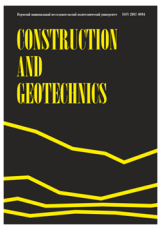
Ковалев, М.А. Полипропилен PP-DVU и гомополимер полипропилена: долговечность геосинтетических и строительных материалов в растворах серной и плавиковой кислот при повышенных температурах / М.А. Ковалев // Construction and Geotechnics. – 2025. – Т. 16, № 3. – С. 98–111. DOI: 10.15593/2224-9826/2025.3.08

Kovalev M.A. Polypropylene PP-DVU and polypropylene homopolymer: durability of geosynthetic and construction materials in high-temperature sulfuric and hydrofluoric acid solutions. *Construction and Geotechnics.* 2025. Vol. 16. No. 3. Pp. 98-111. DOI: 10.15593/2224-9826/2025.3.08

пермский политех

CONSTRUCTION AND GEOTECHNICS
Т. 16, № 3, 2025
http://vestnik.pstu.ru/arhit/about/inf/



DOI: 10.15593/2224-9826/2025.3.08
УДК 691

POLYPROPYLENE PP-DVU AND POLYPROPYLENE HOMOPOLYMER: DURABILITY OF GEOSYNTHETIC AND CONSTRUCTION MATERIALS IN HIGH-TEMPERATURE SULFURIC AND HYDROFLUORIC ACID SOLUTIONS

M.A. Kovalev

Peter the Great St. Petersburg Polytechnic University, Saint Petersburg, Russian Federation

ARTICLE INFO

Received: 11 July 2025
Approved: 29 August 2025
Accepted for publication:
10 September 2025

Keywords:

geosynthetic construction materials, polypropylene, PP-DVU, chemical resistance, hydrofluoric acid, sulfuric acid, aging depth, service life prediction, polymer degradation.

ABSTRACT

The study's object was polypropylene PP-DVU and polypropylene homopolymer. These construction materials are used as components of geosynthetic materials and as a part of pipeline systems and the reactor, which are integrated into a newly built industrial complex designed for the processing of columbite concentrate. During service, the studied materials interact with chemically aggressive environments. The specimens were exposed to a liquid solution of hydrofluoric and sulfuric acids at elevated temperatures. Material degradation was assessed through tensile strength tests, mass changes, microhardness, visual appearance, and moisture absorption. The depth of aging and relative elongation were the most indicative criteria for predicting the lifespan of the polymer material. The aging of the material was determined through water absorption tests and mechanical testing. Aging was also visually evident through a noticeable color change. The water absorption of the aged layer was higher compared to the material that had not come into contact with the medium. The aging depth helped determine the diffusion rate of the medium into the material, which aids in recommending the optimal wall thickness for the product. The material's tensile strength remained the same after the tests, thus making this criterion less valuable. A combination of in-situ and laboratory tests showed a positive effect by reducing the overall testing time. Criteria for predicting the lifespan of polypropylene materials used in the reactor for columbite concentrate processing were proposed and substantiated.

© **Ковалев Марк Андреевич** – инженер I категории, e-mail: kovalev_ma@spbstu.ru

Mark A. Kovalev – Engineer, grade I, e-mail: kovalev_ma@spbstu.ru

ПОЛИПРОПИЛЕН PP-DVU И ГОМОПОЛИМЕР ПОЛИПРОПИЛЕНА: ДОЛГОВЕЧНОСТЬ ГЕОСИНТЕТИЧЕСКИХ И СТРОИТЕЛЬНЫХ МАТЕРИАЛОВ В РАСТВОРАХ СЕРНОЙ И ПЛАВИКОВОЙ КИСЛОТ ПРИ ПОВЫШЕННЫХ ТЕМПЕРАТУРАХ

М.А. Ковалев

Санкт-Петербургский политехнический университет Петра Великого,
Санкт-Петербург, Российская Федерация

О СТАТЬЕ

Получена: 11 июля 2025
Одобрена: 29 августа 2025
Принята к публикации:
10 сентября 2025

Ключевые слова:

геосинтетические строительные материалы, полипропилен, PP-DVU, химическая стойкость, плавиковая кислота, серная кислота, глубина старения, срока службы, деградация полимеров.

АННОТАЦИЯ

Объектом исследования являлись полипропилен PP-DVU и гомополимер полипропилена. Данные строительные материалы применяются в составе геосинтетических материалов, а также как часть трубопроводных систем и реактора, входящих в состав нового промышленного комплекса, предназначенного для переработки колумбитового концентрата. В процессе эксплуатации изучаемые материалы подвергаются воздействию химически агрессивных сред. Для моделирования условий эксплуатации и оценки деградации образцы в лабораторных условиях подвергались воздействию жидкой среды при повышенной температуре, содержащей плавиковую и серную кислоты. Оценка деградации материала проводилась по следующим критериям: прочность на разрыв, изменение массы, микротвердость, внешний вид и водопоглощение. Наиболее показательными критериями для прогноза срока службы полимерного материала стали глубина старения и относительное удлинение. Старение материала определялось визуально по изменению цвета и по результатам испытаний на водопоглощение и механических испытаний. Уровень водопоглощения в зоне старения был выше по сравнению с участками материала, не контактировавшими со средой. Глубина старения позволила определить скорость диффузии среды в материал, что важно для выбора оптимальной толщины стенки изделия. Прочность на разрыв после испытаний не изменилась, поэтому данный критерий непоказателен для оценки деградации. Комбинированное использование натурных и лабораторных испытаний позволило сократить общее время оценки. Предложены и обоснованы критерии для прогнозирования срока службы полипропиленовых материалов, используемых в реакторе для переработки колумбитового концентрата.

