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STRUCTURAL AND MORPHOLOGICAL EVALUATION OF HYBRID POLYMER COMPOSITE FOR RAILWAY RAIL PAD APPLICATIONS

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Annotation. *This study presents a comparative structural and morphological investigation of a novel UHMWPE/HDPE/EVA-based polymer composite and conventional polyurethane (PU) used in railway rail pad applications. The developed composite consists of UHMWPE (50%), HDPE (25%), EVA (10%), DOTF (2%), modifier (3%), and rubber crumb (10%). Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) analyses were employed to evaluate morphology, phase distribution, and elemental composition. The results reveal that the proposed composite exhibits a heterogeneous multi-phase structure with well-dispersed components, contributing to enhanced energy absorption and damping behavior. In contrast, PU shows a more homogeneous morphology with limited phase diversity. EDS analysis confirms the presence of reinforcing mineral elements and improved compositional complexity in the composite system. The findings indicate that the developed material offers superior structural adaptability and functional performance compared to conventional polyurethane.*

Annotatsiya. *Ushbu tadqiqotda temiryo‘l rels tagliklarida qo‘llaniladigan yangi UHMWPE/HDPE/EVA asosli polimer kompozit va an’anaviy poliuretanning (PU) qiyosiy strukturaviy-morfologik tahlili keltirilgan. Ishlab chiqilgan kompozit tarkibiga UHMWPE (50%), HDPE (25%), EVA (10%), DOTF (2%), modifikator (3%) va rezina uvoqlari (10%) kiradi. Morfologiya, fazalarning taqsimlanishi va elementar tarkibini baholash uchun skanerlovchi elektron mikroskopiya (SEM) hamda energiya-dispersiyali rentgen spektroskopiyasi (EDS) tahlillaridan foydalanildi. Natijalar shuni ko‘rsatadiki, taklif etilayotgan kompozit tarkibiy qismlari yaxshi tarqalgan geterogen ko‘p fazali tuzilishga ega bo‘lib, bu uning energiyani yutish va so‘ndirish xususiyatlarini yaxshilaydi. Bundan farqli o‘laroq, poliuretan cheklangan faza xilma-xilligiga ega bir jinsliroq morfologiyani namoyon etadi. EDS tahlili kompozit tizimda mustahkamlovchi mineral elementlar mavjudligini va uning tarkibiy murakkabligi oshganini tasdiqlaydi. Olingan xulosalar ishlab chiqilgan materialning an’anaviy poliuretanga nisbatan yuqori strukturaviy moslashuvchanlik va funksional ko‘rsatkichlarga ega ekanligini ko‘rsatadi.*

Аннотация. *В данном исследовании представлен сравнительный анализ структуры и морфологии нового полимерного композита на основе СВМПЭ/ПЭНД/ЭВА и традиционного полиуретана (ПУ), применяемого в качестве подрельсовых прокладок. Разработанный композит состоит из СВМПЭ (50%), ПЭНД (25%), ЭВА (10%), ДОТФ (2%), модификатора (3%) и резиновой крошки (10%). Для оценки морфологии, распределения фаз и элементного состава были применены методы сканирующей электронной микроскопии (СЭМ) и энергодисперсионной рентгеновской спектроскопии (ЭДС). Результаты показывают, что предлагаемый композит обладает гетерогенной многофазной структурой с хорошо диспергированными компонентами, что способствует повышению энергопоглощения и улучшению демпфирующих свойств. В противоположность этому, ПУ демонстрирует более гомогенную морфологию с*

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ограниченным фазовым разнообразием. Анализ методом ЭДС подтверждает наличие армирующих минеральных элементов и более сложный состав композитной системы. Полученные данные свидетельствуют о том, что разработанный материал обладает лучшей структурной адаптируемостью и более высокими функциональными характеристиками по сравнению с традиционным полиуретаном.

