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Recycling Construction Waste into Hydrophobic Nanoporous Silica Aerogel: A Sustainable Material Transformation Approach

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Abstract*— Construction waste ash (CWA) presents a transformative opportunity for sustainable material development through its recycling into hydrophobic silica aerogels. This study employs a cost-effective sol-gel method combined with ambient pressure drying to convert industrial waste into high-performance nanomaterials. X-ray fluorescence analysis revealed that CWA contains over 50% silica, enabling efficient extraction as a sodium silicate precursor. The resulting silica aerogel demonstrates remarkable properties, including ultra-low bulk density (0.498 g/cm³), a high specific surface area (288.23 m²/g), and nanoscale porosity. Furthermore, surface modification using trimethylsilyl chloride (TMCS) enhances the aerogel's hydrophobicity, achieving a contact angle of 122°, indicative of superior water repellency. The aerogel was extensively characterized using advanced techniques, confirming its structural integrity and nanoscale features. These exceptional properties make it an ideal candidate for various applications, such as thermal insulation, controlled drug delivery systems, and environmental remediation. By integrating waste recycling with nanotechnology, this research not only addresses critical challenges in waste management but also offers an innovative pathway toward the sustainable production of high-value materials, aligning with circular economy principles and advancing the frontier of materials science.

***Keywords:* Aerogel, Construction waste recycling, Hydrophobic materials, Sustainable chemistry.**

I. INTRODUCTION

Construction waste generation has become a critical global environmental challenge, with annual worldwide production exceeding 3.57 billion tons [1]. This massive waste stream not only depletes natural resources but also significantly contributes to environmental degradation through inefficient disposal practices [2]. The urgent need for sustainable waste management strategies has prompted researchers to explore innovative approaches that transform industrial by-products into high-value materials [3].

Silica aerogels emerge as a promising solution, offering exceptional properties including ultra-low density, high porosity, and remarkable thermal insulation capabilities [4]. However, traditional synthesis methods have been constrained by high production costs, complex processing techniques, and limited sustainability [5]. This study introduces an innovative sol-gel methodology that addresses these limitations by converting construction waste ash (CWA) into advanced hydrophobic nanoporous silica aerogels. The proposed approach presents a multifaceted innovation: sustainable material sourcing, cost-effective synthesis through ambient pressure drying, and the development of high-performance materials with potential applications in thermal insulation, environmental remediation, and advanced composite technologies [6].

By demonstrating the feasibility of transforming construction waste into sophisticated nanomaterials, this research contributes to critical advancements in both materials science and waste management [7]. The methodology not only offers a solution to industrial waste challenges but also provides a pathway towards more sustainable material production and circular economy principles [8].

II. EXPERIMENTAL PROCEDURE

A. Materials

In this study, the following materials were used: Sulfuric acid (96%), NaOH (95%), Isopropyl Alcohol (IPA) (99%), n-Hexane (96%), Tetraethyl orthosilicate (TEOS), and Trimethylsilyl chloride (TMCS), all purchased from Merck Co. (Germany).

B. Sample Preperation

Construction Waste Ash (CWA) Preparation

CWA was prepared by grinding in a ball mill for 15 min and heating at 650°C for 6 h in a furnace.

Sodium Silicate Solution Extraction

Seven grams of CWA were mixed with 100 mL of 2.0 mol/L NaOH aqueous solution. The mixture was heated to its boiling point for 1.5 h with stirring and then filtered to remove undissolved residues [9].

Silica Aerogel Synthesis

1 mol/L sulfuric acid was added to the filtered solution until it reached pH 7, forming a silica hydrosol. A small amount of TEOS (volume ratio 1/10 relative to hydrosol) was added to strengthen the network. The gel was aged at room

temperature for 48 h, with gelation completed within 1 h at 60°C [10].

