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Investigating the thermal stability of thermoplastic polymer composite materials containing recycled rubber for railway rail pad applications

U.A. Ziyamukhamedova[1][a], J.H. Nafasov[1][b], E.T. Turgunaliev[1][c], Sh.U. Abdurakhimov[1][d], B.U. Nematov[1][e], M.Sh. Abdulakimov[1][f]

[1]Tashkent state transport university, Tashkent, Uzbekistan

Abstract: Railway rail pads are critical components of rail fastening systems, ensuring vibration damping, load distribution, and structural stability of the track. During operation, these elements are subjected to significant temperature fluctuations and cyclic mechanical loads, which require materials with high thermal stability and durability. In this study, the thermal behavior of newly developed thermoplastic polymer composite materials containing recycled rubber powder was investigated for potential application in railway rail pad systems. Six composite formulations based on high-density polyethylene (HDPE), polypropylene (PP), ultra-high molecular weight polyethylene (UHMWPE), polyvinyl chloride (PVC), ethylene-vinyl acetate (EVA), plasticizer, modifier, and recycled rubber particles were prepared and analyzed. Thermogravimetric analysis (TGA), derivative thermogravimetry (DTG), and differential scanning calorimetry (DSC) were used to evaluate the thermal degradation mechanisms, onset decomposition temperature, and residual mass characteristics of the developed materials. The obtained results demonstrate that the incorporation of recycled rubber particles leads to increased char residue and modifies the degradation kinetics of the polymer matrices. Among the investigated compositions, the UHMWPE–HDPE-based composite exhibited the highest thermal stability, with the main degradation stage occurring at temperatures above 400 °C, indicating enhanced resistance to thermal degradation. Conversely, the PVC-based composite showed early mass loss associated with the dehydrochlorination process. Comparative analysis with a commercially used railway rail pad material revealed that the developed composites exhibit comparable or improved thermal resistance within the operational temperature range of railway fastening systems. The findings suggest that thermoplastic composites containing UHMWPE and recycled rubber powder represent promising candidates for the development of durable and thermally stable railway rail pad materials.

Keywords: polymer composites, recycled rubber powder, railway rail pads, thermal stability, TGA analysis

1. Introduction

Railway rail pads are essential components of rail fastening systems, positioned between the rail and sleeper to ensure vibration damping, load distribution, noise reduction, and structural integrity of the track system. During service, rail pads are exposed to complex operational conditions, including cyclic mechanical loading, dynamic impact stresses, and significant environmental temperature variations. In practical railway applications, the surface temperature of rail fastening elements may reach +60–80 ℃ in summer and drop below freezing conditions in winter, which can significantly influence the performance and service life of polymer-based materials [1-3].

Polymeric materials, particularly thermoplastics such as high-density polyethylene (HDPE), polypropylene (PP), and ultra-high molecular weight polyethylene (UHMWPE), are widely used in railway engineering due to their low density, chemical resistance, and ease of processing. However, these polymers exhibit different thermal degradation behaviors, which can limit their long-term stability under elevated temperature conditions. To improve performance, elastomeric modifiers such as ethylene-vinyl acetate (EVA), plasticizers, and compatibilizers are commonly introduced to enhance flexibility, impact resistance, and interfacial adhesion within polymer blends.

Recently, increasing attention has been given to the development of polymer composites containing recycled rubber powder as a sustainable and functional filler. Recycled rubber particles derived from waste tires offer advantages such as improved damping capacity, enhanced energy dissipation, and reduced material cost. At the same time, the incorporation of rubber phases may influence the thermal stability and degradation kinetics of polymer matrices due to differences in thermal decomposition behavior and interfacial interactions [4-5].

Despite numerous studies on polymer blends and elastomer-modified thermoplastics, there remains a limited understanding of the combined effect of multi-component thermoplastic matrices and recycled rubber on the thermal stability of materials specifically designed for railway rail pad applications. In particular, comparative investigations of HDPE-, PP-, UHMWPE-, and PVC-based systems under identical thermal conditions are still insufficiently reported in the literature [6-8].

