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DURABILITY TESTS OF GEOSYNTHETIC MATERIALS USED IN DIFFICULT ENVIRONMENTAL CONDITIONS

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ABSTRACT

The article describes the ageing process of high-density polyethylene (HDPE) geogrids under the influence of chemical and environmental factors. Research on accelerated ageing of a uniaxial HDPE geogrid incubated in a water solution for a period of 12 months is presented. Three temperatures (25°, 45° and 75°C) were selected for the accelerated ageing tests in aqueous solutions simulating the conditions at a municipal waste landfill. Changes were observed using differential scanning calorimetry (DSC), and correlations with the mechanical properties of the aged geogrid were checked. No significant effect of the loss of antioxidant in the material on the mechanical properties of the uniaxial geogrid was observed. The tests made it possible to determine the mechanical properties, such as tensile strength and deformability of the geogrid – which are extremely important in the analysis of slope stability.

Keywords: accelerated ageing tests, oxidative degradation, strength of polymeric materials, HDPE geogrids

INTRODUCTION

Geosynthetic materials used in engineering structures must be characterised by a specific strength and durability over time. The durability of geosynthetics depends on (Greenwood Schroeder & Voskamp, 2012):

- the type of raw material used, from which material it was made, and the additives used in the production (i.e., antioxidants, stabilisers, fillers, plasticisers);
- resistance to chemical and microbiological influences;
- resistance to mechanical damage caused during storage, installation and operation during the designed period of use.

The mechanism of the oxidative degradation process for polyolefins, consist of three stages: initiation, propagation and termination (Hsuan et al., 2008).

The factors initiating polymer degradation may be the following interactions: physical (e.g., temperature, constant and cyclic loads, UV radiation), chemical (e.g., oxygen, solutions, pH, heavy metals) and biological under the influence of living organisms (e.g., bacteria, fungi – these are organisms commonly found in soil, groundwater, landfills). The actions of degrading factors in the environment are often synergistic, and their effect is interactions between individual stimuli. During degradation in natural climatic conditions, it is very difficult to isolate which degrading factors have a dominant effect on a given synthetic material (Rabek, 2013; Valentin et al., 2021). Polyolefin materials have a semi-crystalline, crystalline and amorphous structure, which means they can undergo oxidative degradation at different rates. The oxidation reaction takes place both in the bulk and on the surface of the polymer depending on the amount of oxygen

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and temperature. The effects of chemical degradation are accelerated by the influence of elevated temperature (Ehrenstein, Riedel & Trawiel, 2004).

Geosynthetic materials are usually made of thermoplastic polymers. In their structure, they contain amorphous domains, where the polymer chains are arranged randomly, and crystalline domains, where the polymer chains are arranged regularly – most often in the form of crystalline lamellae (Fig. 1).

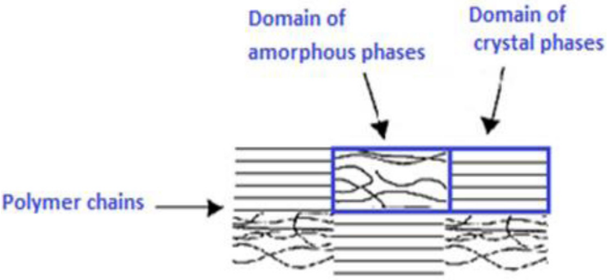


Fig. 1. The structure of thermoplastic polymers

Source: Hawkins (1972).

The durability of polymers used in the production of geosynthetic materials also depends on stabilising additives, thanks to which their degradation can be significantly delayed. The use of stabilising agents, the geosynthetic lifetime is extended 10 or even 100 times, depending on the environment in which it was used (Greenwood et al., 2012; Scholz et al., 2021). Additives, due to their functions in the plastic, can be divided into:

- processing additives (processing stabilisers, processing modifiers);
- functional additives (property stabilisers, property modifiers).

Processing additives affect the course of processing processes, while in the form of functional additives, they affect the usable properties of the material. In addition, in both cases, these agents can be used to stabilise and modify the processing or use properties of polymers.

