EPOXY–NBR COMPOSITES FOR CRITICAL INFRASTRUCTURE: MATERIAL INNOVATIONS FOR RISK REDUCTION AND RESILIENCE

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Abstract

The increasing exposure of critical infrastructure systems to natural, technological, and climate-induced risks underscores the urgent need for resilient and sustainable material solutions. This study investigates epoxy oligomer (EO-20)–based composites modified with liquid butadiene-nitrile rubber (SKN-18-1), acrylic acid (AA), and coke filler, with maleic anhydride (MA) as a hardener. The compositions were prepared in varying proportions and evaluated for their physical, mechanical, and chemical properties. The results demonstrate that the incorporation of 4–6 p.w. SKN-18-1 significantly enhanced tensile strength, impact resistance, adhesion, and chemical stability compared to unmodified epoxy oligomer. Further modification with 0.75 p.w. AA and the addition of 6.0 p.w. coke provided additional improvements in durability and resistance to aggressive environments. These findings highlight the potential of polymer-modified epoxy systems as advanced protective materials for dams, drainage, and reclamation infrastructures, where resistance to seismic stresses, chemical exposure, and long-term environmental degradation is essential. By linking material performance with infrastructure resilience and risk management, the study contributes to risk-oriented design strategies and sustainable investment in critical infrastructure protection.

Keywords: epoxy oligomer, butadiene-nitrile rubber, maleic anhydride, acrylic acid, critical infrastructure, resilience

I. Introduction

Critical infrastructure systems such as dams, drainage networks, and reclamation facilities face growing threats from natural, technological, and climate-induced hazards. Seismic risks, material degradation, and cascading failures across interdependent systems underscore the urgent need for resilient and sustainable engineering solutions. Conventional design approaches, which focus mainly on structural robustness, have proven insufficient to cope with the complexity of modern risk environments. Instead, resilience-oriented design strategies increasingly emphasize material innovation, environmental sustainability, and multi-criteria decision-making.

Among the key challenges in infrastructure safety is the performance of construction and protective materials under extreme conditions. Epoxy resins are widely used due to their strong adhesion, chemical resistance, and mechanical properties; however, their inherent brittleness and limited impact resistance restrict their application in multi-hazard contexts. This limitation is particularly critical in seismic regions, where energy dissipation and impact resistance are decisive factors in maintaining infrastructure functionality.

To address these shortcomings, researchers have explored the modification of epoxy oligomers with elastomers and chemical additives. Butadiene-nitrile rubber (NBR) has shown considerable potential in enhancing flexibility, toughness, and adhesion, while additional modifiers such as acrylic acid and coke fillers contribute to improved durability and resistance in chemically aggressive environments. Such material innovations are directly aligned with the objectives of risk-oriented infrastructure design, where enhanced resilience and sustainability are required for long-term safety.

At the same time, the use of chemical precursors such as phthalic anhydride presents a dual challenge. While it is essential for polymer synthesis and performance enhancement, it also raises concerns related to environmental impact and occupational health risks. Balancing these advantages and drawbacks reflects the broader sustainability paradigm, where technical performance must be integrated with ecological and human safety considerations.

Against this backdrop, the present study examines epoxy oligomer–NBR composites modified with acrylic acid and coke filler. The objective is twofold: (i) to evaluate the mechanical and chemical performance of the modified systems, and (ii) to position these findings within the framework of critical infrastructure resilience. By linking experimental material results with risk management and resilience-building strategies, the study contributes to a holistic understanding of how polymer-modified epoxy systems can enhance the safety, durability, and sustainability of infrastructures exposed to multi-hazard environments.

II. Literature Review

The resilience and sustainability of critical infrastructure have become central themes in contemporary engineering and risk management research. Natural hazards such as earthquakes and floods, technological accidents, and climate-induced stresses increasingly threaten the long-term functionality of lifeline systems, including dams, drainage networks, and reclamation infrastructures. Studies in earthquake engineering emphasize that material degradation and insufficient impact resistance significantly increase vulnerability under seismic loading, highlighting the importance of advanced material applications in risk-oriented design.