Therefore, the objective of this study is to investigate the thermal stability and degradation behavior of newly developed thermoplastic polymer composites containing recycled rubber powder intended for railway rail pad

a https://orcid.org/0000-0001-5005-0477
b https://orcid.org/0000-0002-0415-2584
c https://orcid.org/0000-0003-3257-5434
d https://orcid.org/0009-0008-1018-9851
e https://orcid.org/0009-0007-0912-3401
f https://orcid.org/0009-0005-7359-2267

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applications. The thermal performance of six different composite formulations was evaluated using thermogravimetric analysis (TGA), derivative thermogravimetry (DTG), and differential scanning calorimetry (DSC). The influence of polymer matrix type and recycled rubber content on the onset degradation temperature, mass loss behavior, and thermal resistance was systematically analyzed and compared with a commercially used railway rail pad material.

2. Research methodology

2.1 Composite Formulations

In this study, six thermoplastic polymer composite formulations were developed for railway rail pad applications. The selection of components was guided by the requirements of thermal stability, mechanical strength, damping performance, processability, and sustainability. Each formulation consists of a thermoplastic polymer matrix, elastomeric phase (EVA), plasticizer (DOTF), compatibilizer, and recycled rubber powder, forming a multi-phase system designed to optimize energy dissipation and thermal-mechanical performance.

Table 1

Composition of developed polymer composites

Sample	Polymer matrix	EVA (%)	DOTF (%)	Modifier (%)	Recycled rubber (%)	Description
S1	HDPE (65%)	15	7	3	10	HDPE-based composite
S2	PP (67%)	13	7	3	10	PP-based composite
S3	UHMWPE (50%) + HDPE (25%)	10	2	3	10	High-crystallinity hybrid system
S4	PVC (45%)	10	30	3	12	Plasticized PVC system
S5	PP (40%) + UHMWPE (30%)	15	2	3	10	Hybrid polyolefin system
S6	PP (70%)	15	–	3	15	Rubber-modified PP composite

2.2 Thermal Analysis

The thermal stability of the developed thermoplastic polymer composites was investigated using a simultaneous thermal analysis system BAXIT BXT-DSC-TGA1250S (figure 1), which enables concurrent thermogravimetric (TGA) and differential scanning calorimetry (DSC) measurements under identical experimental conditions.

Fig.1. BAXIT BXT-DSC-TGA1250S

The experiments were carried out in accordance with the general requirements of ASTM E1131-20 (Standard Test Method for Compositional Analysis by Thermogravimetry) and ISO 11358-1:2022 (Plastics — Thermogravimetry (TG) of polymers — Part 1: General principles). Differential scanning calorimetry measurements were interpreted following the principles of ASTM E1356-08(2020) (Standard Test Method for Assignment of the Glass Transition Temperatures by DSC).

All measurements were performed in a single-run simultaneous mode (STA) to ensure data consistency between TGA and DSC signals. Approximately 10–15 mg of each sample was placed in alumina crucibles and heated from room temperature to 800 °C at a constant heating rate of 10 °C/min.

An inert nitrogen (N_2) atmosphere with a flow rate of approximately 50 mL/min was maintained throughout the analysis to prevent oxidative degradation and to ensure that thermal decomposition occurred under controlled non-oxidative conditions.

The TGA curves were used to determine the onset degradation temperature (T_{onset}), maximum degradation temperature (Tmax), and residual mass at 800 °C. The corresponding DTG curves were analyzed to identify the stages of thermal decomposition and the maximum rate of mass loss. DSC curves were used to evaluate thermal transitions, melting behavior, and phase interaction effects in multi-component polymer systems.

The application of standardized thermal analysis methods ensured the reproducibility and reliability of the obtained results, enabling accurate comparison of thermal stability among different composite formulations intended for railway rail pad applications.

The polymer matrix (HDPE, PP, UHMWPE, PVC) serves as the structural backbone of the composite and primarily governs mechanical integrity and thermal resistance. HDPE provides balanced thermal stability and chemical resistance, while PP offers stiffness and processability but is more susceptible to thermo-oxidative degradation. UHMWPE contributes superior wear resistance and enhanced thermal stability due to its high molecular weight and crystalline structure. In contrast, PVC exhibits lower thermal stability owing to dehydrochlorination at relatively low temperatures, limiting its suitability for high-temperature railway applications.

EVA functions as an elastomeric toughening agent, improving impact resistance, flexibility, and damping capacity, particularly under dynamic loading conditions. However, its relatively lower thermal stability may slightly

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reduce the overall thermal resistance of the composites at elevated temperatures.

