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INFLUENCE OF THE COMPOSITION AND STRUCTURE OF POLYMER-BASED BIOCOMPOSITES ON THEIR MECHANICAL AND BIOLOGICAL PROPERTIES

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Abstract

This article presents a detailed analysis of the factors determining the mechanical and biological properties of polymer-matrix biocomposites. The performance of these materials depends not on a single parameter, but on a complex set of interrelated characteristics, including the type of polymer matrix, the nature of the filler, its particle size and distribution, the quality of interfacial adhesion, the porous architecture of the material, and its degradation behavior over time. A comparative assessment was carried out for systems based on PLA, PCL, and PEEK, as well as for composites containing hydroxyapatite, β-tricalcium phosphate, collagen, or cellulose fibers. For bone tissue engineering, the most important properties are stiffness (elastic modulus), compressive strength, osteoconductivity, and structural stability. For materials intended for soft tissue engineering, greater importance is attached to elasticity, surface hydrophilicity, and the ability to promote cell adhesion. It is concluded that purposeful control of the composition and internal structure of a biocomposite makes it possible to achieve the required balance between mechanical strength, biocompatibility, and controlled degradability.

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Keywords: Biocomposites, polymer matrix, PLA, PCL, PEEK, hydroxyapatite, interfacial adhesion, porosity, biocompatibility.

Introduction

Polymer-based biocomposites have become highly important in modern biomedical engineering because they combine the processability of polymers with the beneficial biological characteristics of mineral and natural components. Such materials are used to fabricate both temporary and permanent implants, tissue engineering scaffolds, and surface coatings intended to support regenerative processes.

At the same time, the properties of biocomposites cannot be interpreted simply as the sum of the characteristics of the matrix and the filler. Mechanical strength, degradation behavior, cellular response, and bone integration are governed by the complex interaction of chemical composition, interfacial bonding, and spatial organization.

For this reason, the analysis of biocomposites requires an integrated approach combining materials science and biology. The purpose of this article is to generalize current knowledge about how the composition and structure of polymer-based biocomposites influence their mechanical and biological properties and determine their suitability for specific biomedical applications.

1. Importance of the polymer matrix for mechanical properties

The polymer matrix determines the fundamental properties of a biocomposite, including its stiffness (elastic modulus), deformation behavior, resistance to external loads, hydrolytic degradation rate, and processing characteristics. When selecting a matrix for biomedical applications, it is necessary to consider not only its mechanical strength but also its biocompatibility, degradation profile, and suitability for a specific type of tissue.

Polylactic acid (PLA) is relatively stiff and retains its shape well, which makes it suitable for bone scaffolds and temporary implants. However, PLA is rather brittle, and therefore its properties in composite systems are often improved by adding bioactive or reinforcing fillers. Polycaprolactone (PCL), in contrast, is more ductile and elastic. It is more appropriate for flexible devices and soft tissue systems, although its relatively low stiffness limits its use in load-bearing bone defects. Polyetheretherketone (PEEK) is characterized by high strength, chemical resistance, and long-term durability. However, it is biologically inert by itself, which makes surface modification or the incorporation of bioactive fillers necessary.

Table 1 - Comparative characteristics of polymer matrices used in biocomposites

Matrix	Key mechanical features	Biological/technological properties	Preferred application area
PLA	High stiffness, relatively high strength, limited plasticity	Biodegradable and technologically convenient, but may be brittle without modification	Bone scaffolds, temporary implants
PCL	Low elastic modulus, pronounced viscoelastic behavior, high deformability	Slow degradation; convenient for molding and 3D printing	Soft tissues, flexible matrices, combined scaffolds
PEEK	High strength, wear resistance, and long-term stability	Biologically inert; requires surface modification to improve osteointegration	Permanent implants, load-bearing orthopedic structures

2. Role of fillers in strength and biological activity

Fillers in biocomposites serve a dual purpose: they improve the mechanical properties of the material and influence its interaction with the biological environment. The type of filler, particle size, shape, and degree of dispersion directly affect stiffness, compressive strength, water absorption, cell adhesion, and the rate of tissue integration.