Keywords: *polymer composites, UHMWPE, EVA, polyurethane, railway pads, SEM, EDS, morphology.*

Kalit so‘zlar: *polimer kompozitlar, UHMWPE, EVA, poliuretan, temiryo‘l tagliklari, SEM, EDS, morfologiya.*

Ключевые слова: *полимерные композиты, СВМПЭ, ЭВА, полиуретан, подрельсовые прокладки, СЭМ, ЭДС, морфология.*

Introduction. Railway transportation systems are critical components of modern infrastructure, where safety, durability, and operational efficiency are of paramount importance. Among the key elements of railway track structures, rail pads play a crucial role in reducing dynamic loads, attenuating vibrations, minimizing noise, and protecting both rails and sleepers from excessive stress. With the increasing demand for high-speed and heavy-load railway systems, the performance requirements for rail pad materials have become significantly more stringent. Therefore, the development of advanced materials with enhanced mechanical strength, damping capacity, and long-term durability is a highly relevant and urgent research topic [1-3].

Traditionally, polyurethane (PU) has been widely used in railway rail pads due to its favorable elasticity, wear resistance, and fatigue performance. Numerous studies have investigated the mechanical and viscoelastic properties of PU-based materials, highlighting their ability to provide stable performance under cyclic loading conditions. However, previous research also indicates several limitations associated with PU, including relatively high production cost, limited recyclability, environmental sensitivity, and restricted structural tunability due to its chemically crosslinked nature. In recent years, polymer composite materials based on thermoplastics and elastomers have attracted considerable attention as alternative solutions. Systems incorporating polyethylene (PE), ethylene-vinyl acetate (EVA), and recycled rubber have demonstrated promising results in terms of vibration damping, impact resistance, and sustainability [4-6].

Despite these advancements, there remains a significant research gap in the development of multi-phase hybrid polymer composites specifically tailored for railway pad applications. In particular, the combined use of ultra-high molecular weight polyethylene (UHMWPE), high-density polyethylene (HDPE), EVA, and recycled rubber in a single composite system has not been sufficiently explored. Moreover, the relationship between the structural–morphological characteristics of such hybrid systems and their functional performance, especially in comparison with conventional PU materials, is still not fully understood. The lack of detailed microstructural analysis limits the ability to optimize these materials for real-world railway applications.

The aim of this study is to develop a novel multi-component polymer composite material based on UHMWPE (50%), HDPE (25%), EVA (10%), DOTF (2%), modifier (3%), and rubber crumb (10%), and to perform a comprehensive structural and morphological comparison with conventional polyurethane. The study focuses on analyzing phase distribution, interfacial interactions, and elemental composition using advanced characterization techniques such as scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS), and evaluating their influence on material performance.

The novelty of this research lies in the design and investigation of a hybrid multi-phase polymer composite system that combines high-strength thermoplastics with elastomeric and recycled components to achieve enhanced damping and impact resistance. Unlike conventional PU materials, the proposed composite enables structural tunability through controlled phase

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engineering and improved interfacial compatibility. Additionally, the integration of recycled rubber contributes to environmental sustainability and cost reduction. This work provides new insights into the structure–property relationships of advanced polymer composites and demonstrates their potential as next-generation materials for railway rail pad applications.

Materials and Methods

2.1. Materials

In this study, a multi-component polymer composite was developed using thermoplastic and elastomeric constituents with complementary mechanical and damping properties. The matrix system consisted of ultra-high molecular weight polyethylene (UHMWPE) (50 wt.%) and high-density polyethylene (HDPE) (25 wt.%), selected due to their excellent wear resistance, chemical stability, and structural integrity.

Ethylene-vinyl acetate (EVA) (10 wt.%) was incorporated as a flexible elastomeric phase to enhance elasticity and vibration damping performance. Rubber crumb (10 wt.%), obtained from recycled tire materials, was used as an energy-absorbing filler to improve impact resistance and sustainability. Dioctyl terephthalate (DOTF) (2 wt.%) served as a plasticizer to improve processability and flexibility, while a compatibilizing modifier (3 wt.%) was added to enhance interfacial adhesion between the polyolefin matrix and elastomeric phases.

For comparative purposes, a commercially available polyurethane (PU) rail pad material was used as a reference sample. The PU material represents a conventional solution widely applied in railway infrastructure.