Polymeric materials, particularly rubbers and their composites, have been widely explored to overcome the limitations of conventional epoxy systems. Epoxy oligomers are known for their excellent adhesion, chemical resistance, and mechanical strength; however, they suffer from relatively low impact resistance and brittleness, which limit their application in hazard-prone environments. To address these challenges, modification with liquid rubbers such as butadiene-nitrile rubber (NBR) has been proposed. NBR introduces flexibility, enhances impact absorption, and improves adhesion properties, making epoxy–NBR composites suitable candidates for critical infrastructure applications exposed to seismic and chemical risks.

Recent research has further investigated the role of modifiers such as acrylic acid and fillers such as coke in enhancing the durability and chemical stability of epoxy-based composites. These modifications result in improved tensile strength, reduced swelling in aggressive environments, and enhanced long-term service life. Such improvements align directly with the objectives of infrastructure resilience, where extended durability and reduced maintenance contribute to sustainable investment strategies.

Beyond technical performance, material selection must also account for broader sustainability and risk management considerations. Compounds such as phthalic anhydride, widely used in polymer synthesis, offer functional advantages but pose potential environmental and occupational health risks. This duality reflects the necessity of balancing material innovation with ecological and human safety concerns, consistent with risk-oriented multi-criteria decision-making frameworks.

In summary, the literature demonstrates a growing convergence between material science and infrastructure resilience research. The adoption of epoxy–rubber composites offer promising solutions for enhancing the safety and reliability of dams, drainage, and reclamation systems, thereby contributing to resilient and environmentally sustainable infrastructure strategies.

III. Methodology

The methodological framework of this study integrates experimental material science with a risk-oriented infrastructure perspective. The approach consists of four main stages:

1. Preparation of Modified Epoxy Composites

In this study, an epoxy oligomer (EO-20) was employed as the primary polymeric matrix due to its well-established mechanical integrity and chemical stability. To enhance the impact resistance, elasticity, and toughness of the resulting composites, liquid butadiene–nitrile rubber (SKN-18-1) was incorporated in controlled proportions ranging from 2 to 8 parts by weight (p.w.). Maleic anhydride (MA) functioned as a crosslinking agent, facilitating the curing reaction and improving the network structure of the epoxy matrix. Additionally, acrylic acid (AA) was introduced as a functional modifier to enhance interfacial adhesion and chemical resistance, while coke powder was utilized as a reinforcing filler to improve mechanical strength and durability. All components were carefully blended under rigorously controlled thermal and mixing conditions to ensure homogeneity of the composite mixtures and to minimize phase separation or agglomeration. The curing process was optimized to achieve a uniform crosslinked network, which is critical for maximizing the performance characteristics of the epoxy-based composites.

2. Evaluation of Physical and Mechanical Properties

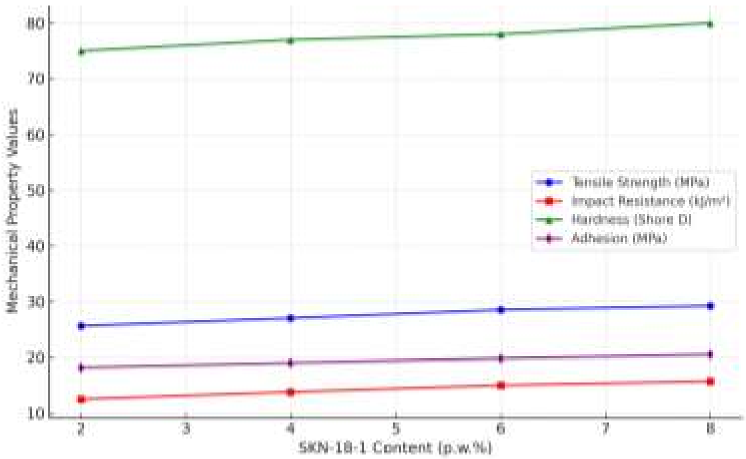

Figure 1. *Effect of SKN-18-1 content on the mechanical properties of EO-20 epoxy composites. The tensile strength, impact resistance, hardness, and adhesion of the composites were evaluated as a function of increasing rubber content (2–8 p.w.%). Incorporation of SKN-18-1 and functional modifiers (acrylic acid and coke filler) enhances toughness, elasticity, and overall mechanical performance, indicating the potential applicability of these composites in dynamic and high-stress infrastructure environments.*

Figure Explanation:

X-axis: SKN-18-1 content (p.w.%). This represents the amount of liquid rubber incorporated into the composite. Increasing rubber content enhances elasticity and energy absorption capacity.

