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POLYURETHANE PROTECTIVE MATERIALS: VISCOELASTIC AND TRIBOLOGICAL PROPERTIES

In order to spread the practice of using polyurethanes previously developed by us as polyurethane anticorrosive coatings (PAC), in addition to their resistance to the action of various destructors. It is also important to resist deformational dynamic loads, which can lead to the destruction of adhesive bonds between the polymer and the surface to be protected, as well as mechanical loads, in particular abrasion. Studies of the PAC based on the blend of network polyurethane/aromatic linear polyurethane NPU/LPU 70/30 and aliphatic linear/aromatic network polyurethane APU/NPU 80/20, reproduced for the verification of the main properties showed that the PAC based on NPU/LPU70/30, APU/NPU 80/20 are characterized by high adhesion — their adhesive strength is less than a point, and have high cohesion indicators: 40.3/40.0 kg/cm^2 respectively. The introduction of inorganic pigments increases these values to 40.3 and 43.7 kg/cm^2, respectively. The thermal stability of both types of PM is estimated at 260 °C, the addition of 5 % inorganic pigment increases this figure to 270 °C, also for both polymers. PACs are resistant to the action of abiotic destructors: distilled and sea water, ethyl acetate, diesel fuel, aviation gasoline, 20 % solutions of H_2SO_4 and KOH, and are also resistant to the flow of complex atmospheric factor NPU/LPU70/30, APU/NPU80/20 retain strength by 82 / 95%, respectively. The introduction of inorganic pigment, 5%, increases the resistance to 115 / 99%. PACs are resistant to dynamic deformation loads, which is confirmed by the presence of damping properties of coatings at temperatures close to the temperatures of use of coatings — tan δ more than 0.1. The use of inorganic pigments increases this indicator — to 0.175. The produced polyurethanes are resistant to abrasion. At the application of a load during the test, which significantly exceeds the practice of using polymeric protective coatings, this value is 0.001 g/cm^2 — 0.006 g/cm^2.

By analogy with building codes, the polymers obtained can be used under certain conditions (load) as protective polymer coatings with anti-slip properties — since their coefficient of friction μ > 0.5. In general, they can be used as matrices for obtaining various protective coatings using functional modifiers and fillers.

***Keywords**: Polyurethanes, coating, protection, resistance, destruction*

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Introduction

An urgent problem today in many sectors of the economy, particularly in construction, infrastructure, housing and communal services and other industries, is the creation of new, more effective, durable and economical materials with specially improved properties as multifunctional coatings and impregnating compositions to extend the life of new and existing structures and objects [1]. The use of polymer compositions with programmed properties allows the creation of fundamentally new technologies for corrosion protection of various types of surfaces operating under conditions of loading by aggressive factors of man-made and natural origin.

The use of polyurethanes, due to the block structure of their macrochain, as a matrix for the creation of protective materials, by introducing into their structure functional reactive compounds of organic and organometallic nature, as well as compounds capable of forming intermolecular bonds with urethane fragments of the macrochain, allows the creation of multifunctional polymers resistant to the action of biotic and abiotic destructors [2—8]. We have previously prepared polyurethanes resistant to the action of various destructors [9, 10].

However, for the expansion of their application it is also important to resist deformational dynamic loads, which can lead to the destruction of adhesive bonds between the polymer and the protected surface and mechanical (abrasion). From the point of view of the maintenance of such coatings, the tribological properties of the coatings (coefficient of friction) are also important [11]. This was the aim of our research.