For bone tissue engineering, hydroxyapatite and β-tricalcium phosphate are of particular importance. Their composition is similar to the mineral phase of bone, and they can enhance the osteoconductive properties of the material. However, an excessive content of the ceramic phase may lead to particle agglomeration, the formation of internal stress concentrations, and increased brittleness. Natural additives such as collagen, chitosan, and cellulose fibers improve surface wettability, promote protein adsorption, and create more favorable conditions for cell attachment and proliferation. Thus, filler selection should be aimed not only at strengthening the material but also at controlling cell-material interactions.

Table 2 - Functional role of fillers in polymer biocomposites

Filler	Main contribution to properties	Potential limitations	Typical application tasks
Hydroxyapatite	Increase in stiffness, bioactivity, and osteoconductivity	Excess content may cause particle agglomeration and brittle fracture	Bone regeneration; bone substitute materials
β-Tricalcium phosphate	Stimulation of mineralization and controlled resorption	Reduced strength under non-uniform distribution	Resorbable bone scaffolds
Collagen	Improved cell adhesion and biomimetic surface properties	Low intrinsic mechanical strength	Materials for soft tissue regeneration and combined scaffolds
Cellulose fibers / chitosan	Increased hydrophilicity, surface roughness, and cellular response	Requires control of matrix compatibility and moisture sensitivity	Hybrid biocomposites with enhanced surface activity

3. Interfacial adhesion and structural organization

For a biocomposite to function effectively, it is essential that load be reliably transferred between the matrix and the filler through their interface. It is precisely in this interfacial zone that stress distribution, crack deflection, and structural stabilization occur. Poor adhesion between the components leads to defects, accelerates failure, and makes the material properties less predictable.

Compatibility between components can be improved by various methods, including plasma treatment, chemical surface activation, the use of silane coupling agents, compatibilizers, or modification of filler roughness. Equally important is the structural organization of the material at all hierarchical levels, from microscopic particles to the overall scaffold architecture. The more precisely the pore size, phase distribution, and interfacial interactions are controlled, the greater the likelihood of obtaining a material with predictable mechanical and biological performance.

4. Porosity, surface characteristics, and degradation behavior

The internal architecture of a biocomposite is critically important for regenerative medicine. Pore size, pore interconnectivity, and the overall permeability of the material affect nutrient transport, cell migration, and the formation of new blood vessels within the regenerating tissue. In general, increased porosity improves tissue integration, but at the same time reduces the mechanical strength of the structure. For this reason, scaffold design always requires a compromise between mechanical reliability and biological functionality.

Surface characteristics also strongly influence cellular response. Moderate roughness and surface hydrophilicity promote protein adsorption and activate cell attachment. Another important consideration is the degradation rate of the material. The scaffold must retain its shape and mechanical integrity for a sufficient period to support tissue formation while at the same time avoiding the accumulation of harmful degradation products. Consequently, when designing a biocomposite, it is necessary to take into account not only its initial mechanical properties but also the way these properties change over time in the physiological environment.

Table 3 - Influence of structural parameters on the mechanobiological behavior of a biocomposite

Structural parameter	Mechanical effect	Biological effect	Optimization trade-off
Interfacial adhesion	Efficient load transfer and reduced risk of early cracking	Surface stability and uniform cellular response	Excessive chemical modification should not impair biocompatibility
Porosity	Reduced strength and stiffness with increasing pore volume	Improved cell migration, nutrient transport, and vascularization	A balance is required between permeability and load-bearing capacity
Surface roughness	Changes in local stress distribution at the surface	Increased protein adsorption and cell adhesion	Excessive roughness may accelerate degradation and wear
Degradation rate	Gradual loss of mechanical stability over time	Creates space for new tissue formation	Degradation kinetics should match the rate of tissue regeneration

Conclusion

The mechanical and biological properties of polymer-based biocomposites depend on a complex combination of factors, including the nature of the matrix, the type and content of fillers, the quality of interfacial adhesion, porosity, surface characteristics, and degradation behavior. None of these factors can be considered in isolation, since any change in composition inevitably affects the structure of the material and its interaction with the biological environment.

Therefore, the development of effective biocomposites requires an integrated design strategy in which composition and structure are optimized simultaneously with regard to the intended biomedical application. For bone tissue engineering, the most important properties remain stiffness, compressive strength, and osteoconductivity, whereas for soft tissue constructs greater emphasis is placed on elasticity, surface hydrophilicity, and the ability to support cell attachment. Rational control of these parameters opens the way to the creation of next-generation biomaterials with predictable functional performance.

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