These include fillers, stabilisers (e.g., antioxidants), softeners (plasticisers), light stabilisers, colouring agents, antistatics and flame retardants (Zweifel, 2000; Bart, 2005). Various types of additives used in the production of geosynthetics are intended to support the manufacturing processes and protect them over time. Polyethylene oxidation reactions can be delayed or inhibited by the use of primary (hindered phenols and sterically hindered amines) and secondary (trisubstituted phosphates or sulphoxides) anti-oxidants that capture free radicals by decomposing hydroperoxides to alcohol and this process prevents further propagation of the chain (Fay & King, 2013). Under certain conditions, additives can be partially or entirely depleted from the material, such as washed out by water or chemicals (e.g., solvents, surfactants) from the surface of the material. As a result of the oxidation of the polymer, the resulting free radicals lead to chain reactions (auto-oxidation). The formation of free radicals causes the breaking of polymer chains, which leads to a decrease in the molecular weight of the polymer. The result of this phenomenon is that the material consequently becomes brittle and at the same time susceptible to stress corrosion cracking (Elias, Kenneth, Fishman, Christopher & Berg, 2009). Under the influence of atmospheric oxygen, the oxidation process occurs with the formation of polar groups such as hydroxyl (-OH), carboxylic (-COOH), hydroperoxide (-OOH) and ketone (>C=O).

The influence of temperature (or radiation) can be catalysed by transition metal ions or catalyst residues from the polymerisation process. It should be emphasised, however, that these processes depend on the availability of oxygen present in the polymer. Moreover, the speed of the initiation process depends on the temperature and concentration of macroradicals.

When using polyolefin geosynthetics, the main problem is assessing their durability under various ageing conditions. The antioxidants used protect the material against its oxidative degradation, but are gradually depleted over time. Oxidative degradation of HDPE geosynthetics can be divided into three distinct stages (Fig. 2):

- Stage I – the time of depletion of antioxidants, is caused by their consumption as a result of chemical reactions (reaction of free radicals with oxygen) or physical losses due to diffusion, extraction or evaporation.
- Stage II – induction time needed for the occurrence of oxidative degradation of the polymer after complete depletion of the antioxidant.

- Stage III – the proper degradation of the polymer leading to the deterioration of its measured properties, primarily mechanical parameters (the polymer becomes brittle). The action of mechanical loads can also destroy molecular chains and enhance the effects of elevated temperature and oxygen (Hsuan & Koerner, 1998).

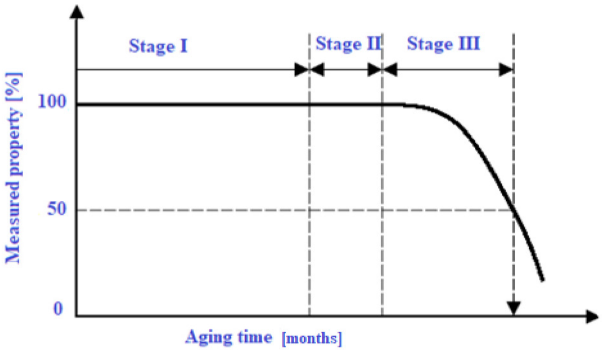


Fig. 2. Three stages of oxidative degradation: Stage I – antioxidation depletion; Stage II – Induction time; Stage III – the half-life of property

Source: Hsuan and Koerner (1998).

This article focuses on determining the durability of uniaxial HDPE geogrid used to strengthen slopes and embankments. The tests of the accelerated ageing process were carried out in a solution simulating the conditions prevailing in a municipal waste landfill for a period of 12 months. Three temperatures (25°C, 45°C and 75°C) were selected for this study. The heavy metals used in the effluents acted as a catalyst for hydroperoxide decomposition to generate free radicals and deplete antioxidants in the plastic. The surfactants used in the effluent increased the wetting capacity of the geosynthetics.

The presented results indicate that uniaxial polyolefin geogrids can be used for soil reinforcement in geotechnical structures, even in places where the influence of chemical factors and elevated temperature is significant.

MATERIAL AND METHODS

The HDPE geogrids were used for laboratory tests. Geogrids belong to the group of related materials (GTP) according to the classification of the PN-EN ISO 10318-1 standard (Polski Komitet Normalizacyjny [PKN], 2018a). They are used where there is a need to increase the shear strength of the soil for structures: slopes, road and railway embankments, and platforms as well as when the structure is founded on a weak foundation (Wesołowski, Krzywosz & Brandyk, 2000). The structure of uniaxial geogrid (with rigid nodes) is obtained by extrusion from the sheet and then stretching at a properly selected temperature, depending on the raw material used, to give the geosynthetic material the appropriate shape and strength characteristics. Table 1 shows the main engineering properties of the uniaxial HDPE geogrid.