Y-axis: Mechanical property values:

Tensile strength (MPa): Resistance of the material to breaking under tension.

Impact resistance (kJ/m²): Resistance to sudden mechanical shocks.

Hardness (Shore D): Surface hardness of the composite.

Adhesion (MPa): Strength of bonding with the substrate.

All measured properties increase with higher SKN-18-1 content, indicating improved toughness and elasticity.

Tensile and impact strengths show particularly significant improvement, highlighting enhanced resilience under seismic and dynamic loading conditions.

Scientific Significance:

The graph demonstrates the synergistic effect of functional modifiers (acrylic acid and coke filler) and rubber on mechanical performance.

Such data are critical for the design and optimization of high-performance epoxy composites intended for infrastructure applications.

The mechanical performance improvements shown in the graph have direct implications for infrastructure resilience and risk mitigation:

Seismic and Dynamic Load Resistance: The increased tensile strength and impact resistance due to SKN-18-1 modification indicate that the epoxy composites can better withstand sudden mechanical shocks and seismic stresses. This reduces the likelihood of structural failure under natural hazards.

Durability and Operational Safety: Enhanced hardness and adhesion improve the composite's long-term stability and bonding with substrates, minimizing risks of delamination or surface degradation over time, which is crucial in critical infrastructure systems.

Risk Mitigation in Engineering Applications: By incorporating functional modifiers (acrylic acid, coke filler) and rubber, the material demonstrates higher energy absorption and toughness. This reduces vulnerability to unexpected loads, vibrations, and mechanical impacts, effectively lowering operational and structural risks.

Holistic Impact: The combination of improved mechanical properties with the controlled modification strategy supports a risk-oriented design approach, allowing engineers to select materials that increase safety margins and resilience against environmental and operational hazards.

The fabricated epoxy composites were systematically characterized for their physical and mechanical performance. Tensile strength, impact resistance, hardness, and adhesion properties were measured using standardized testing protocols to ensure consistency and comparability with prior literature. These evaluations provide comprehensive insight into the structural integrity, deformation behavior, and energy absorption capabilities of the modified composites. Notably, the enhanced mechanical properties—particularly improved toughness and resilience—underscore the potential applicability of these materials in infrastructure systems subjected to dynamic loading, seismic stresses, and other extreme operational conditions. The results highlight the synergistic effect of rubber modification, functional monomer incorporation, and filler reinforcement in tailoring the mechanical performance of epoxy composites for high-demand engineering applications.3. Chemical and Environmental Resistance Testing

The swelling degree and chemical stability of the composites were assessed in aggressive environments, including acidic and alkaline media. The results are particularly relevant for dams, drainage, and reclamation infrastructures, which are frequently exposed to water-chemical interactions, soil contaminants, and climatic degradation.

4. Integration into Risk-Oriented Infrastructure Assessment

Beyond laboratory evaluations, the study interprets the material performance in the context of risk management. Improved impact resistance and chemical stability are analyzed as key factors in reducing vulnerability under multi-hazard conditions (e.g., seismic events combined with chemical exposure). A qualitative multi-criteria decision-making (MCDM) framework was applied, linking material performance to resilience indicators such as durability, sustainability, safety, and cost-effectiveness.

This combined methodology ensures that experimental findings on epoxy–rubber composites are not only assessed for their technical value but also situated within the broader objectives of sustainable and resilient infrastructure design.

After extraction of the composition based on solidified EO-20/SKN-18-1 in acetone for 20 hours, the gel fraction was determined to be 95.8%.

After extraction of the solidified composition EO-20/SKN-18-1, IR-spectroscopic analysis was performed and it was shown that the polymers are chemically intercalated with each other.

After extraction of the composition based on EO-20/SKN-18-1/AA, the gel fraction was determined to be 96.5%.

