A comparative study between the performances of polypropylene and polyester non-woven geotextiles in landfills

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A comparative study between the performances of polypropylene and polyester non-woven geotextiles in landfills

Une étude comparative entre les performances du polypropylène et de la polyester des géotextiles non-tressé dans des décharges

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ABSTRACT: Leachates originating from landfills are often aggressive and alkaline in nature due to their high pH values. These leachates can percolate into the ground and contaminate groundwater. In order to reduce the environmental hazards associated with landfills, non-woven geotextiles manufactured from polypropylene (PP) and polyester (PET) polymers have been widely utilized as part of the multi-layer barrier system in containment of leachates. With the basic pH value of these leachates, the material properties (mechanical and hydraulic) are prone to chemical attack. This study aims to investigate the effect of chemical attack on the material properties of PP and PET non-woven geotextiles as well as develop a system to categorize the environments suitable to PP and PET non-woven geotextiles. Secondary data acquired from previous studies were used to compare the mechanical performances and hydraulic properties of the non-woven geotextiles. Various chemical environments ranging between acidic, neutral, and alkaline media were identified. Using the mechanical and hydraulic properties of the non-woven geotextiles before and after application, the suitability of the PP and PET non-woven geotextiles was established. PP and PET non-woven geotextiles were then categorized according to their applicability and suitability in different environments and resistance to chemical attack.

RÉSUMÉ: le niveau élevé de PH dans les Lessèches d'origine des décharges les rendent agressives et alkalinique de nature. Ces lessèches peuvent infiltrer la terre et contaminer l'eau en dessous. À fin d'éliminer les risques environnementaux que pose les décharges, des géotextiles non-tressé faites à base de là polypropylène (PP) et du polyester (PET) polymers ont été utilisés fréquemment comme barrière multi-couches pour contrôler l'infiltration des lessechès. Le taux de pH basique de ses lessechès rend leur propriétés matérielles (mécaniques et hydraulique) vulnérable à de attaques chimiques. Cette étude vise à comprendre l'effet de l'attaque chimique sur les propriétés matérielles des géotextiles non-tressé de la PP et du PET et développer un système pour catégoriser les environnements favorables pour les géotextiles non-tressé de la PP et du PET. Des données secondaires acquis des études précédentes étaient utilisées pour comparer les performances des propriétés mécaniques et hydraulique des géotextiles non-tressé. Plusieurs environnements chimiques variant de l'acide au neutre et à l'alcaline étaient identifiés. A l'aide des propriétés mécaniques et hydrauliques des géotextiles non-tressé avant et après l'application, l'aptitude de géo-textiles non-tressé de la PP et du PET était établi. Le résultat de cette étude catégorise les géotextiles non-tressé de la PP et du PET selon leurs applicabilité et leurs aptitudes dans des environnements différents et à leur résistance à des attaques chimiques.

KEYWORDS: polypropylene, polyester, chemical attack, leachates, landfills

1 INTRODUCTION

The annual waste generation in the world rises in proportion to population and urbanization growths. As a result of the lifestyles adopted in the cities, the composition of waste has shifted from organic to multi-consumer waste which ranges from packaging materials to plastic and paper contents.

Landfills are normally the most common methods of disposing the generated waste. Leachates that come from landfills are aggressive and basic in nature due to their recorded high pH values. They have the potential to percolate into the ground and contaminate ground water. In order to minimise groundwater contamination and other environmental hazard associated with landfills, geotextiles have been widely utilized in landfills. Geotextiles may function as a component of the barrier system in the containment of leachates, as a protection layer over geomembranes to prevent damage from surcharge loading, and as a separation layer in drainage and leachate collection layers (International Geosynthetics Society 2018). From numerous studies and research (U.S. Department of the interior Bureau of Reclamation 2012; Zornberg & Thompson 2012; Wiewel & Lamoree 2016), there is an indication of which geotextile material works best in different types of chemical environments although this is not fully validated (Sabiri et al. 2020; Wu et al. 2020). Therefore, there is a need to compare the performances of both types of geotextiles in different chemical environments.

