

A REVIEW OF THE IMPLICATIONS OF POLYETHYLENE PLASTICS WHEN UTILIZED AS CHEMICAL STORAGE TANKS.

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Abstract

Many studies have been conducted to investigate the impact or influence of polyethylene (PE) plastic when used as chemical liquid storage. Herein, this literature addresses the factors that contribute to the degradation of chemical storage tanks as a result of PE plastics and how they can be mitigated. This is achieved by reviewing and discussing the significant properties of High-density polyethylene (HDPE), which have been reported to degrade the chemicals stored in these storage tanks. The method of cross-linking the PE was reviewed with its preceding processes that involve chemical and physical processes. The influence of each agent on the resulting properties is discussed in detail including the effect of cross-linking degree. These methods were found to be significant in improving some of the properties of HDPE to better store chemical substances. Nonetheless, it was established that the main concern of PE plastics is environmental stress cracking (ESC), which causes unexpected cracks within the HDPE storage tanks, thus degrading the substance contained. The currently used method or test (bent-strip) to determine the resistance of PE to ESC and techniques used to monitor it were reviewed and discussed in detail. Consequently, the literature suggests that the relationship between the density of PE and its ESC susceptibility has been found to be significant. However, research has shown that relying solely on density as a predictor of ESC in PE when exposed to chemical substances is insufficient, and further studies should be conducted to investigate other parameters that contribute to ESC in PE. In addition, the review suggests that future research should focus on studying ESC resistance of newly developed Nano-filled PE composites or biodegradable PE variants, as these are future materials for storing chemical substances conveniently.

Keywords: Polyethylene, chemical, degradation, high-density polyethylene, environmental stress cracking, storage tank

1 Introduction

Plastics, also known as polymers, have become a major class of engineering materials. Polymers are substances whose molecules have high molar masses and are composed of a relatively large number of repeating units. There are both naturally occurring and synthetic

polymers [1, 2]. They offer several beneficial properties (mechanical, physical, chemical, and optical) when utilised as chemical storage tanks for industrial applications [2]. In contrast to metals, polymers are generally characterised by lower density, strength, elastic modulus, thermal and electrical conductivity, high corrosion resistance, and cost [2, 3, 4]. Thus, this is the reason for the rapid increase in plastic processing on an annual basis. In addition, they are the preferred materials over metals nowadays for numerous industrial applications. However, their setback to date is that they are a waste that affects the environment if they are no longer in use. Nonetheless, there have been developments over the years that aim to rectify this issue, with recycling being the most notable one.

2 History of polyethylene

Many plastic materials fall under the polymer tree. However, for this review study, polyethene (PE) plastics will be discussed. This is due to the growing demand for this material for manufacturing chemical storage tanks [3, 5, 6]. PE have a remarkable history spanning over a century. In 1898, German chemist Hans von Pechmann first synthesized a waxy substance called polyethylene, but it remained largely unnoticed. It wasn't until the 1930s that polyethylene's commercial potential was realized when scientists Reginald Gibson and Eric Fawcett at Imperial Chemical Industries (ICI) in the UK developed a more practical method for producing it [7,8]. This led to the introduction of low-density polyethylene (LDPE) in the 1940s, initially used for insulation and packaging materials during World War II. In the late 1950s, Karl Ziegler and Giulio Natta developed high-density polyethylene (HDPE), bringing enhanced strength and stiffness to the material, enabling applications such as pipes and containers [9,10]. Since then, various forms of PE, including linear low-density polyethylene (LLDPE), have been developed, and it has become one of the most widely used plastics in the world, revolutionizing industries such as packaging, agriculture, automotive, and more with its versatility and affordability.

3 Production methods

There are three primary production methods for PE: high-pressure polymerization, low-pressure polymerization, and advanced or metallocene catalysis. High-pressure polymerization, also known as the free-radical polymerization method, is the oldest and simplest technique. It involves subjecting ethylene gas to high pressures ranging from 1000 to 3000 atmospheres, along with a catalyst such as oxygen or a peroxide initiator [11,12,13]. This process produces low-density polyethylene (LDPE) with branched polymer chains, resulting in a material with excellent flexibility and resilience. Low-pressure polymerization, also called the Ziegler-Natta polymerization method, is a more controlled and efficient process [12,13]. It utilizes transition metal-based catalysts, typically titanium or chromium compounds, supported on a specialty carrier material. The catalyst activates the ethylene monomers and allows for precise control over the polymerization process, resulting in high-density polyethylene (HDPE) with densely packed linear polymer chains. This method offers a broader range of properties, including increased strength and stiffness and can be seen in Figure 1 [14,15].



Figure 1: (a) Simple molecular structure of polyethylene includes no ionic bonds or polar groups typical for other polymers. (b) Branched structure of LDPE molecules compared to the linear-chain structure typical for HDPE and UHMWPE (c) [14].

Advanced or metallocene-catalyzed polymerization is a newer and highly specialized technique that employs metallocene catalysts to produce polymers with unique molecular structures [16]. Metallocene catalysts enable precise control of the polymer chain structure, resulting in enhanced properties such as superior clarity, toughness, and thermal resistance [16, 17, 18]. This method has given rise to specialty polyethylene variants like linear low-density polyethylene (LLDPE) and ultra-high-molecular-weight polyethylene (UHMWPE), which find specific applications in industries such as films, packaging, and medical devices. These production methods have contributed to the wide range of PE grades available today, each offering distinct characteristics to suit various applications and industries.

4 Worldwide usage volume

PE is one of the most widely used plastics globally, and its usage volume has continued to rise significantly. On the other hand, it is worth knowing the production rate of PE over the years. The production rate of PE can vary year by year due to factors such as global economic conditions, shifts in demand, and technological advancements. Nonetheless, previous studies have suggested that the global production rate of PE has significantly grown over the years [19, 20, 21, 22]. Figure 2 depicts the worldwide plastic production statistics over the past decades.

