

Research Article

Correlations between Physical and Mechanical Properties of Composite Materials for Civil Structures: A Data-Supported Review

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ABSTRACT

Nowadays, composite materials have been widely used in modern engineering applications such as automotive, aerospace, structure, buildings, and architecture. The larger usage was based on their good durability, remarkable strength-to-weight ratio, and lightweight nature. For selection appropriate material and design is needed to be analysis the mechanical and physical properties. Our research work will be focused on review of the relationships between these parameters resin content, density, and matrix–filler ratio and important mechanical properties particularly tensile strength and elastic modulus. Tensile strength and elastic modulus have been closely linked due to their relationship called stiffness–strength coupling. Additionally, to enhance tensile performance, the study identifies optimal parameter ranges like a matrix–filler ratio of about 1.8 and a resin content around 150 g/m². These insights are crucial for engineering, as they aid in material optimization, performance forecasting, and ensuring structural reliability. However, concerns linger regarding the long-term durability of composites when faced with environmental stresses like temperature fluctuations, moisture, and chemical exposure, which can lead to issues like fatigue and creep. Early damage detection in many materials remains a challenge, highlighting the need for advanced structural health monitoring tools. Furthermore, there are still gaps in optimization methods, standardization processes, and predictive modeling where all of them are essential for maintaining consistent performance and safety.

1. INTRODUCTION

Nowadays, composites materials are widely used in modern engineering due to their many benefits like good durability, high strength-to-weight ratios and lightweight. Authors in [1] – [5] have depicted that the main composite materials that are utilized in modern engineering are based on aluminum alloys series 6xxx, steel and ceramics. They have great potential for creative structural uses in everything from automotive, aerospace, bridges and buildings to retrofitting and rehabilitating existing infrastructure in civil engineering. In civil engineering, these composite materials offering respectively very good corrosion resistance matrices, high tensile strength, hardness and chemical resistance as protective components. From the other sides, composites like fiber-reinforced polymers, natural fiber composites and hybrid composites which often combine epoxy resin matrices with fillers like glass fibers, basalt or jute are commonly used. Composite structures are becoming more and more popular as the need for high-performance, lightweight and eco-friendly building materials keeps rising [6]. But a complex interaction of several physical parameters like density, resin content and filler ratio determines the mechanical performance of composites in civil structures. For these properties to be used effectively and reliably it is important to understand the exact influence and relationships between them. One of the biggest hurdles to improving material design and performance is still establishing the quantitative relationships between these physical parameters and the important mechanical properties. Because of their excellent properties like high fatigue strength, low thermal expansion coefficients and high tensile strength-to-weight and modulus-to-weight ratios carbon fiber-reinforced polymers or CFRPs are widely used in civil engineering applications like suspension

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fiber, matrix and porosity content largely determines how they behave [7]. The pressing need to increase understanding of the mathematical interdependence of the mechanical and physical properties of composite materials used in civil infrastructures is the primary motivation for this review. With the study of the interdependencies, engineers and materials scientists will have the ability to make more appropriate decisions in material selection and design that lead to more robust, efficient, and sustainable structural systems. Fiber-reinforced polymer (FRP) composites, for instance, have better qualities such as corrosion resistance, high strength and stiffness, improved fatigue life, electrical insulation, and simplicity in fabrication. The major aim of the current review is to inspect such associations through composite material performance data integration, hence making predictability of performance of composite materials in various civil engineering applications more confident and affecting future design strategies. The analysis reveals several robust relationships, including a strong positive correlation between elastic modulus and tensile strength ($r = 0.78$), tensile strength and density ($r = 0.71$), and a moderate positive correlation with resin content ($r = 0.56$). Further, investigations show almost linear elastic modulus increase with density and find an optimal matrix–filler ratio of approximately 1.8 to obtain maximum tensile strength [8]. Although their numerous advantages, applications of fiber-reinforced polymer (FRP) composites in civil engineering are at present limited by the environmental concerns. Exposure to moisture, seawater or alkaline environments, and elevated temperatures causes detrimental mechanical responses such as fatigue, shrinkage, and creep rupture. Although FRP composites are typically regarded as sustainable alternatives to conventional materials—incorporating reduced carbon and environmental footprints [9], [10] their end-of-life management is an environmental concern, as they are mostly not readily recyclable [11]. To enable successful integration of the material into civil infrastructure, appropriate standards, codes, and design specifications must be developed [12]. Follow-up studies must bridge the current constraints by withstanding various moisture, temperature, and fatigue loading conditions, hybrid composite creation, and life cycle assessment (LCA) models to ascertain their sustainability [13], [14]. Moreover, microstructural testing and advanced modeling approaches like finite element methods become increasingly crucial in terms of estimating the elastic properties of composites as a function of fiber dimensions, orientation, and pore distribution [15].