Table 1. The main engineering properties of the uniaxial HDPE geogrids

Parameter	Value
Geometry	
Aperature size [mm]	16 × 235
Rib thickness [mm]	1.1
Cross machine direction (CMD) bar thickness [mm]	2.5–2.6
Rib width [mm]	6
Weight [g·m^{-2}]	500
Mechanical properties	
Tensile strength [kN·m^{-1}]	60.5
Elongation at rupture [%]	12.2
Resin properties	
Melt flow index [g·10 min^{-1}]	0.07
Oxidation induction time [min]	65

Source: Kiersnowska (2017).

The accelerated ageing tests were conducted according to similar studies reported in the literature (Rowe, Islam & Hsuan, 2008) and with the conditions prevailing during the exploitation of geogrids (backfilling with anthropogenic soil). The temperature and composition of the water environment were selected as factors causing degradation, as described in Table 2, the surfactant Triton™ X-100 (Sigma-Aldrich, Germany) at a concentration of 5 ml·l^{-1} was used. Three ageing temperatures of the samples were determined: 25 ±2°C, 45 ±2°C and 75 ±2°C. After analysing the annual reports from the Radiowo landfill No 19932018 (Golimowski & Koda, 1993–2018), the pH of the incubation solution was set at 6. The ageing period of the geogrid samples was planned for 12 months. Test samples were taken from the solutions every 2 months. In order to maintain the continuity of antioxidant depletion from the geogrid, the solution was replaced every 2 months. Geogrid samples (520 × 240 mm) were placed in glass tubes in a 50-litre stainless steel container, poured with a previously prepared solution, heated to a specific temperature and pH adjusted.

Table 2. The composition of the heavy metal solution

Component	Concentration $[mg \cdot l^{-1}]$
Ferrous sulphate ($FeSO_4 \cdot 7H_2O$)	4 480
Zinc sulphate heptahydrate ($ZnSO_4 \cdot 7H_2O$)	360
Cupric sulphate pentahydrate ($CuSO_4 \cdot 5H_2O$)	40
Aluminium sulphate 16-hydrate ($Al_2(SO_4)_3 \cdot 16H_2O$)	30
Manganous sulphate 4-hydrate ($MnSO_4 \cdot 4H_2O$)	60
Nickel(II) sulphate ($NiSO_4 \cdot 6H_2O$)	50

Source: Kiersnowska, Fabianowski and Koda (2020).

In order to perform oxidation induction time tests, geogrid samples were taken from the place where the geogrid ribs had the smallest thickness and width. With these parameters the material after incorporation in this place is most exposed to the influence of the surrounding environment. A thermal analysis apparatus DSC Q200 (TA Instruments, USA) was used for the test (Fig. 3). The test was performed in accordance with the PN-EN ISO 11357-6 standard (PKN, 2018b). An open sample pan and a reference pan (empty aluminium pan) were placed in the measuring cell. The measurement was carried out in a nitrogen atmosphere (with a gas flow of $50 \ ml \cdot min^{-1} \pm 5 \ ml$) at a heating rate of $10°C \cdot min^{-1}$ to the measurement temperature of 200°C. After reaching the assumed temperature, the inert gas (nitrogen) was switched to oxygen and the measurement was continued in isothermal conditions at the heating rate ($5°C \cdot min^{-1}$).

Oxidation induction time (*OIT*) was determined by the intersection of the tangents to the baseline and the rectilinear segment observed while measuring the oxidation signal (oxidation isotherm). Then, the value at