Experimental

Materials

Polyurethane anticorrosive coatings PAC (matrix) based on aromatic network/linear polyurethanes in a ratio of 70/30 ($NPU/LPU_{70/30}$) and aliphatic linear/aromatic network polyurethanes in a ratio of 80/20, respectively, ($APU/NPU_{80/20}$)

Methods

Physical-mechanical properties, namely adhesive properties, were determined in accordance with the current regulatory documentation. Cohesion strength, σ — beyond the tensile strength limit was determined in accordance with the current regulatory documentation and relative elongation ε was determined in accordance with the current regulatory documentation. The reproducibility of the values was verified based on the results of more than five parallel tests. Samples of PAC films of the original type and with different pigment contents for determining cohesive properties were obtained as follows: a sample of the PAC solution was poured into a polyethylene mold, dried for 24 hours in a drying oven at a temperature of 40 °C, then degassed for 5 hours under vacuum at a temperature of 30 °C and kept for (24—48) hours at room temperature.

The viability of the PAC solution was determined visually by daily observation until gelation. To determine this, samples of the original APP and those obtained with different contents of the inorganic pigment were used, which were placed in dark-colored chemical beakers with ground stoppers (to ensure tightness) with a capacity of 150 ml in the amount of 120—130 ml of PAC.

The thermal stability of the PAC film samples was determined by thermogravimetry (Derivatograph Q-1000, MOM Hungary). The temperature of 5% weight loss was considered as the temperature of the onset of destruction.

Testing of the PAC based on $NPU/LPU_{70/30}$, $APU/NPU_{80/20}$ with respect to the influence of complex atmospheric factors: UV and IR radiation (sunlight), elevated temperature (50 ± 5) °C and air humidity (96 %) was conducted in a climatic chamber for 120 hours.

Resistance to water, gasoline and chemical environments has been determined in accordance with current regulatory documentation.

The viscoelastic properties of the $NPU/LPU_{70/30}$, $APU/NPU_{80/20}$ and $NPU/LPU_{70/30}$/pigment samples were investigated by the dynamic mechanical analysis (DMA) method using the DMA Q800 analyzer (TA Instruments, USA). Measurements of elastic modulus (E’), mechanical loss modulus (E”), and mechanical loss tangent (tan δ) were performed in tensile mode at a frequency of forced sinusoidal oscillations of 1 Hz in the temperature range of −70 to 200 °C with a heating rate of 3 °C/min. Samples with dimensions of (30 × 5 × 1) mm were used for the study.

The measurement of the friction coefficient of the polymer coating applied to the surface of a metal plate was determined in accordance with the current regulatory documentation. The friction coefficient is determined experimentally. The essence of the method is to determine the friction force that occurs when a rubber rod moves relative to the test specimen at a constant speed and with a constant pressure of the rod on the test surface. The coefficient of friction is determined by the ratio of the friction force to the normal force pressing the rubber rod against the test surface. The method allows testing on various surfaces in dry, wetted and oiled states.

The tests were performed using a device equipped with an electronic dynamometer to determine the friction force. The device includes clamps for the tested surface, a loading system consisting of a carriage and weights in the form of laboratory weights. The coefficient of friction of the tested samples (metal coating) was determined on a dry surface, a wet surface and a surface with oil. Before the tests, the contacting surfaces were wiped with ethyl alcohol. When testing on a surface with oil, the latter was applied with a brush in a thin uniform layer without gaps, and on a wet surface — it was evenly moistened. Industrial oil I-20 was used as a lubricant. For each sample, five parallel measurements were made with a stepwise increase in the normal load. In this case, the value of the normal load was 110, 210 and 510 grams, taking into account the weight of the rubber bar.

The coefficient of friction shows how exactly the friction force depends on the force of the normal reaction (external weight), what fraction of it it is. The coefficient of friction is a dimensionless quantity and has different values for different friction pairs:

$$\mu = \frac{F_{av}}{N},$$

where F_{av} — is the arithmetic mean value of the friction forces determined for all the groups of specimens tested; N — is the load pressing the rubber rod against the specimens tested.

The determination of abrasion resistance of $NPU/LPU_{70/30}$, $APU/NPU_{80/20}$ was determined according to [12]. For this purpose, the surfaces of concrete cubes measuring 70 × 70 × 70 mm were covered with PAC and kept for 15—20 days at a temperature of (20—25) °C and the abrasion resistance of the obtained PAC was tested using corundum as an abrasive under conditions of 30 m/28 revolutions of the path. t should be noted that the loads applied and the duration of the test are much higher than those used in practice in the application of polymeric protective coatings.

