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STUDY OF THE MAIN CHARACTERISTICS OF POLYSTYRENE AND PHENOL-FORMALDEHYDE RESIN WASTE

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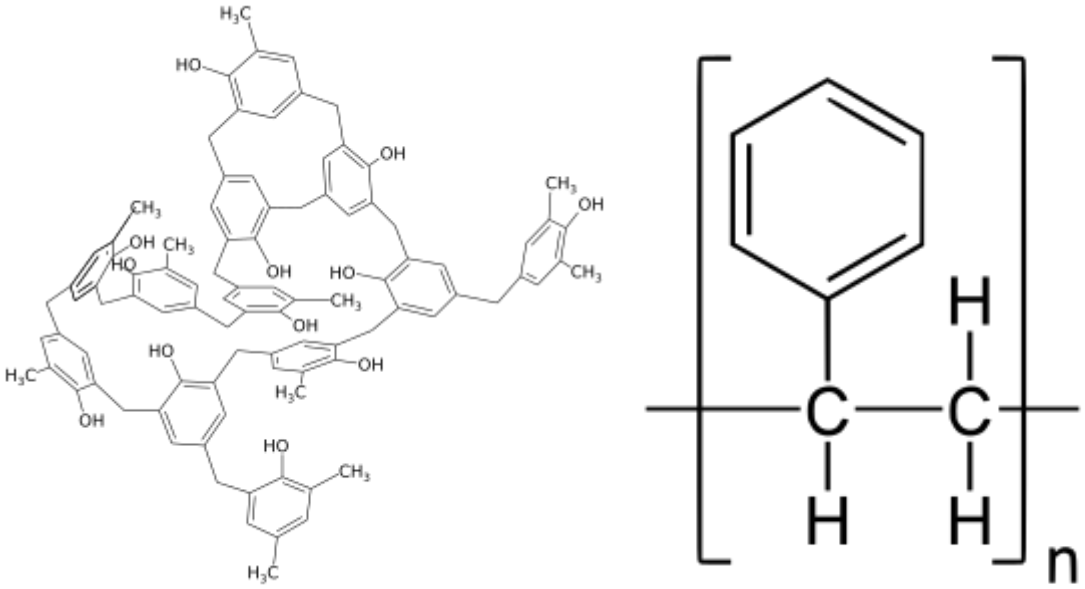
Abstract: This study investigates the physicochemical properties of phenol-formaldehyde resin (PFR) and polystyrene (PS) waste as promising secondary resources for the production of carbon-based adsorbents. A comparative analysis of density, thermal stability, permeability, and mechanical strength was conducted. The results show that PFR, due to its high thermal resistance and dense crosslinked structure, is better suited for the synthesis of microporous carbon materials, while PS, with its lower density and higher permeability, is advantageous for obtaining meso- and macroporous structures. The findings highlight the potential for the effective recycling of polymeric waste into functional adsorbents for environmental protection.

Keywords: Phenol-formaldehyde resin, polystyrene, polymeric waste, carbon adsorbents, thermal decomposition, microporosity, sustainable recycling.

Introduction. Polystyrene (PS) and phenol-formaldehyde resins (PFR) are among the most widely used synthetic polymers, extensively applied in construction, packaging, electrical engineering, and furniture manufacturing. During their processing and use, significant amounts of waste are generated, including trimmings, flash, sprues, as well as defective and rejected products. Due to their high carbon content and structural characteristics, these wastes are considered promising raw materials for the production of porous carbon materials, including adsorbents [1-5].

Polystyrene, especially in its foamed form, is characterized by low density and a homogeneous structure, making it attractive for the production of macro- and mesoporous carbon materials. Phenol-formaldehyde resins, owing to their aromatic structure and high degree of polycondensation, exhibit excellent carbon-forming capability and enable the production of materials with a well-developed microporous structure. Particularly valuable are the wastes from Bakelite press-molded products containing technical carbon (carbon black) and the residues from plywood and laminated board production, where PFR is used as a binding agent [6-8].