Introduction

Polypropylene PP-DVU and polypropylene homopolymer geotextiles are widely used in civil and environmental engineering applications due to their favorable mechanical properties, low density, chemical resistance, and cost-effectiveness. These materials serve as integral components in filtration, separation, reinforcement, and protection systems, particularly in geotechnical and waste containment projects [1; 2]. Also, polymer materials are widely used in construction, particularly when the facilities being built are expected to operate under exposure to aggressive environments [3; 4]. This is especially relevant for pipeline systems in specialized industries, as well as for sewer systems [5]. Despite their general chemical stability, polypropylene-based geotextiles can be subject to degradation when exposed to aggressive chemical environments, such as acidic or alkaline solutions [6; 7]. In practical scenarios, these conditions may arise in contaminated soil, industrial waste facilities, or mining leachate systems, where geosynthetics are required to maintain long-term performance. Recent studies have investigated the durability of PP geotextiles under combined chemical and thermal aging conditions [8; 9]. In these studies demonstrated that exposure to sulfuric acid and other aggressive agents may not cause immediate degradation; however, synergistic effects between acid attack and thermo-oxidative aging significantly accelerate material failure. These findings highlight the need for a more comprehensive

understanding of polypropylene degradation mechanisms in acidic environments, particularly for applications that demand long-term performance under chemically aggressive conditions. One notable example is industrial facilities involved in columbite concentrate processing, where materials must withstand prolonged exposure to sulfuric and hydrofluoric acid solutions. In such operations, aggressive solutions affect both the pipeline systems and the process vessels. The problem of material selection for the construction of pipeline systems, heat exchangers, and storage vessels is particularly common in the mining industry [10].

Polypropylenes PP-DVU and polypropylene homopolymers have high durability against the effects of high-temperature acid solutions. Their high durability allows them to be used as structural materials in reactors and pipeline systems for processing columbite concentrate. The opening is carried out through chemical reactions and physical methods. In general, opening reactors are cylindrical vessels with an internal stirrer for mixing the medium [11]. The opening mechanism in such reactors can be divided into alkaline, acid, and chlorine processes [12]. The process occurs at high temperatures, which approach the maximum operating temperature of some polymer materials. The high concentration of chemicals, as well as constant stirring, are additional aggressive factors. The efficiency of extracting tantalum and niobium from columbite concentrate into solution depends on the concentration of hydrofluoric and sulfuric acids in the reactor and the temperature of the reaction solution [13].

Studies examining the opening processes are often focused on developing new processing methods or optimizing existing ones [14; 15]. Still, they do not discuss the material selection of reactors and pipeline systems used in the construction of such facilities. In industrial reactor and pipeline systems construction, materials with high corrosion resistance, such as monel alloys, are typically used [16]. The downside of corrosion-resistant alloys is their high cost. Therefore, the use of polymer materials as a barrier between the medium and the primary material seems rational. If the polymer has sufficient resistance as a barrier material, it allows for the use of less corrosion-resistant materials, which would reduce the overall equipment cost.

Polypropylene is an affordable polymer material [17], and its use is possible if it shows sufficient resistance in a solution of sulfuric acid, hydrofluoric acid, and zirconium concentrate. This solution serves as the working medium of the opening reactor. In the study [18], data regarding the resistance of polypropylene in 50–60 % sulfuric acid at temperatures of 60–80°C and in 60 % hydrofluoric acid at 40°C are presented. The tests were conducted over 30 days, and the material's resistance, according to the authors' 10-point scale, was rated at 7–8 points. Available literature data [19] suggest that polypropylene may be resistant under the operating conditions of a columbite reactor. Still, they do not provide definitive information on its resistance to acid mixtures or its potential service life.

Standard tests can be conducted to confirm the applicability. These tests are necessary not only for functional design but also to reduce technical, financial, and production risks [20; 25]. In addition to standard tests that assess physical and mechanical properties, the end consumer typically requests a lifespan prediction for the product. Such a calculation is, in most cases, a labor-intensive task. For metal products, an initial estimate of their durability in aggressive operating conditions can be made based on the corrosion rate expressed in mm/year. For polymer products, however, the parameter selection could be more straightforward.

The selection of a material durability criterion is fundamental to calculating its service life. This criterion should clearly indicate the product's condition, be easy to determine, and offer high repeatability. Additional advantages include intuitive understanding and selection based on op-

erational experience. In the study [21], approaches to determining the predicted service life were described. Each method is based on a certain degree of correlation and a specific focus. In the first case, a parameter that correlates well with the expected failure is identified, while in the second case, attention is given to actual operational parameters.

The work [22] noted that most prediction methodologies are similar and can be divided into four levels of testing, varying in simplicity and risk. Summarizing the data presented in the work, the use of standard testing methods increases the risk of premature failure. At the same time, developing a full-fledged prediction methodology is a labor-intensive task.