DOTF plasticizer is introduced to enhance melt processability, reduce brittleness, and improve flexibility of the polymer matrix. Despite these benefits, plasticizers may accelerate thermal degradation onset by increasing chain mobility.

The compatibilizer (3 wt%) promotes interfacial adhesion between immiscible phases, including polyolefin matrices, EVA, and rubber particles. This improves phase compatibility, stress transfer efficiency, and overall structural stability.

Recycled rubber powder acts as a functional and sustainable filler, contributing to improved vibration damping, energy absorption, and increased char residue after thermal degradation. However, its heterogeneous structure may introduce multi-stage degradation behavior and slightly affect initial thermal stability. From a sustainability perspective, its incorporation reduces environmental impact and material cost.

2.3 Composite Preparation

The thermoplastic polymer composites were fabricated via a melt compounding–compression molding route to ensure homogeneous dispersion of multi-phase components. The composite systems consisted of thermoplastic matrices (HDPE, PP, UHMWPE, and PVC), elastomeric modifier (EVA), plasticizer (DOTF), compatibilizer, and recycled rubber powder.

Prior to processing, all raw materials were dried at 60–80 °C for 6–8 h to eliminate moisture and prevent hydrolytic degradation during melt processing. The dried components were then accurately weighed according to the designed formulations and subjected to dry premixing to achieve preliminary homogenization.

Melt compounding was performed using a high-shear mixing system at 170–200 °C, depending on the melting behavior of the polymer matrix. The mixing process was conducted at a controlled rotor speed of 40–80 rpm to ensure sufficient shear-induced dispersion of EVA domains and recycled rubber particles within the thermoplastic matrix. Particular attention was given to achieving uniform distribution of rubber particles to minimize phase agglomeration and ensure stable interfacial interaction.

Subsequently, the compounded materials were pelletized and processed into test specimens using a compression molding technique. The molding process was carried out at 180–200 °C under a pressure of 5–10 MPa for 8–12 min, followed by controlled cooling under pressure to reduce internal stresses and prevent microstructural defects.

The compatibilizer (3 wt%) played a critical role in enhancing interfacial adhesion between immiscible polymer phases, particularly between non-polar polyolefin matrices (HDPE, PP, UHMWPE) and polar components (EVA, PVC, DOTF-modified phases). The incorporation of recycled rubber powder required optimized processing conditions to maintain structural uniformity while improving damping and energy dissipation characteristics.

The test specimens used for thermal analysis were prepared and obtained using the BAXIT BXT-DSC-TGA1250S simultaneous thermal analyzer system (Figure 2

Fig. 2. Laboratory injection molding machine for thermoplastic materials

The resulting composites exhibited stable morphology and were subsequently cut into standardized dimensions for thermogravimetric and calorimetric analysis (TGA/DTG/DSC) in accordance with relevant testing protocols.

3. Results

3.1 Thermal degradation behavior of HDPE-based composite (S1)

The thermogravimetric behavior of Sample S1 (HDPE/EVA/DOTF/rubber system) indicates a two-stage thermal degradation mechanism. The initial region up to approximately 200 °C shows negligible mass loss, confirming adequate thermal stability of the HDPE matrix under moderate temperatures. The main degradation stage occurs within 350–420 °C, corresponding to the simultaneous decomposition of HDPE, EVA, and recycled rubber phases. The DTG curve exhibits a single dominant peak at approximately 390–405 °C, indicating overlapping degradation of polymeric constituents. The presence of recycled rubber contributes to an increase in residual char formation, slightly improving thermal resistance at elevated temperatures.

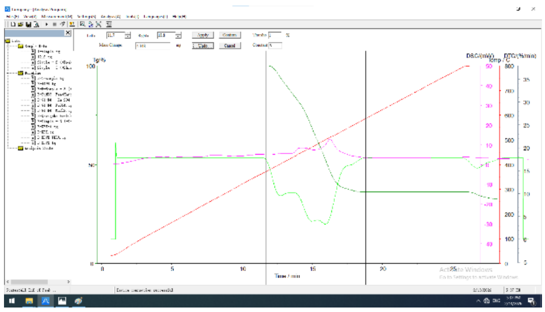

Fig. 3. DTG result for sample 1

3.2 Thermal behavior of PP-based composite (S2)

Sample S2 demonstrates a characteristic polypropylene degradation profile. The main thermal decomposition occurs in the range of 330–450 °C, with a maximum degradation rate observed near 400 °C. Compared to S1, S2 exhibits a slightly earlier onset of degradation, which can be attributed to the lower thermo-oxidative stability of PP chains. The incorporation of EVA and recycled rubber broadens the DTG peak, suggesting a multi-phase degradation process with overlapping thermal events. Despite this, the composite maintains acceptable stability within the operational temperature range of railway rail pads.

