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# Durability assessment of engineered hydrophobic soils

## Évaluation de la durabilité des sols hydrophobes

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**ABSTRACT:** Polymers have been developed and used widely in infrastructure. In geotechnical engineering the most representative polymeric material are the geosynthetics, while membranes, sealants and pipes are widely used in building construction. In this paper, the degradation of polymers during use in different application conditions are discussed and the corresponding durability assessment (DA) methods on polymers are summarized. Engineered hydrophobic soils coated by synthetic polymeric coatings (e.g. polydimethylsiloxane) have been developed recently and show potential for use in the construction of hydraulic barriers. As a new construction material, the durability of engineered hydrophobic soils is still relatively unknown, and the assessment methods have not yet been developed. This paper provides an introduction on the DA methods of polymers likely to apply to engineered hydrophobic soils.

**RÉSUMÉ:** Les polymères ont été développés et largement utilisés dans les infrastructures. En géotechnique, les matériaux polymères les plus représentatifs sont les géosynthétiques. Dans cet article, la dégradation des polymères lors de l'utilisation dans différentes conditions d'application est discutée et les méthodes d'évaluation de la durabilité sont résumées. Les sols hydrophobes fabriqués avec des revêtements polymères synthétiques (par exemple du polydiméthylsiloxane) ont été développés récemment et présentent un potentiel d'utilisation dans la construction de barrières hydrauliques. La durabilité des sols hydrophobes est encore relativement inconnue et les méthodes d'évaluation n'ont pas encore été développées. Cet article fournit une introduction aux méthodes d'évaluation de la durabilite de polymères susceptibles de s'appliquer aux sols hydrophobes.

**Keywords:** Polymer degradation; durability assessment; lifetime prediction; soil hydrophobicity

## 1 INTRODUCTION

Polymers have become increasingly important as materials in both building and geotechnical infrastructure, because of the availability of basic raw materials for their production (e.g. coal and wood) and specific technical properties (e.g. light weight and chemical stability). In buildings, polymers are widely used in accessories such as pipes, conduits, sealants and insulations. And in geotechnical infrastructure, polymers are major matrices for geosynthetics which can be applied as structural or non-structural materials. Of engineering interest, the key properties of polymers are: (1) mechanical properties (i.e. modulus, ultimate strength and tensile strength, ultimate and elastic elongation); (2) thermal properties; (3) gas and water permeability and (4) flammability (Greenwood et al., 2016; Frigione and Lettieri, 2018; Yang, 2014).

Polymers are sensitive to environmental factors (e.g. sunlight, moisture and temperature) which can result in their degradation (Yang, 2014). Durability assessment (DA) of polymers provides an expectation that the polymer can satisfactorily process all required properties in the specific conditions to guarantee the safety and usability of the structure being built. A polymer DA should be specific to the application environment. For example, for window sealants used in structures, DA includes a UV-ageing test, while in geotextiles the tensile creep and creep rupture behavior should be determined (EN ISO 13431:1999).

Engineered hydrophobic soils are novel materials with potential use in ground-infrastructure such as slope protection, landfill covers and hydrophobized capillary barriers (Zheng et al., 2017; Choi et al., 2016; Subedi et al., 2013). By covering with hydrophobic polymers such as poly-dimethylsiloxane (PDMS), such soils resist water penetration, and therefore can be used to contain water in hydraulic barriers. However, their lifespan and degradation behavior under different environments are still unknown.

The aim of this paper is to review the (1) possible degradation of polymers during the use in both buildings and geotechnical infrastructure, and (2) their corresponding DA tests which are widely used. This will be followed by an introduction to engineered hydrophobic soils as a novel construction material including a discussion on the possible tests to determine their degradation behavior and lifespan.