1.1 *Leachate generation*

As rainwater filters through waste placed in a landfill, leachates are produced as a result of the physical, chemical and biological processes occurring within the landfill. Mechanisms such as precipitation, consolidation, surface run-off, or groundwater percolation, and moisture in the waste coupled with biodegradation of organic matter, may also lead to the generation of leachate.

The main features of a landfill are the bottom liner, daily cover, final cap/cover and drainage layer as illustrated in Figure 1. Depending on the potential for leachate generation and size of the landfill, a leachate detection and collection system may be added. The function of the final cover is to reduce the generation of leachate by preventing infiltration of moisture into the landfill. Bottom liners act to contain and prevent the leachate from percolating the ground.

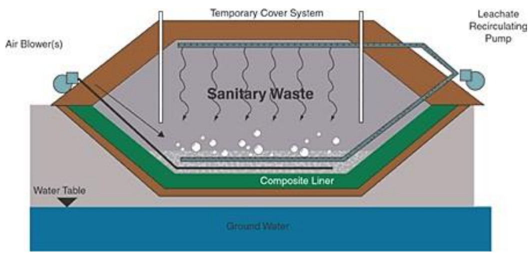

Figure 1. Schematic diagram of a landfill (Aziz 2013).

The first stage during decomposition of waste is the aerobic stage where little or no methane is produced. The transition from aerobic to anaerobic is characterised by the acetogenic stage where organic acids, hydrogen, ammonia and carbon dioxide are produced in large quantities. Nevertheless, methane is not generated in this stage, although the potential of Hydrogen (pH) reduces. Table 1 presents the four stages of landfill biodegradation. The organics and inorganics in the leachate dissolves, resulting in a chemically aggressive leachate with high specific conductance. Within the first year or less, after deposition of the waste, the decomposition process transgresses to anaerobic/methanogenic where the amount of methane increases and the amount of carbon dioxide flattens out (Robinson & Gronow 1993).

With the consumption of the organic acids, the pH increases to a neutral level as the acids are consumed and the leachate becomes less aggressive. In the stable methanogenic phase, the production of methane reaches its peak and subsequently decreases as the acids are consumed rapidly just as they are produced (Anna et al. 2019).

Table 1. The stages of biodegradation in a landfill (Anna et al. 2019).

Stages	Products	Notes
1. Aerobic	CO_2 + Heat + H_2O	Needs O_2; short-lived
2. Acetogenic	CO_2 + H_2O + acids	Anaerobic; creates aggressive leachate
3. Anaerobic	CH_4 + CO_2 + H_2O	Long-lived; methane can be used as energy source
4.Stable methanogenic	CH_4 + CO_2 + H_2O	Peak methane production and subsequent decrease

1.2 *Polymers of geotextiles*

Geotextile polymers are manufactured from crude oil (hydrocarbons) to produce a thermoplastic material which is then melted and extruded as fibres and fabric styles (Institute of Waste Management South Africa 2011). These geotextile polymers have varying level of chemical and environmental endurance.

Polypropylene (PP) and polyester (PET) are some of the commonly available polymers for non-woven geotextiles. Polypropylene is produced from the polymerization of propylene gas formed during the high-thermal cracking of propane and hydrocarbons (Koerner et al. 2007) whereby high-energy radiation, heat and catalyst are used to combine the monomers into long molecules and chains. PP has good mechanical and hydrophilic properties, and a density of 0.90 g/cm^3. Within its glass temperature range (-20°C and 0°C.), PP loses its molecular mobility and becomes susceptible to shatter.

Polyester, also known as polyethylene terephthalate (PET), is manufactured from the polymerization of ethylene glycol with terephthalic acid or dimethyl terephthalate (Koerner et al. 2007). The main chain of PET contains the ester functional group and ester linkage is the type of chemical bonding formed in PET's production. The glass transition temperature of PET is between 60°C and 85°C. PET fibres are resistant to stretching (creep) and shrinking. They also have high strength, modulus, and tenacity with excellent tensile and chemical properties. Additionally, they have good resistance to light, weather and abrasion, good resiliency, dimensional stability, and excellent wear resistance. Relatively, they are thermoplastic and are therefore resistant to fire, micro-organisms, and insects.