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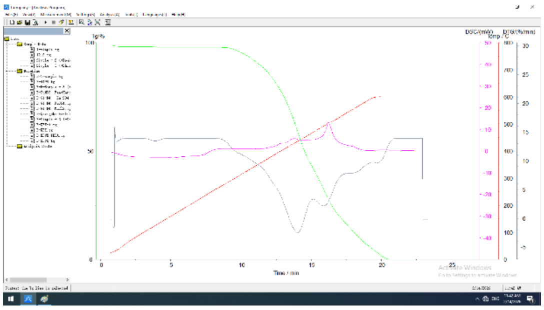

Fig. 4. DTG result for sample 2

3.3 Thermal stability of UHMWPE/HDPE hybrid system (S3)

Among all investigated samples, S3 exhibits the highest thermal stability. The TG curve shows negligible mass loss up to 300 °C, indicating strong resistance to thermal decomposition. The primary degradation stage occurs between 400–480 °C, with the DTG peak shifted toward higher temperatures compared to other samples. This improvement is attributed to the presence of UHMWPE, which possesses long polymer chains, high crystallinity, and strong intermolecular interactions. The reduced DOTF content also contributes to enhanced thermal resistance. The formation of a relatively stable carbonaceous residue at elevated temperatures further confirms improved thermal durability.

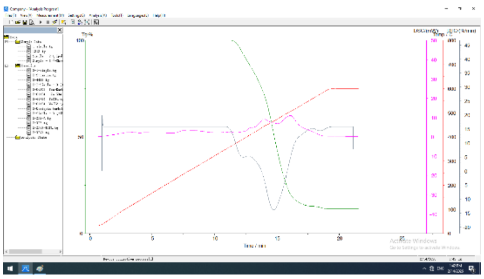

Fig. 5. DTG result for sample 3

3.4 Thermal degradation of PVC-based composite (S4)

Sample S4 exhibits the lowest thermal stability among all formulations. Significant mass loss begins at approximately 200–300 °C, which is associated with the dehydrochlorination of PVC chains. This initial degradation step leads to the formation of conjugated polyene structures, followed by further breakdown at higher temperatures. Although recycled rubber slightly increases residual mass, it does not significantly improve the intrinsic thermal instability of the PVC matrix. The high DOTF content (30%) further accelerates the onset of thermal degradation, resulting in reduced thermal resistance.

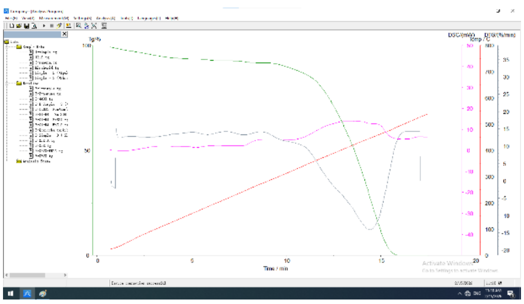

Fig. 6. DTG result for sample 4

3.5 Thermal performance of PP/UHMWPE hybrid composite (S5)

Sample S5 presents a balanced thermal behavior due to the synergistic combination of PP and UHMWPE matrices. The main degradation process occurs within 380–460 °C, with a broadened DTG peak indicating overlapping decomposition mechanisms. The presence of UHMWPE shifts the degradation onset toward higher temperatures, while PP contributes to processability and structural rigidity. Recycled rubber enhances energy dissipation and increases residual char formation without significantly compromising thermal stability. This composition demonstrates a well-balanced thermal profile suitable for railway applications.