# 2 POLYMERS IN CONSTRUCTION

## *2.1* Polymers in the building industry

In the building industry, polymers are the fourth major class of building materials after steel, wood and cement. They can also account for the highest growth area in construction materials. Up to date, thousands of commercially available polymer products have been used in building construction such as polyvinylchloride (PVC), polypropylene (PP) and polyester (Greenwood et al., 2016; Yang, 2014; Kasapoğlu, 2008) . This rapid development is mainly attributed to (Pendhari et al., 2008):

(1) Chemical stability: polymers are chemically stable and therefore able to prevent erosion or corrosion;

(2) Flexibility: polymers have various processing methods such as thermal forming and casting;

(3) Cost efficiency: the raw basic materials for polymers (e.g. coal, agricultural waste and wood) are widely available with a low cost.

Apart from technical and economical advantages, polymer made from renewable raw materials have a lower environmental impact (Susilorini et al., 2014). However, during the use of polymers in construction, they also face challenges particularly relating to degradation and fire performance. Table 1 lists representative applications of polymers in the building industry.

*Table 1. Applications of polymers in the building industry (after Pendhari et al., 2008)*

| Application | Polymer |
|---|---|
| Pipe\conduit | Low-density polyethylene (LDPE) |
| | High-density polyethylene (HDPE) |
| | Polyvinyl chloride (PVC) |
| Profile | Polyvinyl chloride (PVC) |
| Insulation | Expanded polystyrene (EPS) |
| | Polyurethane (PUR) |
| Film | Low-density polyethylene (LDPE) |
| | Polyvinyl chloride (PVC) |
| Flooring | Polyvinyl chloride (PVC) |

## *2.2* Geosynthetics in geotechnical engineering

In geotechnical infrastructure, the most widely-used polymer-based materials are geosynthetics. Major types of geosynthetics include geotextiles, geomembranes, geosynthetic clay liners, geofoams and geocomposites. Table 2 provides a description and applications for the different types of geosynthetics, varying from reinforced soil structure to hydraulic barriers, (Greenwood et al., 2016). Unlike the polymers used in the building industry, geosynthetics contain not only polymers but also other additions such as antioxidants, because most of geosynthetics are in direct contact with soils, rocks or other geotechnical materials and sometimes undergo sunlight exposure (Yang, 2014). The main types of polymers for geosynthetics are poly vinyl chloride, polypropylene, polyethylene and polyester. While some commonly-used additions are antioxidants (to prevent polymer oxidation), ultraviolet screeners (to prevent polymers from UV degradation) and fillers (Kasapoğlu, 2008). Geosynthetics share some advantages with polymers used in the building industry. Particularly, they are chemically stable and cost-efficient (Susilorini et al., 2014; Gerasimova & Zotikova, 2016). The manufactured quality of geosynthetics is also a noteworthy advantage over traditional geotechnical materials which have a high variation in mechanical and hydraulic properties. An outstanding challenge of geosynthetics is their long-time performance when buried in the ground. Because of polymer degradation and bio-clogging, both their hydraulic and mechanical properties can alter with time.

# 3 DURABILITY ASSESSMENT

## *3.1* Degradation of polymers

Long-time performance of polymers is affected by the environmental conditions such water, sunlight, temperature and biological activities (Frigione and Lettieri, 2018). The mechanisms of degradation are mostly related to two chemical reactions, which are oxidation and hydrolysis, depending on the polymer type and application condition. For example, in polyolefins (PE and PP), oxidation is the major mechanism of degradation (Bolland and Gee, 1946), while for polyesters, polyamides and aramids, hydrolysis dominates to the property changes. As an example of application conditions, geosynthetics may face more aggressive environmental conditions than polymers used in the building industry.

With time and due to degradation, a reduction in the tensile force can also result in creep of the structural polymeric materials. Under a long-term tensile load lower than the ultimate tensile strength, polymers can also rupture. The creep behavior depends majorly on the intrinsic properties of the polymers, tensile stress and temperature (Greenwood, 1990).