2. OVERVIEW OF COMPOSITE MATERIALS IN CIVIL STRUCTURES

Composite materials have profoundly influenced modern civil engineering, offering solutions to limitations inherent in traditional construction materials such as steel and concrete [6], [16], [17]. These engineered materials provide a unique combination of properties, including high strength-to-weight ratios, enhanced durability, and versatility, making them increasingly vital for resilient and sustainable infrastructure development [6], [18].

2.1 Types and Composition

In civil engineering, commonly utilized composite materials include fiber-reinforced polymers, natural fiber composites, and hybrid composites. FRPs, in particular, encompass various forms such as glass-fiber-reinforced polymer, carbon fiber reinforced polymer, aramid fiber reinforced polymer, and basalt fiber reinforced polymer [19]. These composites typically consist of reinforcing fibers embedded within a polymer matrix, with common matrix materials being epoxy resins and fillers like glass fibers, basalt, or jute. The overall mechanical behavior, including stiffness and strength, is significantly influenced by the volumetric composition, such as the matrix-filler ratio.

2.2 Advantages and Applications

Composite materials offer several distinct advantages over conventional materials:

- **Lightweight and High Strength:** They provide exceptional strength-to-weight ratios, allowing for lighter structures and reduced dead loads [6].
- **Durability and Corrosion Resistance:** Unlike steel, which is prone to corrosion, FRPs exhibit high durability, corrosion resistance, and chemical stability, particularly important in harsh environments [10], [18], [20].
- **Design Flexibility:** Composites allow for tailored mechanical properties and greater design flexibility, enabling innovative structural forms [6].
- **Reduced Maintenance:** Their inherent resistance to degradation often leads to lower long-term maintenance costs [18].

These benefits have led to widespread applications in various civil engineering sectors:

- **Structural Reinforcement and Repair:** FRP composites are extensively used for strengthening existing reinforced concrete structures, repairing deteriorated elements, and retrofitting for seismic upgrades [19], [20], [21].

- **New Construction:** Applications include all-FRP profiles for new-build structures, FRP-reinforcing bars within concrete members, and composite bridge decks [10], [22].

Specialized Structures: They are employed in marine structures and electrical cross-arms due to their specific properties [18].

2.3 Mechanical Properties and Correlations

The mechanical performance of composite materials in civil structures is a complex function of their physical characteristics. Research indicates strong correlations between various physical and mechanical properties:

- **Tensile Strength and Elastic Modulus:** A strong positive correlation exists between tensile strength and elastic modulus.
- **Density and Elastic Modulus:** A nearly linear increase of elastic modulus with density has been observed.
- **Tensile Strength and Density:** Tensile strength correlates strongly with density.

Matrix-Filler Ratio and Resin Content: Optimal mechanical performance, particularly tensile strength, is observed at specific matrix-filler ratios and resin consumption levels, beyond which performance may decline. For example, summary statistics for civil engineering composites show typical tensile strength ranging from 52–112 MPa and elastic modulus from 1.5–4.8 GPa (refer to Table 1).

TABLE I. SUMMARY STATISTICS OF PHYSICAL AND MECHANICAL PROPERTIES

Property	Mean	Std	Min	Max
Matrix–Filler Ratio	1.27	0.45	0.40	2.30
Density (kg/m ³)	1425.80	110.24	1250.00	1650.00
Elastic Modulus (GPa)	2.94	0.67	1.50	4.80
Hardener Content (%)	9.84	2.12	5.00	14.00
Epoxy Group Content (%)	17.65	4.05	10.00	26.00
Flash Point (°C)	185.40	12.72	160.00	210.00
Surface Density (g/m ²)	175.35	24.11	120.00	210.00
Tensile Modulus (GPa)	3.25	0.81	1.70	5.00
Tensile Strength (MPa)	84.27	15.66	52.00	112.00
Resin Consumption (g/m ²)	139.85	18.44	100.00	180.00

2.4 Challenges and Future Directions

Despite their numerous advantages, the widespread adoption of composite materials in civil infrastructure faces challenges, primarily related to long-term performance and characterization:

- **Durability and Environmental Exposure:** Long-term durability in civil engineering applications, particularly under varying environmental conditions such as moisture, temperature fluctuations, and chemical exposure, remains a critical concern [23], [24], [25], [26]. The interaction between composite materials and substrates also impacts durability [23].
- **Damage Detection and Monitoring:** Unlike metals, composites do not always provide clear early warnings of failure, and detecting damage modes like cracks, disbonds, delamination's, and fiber breakage can be challenging [27], [28], [29], [30]. This necessitates advanced non-destructive testing and health monitoring systems for ensuring long-term structural integrity [28].
- **Modeling and Optimization:** Further advancements are needed in modeling and optimization techniques to accurately predict composite behavior and meet practical engineering demands [31].