Existing methodologies for testing polymer materials do not usually allow for accurate lifespan estimation and require improvements. Accelerated testing methods need to be developed, followed by correlating these with real-world studies, creating mathematical models, and translating the results into service life estimates. Examples of such efforts include standards like ISO 12944-6 and ISO 23936-2. Thus, the development of methods that enable quick assessment of material classes is currently an actual problem.

Predicting service life based on results from in-situ and laboratory studies involves conducting accelerated testing of materials. The experimental data obtained are extrapolated onto a service life graph. The accuracy of such methodologies will depend on understanding the aging processes and the impact of accelerating parameters on them. For example, the study [23] noted that the aging process might include a prolonged period of minor degradation, after which there is a sudden change in properties. This period depends on temperature, and its duration decreases with increasing temperature. Accelerated testing methodologies typically involve enhancing specific factors to levels beyond operational conditions. Given the simultaneous impact of multiple factors on the material, each causing different responses, it is crucial to identify the most significant ones. Temperature is one such parameter affecting the polymer aging process. It is known that increasing temperature generally speeds up the chemical reactions responsible for degradation. However, exceeding the maximum allowable temperature can cause degradation different from operational conditions, leading to increased uncertainty in results. The Arrhenius equation can describe the temperature dependence of chemical reaction rates, but it may only be applicable within a specific temperature range and for certain chemical reactions. A characteristic of polymer materials is the simultaneous occurrence of multiple chemical reactions, each with its activation energy, which results in an inaccuracy in the results [24].

The literature review revealed that the available data need to be more comprehensive to draw definitive conclusions about the durability of the investigated polypropylenes in sulfuric and hydrofluoric acid solutions. The lack of data also hinders the development of predictive methodologies.

This article aims to evaluate the behavior of polypropylene in a high-temperature solution of sulfuric and hydrofluoric acids and develop a prediction methodology based on the obtained results.

The specific objectives of this study are:

- Identify the most representative criteria for the degradation of polypropylene properties in real-world tests;
- Evaluate the degradation of polypropylene properties in sulfuric and hydrofluoric acid solutions at elevated temperatures;
- Validate the applicability of the selected degradation criteria through laboratory testing;
- Propose a forecasting methodology.

Materials and Methods

This study focused on polymer products operating in environments containing sulfuric acid, hydrofluoric acid, and zirconium concentrate. Additional aggressive factors included elevated temperatures and constant mixing.

The studies were conducted using a scaled-down replica of a reactor for opening columbite concentrate. Testing in such a reactor simulates the aggressive effects on construction materials used in similar facilities. This is particularly relevant for pipeline systems, storage vessels, and other components that come into contact with aggressive chemical solutions. The scaled-down reactor, constructed from polymeric and metallic materials, closely replicated the design of an industrial reactor. The reactor is a vessel containing a solution of sulfuric and hydrofluoric acids, along with zirconium concentrate. The test aimed to simulate operational conditions and determine how the properties of the materials under investigation change over time.

The structural elements and the lining of the reactor components were fabricated from polymeric materials. Polypropylene PP-DVU from the German company "Simona," Kirn, Germany (Manufacturer 1), and polypropylene homopolymer PP from the company Rostr, Saint Petersburg, Russia (Manufacturer 2), were evaluated. The polymer specimens were shaped for tensile testing, with dimensions conforming to type 1BA according to ISO 527-2. Additionally, a round through-hole with a diameter of 6 mm was made in the widening section to secure the specimen in the testing apparatus. Figure 1 presents both the schematic and actual appearance of the specimens.

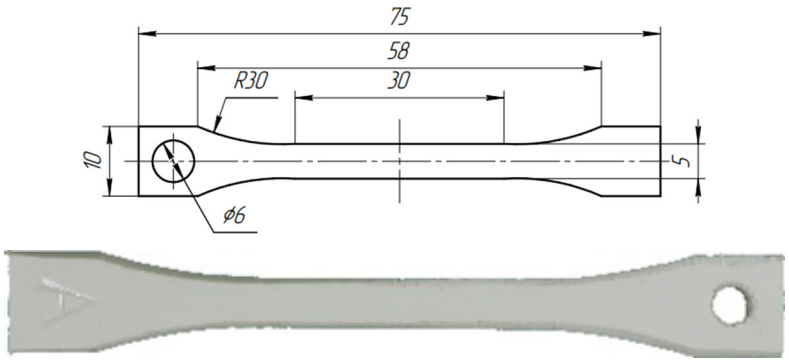


Fig. 1. Testing specimen

The specimens were placed on the equipment inside the reactor's working volume (Fig. 2) and periodically removed from the reactor. Testing was conducted over 720 hours, with periodic specimen removals at 24 and 240 hours of exposure. Upon completion of the tests, the reactor vessel was examined for changes in its properties.

Fig. 2. Equipment used for periodic removal of specimens during testing

The laboratory reactor was filled with a model pulp simulating the columbite processing pulp (Table 1). Table 2 provides the composition of the zirconium concentrate included in the model pulp. The testing temperature was 80+5°C.