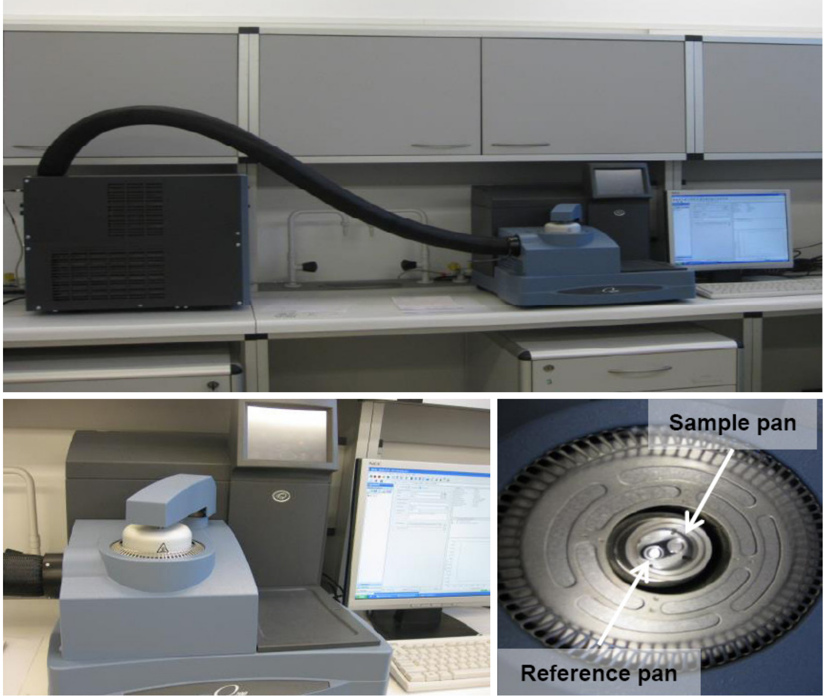


Fig. 3. Differential Scanning Calorimeter Q200 oxidation induction time apparatus

Source: own work.

which the inert gas atmosphere was changed to oxygen was subtracted from the time value for the obtained point (approx. 20 min). Determination of the intersection of the tangents to the baseline and the rectilinear segment observed during the measurement of the oxidation signal (oxidation isotherm) allowed to designate *OIT*. Then, from the time value for the obtained point, the value at which the inert gas atmosphere was changed to oxygen (approx. 20 min) was subtracted (Fig. 4). Each test was conducted in duplicate.

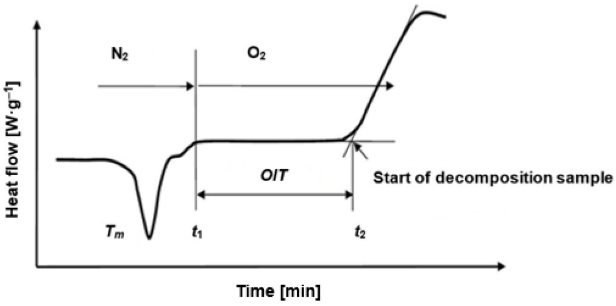


Fig. 4. Schematic diagram of analysis by differential scanning calorimeter of standard oxidation induction time (*OIT*): T_m – melting temperature of polymer; t_1 – the beginning of the oxidation; t_2 – the end of the oxidation

Source: PKN (2018b).

When the geosynthetics function as reinforcement for their tensile strength, the elongation at maximum load are crucial for assessing product stability since the action of elevated or reduced temperature and humidity changes their properties. The tests for new and aged geogrid were carried out in accordance with the PN-EN ISO 10319:2015-08 standard (PKN, 2016) using a tensile testing machine (Instron, USA) with a maximum force of 100 kN. For each test five specimens were used. The monotonic tensile tests were performed at a rate of strain equal to 20% min^{-1}. For each test, five specimens were used.

RESULTS AND DISCUSSION

Figure 5 shows that the antioxidant from the geogrid subjected to accelerated ageing tests at 75°C depleted the fastest. Oxidation induction time (*OIT*) tests for the sample after 8 months of ageing (75°C) showed no antioxidant, so the first stage of geogrid degradation was completed. For the sample aged for 12 months at 25°C, the antioxidant content remained at 60%. For the sample aged for 12 months at 45°C, 38% of the reference sample remained.

