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A Review of the Research Progress and Application of Geopolymer-biochar Composites

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Abstract

Geopolymer-biochar composites combine the durability and mechanical properties of geopolymers with the porous structure and adsorption properties of biochar, becoming a new type of composite material with wide application potential. This paper reviews the basic properties of geopolymers and biochar, the preparation methods of composite materials, key properties and their application prospects in the fields of construction, environmental remediation and carbon sequestration, analyzes the current research hotspots and challenges, and proposes future research directions.

Keywords

Geopolymer-biochar; Environmental Remediation; Carbon Sequestration.

1. Introduction

Geopolymer, as an inorganic polymer material, has high mechanical strength, fire resistance and chemical stability[1]; while biochar is a porous carbon material with a wide range of sources and good adsorption and carbon sequestration capacity[2]. The composite of geopolymer and biochar combines the advantages of both, providing a new technical route for environmental protection, resource recycling and low-carbon construction. This article will systematically summarize the research progress of geopolymer-biochar composite materials from the aspects of basic characteristics, preparation methods, performance and application.

2. Basic Properties of Geopolymers and Biochar

2.1. Characteristics of Geopolymers

Geopolymers are usually made by reacting industrial byproducts rich in silicon and aluminum (such as fly ash, kaolin, slag, etc.) with alkaline solutions (such as NaOH or KOH), and the resulting material has a three-dimensional network structure. Geopolymers exhibit good fire resistance, chemical corrosion resistance and high strength due to their highly cross-linked structure. They release less CO2 during the molding process and are therefore considered to be environmentally friendly alternative materials. Their application areas include fire-resistant building materials, wastewater treatment and heavy metal adsorption.

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2.2. Characteristics of Biochar

Biochar is prepared by pyrolysis of biomass under anaerobic conditions and has a porous structure and a large specific surface area. The chemical composition and pore structure of biochar are affected by the type of raw materials, pyrolysis temperature, etc. Typical biochar contains rich elements such as C, N, O, and has surface functional groups such as hydroxyl and carboxyl, so it has good adsorption. Biochar also has carbon sequestration potential, which can store carbon in biomass in a stable form in the soil, helping to reduce greenhouse gas emissions[3].

3. Preparation Method of Geopolymer-biochar Composite Material

3.1. Raw Material Selection and Pretreatment

The raw materials of geopolymers usually include fly ash, kaolin and slag, which form a three-dimensional network structure in an alkaline environment[4]. Biochar has a wide range of sources, and agricultural waste, wood, urban sludge, etc. can all be used as raw materials for preparation. The pretreatment of biochar (such as acid washing and activation treatment) helps to improve the porosity and surface reactivity of the composite material.

3.2. Preparation Process of Composite Materials

Common composite material preparation processes include blending, sol-gel and hot pressing. The blending method is to add biochar powder directly into geopolymer slurry, dry and solidify after preparation. The sol-gel method dissolves biochar and geopolymer precursors through chemical solvents, forms gel and then dries to obtain composite materials. Different preparation processes will directly affect the pore structure, mechanical strength and chemical stability of the material.

4. Key Properties of Geopolymer-biochar Composites

4.1. Mechanical Properties

The mechanical properties of geopolymer-biochar composites are affected by many factors, including material composition, preparation process and biochar content. Geopolymers usually have high compressive and tensile strengths, which is due to their three-dimensional network structure that gives the material good mechanical properties, while the porous structure and rigidity of biochar can further improve the compressive and flexural properties of this material. The addition of biochar changes the mechanical properties of geopolymers in many aspects. For example, after biochar is filled into the geopolymer matrix, it can improve the interfacial bonding of the composite material, which is very important for enhancing the mechanical properties of the material. The improvement of interfacial bonding strength can reduce stress concentration and reduce the risk of fracture of the composite material under external force, making it more durable under high stress environment.

In addition, the addition of biochar can improve the toughness of geopolymers and make the material more resistant to cracking under external force. Although geopolymers themselves have good compressive properties, they are relatively weak in flexural strength and impact resistance. The addition of biochar enables the composite material to absorb more energy when stress is loaded, thereby improving the fracture toughness and crack resistance of the material. The porous structure of biochar provides a buffer area for the interior of the material, which can effectively alleviate the destructive effects of external stress on the material. Studies have shown that biochar of different particle sizes have different effects on the compressive strength and flexural strength of the composite material. Biochar with smaller particle sizes can usually better fill the geopolymer matrix, thereby improving the overall strength of the material.

