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Influence of Carbon-Containing Materials and Furan Oligomers on The Technological and Performance Characteristics of Rubber Compositions

Dilnoza Nigmatova[1], Jasurbek Sobirov[2], Axmadjan Ibadullaev[3], Sherali Mamaev[4]
[1, 2, 4] Department of Materials Science and Mechanical Engineering, Tashkent State Transport University
[3] Department of Engineering Communications and Systems, Tashkent State Transport University
islamovna.dilnoza@gmail.com[1], jasurbeksobirov19951908@gmail.com[2], ibadullaev1957@bk.ru[3], mamayevsherali@gmail.com[4]

Abstract:

The study aims to investigate the influence of furan oligomers and local carbon fillers on the technological and operational properties of rubber compounds based on butadiene-nitrile elastomers. Key objectives include assessing the effects of these components on mixing, plasticization, vulcanization, and the resultant physical-mechanical and dynamic properties of the filled rubbers.

Rubber compounds were prepared using a rotor-type Brabender Plastograph under industrially relevant shear rates (1–250 s^{-1}) and temperatures up to 473 K. Parameters such as torque, plasticity, and conditional plasticization rate were determined from kinetic curves. Shrinkage and extrusion productivity were evaluated using a syringe-type attachment and laboratory screw extruders. Density was measured pycnometrically, and rheological behavior during vulcanization was assessed using a Monsanto REOMETR-100 vibration rheometer. Carbon-rubber gel values were determined through Soxhlet extraction. Physical-mechanical and dynamic properties, including tensile strength, elongation, hardness, fatigue resistance, and heat generation, were measured in accordance with relevant GOST standards.

The studied vulcanizates showed high conditional tensile strength and relative elongation, that the spatial network was well constructed. Residual tension and deformation after multiple compressions were very low, demonstrating efficient elastic recovery. Energy dissipation and hysteresis losses were low according to the heat generation and rebound elasticity data. In general, furan oligomers and local carbon fillers have contributed in the enhancement of the performance of rubber compositions.

The work offers an in-depth procedure for the assessment of the interaction between filler nature, mixing conditions and mechanical-dynamic response in butadiene-nitrile rubber blends with a specific focus on network development triggered by functional oligomers contribution to vulcanization process.

The results are conducive to the utilization of furan oligomers and local carbon fillers in the industrial processing of rubber by developing composites with high strength, elasticity and fatigue durability; these can be employed in industries like mechanical engineering, electrical engineering.

The work was undertaken at a lab level and some further work still needs to be carried out in order to validate the performance for industrial scale production and service conditions.

Keywords: Butadiene-nitrile rubber (NBR), furan oligomers, local carbon fillers, vulcanization, mechanical–dynamic properties.

Introduction

The work on the composite materials of butadiene-nitrile elastomers is a great achievement in today's polymer science and industry. Owing to their good stability against oil, fuel and mechanical stress, as well as their combination of strength, elasticity and fatigue resistance, such elastomers are used in mechanical engineering, automotive components technology, electrical insulation technology and other technical fields. The performance of such composites relies, in addition to the intrinsic properties of the base polymer, on those of the fillers/additives and on processing conditions[1,2]. Thus, systematic investigation of the properties of original components and blends is necessary for rational designing rubber materials with outstanding performance.

Among the prominent factors determining B-N properties are (i) physical and chemical properties of the polymer and fillers, (ii) interactions among a rubber and fillers during mixing/plasticization processes, as well as (iii) cross-linked structure. Process parameters: the shear rate, rotor speed, mixing temperature and chamber volume have a significant impact on compound homogeneity, filler dispersion efficiency and plasticization rates[3]. Other positive impacts on plant operational properties have been proved when furan oligomers and raw carbon materials of local origin have been applied in rubber compositions. These elements serve to stabilise the vulcanization structure, promote adhesion of filler to matrix and improve resistance to repeated deformations in a manner that adds both strength and elasticity.