Results and discussions

Network polyurethane (NPU) is obtained by synthesizing a precursor — the product of the interaction of 2,4(2,6)-toluene diisocyanate and trimethylolpropane (TDI/TMP) in a molar ratio of 3:1, respectively, in ethyl acetate (EA) in a ratio of precursor (TDI/TMP):EA = (7:3), a chain extender (polyether L-1000 or P-1000) is added in a mass ratio of TDI/TMP/EA:PL = 100:40, respectively, the reaction mixture is homogenized by intensive stirring, linear polyurethane (LPU — the product of the interaction of TDI and polyether L-1000 in a molar ratio of TDI:L-1000 = 2:1) is added with intensive stirring in a percentage ratio of NPU:LPU = = 70:30 ($NPU/LPU_{70/30}$), respectively, EA is added in a mass ratio of $NPU/LPU_{70/30}$:EA = 1:1, respectively, homogenized by mixing and poured into films, or inorganic pigment (5—10 wt. %) is added, homogenized by mixing and poured into films (for storage hermetically sealed in special containers). Obtain the original $NPU/LPU_{70/30}$ PAC and with different pigment content.

The synthesis of polyurethanes based on aliphatic hexamethylene diisocyanate (HMDI) is carried out as follows: HMDI is mixed with L-1000 in the molar ratio NCO:OH = 2:1, network polyurethane (NPU) — the product of the interaction of toluene diisocyanate (TDI) and trimethylolpropane is added in the percentage ratio HMDI/L-1000:NPU 80:20 are mixed intensively, cooled to room temperature by stirring, EA is added in the ratio HMDI/L/NPU:EA = 1:1, the reaction mixture is homogenized by intensive stirring and hermetically sealed, or pigment (5-10 %) is added, homogenized by stirring and films are cast (for storage hermetically sealed in special containers). The initial APU/NPU80/20 APP is obtained, as well as with different pigment contents.

Studies of physical-mechanical properties showed that the $NPU/LPU_{70/30}/APU/NPU_{80/20}$ both types PAC are characterized by high adhesion, their adhesion strength is less than one point and have high cohesion indicators, which are 40.0; 40.3 MPa for $NPU/LPU_{70/30}$ without pigment and with a 5 % pigment content, respectively, and 40.0; 43.7 MPa for $APU/NPU_{80/20}$. The thermal stability of both types of PACs is estimated at 260 °C, and the addition of 5 % inorganic pigment in an amount of 5 % increases this indicator to 270 °C also for both polymers.

The results of the study of the influence of complex atmospheric factors: UV and IR radiation (sunlight), elevated temperature (50 ± 5) °C and air humidity (96 %) on the properties of PAC based on NPU/LPU$_{70/30}$, APU/NPU$_{80/20}$ — cohesive strength, σ, before/after the climatic chamber (30 days) is equal for NPU/LPU$_{70/30}$ — 40.0/32.6 MPa, for APU/NPU$_{80/20}$ — 43.0/40.7 MPa. Relative elongation, ε, before/after the climate chamber (30 days) NPU/LPU$_{70/30}$ — 200.0/100 %, for APU/NPU$_{80/20}$ — 40.7/29.0 %. For PAC samples containing 5 % pigment, an increase in the values of both σ and ε is observed — up to 40.3/40.7 for NPU/LPU$_{70/30}$ and APU/NPU$_{80/20}$: 43.7 — 43.6, respectively. It should be noted the greater stability of the APU/NPU$_{80/20}$ polymer, which is explained by the aliphatic nature of the polymer, in contrast to polymers of aromatic nature, which are characterized by the formation of quinoid structures under the influence of light irradiation, which leads to photodestruction of polymers. It should be noted the influence of the pigment in increasing the resistance of NPU/LPU$_{70/30}$ to the action of complex atmospheric factors.