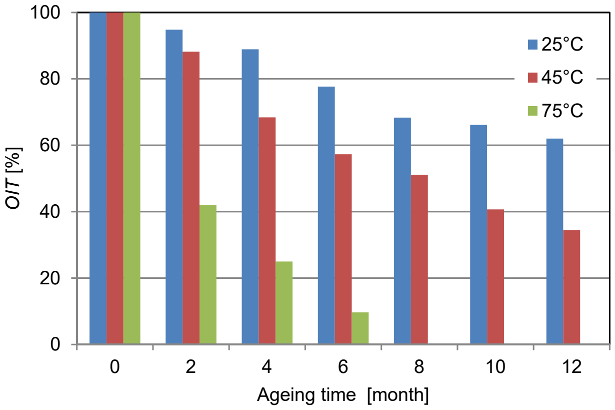


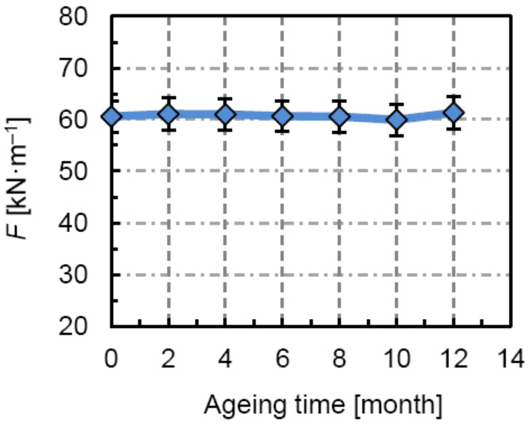
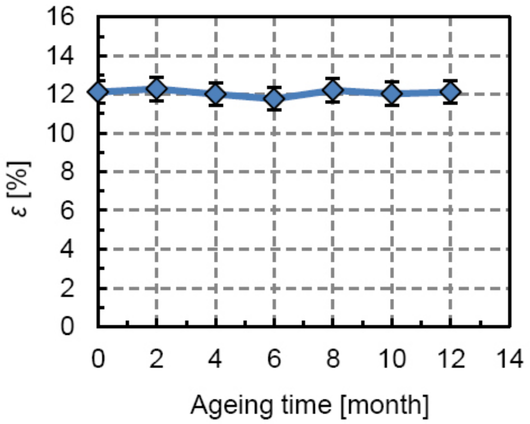
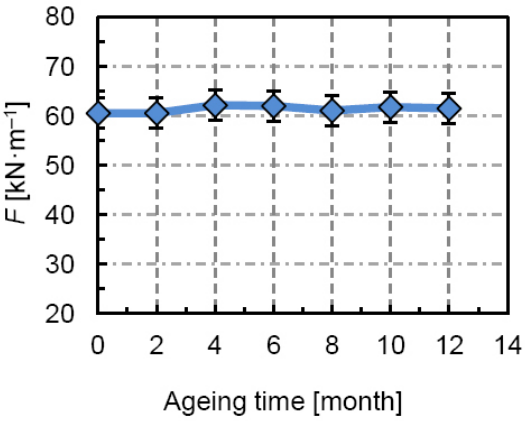
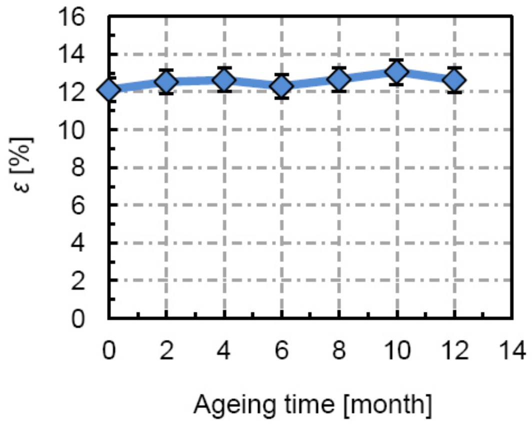
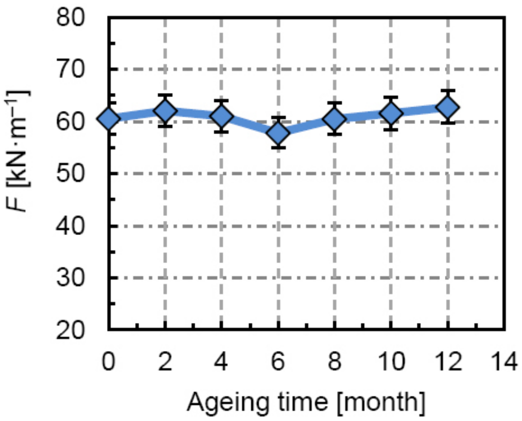
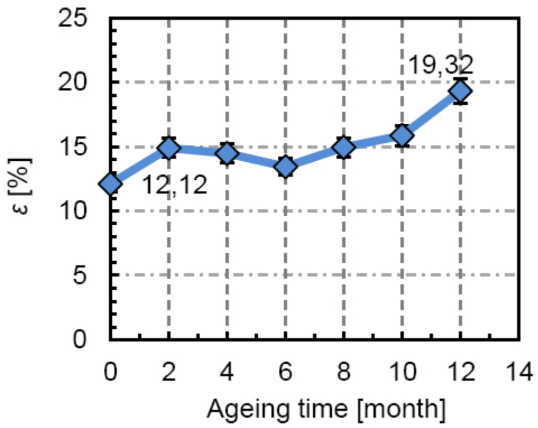
Fig. 5. Oxidation induction time (*OIT*) for samples subjected to accelerated ageing tests for 12 months at three selected temperatures

Source: Kiersnowska, Fabianowski, Koda, Trach and Kawalec (2022).