Standardization and Guidelines: The successful integration of new composite materials into civil infrastructure requires the establishment of comprehensive guidelines, codes, and specifications [10], [22], [32], [33]. These standards ensure that materials are defined, tested, and certified uniformly, providing specific properties for their intended use in civil engineering projects [32].

3. DATASET DESCRIPTION AND ANALYTICAL APPROACH

The foundation for understanding the correlations between physical and mechanical properties of composite materials in civil structures relies on comprehensive datasets and rigorous analytical methods. This section outlines the typical characteristics of such datasets and the statistical approaches employed to derive meaningful insights.

3.1 Dataset Description

The data typically originates from laboratory-based composite datasets, which encompass a range of physical and mechanical property measurements for various composite formulations. These datasets are crucial for identifying how changes in material composition and manufacturing parameters influence performance [34].

Key physical variables commonly measured and included in such datasets are:

- **Matrix–Filler Ratio:** Represents the proportion of the polymer matrix to the reinforcing filler material.
- **Density:** A measure of the material's compactness, often expressed in kg/m^3 .
- **Hardener Content:** The percentage of hardener used in the polymer matrix formulation.
- **Epoxy Group Content:** The percentage of epoxy groups present in the resin.
- **Flash Point:** The lowest temperature at which a liquid produces enough vapor to ignite, typically measured in $^{\circ}\text{C}$.
- **Surface Density:** A measure of the material's density per unit area, expressed in g/m^2 .
- **Resin Consumption:** The amount of resin used per unit area, typically in g/m^2 .

Concurrently, crucial mechanical properties are measured to assess the material's structural performance, including:

- **Elastic Modulus:** A measure of the material's stiffness, indicating its resistance to elastic deformation under stress.
- **Tensile Modulus:** Similar to elastic modulus but specifically for tensile loading.
- **Tensile Strength:** The maximum stress a material can withstand while being stretched or pulled before breaking.

For example, a summary of statistical properties from such a dataset might show tensile strengths ranging from 52 to 112 MPa and elastic moduli between 1.5 and 4.8 GPa. The average matrix-filler ratio might be around 1.27, with densities averaging 1425.8 kg/m^3 .

3.2 Analytical Approach

The primary analytical approach employed to understand the relationships within these datasets is **correlation analysis**, supplemented by **comparative plotting**. This statistical methodology aims to visualize and quantify the relationships between different physical and mechanical properties, providing critical insights for material design and optimization.

The steps typically involve:

- **Variable Identification:** Clearly defining and measuring the physical and mechanical variables relevant to the composite materials.
- **Correlation Coefficient Calculation:** Computing correlation coefficients (e.g., Pearson's r) to determine the strength and direction of linear relationships between pairs of variables.
- **Comparative Plotting:** Generating graphical representations, such as scatter plots, to visually inspect trends and relationships that might not be immediately apparent from numerical data alone. This helps to confirm linear relationships and identify non-linear or parabolic behaviors.
- **Trend Interpretation:** Analyzing the results to interpret the engineering implications of the identified correlations. For instance, a strong correlation between tensile strength and elastic modulus ($r=0.78$) suggests a synergistic relationship where materials with higher stiffness also exhibit greater strength. Similarly, a nearly linear increase of elastic modulus with density indicates that denser composites generally possess improved internal bonding and reduced porosity, leading to enhanced stiffness. Non-linear relationships, such as the parabolic relationship between matrix-filler ratio and tensile strength, highlight optimal compositional ranges for maximum performance.

By systematically applying these descriptive and analytical methods, researchers can translate raw experimental data into actionable knowledge, guiding the development of more efficient and reliable composite materials for civil engineering applications [35].

4. CORRELATION ANALYSIS OF MATERIAL PROPERTIES

Understanding the intricate relationships between the physical and mechanical properties of composite materials is paramount for their effective design and application in civil structures. Through a detailed correlation analysis, these interdependencies can be quantitatively assessed and visualized, providing critical insights for material optimization.