Surface Modification and Drying

The wet gels were immersed in an IPA/TMCS/n-Hexane solution with the following optimum conditions:

Mole ratio of TMCS: pore water: IPA = 0.4: 1: 0.4
Volume ratio of n-Hexane/TMCS = 10
The modified alcogels were dried at:
50°C for 12 h
80°C for 2 h
200°C for 1 h

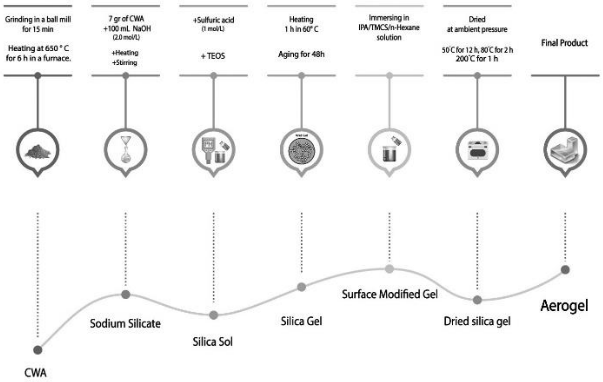

Fig. 1. Preparation process of the hydrophobic silica aerogels synthesized from CWA

C. Characterization Methods

Fourier Transform Infrared Spectroscopy (FTIR)
Performed at room temperature
Shimadzu-8400S spectrometer
Range: 4000–400 cm-1
KBr pellets used

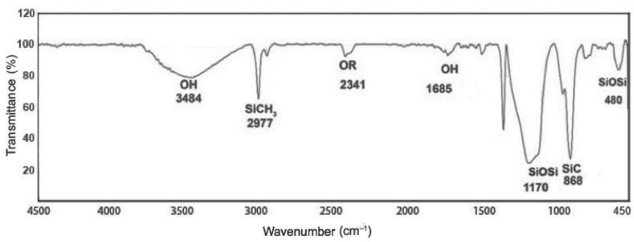

Fig. 2. FT-IR spectrum of the hydrophobic silica aerogel synthesized from CWA

X-ray Diffraction (XRD)

X' Pert Pro X-ray diffractometer
Cu Kα source
40 mA and 40 kV
2-theta range: 10° to 60°

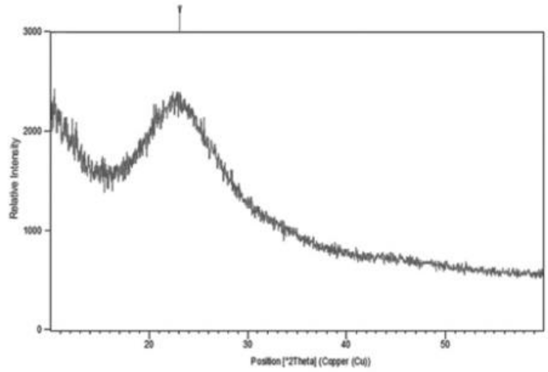

Fig. 3. XRD patterns of the hydrophobic silica aerogel synthesized from CWA

X-ray Fluorescence (XRF)

ED 2000 system
40 kV and 40 mA

Table I. Elemental analysis of the construction waste ash (wt.%).

Compound	Weight Percentage (%)
MgO	1.38
Al_2O_3	8.70
SiO_2	62.07
P_2O_5	0.74
SO_3	1.04
K_2O	2.07
CaO	17.39
TiO_2	0.49
MnO	0.14
Fe_2O_3	4.74
SrO	0.10
Cr_2O_3	0.12

Scanning Electron Microscopy (SEM)

VEGA/TESCAN model
Surface Area and Pore Analysis
Brunauer-Emmitt-Teller (BET) method
Barrett-Joyner-Halenda (BJH) method
BElSORP Mini instrument

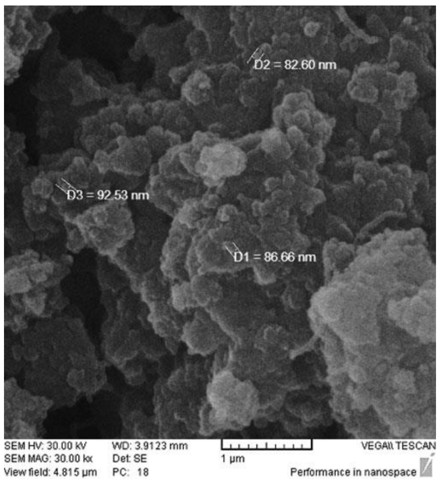

Fig. 4. SEM images of the hydrophobic silica aerogels synthesized from CWA

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Density and Porosity Calculation
Bulk density calculated by mass-to-volume ratio
Skeletal density tested by helium pycnometry
Porosity calculated using the formula:

$$\text{Porosity} = (1 - \rho b/\rho s) \times 100\% \quad (1)$$

Where ρb and ρs are bulk and skeletal densities [11].

Hydrophobicity Test

Contact angle measurement
Calculated using the formula:

$$\theta = 2\tan{-1}(2h/w) \quad (2)$$

Where h is height and w is width of water droplet [12].

