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THE EFFECT OF NANOCARBON ON THE MECHANICAL PROPERTIES OF HIGH-PRESSURE POLYETHYLENE

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ABSTRACT

New polymer nanocomposites based on high-pressure polyethylene grade 10803-020 and carbon nanotubes were developed, and the conditions for obtaining nanocomposites with optimal physical properties were determined. The primary goal of this work was to incorporate carbon nanotubes into polyethylene to produce nanocomposites with superior properties for construction applications. The composition and concentration of the nanoadditive which led to significant improvement in the electromechanical properties of high-pressure polyethylene were experimentally determined. Nanocarbon was used as a modifying additive. The developed nanocomposite is notable for the first-time introduction of a very small amount of nanocarbon into HPPE, varying within 0.01–0.1 mass %. It was found that including 0.05 mass % nanocarbon in high-pressure polyethylene significantly increases its mechanical strength.

The physicochemical changes in the resulting composite materials under electrical discharges in air and UV radiation were studied. It was shown that adding 0.05 mass % nanocarbon significantly enhances the material's resistance to electrical discharges and UV radiation. Considering the characteristics and technical parameters of high-pressure polyethylene + 0.05 mass % nanocarbon, this material can be widely used in various industries, including construction.

1.Introduction

Carbon nanotubes have been widely used in construction since the 1980s to strengthen structures in seismically active zones, such as California. They have proven effective in improving various materials, including reinforced concrete, metal, and stone [1]. Most commonly, carbon nanotubes are utilized to reinforce concrete structures. Durable surface layers for road pavements have been developed, using a "Carbon-polymer" binder. Structural panels

are employed in the construction of wall enclosures for low-rise buildings in cold climate regions. A distinguishing feature of these panels is the use of multi-layered insulating boards containing carbon. For enhanced thermal insulation with greater compression strength, carbon dioxide is used in the production process. Carbon particles are also added to professional-grade insulation boards used for roofing large areas such as shopping centers, industrial facilities, and residential complexes. Beyond construction, nanocarbon finds applications in other industries, including automotive, aviation, aerospace, sports equipment, medicine, and electronics [2–6]. Recently, carbon has started to influence interior design as well.

All the aforementioned data have led to the rapid growth of research into the physicochemical properties of nanoparticles and polymer composites based on them in recent decades [7]. Due to the small size of organic and inorganic nanoparticles, comparable to that of macromolecules, polymer nanocomposites exhibit unique electronic, photophysical, sensory, and other properties. Literature indicates the potential for significantly improving the physicomechanical properties of polymer compositions and materials through relatively small additions of nanodispersed powders [8]. The small size and surface properties of nanoparticles play a crucial role in determining their "compatibility" with the polymer matrix. Research efforts have focused on solving problems related to the distribution of carbon nanotubes (CNT) and enhancing the final properties of the composite. In [9], it was found that nanocomposites exhibit superior thermal stability compared to polyolefin materials, and it was demonstrated that the inclusion of nanotubes affects the crystalline behavior and structure of the polyethylene matrix. Studies [4–6] have explored the challenges faced by polyolefin-based composites in terms of manufacturing processes and industrial production of components for advanced engineering applications.

In [10-12], the study revealed that materials with carbon nanotubes possess exceptional qualities such as high strength, lightweight, corrosion resistance, and the ability to enhance structural rigidity and thermal conductivity. The use of nanofillers based on nanotechnology allows for the development of polymers that combine traditional and new qualitative characteristics, which may initially seem mutually exclusive. This is particularly beneficial in cases where it is necessary to simultaneously ensure transparency and flexibility, a certain degree of impact resistance and rigidity, as well as specific physical, insulating, and conductive properties.

The aim of this work is to develop a nanocomposite based on high-pressure polyethylene (HPPE) with nanocarbon additives to produce materials with enhanced mechanical and dielectric properties, improved thermal resistance, and reduced aging rate of the film during operation.