Phenol-formaldehyde resins are thermosetting polymers synthesized by the condensation of phenol and formaldehyde, containing aromatic rings, methylene bridges, and residual hydroxyl groups in their structure. Polystyrene, classified as a thermoplastic, is a polymer of styrene consisting of linear macromolecules with phenyl side groups. It is chemically inert, has a high carbon yield upon pyrolysis, and during thermal decomposition, mainly produces volatile products with the formation of a fine carbonaceous residue [9-13].



1 2

Fig. 1. Structure of polymers: 1) PFR; 2) PS

PFRs (phenol-formaldehyde resins) are polycondensation products of phenol and formaldehyde, characterized by the presence of aromatic nuclei linked by methylene bridges (-CH_2-). Depending on the synthesis conditions, novolac and resol types of PFRs are distinguished, with novolac resins, which do not contain residual formaldehyde, being more commonly used in processing. The main functional groups include phenolic hydroxyl groups (-OH), carbonyl groups (C=O), and methylene fragments capable of further crosslinking. The molecular weight of PFRs typically ranges from 300 to 800 g/mol, depending on the degree of polymerization and type of modification. Due to the high content of aromatic structures, PFRs exhibit good thermal stability and a high carbon yield upon thermal decomposition [11-16].

Polystyrene (PS) is a thermoplastic polymer composed of styrene monomer units [-CH_2-CH(Ph)-]$_n$. Its structure represents a linear chain with pendant aromatic radicals, which impart rigidity to the macromolecules and high chemical resistance. PS does not contain polar functional groups but can be modified by the introduction of oxide, nitro, or sulfo groups. The average molecular weight of commercial PS grades ranges from 100,000 to 300,000 g/mol. During thermal decomposition, PS readily depolymerizes to form volatile compounds; however, under controlled conditions, it is possible to obtain carbon materials with a developed porous structure.

Objects and Methods of Research. Secondary PFR and PS materials, acquired from LLC "Termozon" (Uzbekistan), were used as the initial objects of study (Fig. 2). The PFR sample was a granulated, crushed black press material containing carbon black as a filler, with a typical sprue shape. This material is characterized by high hardness, brittleness, and a lack of plasticity at room temperature.

The polystyrene samples included two types of waste: expanded white polystyrene boards with a thickness of 20–30 mm, and spherical granules of expandable polystyrene (EPS) with a diameter of 1–3 mm.

1 2 3

Fig. 2. Appearance of secondary materials: 1) PFR; 2) PS; 3) PS

The physical and chemical characteristics of the studied samples were determined using standard methods. The bulk density (ϱ) was measured gravimetrically by determining the mass and volume of the material. The decomposition temperature (t_{st}) was determined by thermogravimetric analysis (TGA) under an inert atmosphere. The melting or softening temperature (t_{pl}) was assessed using differential scanning calorimetry (DSC). Transparency (Pr) was evaluated visually for films and granules under standard illumination conditions. The oxygen permeability coefficient (K_p) was determined using gas permeability analysis according to GOST and ISO 15105 standards. The refractive index (PP) was measured using a refractometer. Mechanical strength (RM) was evaluated by compression testing for PFR samples and tensile testing for PS samples according to GOST and ASTM D638 standards.

Results and Discussion. Analysis of the data presented in Table 1 provides a comparative assessment of the physicochemical properties of phenol-formaldehyde resin (PFR) and polystyrene (PS), which is important for selecting suitable materials for the production of carbon adsorbents.

PFR exhibits a higher density (1.30–1.35 g/cm³) compared to PS (1.03–1.06 g/cm³), reflecting its more compact aromatic and crosslinked structure. The thermal decomposition temperature of PFR (~300–350 °C) is also higher than that of PS (~280–320 °C), indicating greater thermal stability. Moreover, as a thermosetting polymer, PFR does not possess a defined melting point, in contrast to PS, which softens at approximately 100 °C.