A precise characterization of plasto-elastic and vulcanization properties is essential for the rubber material research. Work ability and processing effectiveness can be measured by rotor-type mixing, extrusion, and determinations of shrinkage, density, and plasticity[4,5]. Rheological investigation measuring torque change and carbon rubber gel content was used to understand fillerpolymer interactions, the role of functional additive on formation of the network. In addition, several performance-based physical-mechanical and dynamic characterization tests such as tensile strength, relative elongation, hardness (both Shore C and Shore D), fatigue properties, and amount of energy dissipation are essential to understanding the behavior of composites over a range of operational conditions.

The aim of this study is to characterize the impact of furan oligomers and local carbon fillers in butadiene-nitrile rubber mixtures, with a focus on technological and operation properties. The research work focuses on mixing torque behavior, extrusion shrinkage, vulcanization kinetics and the resulting mechanical dynamic performance so that a better understanding of these composites from structure to properties is possible. The results are believed to facilitate the optimization of rubber compounds with better processability, mechanical properties and durability in technical applications[6,7].

Thus, this research addresses the critical need for developing advanced elastomeric materials by evaluating the combined effect of innovative fillers and oligomeric additives. The obtained results confirm that the use of carbon-containing materials and furan oligomers positively affects the technological and operational properties of rubber compositions, enhancing strength, elasticity, and resistance to repeated deformations, which is essential for high-performance applications in mechanical and electrical engineering industries[8,9].

Methodology: The study of the technological process for producing rubber compounds was carried out using a rotor-type mixing attachment — the Brabender Plastograph. Mixing was performed at shear rates from 1 to 250 s^{-1}, corresponding to industrial rubber processing conditions, and at temperatures up to 473 K. The model compounds consisted of rubber and filler.

Experimental conditions:

Rotor speed: 30 rpm

Thermostat chamber temperature: 353 K

Chamber fill volume: $7 \cdot 10^{-5}$ m^3

Based on the kinetic curves obtained from the Plastograph, which reflect the change in torque over time, the following parameters were determined:

$\lambda = (M_\delta - M_m)/M_{sr}$

Where:

$M\delta$ — maximum torque;

Mm — minimum torque;

Mcp — average torque.

Plasticity:

Plasticity is the ratio of the maximum torque to the minimum torque:

$Plasticity = M_m/M_\delta$

Relative increase in maximum torque upon filler addition:

$M_{отн} = (M_{max} - M_{kr})/M_{kr} \cdot 100\%$

Where:

Mmax — maximum torque after filler addition;

Mkr — torque after 3 minutes of rubber plasticization.

Conditional plasticization rate after 16 minutes of mixing rubber and filler:

$V_{plast} = (M_{max} - M_{sr})/(\tau \cdot 60)$

Where:

M_{sr} — average amplitude of oscillation (at the 15th minute;

M_{max} —maximum torque after filler addition;

τ — corresponding time for V_{plast}. Determination

Reproducibility of the obtained data was verified based on at least three experiments conducted under identical conditions.

Determination of shrinkage of rubber compounds was carried out using a syringe-type attachment on laboratory screw machines with a die of d=3 mm and a "Harvey" nozzle. Extrusion of samples was performed at screw rotation speeds of 20–50 rpm and temperatures of 293–363 K. During extrusion, the pressure in the syringe head was measured using a mesdose and an electronic measuring device.

Shrinkage was determined by the weight method according to the formula:

$\Theta = P_e / P_t$

Where:

P_e — mass of extrudate of length l, kg;

P_t — theoretical mass of non-shrinking extrudate of length l, kg

$P_t = S_0 \cdot \gamma \cdot l$

Where:

S_0 — cross-sectional area of the die, m2;

γ — density of the compound, kg\m3;

l — extrudate length, m.

Extrusion productivity (N/s) through a circular die was determined by the formula:

$Q = (\pi \cdot d_1^2 \cdot l)/(4 \cdot \tau) \cdot \gamma \cdot 10$

Where:

$d_1 = \sqrt{(4 \cdot P_э)/(l \cdot \gamma \cdot \pi)}$ – average diameter of the extrudate;

l - extrudate length;

τ – extrusion time, s.