2 METHODOLOGY

A desktop study was carried out to categorize waste by accessing published data from the South African Waste Information Centre and the Institute of Waste Management, South Africa. Using the database of the South African Department of Water Affairs and Forestry, the Department of Environmental Affairs and the International Geosynthetics Society, a review of landfill as a waste disposal method was carried out. A bibliographic search was performed to identify, extract and compile available information on the hydraulic and tensile properties of PP and PET geotextile polymers with information acquired from published articles and standardized method for the testing of geotextiles from South African National Standard (SANS) 10221:2007. Key sources include research journals, firms and agencies publications, government gazettes, scientific databases and archives. Together these sources provided the general background information for the study. These sources are referenced as discussed in the next section.

Secondary data were collected from various search engines to compare the performances of PP and PET non-woven geotextiles in landfills. This assisted in determining the responses of the non-woven geotextile polymers to chemical attack. Figure 2 gives the research framework.

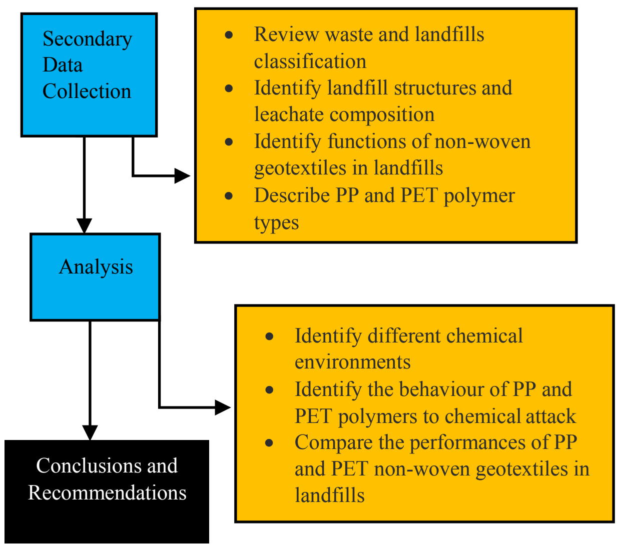

Figure 2. Research framework of the research study.

3 RESULTS AND DISCUSSIONS

The durability of a geotextile is defined as the ability to remain intact and perform its function throughout its entire service life; the typical service life of a geotextile is 200 years

(Mathur et al. 1994; Geofabrics 1998; Propex 2017). Non-woven geotextiles should have adequate strength and ability to resist failure when punctured, compressed, stretched, ruptured, cut or slit.

The long-term performance of geotextiles may be negatively affected by factors such as oxidation, chemical attack and ultraviolet light. In landfills, chemical attack is initiated by the presence of leachates and the acidity or alkalinity of the soil (Jeon 2006); the ensuing degradation may be accelerated by elevated temperatures. Contact with leachates may reduce the molecular weight of the polymer and a further deterioration in their engineering characteristics. Leachate formation and the varying concentrations, dependent on the type of waste, could lead to the formation of acidic conditions (sulphuric acid, hydrochloric acid, carbonic acid, etc.), and/or alkaline conditions (calcium hydroxide, etc.), thus affecting the performance of the non-woven geotextiles be (Govender et al. 2018). Carneiro et al. (2014) found that the combination of chemical agents had more damage than a single chemical, hence leachates comprising of various chemicals and the synergies of various degradation agents may increase the rate of degradation.

The pH value of these leachates changes from pH 3 to pH 12 and to pH 8 in approximately three months as the landfill ages. The final value of the waste leachate is usually pH 8 (Tejera et al. 2019). Due to the type of chemical compound in these leachates, the structure of the geotextile polymer changes. Some of these changes include chain scission, oxidation, dissolution, cross-linking, increase in crystallinity, swelling, and extraction or volatilization of ingredients in the polymeric compound (Koerner et al. 2007). The chemical environments under which non-woven geotextile polymers may degrade in a landfill are:

- neutral (pH of 7) media
- alkaline (pH between 8 and 12) media
- and acidic (pH between 1 and 6) media

3.1 *Degradation of polyester*

Polyesters degrade through hydrolysis which is the reverse reaction of its production. Hydrolysis is a slow chemical process but may be accelerated by the nature of the *in situ* media and temperatures. Internal hydrolysis which occurs in acidic or neutral environments is initiated by the carboxyl end groups (CEG) present at the end of the PET macromolecule polymer chain and catalyzed by free hydrogen ions (H^+) through molecular chain (Mathur et al. 1994).