2.2. Composite Preparation

The polymer composite samples were prepared using a laboratory-scale injection molding system equipped with a heated barrel and screw-based feeding mechanism (Fig. 1). The processing unit allows precise control of temperature, pressure, and material feeding rate, ensuring uniform melting and homogenization of multi-component polymer systems [7,8].



Figure 1. Laboratory injection molding machine for thermoplastic materials

Prior to processing, all raw materials (UHMWPE, HDPE, EVA, rubber crumb, DOTF, and modifier) were accurately weighed according to the designed composition. The materials were mechanically pre-mixed to achieve an initial homogeneous blend and to prevent segregation during feeding.

The prepared mixture was then introduced into the hopper of the injection molding unit. Inside the heated barrel, the materials were subjected to controlled thermal and shear conditions. The processing temperature was maintained within the range of 170–190°C, which is sufficient to melt HDPE and EVA phases while allowing UHMWPE to be uniformly dispersed within the matrix without thermal degradation.

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During processing, the rotating screw facilitated:

- uniform melting of thermoplastic components
- dispersion of rubber particles within the polymer matrix
- improved interfacial interaction between phases

The molten composite was subsequently injected into a mold cavity under a pressure of approximately 8–12 MPa, forming rail pad specimens with defined geometry. The holding time was maintained for 5–8 minutes to ensure proper filling and consolidation.

After molding, the samples were cooled gradually under controlled conditions within the mold to minimize internal stresses, shrinkage, and structural defects. The resulting specimens exhibited stable geometry and consistent structural integrity.

For comparison, polyurethane (PU) samples were prepared using conventional casting or industrial molding techniques and were used as reference materials without additional processing.

The use of injection molding in this study enables better control over phase distribution, improves dispersion of elastomeric components, and enhances the overall structural homogeneity of the composite material.

2.3. Structural and Morphological Analysis

The structural and morphological characterization of the developed composite and reference polyurethane (PU) samples was carried out using advanced analytical instruments.

Scanning Electron Microscopy (SEM)

The surface morphology and phase distribution of the samples were examined using a field-emission scanning electron microscope (FE-SEM), ZEISS GeminiSEM 500 (Carl Zeiss, Germany), as shown in Fig. 2.

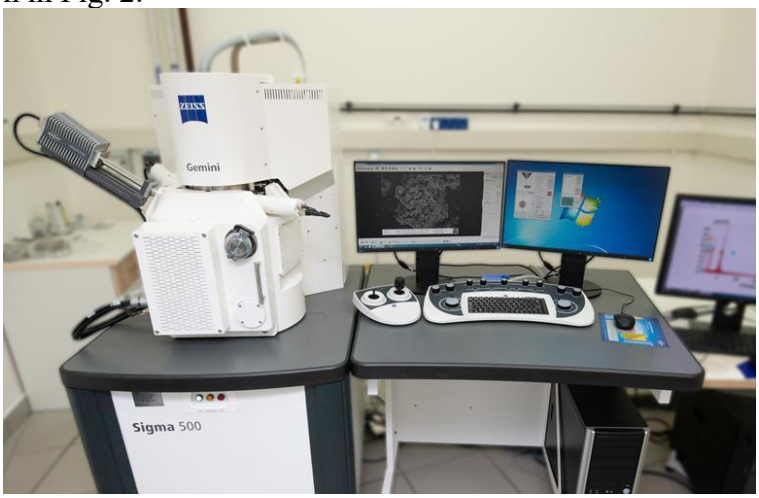

Fig. 2. Field-emission scanning electron microscope (ZEISS GeminiSEM 500) used for morphological analysis

Prior to SEM observation, the samples were cryogenically fractured using liquid nitrogen to preserve their internal microstructure. The fractured surfaces were then sputter-coated with a thin conductive gold layer (~10 nm) to minimize charging effects during electron beam exposure.

SEM analysis was conducted at an accelerating voltage of 5–15 kV, depending on the required resolution and contrast. High-resolution micrographs were obtained to evaluate:

- phase distribution and dispersion quality
- interfacial adhesion between matrix and filler
- morphology of rubber crumb domains
- presence of voids, agglomerates, and micro-defects

The comparative analysis between the composite and PU samples was performed to identify key structural differences governing mechanical and damping performance.