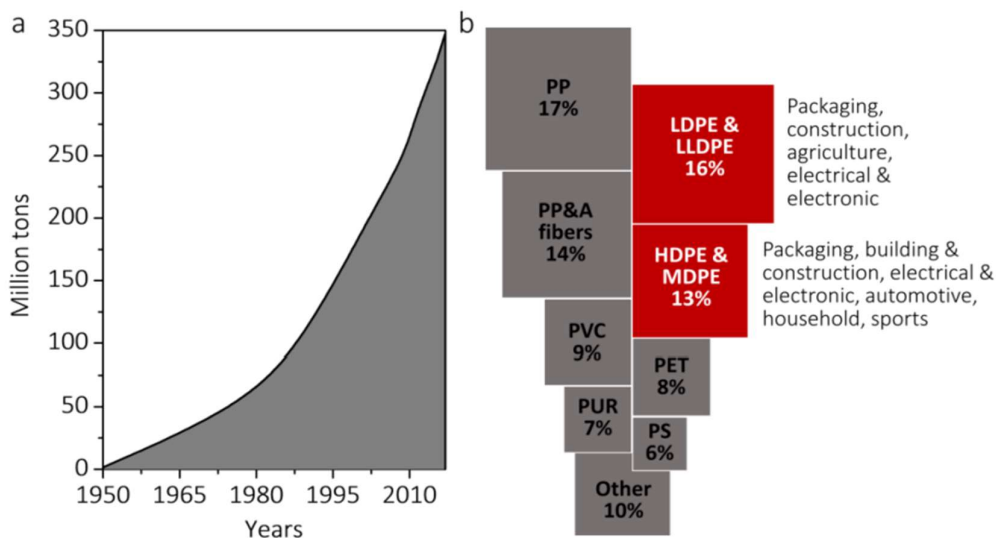


Figure 2: Worldwide plastic production statistics. (a) In 2017, around 350 million tons of plastic were produced worldwide. (b) Polyethylene comprises nearly 30% of all the plastic

production, owing to its widespread use across many industries and consumer markets. (PP=polypropylene, PP&A=acrylic, PVC=polyvinylchloride, PET=polyethylene terephthalate (polyester), PUR=polyurethane, PS=polystyrene) [19].

On the other hand, the worldwide usage volume of PE has been steadily increasing over the years, according to available data [20]. In 2022, the global production of PE reached approximately 110.13 million metric tons. Research suggests that by 2030, the global market volume of polyethylene is expected to rise to around 135.08 million metric tons [21, 22, 23]. This growth can be attributed to its widespread applications in various industries. The packaging sector is one of the largest consumers of PE, with uses ranging from flexible films for food packaging to rigid containers for beverages and personal care products. Additionally, the construction industry utilizes polyethylene pipes, fittings, and geomembranes for infrastructure projects. The automotive sector relies on PE for manufacturing components such as fuel tanks, bumpers, and interior parts due to its light weight and durability. Agriculture utilizes polyethylene films for greenhouse applications, irrigation systems, and mulching. Geographically, Asia-Pacific remains the dominant region in terms of polyethylene usage [24]. Countries like China and India have seen rapid growth in their consumption due to industrialization and population expansion. North America and Europe also contribute significantly to the global usage volume of polyethylene, driven by their well-established manufacturing sectors [24, 25]. Several factors contribute to the continued growth in PE consumption, including its versatility, low cost, ease of processing, and increasing demand from emerging economies. As a result, the global usage volume of PE is expected to keep expanding in the coming years [26].

According to the best knowledge of the researcher and based on the current literature, the present study is a novelty that seeks to evaluate the impact of PE plastics when used as a chemical storage tank. The study analyses the possible methods (cross-linking) that can be used to avoid environmental stress cracking (ESC) on PE. This is achieved by thoroughly evaluating the influence of each agent on the resulting properties, the effect of cross-linking degree, the methods used to test ESC on PE, and the monitoring techniques that are used.

5 High-density polyethylene

PE is undoubtedly the most popular plastic material in the world. It is a commodity material that statistically accounts for about 70% of the plastic family [27, 28]. PE is thermoplastic in nature, so it can be reprocessed repeatedly. This is why it is easily available at a relatively low cost and can be easily processed [29]. Moreover, it can be utilised for diverse industrial applications. PE is often classified by the density it contains. Therefore, there is low-density polyethylene (LDPE) ($0.910 < \text{density} < 0.925$), Medium-Density Polyethylene (MDPE) ($0.926 < \text{density} < 0.940$), and High-Density Polyethylene (HDPE) [30]. Consequently, changing the density of the PE will alter its properties. The effect of changes in density, melt index, and molecular weight distribution on the properties of PE. Fairbrother et al. [31] investigated the effects of temperature and light intensity on photodegradation of HDPE

HDPE is frequently employed in the fabrication of chemical or liquid storage tanks owing to its ability to generate a seamless finished product that exhibits enhanced strength and resistance to corrosion [32, 33]. HDPE is a thermoplastic polymer consisting primarily of carbon and

hydrogen atoms that are chemically bonded to create a high molecular weight substance, as depicted in Figure 3 [34]. The conversion of methane gas to ethylene is followed by a subsequent conversion to PE with the application of heat and pressure. The length of the polymer chain can range from 500,000 to 1,000,000 carbon units. According to previous research [35, 36], an increase in the length of the primary chain is directly proportional to a higher count of atoms. As anticipated, the characteristics of HDPE or any plastic substance are contingent upon the configuration of the molecular chains.