Table 1

Model pulp composition

Parameters	Value
Concentration H_2SO_4	400 g/l
Concentration HF	230 g/l (по HF)
Concentration of zirconium concentrate	200 g/l

Table 2

Composition of zirconium concentrate

Name	Content of the component, % mass				
	ZrO_2+HfO_2	Fe_2O_3	TiO_2	Al_2O_3	Mohs hardness
ZETA ZIRCON SUPERFINE	66.5	0.12	0.5	1.0	7.5

After the tests were completed and the medium neutralized and removed, the reactor vessel was examined. It was hypothesized that the medium's aggressiveness would increase with the depth of immersion, so the specimen placement area was divided into three zones by height (bottom, middle, top). Specimens of the same material were placed in all zones to evaluate different levels of aggressiveness. The investigation of the polymer specimens included visual inspections, gravimetric control methods, structural analysis, and mechanical property testing.

The determination of mechanical properties under tensile stress was conducted using a tensile testing machine in accordance with ISO 527-2. Ultimate tensile strength and elongation at break were measured. The traverse speed was set to 50 mm/min. Visual assessments and mass change evaluations were carried out according to ISO 175. Visual assessments and mass change measurements were conducted in accordance with ISO 175. Structural investigations were performed using an optical microscope, examining both the surface and cross-section of the specimens. Microhardness measurements were conducted using the Vickers scale, with a 30-gram load on the indenter and a holding time of 15 seconds at maximum load. Microhardness was chosen as an additional criterion for evaluating degradation.

The examination of the reactor vessel involved visual inspections, structural investigations, and mechanical testing. Segments were taken from each aggressive zone and used to create specimens. The testing procedure was similar to that used for the standard specimens to achieve a better correlation of results. Additionally, water absorption was evaluated following the methodology described in ISO 62. Table 3 provides general data on the tests that were conducted.

After the tests were completed and the medium neutralized and removed, the reactor vessel was examined. It was hypothesized that the medium's aggressiveness would increase with the depth of immersion, so the specimen placement area was divided into three zones by height (bottom, middle, top). Specimens of the same material were placed in all zones to evaluate different levels of aggressiveness. The investigation of the polymer specimens included visual inspections, gravimetric control methods, structural analysis, and mechanical property testing.

The determination of mechanical properties under tensile stress was conducted using a tensile testing machine in accordance with ISO 527-2. Ultimate tensile strength and elongation at

break were measured. The traverse speed was set to 50 mm/min. Visual assessments and mass change evaluations were carried out according to ISO 175. Visual assessments and mass change measurements were conducted in accordance with ISO 175. Structural investigations were performed using an optical microscope, examining both the surface and cross-section of the specimens. Microhardness measurements were conducted using the Vickers scale, with a 30-gram load on the indenter and a holding time of 15 seconds at maximum load. Microhardness was chosen as an additional criterion for evaluating degradation.

The examination of the reactor vessel involved visual inspections, structural investigations, and mechanical testing. Segments were taken from each aggressive zone and used to create specimens. The testing procedure was similar to that used for the standard specimens to achieve a better correlation of results. Additionally, water absorption was evaluated following the methodology described in ISO 62 [23]. Table 3 provides general data on the tests that were conducted.

Table 3

General data on the tests

Material	Total number of specimens	Number of control specimens	Estimated parameters	Total duration, hours
Polypropylene PP-DVU (Manufacturer 1)	20	5	Tensile strength Elongation at break Microhardness Mass change	720 (partial removal after 24 and 240 hours)
Polypropylene PP (Manufacturer 2)	20	5		
Reactor vessel (PP-DVU) (Manufacturer 1)	-	-	Tensile strength Elongation at break Water absorption	720

Results and Discussion

During the exposure period, the materials gradually changed color (Figure 3), indicating potential structural changes.