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Energy Dispersive Spectroscopy (EDS)

Elemental composition analysis was performed using an EDS detector integrated with the SEM system. The EDS spectra were used to identify the distribution of key elements such as C, O, Si, Al, Mg, Ca, and Zn, confirming the presence of both polymeric and inorganic phases within the composite.

The elemental mapping further provided insight into the dispersion of mineral fillers and the heterogeneity of the composite structure in comparison with the relatively uniform composition of PU.

X-ray Diffraction (XRD) Analysis

The crystalline structure and phase composition of the materials were analyzed using an X-ray diffractometer, Rigaku SmartLab (Rigaku Corporation, Japan), shown in Fig. 3.



Fig. 3. Rigaku SmartLab X-ray diffractometer used for phase and crystallinity analysis

XRD measurements were performed using Cu Kα radiation (λ = 1.5406 Å) over a 2θ range of 5° to 80°, with a scanning rate of 2°/min. The diffraction patterns were analyzed to determine:

- degree of crystallinity of UHMWPE and HDPE phases
- presence of amorphous EVA and elastomeric components
- identification of inorganic filler phases (e.g., silica-based compounds)
- structural differences between composite and PU

The XRD results provided complementary information to SEM observations, enabling a comprehensive understanding of the structure–property relationship.

2.4. Statistical Analysis

All experimental observations were analyzed using standard statistical methods to ensure reliability and reproducibility. Morphological features were evaluated based on multiple SEM micrographs obtained from different regions of each sample.

Quantitative assessments, such as particle distribution and elemental composition, were averaged over several measurements. Data variability was expressed in terms of standard deviation. Comparative analysis between the composite and PU samples was performed to identify statistically significant differences in structural characteristics.

Where applicable, analysis of variance (ANOVA) was used to assess the influence of material composition on morphological features, with a significance level of $p < 0.05$.

Results and Discussion

3.1. Morphological Analysis by SEM

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The microstructural features of the developed UHMWPE/HDPE/EVA-based composite and conventional polyurethane (PU) were investigated using SEM, and the results are presented in Fig. 4 and Fig. 5, respectively.

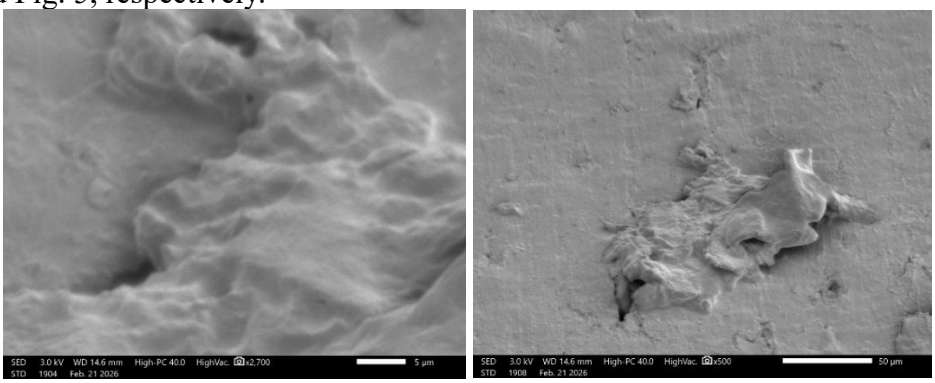

Fig. 4. SEM micrographs of the developed UHMWPE/HDPE/EVA composite

The SEM micrographs of the developed composite (Fig. 3) reveal a heterogeneous multi-phase morphology, which is characteristic of hybrid polymer systems. The structure consists of a continuous thermoplastic matrix formed by UHMWPE and HDPE, within which elastomeric domains (EVA and rubber crumb) are finely dispersed. The rubber particles appear as distinct inclusions embedded within the matrix, indicating effective mixing and distribution during processing.

A detailed examination of the micrographs shows:

- relatively uniform dispersion of rubber crumb particles
- well-developed interfacial regions between phases
- absence of significant voids or microcracks
- formation of micro-scale heterogeneities acting as stress-dissipation zones

Such a morphology is highly advantageous for railway pad applications, where materials are subjected to repetitive dynamic loading. The presence of elastomeric domains within a semi-rigid matrix facilitates energy dissipation through localized deformation mechanisms, thereby enhancing vibration damping and impact resistance.