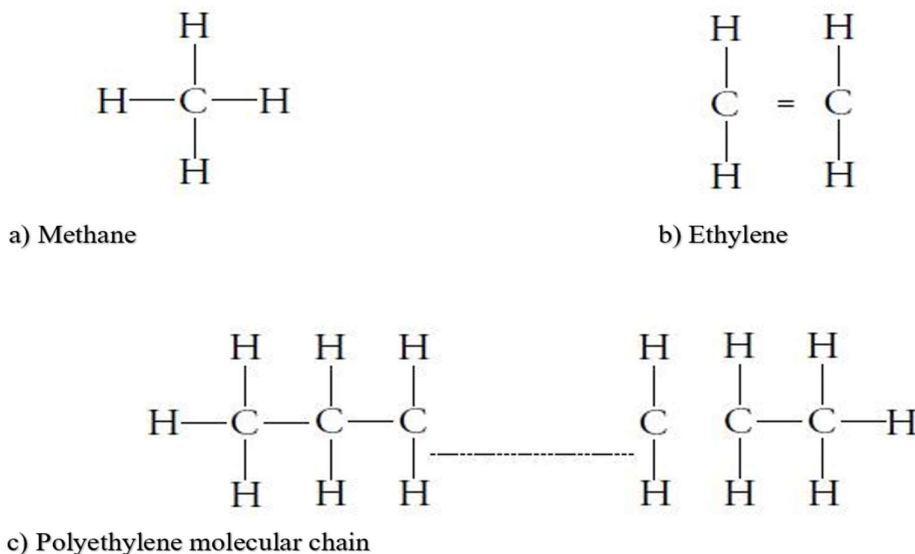


Figure 3. Methane gas (a), ethylene (b) and polyethylene (c) [34].

HDPE plastic is superior to other materials and alternatives due to the extensive benefits it presents in all applications whether it be residential, commercial or industrial. For the present review, HDPE is of importance when it is utilized as a chemical storage tank in several chemical industries as can be seen in Figure 4. However, it's important to note that while HDPE is highly resistant to many chemicals, there may be specific substances or conditions that could affect its performance. It is important to consult chemical compatibility charts, follow proper storage guidelines, and consider any specific requirements or regulations related to the chemicals being stored. Additionally, the design, construction, and installation of the HDPE tank should comply with relevant industry standards and local regulations to ensure safe and effective chemical storage.

HDPE is commonly used for manufacturing of chemical storage tanks due to several advantages and benefits it offers when compared to other types of PE such as LDPE, LLDPE and MDPE. These are discussed in detail in Table 1.



Figure 4: HDPE chemical storage tanks used in various chemical processing industries [36].

Table 1: Comparisons of various polyethylene materials [37].

Properties	HDPE	LDPE	LLDPE	MDPE
Density	High	Low	Low	Medium
Strength	High	Low	Low	Medium
Flexibility	Rigid	Flexible	Flexible	Semi-flexible
Stiffness	High	Low	Low	Medium
Chemical resistance	Excellent	Good	Good	Good
UV resistance	Excellent	Poor	Good	Good
Moisture Resistance	Excellent	Good	Good	Good
Impact Resistance	Excellent	Poor	Good	Good
Environmentally Friendly	Recyclable	Recyclable	Recyclable	Recyclable

Based on Table 1, it can be seen that HDPE has a higher density, providing it with superior strength, rigidity, and impact resistance. It exhibits excellent chemical resistance, making it suitable for applications involving chemicals. HDPE also possesses excellent UV and moisture resistance, making it ideal for outdoor and moisture-prone environments. Additionally, HDPE is environmentally friendly as it is recyclable, contributing to sustainable practices [38]. Overall, HDPE outperforms LDPE, LLDPE, and MDPE in various key aspects, making it a preferred choice in many applications.

6 Cross-linked polyethylene (PEX)

Many researchers have been making efforts to obtain a PE with specific chemical, mechanical, and thermal characteristics for the fabrication of complex-shaped products or for use in adverse environmental conditions [39, 40]. In general, plastic is a light and weak substance that easily

melts when exposed to heat. However, altering the carbon atoms within the structure changes this perspective. To be precise, cross-linking the carbon atoms within the structure usually transforms such material into a superior material that may be resistant to temperature, pressure, and corrosion, and that can be used in a variety of applications [41]. Crosslinking is known as a process in which carbon atoms of the same or different polyethylene chains are joined together to form a three-dimensional network structure [42, 43].

The crosslinking technique was first discovered in the late 1960s by the European scientist known as Engel [44]. The introduction of cross-linked polyethylene (PEX) was another milestone in the plastic era. As a consequence, when PE is cross-linked, it is advantageously employed in the manufacturing of storage facilities due to the advanced resulting properties. The fundamental way to enhance material properties such as impact strength, chemical resistance, and thermal characteristics is via cross-linking [45]. Cross-linking will, however, change the nature of the polymer from thermoplastic to thermosetting polymer, thus yielding a non-melting and more durable polymer matrix [46, 47]. Crosslinking is easily achieved in branched polymers. With the branched HDPE, it is convenient to crosslink the polymer. However, this is a long and tiring process as compared to LDPE. Since HDPE has a linear molecular structure, crosslinking this type of polymer requires special attention as compared to LDPE. Figures 5 and 6 show the process of branching HDPE and LDPE, respectively.

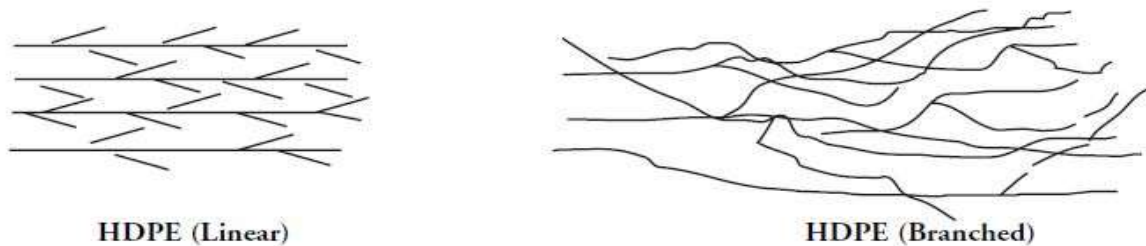


Figure 5: Linear and branched HDPE [46].

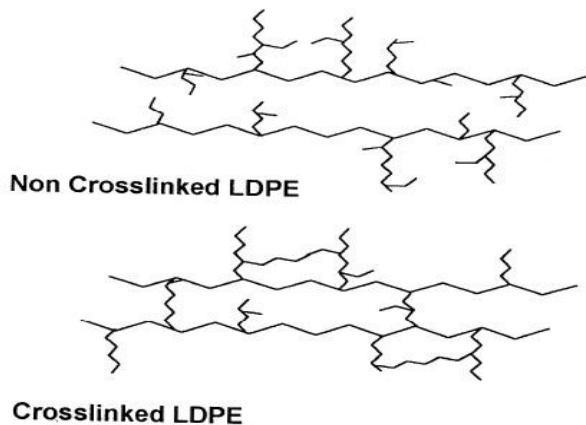


Figure 6: Crosslinked and non-crosslinked LDPE [46].