In contrast, external hydrolysis takes place at the surface of the fibre since the more aggressive hydroxyl (OH^-) ions are unable to penetrate the fibre in alkaline environments. External hydrolysis is more rapid than internal hydrolysis due to the OH^- being highly reactive. Internal hydrolysis leads to viscosity degradation while external hydrolysis, leads to surface erosion. Together, both mechanisms result in a strength loss of the polyester fibres (Elias et al. 1999).

3.1.1 *Change in mechanical properties*

Researchers (Sprague 1990; Mathur et al 1994; Elias et al. 1999; Jeon 2006) have studied the changes in mechanical properties of PET when subjected to different chemical environments. Table 2 summarizes the various chemical environments in which PET polymer has shown a negative change in its mechanical properties.

PET fibres exhibited a gradual reduction in tensile strength when placed in an alkaline environment of pH 10 for four weeks. Nevertheless, there was a slight increase in tensile strength before the final drop at ambient temperatures due to water absorption (Jeon 2006). At the end of four weeks, 80% drop in tensile strength was recorded. Elias et al. (1999) noted the development of fibre surface erosion in the form of pitting on PET non-woven geotextile fibres when placed in an aqueous alkaline solution of pH 10 and pH 12 for 35.8 weeks respectively. Additionally, Jeon (2006) reported an average retention of the tensile properties of PET fibre as -55% when immersed in an aqueous solution of pH 8 and -70% in pH 12 at 80°C for 25.7 weeks.

Elias et al. (1999) further documented the tensile strength loss of PET non-woven geotextile fibres when immersed in distilled water (pH 7) from 0 to 148 weeks at temperatures ranging between 50°C and 90°C. The PET fibres also followed a similar trend when immersed in an acidic solution of pH 3 (Mathur et al. 1994). The hydrolysis test on soaked PET fibres immersed in an acidic solution of pH 1 showed similar loss in tensile strength, however noting that the degradation of PET fibre in acidic solution is much faster than in neutral solution. Similarly, Jeon (2006) indicated about 10% average retention of the tensile properties of PET fibre inserted in an acidic solution of pH 3 for 25.7 weeks at ambient temperature.

Table 2. Various chemical environments in which PET polymer showed a change in its mechanical properties.

Chemical environment	Acid		Neutral	Alkali			Leachate
pH value	1	3	7	8	10	12	
Tensile strength	a	b, c	a	c	a, b	a, c	c
Fibre strength	x	b	x	x	b	x	x
Puncture strength	x	x	d	x	x	d	d

Elias et al. (1999)[a], Mathur et al. (1994)[b], Jeon (2006)[c], Sprague (1990)[d], No data[x]

Additionally, (Jeon 2006) performed tensile strength test on PET fibres in waste leachate. The average retention of tensile properties on the PET fibre was about -50% at 26 weeks. Severe loss was recorded in waste leachate containing lime (pH 12) or calcium hydroxide (Sprague 1990).

The change in fibre strength for PET fibre was analogous to the change in tensile strength (Mathur et al 1994; Jeon 2006). Sprague (1990) observed that the change in puncture strength for PET fibres when immersed in waste leachate and alkaline media as 24% and 23%. Overtime, there was an increase in puncture strength except for calcium hydroxide solution where the PET fabric was destroyed.

3.1.2 *Change in hydraulic properties*

Several researchers (Sprague 1990; Mathur et al. 1994; Elias et al. 1999; Jeon 2006) have remarked the responses of PET and PP to chemical attack through the change in their hydraulic properties as summarized in Table 3.

The scission of the ester linkages during hydrolysis leads to a reduction of the molecular weight of the polymer (Greenwood et al. 2015). This molecular weight has a relationship with the intrinsic viscosity of the polymer. Under elevated temperatures, the molecular weight of the polymer reduces significantly (to about 50%) thereby confirming the molecular chain scission taking place at the end of hydrolysis in both acidic (pH 3) and alkaline (pH 10) conditions (Mathur et al. 1994).