2. Methodology and Experimental

The study focused on HPPE grade 10803-020 as the base material, with carbon used as the additive. Carbon, represented by the symbol (C), manifests in various forms such as soft graphite and hard diamond [13] and disperses well in molten polymers. Additives of multi-layer carbon nanotubes in the range of 0.01–0.1 mass% were incorporated into the HPPE matrix via mechanical mixing in the molten state (table 1). For the production of films, a manual electrically heated hydraulic press (PG-60 model) was employed. The prepared HPPE – CNT mixture was loaded into a polished flat mold with a spacer thickness of 0.1 mm. To prevent adhesion, a fluoroplastic film (foil) was used. The mold was heated to 140–150°C and compressed under a pressure of 150 atm. After cooling, the films were extracted from the mold. The resulting films,

with a thickness of 60–80 μm, were used to prepare samples for the measurement of physical, mechanical, electrical, and optical properties.

Table 1. Characteristics of Multi-Layer Carbon Nanotubes

Indicator	**Physicochemical characteristics of** multi-layer CNT
1 Appearance	Black powder
2 Number of walls	8-9
3 Length	>100 mkm
4 Specific surface area	190 m^2/q
5 Average diameter	12-13 nm
6 Bulk density	0,056 kg/dm^3
7 Purity, at least	85 %

The uniformity of the films was assessed by measuring their thickness across the entire surface. Film thickness was determined using an optical thickness gauge (N3B-2) and a micrometer. The thickness value of each sample represents the arithmetic mean of 10 measurements.

UV irradiation was provided by the DRSH-500 light source. The main components of the light source are a spherical mercury-quartz lamp of high pressure (type DRSH-500) and a semi-spherical reflector (fig.1). The DRSH-500 mercury-quartz lamp is a powerful, concentrated radiation source in the visible and ultraviolet parts of the spectrum. The lamp operates in a confined space (housing) under conditions where the housing size and ventilation are such that the air temperature at a distance of 60 mm from the walls does not exceed 250°C.

A sample with a thickness of 50 μm, supported by an duralumin frame using a holder, is mounted on a stand. UV rays are directed towards the center of the melt. The distance from the source to the sample is 250 mm. The distance of 250–200 mm enhances the effect of UV irradiation (aging).

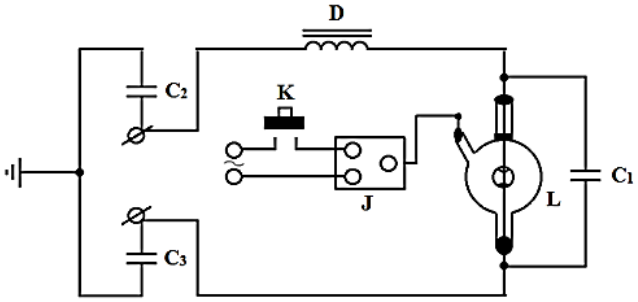

Figure.1. Ignition block for the DRSH-500 lamp: D – ballast; L – lamp; K – end switch;
J – ignition inductor with spark length of 15-20 mm; C1 – capacitor for shunting the lamp with a capacitance of 0.05 μF, rated for at least 250V; C2, C3 – capacitors with capacitance of 0.5 μF for grounding the network, with a rated voltage of at least 250V. Calibration of the effective UV radiation is attempted every 300 hours.

UV rays hit the sample at a right angle. The experiment was conducted at room temperature (20°C). The experimental procedure is as follows: the lamp is clamped using an inductor with a spark length of 15-20 mm. The nominal voltage on the lamp is 70V, with a current of 7.5A. This generates a nominal light flux of 22,500 lm. The sample was irradiated for 15 and 30 hours.

Measurement of mechanical durability σ, i.e. the time elapsed from the moment of sample loading to its fracture, at different load values in the test cell, is shown in fig. 2.

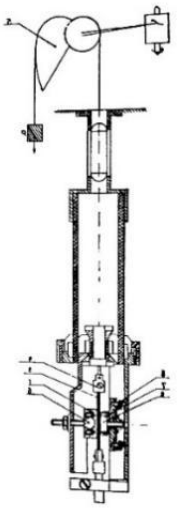

Figure. 2. Setup for determining the mechanical strength of polymer film materials: 1, 2 - electrodes; 3 - sample; 4 - clamps; 5 - lever mechanism; 6 - ball; 7 - safety ring; 8 - springs.

