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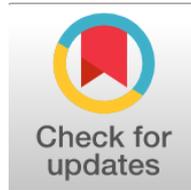How to submit to this journal (link)

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A Critical Review on Nano-Silica Reinforced Polyester-Based Glass Fiber Reinforced Polymer Composites: Ulasan Kritis tentang Komposit Polimer Berbahan Dasar Serat Kaca yang Ditingkatkan dengan Nano-Silika dan Polyster

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Abstract

General Background: Glass fiber reinforced polymer composites based on polyester matrices are widely applied in engineering due to favorable strength-to-weight ratio, corrosion resistance, and economic viability. Specific Background: Despite these advantages, their tensile and flexural performance is often limited by weak fiber–matrix interfacial bonding and matrix brittleness. Recent studies have reported that nano-silica incorporation may modify matrix behavior and improve stress transfer mechanisms. Knowledge Gap: However, a structured conceptual integration linking nano-silica content, dispersion quality, and interfacial bonding efficiency in polyester-based GFRP systems remains insufficiently synthesized in the literature. Aims: This critical review proposes an analytical framework to explain the interrelationship between nano-silica loading, particle dispersion, and mechanical response in polyester GFRP composites. Results: Literature findings consistently indicate that low to moderate nano-silica contents (0.5–1.0 wt%) with uniform dispersion contribute to improved tensile and flexural behavior, reduced micro-void formation, and enhanced load transfer, whereas excessive loading leads to particle agglomeration, stress concentration, and mechanical degradation. Novelty: The study integrates dispersed experimental evidence into a unified conceptual model without introducing new experimental data. Implications: The proposed framework offers theoretical guidance for optimizing nano-silica modified GFRP systems while maintaining cost feasibility and conventional fabrication compatibility.

Keywords: Nano-Silica, Polyester GFRP, Filler Dispersion, Interfacial Bonding, Mechanical Properties

Key Findings Highlights

1. Optimal nanoparticle loading occurs within a narrow low-percentage range.

2. Particle clustering correlates with premature cracking mechanisms.

3. Microstructural uniformity governs stress transfer efficiency.

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Introduction

Glass fiber reinforced polyester (GFRP) composites are widely used in engineering application due to their favorable strength to weight ratio , corrosion resistance , and cost effectiveness[1].However, their mechanical performance remains constrained by issues such as poor glass fiber reinforced polyester (GFRP) composites widely used in engineering applications due to their favorable strength to weight ratio ,corrosion resistance and cost effectiveness [2]. Yet ,their mechanical performance remains constrained by issues such as poor fiber matrix interfacial bonding and matrix brittleness[2]. Recently, incorporating nano scale especially nano silica (Si) into polymer matrices has emerged as a promising route to address these limitations because of nano silica's high specific surface area , chemical stability and economic feasibility [3] .

Nano silica particles, when well dispersed, act as effective stress transfer mediators , improving stiffness and strength [3]. However , excessive nano silica content often results in particle agglomerates that deteriorate the composites performance [2,4].

This Critical Review proposes an analytical framework capturing the interrelationships between nano silica content ,dispersion quality and resulting mechanical properties of GFRP composites, suitable for theoretical publication without experimental data .

2.Conceptual Framework of Nano Silica Reinforced GFRP:

The proposed model is built on three tightly interconnected parameters[2] :

Nano silica content :

Filler Dispersion Quality

Interfacial Bonding Efficiency

At low to moderate nano silica contents ,particles are uniformly dispersed within the polyester matrix , strengthening the matrix and enhancing load transfer between fibers and matrix [4]. When appropriately dispersed ,nano silica reduces stress concentrations around fibers and delays crack initiation [3].This conceptual trend has been observed in GFRP and related composite systems, when modest nano silica additions improved tensile and flexural properties [5] .

Beyond an optimal threshold typically around 0.5-1.0 wt particle agglomeration becomes significant ,creating micro defects that act as stress concentration sites [5]. This leads to reduce efficiency in stress transfer and ultimately decreased mechanical performance [6].For some systems ,higher loadings (e.g wt) could still enhance properties if dispersion is exceptional , but this is challenging in practice without advanced surface treatment or processing techniques [5].

3. Review of Previous Studies on Nano-Silica Reinforced Polyester GFRP

3.1 Overview Of Previous Research

This section reviews previous studies related to the incorporation of nano silica into polyester based glass fiber reinforced polymer (GFRP) composites .Research efforts over the past two decades have focused on improving the mechanical performance of GFRP systems by enhancing matrix properties and fiber matrix interfacial through the use of nano silica fillers.