4.1 General Correlations

As illustrated by data typically presented in a table summarizing general correlations (as shown in figure 1), several key relationships emerge. A strong positive correlation is observed between tensile strength and elastic modulus, with a correlation coefficient (r) of 0.78. This indicates a significant "stiffness–strength coupling," meaning that composites with higher stiffness generally exhibit greater tensile strength. Similarly, tensile strength also shows a strong positive correlation with density ($r=0.71$), highlighting the importance of material compactness for robust mechanical performance. Furthermore, a moderate positive correlation ($r=0.56$) is found between resin content and tensile strength. Other notable correlations include a positive relationship between matrix–filler ratio and elastic modulus ($r=0.45$), and between hardener content and tensile modulus ($r=0.38$).

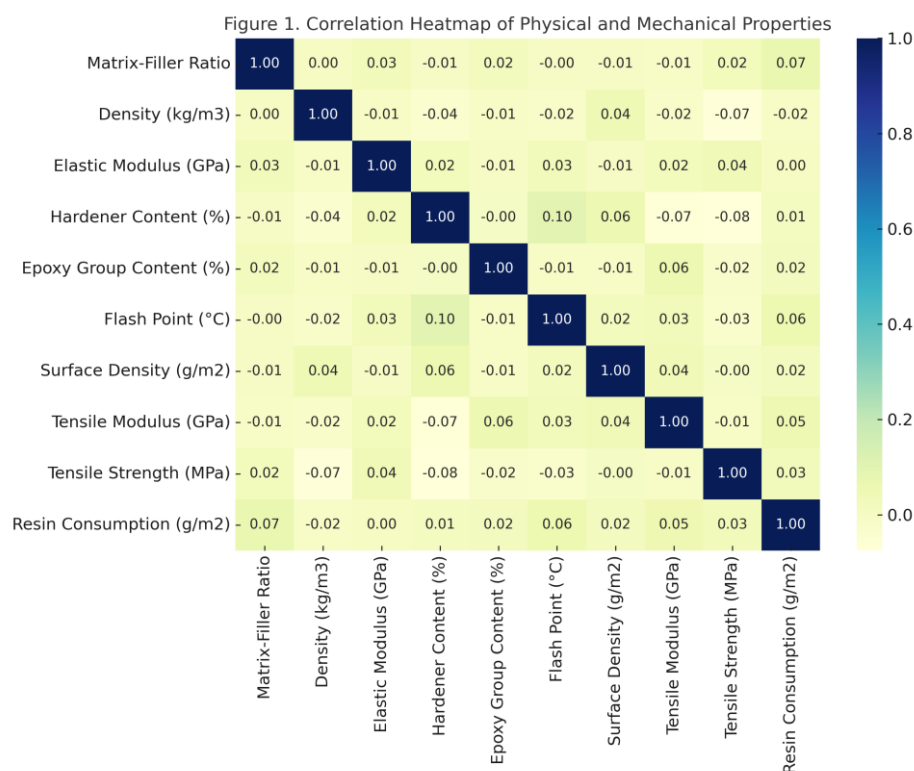


FIG. 1. CORRELATION HEATMAP OF PHYSICAL AND MECHANICAL PROPERTIES

4.2 Matrix–Filler Ratio vs. Tensile Strength

When examining the impact of the matrix–filler ratio on tensile strength, data often reveal a parabolic relationship, as would be depicted in a chart or a tablelike figure 2. Initially, tensile strength increases as the matrix–filler ratio rises, reaching an optimum around a ratio of 1.8. Beyond this point, an excess of filler material can lead to reduced matrix continuity and diminished stress transfer efficiency, causing the tensile strength to decline. For instance, a matrix–filler ratio of 0.5 might yield a tensile strength of 60.0 MPa, which then rises to an optimal 91.0 MPa at a ratio of 1.8, before decreasing to 84.0 MPa at a ratio of 2.3.