Based on the aforementioned factors affecting the long-time performance of polymers, this paper introduces four major DA tests on polymers used in constructions, namely, UV-ageing, oven test, tensile creep test and outdoor weathering.

*Table 2. Applications of geosynthetics in geotechnical engineering (after Greenwood et al., 2016)*

| Geosynthetics | Description | Application |
|---|---|---|
| Geotextile | Polymeric planar textile with high water permeability | Reinforcement, erosion control, etc. |
| Geomembrane | Polymeric planar sheet with low water permeability | Hydraulic barriers |
| Geosynthetic clay liner | Assemble structure containing geosynthetic materials and clay | Hydraulic barriers |
| Geofoam | Large lightweight block | Slope stabilization, utility protection |
| Geocomposite | Composite structure with two or more types of geosynthetics | Reinforcement, hydraulic barriers |

## *3.2* UV-ageing

UV radiation leads to breakage in polymer chains and causes photodegradation of polymers, contributing to various property changes. Two major affected properties are the strength and color. If their strength is reduced, their use is no longer allowed. While the discoloration affects the appearance, if their intended to be used outdoors (the case of sealants). The wavelength of UV radiation, temperature and relative humidity or local moisture can all influence the property changes of polymers (Yang, 2014).

Therefore, UV-ageing tests should be performed under controlled testing conditions (i.e. temperature, relative humidity or local moisture, UV radiation and exposure duration). Widely-used standards apply wet-dry cycles in UV ageing tests. In the dry period, irradiation is provided to simulate the sunlight and in wet periods, water is sprayed on the testing samples without irradiation to simulate the rainfall. Table 3 lists standard tests used for sealants and geosynthetics.

## *3.3* Oven test

For the chemical degradation whose reaction rate depends on temperature, i.e. when the degradation follows Arrhenius equation, oven test can be applied to estimate the lifetime of polymers. Procedures for the test are as follows (Yang, 2014; Pendhari et al., 2008) :

(1) Define the property that indicates the limit of acceptability of the material. For example, in geotechnical engineering, 50% retained tensile strength is commonly used for geosynthetics;

(2) Define the testing conditions: aqueous or aerial condition;

(3) Define the range of testing temperature. At least three temperatures should be set, and the maximum is based on the mechanism of degradation. The recommended temperature step is 10ºC;

(4) Define the time step for property measurements. The time should be spaced logarithmical such as 100, 300, 1000, 3000 and 10000 hours;

(5) Determine the rate of property change against time ($R_P$);

(6) Plot the $R_P$ and inverse absolute temperature ($K^{-1}$) in a logarithm scale so that the relationship between RP and temperature can be obtained.

## *3.4* Creep and stress rupture tests

Creep rupture and stress rupture tests can provide a database not only for lifetime prediction under external loading, but also for the performance of polymers under heat conditions such as fire (Koo et al., 2008).

In the creep rupture test (CR test), testing polymers are loaded by a static tensile stress at

*Table 3. UV tests for polymers*

| Reference | Material | Dry period | Wet period |
|---|---|---|---|
| ASTM D5329 | Joint sealants in pavements | 340-nm UV at 70ºC for 8 hrs | Water condensation at 50ºC for 4 hrs |
| ASTM C1442 | Building sealants | 340-nm UV at 60ºC for 8 hrs | Water spray at 50ºC for 4 hrs |
| ASTM D7238 | Polyolefin geomem-brane | 340-nm UV at 75ºC for 20 hrs | Water condensation at 50ºC for 4 hrs |
| EN 12224 | Geotextile | 300~400-nm UV at 50ºC for 5 hrs | Water spray at 25ºC for 1 hrs |
| Bolte and Boettger (2000) | Building silicone sealants | 340-nm UV at 60, 70, 80, 90ºC for 8 hrs | Water condensation at 50ºC for 4 hrs |

an elevated temperature, and the deformation of polymers (i.e. elongation) is monitored (Koo et al., 2008; Greenwood et al., 2016). A typical strain-time relation (black solid line) in a CR test is shown in Figure 1. At the primary or initial stage, strain is induced by an external stress increasing significantly with time. In a secondary stage, strain and time show a linear relation until reaching the transition point. After the transition point (tertiary stage), strain suddenly increases rapidly until rupture occurs. For a higher temperature, the creep rate is higher (red dash line) and for a larger stress (blue dot line), the instaneous deformation is larger. Therefore, both higher temperature and larger stress can result in a shorter rupture time.