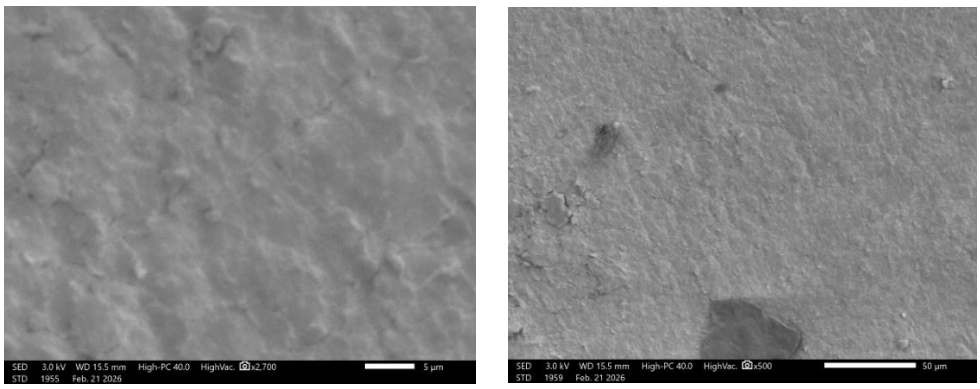

Fig. 5. SEM micrographs of conventional polyurethane (PU)

In contrast, the SEM images of PU (Fig. 4) exhibit a dense and homogeneous morphology with minimal phase separation. The surface appears relatively smooth, indicating a chemically crosslinked network structure. While this uniformity ensures consistent elastic behavior, it limits the formation of microstructural energy-absorbing mechanisms. Consequently, PU materials primarily rely on bulk elastic deformation rather than microstructural heterogeneity for load accommodation.

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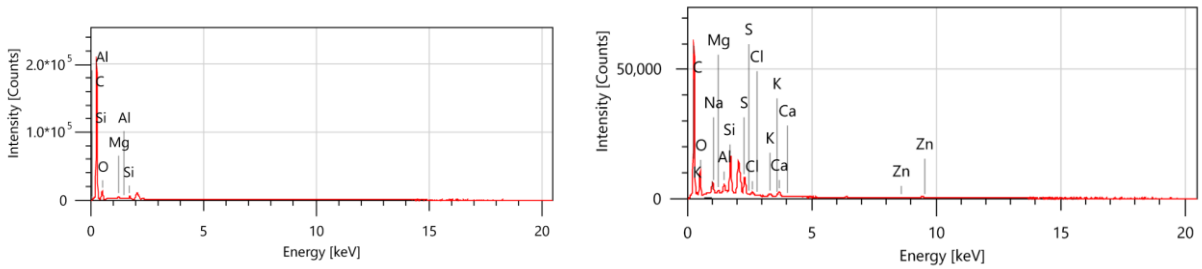
3.2. Elemental Composition Analysis (EDS)

The EDS spectra of the developed composite and PU are shown in Fig. 6(a) and Fig. 6(b), respectively.



a) b)

Fig. 6. EDS spectra of (a) developed composite and (b) polyurethane (PU)

The composite material exhibits dominant peaks corresponding to carbon (C) and oxygen (O), which originate from the polymer matrix components (UHMWPE, HDPE, and EVA). In addition, distinct peaks corresponding to silicon (Si), aluminum (Al), and magnesium (Mg) are observed. These elements indicate the presence of inorganic constituents, likely introduced through modifiers, fillers, or impurities associated with recycled rubber.

The incorporation of such inorganic elements suggests the formation of a hybrid organic–inorganic system, which plays a crucial role in enhancing:

- mechanical reinforcement
- wear resistance
- thermal stability

Furthermore, the relatively uniform distribution of these elements (as inferred from the spectra) supports the conclusion that the composite exhibits good phase compatibility and dispersion.