In alkaline medium (pH 10 and pH 12), PET non-woven geotextile fibres recorded significant weight losses, however, no significant weight loss was observed in both neutral and acidic conditions. There was a reduction in permittivity (by about 17%) for the first few weeks of immersion. Nevertheless, permittivity increased as temperatures increased over time regardless of the chemical environment be it neutral or alkaline for PET geotextile (Sprague 1990). The change in permittivity depends on the mass per unit area of the geotextile.

Table 3. Different chemical environments in which hydraulic properties of polyester was altered as reported by several authors.

Chemical environment	Acid		Neutral	Alkali		Leachate
pH value	a	3	7	10	12	
Intrinsic Viscosity	a	b	a	a, b	a	x
Permittivity	x	x	c	c	x	c

Elias et al. (1999)[a], Mathur et al. (1994)[b], Sprague (1990)[c], No data[x]

3.2 *Degradation of polypropylene*

Oxidation is a process whereby a polymer reacts with molecular oxygen that permeates the amorphous region of the polymer. Oxidation takes place both at the surface and within the polymer. For every successive chemical reaction, the radicals (molecular fragments) combine rapidly with oxygen, reacting with the polymer to produce peroxides and other compounds. The chain reaction only ends when the local supply of oxygen diminishes, or if the number of active radicals is extremely huge. The final outcomes of oxidation are discolouration, surface cracking, embrittlement, reduction in molecular weight and a loss in tensile strength (Geofabrics 1998; Elias et al. 1999). Since there is no oxygen in polypropylene, it is less susceptible to thermo-oxidative degradation when compared to PET (which has an ester group in its main chain).

There is limited literature available on the chemical degradation of polypropylene non-woven geotextiles in landfills. Longo et al. (2011) reported that polypropylene films buried for 11 months in a sanitary landfill showed a reduction in the percentage of crystallinity as a result of molecular scission that took place during oxidation. The landfill was in its methanogenic phase and had stopped receiving waste at the time of burial. Potrykus et al. (2021) confirmed the formation of hydroxyl end groups from PP plastic samples recovered from a five-year-old waste landfill of pH 8. The presence of end groups initiates oxidation which lead to surface cracking of the Polypropylene (Canopoli et al. 2020).

PP exhibits a longer elongation at break than PET due to the higher number of fibre entanglements. The hydrocarbon chains which constitute the polypropylene fibres are relatively inert to chemical attack. PP showed an increase in puncture strength with decreased elongations when subjected to a chemically aggressive leachate environment for 62.2 weeks at a temperature of 35°C. This puncture strength increase was due to a combination of material stiffening and reinforcement of the PP fibre (by the lodging of free-floating articles within the matrix of the fibre) (Geofabrics 1998).

Researchers (Mathur et al. 1994; Geofabrics 1998; Greenwood et al. 2015) recorded no strength loss either in acidic or alkaline conditions, neither was there a strength loss under elevated temperatures. However, brittleness was recorded within six weeks. The surface of the PP fibres was smooth when subjected to alkaline and acidic environments unlike PET fibres which had irregularities (pitting or etching marks) on its surface. This indicated that PP is inert to a range of chemical including alkaline solutions (Govender et al. 2018) since they show little or no strength loss.

Jeon (2006) also performed tensile strength tests on PP fibres immersed in waste leachate solution and aqueous solutions of pH 3, pH 8 and pH 12 respectively. The average retention of tensile properties by the PP fibre was approximately 15% in the acidic solution and approximately 10% in the alkaline solution unlike polyester whose average retention of tensile strength was -70 and 10% in acidic and alkaline solutions respectively. In waste leachate solution, the average retention of tensile properties was about -20%. In summary, both PP and PET fibres showed a decrease in tensile strength. Nevertheless, the decrease experienced in PET was more than that in PP.

3.3 *Discussion*

The results of the immersion test of polyester (PET) and polypropylene (PP) nonwoven geotextiles in various environments (acidic, alkaline and leachate) showed that PET is susceptible to degradation in acidic, alkaline, and waste leachate solutions with the rate of degradation being the greatest in highly acidic/alkaline environments.