Over the past decades, several crosslinking methods have been developed. However, to date, two tested methods have been used to crosslink polymers: chemical and radiation (physical) methods [47, 48]. These two methods are unique in their own way and are often utilized for a

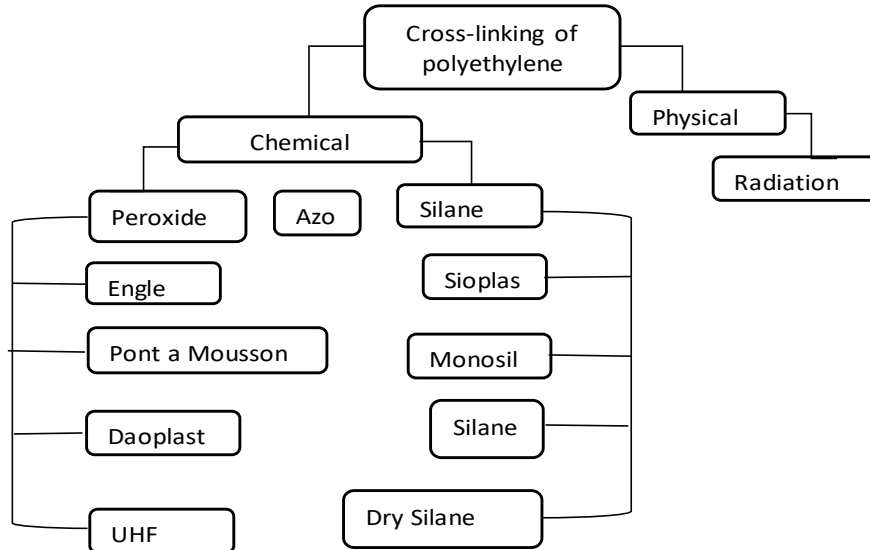


Figure 7: Methods available for crosslinking PE [49].

specific purpose. They usually depend on the state (molten or solid) of the polymer during crosslinking and the type of activator used to promote crosslinking [47, 49]. Figure 7 illustrates the available crosslinked methods in detail, as discussed above.

7 Chemical processes

The method described is widely employed for the purpose of crosslinking polymers. In order to achieve the desired outcome of the approach, it is necessary to employ a chemical agent, typically peroxide or silane, to effectively activate the bonds within the polymer chain. Consequently, this process is commonly referred to as a chemical process [50, 51]. Crosslinking occurs by the formation of direct carbon-to-carbon bonds during the chemical process. One such solution could involve the utilisation of chemical bridges that establish connections between different polyethylene molecules (50).

In recent years, most researchers have been interested in knowing the crosslinking method that yields quality thermoplastic. The recent relevant literature suggests that the intensity of crosslinking in thermoplastic resin usually varies with the crosslinking process. Chemical crosslinking using peroxide significantly results in the highest and most uniform degree of crosslinking as compared to the radiation process [52, 53]. Tamboli et al. [54] experimentally investigated the difference in the degree of crosslinking polymers using chemical and radiation processes. The outcome was that radiation crosslinking yields a degree of crosslinking between 34 and 75%. In the chemical crosslinking method, peroxide gives a much higher degree of crosslinking (up to 90%), while silane-based crosslinking can have a 45-70% degree of crosslinking.

8 Peroxide processes

The procedure of peroxide crosslinking has been employed for over four decades and is the predominant method of crosslinking for thermoplastic materials, particularly polyethylene. The present technique employs organic peroxide as the initiator. Typically, an unaltered form of an organic peroxide is employed in the majority of instances [55]. It is vital to acknowledge that this phenomenon exclusively transpires when the thermoplastic material is in a liquefied state. Moreover, the aforementioned process can be described as a carbonaceous chemical reaction involving a minimum of two oxygen atoms that are covalently bound together, forming a molecular entity denoted as (-O-O-). The formula in question is the generic formula.



Where R^1 and R^2 values can be aryl, alkyl, or acyl groups, and O is the two oxygen atoms that are bonded together. The alkyl peroxides significantly produce the most reactive free radicals; thus, they are the most commonly used peroxides for crosslinking [56]. Figure 8 shows the entire schematic representation of crosslinking polyethene using the peroxide substance. The peroxide process has the advantage of producing products with high thermal stability due to the C-C bonds; however, this is achieved at relatively high costs [57].

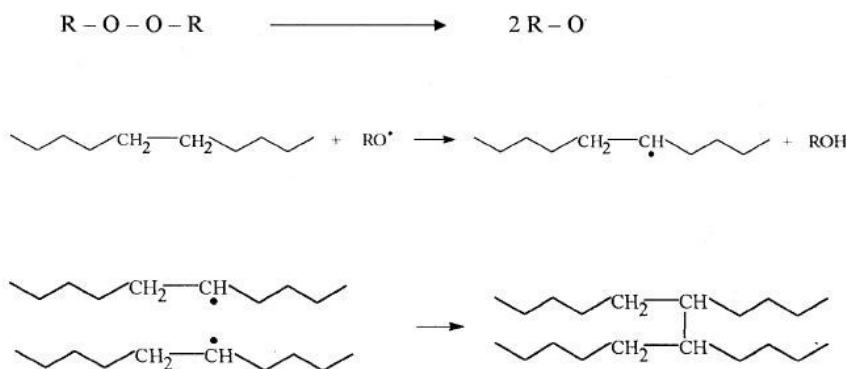


Figure 8: Process of crosslinking using the organic peroxide as the initiator [56].