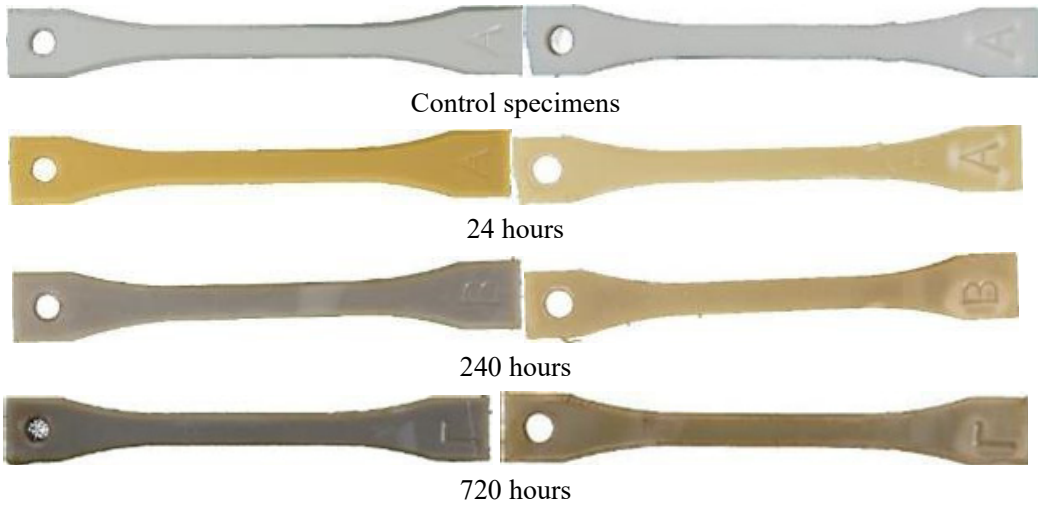


Fig. 3. Changes in the appearance of polymer specimens: *a*) PP-DVU; *b*) PP

The PP-DVU material exhibited a trend of gradual mass increase, indicating sorption during exposure. The PP material showed a high variation in values within the same specimen, which may indicate more active chemical processes occurring within the material. Microhardness changes during exposure varied by several units. The microhardness decrease for PP-DVU averaged 2 units, likely due to medium sorption, as confirmed by mass changes. PP showed similar degradation, with an average decrease of 0.7 units.

Tables 4, 5 summarize the results of mass and microhardness assessments for PP-DVU and PP materials after testing. The values are averaged across all specimens taken from a single aggressiveness zone. Data are provided for specimens tested at 24, 240, and 720 hours.

Table 4

Results for PP-DVU

Height	Mass change, %			Microhardness, HV		
	24 hours	240 hours	720 hours	Control specimens – (8,83 HV)		
				24 hours	240 hours	720 hours
Top	+0.73	+2.71	+3.04	7.2	6.8	7.3
Middle	+0.81	+2.79	+3.11	7.3	6.8	7.2
Bottom	+0.82	+2.74	+3.10	7.2	7.0	7.4

Table 5

Results for PP

Height	Mass change, %			Microhardness, HV		
	24 hours	240 hours	720 hours	Control specimens – (6,68 HV)		
				24 hours	240 hours	720 hours
Top	+1.88	+2.2	-1.15	6.4	6.2	6.5
Middle	+0.87	+2.70	+1.63	6.5	6.1	6.4
Bottom	+0.76	+0.28	+0.61	6.3	6.7	6.3

The results of mechanical testing of specimens after exposure did not show clear degradation in the PP-DVU material. The tensile strength values remained unchanged compared to the control specimens. For the PP material, mechanical testing showed a gradual decrease in relative elongation. The results are shown in Tables 6, 7, with data for specimens after 24, 240, and 720 hours of immersion.

Table 6

Mechanical test results for PP-DVU

Height	Tensile strength, MPa				Elongation at break, %			
	Control specimens	24 hours	240 hours	720 hours	Control specimens	24 hours	240 hours	720 hours
Top	33	33	34	32	31	26	27	25
Middle		32	33	32		29	33	28
Bottom		32	32	33		16.5	29	41
Average	33	32	33	32	31	24	30	31

Table 7

Mechanical test results for PP

Height	Tensile strength, MPa				Elongation at break, %			
	Control specimens	24 hours	240 hours	720 hours	Control specimens	24 hours	240 hours	720 hours
Top	25	26	24	24	175	280	254	81
Middle		26	25	25		188	141	63
Bottom		27	25	26		219	104	99
Average	25	26	25	25	175	229	166	81

The results obtained for the reactor vessel made from PP material are discussed next. The inner side of the wall exhibited color heterogeneity. In the area in contact with the liquid, the material predominantly exhibited a grayish hue, while in the area exposed to the vapor phase, it was brown. Three segments were cut from the reactor vessel at different heights to correlate the material's properties with its color. The height of the upper segment (brown color) was at the level of contact with the vapor phase, while the middle and lower segments (gray color) were at the levels of the middle and lower zones of the test rig, respectively.

In the cross-section of the segments, the layer of aged material was clearly distinguishable (Figure 4). The section's boundary was uniform, and its pattern did not change with the height of the segment extraction. Additionally, the upper segment showed a separation within the aged layer, which likely caused the color difference (Zone 1, Zone 2).

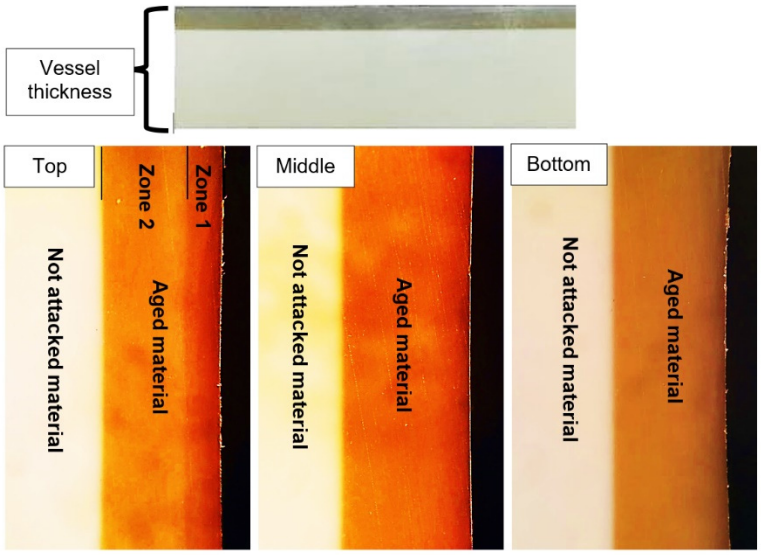


Fig. 4. Cross-section of the reactor wall after 720 hours of exposure, ×4.5

After 720 hours, the aging depth was approximately 2.0 to 2.3 mm (~18 % of the original wall thickness) and was consistent across all three segments. The transition zone was characterized by a color gradient approximately 180 μm thick. The depth of aging in the reactor wall was only measured at one point, after 720 hours of testing. Cross-sectional specimens were prepared from the widened area of the used tensile test specimens to correct the aging rate of PP-DVU and determine the aging rate for PP. This area experienced the least deformation, allowing for more accurate measurement of the aged layer depth.