Compositions based on SKN-18-1 and SKN-18-1/AA modified epoxy oligomer were prepared and their properties were compared with the properties of the composition based on EO-20 and it was shown that the properties of the modified compositions were significantly improved compared to the unmodified ones.

The effect of coke as a filler on the properties of the composition based on EO-20/SKN-18-1/At-94/6/0.75 was studied and it was shown that coke plays a significantly important role in improving the properties of the composition.

The overall methodological framework of the study is illustrated in Figure 1, linking hazard risks with material modification, performance evaluation, and infrastructure applications.

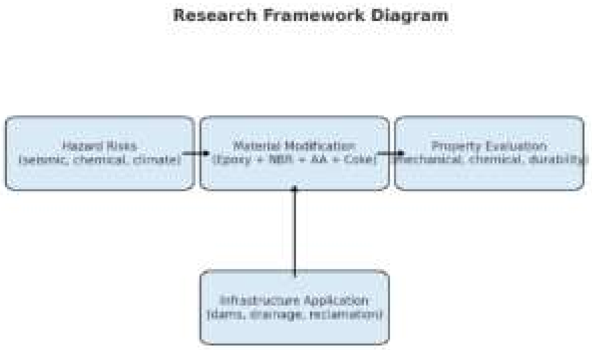

Figure 1. *Research framework linking hazard risks, material modification, property evaluation, and infrastructure applications for resilient and sustainable infrastructure systems.*

V. Results and Discussion

1. Mechanical Performance Improvements

The incorporation of liquid butadiene-nitrile rubber (SKN-18-1) into epoxy oligomer (EO-20) compositions resulted in significant enhancements in impact resistance and elasticity. At 4–6 p.w. SKN-18-1, the composites demonstrated optimal tensile strength and improved adhesion to substrates. These improvements are crucial for seismic-prone infrastructures, where materials must dissipate energy and maintain structural integrity under dynamic loading.

2. Chemical Resistance and Environmental Stability

Chemical testing revealed that epoxy–NBR composites exhibited lower swelling and higher stability in aggressive media compared to unmodified epoxy systems. Additional modification with 0.75 p.w. acrylic acid and 6.0 p.w. coke filler further increased durability, particularly against acidic and alkaline environments. This property has direct implications for dams, drainage, and reclamation systems, where contact with chemically active water and soil is unavoidable.

3. Relevance to Infrastructure Risk Management

The results demonstrate that improved material properties directly reduce vulnerabilities in critical infrastructures. Enhanced impact resistance strengthens resilience against seismic risks, while chemical stability mitigates degradation caused by climate-induced and technological hazards. These outcomes align with risk-oriented design principles, where material performance is integrated into strategies for long-term sustainability and safety.

4. Integration with Multi-Criteria Decision-Making (MCDM)

The experimental findings were evaluated within a qualitative MCDM framework. Criteria such as mechanical performance, environmental resistance, sustainability, and cost-effectiveness were considered. EPDM and NBR-based composites ranked highly in terms of durability and risk reduction, although considerations related to the environmental risks of precursors such as phthalic anhydride remain critical. This dual perspective highlights the need to balance performance gains with ecological and human health concerns.

5. Implications for Infrastructure Systems

The study demonstrates that material innovations can serve as risk-mitigation tools in infrastructure systems. In dams, epoxy–NBR composites can be applied as protective coatings or sealing materials, extending service life and minimizing maintenance needs. In drainage and reclamation systems, their resistance to aggressive environments reduces the likelihood of premature failures. The broader implication is that infrastructure investments should increasingly incorporate advanced material science as a core element of resilience-building.