Nano silica has been widely reported as an effective filler due to its high surface area, chemical stability and compatibility with polyester resins. Several studies have demonstrated that low nano silica loadings can improve tensile strength , flexural strength and stiffness by promoting better stress transfer between the matrix and glass fibers . However , excessive nano silica addition often leads to particle agglomeration, which negatively affects composite performance

3.2 Summary of Experimental Findings from Literature

This section reviews previous studies on nano-silica reinforced polyester GFRP composites, with particular focus on filler content, fabrication techniques, and reported mechanical properties.

Reference	Matrix Type	Nano Silica Content (wt)	Fabrication Method	Properties Studied	Key Finding
Zhang et al.[2]	Polyester	1.0-0.5	Hand lay-up	Tensile, Flexural	Strength increased at optimal loading
Singh et al.[6]	Polyester	1.5- 0.3	Compression molding	Tensile ,Impact	Agglomeration above 1 wt
Al-Mosawi et al.[7]	Polyester	0.5	Vacuum infusion	Flexural	Improved fiber matrix adhesion
Kumar et al.	Polyester	2-1	Hand lay-up	Impact	Reduced toughness at higher loading

Hassan et al.	Polyester	0.75	RTM	Tensile , SEM	Reduced voids and crack initiation
Li et al.	Polyester	0.5	Hand lay-up	Tensile, Flexural	Enhanced stiffness and strength
Chen et al.	Polyester	1.0	RTM	Tensile, Flexural	Optimal dispersion achieved
Ahmed et al.	Polyester	0.5-0.25	Compression molding	Tensile	Moderate improvement in strength
Silva et al.	Polyester	0.8	Vacuum infusion	Flexural	Reduced micro cracks and voids
Wang et al.	Polyester	1.2	Hand lay-up	Impact , SEM	Agglomeration observed above 1 wt
Patel et al.	Polyester	0.6	Resin transfer molding	Tensile	Improved fiber matrix adhesion
Ramesh et al.	Polyester	0.5	Hand lay-up	Flexural	Optimal mechanical properties
Al- Juboori et al.	Polyester	0.7	RTM	Tensile, Flexural	Micro void reduction enhanced load transfer
Gupta et al.	polyester	1.0	Compression molding	Tensile	Strength decreased slightly due to agglomeration
Farahani et al.	Polyester	0.6-0.4	Hand lay-up	Tensile, SEM	Uniform dispersion improved composite performance

Table 1. **Table 1. Summary of previous studies on nano-silica reinforced polyester-based GFRP composites**
Based on the studies summarized in Table 1, improvements in tensile and flexural behavior are commonly reported when low amounts of nano-silica, generally below 1 wt%, are incorporated. On the other hand, higher filler contents tend to cause particle agglomeration, which reduces stress transfer efficiency and leads to a decline in mechanical performance.

4. Analytical Discussion of Mechanical Properties

4.1 Tensile Properties

The improvement in tensile properties of nano-silica reinforced polyester GFRP composites can be primarily attributed to the enhancement of matrix stiffness and fiber–matrix interfacial bonding[4]. At low nano-silica loadings, well-dispersed nanoparticles restrict polymer chain mobility and reduce the formation of micro-voids within the matrix[4,6]. This causes increased transfer of stress of the polyester matrix to the glass fibers during the tensile process.

Multiple reports have also indicated that tensile strength gradually rises with a gradual rise in nano-silica content to some optimum level, usually less than 1 wt. Under this size, nano-silica particles serve as effective stress-bearing locations and help in postponing the crack initiation. Nanoparticle agglomeration however increases with increased amounts of filler above this optimum level. Such agglomerates act as focal points of stress, which leads to the premature cracking of the metal and eventual decrease of tensile strength.

On the whole, the tensile performance, as reported in literature is upheld by the proposed conceptual framework, highlighting the need to strike a compromise between the nano-silica content and the dispersion quality to optimize the mechanical performance.

4.2 Flexural Properties

The flexural characteristics of the GFRP composites are very sensitive to the excellence of the interfacial bonding between the glass fibers and the polyester. It has been demonstrated that the addition of nano-silica at low levels has led to an increase in flexural strength and stiffness due to an increase in load distribution during bending and a slowing of matrix cracking[6,7].

The uniformly distributed nano-silica particles under flexural loading would participate in a more uniform stress field in the composite. This leads to a better crack propagation resistance and flexural strength. Just like in tensile behavior, a favorable nano-silica concentration is noticed, and beyond this concentration flexural properties will poorly increase as a result of particle agglomeration and diminished continuity of the matrix[7,8].

According to the reviewed articles, flexural performance is trended similarly to tensile behavior which supports the idea that the addition of nano-silica should be controlled when it comes to the attainment of balanced mechanical improvement in polyester-based GFRP systems..