Table 1. Physicochemical Characteristics of the Studied Samples

№	Parameter	PFR	PS
1	ϱ, г/см³ (Density)	1,30-1,35	1,03-1,06
2	t_{st}, °C (Decomposition Temperature)	~300-350	~280-320
3	t_{pl}, °C (Melting Temperature)	None (thermosetting polymer)	~100 (Softening Temperature)
4	Transparency, %	0 (Opaque)	80-90 (In film or granules)
5	Oxygen Permeability (OP), ml/m²· day	<10 (Very Low)	1000-3000 (Depending on the type)
6	Refractive Index	1,60-1,65	1,59-1,60
8	Mechanical Strength, MPa	60-80 (In Compression)	35-50 (In tension)

The comparative analysis of the data presented in Table 1 highlights significant differences in the physicochemical properties of phenol-formaldehyde resin (PFR) and polystyrene (PS), which are critical for evaluating their suitability as precursors for adsorptive materials.

PFR exhibits a higher density (1.30–1.35 g/cm³) compared to PS (1.03–1.06 g/cm³), reflecting its more compact, crosslinked aromatic network. A denser structure suggests a higher initial carbon content, which is advantageous for the production of carbon materials with greater yield and structural integrity after carbonization. In contrast, the lower density of PS, especially in foamed forms, makes it more suitable for creating highly porous carbon structures, emphasizing macroporosity and mesoporosity.

The decomposition temperature of PFR (~300–350 °C) is slightly higher than that of PS (~280–320 °C). This indicates that PFR has better thermal stability, a result of its crosslinked and aromatic molecular framework. Such thermal behavior is important during carbonization processes, where higher stability promotes the formation of stable carbon structures with minimal volatile loss. PS, due to its thermoplastic nature, decomposes at lower temperatures, producing a greater proportion of volatiles, which may affect the consistency and yield of the carbon residue.

PFR, being a thermosetting polymer, does not exhibit a defined melting point; instead, it undergoes thermal degradation. This property implies that PFR retains its shape under heating until decomposition begins, which is favorable for the fabrication of structured carbon materials. In contrast, PS softens at around 100 °C, limiting its thermal stability during processing but allowing for easier shaping and molding prior to carbonization.

PFR is completely opaque (0%), consistent with its dense, filled structure (often containing fillers like carbon black). PS demonstrates high transparency (80–90% in films and granules), indicating a uniform, less filled molecular structure. Transparency itself is

less critical for adsorbent applications but reflects differences in internal structure that influence porosity and subsequent carbonization behavior.

The oxygen permeability of PFR is very low (<10 ml/m²·day), whereas PS shows significantly higher permeability (1000–3000 ml/m²·day depending on the type). Low permeability in PFR suggests a tightly packed, crosslinked network that restricts gas diffusion, an advantageous feature for the production of dense, microporous carbon adsorbents. High permeability in PS implies a more open structure, beneficial for creating materials favoring gas adsorption processes requiring faster diffusion rates through meso- and macropores.

Both materials have similar refractive indices: PFR (1.60–1.65) and PS (1.59–1.60), indicative of their aromatic nature. Slightly higher values for PFR correlate with a denser and more heavily crosslinked molecular architecture.

PFR demonstrates higher mechanical strength (60–80 MPa under compression) compared to PS (35–50 MPa under tension). This difference is a consequence of PFR's crosslinked structure, which imparts brittleness but significant compressive strength. PS, being a thermoplastic with a linear structure, shows better tensile properties but lower resistance to compressive forces. High mechanical strength of PFR makes it more suitable for applications where structural stability of adsorbents under pressure is required.

Conclusion. The conducted analysis demonstrated that both phenol-formaldehyde resin (PFR) and polystyrene (PS) waste possess valuable characteristics for the development of carbon-based adsorbents. PFR, due to its higher density, greater thermal stability, low oxygen permeability, and superior compressive strength, is a promising precursor for the synthesis of microporous carbon materials with high structural stability. In contrast, PS, characterized by lower density, higher oxygen permeability, and ease of processing, is more suitable for the production of meso- and macroporous carbon adsorbents. The complementary properties of these materials provide wide opportunities for tailoring the structure and functional performance of adsorbents, supporting the sustainable recycling of polymeric waste into high-value-added products for environmental applications.

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