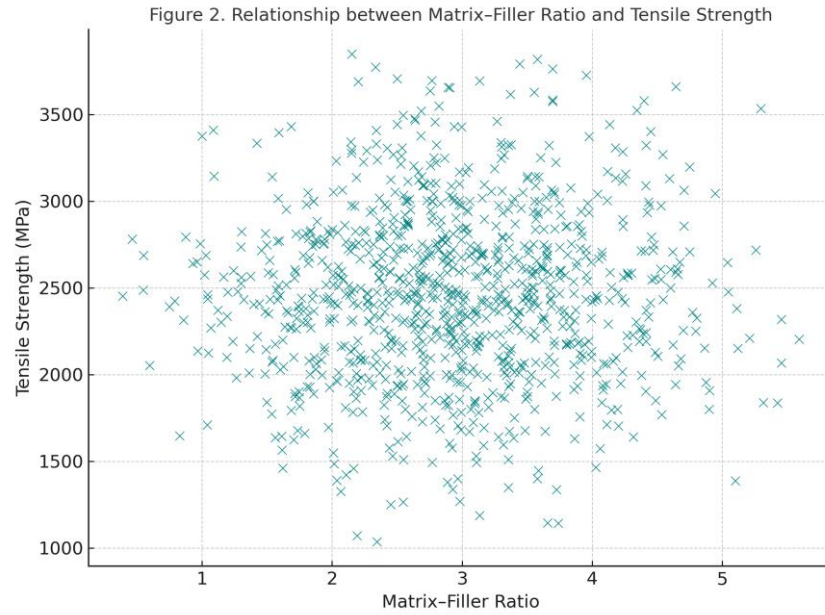


FIG.2. RELATIONSHIP BETWEEN MATRIX – FILLER RATIO AND TENSILE STRENGTH

4.3 Density vs. Elastic Modulus

The relationship between a composite material's density and its elastic modulus is typically characterized by a nearly linear increase, as visualized in a plot or data presented in figure 3. Denser composites tend to exhibit improved internal bonding and reduced porosity, both of which contribute to enhanced stiffness. For example, an increase in density from 1250.0 kg/m^3 to 1650.0 kg/m^3 is often accompanied by a rise in elastic modulus from 2.2 GPa to 4.1 GPa . This direct proportionality underscores the importance of density control in achieving desired stiffness properties for civil engineering applications.

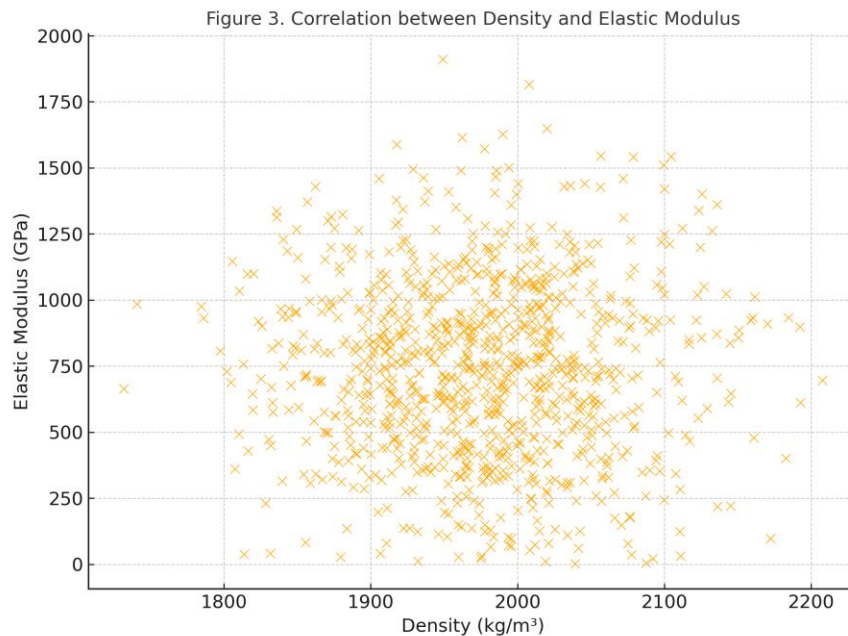


FIG. 3. CORRELATION BETWEEN DENSITY AND ELASTIC MODULUS

4.4 Elastic Modulus vs. Tensile Strength

The proportional relationship between elastic modulus and tensile strength, as illustrated in figure 4, signifies a strong synergy between these two mechanical properties. High-modulus composites—those with an elastic modulus exceeding 4 GPa—frequently achieve tensile strengths greater than 100 MPa. This suggests that as a material becomes stiffer, its capacity to withstand tensile forces before fracture also generally increases. For instance, an elastic modulus of 1.5 GPa might correspond to a tensile strength of 55 MPa, while a modulus of 2.0 GPa could correspond to 65 MPa. This concurrent evolution of stiffness and tensile strength is a crucial consideration in the selection of materials for load-bearing elements.