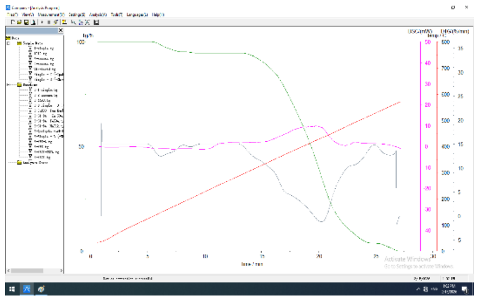

Fig. 7. DTG result for sample 5

3.6 Thermal behavior of PP/EVA/rubber-rich composite (S6)

Sample S6 shows moderate thermal stability with a primary degradation stage occurring between 340–440 °C. The relatively high EVA (15%) and recycled rubber (15%) contents contribute to improved flexibility and damping characteristics but slightly reduce the onset degradation temperature. The DTG curve indicates a relatively sharp degradation peak, typical for PP-dominated systems. Despite reduced thermal resistance compared to S3 and S5, the composite remains stable within the expected service temperature range of railway rail pad applications.

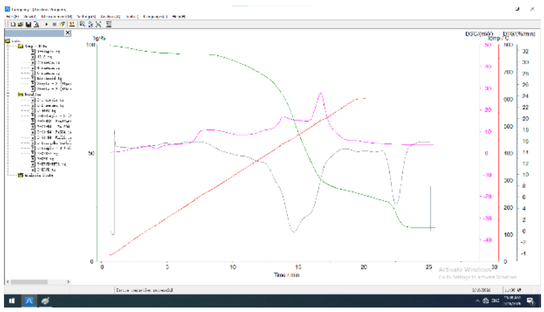

Fig. 8. DTG result for sample 6

The thermal degradation behavior of the investigated thermoplastic composites is fundamentally governed by the synergistic and competitive interactions between the polymer matrix architecture, elastomeric modification, plasticizer content, and recycled rubber incorporation. The TGA/DTG results clearly indicate that thermal stability is not a single-component-dependent property but rather a complex manifestation of multi-phase structure–property relationships, where molecular architecture, phase compatibility, and interfacial interactions collectively determine degradation kinetics.

A comparative evaluation demonstrates that UHMWPE-containing systems (S3 and S5) exhibit superior thermal resistance, which can be attributed to their exceptionally high molecular weight, extensive chain entanglement density, and elevated degree of crystallinity. These structural characteristics effectively restrict segmental chain mobility and delay the initiation of thermal scission processes under elevated temperature conditions. In particular, S3 shows the highest thermal stability, suggesting that the synergistic combination of UHMWPE and HDPE promotes the formation of a thermally robust semi-crystalline network with enhanced carbonaceous residue formation. This behavior confirms that crystalline phase density and molecular packing efficiency play a decisive role in improving thermal endurance.

In contrast, PP-based systems (S2 and S6) exhibit comparatively lower thermal stability, characterized by an earlier onset of degradation and a higher degradation rate. This behavior is primarily associated with the relatively weaker thermal stability of polypropylene's tertiary carbon atoms, which are more susceptible to random chain scission and thermo-oxidative degradation. Nevertheless, the incorporation of EVA and recycled rubber modifies the degradation pathway, resulting in a broadened DTG response and a more distributed multi-step decomposition process. This indicates partial energy dissipation through elastomeric domains, which is particularly advantageous for vibration damping in railway applications.

The HDPE-based composite (S1) presents an intermediate thermal response, with a relatively well-defined decomposition region centered around 390–405 °C. HDPE contributes a balanced crystalline–amorphous morphology, ensuring moderate thermal resistance and structural stability. The addition of recycled rubber increases the formation of thermally stable char residues, which may act as a transient thermal barrier during decomposition. However, its influence on the initial degradation onset temperature remains limited due to insufficient chemical interaction with the polymer matrix.

The PVC-based composite (S4) exhibits the lowest thermal stability among all investigated systems. The early degradation stage (200–300 °C) is dominated by dehydrochlorination reactions, which initiate autocatalytic degradation and lead to rapid structural collapse of the polymer backbone. The high DOTF plasticizer content further increases chain mobility and reduces thermal resistance by facilitating earlier molecular breakdown. Although recycled rubber contributes marginally to char yield, it cannot compensate for the inherently unstable degradation mechanism of PVC under elevated thermal conditions, rendering this system unsuitable for railway rail pad applications.