Density of rubber compounds was determined by the pycnometric method, which is based on measuring the amount of liquid of known density displaced by a given sample of rubber at 293 K (Fig. 1).

Figure 1. Determination of the plasto-elastic properties of filled rubber compounds.

The plastic-elastic properties of the studied SKI-3, nairit KR-50, SKIS-30, ARKM-15, and SKN-18M rubbers and filled mixtures were determined according to GOSTs:

- rigidity and elastic recovery - GOST 10201-75;

- Plasticity - GOST 415-95;

- Muni viscosity - GOST 10722-96.

The viscosity was determined on a Muni "Monsanto" viscometer at temperatures of 373 and 408 K.

The study of the vulcanization processes of unfilled and filled rubber mixtures was carried out on the vibration rheometer-100 of the "Monsanto" company under the following conditions:

The vulcanization process was studied on the "Monsanto" company's REOMETR-100 vibration rheometer at:

Rotor oscillation frequency: 1.7 s−1;

Rotor rotation angle: 0.051 rad;

Chamber temperature: 423 K.

Determination of the carbon-rubber gel (RCG) value:

Based on the carbon value of the rubber gel, we indirectly assessed the interaction of rubbers with the carbon filler. A sample of the test mixture in a calico bag is placed in a Soxhlet apparatus and extracted for 72 hours with hot acetone to remove non-rubber impurities. After this, the mixture is dried under vacuum at 60-70°C to a constant mass. Then, to remove the unbound rubber, the mixture is extracted with hot cyclohexane for 72 hours. The number of CCs was calculated using the formula. Further, a diagram of determining the value of the carbon-rubber gel is presented (Figure 2).

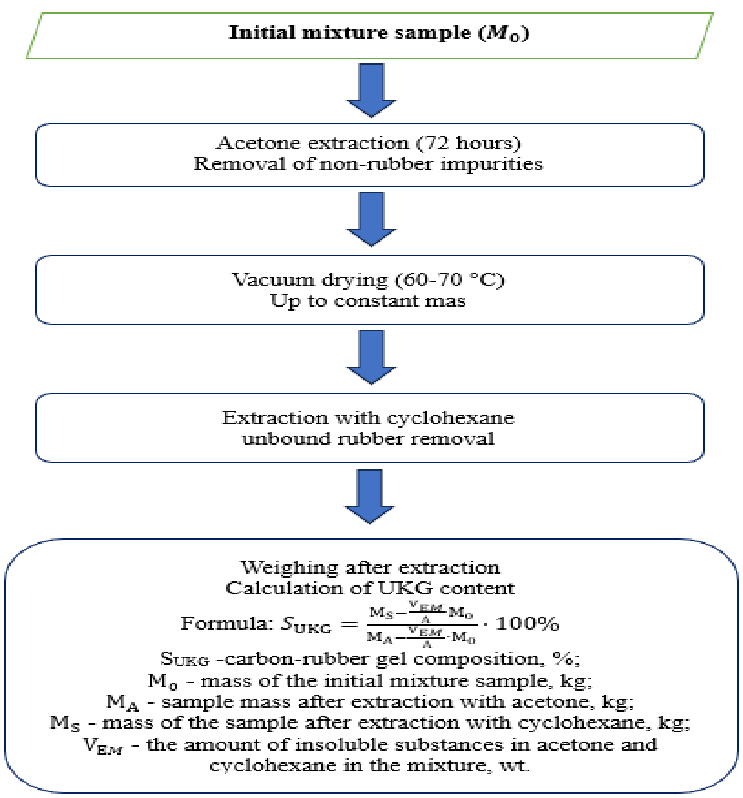

Figure 2. Diagram for determining the value of carbon-rubber gel.

Result:

The physical-mechanical and dynamic indicators of the studied volcanizations were determined in accordance with current state standards. Abrasion resistance was determined according to GOST 262-03, hardness according to Shor A - according to GOST 263-03. The tensile strength properties, including the conditional tensile strength (σp), the relative elongation at break (εotn), and the residual elongation (εost), were measured according to GOST 270-95. Residual deformation during compression under constant deformation conditions was determined according to the SEV 1217-78 standard. Tests of rubbers for multiple stretching under constant deformation were conducted in accordance with GOST 261-94[10,11].