The results of the study of the resistance to chemical media of samples of PAC and PAC with pigment are presented in Table 1, which shows that the resulting coatings are resistant to water, oil, gasoline, diesel fuel, organic solvents, dilute acids and alkalis, and the weight gain (loss) during exposure to chemical agents for 90 days is given in Table 1.

The results of the study show a slight increase in distilled and sea water of the studied PACs NPU/LPU$_{70/30}$ and APU/NPU$_{80/20}$ both without pigment and with pigment and demonstrate the resistance of PACs NPU/LPU$_{70/30}$ and APU/NPU$_{80/20}$ to the action of gasoline, diesel fuel, 20 % aqueous solution of potassium hydroxide, 20 % aqueous solution of sulfuric acid and ethyl acetate (Table 1). Thus, PACs based on NPU/LPU$_{70/30}$ and APU/NPU$_{80/20}$ were found to be resistant to water, oil, gasoline, diesel fuel, organic solvents, dilute acids and alkalis.

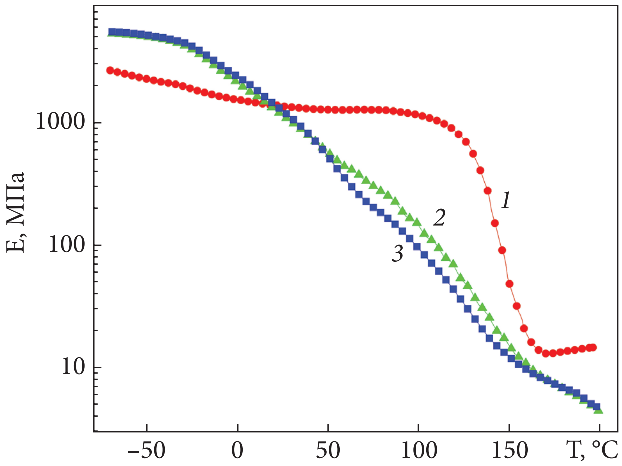


Fig. 1. Temperature moduli of elasticity E' for the sample NPU/LPU$_{70/30}$ (*1*), the sample NPU/LPU$_{70/30}$/pigment$_5$ (*2*) and the sample APU/NPU$_{80/20}$ (*3*)

It is well known that DMA is one of the most commonly used methods to determine the viscoelastic properties of polymers in order to obtain information about their structural characteristics [13].

The viscoelastic properties of the NPU/LPU$_{70/30}$ (1), NPU/LPU$_{70/30}$/pigment$_5$ (2) and APU/NPU$_{80/20}$ (3) samples are shown by the temperature dependence of E' (Fig. 1), tan δ (Fig. 2) and E" (Fig. 3). Table 2 shows their glass transition temperatures (Tc), which were determined by the position of the maximum on the temperature dependence of tan δ, as well as the viscoelastic properties at temperatures close to the service temperatures of the material, namely: T = −10 °C, T = 25 °C and T = 50 °C.

Table 1. **Study of resistance to chemical mediums of PACbased on NPU/LPU$_{70/30}$ and APU/NPU$_{80/20}$, original and with pigment (5 %)**

PC	Weight gain (loss) of PAC samples based on NPU/LPU$_{70/30}$ APU/NPU$_{80/20}$ initial and with inoganic pigment after exposure to chemical agents for 90 days						
	Water$_{dist}$	Water$_{marine}$	EA	Diesel fuel	Gasoline-aviation	H_2SO_4 solution, 20%	KOH solution, 20%
NPU/LPU$_{70/30}$	–0,97	0,804	–9,99	0,36	0,57	–0,42	–0,23
APU/NPU$_{80/20}$	–1,0	–0,17	–14,9	3,94	0,55	–0,74	–0,31
NPU/LPU$_{70/30}$ / pigment$_{5\,\%}$	0,11	0,34	0,04	–2,6	0,27	11,94	–0,03
APU/NPU$_{80/20}$ pigment$_{5\,\%}$	–0,44	0,87	–9,02	3,37	–3,14	–0,30	–0,18