3. Results and discussions

In fig.3, the graphs show the dependence of the logarithm of the durability time $\lg\tau_\sigma$ on the mechanical stress of the HPPE film without additives and the influence of CNT additives containing 0.01-0.1 mass%. As can be seen from fig. 3, the time dependence of the strength is characteristic for all the investigated materials, and the relationship between durability and stress follows an exponential law:

$$\tau = Ae^{-\alpha\sigma} \qquad (1)$$

here A is the coefficient, α is the structurally sensitive coefficient, which depend on the nature of the material being studied and the test temperature [14].

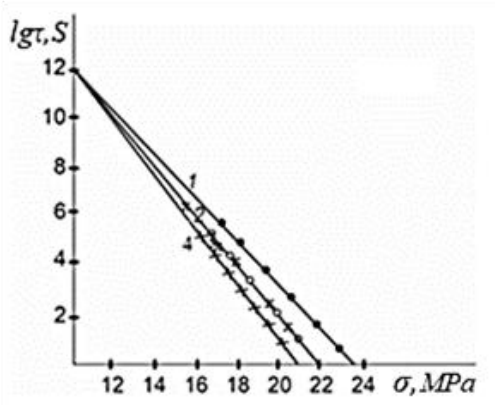

Figure.3. Stress dependence of the mechanical durability of HPPE film (initial) and its modifications: 1 - HPPE + 0.05 mass% CNT, 2 - HPPE (initial), 3 - HPPE + 0.03 mass% CNT, 4 - HPPE + 0.1 mass% CNT.

From fig.3, it is evident that the introduction of a small amount of CNT into HPPE leads to an increase in its mechanical strength, i.e., an improvement in the strength properties of HPPE when 0.05 mass% CNT is added (line 1) compared to HPPE without additives (line 2) and HPPE + 0.03 mass% (line 3). As the CNT content increases further (up to 0.1 mass%), a sharp decrease in the material's mechanical strength is observed (line 4).

Based on the experimental results, it can be concluded that the observed increase in the strength properties of HPPE when 0.05 mass% CNT is added is related to a change in the coefficient α, as α—the structural coefficient—depends not only on the nature of the material but also on its structure.

As follows from the obtained experimental results, the introduction of the optimal content of the proposed CNT additive into HPPE leads to an increase in mechanical strength by more than 15%. The optimal concentration of the additive depends on the specific application area of the polymer matrix. Therefore, when using organic and inorganic additives, it is recommended to determine the optimal concentration through tests with several different concentrations. After multiple experimental studies of the physico-mechanical properties, the effectiveness of adding 0.05 mass% CNT was proven.

It is known that the linear dependence of lgτ on σ is valid at different temperatures. Through prolonged mechanical testing of the material, the temperature-time dependence of the material's mechanical strength was determined.

For practical purposes, the most significant interest lies in determining the mechanical durability at different temperatures. To verify this, the durability dependence on mechanical stress was studied in the temperature range of 223 - 138 K for HPPE films and their optimal modification.

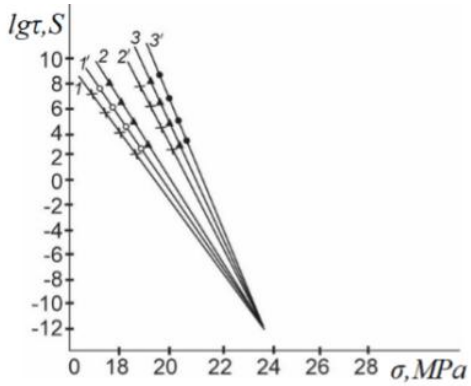

Figure.4. Strength dependence of the durability of HPPE film (1-3) and its optimal modification (1'-3') at different temperatures.