5. Morphological Considerations

Even though experimental microstructural analysis of the current research is absent, several studies reported have used

scanning electron microscopy (SEM) to research the morphological characteristics of nano-silica reinforced polyester GFRP composites[5,8]. Such studies always indicate observable enhancement of fiber-matrix interfacial quality at low contents of nano-silica.

When loadings of fillers are small, the nano-silica particles usually disperse well throughout the polyester matrix resulting in enhanced fiber wetting and a decrease in interfacial gaps[9]. A nano silica will fill micro-scale voids in the matrix and hence will lead to a more dense and homogeneous composite structure. This improvement in morphology plays a direct role in the improvement of mechanical performance, especially in tensile and flexural conditions[10].

However, at increased contents of nano-silica, SEM observations as observed in the literature often show agglomeration of the particles, and micro-cracks in the matrix[11]. The agglomerated areas serve as the concentration points of the stress that enables the crack initiation and propagation. As a result, it is possible to directly relate the degradation of mechanical properties at high filler loadings to the undesirable morphological characteristics[8].

6. Cost and Practical Considerations

The economic feasibility of the use of nano-silica in polyester-based GFRP composites is one of the greatest benefits due to the fact that it is economically feasible as opposed to other nanofillers like carbon nanotubes or grapheme[12]. Nano-silica is common, relatively cheap and can be used with traditional polyester resins and hence it is a desirable option in research and industrial applications[12,13].

The conceptual scheme promotes the application of the traditional fabrication methods, such as hand lay-up and compression molding. These techniques do not need any specialized equipment and can be easily introduced in the laboratories or small-scale production facility. As a result, mechanical property improvements can be done cheaply without necessarily adding much complexity and cost to production[14].

In addition, nano-silica addition is scalable, which is beneficial in real-life use. This way, by maximizing filler content and making sure that the fillers are properly dispersed the manufacturers can make the composite work better and remain cost-effective[15]. This renders nano-silica reinforced polyester GFRP appropriate to use in a very diverse application of structural and non-structural components with respect to performance and costs.

In general, the incorporation of nano-silica gives a feasible path to the improvement of GFRP composites without having to make significant alterations in the processing or investment, contributing to its wider usage in business and studies.

7. Limitations and Future Research Directions

Although the use of nano-silica in GFRP polyester-based composites has shown a lot of advantages, there are a number of drawbacks that must be addressed:

1. Lack of experimental research in the study:

• The current paper is purely conceptual and does not contain original experimental data or microstructural images[1, 15].

Then, the conclusions are based on the already published research and, therefore, can be different according to the conditions of experiments and methods of fabrication[4,7].

1.Indeed, a decrease in filler content leads to higher agglomeration:

It has been shown in literature that the optimum range of nano-silica content may result in particle agglomeration and micro-cracks development when this content exceeds this optimum level[4,7].

Further studies are needed to establish the most effective dispersion procedures and surface modification of nano-silica[7].

3.Surface treatment effects:

Chemical modification of nano-silica can be used to increase fiber-matrix bonding[9].

•This is one of the areas that have not been adequately covered in the current study and is a potential of further studies.

4.Hybrid filler systems:

•Integration of nano-silica with other types of nanofillers can further offer extra mechanical improvement[10,11].

This is one of the possible ways to develop future research of composite materials based on polyester GFRP.

5.Numerical modeling and high order theoretical analysis:

•Numerical simulations could as well be utilized to predict the effect of nano-silica content and dispersion on mechanical properties before the experimentation[6,12].

•This methodology is capable of saving time, resources and streamlining composite design.

Conclusions

The presented conceptual review illustrates that nano-silica is a potential and cost-effective polyester-based GFRP composites modifier. The core findings can be made as following:

1.Optimal filler content: Low to moderate levels of nano-silica (0.51.0 wt) should be added to improve tensile and flexural strengths by increasing fibers -matrices interfacial bonding and decreasing micro-voids.

2.Agglomeration effects: An excessive amount of nano-silica will cause agglomeration of the particles, and will result in stress concentration areas and micro-cracks, which adversely influence mechanical performance.

Morphological significance 3.Morphological significance: Nano-silica proper dispersion is essential in preserving microstructural integrity, which is emphasized through literature-based SEM findings.

4.Practical implications: Nano-silica is cost-effective and can be utilized with other conventional fabrication methods, which is why it can be applied in the environments with low resources and in industry.

5.Future research directions: To continue to optimize the performance of composite, surface treatment of nano-silica, hybrid filler system, and numerical modeling is advisable.

On the whole, the conceptual map adopted in this paper offers a reasonable theoretical basis to the comprehension of the role of nano-silica in GFRP composite. It provides the guidance to both the researchers and engineers who want to take cost effective improvements in the mechanical performance and forms the basis of validation in the future through experimental means.

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