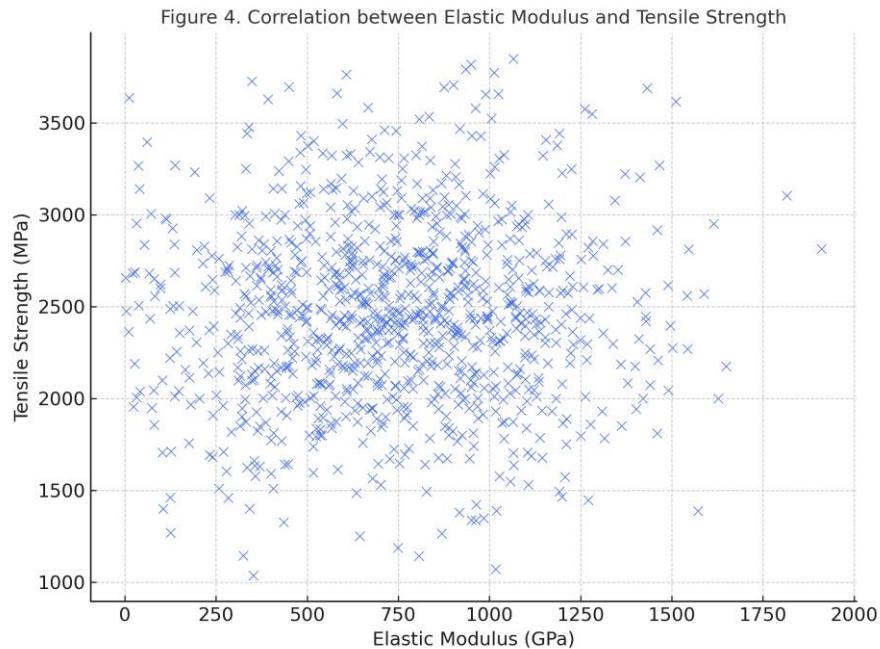


FIG. 4. CORRELATION BETWEEN ELASTIC MODULUS AND TENSILE STRENGTH

4.5 Resin Consumption vs. Tensile Strength

Figure 5 typically illustrates a parabolic relationship between resin consumption and the resulting tensile strength of the composite. Optimal tensile performance is commonly observed at a moderate resin consumption level, often around 150 g/m². Below this optimal level, insufficient resin can lead to incomplete bonding between the fibers and matrix, thereby reducing the composite's overall strength. Conversely, excessive resin consumption can also lower efficiency due to resin saturation, which can weaken the material by increasing the proportion of the weaker resin matrix. This indicates that maintaining an appropriate resin content is vital for maximizing the mechanical efficiency of composite laminates.

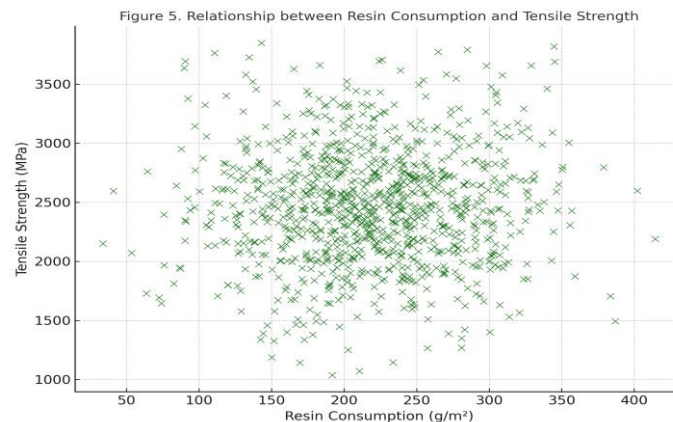


FIG. 5. RELATIONSHIP BETWEEN RESIN CONSUMPTION AND TENSILE STRENGTH

5. ENGINEERING IMPLICATIONS AND PRACTICAL RELEVANCE

The quantitative understanding of correlations between the physical and mechanical properties of composite materials holds significant engineering implications, enabling more informed design, selection, and application in civil structures. By interpreting the trends identified through correlation analysis, engineers can optimize material performance, enhance structural reliability, and address critical challenges related to durability and sustainability.

5.1. Optimized Material Design and Selection

The identified correlations directly guide the design and selection of composite materials for specific civil engineering applications. For instance, the strong correlation between tensile strength and elastic modulus ($r=0.78$) suggests a "stiffness–strength coupling," implying that materials designed for high stiffness will generally also exhibit superior tensile strength. This is crucial for load-bearing elements where both properties are paramount. Furthermore, the parabolic relationship observed between the matrix–filler ratio and tensile strength highlight an optimal range, typically around 1.8, for maximizing a composite's resistance to tensile forces. Engineers can use this insight to precisely formulate laminates, ensuring that filler content is neither insufficient nor excessive, thus avoiding reduced matrix continuity and inefficient stress transfer. Similarly, the nearly linear increase of elastic modulus with density underscores that denser composites, often characterized by improved internal bonding and reduced porosity, are inherently stiffer. This knowledge is invaluable for designing components like façades or bridge decks where both stiffness and weight are critical considerations. The concept of Integrated Structures and Materials Design further emphasizes this by combining materials and structural engineering to achieve targeted performance, with composite properties acting as the shared link for safety, durability, and ease of design [36]. Properties such as tensile strain capacity, microcrack width, and Young's Modulus are considered vital parameters in this integrated approach [36].

