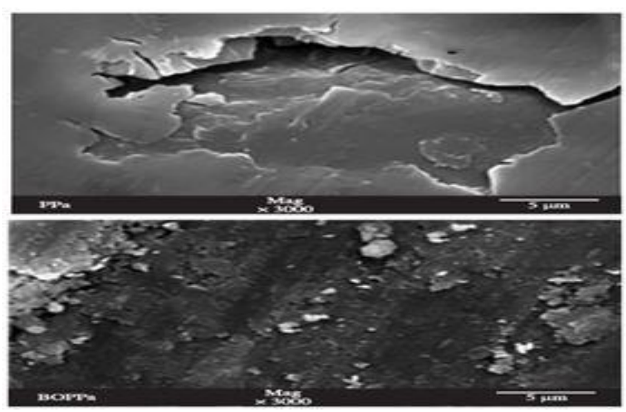
Introduction

The versatility of polymeric materials has prompted the use of such materials in the construction and design of a wide array of equipment. However, despite their structural versatility, the deterioration of these materials is their main undoing. When used as insulators, the contamination of the surface by particles from the environment which leads to surface tracking is one of the major problems. In damp conditions, the formation of biofilm on the surface can also lead to the weakening of the structural integrity and its eventual degradation [1].

Some of the factors that are determinants in the biodegradation of polymers are the structure and composition of the polymeric material. Research shows that despite having a common structure, the type of the variation of the chain and components will either reduce or increase the rate of biodegradation. A polymer can include a variety of carbon blends, resin, and plasticizers within its complex structure. However, in most circumstance, track formation is not necessary needed for graphite formation. Other factors include the melting temperature and the crystalline nature of the surface of the polymers. Additionally, environmental factors also play a role in the degradation process. It looks at the processes that are involved in the same and the factors that amplify the biodegradation process as shown in Figure 1, (a,b), and 2 [5]. Figure 1,(a) shows the micrographic picture of samples of polymeric insulators surface before and after biodegradation, and Figure 1,(b) is a cross-section of power cables with polymeric insulators beginning to weather due to the formation of biofilms [2]. On its part, Figure 2 shows the ejection of polymer molecules from the surface of the insulators after hydrolysis.

As a source of carbon, these materials can be broken down by the enzymes secreted by a heterotrophic organism to produce food [3]. This normally happens when the material is subjected to certain conditions and the enzymes that weaken and breaks down their structure. The enzymes are produced by naturally occurring organisms which have the capacity to weaken the structural integrity of carbon materials. It is noted that heterotrophic organism can produce enzymes that have the ability to interfere with the structural integrity of both natural and synthetic material that contains carbon. This work examines the processes involved in the degradation of the polymeric materials used as insulators. It highlights the enzymes involved at each stage of the degradation and the factors that contribute to the enhancement of the process.

Besides, it is rather difficult to predict degradation mechanisms by just inspecting the molecular stereochemistry. The degradation of polymeric insulators is one factor that affects the performance of the insulators. One of these forms of degradation is biodegradation. The environment is usually contaminated thereby presenting a significant threat to the efficient operation of polymeric insulators. For instance, in damp conditions, the formation of biofilm on the surface can result in the weakening of the structural integrity and its eventual degradation [4].



(a) (b)

Figure 1. Micrographic picture of samples of polymeric insulators surface before and after biodegradation

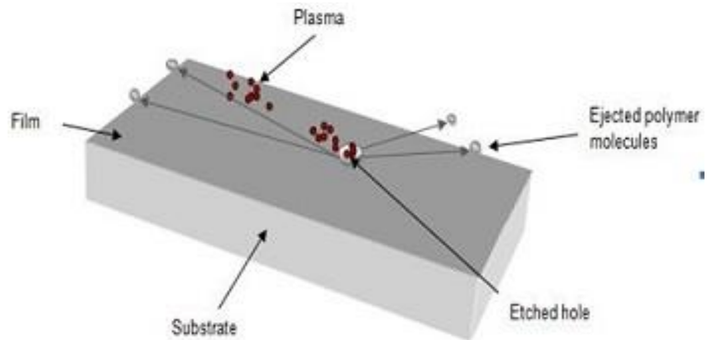


Figure 2. Ejection of polymer molecules from the surface of the insulators after hydrolysis

Formation of Biofilms

A biofilm is regarded as any type of microorganisms whereby cells stick together and in most circumstances these cells adhere to a surface. These cells that have stuck together are frequently characterized by a self-produced matrix of extracellular polymeric substance (EPS). Biofilms can exist as a single species or a group of species. However, in most scenarios, biofilms are not only bacteria, but they can also comprise of other living things in the form of algae and fungi. The fact that a biofilm can be adapted internally to the environmental conditions by its inhabitants makes it one of the factors affecting polymeric insulators.