9 Silane process

Silane coupling agents, which react with many chemicals, including polymers, through typical organic chemistry reactions, significantly activate crosslinking, making this process possible. The organ silane molecule critically includes a central silicon atom (Si) bound to two different categories of groups (vinyl and alkoxy), which usually display different reactivity [57, 58, 59]. Both of these groups are vital in the process of cross-linking. The vinyl groups usually allow silane grafting to the PE, and the alkoxy groups generate a three-dimensional network of siloxane linkages in the presence of water or moisture (through condensation or hydrolysis).

In contrast to the peroxide process, the PE is cross-linked in the crystalline state in the silane process. Thus, the use of silanes results in the formation of siloxane (Si-O-Si) bridges, which are less rigid than carbon-to-carbon (C-C) bonds produced in the peroxide process [60]. The

silane process is shown in Figure 9 as a two-step process, starting from the grafting of silane on PE to condensation (cross-linking). At first, silane is grafted on PE, and then condensation takes place, yielding cross-linking. One of the advantages of the silane process is that it can be achieved at room temperature and at a relatively low cost.

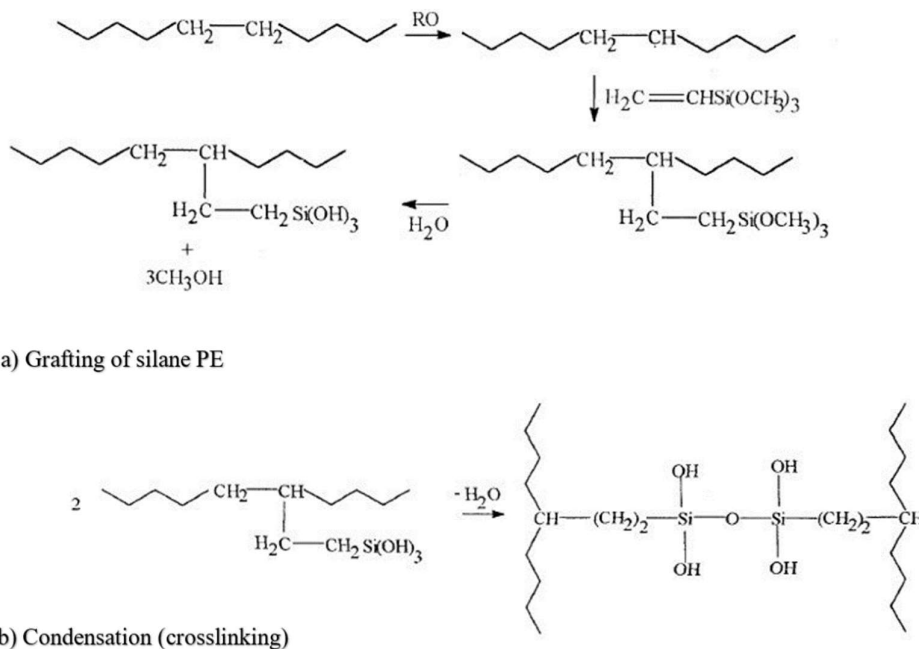


Figure 9: Silane grafted polyethylene crosslinking reaction [60].

10 Radiation (physical) processes

In contrast to chemical processes, radiation processes do not necessarily require the addition of any sort of chemical to the original compound of PE. In the radiation method, crosslinking is significantly achieved by the free radical mechanism, which is generated in a radiation polymer chain using high energy [61]. As a consequence, two or more chains will join together where the free radical is generated. Figure 10 shows the schematic process of crosslinking PE by radiation.

The involvement of high-energy radiation on polymeric materials can critically produce crosslinking or cause a degradation in the main chain, which is termed 'scission' [62, 63]. In this way, both chain scission and crosslinking occur simultaneously and competitively. However, the dominance of one or the other may significantly depend upon several factors, such as the sensitivity of the polymer to radiation, the irradiation dose, and the polymer radiation environment [61, 62, 63, 64]. To be precise, in the presence of oxygen (O_2), scission is relatively dominant over crosslinking, while in an environment that contains other gases such as nitrogen (N_2), crosslinking is normally dominant [65]. However, the changes and chemical properties of the finished product depend mostly on the efficiency of the crosslinking reaction and its relative ratio with degradation [66].

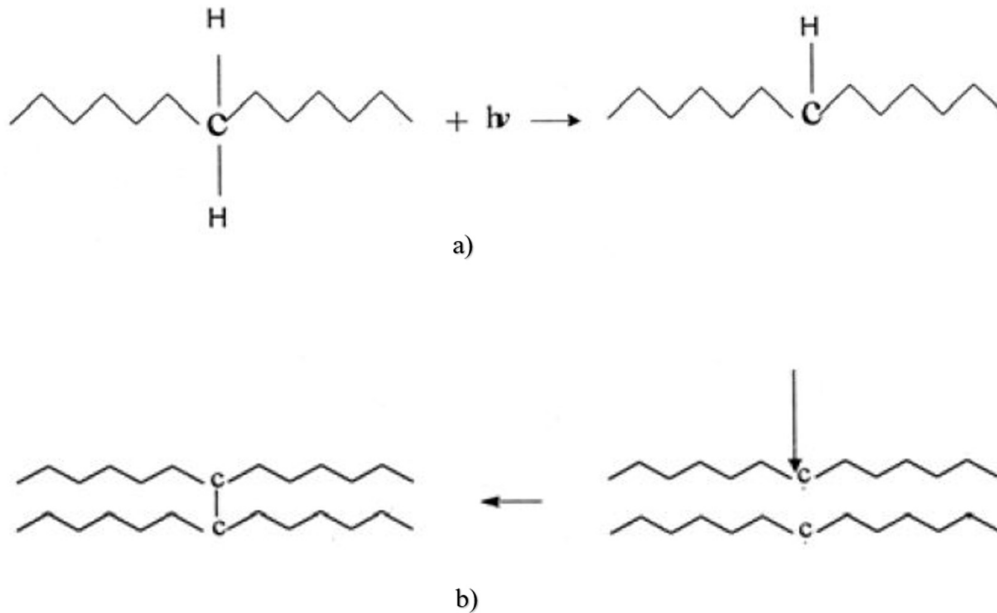


Figure 10: Polyethylene energy radiation (a) and the resulting cross-linked PE (b) [61].