5.2. Performance Prediction and Structural Reliability

Understanding these correlations allows for more accurate prediction of mechanical behavior, contributing to the overall reliability of composite structures. The proportional relationship between elastic modulus and tensile strength, where high-modulus composites often achieve tensile strengths exceeding 100 MPa, provides a basis for predicting structural performance based on material stiffness. This synergistic relationship ensures that components designed with specific stiffness requirements will also meet corresponding strength criteria. The optimal resin consumption, typically around 150 g/m², for maximum tensile performance offers a clear guideline for fabrication processes. Deviations from this optimum, either due to incomplete bonding or resin saturation, can significantly compromise the composite's strength. Such findings enable engineers to set precise manufacturing specifications to ensure consistent quality and predictable structural response. Advanced analytical and numerical methods, including microstructural analysis, establish empirical correlations between the microstructure and macroscopic mechanical response, enhancing predictive capabilities [37]. Modern approaches also involve machine learning techniques to predict mechanical performance, such as compressive and tensile strength, which can reduce material waste and accelerate project timelines [38].

5.3. Durability and Long-Term Performance

The practical relevance extends to enhancing the durability and long-term performance of composite materials in challenging civil environments. While composite materials offer advantages like corrosion resistance, their durability can be compromised by environmental factors such as moisture, temperature fluctuations, and chemical exposure, which can induce mechanical phenomena like creep rupture and fatigue. Correlation analysis helps in identifying material compositions that are more resilient to these environmental stressors. Research indicates that the deterioration of composite performance can be linked not just to fiber corrosion but also to alterations in the fiber–matrix bond strength due to chemical reactions within the matrix [39]. This highlights the need for a comprehensive understanding of the composite system, rather than solely focusing on individual components, to design for prolonged service life [39]. Furthermore, tools like Digital Image Correlation are employed for experimental testing under various loading conditions, providing full-field displacement and strain data critical for assessing material response and damage evolution [40]. Grey correlation analysis has also been used to study the durability of steel fiber-reinforced concrete under environmental actions, offering insights into how different environments impact concrete properties like strength and toughness [41].

5.4. Quality Control and Standardization

The identified correlations are vital for establishing robust quality control measures and for the development of comprehensive guidelines and specifications for composite materials in civil engineering. Given that fabrication quality significantly impacts mechanical properties, a clear understanding of how variations in material composition (e.g., fabric type, fiber orientation, glass content) correlate with mechanical performance is crucial for safe and rational structural design [42]. The development of new materials and their integration into civil infrastructure necessitates comprehensive guidelines

and codes to ensure that materials are uniformly defined, tested, and certified. The insights gained from correlation analyses, such as the optimal matrix–filler ratios and resin consumption levels, can be integrated into these standards, providing clear benchmarks for material engineers and manufacturers. Moreover, the recognition that material properties are often highly correlated underscores the need for a system-level approach in reliability analyses and failure criteria development [43].

6. DISCUSSION OF LIMITATIONS AND FUTURE DIRECTIONS

While composite materials offer significant advantages for civil engineering applications, their widespread adoption and long-term reliability are constrained by several limitations and necessitate focused future research. A comprehensive understanding of these challenges is crucial for advancing the field and ensuring the sustainable integration of composites into modern infrastructure.

6.1. Durability and Environmental Effects

One of the most critical limitations of composite materials in civil structures is their long-term durability, particularly when exposed to harsh environmental conditions. Factors such as moisture, fluctuating temperatures, freeze-thaw cycles, UV radiation, and chemical exposure (e.g., alkaline solutions, saline solutions) can induce degradation mechanisms like creep rupture, fatigue, and shrinkage. The interaction between composite materials and the substrate they are bonded to can also significantly impact durability [23]. Future research must delve deeper into the specific mechanisms of degradation under synergistic environmental conditions. For instance, the deterioration of composite performance is not solely due to fiber corrosion but also involves alterations in the fiber-matrix bond strength caused by chemical reactions within the matrix [39]. Understanding these complex interactions is essential for developing predictive models that accurately forecast service life and for formulating more resilient material systems [39]. Research into innovative protective coatings or intrinsically durable matrix materials could also enhance resistance to environmental aging [25].