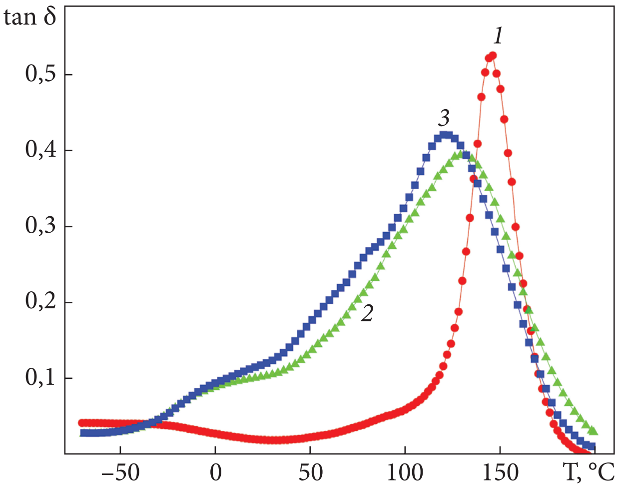


Fig. 2. Temperature dependences of the mechanical loss tangent tan δ for the NPU/LPU$_{70/30}$ sample (*1*), the NPU/LPU$_{70/30}$/pigment$_5$ sample (*2*) and the APU/NPU$_{80/20}$ sample (*3*)

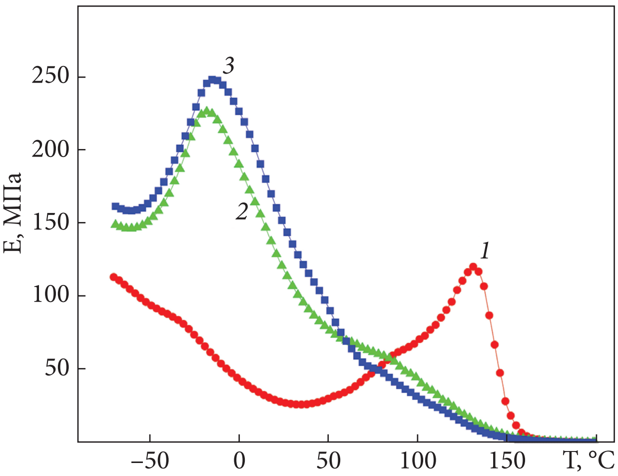


Fig. 3. Temperature dependences of the loss modulus E" for the NPU/LPU$_{70/30}$ sample (*1*), the NPU/LPU$_{70/30}$/pigment$_5$ sample (*2*) and the APU/NPU$_{80/20}$ sample (*3*)

It is shown that the values of E' of the studied samples are determined by the structure of the material and depend on the temperature, but all synthesized polymers are characterized by high elastic modulus indices. It was found that the T_c of samples 2 and 3 is lower than that of sample 1, and the maximum tan δ expands significantly towards lower temperatures (Fig. 2), indicating an increase in structural heterogeneity in samples 2 and 3. Sample 3 showed the lowest Tc value and the highest E" and tan δ indices, indicating a higher damping capability of this polymer material [13].

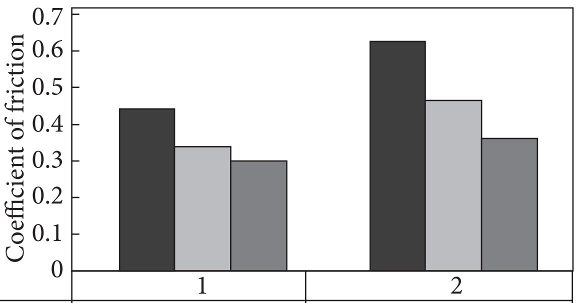
PAC are resistant to dynamic deformation loads, which is confirmed by the presence of damping properties of coatings at temperatures close to the temperatures of use of coatings -tan δ greater than 0.1.