Heat generation, residual deformation, and fatigue strength under multiple compression were assessed according to GOST 2048-95. Elasticity by recoil was determined on a Shoba type device according to GOST 6950-03. The obtained experimental data on the physical-mechanical and dynamic properties of vulcanizations are presented in Figure 3.

Fig. 3. Instruments for determining the technical indicators of filled vulcanizations: a) Rupture, device: IR-5 type rupture machine Standard: GOST 262-03 Measured characteristic: rupture resistance (Ra); b) Hardness (Shor-A) Device: Shor-A hardness tester Standard: GOST 263-03; c) Multiple stretching Device: IR-5080 type stretching machine Standard: GOST 270-95 Measured characteristics: conditional strength (σ), relative elongation (εrelative), residual elongation (ε_{rest}); d) Fatigue compression. Device: Press with control load. Standard: SEV 121-78.

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Discussion: Analysis of the obtained results showed that the investigated vulcanizations have a satisfactory level of physical and mechanical characteristics, corresponding to the requirements for technical elastomeric materials. The values of conditional tensile strength and relative elongation indicate the formation of a strong spatial structure of vulcanizations, ensuring a combination of high strength and elasticity of the material. Low values of residual elongation indicate good elastic-elastic recovery of rubber compositions after removal of the load[12,13]. The results of determining the residual deformation under compression and fatigue strength under repeated loading cycles confirm the stability of the operational properties of vulcanizations under prolonged mechanical impact[14]. Rebound heat generation and elasticity indicators characterize efficient energy dissipation and low hysteresis losses, which is an important factor in the use of these materials in products operating under dynamic loads. Thus, the obtained physical-mechanical and dynamic characteristics confirm the expediency of using the investigated rubber compositions in the relevant fields of mechanical engineering and electrical engineering products[15].

Conclusion: A complex study of the technological, physical–mechanical, and dynamic properties of rubber compounds made from butadiene-nitrile elastomers was performed. The important technical parameters (workability, plasticizability, relative torque increase and conditional plasticization rate) were characterized. An evaluation of the efficiency of mixing and extrusion action time from the standpoint of producing homogeneous and capable-of-processing rubber mixtures is using these characteristics. The results of shrinkage development, extrusion productivity, and extrudate density calculations also showed that the compositions prepared are applicable for industrial process applications. The layer-elastic behavior of the rubber and its filled compounds, hardness, elastic recovery, plasticity and Moni viscosity were investigated systematically. These analyses provide a realistic prediction of the behaviors of the rubber compounds in processing, as well as in service. The investigation of vulcanization behaviour in addition to obtaining data on carbon-rubber gel formation gave valuable information about interaction mechanisms between rubber matrix and carbon fillers. This investigation pointed out the positive effect of local sourced raw materials as well as furan oligomers in the structural and performance development of the compositions, resulting in a strengthened vulcanization network. Physical, mechanical, and dynamic indicators of the vulcanized materials were measured using standard equipment, including the IR-5 rupture machine, Shor-A hardness tester, IR-5080 stretching machine, press with controlled load, and Shoba-type elasticity device. These measurements enabled a comprehensive assessment of the strength, elastic behavior, residual deformation, and fatigue resistance of the rubber compounds. The experimental results demonstrate that the introduction of carbon-containing materials and furan oligomers significantly enhances the technological and operational performance of the rubber mixtures. Specifically, these additives improve the strength, elasticity, and resistance to multiple deformations, ensuring that the vulcanized rubbers meet the requirements for high-performance technical applications.
Overall, the study confirms that the combined use of functional fillers and oligomeric additives is an effective approach to optimizing the properties of butadiene-nitrile elastomer composites. The findings provide both theoretical understanding and practical guidance for the design of advanced rubber compositions with improved processing characteristics and operational durability, suitable for use in mechanical, automotive, and electrical engineering applications.

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