The aging depth of the material after 24 hours of exposure for PP-DVU and PP was ~0.5 mm and ~0.6 mm, respectively. The boundary of the aged layer was clearly visible, and the aging pattern was similar to that observed at the reactor wall (Fig. 5). After 240 hours of exposure, the aging appeared to penetrate the full depth, and it can be estimated that the actual aging was at least ~2.5 mm for PP and ~2 mm for PP-DVU, respectively, considering the thickness of the specimens. The results suggest that the aging rate of polypropylene is nonlinear, with maximum intensity occurring during the first 240 hours of contact with the model medium and then significantly decreasing.

PP/ PP-DVU 24 hours PP/ PP-DVU 240 hours

Fig. 5. Cross-section of the specimens after exposure in 24/240 hours

The average change in microhardness of the aged layer was 13 % compared to the initial material.

The not-attacked material was removed layer by layer from the outer side to prepare tensile test specimens from the wall after flat specimens were cut out, and final polishing was performed. The layer-by-layer removal was carried out using a milling machine until the aged layer was reached. The dimensions of the specimens were approximately 80×10×2 mm. Specimens of the not-attacked material were prepared similarly and had comparable thicknesses. Tensile testing revealed an increase in relative elongation with greater depth. The specimens' fracture modes transitioned from brittle to ductile (Table 8, Fig. 6).

Table 8

Mechanical test results for vessel specimens

Specimen, №	Tensile strength, MPa				Elongation, %			
		Height				Height		
	Control	Top	Middle	Bottom	Control	Top	Middle	Bottom
1	32	32	33	32	6.5	9.9	17	23.5
2	33	30	36	34	8.4	8.6	18.5	27
3	34	29	36	32	6.9	8.8	37	21.5
4	31	32	31	29	18	25	23	7.8
5	X	30	35	34	X	13.5	44	40
Average	33	31	34	32	10	9	28	24
Change, %	X	-6	+3	-3	X	-10	+180	+140

Water absorption evaluation was conducted as an additional qualitative method to assess aging, given that polypropylene is hydrophobic in its initial state. The specimen preparation technology was similar to that used for tensile test specimens, but the specimens were square-shaped.

After 504 hours of exposure, contact with the model medium resulted in a loss of hydrophobic properties, but no signs of material saturation were observed during this period. Additionally, the mass change of the specimen from the segment that had been in contact with the gas phase was lower compared to the others. The control specimen of PP-DVU was hydrophobic (Table 9, Fig. 7).

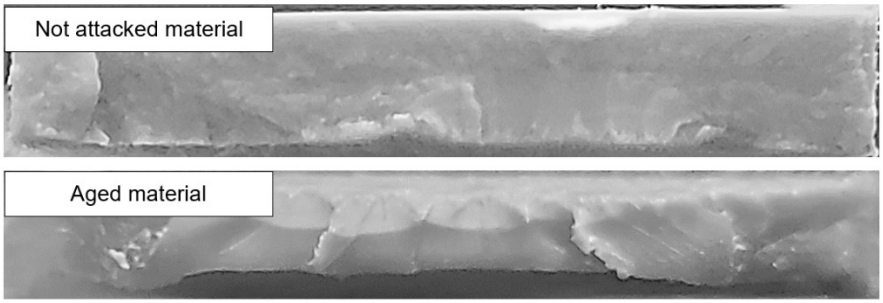


Fig. 6. Fracture pattern of vessel specimens

Table 9

Results of moisture absorption assessment for PP-DVU

Height	Moisture absorption, %					
	Immersion time, hours					
	24 h	48 h	96 h	168 h	360 h	504 h
Top	0.13	0.19	0.30	0.39	0.55	0.65
Middle	0.14	0.24	0.33	0.45	0.66	0.76
Bottom	0.19	0.20	0.32	0.44	0.63	0.77
Control specimen	0.01	0.01	0.01	0.01	0.01	0.01