Mathematically, the scission and crosslinking can be related to estimating the probability between them. This probability can be expressed as a ratio that is given by the following equation.

$$\frac{\beta}{\alpha} = \frac{1 G(S)}{2 G(X)} \quad (6)$$

Where: α is a probability of crosslinking of chains after one electron volt of energy absorbed.

β is a probability of chain scission after one electron volt of energy absorbed.

$G(X)$ is a number of crosslinking per 100eV of radiant energy absorbed.

$G(S)$ is a number of scission per 100eV of energy absorbed.

According to several scientists, the bond energy for breaking the C-H bond is typically 364 KJ/mol [67]. Therefore, an electron beam having sufficient energy to break the C-H bond is normally suitable for crosslinking rather than scission [68]. The technique of crosslinking PE by radiation normally involves four main variables.

- The type of radiation and its sources.
- The nature of PE structure to irradiate.
- Mechanisms and theories of reaction.
- The properties of the network formation, especially physical, chemical, and mechanical.

11 Influence of peroxide and silane on resulting properties

The cross-linking of PE can be achieved using various agents, each having its own influence on the resulting properties of the material. The cross-linking agents used in the process are

peroxide and silane as aforementioned and their respective influences are discussed in depth below:

Peroxide Cross-linking Agents: Peroxides such as dicumyl peroxide (DCP) or benzoyl peroxide (BPO) are commonly used for cross-linking polyethylene. When heated, these peroxides decompose and generate free radicals that initiate cross-linking reactions [69]. The influence of peroxide cross-linking agents includes:

- **Increased Cross-linking Density:** Peroxide cross-linking agents can contribute to a higher degree of cross-linking in polyethylene, resulting in improved mechanical properties and thermal stability.
- **Enhanced Heat Resistance:** Cross-linking with peroxides improves the heat resistance of polyethylene, allowing it to withstand higher temperatures without significant degradation.
- **Improved Chemical Resistance:** Cross-linked PE formed with peroxides exhibits improved resistance to chemical degradation, making it more resistant to acids, bases, and solvents [69, 70].

Silane Cross-linking Agents: On the other hand, silane-based cross-linking agents, such as vinyltrimethoxysilane (VTMO) or vinyltriethoxysilane (VTES), are commonly used in a process known as silane grafting as discussed in Section 3.1.2 [70, 71]. Silane cross-linking agents react with moisture in the presence of heat to initiate cross-linking of PE. The influence of silane cross-linking agents includes:

- **Enhanced Bonding with Fillers:** Silane cross-linking agents facilitate bonding between PE and fillers, such as mineral fillers or flame retardants, leading to improved mechanical properties and dimensional stability.
- **Improved Water Resistance:** Cross-linked PE formed with silane agents exhibits enhanced resistance to water absorption, making it suitable for applications requiring water resistance.
- **Adjustable Cross-linking Degree:** The cross-linking degree in silane-cross-linked PE can be controlled by adjusting the amount and type of silane agent used, allowing for flexibility in tailoring the material's properties [70, 71, 72].

The choice of cross-linking agents in PE is influenced by several factors. Key considerations include the intended application and desired properties of the cross-linked PE material, such as strength, durability, and chemical resistance [73]. Compatibility with the PE polymer, both in terms of chemical reactivity and potential impacts on the material's structural integrity, is also crucial. Process requirements, including the chosen cross-linking method and associated conditions, may dictate the selection of appropriate agents [72,73, 74]. Additionally, factors like cost-effectiveness, regulatory compliance, and availability of cross-linking agents can further influence the decision-making process. An informed evaluation of these factors is important in determining the most suitable cross-linking agents for PE.

12 Effects of cross-linking degree

The cross-linking degree in PE refers to the extent to which the polymer chains are connected through chemical bonds, forming a three-dimensional network structure [39, 41, 43]. It can vary depending on the specific application and processing techniques used. It is typically quantified by measuring the gel content of the material. The gel content represents the amount of insoluble, cross-linked polymer in the sample [74]. Moreover, the degree of cross-linking has significant effects on the properties of PE and these are discussed thoroughly below:

1. **Mechanical Strength:** Cross-linking enhances the mechanical strength of PE by providing resistance to deformation under stress. PEX has improved toughness, stiffness, and dimensional stability compared to non-cross-linked polyethylene.
2. **Thermal Stability:** Cross-linking improves the thermal stability of PE. PEX can withstand higher operating temperatures without significant degradation or softening. This makes it suitable for applications that require heat resistance.
3. **Chemical Resistance:** PEX exhibits improved resistance to chemical degradation compared to non-cross-linked polyethylene. It is more resistant to various solvents, acids, and bases, resulting in increased durability and longevity.
4. **Electrical Properties:** Cross-linking affects the electrical properties of polyethylene. PEX has lower dielectric constant and dissipation factor, allowing for better insulation properties and reduced energy loss in electrical applications.
5. **Environmental Stress Cracking Resistance:** PEX possesses superior resistance to environmental stress cracking. It is more capable of withstanding the effects of chemical exposure, such as in corrosive environments or contact with certain fuels or oils [74, 75].

It is important to note that the cross-linking degree needs to be carefully controlled to achieve desired properties. Over-cross-linking may lead to brittleness, while under-cross-linking may limit the improvements in the material's properties. As for PE chemical storages, brittleness of the tank may cause Environmental Stress Crack (ESC), which may then compromise the quality of the product stored in the tank.

13 Environmental Stress Crack Resistance

With liquid materials that contain sensitive chemicals within their composition, under certain temperature and stress conditions, the PE material may begin to crack sooner than expected. It has been experimentally proven that storage tanks containing chemically free liquids do not suffer from cracks as much as those containing chemical liquids [76, 77]. Environmental stress cracking (ESC) is the single biggest cause of failure in engineering plastics as can be seen in Figure 11, accounting for approximately 30% of all failures. ESC occurs due to the combined effect of stress and chemical exposure that results in brittle failure at stresses far lower than those expected in air.