The hybrid PP/UHMWPE system (S5) demonstrates a more balanced thermal response due to the complementary interaction between PP and UHMWPE phases. While PP ensures processability and structural rigidity, UHMWPE enhances thermal stability through its highly ordered crystalline domains. The resulting thermal profile is characterized by a broadened DTG peak, indicating overlapping degradation events and a more gradual thermal decomposition process. The presence of recycled rubber further improves damping performance without significantly compromising the thermal stability, suggesting an optimal balance between mechanical functionality and thermal resistance.

Across all formulations, recycled rubber exhibits a dual-functional role. On one hand, it enhances energy dissipation capacity and increases residual char yield due to its carbon-rich structure. On the other hand, its heterogeneous morphology introduces multiple degradation pathways, slightly affecting the onset thermal stability in certain matrices. Despite this trade-off, its overall contribution remains beneficial, particularly in applications requiring high damping efficiency and sustainability considerations.

4. Conclusion

This study systematically investigated the thermal stability and degradation behavior of newly developed thermoplastic polymer composites containing HDPE, PP, UHMWPE, PVC, EVA, DOTF plasticizer, compatibilizer, and recycled rubber powder for railway rail pad applications using simultaneous TGA/DTG/DSC analysis. The results demonstrated that the thermal response of the investigated materials is strongly dependent on polymer matrix architecture, crystallinity, and the nature of interfacial interactions within multi-phase systems.

Among all formulations, UHMWPE-containing composites (S3 and S5) exhibited the highest thermal stability, which is attributed to their high molecular weight, enhanced chain entanglement, and increased crystalline phase density. These structural features effectively delayed thermal scission and improved resistance to high-temperature degradation. In particular, S3 demonstrated the best overall performance, showing the highest decomposition temperature and improved char residue formation, confirming its superior thermal endurance.

In contrast, PP-based systems (S2 and S6) showed moderate thermal stability with earlier onset degradation due to the inherent susceptibility of polypropylene chains to thermo-oxidative scission. HDPE-based composite (S1) exhibited intermediate behavior, while the PVC-based system (S4) showed the lowest thermal stability due to early dehydrochlorination and rapid degradation kinetics, making it unsuitable for elevated temperature railway applications.

The incorporation of recycled rubber powder was found to play a dual role: enhancing residual char formation and energy dissipation capability, while slightly affecting the initial degradation onset depending on matrix compatibility. Despite this trade-off, recycled rubber significantly contributes to sustainability and functional damping performance, which are essential for railway rail pad applications.

Comparative analysis with a commercial rail pad material confirmed that UHMWPE-based hybrid systems exhibit equal or superior thermal resistance under identical thermal conditions, highlighting their potential for practical implementation.

Overall, the study confirms that optimized UHMWPE/HDPE-based hybrid composites containing controlled amounts of EVA and recycled rubber represent the most promising candidates for thermally stable, durable, and high-performance railway rail pad applications. These findings provide a strong theoretical and practical basis for the development of next-generation sustainable polymer composites for railway infrastructure.

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Information about the author

Umida Ziyamukhamedova	Toshkent davlat transport universiteti “Mashinasozlik texnologiyasi” kafedrasi professori t.f.d. E-mail: shoazimovau@gmail.com Tel.: +998911915665 https://orcid.org/0000-0001-5005-0477
Jasurbek Nafasov	Toshkent davlat transport universiteti “Materialshunoslik va mashinasozlik” kafedrasi dotsenti t.f.f.d., dotsent E-mail: nafasovz@mail.ru Tel.: +998770208857 https://orcid.org/0000-0002-0415-2584
Elbek Turgunaliev	Toshkent davlat transport universiteti “Materialshunoslik va mashinasozlik” kafedrasi dotsenti t.f.f.d., dotsent E-mail: mrelbek@mail.ru Tel.: +998999812123 https://orcid.org/0000-0001-5005-0477
Shokhjakhon Abdurakhimov	Toshkent davlat transport universiteti tayanch doktoranti E-mail: shohjahon.abduraximov@mail.ru Tel.: +9989919562168 https://orcid.org/0009-0008-1018-9851
Behruz Nematov	Toshkent davlat texnika universiteti tayanch doktoranti E-mail: Bekhruz.Nematov@uzgtl.com Tel.: +998904432111 https://orcid.org/0009-0007-0912-3401
Mirjalol Abdulakimov	Toshkent davlat texnika universiteti tayanch doktoranti E-mail: Bekhruz.Nematov@uzgtl.com Tel.: +9989958585200 https://orcid.org/0009-0005-7359-2267

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