Table II. The physical properties of hydrophobic silica aerogel synthesized from CWA

Mean pore diameter (nm)	Pore volume (cm^3/g)	BET specific surface area (m^2/gr)	Bulk density (g/cm^3)
13/472	0/8263	288/23	0/498

Fig. 5. Shape of a water droplet on silica aerogel synthesized from CWA

III. RESULTS AND DISCUSSION

A. Elemental Composition Analysis

the top axis label in Fig. 1 meant 16000 A/m or 0.016 A/m. Figure labels should be legible, approximately 8 to 12 point type.

B. Structural Characterization X-Ray

Diffraction (XRD) Analysis

Figure 2 presents the XRD pattern of the synthesized silica aerogel. A wide peak observed in the 20° to 30° range indicates the amorphous nature of the silica structure. This amorphous characteristic is typical of silica aerogels and contributes to their unique properties.

Microstructural Examination

Scanning Electron Microscopy (SEM) images (Figure 3) revealed the nanostructure of the silica aerogel. The micrographs clearly show a highly porous material with nanoscale pore sizes, confirming the successful synthesis of a nanoporous silica aerogel. (see Table I).

C. Physical Properties

Table II summarizes the key physical properties of the hydrophobic silica aerogel:
Bulk Density: 0.498 g/cm³
Specific Surface Area: 288.23 m²/g
Pore Volume: 0.8263 cm³/g
Mean Pore Diameter: 13.472 nm
These characteristics demonstrate the exceptional properties of the synthesized aerogel, particularly its ultra-low density and high surface area.

D. Surface Modification and Hydrophobicity

1. Fourier Transform Infrared (FTIR) Analysis The FTIR spectrum (Figure 4) provided insights into the chemical composition and surface modification:
   - Peaks at 1170, 868, and 480 cm-1: SiO_2 symmetric and asymmetric modes
   - Bands at 3484 and 1685 cm-1: Hydroxyl groups
   - Peaks at 2977 and 868 cm-1: Surface modification by TMCS
2. Hydrophobicity Characterization Contact angle measurements confirmed the hydrophobic nature of the aerogel. Figure 5 shows a water droplet on the aerogel surface, with calculations revealing a contact angle of 122°. This high contact angle indicates excellent water repellency, achieved through surface modification with trimethylsilyl chloride (TMCS).

E. Significance of the Approach

synthesis of a hydrophobic silica aerogel from construction waste ash demonstrates a promising approach to:

- Recycling industrial waste
- Reducing material production costs
- Creating high-value nanomaterials
- Addressing environmental waste management challenges

The low-cost synthesis method and the ability to transform construction waste into a high-performance material represent a significant advancement in sustainable material science.

IV. CONCLUSION

This research successfully demonstrated an innovative approach to recycling construction waste by converting it into high-performance hydrophobic silica aerogels through a cost-effective sol-gel method with ambient pressure drying. The key findings of the study can be summarized as follows:

1. **Material Composition and Recycling:** Construction waste ash (CWA) was found to contain over 50% silica, enabling direct extraction as a sodium silicate precursor. This approach provides a sustainable solution to waste management by transforming industrial by-products into valuable nanomaterials.

2. **Aerogel Characteristics:** The synthesized silica aerogel exhibited exceptional properties:
   - Ultra-low bulk density of 0.498 g/cm³
   - High specific surface area of 288.23 m²/g
   - Nanoscale porosity with mean pore diameter of 13.472 nm
   - Hydrophobic surface with a contact angle of 122°
3. **Synthesis Methodology:** The ambient pressure drying method, combined with surface modification using trimethylsilyl chloride (TMCS), successfully created a hydrophobic silica aerogel with remarkable physical and chemical properties.

Potential Applications: The developed material shows promising potential in various fields, including:

- Thermal insulation
- Drug delivery systems
- Environmental remediation
- Advanced composite technologies

Broader Impact: This research contributes to circular economy principles by demonstrating a practical approach to converting waste materials into high-value nanomaterials, addressing both waste management and material innovation challenges.

Future Work: Additional research could explore:

- Further optimization of the synthesis process
- Investigation of additional surface modifications
- Expanding potential applications of these recycled silica aerogels

By demonstrating the transformation of industrial waste into advanced nanomaterials, this study highlights the potential for innovative solutions at the intersection of materials science and sustainable development.

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