Study of the tribological properties of PAC based on aromatic polyurethanes NPU/LPU$_{70/30}$. According to modern concepts, friction has a dual molecular — mechanical nature [14]. On the planes of actual contact of surfaces, molecular attraction forces act, forming adhesive bonds. Relative displacement of bodies causes their destruction, which requires energy expenditure in an irreversible form. The mechanical component of the friction force depends on the depth of penetration of the protrusions of one body into another and is a complex function of the load, geometric and physical-mechanical properties of the surface. Given the variety of factors that affect the magnitude of the friction force, the friction coefficient is determined experimentally.

The force of external friction is the resistance force that occurs when one body is displaced along the surface of another and is directed tangentially to the common boundary between the two bodies. In engineering calculations, the friction force is calculated as a fraction of the normal component of the pressure reaction of the rubbing surfaces. This approach allows you to minimize the number of unknown forces in the dynamic equations of motion of friction pairs. Then the friction force: F = μN, where N is the normal component of the reaction of the rubbing surfaces, and μ is the friction coefficient.

Table 2. **Viscoelastic properties of PAC samples**

Sample	PAC	T_c, °C	E', МПа			E", МПа			tan δ		
			Temperature, °C								
			−10	*25*	*50*	*−10*	*25*	*50*	*−10*	*25*	*50*
1	NPU/LPU$_{70/30}$	145	1650	1370	1280	54	27	30	0,033	0,020	0,023
2	NPU/LPU$_{70/30}$/pigment$_5$	130	2730	1150	574	215	118	77	0,080	0,103	0,135
3	APU/NPU$_{80/20}$	120	3018	1255	532	246	149	93	0,082	0,119	0,175



	1	2
■ Dry	0.44	0.62
■ Wetted	0.34	0.46
■ Oiled	0.3	0.36

Fig. 4. Average values of the coefficient of friction of different coatings on metal in different media

The samples of coatings on metal were examined: No. 1 — metal not protected by polymer, No. 2 — metal protected by polymer NPU/LPU$_{70/30}$. The test results were taken as the arithmetic mean of the test results at different loads, the calculated values are given in Table 3.

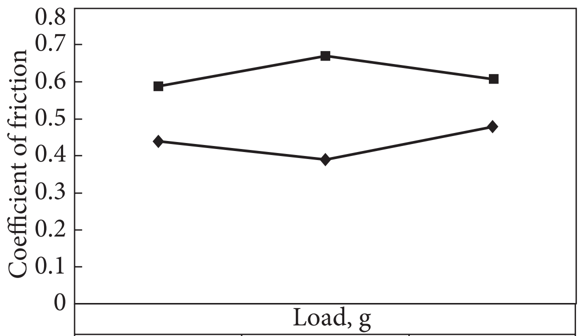
Fig. 4 shows the average values of the friction coefficient measurements of coatings on metal in different states — dry, wet, and oiled.

After analyzing the test results, the following conclusions can be drawn: the coefficient of friction on a dry metal surface increases from 0.44 to 0.62 for polymer-coated metal, from 0.34 to 0.46 for wetted surface, and from 0.3 to 0.36 for oil-coated surface. To evaluate the influence of normal load on the coefficient of friction, the arithmetic mean of five parallel tests was calculated for each load. Figures 5, 6 and 7 show the results of friction coefficient measurements for different conditions.

