

Development and Characterization of Magnetic Carbon Foam from Starch and Ferromagnetic Fillers

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Abstract

Magnetic carbon foam was synthesized using tapioca starch as a carbon precursor, combined with iron oxide and cobalt ferrite as ferromagnetic additives, and sodium bicarbonate as a foaming agent through a process involving mixing, foaming, drying, and carbonization. This study investigates the effect of varying ferromagnetic powder concentrations on the physical, structural, mechanical, and magnetic properties of the resulting foam. Density and porosity measurements were used to evaluate physical characteristics, while mechanical performance was determined through compression testing using a Universal Testing Machine (UTM). Microstructural features were analyzed via Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray (EDX) analysis, and magnetic responsiveness was assessed using magnet-based testing. The results provide comprehensive insight into the behavior of magnetic carbon foam and highlight its potential for advanced functional applications.

1. Introduction

In recent years, the quest for innovative materials that possess unique properties and versatility has driven substantial research efforts within the field of materials science and engineering. Magnetic carbon foam composites, a class of advanced materials, have emerged as promising candidates due to their exceptional combination of lightweight, magnetic responsiveness, and porous structure. These attributes make them highly adaptable for a wide range of applications across multiple industries, from environmental remediation to biomedical devices and beyond [1].

Magnetic carbon foam is a novel composite material that combines the structural advantages of carbon foam with the magnetic properties of ferromagnetic nanoparticles. This innovative material is distinguished by its lightweight and porous nature, stemming from the carbon foam's inherent characteristics, which include a high surface area, robust thermal stability, and considerable mechanical strength. The integration of ferromagnetic nanoparticles, such as iron, cobalt, or nickel, imparts unique magnetic properties to the foam. These nanoparticles are embedded within the carbon matrix, transforming an otherwise non-magnetic material into one with magnetic capabilities. This development is pivotal, as it enhances the functionality and application scope of carbon foam [2-4].

Furthermore, magnetic carbon foam has emerged as a versatile material with promising applications due to its unique combination of magnetic and carbon-based properties. This section provides an overview of the

fundamental concepts and properties associated with magnetic carbon foam, highlighting its significance in various applications [5] Ferromagnetic particles, such as iron, cobalt, and nickel, play a vital role in imparting magnetic properties to the foam. These particles exhibit intriguing behaviors at the nanoscale, influencing the foam's electrical and magnetic properties [6]

2. Experimental

In the material selection process, a more direct approach was adopted to understand the impact of different ferromagnetic nanoparticles on the properties of the resulting magnetic carbon foam. This involves a comparative analysis of various ferromagnetic nanoparticles between iron oxide (Fe₃O₄), and cobalt ferrite (CoFe₂O₄) [7]. The carbon precursor used was starch flour and sodium bicarbonate food grade was used as foaming agent.

2.1 Fabrication

The mixing of the carbon foam precursor and ferromagnetic powder is a crucial step in the synthesis process, as it determines the uniform dispersion of magnetic components within the carbon matrix. Achieving homogeneity in this stage is essential for producing magnetic carbon foam with consistent properties. Start with weighing the starch at 50 grams and ferromagnetic powder based on the targeted composition ratio as shown in Table 1.

Table 1 An example of a table

Ferromagnetic Powder	Sample 1 Ratio	Sample 2 Ratio	Sample 3 Ratio
Iron Oxide	1:0.25	1:0.5	1:1
Cobalt Acetate	1:0.5	1:1	1:2

2.1.1 Foaming Process

The initial foam formation, sodium bicarbonate, was used as a foaming agent at a concentration ratio of 1:50 to the total mixture mass. The foaming agent was added to the mixture and mixed properly to get even distribution for uniform foaming. This process occurred at room temperature to maintain the stability of the sodium bicarbonate. Mechanical agitation was used to induce foam formation. Start mixing at 250 rpm, then gradually increased to 600 rpm until air bubbles were released and the mixture volume raised to form foam. Observe the foam's stability visually. Good quality foam should be light with a consistent bubble structure, neither too liquid nor too stiff. If the foam is too dense, increase the mixing speed or duration. If the foam is too light or unstable, reduce the mixing speed or briefly stop to let it stabilize.

2.1.2 Drying

For drying preparation, the foam was transferred gently to a tray, maximizing air exposure. Dried the foam in an oven at 200°C for 1 hour with regular monitoring to prevent shrinkage or deformation. The foam then cooled to room temperature before further handling. Examine the dried foam for cracks or deformation; it should maintain its shape. Ensure uniform drying to prevent internal moisture pockets.