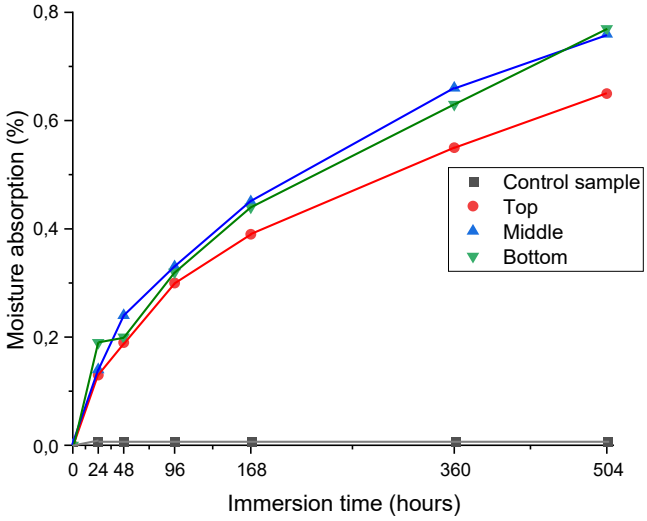


Fig. 7. Comparative assessment of continuous moisture absorption for PP-DVU before and after 720 hours of immersion in the reactor

The polymer's increased sorption capacity can be attributed to both pore/crack formation and structural changes due to aging. A similar monotonic sorption pattern was observed in specimens exposed to the model medium.

The obtained results allow for ranking criteria suitable for developing predictive models and assessing polymer durability.

The following conclusions can be drawn by summarizing the data on polymer durability in a high-temperature environment with sulfuric and hydrofluoric acids:

• PP-DVU tended to increase absorption (mass increased by ≈ 3 %). After testing, the specimens showed changes in appearance. Microhardness decreased in comparison to the control

specimens. Tensile strength remained unchanged, while elongation varied non-linearly depending on the location of the specimens within the reactor (degree of medium aggressiveness);

- Material PP generally showed a tendency for mass increase (≈1 %), but there were also values that deviated from this trend. Microhardness remained unchanged. After testing, the specimens showed changes in appearance. Mechanical properties, in terms of tensile strength, were similar for control specimens and after immersion. The average elongation value after 720 hours of exposure decreased by more than half;
- Visual degradation of the reactor vessel material made from PP-DVU was evident in color changes both upon visual inspection and when examining cross-sections. The tensile strength of the material exposed to the solution remained unchanged while the elongation increased. Water absorption of the reacted material also increased compared to the control specimens.

Based on the research results, aging depth and elongation proved to be the most suitable criteria for predicting the service life of polymer materials. No significant changes in tensile strength were observed after testing, making this criterion less relevant. The combination of in-situ and laboratory tests demonstrated a positive effect, as it reduced the overall testing duration. A methodology for further laboratory testing was developed to confirm the effectiveness of these criteria for predicting material performance.

The assessment of the degree of degradation of the aged layer, followed by the calculation of the critical aging depth and the prediction of the time to reach it, forms the basis of the methodology. The tests involve exposure of the specimen to one-sided contact with the model medium. Standard ISO 1817 [20] describes a setup that allows for one-sided contact with the model medium. The key specimen requirements are as follows:

- The test specimen for one-sided contact must be flat;
- The dimensions of the specimen should be larger than the contact area with the aggressive medium and should include some margin;
- The thickness of the specimen must be sufficient to ensure that aging does not penetrate through the entire depth during testing;
- The test temperature is selected based on the operating conditions and the maximum allowable temperature for the material being studied. Additional external means (e.g., using an oven, heating tape, or water bath) can increase the temperature.

The total exposure duration and measurement frequency for different materials can be determined after preliminary tests and the creation of an experimental database. The results indicate that during the first 240 hours of exposure, the aging rate reaches its maximum before significantly decreasing. "Taking more frequent measurements during this period will improve the accuracy of the aging curve. Therefore, the exposure schedule could be as follows: 24, 48, 72, 120, 168, 240, 720, 1440 hours. After testing, the specimens are evaluated for aging depth using optical microscopy, tensile tests are conducted, and the changes in hydrophobic properties in the reacted layer are assessed.

If sufficient experimental data are available, a laboratory method using the predictive criteria proposed in this article will allow for more accurate forecasting of polymer material lifespan.

Conclusions

In the study aimed at assessing the durability of polypropylene materials in high-temperature sulfuric and hydrofluoric acid solutions, both field and laboratory tests were conducted. The tests involved exposure to an aggressive medium followed by an evaluation of

changes in the physical and mechanical properties of the materials. Based on the results of these tests, a methodology for predicting the service life of construction materials under the studied conditions was proposed.

The results obtained allow for the following conclusions:

• The depth of aging and the elongation at break are the most suitable criteria for determining the degradation of polypropylene properties during in-situ testing.

• When polypropylene is in contact with a sulfuric and hydrofluoric acid solution at 80+5°C, the medium diffuses into the material. The rate of diffusion is nonlinear, with maximum intensity observed in the first 240 hours of contact. In the layer of polypropylene that has reacted with the medium, changes in elongation at break are noted compared to the control specimens.

• Laboratory tests confirmed the change in elongation at the break of polypropylene in contact with the medium and an increase in water absorption compared to the original material.