From the presented data, it is clear that for all media the friction coefficient increases relative to the metal surface not protected by the polymer. At the same time, the dependence of the friction coefficient on the load is ambiguous. For example,

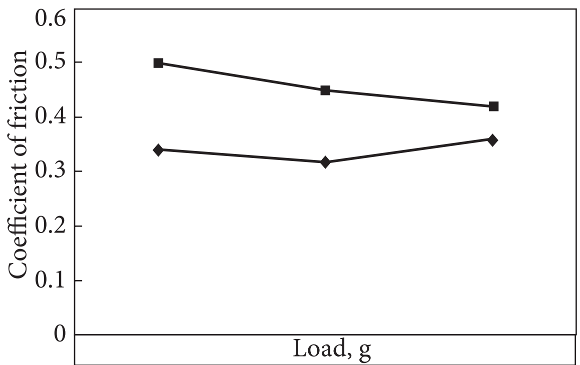
Table 3. **Average value of the friction coefficient**

Load, g	Average value of the coefficient of friction at different loads and different mediums					
	Dry surface / sample no.		Wet surface/ sample no.		Oiled surface / sample no.	
	1	2	1	2	1	2
110	0.442	0.591	0.342	0.5	0.304	0.394
210	0.340	0.667	0.324	0.453	0.278	0.417
510	0.477	0.613	0.364	0.418	0.306	0.275



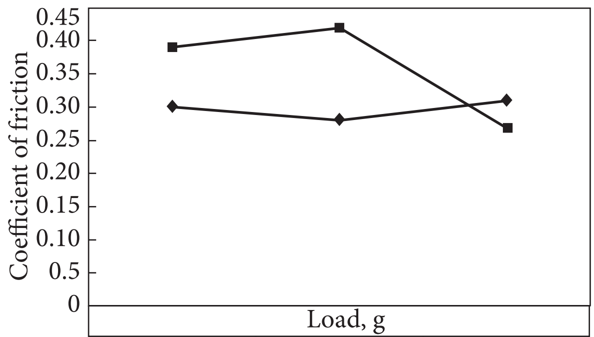
	110	210	510
No. 1	0.44	0.39	0.48
No. 2	0.59	0.67	0.61

Fig. 5. Dependence of the coefficient of friction on the load (dry metal surface)



	110	210	510
No. 1	0.34	0.32	0.36
No. 2	0.5	0.45	0.42

Fig. 6. Dependence of the coefficient of friction on the load (wet metal)



	110	210	510
No. 1	0.3	0.28	0.31
No. 2	0.39	0.42	0.27

Fig. 7. Dependence of the friction coefficient on the load (oiled metal)

for a dry and oiled metal surface protected by the polymer, it is extreme as the load increases, whereas for a wet surface, there is a monotonic decrease.

Table 4. **Results of abrasion tests of polyurethane anticorrosive coating (PAC)**

Sampe	APC	Mass of the sample (concrete cube, protected by an PAC) before testing, g	Test load, g	Sample area, cm^2	Erasability, g /cm^2
1	$NPU/LPU_{70/30}$	738,3	2020,4	49,35	0,002
2	$NPU/LPU_{70/30}$ / $pigment_5$	787,4	2020,4	49,70	0,001
3	$APU/NPU_{80/20}$	741,7	2020,4	48,28	0,006

The abrasion test of the coating samples was carried out on concrete under experimental conditions: 30 m /28 revolutions of the path. The results of the study are shown in Table 4.

The results of the abrasion resistance tests of the protective polymer coating show that the PAC are resistant to abrasion and this indicator ranges from 0.001 g/cm^2 to 0.006 g/cm^2.

CONCLUSIONS

1. Studies of physical and mechanical properties showed that the $NPU/LPU_{70/30}$, $APU/NPU_{80/20}$ PAC are characterized by high adhesion — their adhesion strength is less than one point, and have high cohesion indicators: 40.3 / 40.0 kg/cm^2, respectively. The introduction of inorganic pigment increases these indicators to 40.3 and 43.7 kg/cm^2, respectively. The thermal stability of both types of PACs is estimated at 260 °C, the addition of 5 wt.% inorganic pigment increases this indicator to 270 °C, also for both polymers.