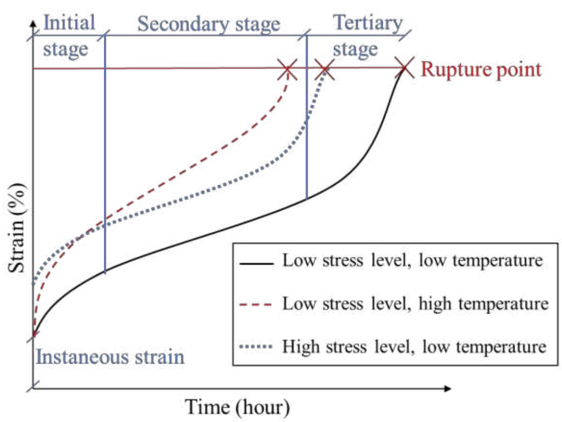


*Figure 1. Creeping behaviour of polymers at different temperatures and stress levels*

Stress rupture tests are similar to creep rupture test except for the external loading applied at a higher level. At controlled elevated temperature, an external loading is applied until the polymer fails, and the time at failure is determined. The result is plotted in a strength versus rupture time relation in a logarithmic scale (Figure 2). At low temperatures, the relation is close to a straight line (black). While for higher temperatures, the curves (from blue to red) shift downward. The change of slope in the strength-rupture time indicates a chemical change of testing polymers such as oxidation, recrystallisation and spheroidization (Greenwood et al., 2016)

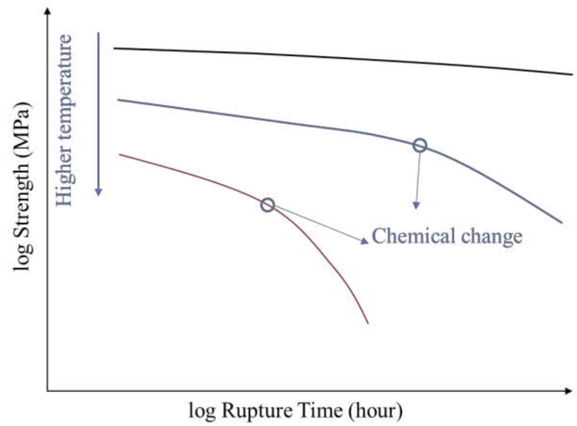


*Figure 2. Strength - rupture time relation of polymers at different temperatures*

## *3.5* Outdoor (natural) weathering

By placing the testing polymers in an open area exposed directly to sunlight or rainfall, outdoor weathering represents the real condition in which polymers undergo degradation. Outdoor weathering can also involve submersion in which hydrolysis domains the degradation or buried in soils where biological activity could affect the polymer properties (Greenwood et al.,1996).

Given that in outdoor weathering the environmental factors such as relative humidity, temperature, irradiation and exposure time are not controllable, outdoor weathering tests cannot be repeated and the testing results vary according to the location (Yang, 2014).

# 4 ENGINEERED HYDROPHOBIC SOILS

Engineered hydrophobic soils (EHS) refer to hydrophobicity induced in soils by synthetic or natural substances. The use of EHS not only offers a series of new opportunities for ground improvement, but also contributes to elucidating the natural processes linked to these soils

(Lourenço et al., 2017). Some examples of engineering applications include: slope protection, landfills, water harvesting and other ground-related engineering works (Zheng et al., 2017; Choi et al., 2016).