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The preparation process of the composite material is also a key factor affecting its mechanical properties. For example, in the conventional blending method, the mixing uniformity of geopolymer and biochar has an important influence on the final performance. The composite material prepared by the sol-gel method can achieve uniform biochar dispersion at the microscopic level, reduce internal defects of the material, and improve the overall mechanical properties. In addition, the pressure, temperature and other conditions during the preparation process also affect the interfacial bonding between biochar and the geopolymer matrix. In order to improve the mechanical properties of the composite material, the geopolymer-biochar composite material with excellent mechanical properties can be prepared by optimizing the biochar content, controlling the particle size, and selecting a suitable preparation process.

4.2. Adsorption Properties

The addition of biochar provides excellent adsorption performance for geopolymer-biochar composites, especially in the adsorption of heavy metals and organic pollutants. Biochar has a unique porous structure with a large specific surface area and a variety of surface functional groups, such as carboxyl, hydroxyl and carbonyl, which provide more active sites in the adsorption process. The matrix of geopolymer provides support for the distribution of biochar and enhances the contact efficiency between biochar and pollutants, thereby greatly improving the adsorption capacity of the composite. In addition, biochar has good cation exchange capacity and can efficiently adsorb heavy metal ions such as lead, cadmium and mercury through mechanisms such as ion exchange and physical adsorption.

When geopolymer-biochar composites adsorb heavy metals, the adsorption mechanism involves multiple processes such as surface complexation, ion exchange and electrostatic adsorption. In heavy metal adsorption, the presence of functional groups on the surface of biochar makes it have high hydrophilicity and cation binding ability, so that it can effectively capture and fix heavy metal ions. At the same time, the matrix structure of geopolymer provides better mechanical strength for the composite material, enabling it to maintain high stability in complex environments. In terms of organic pollutant adsorption, the porous structure of biochar facilitates the entry and retention of macromolecular organic matter, increases the retention time of pollutants on the surface of the material, and improves the adsorption efficiency.

In order to improve the adsorption performance, researchers have tried to modify biochar through different pre-treatment methods, such as acid washing, alkaline washing and activation treatment, etc. These modification methods can increase the active sites on the surface of biochar and improve the adsorption capacity of the composite material. At the same time, the pore structure of the composite material is also a determining factor in the adsorption performance. Optimizing the pore size and distribution of the composite material can increase the specific surface area of the material, thereby improving the adsorption efficiency. Geopolymer-biochar composites have broad application prospects in wastewater treatment and soil remediation, and their adsorption performance provides an efficient and low-cost solution for environmental remediation.

4.3. Thermal Stability and Chemical Resistance

Geopolymer-biochar composites exhibit excellent thermal stability and chemical resistance in high temperature and acid-base environments, which is a key advantage for their application in harsh environmental conditions. The three-dimensional network structure of geopolymers gives the material good thermal stability, allowing it to maintain structural integrity at high temperatures. As a carbon-based material, biochar also has high thermal stability and can maintain its shape in high temperature environments. The composite of geopolymers and biochar further enhances the stability of the material in high temperature environments,

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making it potential for application in the fields of construction and high temperature resistant materials.

In terms of chemical resistance, geopolymers themselves exhibit high acid and alkali resistance and can maintain stability for a long time in strong acid or strong alkali environments. The addition of biochar can not only improve the chemical resistance of the material, but also further enhance the corrosion resistance of the material through the combination of its surface functional groups with acidic or alkaline substances. In addition, the alkaline properties of geopolymers have a natural buffering effect on acidic pollutants in acidic environments, while the carbonized structure of biochar can effectively prevent the penetration of acidic and alkaline substances and reduce the impact of chemical corrosion.

In order to further improve the high temperature and chemical corrosion resistance of composite materials, researchers are exploring the addition of nano-scale modified materials, such as nano-silica or nano-alumina, to enhance the thermal stability and corrosion resistance of composite materials. These nanomaterials can fill the pores of the composite material to form a dense structure, thereby reducing the damage to the material in high temperature or chemical environments. In addition, improving the pyrolysis process of biochar to increase its carbon content and structural stability is also considered to be an effective method to improve the heat and chemical resistance of composite materials. The excellent thermal stability and chemical resistance of geopolymer-biochar composites make their application in harsh environments possible and expand the potential use of this material in industry and construction.