2.1.3 Carbonization

Carbonization removes non-carbon components, such as oxygen and hydrogen, by pyrolysis. The dried foam was placed in high-temperature trays or crucibles and loaded them into a furnace. Initially the furnace was purged with argon gas to remove oxygen, preventing burning. The process was started at room temperature and gradually increased the furnace temperature by 10°C/min until reaching 800°C. Hold at 800°C for 120 minutes to ensure complete carbonization. Let the foam cool naturally in an argon atmosphere. Once cooled, carefully remove the foam from the furnace. The foam will be lighter, black, and have increased electrical conductivity, thermal stability, and a porous carbon structure. Handle gently to avoid breakage.

2.2 Characterization

The synthesized magnetic carbon foams undergo comprehensive characterization to assess its structural and magnetic properties. Techniques used include scanning electron microscopy (SEM), X-ray diffraction (XRD),

magnet pulling, porosity and density assessment, and compression testing. These methods provide detailed insights into the material's structure, crystallinity, and magnetic behavior.

2.2.1 Morphology

A scanning electron microscope (SEM) examines a sample's microstructure by focusing a high-energy electron beam on it, which interacts with the sample's atoms to produce signals revealing surface topography, texture, and composition. Since magnetic carbon foam is already conductive, no coating is needed. Cut a small piece of foam and place it on the SEM stub. Set the voltage to 15 kV and use secondary electrons for imaging.

2.2.2 Density and Porosity

Every material has its own density values, which can be affected by temperature and pressure. Using Archimedes' principle, the density of an object can be determined by comparing its weight in air to its displacement in water or another liquid with a known density. First, measure the sample's weight in air. Then, submerge the sample fully in water and measure its weight again. By deducing the mass of the displaced water, you can calculate the sample's volume. This method is suitable for samples with irregular shapes, uneven surfaces, or porosity.

2.2.3 Compression test

A compression test is a mechanical test that applies forces to push, compress, squash, crush, and flatten a sample. It is often performed using a universal testing machine (UTM). Before testing, ensure the sample is defect-free (ASTM D3574-17). The compression test begins with a magnetic carbon foam sample measuring 25 mm x 25 mm x 25 mm. This test determines the material's stiffness and strength under crushing forces. During the test, properties such as stress and strain are measured, and the results are displayed on a stress-strain diagram. This data can be used to calculate compressive strength, elastic limit, proportional limit, yield point, yield strength, and modulus of elasticity.

2.2.4 Magnetic test

To analyze the magnetism of magnetic carbon foam using a bar magnet, first ensure the sample is clean and dry and use a bar magnet with a known strength. Begin by holding the magnet close to the foam without touching it and observe if there is any attraction. Next, slowly move the magnet towards the foam and note the distance at which the foam starts to move towards the magnet, indicating the magnetic strength. Then, place the magnet on a flat surface and bring the foam near it, observing whether the foam aligns along the magnetic field lines of the magnet. Additionally, suspend the foam using a non-magnetic thread and bring the magnet close to it, observing any movement or rotation of the foam, which can indicate magnetic interaction. For a more precise measurement, use a gaussmeter to measure the magnetic field strength around the foam when the magnet is applied. These steps provide a straightforward method to qualitatively and quantitatively assess the magnetic properties of the foam using a bar magnet, although more precise measurements would require advanced equipment like a vibrating sample magnetometer (VSM) [8].

3. Results and Discussion

This topic presents the results obtained from the various tests conducted on the synthesized magnetic carbon foam. The data is analyzed to understand the impact of different concentrations of ferromagnetic powder on the physical, mechanical, and magnetic properties of the foam. The discussion will compare these findings with existing literature to highlight the significance and implications of the results.

3.1 Density and Porosity

The physical properties of magnetic carbon foam were evaluated through density and porosity assessments. Table 2 presents the weight measurements of different samples. While Table 3 shows the density and porosity of the samples were calculated using Archimedes' principle.

Table 2 *The data of weighing sample*

Sample	Dry Weight (g)	Wet Weight (g)	Submerged Weight (g)
CF_IO-0.25	0.361	1.792	0.216
CF_IO-0.5	1.827	6.624	1.221
CF_IO-1.0	2.605	6.880	1.991
CF_CA-0.25	0.332	1.469	0.160
CF_CA-0.5	1.100	3.827	0.799
CF_CA-1.0	1.169	3.216	0.812

Table 3 *The bulk density and porosity of carbon foam*

Sample	Dry Weight (g)	Wet Weight (g)
CF_IO-0.25	0.2291	90.75
CF_IO-0.5	0.3374	88.60
CF_IO-1.0	0.5328	87.44
CF_CA-0.25	0.2541	86.84
CF_CA-0.5	0.3633	90.07
CF_CA-1.0	0.4863	85.13

The results indicate that increasing the concentration of ferromagnetic powder slightly increases the density of the foam while reducing its porosity. This can be attributed to the filling of pores with ferromagnetic particles, which also contributes to a higher weight.