Table 1. *Performance improvements of epoxy oligomer (EO-20) modified with NBR*

Composition (EO-20 + additives)	Mechanical Properties (tensile, impact, adhesion)	Chemical Resistance (swelling in aggressive media)	Relevance for Infrastructure Applications
Pure EO-20 (control)	High strength but brittle; low impact resistance	Moderate resistance; swelling in acids/alkalis	Limited suitability; prone to cracking under seismic loads
EO-20 + 4–6 p.w. NBR	Increased tensile strength and elasticity; significant improvement in impact resistance	Lower swelling; enhanced stability in aggressive environments	Suitable for seismic zones; protective coatings for dams and drainage
EO-20 + NBR + 0.75 p.w. AA	Additional improvements in durability and adhesion	Improved resistance against acidic/alkaline environments	Longer service life in reclamation and drainage infrastructures
EO-20 + NBR + AA + 6.0 p.w. Coke	Optimal balance: high impact strength, good adhesion, durable performance	Strongest resistance to chemical degradation	Most promising for long-term safety of dams and drainage systems

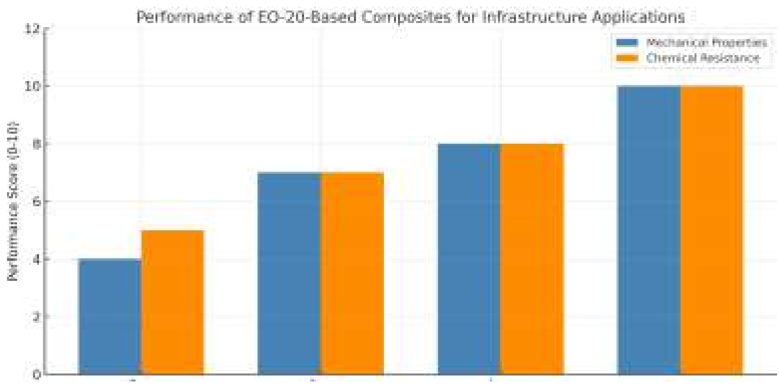

Figure 2. *Performance evaluation of EO-20-based epoxy composites with various additives for infrastructure applications. Mechanical properties (tensile strength, impact resistance, and adhesion) and chemical resistance (swelling in aggressive media) are shown for different compositions: pure EO-20, EO-20 with NBR, EO-20 with NBR and acrylic acid (AA), and EO-20 with NBR, AA, and coke filler. Incorporation of NBR and functional modifiers progressively enhances toughness, adhesion, and chemical stability, indicating improved suitability for seismic zones, dams, drainage, and other critical infrastructure systems.*

V. Conclusion and Recommendations

This study demonstrated that epoxy oligomer (EO-20) composites modified with butadiene-nitrile rubber (SKN-18-1), acrylic acid, and coke filler exhibit significantly improved mechanical and chemical properties compared to unmodified epoxy systems. The addition of 4–6 p.w. SKN-18-1 yielded optimal tensile strength, impact resistance, and adhesion, while acrylic acid and coke filler further enhanced environmental stability. These findings confirm the suitability of polymer-modified epoxy systems for use in critical infrastructure applications such as dams, drainage, and reclamation systems, where materials are exposed to seismic loading, aggressive chemical environments, and long-term climatic degradation.

By linking experimental material science with risk-oriented infrastructure design, the research highlights the role of advanced composites in reducing vulnerabilities and building resilience. Improved impact resistance addresses seismic risks, while chemical stability supports long-term sustainability and reduces maintenance costs. At the same time, the dual nature of chemical precursors such as phthalic anhydride emphasizes the importance of balancing material innovation with environmental and human safety considerations.

Recommendations

Application in Critical Infrastructure: Epoxy–NBR composites should be considered for protective coatings, sealing systems, and structural reinforcements in dams, drainage, and reclamation projects.

Integration into Risk-Oriented Frameworks: Material performance should be explicitly incorporated into infrastructure risk assessments, scenario analyses, and resilience strategies.

Multi-Criteria Decision-Making: Stakeholders and engineers should evaluate material choices based not only on technical performance but also on environmental, economic, and social criteria.

Sustainability Considerations: Alternatives to environmentally hazardous precursors such as phthalic anhydride should be explored to align material innovations with sustainable development goals.

Future Research: Further studies should investigate the long-term field performance of epoxy–NBR composites under real multi-hazard conditions, supported by monitoring technologies and predictive modeling.

By integrating risk management, materials engineering, and sustainability considerations, this study contributes to a holistic framework for developing resilient and environmentally sustainable infrastructure systems.

CONFLICT OF INTEREST
Authors declare that they do not have any conflict of interest

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