5. Application Prospects of Geopolymer-biochar Composites

5.1. Environmental Remediation

Geopolymer-biochar composites show significant potential in environmental remediation, especially showing excellent performance in heavy metal removal and organic pollutant adsorption. The porous structure of the composite material and the rich functional groups on the surface of biochar give it good adsorption capacity for heavy metal ions. In the field of wastewater treatment, heavy metal pollutants such as lead, cadmium, mercury, etc. are highly toxic and difficult to remove through conventional treatment methods. However, geopolymer-biochar composites can effectively pass through surface complexation, ion exchange, electrostatic Mechanisms such as adsorption capture and immobilize these heavy metal ions. The porous nature of biochar not only provides a large number of adsorption sites, but also enhances the specific surface area of the composite material through its porosity, thereby increasing the contact probability of pollutants. At the same time, the alkaline matrix of geopolymers has a positive effect on the stability of heavy metal ions, helping to seal and solidify pollutants for a long time and reduce the risk of secondary pollution.

In terms of the removal of organic pollutants, the adsorption capacity of geopolymer-biochar composites is equally outstanding. Since biochar forms a rich pore structure during the pyrolysis process, it exhibits strong adsorption properties for polycyclic aromatic hydrocarbons, pesticides and other organic pollutants. These pores not only increase the surface area of the composite material, but also increase the residence time of pollutants, helping to efficiently remove organic matter. In addition, geopolymers have good chemical stability in the environment and are not easily degraded and dissolved, ensuring the durability and durability of composite materials in contaminated sites. Therefore, geopolymer-biochar composite material is a low-cost, high-efficiency green alternative material in the field of environmental remediation, especially in wastewater treatment, soil remediation and abandoned mine management. It has broad application prospects.

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5.2. Building Materials

In the field of building materials, geopolymer-biochar composites have become strong candidates for green buildings and sustainable building materials due to their excellent mechanical properties, fire resistance and thermal insulation properties. Geopolymers have high compressive and flexural strengths that enable them to withstand high-load construction applications, while biochar's porosity provides the material with lightweight and insulating properties. This kind of composite material can not only meet the strength requirements of the building structure, but its porous structure has good thermal insulation properties, which helps to reduce building energy consumption. The introduction of biochar also significantly reduces the density of the geopolymer, making the composite material lighter in weight, thereby reducing the structural load of the building, especially for wall and floor materials.

The fire resistance of geopolymer-biochar composites also gives them potential applications in fire-resistant building materials. The inorganic matrix of geopolymers can withstand high temperatures, and the carbonization properties of biochar also prevent the release of harmful gases during combustion, making it ideal as a fire-resistant insulation material. In addition, the composite material produces low carbon dioxide emissions during the production process, which meets the requirements of modern architecture for environmentally friendly building materials. Compared with traditional cement-based materials, geopolymer-biochar composite materials can reduce carbon footprint and environmental impact during the production process. Therefore, this composite material is not only a high-performance building material, but also conforms to the trend of green building and low-carbon environmental protection, and is especially suitable for application in low-carbon buildings, passive houses and fire-proof buildings.

5.3. Carbon Sequestration

The carbon sequestration potential of biochar makes geopolymer-biochar composites a key material for achieving carbon neutrality goals. Biochar is a porous carbon material generated by pyrolysis of biomass. The carbon structure is stable and not easy to decompose. It can be sequestered in soil or building materials for a long time. This characteristic is of great significance in the context of global carbon emission reduction. The composite of biochar and geopolymer can further improve the carbon sequestration efficiency. The inorganic matrix of geopolymer can not only physically wrap the biochar particles, but also provide protection to prevent the decomposition and carbon loss of biochar during the application process, thereby achieving long-term carbon sequestration.

The biochar in the composite material can be used as a soil conditioner in agricultural production, and can also be made into building materials for fixing carbon in the atmosphere. The application of geopolymer-biochar composites in soil can improve soil structure, enhance water retention capacity and improve soil fertility, thereby improving the photosynthesis efficiency of plants and fixing more carbon in organisms. At the same time, the aluminosilicate in the geopolymer matrix has acid and alkali resistance, which can provide a long-term stable chemical environment in the soil, further improving the carbon fixation capacity. The carbon sequestration function of composite materials makes them have application potential in many fields such as agriculture, forestry, and construction. By promoting such composite materials on a large scale, the concentration of carbon dioxide in the atmosphere can be effectively reduced, providing technical support for climate change mitigation and ecological environmental protection.