Heterotrophic organisms such as fungi and bacteria occur naturally in the environment. When these organisms come into contact with a wet surface containing carbon, they adhere to this surface and form a conglomerate of extracellular biopolymers that is of various structural forms. The system formed appears like a film on a surface and the inhabitants can adapt or survive in the internal environmental conditions [6]. In most cases, the formation of the biofilm is in response to the nutritional cues of the inhabitants. In this regard, the secretion of enzymes is jointly done under the dome of the biofilm by the microorganisms that live in it. Figure 3 represents the biofilm formed by Staphylococcus aureus in a tube [6].

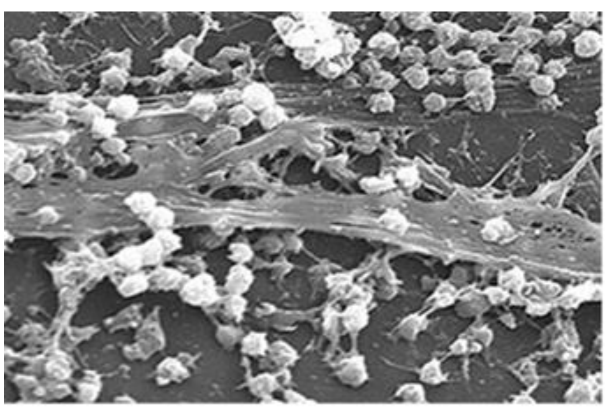


Figure 3. An image of staphylococcus aureus viewed under a microscope

Biodegradation of Polymers by Biofilms

Polymeric insulators are a potential source of carbon despite being synthetically manufactured. This fact implies that organisms that decompose carbon will be attracted to a biofilm on its surface and try to digest the material to gain food. In this case, the loss of structural integrity of the polymers will be instigated by the natural chemical process of enzyme action. The degradation occurs in four phases or stages discussed below.

Aerobic Stage

The buildup of moisture on the surface of the polymer aided by the matrix of the biofilm is the initial process at this stage. The microbes then secrete enzymes that will aid the initial breakdown of the structure of the polymer. Under normal conditions, the absorption of water by plastics and polymers is very low. However, the enzymes will increase the rate of reaction at this stage and allow the polymer to absorb water and swell [7]. It is recorded that enzymes have the capacity to increase the rate of reaction by between 10^6-10^{20} with no defective products to the system being produced. It is this high rate of reaction that will force the polymer to swell and break or have weaker bonds [7].

The enzymes produced by the microbes have a high molecular weight as they contain hydrophilic groups such as $-NH_2$, -OH and COOH [8]. They are proteins that are very strong and can attack and destroy anything. The effect of their reaction with the polymers is that they will create molecular holes that give a platform for microbes to grow. This process consumes oxygen and CO_2. These are the main product of the process. In this hydrolysis process, oxygen is consumed within the biofilm to almost zero oxygen levels. The microorganisms also eat some of the particles of the polymer through enzyme action.

Anaerobic, Non-Methanogenic Phase

This stage begins with the oxygen leveling within the biofilm have reduced substantially. The breakdown of the particles of the polymers to monomers by the enzymes leads to increased swelling due to more moisture being absorbed. The new particles of monomers generated cause quorum sensing which then excites the organisms to consume further the polymer chain. The underlying layers of the polymer are also attacked leading to further colonization of the material.

This stage is also known as acidogenesis [9]. The monomers that are produced are converted to fatty acids. There is a high rate of CO_2 production in this conversion of the monomers [10].