2. PAC are resistant to the action of abiotic destructors: distilled and sea water, ethyl acetate, diesel fuel, aviation gasoline, 20 % solutions of H_2SO_4 and KOH. According to the data of the study of the influence of the complex atmospheric factor $APU/LPU_{70/30}$, $APU/NPU_{80/20}$ retain strength by 82 % / 95 %, respectively. The introduction of inorganic pigment (5 wt. %), increases the resistance to 115 / 99 %. The higher resistance of the $APU/NPU_{80/20}$ polymer is explained by the aliphatic nature of the polymer, in contrast to aromatic polymers, which are characterized by the formation of quinoid structures under the influence of light irradiation, which leads to photodestruction of polymers.

3. PAC are resistant to dynamic deformation loads, which is confirmed by the presence of damping properties of coatings at temperatures close to the temperatures of use of coatings — tan δ more than 0.1. The use of inorganic pigment increases this indicator — up to 0.175.

4. Polyurethane anticorrosive coatings are resistant to abrasion. When applying a load during testing, which significantly exceeds that which exists in the practice of using polymer protective coatings, this indicator is 0.001 g/cm^2 — 0.006 g/cm^2.

5. According to building regulations, the obtained polymers can be used under certain conditions (environment, load) as protective polymer coatings with anti-slip properties — since their friction coefficient $\mu > 0.5$. In general, they can be used as matrices for obtaining such coatings using functional modifiers and fillers.

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ПОЛІУРЕТАНОВІ ЗАХИСНІ МАТЕРІАЛИ:
В'ЯЗКО-ПРУЖНІ ТА ТРИБОЛОГІЧНІ ВЛАСТИВОСТІ

Для поширення практики застосування створених нами раніше поліуретанів як захисних антикорозійних полімерних покриттів (АПП), крім їхньої стійкості до дії різноманітних деструкторів, важлива також здатність до протистояння деформаційним динамічним навантаженням, які можуть призвести до руйнування адгезійних зв'язків полімеру та захищуваної поверхні, і механічним навантаженням, зокрема стиранню. Дослідження АПП на основі сумішей ароматичний лінійний/сітчастий поліуретан СПУ/ЛПУ$_{70/30}$ і ароматичний сітчастий/лінійний аліфатичний поліуретан АлПУ/СПУ$_{80/20}$, відтворені для верифікації основних властивостей, показали, що ці матеріали характеризуються високою адгезією — адгезійна міцність менше одного бала, та мають високі показники когезії 40,3 і 40,0 кг/см^2. Введення неорганічного пігменту підвищує ці показники до 40,3 і 43,7 кг/ см^2 відповідно. АПП обох типів термостабільні до T = 260 °C, додавання 5 % неорганічного пігменту підвищує цей показник до 270 °C. АПП стійкі до дії абіотичних деструкторів: води дистильованої та морської, етилацетату, дизельного палива, авіабензину, 20 %-вих розчинів H_2SO_4 і KOH, а також до впливу комплексного атмосферного фактора — СПУ/ЛПУ$_{70/30}$ і АлПУ/СПУ$_{80/20}$ зберігають 82 і 95 % міцності. Введення 5 % неорганічного пігменту підвищує стійкість до 115 і 99 %. АПП стійкі до дії динамічних деформаційних навантажень, що підтверджено наявністю демпфірувальних властивостей покриттів за температури, наближеної до температури використання покриттів — tan δ понад 0,1, за наявності пігменту — 0,175. Створені поліуретани стійкі до стирання: показник стиранності становить 0,001—0,006 г/см^2 за випробувального навантаження, яке істотно перевищує практичні навантаження при застосуванні полімерних захисних покриттів. За аналогією з будівельними нормами отримані полімери за певних умов (середовище, навантаження) можуть бути використані як захисні полімерні покриття з нековзними властивостями, оскільки їхній коефіцієнт тертя μ > 0,5, а загалом — як матриці для отримання захисних покриттів з використанням функціональних модифікаторів і наповнювачів.

Ключові слова: поліуретани, покриття, захист, стійкість, деструкція хімічна, динамічна, механічна.