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6. Current Challenges and Future Prospects

6.1. Cost and Process Optimization

Geopolymer-biochar composites usually require high-temperature pyrolysis, chemical activation and other steps during the preparation process. The complexity and energy consumption requirements of these processes lead to high production costs. The preparation of biochar requires a stable supply of biomass resources, and the high temperature conditions of the pyrolysis process make it energy-intensive. The synthesis of geopolymers also involves the consumption of activators and mineral sources, which further increases the overall cost of the material. In addition, the pretreatment of biochar (such as acid-base activation, particle size control, etc.) and the composite process with geopolymers require precise process control to ensure the performance consistency and quality stability of the product. How to reduce production costs while meeting material properties has become one of the key challenges restricting its large-scale application. In the future, we can start from optimizing the preparation process, reducing energy consumption and exploring low-cost raw materials. For example, using biomass waste such as agricultural waste or urban sludge as raw materials is expected to reduce the raw material cost of biochar. In addition, the energy consumption of biochar preparation can be effectively reduced by introducing new low-temperature or microwave-assisted pyrolysis technology. In terms of geopolymers, the synthesis cost can be reduced by selecting silicon-aluminum mineral waste (such as fly ash, blast furnace slag, etc.) as raw materials and using environmentally friendly activators. Overall, process optimization and diversification of material selection are important means to reduce costs, and can also enhance the market competitiveness and industrialization prospects of composite materials.

6.2. Environmental Impact Assessment

Environmental impact assessment of geopolymer-biochar composites is an important issue that needs to be addressed before their large-scale application. Although composites have good environmental benefits in theory, such as strong carbon sequestration capacity and low carbon emissions, they may face some environmental impacts in practical applications. First, biochar involves high-temperature pyrolysis during production, which may release a certain amount of volatile organic compounds (VOCs) and other harmful gases. These byproducts may have a negative impact on the environment and air quality if not properly handled. Therefore, waste gas treatment and emission control in the production process are important contents of environmental impact assessment. Secondly, the production and application of geopolymers also have certain environmental risks, especially in acidic or alkaline environments, which may cause solubility problems, leading to the release of certain harmful ions. In order to ensure the long-term safety of composites in the environment, it is necessary to systematically study their stability, degradation behavior and potential toxicity under different natural conditions. Finally, the long-term effects of geopolymer-biochar composites in soil and water bodies also need to be further evaluated to ensure that there will be no potential negative impact on the ecosystem during application. Therefore, a comprehensive environmental impact assessment can help provide a scientific basis for the application of geopolymer-biochar composites and ensure their eco-friendliness and sustainability.

6.3. Material Structure Design

Material structure design is the key to improving the performance of geopolymer-biochar composites. The structural properties of composites, such as porosity, pore size distribution, specific surface area, surface functional groups, etc., directly affect their performance in heavy metal adsorption, carbon sequestration and mechanical strength. The combination of the porosity of biochar and the network structure of geopolymers can form a multifunctional composite structure, which can not only improve the adsorption efficiency of the material, but

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also enhance its chemical stability in the water environment. In order to meet the needs of specific application fields, researchers can achieve precise control of the structure of composite materials by controlling the particle size of biochar, adjusting the pore size distribution of biochar and chemically modifying the surface structure of geopolymers. For example, through acid-base treatment or plasma treatment, the surface functional groups of biochar can be activated, making it more closely integrated with the geopolymer matrix in the composite material, thereby improving the adsorption performance. In addition, the pore structure in the composite material can also be controlled by adjusting the synthesis temperature and chemical additives to achieve controllable design to increase the specific surface area and porosity. The precise design of material structure can not only improve the functional properties of the composite material, but also significantly extend its service life and durability, ensuring that the material maintains excellent performance under various environmental conditions. Future research can continue to explore nanoscale structural design, novel surface modification techniques, and the composite effects of different types of biochar to further enhance the performance of geopolymer-biochar composites in different application scenarios.

7. Conclusion

Geopolymer-biochar composites effectively combine the strength of geopolymers and the adsorption capacity of biochar, and have broad application prospects in environmental remediation, low-carbon construction and carbon sequestration. However, large-scale applications still need to solve problems such as cost, process optimization and environmental assessment. Future research should focus on optimizing the preparation process, exploring different material ratios and structural designs, and promoting the industrialization of geopolymer-biochar composites.

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