Acetogenesis

In this phase, the formation of large spaces between the molecules of the polymer continues. The action of the biofilm enzymes also continues in a process that has limited or no supply of oxygen. The colony of the microorganisms continues to increase and eat away the particles of the polymers breaking them into monomers while the fatty acids that are produced are also eaten away. The enzymes convert the fatty acids into carbon dioxide, acetic acid, and hydrogen. In this stage, the level of carbon dioxide is reduced, but there are high amounts of hydrogen that are emitted by the enzymes action [11].

Anaerobic, Methanogenic Steady Phase

This is the final phase of the decomposition of the polymers. As the chemicals produced to keep reacting with the particles on the surface of the polymers, the acetates that were initially produced are turned into carbon dioxide and methane. This process is known as methanogenesis and hydrogen is consumed here [12]. The final products are organic material that contains a variety of soil-like components called humus. This stage is called mineralization since ammonium and other nutrients that are essential for the growth of plants are produced. This is shown in Figure 4 below [19].

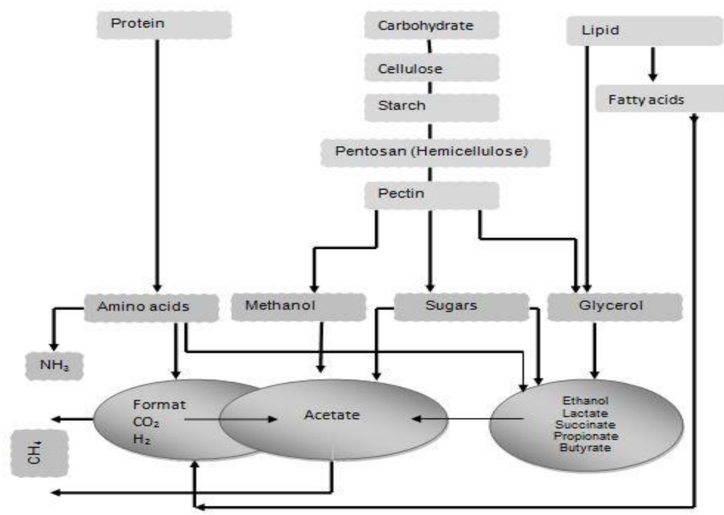


Figure. 4. The anaerobic breakdown of biopolymers to give rise to methane

Some studies opine that the process of biodegradation does not progress from hydrolysis to mineralization direct. For some polymeric compounds used in insulators, the process of deterioration can end at any stage. Thus, the degradation is categorized as either bio-deterioration, bio-fragmentation, assimilation or mineralization. As shown in the polymeric degradation process above, mineralization is the complete destruction of the molecules of the polymers into metabolites such as CO_2, CH_4, H_2O and N_2 [13].

Bio-deterioration, on the other hand, is the definition of the action of microbes that result in the loss of structural integrity of the polymer. This can be achieved through the process of hydrolysis that causes the surface of the polymeric insulators to take in water and swell. The result is the creation of holes and cracks on the surface of the polymer that makes it lose its structural integrity.

The actions of ectoenzymes and free radicals produced by biofilms also cleave the polymeric plastics. The cleaving of the bonds that form the polymeric material is enhanced or fully caused by a chain of reactions instigated by the enzymes. The polymeric bonds are broken down to form monomers, or oligomers [12]. This leaves the material susceptible to other forms of degradation that can be mechanical or chemical processes.

Further degradation can be caused by the absorption and transportation of the broken down particles in the cytoplasm for microbes' metabolic processes. This implies that the breakdown of the polymers can stop at this stage if the type of organism cannot have its cytoplasm absorb or utilize the monomers in its metabolic processes. Therefore, the process of biodegradation of polymeric insulators still happens in 4 phases that are similar to the initial four stages of polymer degradation discussed previously. The stages are represented in Figure 5 below [13].