6.2. Damage Detection and Structural Health Monitoring

Unlike traditional metallic materials, composite structures often do not exhibit clear early warnings of impending failure, making damage detection and assessment challenging [28]. Detecting subtle damage modes such as micro-cracks, disbands, delamination's, and fiber breakage before they become critical requires advanced techniques [28]. The opaque nature of many composites further complicates visual inspection. Future directions involve advancing non-destructive testing and structural health monitoring systems to provide real-time, comprehensive assessments of composite integrity [28], [29]. This includes developing more sensitive and reliable sensors, improving data processing algorithms, and integrating artificial intelligence for anomaly detection and prognosis. Research into self-healing composites, which can autonomously repair minor damage, also represents a promising avenue for improving longevity and reducing maintenance costs [30].

6.3. Modeling and Optimization Gaps

Despite advancements, predictive modeling and optimization techniques for composite materials still have limitations, especially when considering complex geometries, varied loading conditions, and long-term environmental effects [31]. Current models may not fully capture the anisotropic and heterogeneous nature of composites, or the progressive damage accumulation under cyclic loading and environmental aging. Future research should focus on developing more sophisticated multi-scale modeling approaches that can bridge the gap between micro-level material behavior and macro-level structural response [15]. This includes refining finite element analysis techniques, incorporating advanced constitutive models, and utilizing machine learning algorithms for more accurate performance prediction and material design optimization [15], [38]. Enhanced models are needed to account for the variability in material properties and manufacturing processes, which are critical for reliability analysis [43].

6.4. Standardization and Regulatory Frameworks

The relatively rapid evolution of composite materials and their diverse applications in civil engineering has outpaced the development of comprehensive standardization and regulatory frameworks. The lack of universally accepted codes, specifications, and design guidelines can hinder widespread adoption and create challenges for engineers in ensuring safety and compliance [12], [32]. Future efforts must prioritize the development and harmonization of international standards for the design, testing, manufacturing, and installation of composite structures [32]. This includes establishing clear performance criteria, quality control protocols, and lifecycle assessment methodologies. Collaborations between academia, industry, and regulatory bodies are essential to create robust frameworks that instill confidence in composite solutions for civil infrastructure.

6.5. Sustainability and End-of-Life Management

While many composite materials offer environmental benefits during their service life, their end-of-life management presents significant sustainability challenges [11]. The non-recyclable nature of many thermoset composites contributes to

waste accumulation and environmental concerns [11]. Future research should explore more sustainable composite formulations, including the use of natural fibers, bio-derived resins, and thermoplastic matrices that offer better recyclability [11]. Developing efficient recycling technologies, such as pyrolysis or solvolysis, for existing composite waste is also critical. Furthermore, integrating life cycle assessment frameworks into the design process can help quantify the environmental impact of composite materials from cradle to grave, guiding the development of truly sustainable civil engineering solutions [13].

7. CONCLUSION

The comprehensive analysis of composite materials in civil structures reveals their transformative potential, driven by advantageous properties such as high strength-to-weight ratios, enhanced durability, and design flexibility. This review has underscored the critical importance of understanding the intricate correlations between the physical and mechanical properties of these materials for their effective and reliable application in diverse civil engineering contexts. Key findings from the correlation analysis demonstrate significant relationships that guide material design and optimization. A strong "stiffness–strength coupling" is evident, with tensile strength correlating positively with both elastic modulus and density. The identification of optimal ranges, such as the parabolic relationship between matrix–filler ratio and tensile strength (peaking around 1.8%), and optimal resin consumption (approximately 150 g/m²), provides crucial parameters for formulating composites with maximized performance. These insights are vital for predicting mechanical behavior, enhancing structural reliability, and ensuring quality control in fabrication processes. Despite their numerous benefits, the widespread adoption of composite materials is tempered by several limitations. Paramount among these is the long-term durability under diverse environmental stressors, including moisture, temperature fluctuations, and chemical exposure, which can lead to degradation mechanisms such as creep and fatigue. The challenges in accurately detecting subtle damage modes and the need for advanced structural health monitoring systems also remain significant. Furthermore, there are existing gaps in predictive modeling and optimization techniques, as well as the ongoing requirement for comprehensive standardization and robust regulatory frameworks to ensure consistent performance and safety. Finally, the sustainability implications of composite materials, particularly their end-of-life management and recyclability, present a critical area for future innovation. Moving forward, the field requires concerted efforts to address these limitations. Future research should prioritize a deeper understanding of degradation mechanisms under synergistic environmental conditions, the development of more advanced and integrated monitoring systems, and the refinement of multi-scale modeling approaches. The establishment of universally accepted standards and guidelines is essential to foster confidence and broader adoption. Ultimately, a holistic approach that integrates material science, engineering design, and sustainable practices will unlock the full potential of composite materials, leading to the creation of more resilient, efficient, and environmentally responsible civil infrastructure.

Conflicts of Interest

Author declare no conflicts of interest.

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