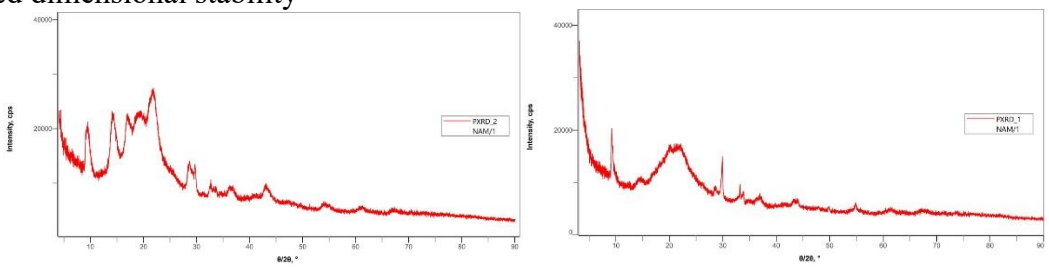
In contrast, the PU sample shows a simpler elemental composition dominated by carbon and oxygen, with additional minor peaks corresponding to Na, Cl, Ca, and Zn. These elements are typically associated with catalysts, stabilizers, or additives used during PU synthesis. However, the absence of structured reinforcing inorganic phases indicates that PU is primarily a chemically homogeneous system with limited compositional complexity.

3.3. X-ray Diffraction (XRD) Analysis

The XRD patterns of the developed composite and PU are presented in Fig. 7(a) and Fig. 7(b), respectively.

The composite material exhibits distinct diffraction peaks at approximately $2\theta \approx 21°$ and 23°, which are characteristic of the crystalline phases of polyethylene (UHMWPE and HDPE). These peaks confirm the presence of a semi-crystalline structure, which is responsible for:

- high stiffness and load-bearing capacity
- improved wear resistance
- enhanced dimensional stability



a) b)

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Fig. 7. XRD patterns of (a) developed composite and (b) polyurethane (PU)

In addition to the crystalline peaks, a broad diffuse region is observed, indicating the presence of amorphous phases associated with EVA and rubber components. This combination of crystalline and amorphous phases confirms the multi-phase nature of the composite, which is essential for achieving a balance between strength and flexibility.

In contrast, the XRD pattern of PU exhibits a predominantly broad amorphous halo with no significant sharp peaks. This indicates that PU lacks long-range crystalline order and is primarily an amorphous polymer. While such a structure contributes to elasticity, it limits structural rigidity and resistance to permanent deformation under load.

Conclusion. This study presented a comprehensive structural and morphological investigation of a novel UHMWPE/HDPE/EVA-based polymer composite designed for railway rail pad applications, in comparison with conventional polyurethane (PU). The results obtained from SEM, EDS, and XRD analyses provided a clear understanding of the structure–property relationships governing the performance of both materials.

The developed composite exhibited a heterogeneous multi-phase morphology characterized by a semi-crystalline polyethylene matrix reinforced with elastomeric domains and inorganic constituents. SEM analysis confirmed the uniform dispersion of rubber particles and the presence of well-developed interfacial regions, which contribute to effective stress distribution and energy dissipation. In contrast, PU demonstrated a homogeneous and dense morphology with limited structural heterogeneity.

EDS results revealed that the composite possesses a hybrid organic–inorganic composition, including elements such as Si, Al, and Mg, which enhance mechanical reinforcement and structural stability. Meanwhile, PU showed a relatively simpler elemental composition dominated by carbon and oxygen, with minor additive-related elements.

XRD analysis further demonstrated that the composite exhibits a semi-crystalline structure with characteristic polyethylene peaks, providing superior stiffness, wear resistance, and dimensional stability. Conversely, PU displayed a predominantly amorphous structure, which, although beneficial for elasticity, limits its load-bearing capacity and long-term mechanical performance.

Overall, the integration of crystalline thermoplastic phases, elastomeric components, and reinforcing elements in the developed composite results in a synergistic improvement in mechanical strength, vibration damping, and durability. Compared to conventional PU, the proposed material offers enhanced structural tunability, improved energy dissipation capability, and greater potential for sustainable and cost-effective production.

Therefore, the UHMWPE/HDPE/EVA-based composite can be considered a promising alternative material for next-generation railway rail pad systems, particularly in applications requiring high resistance to dynamic loading and long-term operational reliability.

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