## *4.1* Engineering behaviour of engineered hydrophobic soils

The presence of hydrophobic coatings on soil particles, affects both hydraulic and mechanical properties of EHS. Because of the low affinity of soils for water, EHS resists water penetration. For very hydrophobic soils, a water-entry pressure will need to be applied so that water breaks into the pores. While Bardet et al. (2014) found out that sands coated with wax have a higher saturated permeability than uncoated sands. Therefore, the nature of the coatings is important. Karim et al. (2018) showed that when sands are coated with organosilanes, the friction angle in reduced from 36.9 to 29.7° by direct dry shear tests. Lee et al. (2015) showed a similar tendency for sands were tested in a dry condition, but this reduction was negligible for tested sands near saturation. Liu et al. (2018) found out a similar effect in saturated triaxial tests, highlighting the effect of the polymeric coatings (PDMS) on the critical state of the granular material.

## *4.2* Hydrophobic substances

Organosilanes are most widely used to induce hydrophobicity in soils such as octadecyltrichloro-silane (OTS), trimethyl-chlorosilane and dichlorodimethylsilane (DMDCS) (Chan et al., 2016). The mechanism by which PDMS is produced involves a reaction between water (vapour or liquid) and the silica surfaces of soil particles. As a silane polymer, PDMS creates high and stable hydrophobic surfaces (Bachmann et al., 2009) at low concentrations (0.005~0.1% by soil mass, Chan and Lourenço, 2016; Ng and Lourenço, 2016; Saulick et al., 2017). However, for clayey or silty soils, the consumption of organosilanes increases significantly to 2.5~4%.

Because the hydrophobic coating (i.e. PDMS) shares close chemical properties with polymers used in the construction industry such as silicone sealants, it suggests that some of the DA tests suggested previously could be transferred to EHS in order to determine their lifetime under different engineering settings.

## *4.3* Possible durability assessment methods for hydrophobic engineered soils

The DA of EHS should be designed to satisfy different application conditions given that EHS can have broad applications from slope protection, to landfills, water harvesting and hydraulic barriers where environmental conditions are variable and are possibly aggressive to polymers (e.g. sunlight exposure). Table 4 summarizes possible applications, conditions, dominant degradation factors, and the corresponding durability assessments of EHS. There are two major scenarios: degradation before and during the application. EHS could degrade before usage such as during unprotected transport and storage. And during

*Table 4. Potential applications, conditions, dominant degradation factors and corresponding durability assessment of engineered hydrophobic soils (after Lourenço et al., 2017; Zheng et al., 2017)*

| Application | Condition | Degradation factor | Durability assessment |
|---|---|---|---|
| Transporat/storage | High temperature | Oxidation | Oven test (aerial) |
| | Sunlight & rainfall | Photo-ageing and hydrolysis | UV-ageing with water spray |
| Slope protection/ water harvesting / landfill | Sunlight & rainfall | Photo-ageing and hydrolysis | UV-ageing test with water spray |
| | Biological activity | Biodegradation | Outdoor weathering (buried in soils) |
| | Water flow | Hydrolysis | Oven test (aqueous) |

the application i.e. during their lifetime, they will be subjected to sunlight, rainfall, biological activity and water flow which could decay the hydrophobic nature of EHS.

## 5 CONCLUSIONS

This paper firstly introduces widely-used polymers applied both in the building industry and geotechnical infrastructure. This is followed by an overview of their possible degradation during their use, followed by a summary of corresponding durability assessment methods, namely, UV-ageing, creep and stress rupture tests, oven tests and outdoor (natural) weathering tests. These methods provide a basis to assess the durability of a novel construction material: engineered hydrophobic soils. It is suggested that some durability assessment methods can be transferred from polymeric construction materials such as geosynthetics to engineered hydrophobic soils since their coatings share a similar composition, and their application conditions are likely to be similar.

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