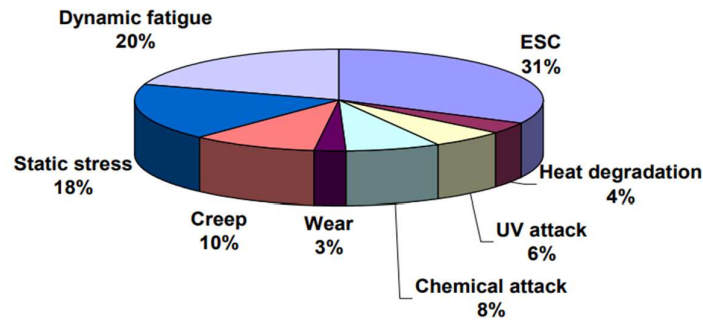


Figure 11: Cause of premature failures that are observed in polymer during service [76].

The chemicals responsible for ESC may be present by design as in chemical storage tanks but are more often present as secondary fluids such as cleaning agents or lubricants [76]. ESC also requires mechanical stress this can be either an applied load or from residual stresses produced during manufacture.

All engineering materials that are suitable for storing liquids containing chemicals are critically evaluated against ECS, as cracking resistance test (mechanical testing) for PE can be seen in Figure 12. For PE, normally the stress-cracking agents are polar materials such as alcohols, detergents, halogens, and aromatics [77]. The property of a material to resist ESC is called environmental stress crack resistance (ESCR) [78]. Researchers have been working on understanding the mechanism of ESCR; however, to date, it is not entirely understood. In most instances, failures of PE polymers that are caused by ESC tend to be due to the development of cracks in the area of tensile stress, which gradually grow and propagate over time (see Figure 12) [79].

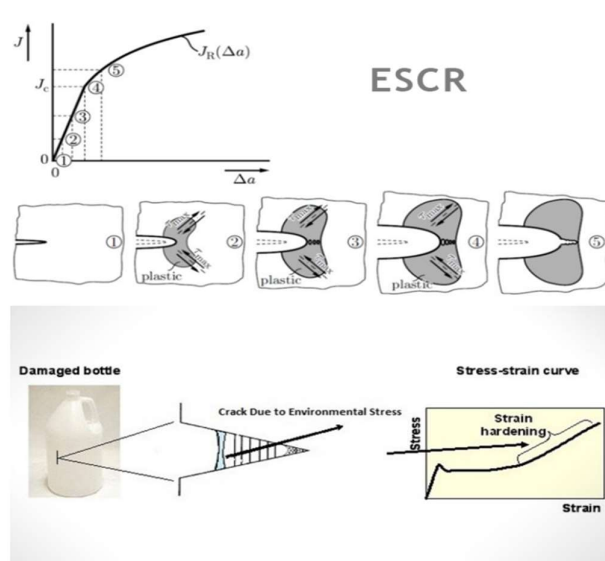


Figure 12: ESCR Environmental Tension Cracking Resistance Test [79].

Over the past years, there have been several efforts made to avoid ESC [80, 81]. Therefore, using an appropriate resin formulation of ESCR materials, designing the geometry appropriately, carefully using the manufacturing controls that prevent the occurrence of severe stress risers, and limiting stresses and strains during the storage facility installation are usually sufficient to avoid ESC [82]. Moreover, PE polymers may be cross-linked to improve their chemical properties and thus resist cracking. With this regard, it is vital to test the compatibility of PE, especially PEX, with various chemical substances to avoid unexpected circumstances. Another alternative is to monitor its ESC on regular basis, using various techniques which are tabulated in Table 2. These techniques offer various ways to assess and monitor environmental stress cracking in PE. It is worth noting that the selection of techniques often depends on factors such as the specific plastic material, the application, and the desired level of analysis and detection [83]. Additionally, a combination of these techniques may provide a more comprehensive evaluation of ESC in plastics.

Table 2: Different techniques at which the development of ESC in a PE can be monitored [83].

Monitoring Technique	Description
Visual inspection	Direct observation of cracks
Liquid Penetration Testing	Applying a colored liquid to assess penetration
Dye Penetration Testing	Applying a fluorescent dye to identify cracks
Microscopy Techniques	-Optical Microscopy -Scanning Electron Microscopy (SEM)
Acoustic Emission Monitoring	Detecting stress-induced cracking using sensors
Fourier Transform Infrared Spectroscopy	Analyzing chemical composition changes
Mechanical Testing	-Tensile Testing -Impact Testing

Research shows that the density of the PE polymer plays a critical role in ESCR [83]. For PE resins of the same molecular weight, the lower the density, the greater the ESCR. The greater the proportion of crystals, the greater the density and brittleness of the resin, which causes rapid crack initiation [84, 85]. However, since the phenomenon of ESC is not fully understood, density alone is inadequate to predict ESCS of PE when exposed to chemical substances.

14 Evaluation of bent-strip test

To date, there are over 40 different ESCR test methods that are used to determine the chemical resistance of various materials. The standard test that is currently used in the PE industry is the bent-strip test [86, 87]. The bent strip test [12] involves clamping the test specimen to a semicircular former to apply a known strain to the specimen. The radius of curvature of former can be varied to induce different levels of stress in the specimen. This strain may be calculated using the following equation:

$$\varepsilon(\%) = \frac{d}{2r+d} \quad (3)$$

where d is the thickness of the specimen and r is the radius of the former. Once the specimen has been strained it is brought quickly in contact with the chemical environment. After an agreed time, the specimen is removed from the apparatus and either visually inspected for crazing or mechanically tested to assess their residual strength. This method is normally used to assess the performance of PE cable insulation but can be cautiously used to evaluate the performance of PEX storage tanks in the presence of chemical substances. The bent-strip test is shown in Figure 13. Where the specimen is immersed in a chemical substance of interest and the time to failure is noted. The results are reported using the notation, where xx is the percentage of samples that have been tested.