1, 2' - 173 K; 2 - 153 K; 3, 3' - 138 K; 1' - 223 K

It follows from fig. 4 that for all films in the investigated temperature range, the well-known durability equation (1) is satisfied at a constant temperature. According to experimental studies, when the optimal amount of additives (HPPE + 0.05 mass% CNT) is introduced, there is an increase in its mechanical strength (line 1') and a slight decrease in the lifetime at different temperatures (lines 2', 3'), whereas for the CNT -free film, a decrease in strength is observed (1, 2, and 3).

The change in mechanical strength of HPPE and its optimal modification as a function of temperature is depicted by a fan-shaped family of lines, which, when extrapolated, converge at one point – the pole, at a durability value of $\tau_\sigma = 10^{-2}$s.

The increase in the mechanical strength of HPPE at the optimal content (0.05 mass% CNT) is likely related to structural changes occurring after the addition of the additives [15].

Considering the key characteristics and technical parameters, HPPE can be widely used in various industries: from packaging and pipelines to automotive and construction.

The physicomechanical characteristics of HPPE are sensitive to the introduction of nanocarbon additives. A content of 0.05 mass% nanocarbon is optimal as it provides the greatest resistance to mechanical stresses and UV radiation compared to both the original HPPE and HPPE with other additive concentrations.

The introduction of the proposed nanocarbon additive in the specified amount into HPPE prevents processes leading to its electrical aging and UV radiation, thereby enhancing its physicomechanical properties within this temperature range.

Based on this, we have studied the effect of nanocarbon in the optimal amount on the change in mechanical strength under UV radiation in air. The obtained experimental data are presented in fig. 5.

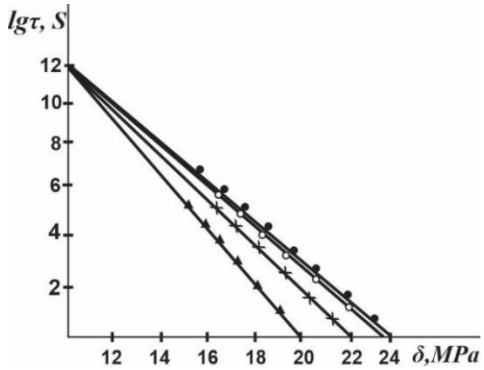

Figure. 5. Strength dependencies of the mechanical durability of the HPPE film and its modification before and after UV radiation in air: 1,2 - HPPE + 0.05 mass% CNT before and after UV radiation; 3,4 - HPPE (original) before and after UV radiation, t_{ob}=15 hours.

From fig. 5, it can be seen that UV radiation on HPPE films without any additives leads to a noticeable decrease in its mechanical strength (lifetime) (line 4). However, under the same conditions, the introduction of the proposed nanocarbon into HPPE, in the optimal amount, contributes to the stability of its modified mechanical properties.

Indeed, when evaluating the data from Figure 4, it becomes evident that the introduction of nanocarbon into HPPE in the optimal amount results in enhanced properties, with the modified HPPE remaining unchanged (line 2) after UV radiation exposure for 15 hours in air. The observed increase in mechanical strength and stability of the HPPE modification can be attributed to the structuring features of the specified additive, which ensures the dense packing of macromolecules during the film formation process.

4. Conclusion

The effect of a small amount of nanocarbon on the mechanical strength of HPPE was studied. Through experimentation, the possibility of obtaining a nanocomposite with physical and mechanical properties based on HPPE grade 103-03-020, with added CNT, was established. The range of filler content was experimentally determined, i.e., the optimal composition of the studied nanocomposite was identified to improve operational characteristics. The developed nanocomposite of HPPE is distinguished by the fact that for the first time, a significant small amount of CNT additives was introduced into the composition of HPPE, varying from 0.01 to 0.1 mass %. It was found that increasing the CNT content in HPPE significantly reduces its mechanical strength, with a positive effect observed only at 0.05 mass% of the additive. It was established that the developed HPPE nanocomposite has relatively enhanced resistance to

electrical and UV radiation exposure. The effect of CNT on the mechanical strength of HPPE at different temperatures was studied. It was determined that CNT in small amounts (0.05 mass%) significantly increases the mechanical strength at various temperatures.

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