3.2 Compression Strength

The mechanical properties were assessed through compression testing using a Universal Testing Machine (UTM). The stress-strain behavior was recorded, and the results are summarized in Table 4.

Table 4 *The maximum force and displacement of carbon foam*

Sample	Maximum Force (N)	Maximum Displacement (mm)
CF_IO-0.25	34.36	7.38
CF_IO-0.5	45.31	8.09
CF_IO-1.0	148.13	14.40
CF_CA-0.25	146.88	6.21
CF_CA-0.5	125.83	5.68
CF_CA-1.0	2.81	3.00

The compression test results show that the compressive strength and elastic modulus increase with the concentration of ferromagnetic powder. This improvement in mechanical properties can be attributed to the reinforcement provided by the ferromagnetic particles, which enhances the foam's ability to withstand mechanical loads [9].

3.3 Morphology Observation

The microstructure of the magnetic carbon foam was characterized using Scanning Electron Microscopy (SEM). Figs. 1 to 3 present the SEM images at 150x magnifications for different samples.



Fig. 1 SEM Image of CF₁₀-0.25 at 150x Magnification

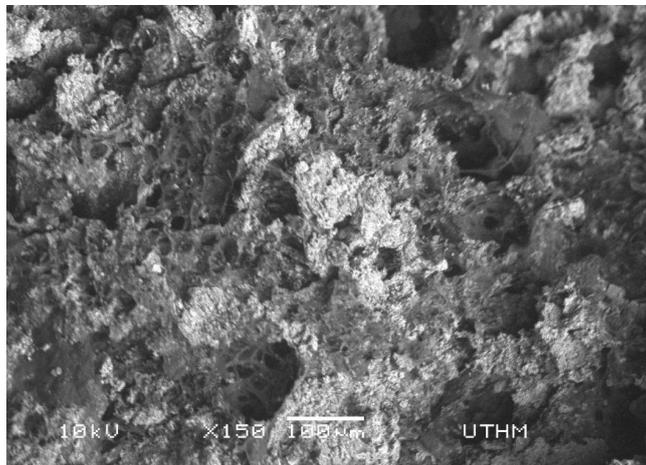


Fig. 2 SEM Image of CF₁₀-0.5 at 150x Magnification

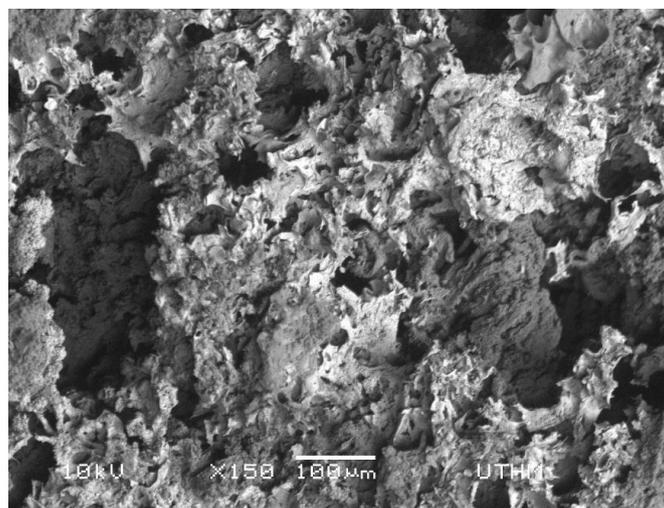


Fig. 3 SEM Image of CF_{CA}-1.0 at 150x Magnification

The SEM images reveal a porous structure with well-distributed ferromagnetic nanoparticles. The micrographs show that higher concentrations of ferromagnetic powder result in a more densely packed structure, which correlates with the observed increase in density and mechanical properties [10].

3.4 Elemental Analysis

Energy Dispersive X-Ray (EDX) analysis was performed to determine the elemental composition of the magnetic carbon foam. The results are shown in Fig. 4 and 5.