PP showed no strength loss in acidic, alkaline, or waste leachate solutions; hence it is suitable for use in various chemical environments when compared to PET. Table 4 compares the performances of PET and PP non-woven geotextiles in different chemical environment while Table 5 shows their suitability for use in these environments.

Table 4. Comparison of the performances of polyester (PET) and polypropylene (PP) nonwoven geotextiles in various chemical environments.

	Chemical environments			
	Acidic	Neutral	Waste leachate	Alkali
PET	Loss in tensile strength, puncture strength, fibre strength, intrinsic viscosity and permittivity	Moderate loss in tensile strength, puncture strength, fibre strength, intrinsic viscosity and permittivity	Moderate to severe loss in tensile strength, puncture strength, fibre strength, intrinsic viscosity and permittivity depending on the waste pH value.	Severe loss in tensile strength, puncture strength, fibre strength, intrinsic viscosity and permittivity
PP	No loss in strength	No loss in strength	Increase in puncture strength due to reinforcement effect	No loss in strength

Table 5. Suitability of polyester (PET) and polypropylene (PP) nonwoven geotextiles in various chemical environments.

	Chemical environments			
	Acidic	Neutral	Waste Leachate	Alkali
PET	Appropriate. PET undergoes internal hydrolysis; high temperature may cause unsuitability	Moderately appropriate. PET undergoes internal hydrolysis, may be unsuitable in high temperature	Appropriate (not appropriate for waste containing lime)	Not appropriate. PET undergoes external hydrolysis
PP	Appropriate	Appropriate	Appropriate	Appropriate

4 CONCLUSIONS

Polypropylene (PP) and polyester (PET) non-woven geotextiles are used in many landfills around the world. Throughout their lifetime, they are subjected to harsh environmental conditions. This is a problem because they are prone to deterioration by the action of chemicals and leachates emanating from the landfill, which may percolate into the ground and contaminate the groundwater. In some ways, the polymers may show resistance to the chemical attack. This study was undertaken to investigate how polypropylene, and polyesters resist chemical attack when used in landfills. The following presents the conclusions from the analysis of the secondary data in the desk study.

4.1 *Chemical resistance of polyester non-woven geotextile*

Polyester (PET) non-woven geotextiles degrade by the mechanisms of hydrolysis in which water molecule is added to the PET chemical structure. Two forms of hydrolysis exist namely: internal hydrolysis and external hydrolysis. Internal hydrolysis occurs in acidic and neutral environments and leads to a molecular weight loss. External hydrolysis occurs in alkaline environment and results in the fibre surface erosion.

All polyesters showed a reduction in strength in various chemical environments as a result of internal hydrolysis. Polyester fibre experienced the most severe degradation in alkaline environment. Degradation also takes place in waste leachates, with extreme levels in waste leachates of pH 12 or waste treated with lime. Therefore, it is recommended that PET non-woven geotextiles are not used in environments with high alkalinity or acidity.

4.2 *Chemical resistance of polypropylene non-woven geotextile*

Polypropylene (PP) degrades by the mechanism of oxidation that takes place in the amorphous region of its chemical structure. Polypropylene is relatively inert to chemical attack irrespective of the chemical media. It is therefore recommended that PP non-woven geotextiles can be used in all chemical environments irrespective of their alkalinity or acidity.

4.3 *Recommendations for further research*

The following is recommended for further research:

1. There is limited literature regarding the behaviour of polypropylene in waste landfills. More research is required to ascertain the chemical resistance of polypropylene non-woven geotextiles.
2. The pH value of the chemical medias used in the durability tests were acidic media (pH 1 and pH 3), alkaline media (pH 8, pH 10 and pH 12), neutral media (distilled water of pH 8) and waste leachate. Further investigations are vital to study the chemical behaviour of polypropylene and polyester non-woven geotextiles in other acidic and alkaline media whose pH value are not referenced in this study.
3. It was recommended that geotextile manufacturers and users engage in suitable durability tests to determine the chemical nature of the surrounding media for the application of polypropylene and polyester nonwoven geotextiles.
4. Moreover, additives and chemical stabilizers are used to mitigate the chemical attack of polyester and polypropylene. The efficiency of these additives could be further examined to guide manufactures and designers in selection phase of a suitable non-woven geotextile.

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