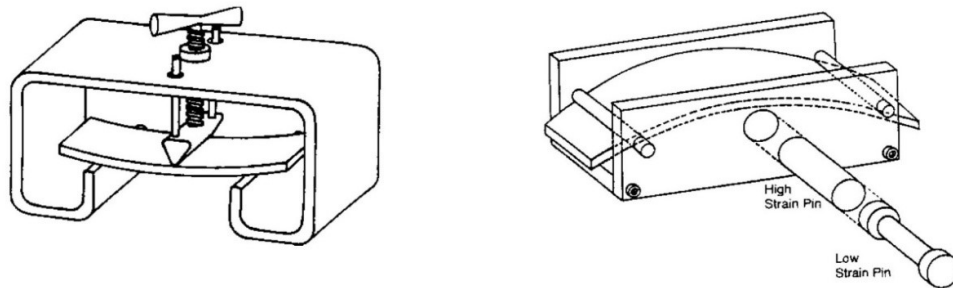


Figure 13: Three-point bending apparatus for testing ESCR under constant strain [87]

One advantage of the bent-strip method is its simplicity and ease of implementation [86]. It requires minimal equipment and can be performed relatively quickly, making it a convenient option for evaluating ESC resistance. Additionally, the method provides a qualitative assessment of the material's performance, indicating whether or not cracking has occurred. However, there are some limitations and considerations to be aware of when using the bent-strip method. Firstly, the results obtained are subjective and rely on visual inspection [87, 88]. This can introduce some level of subjectivity and variability in the interpretation of results. Consequently, quantitative data may be lacking, and direct comparisons between different materials or test conditions can be challenging.

Furthermore, the bent-strip method may not fully simulate the complex and varied conditions that can contribute to ESC in real-world applications. Factors such as temperature, stress levels, duration of exposure, and the presence of different chemicals can significantly impact the material's performance [86, 88]. The simplicity of the bent-strip method may overlook these factors, limiting its ability to accurately predict ESC resistance in diverse environments. To overcome these limitations, it is recommended to complement the bent-strip method with additional testing techniques, such as tensile testing, accelerated aging tests, or exposure to more realistic and specific environmental conditions [89]. This holistic approach provides a more comprehensive assessment of PE's resistance to environmental stress cracking, enhancing the accuracy and reliability of the results.

15 Economical cost

The cost of using PEX can vary depending on various factors such as the application, specific requirements, and market conditions. However, generally speaking, PEX is considered to be a

cost-effective material for many applications. For chemical storage tanks this can vary depending on the tank size, thickness, design, manufacturer, and specific requirements of the application. PEX tanks are often favored for their durability, corrosion resistance, and long service life, which can contribute to cost savings over time [90, 91, 92]. Compared to other materials like steel or fiberglass, PEX tanks are generally more economical due to lower material and installation costs. PEX tanks are lightweight, making them easier and less expensive to transport and install [91].

In terms of material costs, cross-linked PE is typically less expensive than some alternatives, such as HDPE or fiberglass-reinforced plastic (FRP). PEX tanks often require fewer maintenance and repair expenses due to their resistance to chemicals and UV degradation, reducing ongoing costs [93]. It's worth noting that the cost of PEX chemical storage tanks may also depend on the manufacturer and any additional customization requirements for specific applications. Overall, while the upfront cost of PEX chemical storage tanks may vary, they are generally considered an economical choice due to their long-term durability, low maintenance needs, and resistance to chemical degradation [94,95].

16 Conclusion and future recommendations

This article presents a qualitative analysis of the implications associated with the use of polyethylene as a material for chemical storage tanks. The review offers a comprehensive understanding of the fundamental concepts underlying polyethylene plastics and the reasons for their widespread adoption as the preferred material for chemical storage tanks. These reasons include its cost-effectiveness, highly desirable functional properties, and ease of processing. However, the review also acknowledges certain limitations of polyethylene in industrial applications, particularly its potential to become an environmentally harmful waste when no longer in use. The article briefly discusses common methods employed to mitigate this issue, with recycling being one such method. The scope of the review is focused on HDPE, as it is the most commonly used form of polyethylene for storing chemical or liquid substances. The emphasis is placed on the advantageous properties of HDPE and how they can be further optimised to enhance the storage of chemical substances.

The existing literature review has shown that PE has the capability to undergo cross-linking, resulting in the formation of cross-linked polyethylene (PEX). The method described herein is widely acknowledged as an effective means of enhancing the characteristics of PE, contingent upon the intended use. The two fundamental procedures often employed for the cross-linking of PE were comprehensively examined. The transformation from PE to cross-linked polyethylene (PEX) involves a combination of chemical processes, specifically the utilisation of peroxide and silane, as well as a physical process involving radiation. These processes induce reactions and bring about structural modifications in the material. The review demonstrated that in order to achieve the desired functionality of a chemical process, the activation of polymer chain links necessitates the presence of a chemical agent, typically peroxide or silane. In contrast to chemical processes, radiation operations do not require the introduction of any chemical substance into the initial polyethylene complex. The crosslinking process in radiation techniques primarily involves the utilisation of the free radical mechanism, which is initiated within a polymer chain subjected to high energy radiation.

The present review study provides a comprehensive analysis of the Environmental Stress Crack (ESC) phenomenon in polyethylene materials, with a specific focus on its potential implications for the containment of chemical within storage tanks. The Environmental Stress Crack Resistance (ESCR) test method was critically examined and succinctly deliberated over, as it stands as a presently employed technique for assessing the chemical resistance of PE. The relationship between the density of PE and its ESC susceptibility has been found to be significant. Nevertheless, the existing body of literature indicates that there is still a lack of comprehensive understanding regarding the phenomenon of ESC. It has been determined that relying solely on density as a predictor of ESC in PE when exposed to chemical compounds is insufficient.

The study also examined the existing initiatives that have been implemented to mitigate the occurrence of the ESC. Several strategies can be employed to mitigate the occurrence of ESC. These strategies encompass the utilisation of a suitable resin formulation for materials with enhanced ESCR, the appropriate design of the geometry, the meticulous implementation of manufacturing controls to prevent the formation of significant stress risers, and the imposition of limitations on stresses and strains during the installation of storage facilities. By adhering to these measures, ESC can typically be effectively avoided. In conclusion, the review suggests that future research should focus on studying ESC resistance of newly developed Nano-filled PE composites or biodegradable PE variants, as these are future materials for storing chemical substances conveniently.

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