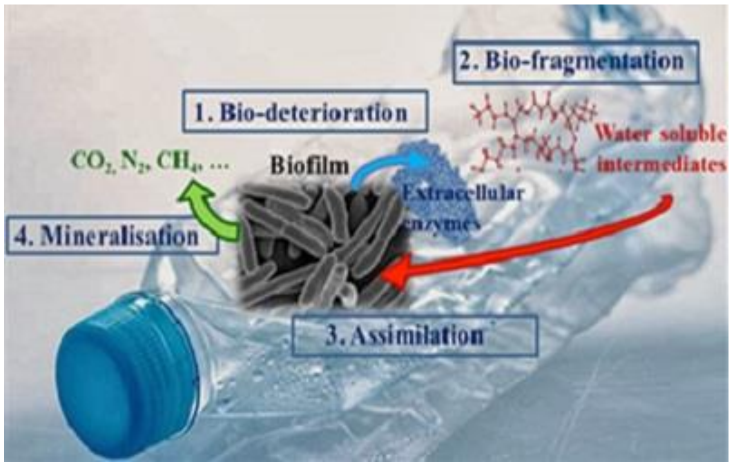


Figure 5. Illustration of the 4 stages of polymeric materials

Factors Enhancing the Polymer Degradation

As discussed above, the process of weakening of structural integrity of polymers begins with hydrolysis instigated by the action of the enzymes acting on the metabolic products of microbes such as CH_4, CO_2, and H_20. This process takes place with the aid of several environmental factors that are discussed in the subheadings below.

Composition of the Polymers

Polymers just as the name suggests consists of several component chemicals. This is the reason for the heterogeneous nature of the decomposition of the surface of the polymers described above. In the above process, it is noted that virtually all polymers are biodegradable by virtue of containing carbon despite being synthetic products [14].

A polymer can include a variety of carbon blends, resin, and plasticizers within its complex structure. This composition makes it a potential store of rich minerals for the huge variety of microorganisms that are present in the air. During the process of conversion of the polymer particles to monomers, the composition of the polymer will dictate the speed and chemical components produced. The chemicals produced either react with the enzymes of the microorganism at a different rate or will not be consumed at all.

The process that inhibits the degradation of polymers is called stabilization. The chemical composition of the polymer can lead to its surface stiffening under ultraviolet light. Some formulations of polymers are relatively stable in most environments due to the reaction of the components to the environmental factors. The discoloration of their surface is the worst form of degradation that the polymers can undergo which also limits the ability of a biofilm to form on the surface of the polymer. In Mohan and Krishna [8], the polymer's structural characteristic is the described as a possible determinant in the deterioration process. It

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states that despite the polymers having a similar overall composition, the arrangement of the chains can affect the way each of the degradable components is accessed.

The study also looks at the effect of the molecular weight on the biodegradability of the polymers. It states that the synthetic addition polymers except polyvinyl alcohol are not biodegradable at molecular weights above 1000. This shows that the modification of the structure of the polymers has a significant input on the biodegradability [15].

Crystalline Nature of the Polymer

This is a process associated with the partial alignment of the molecular chains of the polymers. The chains are characterized by folding together and the formation of the ordered regions called lamellae. Upon cooling from the melt, polymers can crystalize. Besides, mechanical stretching or solvent evaporation can result to crystallization of polymers. It is worth noting that crystallization of polymeric insulator can affect its thermal, optimal, mechanical and chemical properties. However, the degree that is associated with the cystallinity of the polymeric insulator is estimated by different analytical methods and most of the time the degree ranges between 10 and 80%.

Another study [16], suggests that the nature of the surface of the polymer will determine the possibility of attack according to this research, the degree of crystallinity of the polymer will affect the rate at which the enzymes can attack the polymer. It states that the enzymes attack prominently in the amorphous region of the polymer than the fine crystalline surface. The argument is that the molecules of the amorphous region are packed in a loose manner, and this gives the enzymes more surface area to attack and break the chain of the polymer.

Melting Temperature

Some studies also indicate that the melting point of a polymer has a relation to the biodegradability of the same insulator. The susceptibility of the polyesters was tested with the enzyme Arrhizus lipase. The Figure 6 below illustrate the results obtained from the experimentation. The experimentation concluded that the higher the melting temperature of the polyesters the less susceptible it was to the effect of the enzyme.