• The forecasting methodology based on the obtained results involves laboratory testing of material specimens. The specimens are tested under one-sided contact with the medium, with periodic assessments of the depth of the reacted layer and changes in properties within this layer compared to the original material. This methodology enables the determination of the medium's diffusion rate into the material, changes in properties within the reacted layer, and monitoring the stabilization of diffusion processes. The obtained results provide a reliable basis for determining the minimum allowable thickness of polypropylene-based components–such as sheets, pipes, tanks, and geosynthetic materials – used in environments involving exposure to sulfuric and hydrofluoric acid solutions. This contributes to the safe and durable performance of structural and protective elements in corrosive industrial applications

Финансирование. *Исследование не имело спонсорской поддержки.*
Конфликт интересов. *Авторы заявляют об отсутствии конфликта интересов.*
Вклад авторов. *Все авторы сделали равный вклад в подготовку публикации.*

References

1. Rawal A., Shah T. H., Anand S. C. Geotextiles in civil engineering // Handbook of technical textiles. – Woodhead Publishing, 2016. – С. 111-133.

2. Carneiro J. R., Morais M., de Lurdes Lopes M. Degradation of polypropylene geotextiles with different chemical stabilisations in marine environments // Construction and Building Materials. – 2018. – Т. 165. – С. 877-886.

3. James M. B. Polymers in Civil Engineering: Review of alternative materials for superior performance // Journal of Applied Science and Computations. – 2019. – Т. 6. – №. 5. – С. 1770-1773.

4. Hollaway L. Polymer composites for civil and structural engineering. – Springer Science & Business Media, 2012.

5. Lasfar S. et al. Resistance of different materials used in sewers systems: Polyvinyl chloride (PVC), polypropylene (PP) and high density polyethylene (HDPE), to sulfuric acid and sodium sulfate attack // Int. J. Eng. Res. Appl. – 2014. – Т. 4. – С. 670-678.

6. Carneiro J. R., Almeida P. J., de Lurdes Lopes M. Some synergisms in the laboratory degradation of a polypropylene geotextile // Construction and Building Materials. – 2014. – Т. 73. – С. 586-591.

7. Mathur A., Netravali A. N., O'rourke T. D. Chemical aging effects on the physio-mechanical properties of polyester and polypropylene geotextiles // Geotextiles and Geomembranes. – 1994. – Т. 13. – №. 9. – С. 591-626.

8. Scholz P. et al. Investigation on the durability of a polypropylene geotextile under artificial aging scenarios // Sustainability. – 2024. – Т. 16. – №. 9. – С. 3559.

9. Valente I. M. et al. Chemical studies about the durability of polypropylene geotextiles // Proceedings of the 9th International Conference on Geosynthetics. – 2010. – Т. 2. – С. 785-788.

10. Bazgir M., Rahmani K. Anodic protection of 316L stainless steel piping in sulfuric acid service: failure causes and remedial actions // Corrosion Reviews. – 2021. – Т. 39. – №. 5. – С. 453-464.

11. Vignes A. Extractive metallurgy 2: metallurgical reaction processes. John Wiley & Sons, 2013.

12. Nete M., Purcell W., Nel J. T. Hydrometallurgical separation of niobium and tantalum: A fundamental approach // Jom. – 2016. – Т. 68. – С. 556-566.

13. Rajak D. K. et al. Extractive metallurgy of columbite-tantalite ore: A detailed review // Minerals Engineering. – 2022. – Т. 190. – С. 107917.

14. Mirji K. V. et al. Technological challenges in extractive metallurgy and refining of Nb, Ta and preparation of their compounds & alloys // Materials Today: Proceedings. – 2016. – Т. 3. – №. 9. – С. 3151-3161.

15. Mirji K. V. et al. Technological challenges in extractive metallurgy and refining of Nb, Ta and preparation of their compounds & alloys // Materials Today: Proceedings. – 2016. – Т. 3. – №. 9. – С. 3151-3161.

16. Rodriguez M. H. et al. Effect of Na+ ion on the dissolution of ferrocolumbite in autoclave // Hydrometallurgy. – 2016. – Т. 159. – С. 60-64.

17. Maddah H. A. et al. Polypropylene as a promising plastic: A review // Am. J. Polym. Sci. – 2016. – Т. 6. – №. 1. – С. 1-11.

18. Baur E., Ruhrberg K., Woishnis W. (ed.). Chemical resistance of commodity thermoplastics. – William Andrew, 2016.

19. Lasfar S. et al. Resistance of different materials used in sewers systems: Polyvinyl chloride (PVC), polypropylene (PP) and high density polyethylene (HDPE), to sulfuric acid and sodium sulfate attack // Int. J. Eng. Res. Appl. – 2014. – Т. 4. – С. 670-678.

20. Floyd, F.L. American Chemical Society, 1999. P. 21-33.

21. Buxton A. et al. Controlled temperature natural weathering // Service Life Prediction of Polymeric Materials: Global Perspectives. – Boston, MA: Springer US, 2009. – С. 93-114.

22. Pickett J. E., White K. M., White C. C. Service Life Prediction of Polymers and Plastics Exposed to Outdoor Weathering. William Andrew Publishing, 2018. – P. 1-18.

23. Brown, R. A review of accelerated durability tests. VAMAS Report. 1995.

24. Celina M., Gillen K. T., Assink R. A. Polymer Degradation and stability. 2005. Vol. 90. №. 3. P. 395-404.

25. Davydov A. D., Kovalev M., Lyashenko D. Evaluation of Protective Properties of Lacquer Coatings on Copper Products Operating in a Low Aggressive Corrosive Environment // Key Engineering Materials. – 2023. – Т. 943. – С. 135-141.