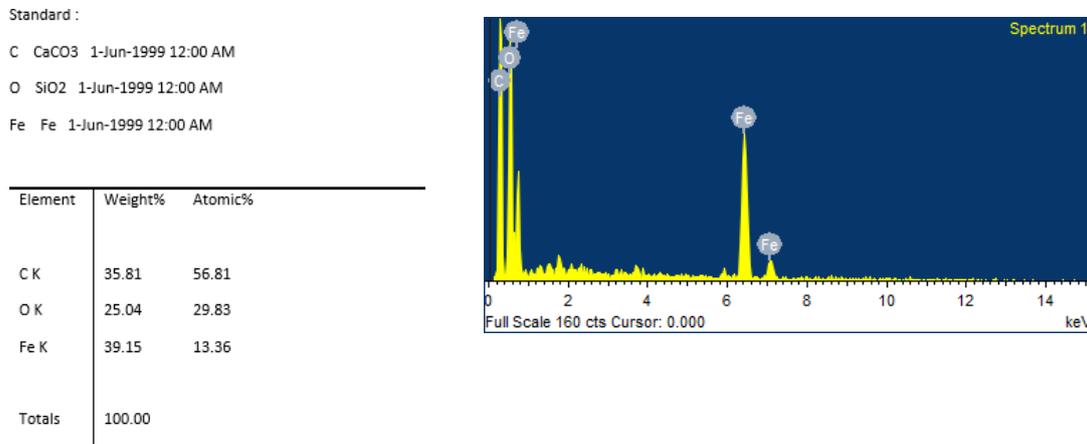


Fig. 4 EDX Spectrum of CF_IO-1.0

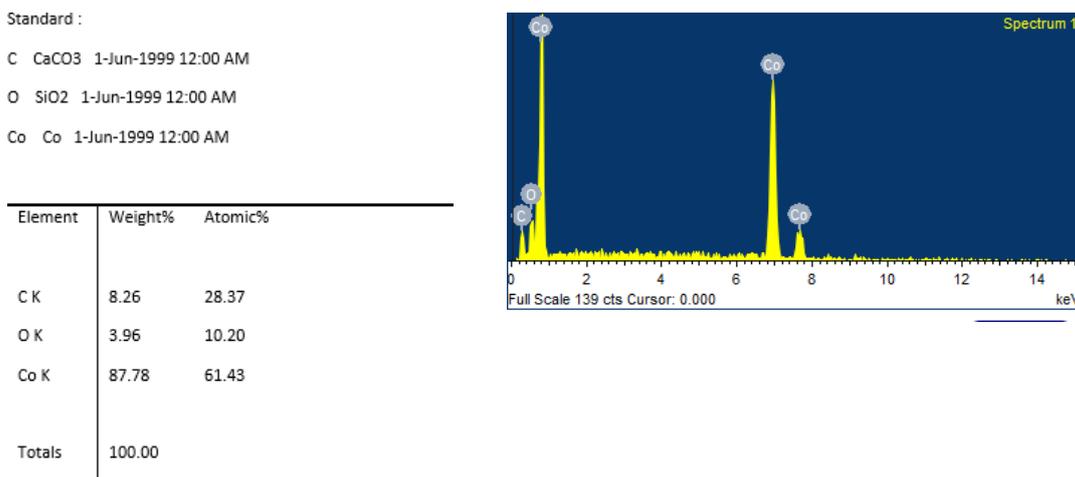


Fig. 5 EDX Spectrum of CF_CA-1.0

The EDX spectra confirms the presence of iron and cobalt in the respective samples, verifying the successful incorporation of ferromagnetic nanoparticles into the carbon foam matrix. The elemental distribution is uniform, indicating a homogeneous mixture of components.

3.5 Magnetic Properties

The magnetic properties were evaluated using a Neodymium magnet bar. The results, shown in Table 5, indicate the foam's responsiveness to the magnetic field. The magnetic tests show that the samples with higher concentrations of ferromagnetic powder exhibit stronger magnetic properties, such as increased attraction distance and magnetic strength. This enhancement is due to the higher volume fraction of magnetic particles within the foam, which boosts its overall magnetic responsiveness [11-12].

Table 5 Distance of sample movement respond to magnetic field

Sample	Distance between magnet and sample (cm)
CF_IO-0.25	0.6
CF_IO-0.5	0.9
CF_IO-1.0	1.15
CF_CA-0.25	0.6
CF_CA-0.5	0.9
CF_CA-1.0	1.0

4. Conclusion

This study successfully synthesized and characterized magnetic carbon foam using tapioca starch, iron oxide, cobalt acetate, and sodium bicarbonate. The results demonstrate that ferromagnetic nanoparticles were uniformly embedded within the carbon matrix, contributing to improved physical, mechanical, and magnetic performance. Increasing the concentration of ferromagnetic powder enhanced density, reduced porosity, and significantly increased both compressive strength and elastic modulus. The material also exhibited stronger magnetic responsiveness with higher ferromagnetic content. These combined properties indicate strong potential for applications such as electromagnetic shielding, sensing devices, and environmental remediation technologies. In moving forward, several recommendations can guide further development and practical implementation of magnetic carbon foam. Exploring alternative ferromagnetic materials such as nickel and manganese could broaden performance capabilities. Advanced characterization tools, including vibrating sample magnetometry (VSM), are recommended to gain deeper insight into the material's magnetic behavior. Finally, environmental performance testing and long-term durability evaluations are also crucial to ensure real-world applicability.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **sample fabrication and testing:** Muhamad Darwish; **analysis and interpretation of results:** Muhamad Darwish, Mohamed Nasrul; **draft manuscript preparation:** Muhamad Darwish. All authors reviewed the results and approved the final version of the manuscript.

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