Table 3 shows the relationship between the average tensile strength (*F*) and the ageing time of geogrid samples. The average tensile strength of geogrid samples not subjected to ageing tests was 60.56 kN·m^{-1}. The average tensile strength values for samples incubated at 25°C ranged from 61.00 kN·m^{-1} (after 4 months of incubation) to 61.35 kN·m^{-1} (after 12 months of incubation). On the other hand, the average tensile strength values of the samples incubated at 45°C ranged from 62.20 kN·m^{-1} (after 4 months of incubation) to 61.55 kN·m^{-1} (after 12 months of incubation). For samples incubated at 75°C, mean *F* values ranged from 61.06 kN·m^{-1} (after 2 months of incubation) to 62.75 kN·m^{-1} (after 12 months of incubation). After 12 months of accelerated ageing tests at individual temperatures, there were no statistically significant changes affecting the average tensile strength in wide sample tests.

No significant changes in the influence of accelerated ageing tests on the average relative elongation at 25°C and 45°C of the tested material were observed. Accelerated ageing tests at 75°C showed that the

Table 3. Influence of incubation time on tensile strength (F) and elongation at maximum force (F) at selected temperatures for unidirectional HDPE geogrid samples

T [°C]	Tensile strength (F) [kN·m^{-1}]	Elongation (ε) at maximum strength (F) [%]
25		
45		
75		

Source: Kiersnowska et al. (2022).

average elongation of 12.12% for the sample not subjected to accelerated ageing tests (the new sample) increased to 19.32% (after 12 months of incubation). This study indicates that high-temperature incubation was not indicated for unidirectional geogrids. A further increase in temperature may result in reaching values that may significantly affect the strength parameters of this material.

Studies confirm that in the aggressive environment of landfills, accelerated ageing of the material and reduction of mechanical parameters may occur. This is particularly important when a uniaxial geogrid is used in slopes landfills – which in extreme conditions – may lead to landslides and other threats to the environment.

CONCLUSIONS

Accelerated ageing tests of uniaxial HDPE geogrid incubated in water solution for 12 months simulating conditions at a municipal waste landfill at three temperatures (25°, 45° and 75°C) showed:

- The rate of antioxidant depletion depends on temperature (*OIT*). No antioxidant in the geogrid after 8 months of ageing tests at 75°C.
- No significant deterioration of the geogrid's mechanical parameters (tensile strength, relative elongation). Accelerated ageing tests at 75°C showed that the average elongation increased to 19.32% compared to 12.12% for the sample not subjected to accelerated ageing tests. The tensile strength did not change at 75°C.

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BADANIA TRWAŁOŚCI MATERIAŁÓW GEOSYNTETYCZNYCH STOSOWANYCH W TRUDNYCH WARUNKACH ŚRODOWISKOWYCH

STRESZCZENIE

W artykule opisano proces starzenia się georusztów z polietylenu o wysokiej gęstości (PEHD) pod wpływem czynników chemicznych i środowiskowych. Przedstawiono badania przyspieszonego starzenia jednokierunkowego georusztu PEHD inkubowanego w roztworze wodnym przez 12 miesięcy. Do przeprowadzenia przyspieszonych testów starzeniowych w roztworach wodnych symulujących warunki na składowisku odpadów komunalnych wybrano trzy wartości temperatury (25°C, 45°C i 75°C). Zmiany zarejestrowano za pomocą różnicowej kalorymetrii skaningowej (DSC), dzięki której sprawdzono także korelacje z właściwościami mechanicznymi starzonego georusztu. Nie zaobserwowano znaczącego wpływu ubytku przeciwutleniacza w tworzywie na właściwości mechaniczne georusztu jednokierunkowego. Badania pozwoliły na określenie właściwości mechanicznych takich jak wytrzymałość na rozciąganie i odkształcalność georusztu, cech niezwykle istotnych w analizie stateczności skarp.

Słowa kluczowe: testy przyspieszonego starzenia, degradacja utleniająca, wytrzymałość materiałów polimerowych, georuszty PEHD