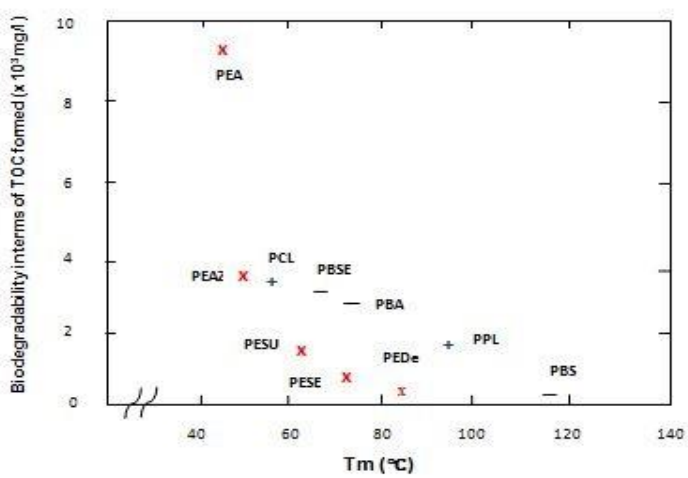

Figure 6. Results obtained from the experimentation

Key: PEA: PCL: PEDe: poly(ethylene decamethylate); polycaprolactone;poly(ethylene adipate); PEAz: poly(ethylene azelate); PESu: poly(ethylene suberate); PESE: poly(ethylene sebacate); PBS: poly(butylene succinate); PBA: poly(butylene adipate); PBSE: poly(butylene sebacate); PPL: polypropiolactone. Tm- melting temperature.

Enzymes and Enzyme Action

The enzymes produced by the microbes are the main reason for the deterioration of the surface of polymeric insulators. Most enzymes have a complex structure that is similar to those found in the polymers and have the capacity to break down polymers into monomers or dimers. In the process of breaking down the polymers, the enzymes can also lead to the absorption of some complex structured polymers into the cytoplasm of the microorganism [17].

In this study, three bacterial strains that can assimilate acrylic trimmer as carbon are studied. The bacterium was found to secrete enzymes that could allow it to assimilate the trimmer and dimmer. As compared to the polymer component of the plastics to be consumed, the results showed that one molecule of the polymers was destroyed for every 120 particles of the monomers or trimmer.

Mohan and Krishna [8] also agrees that the rate of polymer degradation is affected by the specificity of the enzyme availability on the surface and the precise nature of the enzyme to the polymer. It demonstrates that enzyme action on the surface of the polymers can either occur by single displacement or double displacement. Therefore, if a polymer can only be degraded through a single displacement mechanism, then it would be difficult for organisms that produce double displacement reaction enzymes to break their surfaces.

Some studies also describe other factors that support the action of the enzyme, such as environmental temperatures and the availability of moisture, as affecting the rate of degradation of the polymeric insulators [18]-[19]. Research shows that prevailing environmental conditions can either support or destroy the biofilms and the enzymes produced. Therefore, these environmental factors also contribute to the rate of polymeric insulator degradation by microbes.

Conclusion

Polymers provide versatile material for several industrial applications. Despite the high level of versatility, the material is still susceptible to some level of degradation. In electrical insulation, the most common challenges are surface tracking chemical and bio-degradation. In this article, the process of biodegradation has been examined with its mechanisms and factors that promote its occurrence.

Despite these many benefits of the polymeric insulators, there are still mechanical, electrical and environmental conditions that affect the polymeric insulators. Environmental factors such as Ultraviolet light, wind, fog, ozone, high-temperature, humidity and inorganic pollution still affect the polymeric insulators. These factors either lead to surface tracking or aid the aging of the polymeric insulators. It is important that proper management is undertaken for polymeric insulators. The main advantages of any type of insulators are related to the weight and performance in adverse weather. The more protected the insulator the higher its ability to perform.

The process of biodegradation through biofilms begins by the microorganism-adhering to the surface of the polymeric insulators and forming a network or matrix of interconnected extracellular organisms. This network then secretes enzymes that have the ability to force hydrolysis on the surface of the polymer breaking it down and establishing further growth. As for the growth progresses, the polymers are broken down to monomers and subsequently end up as metabolites for the microbes. These are a combination of processes that leads to the breakdown of the structural integrity of the polymeric insulators. The process is affected by the chemical composition and structure of the polymers, environmental factors and the molecular weight of the polymeric material used in insulation. Despite the demand and the importance of polymeric insulators globally, the way they are maintained will determine their ability to perform effectively.

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